Carbon Emissions Evaluation for Highway Management and Maintenance

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CARBON EMISSIONS EVALUATION FOR HIGHWAY MANAGEMENT AND MAINTENANCE

By
Emioshor Itoya

A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

December 2012

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ABSTRACT

Highway clients are increasingly concerned with the environmental consequences and sustainability implications of their highway maintenance service. This is because the service consumes a significant amount of natural resources, is financial and energy-intensive and is a large Greenhouse gas (GHG) emitter responsible for global warming and climate change. This has placed the highway maintenance sector, including its supply chain under increasing pressure to deliver well-maintained low-carbon maintenance service, whilst addressing its climate change impacts. The highway stakeholders' increasing focus on carbon footprinting is a direct response to the legal obligation presented by the enactment of the UK's Climate Change Act (2008) and the Carbon Reduction Commitments. Investment decisions on highway infrastructure must now account for carbon and financial costs in a balanced manner. Highway clients now require their supply chains to demonstrate the capacity to reduce both direct and indirect carbon, and provide carbon footprint information relating to the work done or being tendered for. This is driving the sector to re-think its business operations within environmental, economic and social limits, which inherently presents risks and opportunities poorly understood by the stakeholders. It requires an in-depth understanding of the business operations, inputs and outputs. These business requirements are compounded given the lack of an agreed industrial methodology standard focusing on carbon footprinting, the knowledge and skill gaps, system boundary definitions, credible industrial data and their collection approach. The aim of this study is to develop a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool to assist carbon management decision-making in highway maintenance planning and operation. This study then explored how the PAS2050 protocol can enhance the highway maintenance service delivery carbon footprinting and identify opportunities for reduction. It briefly reviews carbon emissions performance and the UK's highway maintenance sector, and developed a methodological framework that includes a carbon evaluation tool (the sponsor's business focus tool) based on the PAS2050 protocol. The framework developed is specific to highway maintenance planning and operation. It offers a carbon Life Cycle Assessment (LCA) tool that can identify emission "hotspots" across the process value chain, and inform a carbon reduction hierarchy. The implementation of the PAS2050-compliant methodology framework and the carbon evaluation tool for core highway maintenance processes (for example, pavement resurfacing, pavement marking, bulk lamp replacement and grass cutting), in addition to carbon footprinting across different site locations (urban, semi-urban and rural) are presented. The results indicate that materials production and their delivery to site (embodied carbon) are areas of carbon hotspots. This represents an important decision point for highway designers, managers and maintainers in order to deliver low-carbon service. These carbon hotspots suggest a less energy-intensive or green materials manufacturing process, responsible sourcing, use of recycled and secondary materials sourced locally (closer to sites) and delivered in bulk. The step-by-step carbon footprinting approach presented in this study is unique. It can be used by other sectors within the built environment as a pragmatic means of identifying and prioritising areas of potential carbon reduction through informed decision-making.

KEY WORDS

Operations Management, Highway Maintenance, Supply Chain, Life Cycle Assessment, PAS2050 protocol; Carbon Footprinting; Carbon Management and Reduction, Decision-making

PREFACE

This thesis presents the result of the research project undertaken as part of the requirements of an Engineering Doctorate (EngD) at the Centre for Innovative and Collaborative Construction Engineering (CICE), Loughborough University. The research was sponsored by Balfour Beatty Highway Service Team (BB-HST) in the UK.

This thesis has been produced in compliance with the CICE's thesis guidelines. It is supported by four refereed papers (the EngD papers: one conference and three journal papers) which must be read in conjunction with the discourse in order to allow the reader to have a better understanding of the research. It presents the key learning and the research undertaken during the past four years is further explained by the thesis.

ACRONYMS/ABBREVIATIONS

ADB	Asian Development Bank
BB	Balfour Beatty
BBLP	Balfour Beatty Living Places
BBMCE	Balfour Beatty Major Civil Engineering
BIS	Department of Business, Innovation and Skills
BSI	British Standards Institution
CF	Carbon Footprinting
CICE	Centre for Innovative and Collaborative Construction Engineering
CMS	Carbon Management System
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
EngD	Engineering Doctorate
EPSRC	Engineering and Physical Sciences Research Council
FHWA	Federal Highway Administration
GHG	Greenhouse Gases
GWP	Global Warming Potential
HA	Highway Agency
ICE	Inventory of Carbon and Energy
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LA	Local Authorities
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
NGO	Non-Governmental Organisations
RE	Research Engineer
SERI	Swedish Environmental Research Institute
SETAC	Society of Environmental Toxicology and Chemistry
TRL	Transport Research Laboratory Limited
UNEP	United Nations Environment Programme
WBCSD	World Business Council for Sustainable Development (WBCSD)
WRI	World Resources Institute

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LIST OF PAPERS

The following papers, included in the appendices, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research.

PAPER 1 (SEE APPENDIX A)

Itoya et al (2012). Carbon Emissions Performance and the UK's Highway Maintenance Sector: Review of the Issues. In: proceedings of the *40th European Transport Conference (ETC)*, Association of European Transport (AET), Glasgow, Scotland.

PAPER 2 (SEE APPENDIX B)

Itoya, et al (2012). Framework for Carbon Emissions Evaluation of Road Maintenance. In Transportation Research Record (TRR): Journal of the Transportation Research Board, No. 2292, Transportation Research Board of the National Academies, Washington, D. C. pp. 1 – 11

PAPER 3 (SEE APPENDIX C)

Itoya, E., Ison, S.G., Frost, M.W., EL-Hamalawi, A. and Hazell, K. (2012). Highway Routine Maintenance Carbon Emissions Assessment. In *Proceedings of Institution of Civil Engineers (ICE): Journal of Engineering Sustainability*. (Accepted for publication)

PAPER 4 (SEE APPENDIX D)

Itoya, E., EL-Hamalawi, A., Ison, S.G., Frost, M.W. and Hazell, K. (2012). Development and Implementation of a Life Cycle Carbon Tool for Highway Maintenance. The American Society of Civil Engineers (ASCE): *Journal of Transportation Engineering.* (under review)

1 CHAPTER ONE: INTRODUCTION

1.1 INTRODUCTION

This chapter presents the background to the EngD research project undertaken in this thesis. It provides a general introduction to the subject domain; justifies the need for the research and sets the research within the industrial context. The chapter also presents the concepts of Life Cycle Assessment (LCA) and Carbon Footprinting (CF) within the context of highway maintenance service and outlines the research aim and objectives. The existing, current and emerging standards promoting CF, their business benefits and related drawbacks are also discussed. The structure of the EngD thesis is presented to provide clarity and direction. A synopsis of the published papers from the EngD research is provided; to be read in conjunction with the thesis in areas where references are made.

1.2 HIGHWAY MAINTENANCE SERVICE FROM LIFE CYCLE PERSPECTIVE

The highway system represents an integral part of any modern society and it forms the basis for vehicle transportation. The highway system maintenance is technically relatively complex and diverse (Stripple, 2001). The need to design and provide a sustainable highway maintenance service is becoming a priority among highway customers and other stakeholders, with the intention to reduce the service's impacts on the environment and tackle climate change. The Swedish Environmental Research Institute (SERI) indicates that the highway system consists not only of the road pavement itself, but other systems such as the traffic control system, road lighting, pavement marking, road signs, geotechnical asset, bridges and tunnels (Stripple, 2001). The US Federal Highway Administration (FHWA) has provided useful definitions of the highway system maintenance namely:

- Preventive Maintenance is "a planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system : without significantly increasing the structural capacity" (FHWA, 2005).
- Routine Maintenance "consist of work that is planned and performed on a routine basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highway system to an adequate level of service" (FHWA, 2005).

These definitions provided useful insights into the highway maintenance activities and the scope of the service that can be used to assess its environmental contributions. Within the context of this study, the highway routine maintenance and the SERI's definitions are adopted, since the definitions offer the service scope, which reflects the EngD sponsor's integrated highway maintenance service delivery within the UK.

In practice, delivering this level of highway maintenance service (integrated highway maintenance service), and meeting the goals of the UK's Strategy for Sustainable Construction (BIS, 2008) requires an in-depth understanding of the system, and their interactions with the supply chains. Zammataro (2010) argued that a well-maintained sustainable highway can only be provided by highway practitioners that are fully aware of the ecological consequences of their business activities (Zammataro, 2010). Figure 1.1 presents the highway system life cycle phases. It categorises the activities that occur over the system life cycle phases, and presents four distinct life cycle phases: materials phase, construction phase, maintenance phase and end-of-life phase. Figure 1.1 also indicates that the highway maintenance phase involves its own materials, construction (on-site activities), use and end-of-life phases.

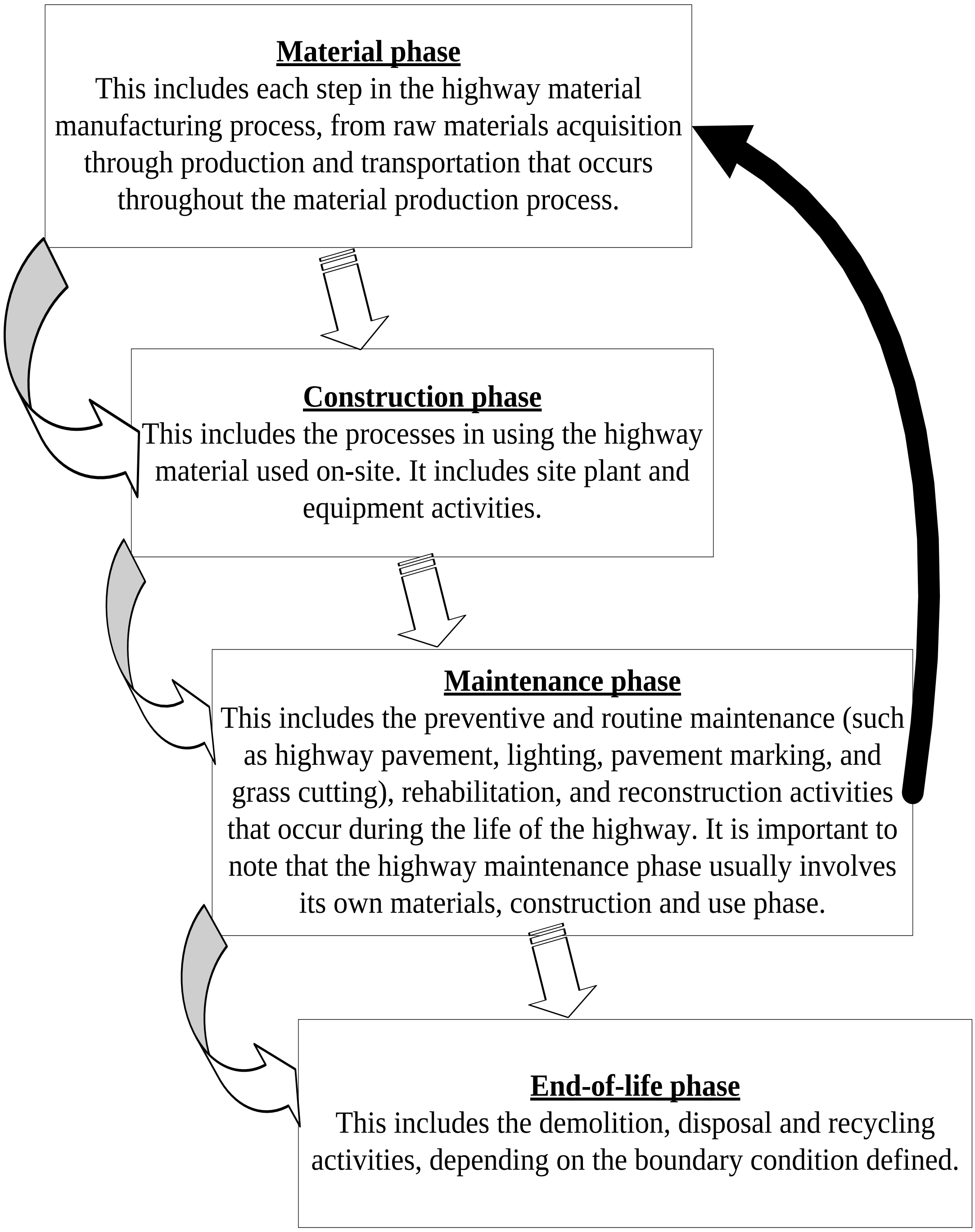


Figure 1.1 Phases of Highway Life Cycle and Related Maintenance Process

(Source: Adopted from (Santero, 2009))

The Life Cycle Assessment (LCA) concept has being accepted by the road industry to measure its key environmental contributions such as the energy consumption and the carbon footprint of its materials and laying processes (Huang *et al.*, 2009).

1.2.1 LIFE CYCLE ASSESSMENT (LCA) AND CARBON FOOTPRINTING (CF)

Life Cycle Assessment (LCA) is a technique that is used worldwide by clients and decision makers for identifying all "cradle to grave" inputs and outputs of their projects on the environment (Treloar *et al.*, 2004 Weiland and Muench, 2010). It is becoming popular in the transportation community given its potential to support business decision-making with quantitative data (Treloar *et al.*, 2004).

The Society of Environmental Toxicology and Chemistry (SETAC) defined LCA as "an objective process to evaluate the environmental burdens associated with a product, process, or activities for identifying and quantifying the energy and material usage and environmental releases, to assess the impacts of those energy and material uses and releases into the environment, and evaluate and implement opportunities to effect environmental improvements" (Society of Environmental Toxicology and Chemistry, 1993). The International Organisation for Standardisation (ISO) also defined LCA as a process that address the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences) throughout a product's life cycle from raw material acquisition, through materials production, use and end-of-life treatment including recycling and final disposal (International Organisation for Standardisation, 2006a). The ISO14040/14044:2006 standards provided the general principles, methodology and requirements of carrying out a full life cycle assessment (International Organisation for Standardisation, 2006a, 2006b).

Carbon Footprinting (CF) is a subset of LCA. It is "a measure of the exclusive total amount of carbon emissions that is directly and indirectly caused by an individual or organisation's activities accumulated over the life stages of a product" (Wiedmann and Minx, 2007). Similarly, CF is viewed as " a methodology that can estimate the total emissions of greenhouse gases (GHG) in carbon equivalents from products across the life cycle, including the acquisition of the raw material used in the product manufacturing to the disposal of the finished product (excluding in-use emissions)" (Carbon Trust, 2011). The Asian Development Bank (ADB) suggests that carbon footprinting is a methodological approach commonly used to describe a product's total amount of CO_2 and other greenhouse gas (GHG) emissions defined by the Kyoto Protocol and the Intergovernmental Panel on Climate Change (IPCC) over the product or service life cycle for which an individual or organisation is responsible (ADB, 2010)

Although the above definitions vary slightly in emphasis and focus, they all acknowledge the environmental consequences of business activities in life cycle terms. The definitions present the LCA and CF as two separate and complementary methodological life cycle approaches that can be used to assess environmental aspects and impacts associated with business activities. By synthesising these definitions the scope for business carbon footprinting and related impacts is provided. Within the context of this study, the term "carbon footprint" or "carbon emissions" or "carbon" is used in this thesis to describe the total amount of carbon dioxide and other Greenhouse gas (GHG) emissions produced directly and indirectly by an individual, organisation, services, processes and activities expressed in carbon equivalent (Asian Development Bank, 2010 BSI, 2008 Carbon Trust, 2011). The concept of highway maintenance carbon footprinting from the sponsor's business perspective is discussed in the next section (section 1.3).

1.3 HIGHWAY MAINTENANCE AND CARBON FOOTPRINTING

Highway maintenance carbon footprinting and reduction is attracting growing attention among highway stakeholders (e.g. Clients, contractors, subcontractors, material suppliers and waste management companies). There is a real and pressing need for businesses within the sector to undertake carbon footprinting, to identify areas of carbon hotspots and opportunities for reduction, and establishes a reduction hierarchy that can allow carbon reduction efforts to be prioritised and supports carbon reduction investments decision-making processes. Huang *et al* (2012) has argued that the adoption of a standard LCA methodology will assist in transparency and the decision-making process. This requires a thorough understanding of the business operations, inputs and outputs. Carbon footprinting offers businesses a process to understand the nature and scale of their contributions to climate change impacts (Sykes, 2011). From the sponsor's highway maintenance business perspective, there is a requirement of the assessment of the material flow, energy flow and the carbon footprint from the raw materials acquisition and production process, transportation, on-site activities and end-of-life treatment across the business value chain. The purpose is to obtain credible carbon information to support decision-making and inform the reduction hierarchy that can prioritise carbon reduction efforts across its supply chain. This business need suggests Life Cycle Inventory (LCI) analysis of the highway maintenance process which the sponsor operates within the UK. Although this presents a significant challenge, it also offers huge business benefits and opportunities.

1.3.1 THE BENEFITS OF BUSINESS CARBON FOOTPRINTING

Business carbon footprinting offers numerous benefits as well as opportunities to:

1. Measure, manage and reduce its carbon expenditure and save costs across the business value chain. This offers businesses the chance to assess their carbon performance in life cycle terms and drive internal change that can build stakeholders' confidence in their business operations.
2. Develop a corporate strategy to understand the concept of business carbon footprinting within the context of the drivers, approaches and related business benefits, and addresses the risks that businesses are expected to manage in order to enhance their business competitiveness, green and sustainability credentials, and Corporate Social Responsibility (CSR) image.
3. Develop a robust corporate strategy that can provide a pragmatic means of identifying areas of maximum carbon usage and opportunities for reduction and support investment decision-making.
4. Show existing and potential customers a proof of commitment to addressing environmental and climate change issues associated with their daily business activities. This offers opportunities to build new business streams and enhance long-term sustainable business success.

The lack of commonly accepted industrial (construction) standard, tools, credible data, methodology, carbon allocation, functional units and system boundary definitions within the sector are frustrating business efforts to undertake carbon footprinting.

1.3.2 STANDARDS ON CARBON FOOTPRINTING

The existing, current and emerging standards discussed in Table 1.1provide guidance, specifications and specific scope on carbon footprinting in life cycle terms. The International Organisation for Standardisation ISO14040 (International Organisation for Standardisation, 2006a) and ISO14044 (International Organisation for Standardisation, 2006b) present the “principles and framework” and the “requirements and guidelines” on “Environmental Management Life Cycle Assessment”. Table 1.1 presents the existing, current and emerging standards promoting carbon footprinting and reporting which build on the existing ISO life cycle principles and requirement.

Table 1.1 Standards Promoting Carbon Footprinting and Reporting

Standards	Sources	Focus
World Business Council for Sustainable Development (WBCSD) and World Resources Institute (WRI) GHG Protocol.	World Business Council for Sustainable Development (WBCSD) and World Resources Institute (WRI).	To develop an internationally accepted life cycle Greenhouse gas (GHG) emissions accounting and reporting standards at corporate and project levels. The standards offer step-by-step guidance and specific requirements for quantifying and reporting businesses and project level carbon footprint (WRI and WBCSD, 2011).
United Nations Environmental Programme (UNEP)/ Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative.	UNEP/SETAC project group on carbon footprinting	To develop an internationally recognised GHG protocol for organisational GHG emissions accounting and reporting across their supply chain (UNEP/SETAC, 2009)
ISO 14064-1:2006	International Organisation for Standardisation (ISO)	To provide guidance for quantification and reporting of GHG emissions and removal at the organisational level (International Organisation for Standardisation, 2006c).
DEFRA’s Environmental Key Performance Indicators (KPI)	UK’s Department for Environment, Food and Rural Affairs (DEFRA)	To provide a guidance to enable the UK’s businesses key environmental impacts to be assessed, managed and reported (Department for Environment Food and Rural Affairs, 2006).

Carbon Trust guidance on carbon footprinting	Carbon Trust Limited	Offers a step-by-step guidance on carbon footprinting and reporting, which include: methodology, system boundary and scope definitions, data collection approach and carbon calculation, verification of the footprints result and reporting (Carbon Trust, 2011)
Inventory of Carbon & Energy (ICE)	University of Bath (Inventory of Carbon and Energy) ICE.	This provides an inventory of carbon and energy of building materials (embodied carbon and energy coefficients) from secondary data sources. It represents an important emissions factor source for construction materials currently used in the UK (Hammond and Jones, 2011)

The carbon footprinting and reporting standards outlined in Table 1.1 reveal the scope of carbon footprinting and input from multi-stakeholders . These standards offer a starting point for businesses to undertake carbon footprinting and reporting at corporate, project and product levels in life cycle terms. The standards promote life cycle methodology for business carbon emissions assessment, but fail to shed light on the specific carbon data type required and their collection approach, and the standards lack specific requirements for carbon footprinting. The scope and system boundary definition issues, consistent functional unit specifications and the inability of the standards to offer easy to use and auditable guidance for organisations' carbon footprinting and reporting across different product types are other shortcomings. In addition, the standards also lack the capacity to provide organisations with a pragmatic means of identifying areas of carbon hotspots and opportunities for reduction that can inform a reduction hierarchy and allow carbon reduction efforts to be prioritised. The drawbacks inherently presented by these shortcomings are critical issues in which organisations' carbon footprinting and reduction are deeply rooted.

It is important to note that a business with the capacity to measure; manage and communicate its carbon footprint and environmental performance efficiently has competitive advantage over others. It will understand how to improve its business process and reduce its operational costs, whilst meeting carbon footprinting regulatory drivers (Department for Environment Food and Rural Affairs, 2006). There is a need for more appropriate mechanisms that can offer businesses the capacity (expertise and resource) to account for both direct and indirect carbon footprinting across their value chain; identify areas of carbon hotspots; opportunities for reduction and give carbon information appropriate profile in business decision-making. This presents scope for businesses to improve their competitiveness by understanding the issues that they are expected to manage and address, and enhance their carbon performance in life cycle terms.

The emergence of the Publicly Available Specification (PAS2050:2011) standard (the protocol builds on existing and current environmental performance standards) offers businesses with the capacity to address some issues (discussed above) on carbon footprinting. If properly employed, it can provide businesses with a methodological framework with a high level of analytical rigour that can evaluate and communicate their environmental contributions. The life cycle methodology described by the PAS2050 protocol (see section 1.4.2) is adopted for this study for highway maintenance carbon footprinting, given its capacity to:

- Assist businesses to obtain a representative carbon inventory that can create baseline carbon information for carbon benchmarking through the use of a standardised principle and approach;
- Provide credible carbon information that can be used to develop a robust corporate strategy to measure, manage and reduce the related carbon footprint through informed decision-making, and facilitates business participation in carbon reduction initiatives, whilst meeting the regulatory and non-regulatory requirements driving the agenda.

1.4 BACKGROUND TO THE RESEARCH

1.4.1 THE RESEARCH FOCUS

The UK through its Climate Change Act (CCA) and Carbon Reduction Commitment (CRC) Energy Efficiency Scheme has made commitments to reduce its carbon and other Greenhouse Gases (GHG) emissions by at least 80% by 2050, and 34% below 1990 levels by 2020 through a system of carbon budgeting (DECC, 2010). In addition, the strategic review undertaken on behalf of the UK's Department of Business, Innovation and Skills (BIS) on the of the UK's construction industry capacity to meet the challenge of the low-carbon agenda provides a preliminary estimate (48% of the UK total emissions) of the carbon emissions the industry has the capacity to influence (BIS, 2010). The review indicates that the strategy by which these targets can be achieved reach deep every aspect of the UK economy. Therefore, numbers of initiatives have been introduced to enable the UK meeting these targets. These include:

- the UK's Low-Carbon Transition Plan (DECC, 2010), which set out a route-map to meet the 34% emissions reduction target by 2020 (DECC, 2010),
- the "2050 Pathways Analysis" (DECC, 2010) which details the changes that must occur in the UK's sectors to enable the 80% emissions reduction target to be achieved by 2050 and,
- the Carbon Plan (DECC, 2011), which provides the policies and proposal to meet the first four carbon reduction budgets (DECC, 2010).

The transport sector currently account for 24% of the total UK's domestic emissions (BERR, 2008), and the sector and its supporting infrastructure is required to play a significant role towards meeting the UK's carbon emissions reduction targets. As such, Civil infrastructure, including the highway maintenance sector is under increasing pressure to deliver low-carbon services following the enactment of the UK's Climate Change Act (2008),and highway customers (e.g. HA and LA) are increasingly concerned with the environmental consequences and sustainability implications of their highway maintenance service. This is because the service consumes a significant amount of resources, is financial and energy-intensive and is a large Greenhouse gas (GHG) emitter. Carbon footprint reduction and its consideration in business decision-making are attracting growing attention, which requires a deeper understanding of the business operations, inputs and outputs. Meanwhile, measuring and reducing carbon from business operations have become a legal obligation following the enactment of the UK's Climate Change Act (2008) and the Carbon Reduction Commitments (2010). Reducing the carbon footprint from highway maintenance can help meet the carbon emissions reduction targets set under the UK's Climate Change Act (DEFRA, 2008).

Following these developments, carbon footprinting is now often a contractual requirement and part of the tender selection criteria, particularly from the highway maintenance sector. Investment decisions on highway infrastructure must now account for carbon and financial costs in a balanced manner. Highway customers now require their supply chain to demonstrate the capacity to reduce both direct and indirect carbon, and provide carbon footprint information relating to the work done or being tendered for. This promotes carbon consideration in the business decision-making process. Furthermore, highway maintenance procurement and investment decisions are now being examined not only from economical and technical view points, but also from an environmental perspective (Hoang *et al.*, 2005 Muench, 2010), with the intention of designing and delivering a well-maintained low carbon highway service within economic, social and environmental limits. This thesis covers research work undertaken on highway routine maintenance carbon footprinting using the Life Cycle methodology presented by the PAS2050 protocol.

1.4.2 BACKGROUND TO THE PAS2050 PROTOCOL

The PAS2050 protocol provides the "specification for the assessment of the life cycle greenhouse gas emissions for goods and services". The protocol was developed by the British Standard Institute (BSI) in 2008, and updated in 2011(British Standards Institution, 2008, 2011 Transport Research Laboratory Limited, 2010) co-sponsored by the Carbon Trust and Department of Environment, Food and Rural Affairs (DEFRA) with significant input from international stakeholders, industries, government and NGOs, and experts across business and academia (British Standards Institution, 2008 Sustain Limited, 2010).

The protocol was developed as a direct response to the wider industry and business demand for a consistent and robust methodology of assessing life cycle carbon emissions associated with goods and services. It provides a common basis for carbon emissions quantification from goods and services; so as to inform a reduction strategy across the product's supply chain. PAS2050 is not a British standard, European or International standard (Sustain Limited, 2010), but an independent standard that builds on existing environmental management life cycle assessment methodology created by the ISO14040: Principles and Framework (International Organisation for Standardisation, 2006a) and ISO14044: Requirements and Guidelines (International Organisation for Standardisation, 2006b) discussed in section 1.3.2. The use of the PAS2050 methodology for carbon footprinting is a three stage iterative process, which includes (1) setting up, (2) carbon emissions calculation and (3) the next step (validate results and reduce emissions). The three processes are further expanded to include objective and scope definition, collection of relevant carbon data defined by the protocol's data quality rules, and the analysis and interpretation of results within the scope and system boundary defined. The protocol has the capacity to assess the carbon footprint across system boundaries outlined :

(1) "Business-to-Consumer (B2C)": Where the customer is the end user of the product.

(2) "Business-to Business (B2B): Where the customer is another business using the product as part of its own business activities.

Although PAS2050 provides a life cycle methodology framework that can identify areas of carbon hotspots and opportunities for reduction, it also provides the biggest potential carbon reduction opportunity within the product. Yet like other complementary carbon emissions assessment approaches, the protocol has its drawbacks. For example, it focuses on a single environmental issue (carbon emissions) over the product or service life cycle, and excludes other potential environmental impacts associated with the goods and services. Hence its wider adoption in the construction industry as a carbon emissions assessment industrial standard has been slow. (Huang *et al.*, 2012). Business decisions based on a single environmental impact may have disruptive consequences. However, the protocol offers many advantages in terms of completeness, consistency and reproducible carbon emissions results(British Standards Institution, 2008 Sustain Limited, 2010), which are obviously lacking in other approaches and standards. This then reveals why the methodology is being considered as a default approach for carbon footprinting across different product or service types. Its robustness as a product or service carbon assessment methodology is inherent in the significant inputs received from multi-stakeholders through formal consultation and multiple technical working groups (British Standards Institution, 2008).

1.4.3 THE PROTOCOL ALIGNMENT WITH EXISTING STANDARDS

A number of methodologies have been developed to support the carbon footprinting of products and services. These include PAS2050:2011(British Standard Institute, 2011), the recent “GHG protocol for product life cycle carbon accounting and reporting standard” (WRI and WBCSD, 2011) and the expected ISO equivalent of the PAS2050 protocol (PCF World Forum, 2012) “Standard for products Carbon footprinting” (Atkins, 2012). ISO 14067:2013 builds on the carbon assessment methodology provided by the PAS2050 protocol (PCF World Forum, 2012). The application of PAS2050 protocol for highway maintenance service carbon footprinting is the primary focus of this study. Figure 1.2 presents how the PAS2050 carbon footprinting principles can be aligned with the existing standards on environmental life cycle assessment. This can be used to develop an inventory of a service carbon footprint, subsequent management and communication of the service footprint.

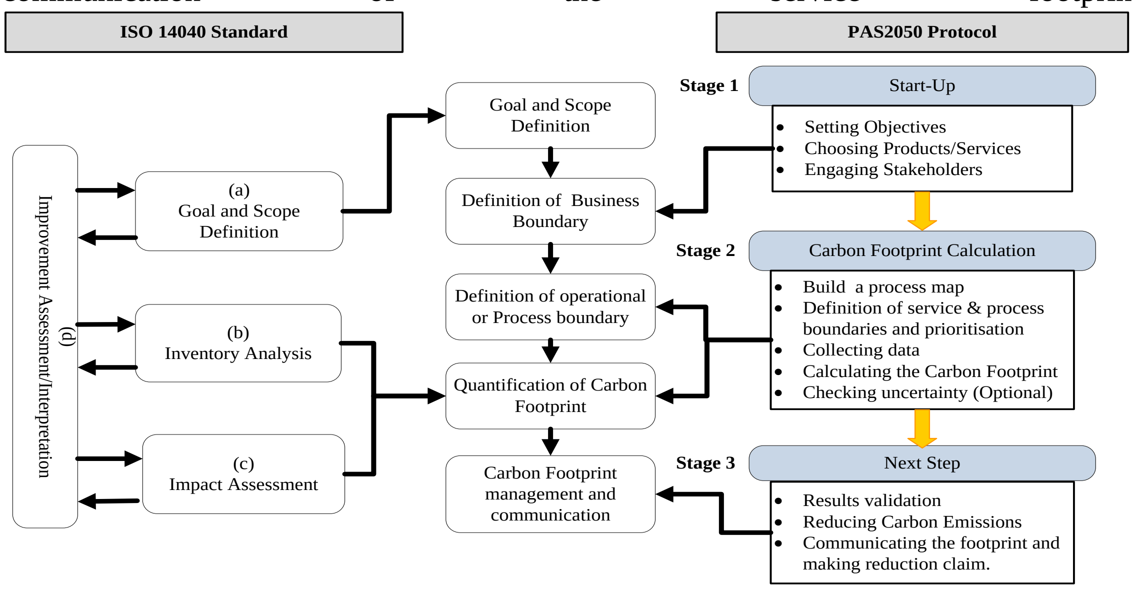


Figure 1.2 PAS2050 Compliant Model for Carbon Footprinting at Service and Process

(Source: (Scipioni *et al.*, 2012) (modified))

1.4.4 EXAMPLES OF PAS2050 PROTOCOL APPLICATIONS

Table 1.2 presents examples of areas where the PAS2050 protocol has been applied, with key benefits and related drawbacks shown.

Table 1.2 Applications of PAS2050 Protocol for Carbon Footprinting

Examples of Application	Benefits	Drawbacks
The Transport Research Laboratory (TRL) in collaboration with the Highway Agency (HA), Mineral Products Association and Refined Bitumen Association in 2009, produced the asphalt Pavement Embodied Carbon Tool (asPECT) using the PAS2050 protocol	• The asPECT tool is currently used as the UK road industry standard for carbon footprinting associated pavement construction and maintenance. • Major asphalt manufacturers and aggregate suppliers in the UK (e.g Tarmac Limited and Midlands Quarry Products Limited (MQP)) have adopted the asPECT methodology • Accounts for potential GHG emissions of different alternatives at the procurement stage.	• The asPECT tool accounts for GHG emissions only. • The tool mainly focuses on carbon information “cradle to site”, but excludes other life cycle phases. • The asPECT tool is focused on asphalt pavement carbon assessment. Other highway maintenance processes such as pavement making, bulk lamp replacement and grass cutting operations are outside the scope of the tool.
The Carbon Management System (CMS) - a range of carbon tools developed by Halcrow Limited in 2010 on behalf of Transport Scotland. The primary goal was to allow carbon optimisation through highway design and construction processes (Fox *et al.*, 2011)	• The CMS demonstrates robust carbon analytical capacities. • It provided a range of carbon tools that can evaluate pavement carbon footprint at the design and construction stages expressed in carbon equivalent (CO2e).	• The CMS does not allow end-of-life emissions treatment and sensitivity analysis based on emission variables (see Table 2.1).

1.5 RESEARCH CONTEXT

1.5.1 THE AUTHOR

The author has a background in civil engineering and has spent the majority of the four years of the Engineering Doctorate research working as a Research Engineer (RE) in the sponsor's (Balfour Beatty Highway Service Team (BB-HST)) Sustainability Department (consists of a director, sustainability manager, research engineer, practitioner and coordinator) responsible for overseeing and implementing BB-HST's sustainability strategy and action plan; which sets out BB-HST's sustainability objectives, targets, actions, responsibility allocations, programme and reporting plans for both internal and external stakeholders.

1.5.2 THE INDUSTRIAL SPONSOR

BB-HST (the industrial sponsor) is a leading UK provider of integrated highways and transportation solutions for both the Local Authorities (LA) and Highway Agency (HA). It comprises two Operating companies (OpCo) within Balfour Beatty group namely: Balfour Beatty Living Places Limited (BBLP Limited) responsible for maintaining Local Authorities (LA) owned highways, and Balfour Beatty Major Civil Engineering (BBMCE) responsible for the maintenance of Highway Agency (HA) owned highways within the UK. The industrial sponsor's business operation covers highway management and maintenance and civil engineering works, together with related design, consultancy and specialist services. BB-HST has recognised the need to meet highway client's demand on business sustainability and carbon footprint reduction in order to consolidate its market position and improve its competitive advantage, whilst enhancing its green and sustainability credentials. In addition, BB-HST also understands that undertaking carbon footprinting for highway maintenance operations and reducing the resulting emissions is crucial to the success of the service it provide to its customers (LA and HA), both as part of its commitment to sustainability, and to help its customers to meet their needs in the UK's low-carbon conscious economy.

However, the sponsor had not been able to identify a pragmatic means of maximising the potential opportunities of carbon emissions reduction initiatives within its highway maintenance planning and operation. It was therefore, necessary to establish a hierarchy of optimum carbon reduction opportunities. These opportunities needed to be balanced against any sensitive input and output requirements to effect a change. To address this business need within the sponsor business context, BB-HST sponsored the EngD research project with the intention of developing a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool (sponsor's business focus tool) that can support its carbon management decision-making in highway maintenance planning and operation. This suggests the need to develop a carbon footprinting framework including a carbon evaluation tool underpinned by a robust methodology, outputs from complementary studies and a credible carbon data and collection approach. This will enable the sponsor to evaluate its business carbon footprint holistically, and identify carbon "hotspots", related opportunities for reduction and inform a hierarchy to prioritised carbon reduction efforts across the business value chain.

The Centre for Innovative and Collaborative Construction Engineering (CICE) at Loughborough University was established in 1999 to provide a centre of excellence committed to advanced innovation, and provide cutting-edge research in Engineering and Management which particular emphasis on the built environment (CICE, 2012). To meet the sponsor's business needs from its business operation perspective, the CICE's prestigious four-year Engineering Doctorate (EngD) programme (a radical alternative to the traditional PhD) offers an excellent collaborative opportunity for the current EngD research project to be initiated by the sponsor, in collaboration with the CICE in 2008, co-sponsored by the UK's Engineering and Physical Sciences Research Council (EPSRC). As such, a Research Engineer (RE) was then employed (who spends 70% or more of his time working at the sponsor's premises and the 30% of the time at the centre) to undertake the research on behalf of the industrial sponsor within the research scope, aim and objectives discussed below.

1.5.3 RESEARCH STAKEHOLDERS DEFINITION

BB-HST's business operation covers integrated highway management and maintenance services for both the HA and LA across the UK. Its' internal stakeholders (Highway Asset Management and Sustainability Teams) and external stakeholders (subcontractors, material manufacturers, suppliers and waste management companies) are required to play a significant role in delivering these scope of service in order to retain its leading position as integrated highway service provider in the UK. Table1.3 presents the research stakeholders considered and summaries their responsibilities within the context of the sponsor's business operation and the EngD research. Chapter three (section 3.5.2, Table 3.6) provides detail of the initial stakeholder engagement process that allow early definition of the research scope, objectives, expected business benefits and allocate responsibilities to enhance the data collection process and address issues around safety/legal/commercial confidentialities.

Table 1.3 Research Stakeholders Definition

<table>
<tr><th>Research Stakeholders</th><th>Highway Maintenance Processes Considered</th><th>Who they are?</th><th>Summary of Responsibility</th></tr>
<tr><td rowspan="2">Balfour Beatty Highway Service Team's (BB-HST) Internal Stakeholders (Asset Management and Sustainability Teams).</td><td rowspan="2">• Pavement Resurfacing.
• Pavement Marking.
• Bulk Lamp Replacement
• Grass Cutting.</td><td>Highway Process Managers/Owners.</td><td>• Responsible for the planning, managing and delivery of specific highway maintenance process.
• Manage other BB-HST's business stakeholders (e.g. subcontractors).</td></tr>
<tr><td>Industrial supervisor (Sustainability Manager).</td><td>• Provides industrial context of the EngD research from BB-HST's business perspective.</td></tr>
</table>

		Highway Designers.	• Undertake highway design and materials specification. • Support the delivery of BB-HST's Quality Management System.
		Site Supervisors and Operatives.	• Co-ordinate all site activities, and ensure all planned works are perform based on the design and materials specification.
Balfour Beatty Highway Service Team's External Stakeholders (Supply Chain).		Material Manufacturers.	• Manufacture highway materials. • Manufacture, transport and lay materials on site (sometimes work as a subcontractor e.g. Tarmac Limited).
		Materials Supplier.	• Supply highway materials to BB-HST depots from manufactures.
		Waste Management Companies.	• Transport waste off-site and manage waste based on BB-HST's Waste Management Plan (WMP).

1.6 SCOPE OF RESEARCH, AIM AND OBJECTIVES, RESEARCH DESIGN

1.6.1 RESEARCH SCOPE

The study was primarily undertaken to develop a project-focused and process-based carbon footprinting methodology framework based on PAS2050 protocol, and explore how the methodology can be embedded in the highway maintenance process value chain. The intention was to design and deliver a highway maintenance service with minimum carbon impact. The PAS2050 protocol application is finding its wider application in the UK (Huang *et al.*, 2012) as asphalt pavement embodied carbon assessment tool, called asPECT (Wayman *et al.*, 2011) and Carbon Management System (CMS) at design and construction stages (Fox *et al.*, 2011). However, this is the first time a project-specific and process-based methodology framework that includes a carbon evaluation tool has been developed based on the PAS2050 protocol to evaluate the carbon emissions associated with highway system (defined by SERI) across its value chain. The framework developed has the capacity to evaluate the carbon footprint from selected core highway maintenance processes namely: pavement resurfacing, bulk lamp replacement, pavement making and grass cutting) undertaken at different site locations (urban, semi-urban and rural). The material and energy (e.g. diesel, electricity and natural gas) consumed during the raw material extraction stage through manufacturing, transportation, on-site activities and related waste recycling "cradle-to-grave" are collated and analysed in terms of carbon. This presents a life cycle approach that can identify areas of maximum carbon usage, and opportunities for reduction and provides for the biggest potential emissions reduction opportunity through informing decision-making.

1.6.2 RESEARCH AIM AND OBJECTIVES

1. The main aim of this research is to develop a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool to assist carbon management decision-making in highway maintenance planning and operation. The methodology and carbon evaluation tool are specific to Balfour Beatty's highway maintenance planning and operation. Four specific objectives were identified in order to achieve the main research aim. These objectives were:To undertake a literature review of carbon emission performance issues and highway pavement emission Life Cycle Assessment;
2. To develop and evaluate a project-specific and process-based carbon footprinting methodology based on PAS2050 Protocol;
3. To develop and evaluate a process-based carbon evaluation tool and demonstrate its suitability for carbon-based decision-making;
4. To produce and implement the carbon evaluation tool dissemination strategy to allows for the tool improvement and adoption.

1.6.3 RESEARCH DESIGN

The sponsor has not been able to identify a practical means of maximising its potential carbon reduction initiatives within its highway maintenance planning and operation, and enhance its business competitiveness. It was therefore necessary to establish a reduction hierarchy that can support carbon management decision-making and allows carbon reduction efforts to be prioritised. This suggests a knowledge framework (conceptual) that can be used as information source to develop corporate reduction strategy for carbon emissions performance. The strategy should include carbon evaluation tool underpinned by a robust methodology and outputs from complementary studies, credible carbon data and collection approach. The research work detailed in Chapter Four (section 4.3) follows the research stages outlined in table 3.5 (Chapter 3), which commenced with the state-of-the-art literature review to understand the contents and requirements of business carbon footprinting and reduction from the regulatory and non-regulatory policy drivers' perspective. This was followed by an additional literature review to explore current carbon management practices in civil infrastructure including the highway infrastructure maintenance sector and opportunities presented by the sector to enhance carbon performance (see EngD Paper 1, Appendix A). A knowledge framework that can be used as information source by businesses to develop a robust corporate strategy to enhance their carbon performance was developed (*Preliminary data gathering and research problem definition*). The next stage was to understand the current carbon footprinting practices within the civil infrastructure sector including highway maintenance. This led to a highway maintenance specific methodology framework (see EngD Paper 2, Appendix B) that includes a carbon evaluation tool to be developed based on the PAS2050 life cycle methodology (see EngD Paper 4, Appendix, D). The framework was then evaluated based on the selected core highway maintenance processes (see EngD Paper 3, Appendix C) to demonstrate its business implementation as carbon footprinting and decision-support tool (*Investigation stage*). This is to facilitate effective carbon management from highway maintenance processes through informing decision-making.

The next stage of the research is to produce and implement the carbon evaluation dissemination strategy that can allows for the tool improvement and subsequent adoption for use within the sponsor's and its' stakeholders (see Table 1.3) business activities. This is crucial to understand the stakeholders' shared views on the carbon evaluation tool developed and capture suggestions for the tool improvement (*Application stage*).

The EngD research with respect of its overall aim, objectives defined, and the research work tasks undertaken, findings and conclusions drawn from the study are detailed in the subsequent chapters of this thesis. Table 1.4 presents the research aim, objectives defined, method employed and how they relate to the EngD papers published.

Table 1.4 Research Objectives, Method and the EngD Papers Published

Aim : To develop a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool to assist carbon management decision-making in highway maintenance planning and operation		
Objectives	**Method**	**EngD Paper**
Objective 1 To undertake a literature review of carbon emission performance issues and highway pavement emission Life Cycle Assessment.	Literature Review (LR)	Carbon Emissions Performance and the UK's Highway Maintenance Sector: Review of the Issues. EngD Paper 1 (see Appendix A)
Objective 2 To develop and evaluate a project-specific and process-based carbon footprinting methodology based on PAS2050 Protocol	• Literature Review • Modelling • Process Mapping • Survey • Quantitative Data Analysis	Framework for Carbon Emissions Evaluation of Road Maintenance. EngD Paper 2 (see Appendix B) Highway Routine Maintenance Carbon Dioxide Emissions Assessment. EngD paper 3 (see Appendix C)

Objective 3 To develop and evaluate a process-based carbon evaluation tool and demonstrate its suitability for carbon-based decision-making	• Literature Review • Modelling • Quantitative Data Analysis	Development and Implementation of a Life Cycle Carbon Evaluation Tool for Highway Maintenance. EngD paper 4 (see Appendix D)
Objective 4 To produce and implement the carbon evaluation tool dissemination strategy to allows for the tool improvement and adoption	• Action Research • Observation	See the EngD Thesis (Chapter Four in section 4.4.2)

1.7 THESIS STRUCTURE

This thesis documents the research work undertaken during the four year EngD research project. It is structured as follows:

Chapter One: The chapter introduces the research project and provides the background to the project general subject domain. It justifies the need for the research, sets it within an industrial context and discusses the research scope, overall aim and objectives, and outlines the steps taken for this study.

Chapter Two: provides a background to the EngD by reviewing related work on the Life Cycle Assessment and process-based carbon footprinting. It also provides a knowledge framework in which the EngD project is defined and established, and highlights the contribution of the research in demonstrating innovation in the application of the PAS2050 protocol for business carbon footprinting and decision-making within the context of the highway maintenance planning and operations.

Chapter Three: reviews a range of research methodologies including quantitative and qualitative methods and highlights those adopted for the EngD project; and the reason for their adoption. The chapter also presents the research process adopted in this study.

Chapter Four: presents the research work undertaken to meet the aim and objectives of the study. This includes details of the development of the PAS2050 compliant methodology framework and carbon evaluation tool. The implementation of the framework and tool for the highway maintenance process carbon footprinting and decision-making are demonstrated, and illustrated using screen shots.

Chapter Five: summarises and discusses the key research findings, and sets out how the research objectives are met and the contribution to knowledge. It also identifies the impacts of the study on the industrial sponsor and its implications for the wider industry. A critical evaluation of the research presents the study limitations and outlines areas for further study.

The Appendices contain the four peer-reviewed published papers that resulted from this research. These papers form an integral part of this research project and should be read in conjunction with this thesis. As such, throughout the discourse, references are made to the papers which contain further details of the research work undertaken.

1.8 SYNOPSIS OF PAPERS

The EngD papers published as part of this research in order to disseminate the research findings, are included in this thesis as outlined in Table 1.54. Alongside the title, status and place of publication, a brief description of each paper is provided which detailed its contribution to the achievement of each research objective. A number has been assigned to each paper for identification together with its location within the thesis appendices. Table Synopsis of the EngD Papers

ID	Title	Journal/ Conference	Status	Description
Paper1 Appendix A	Carbon Emissions Performance and the UK's Highway Maintenance Sector: Review of the Issues.	Proceedings of the European Transport Conference (ETC), October, Glasgow, Scotland, UK (October 2012)	Published (conference) Peer Reviewed	This paper presents a knowledge framework that can be used as an information source by business to develop a robust corporate strategy for carbon performance.
Paper 2 Appendix B	Framework for Carbon Emissions Evaluation of Road Maintenance	Transportation Research Record, No. 2292 (January 2012)	Accepted (Journal) Peer Reviewed	This paper describes the development process of a PAS2050-compliant methodology framework that can offer businesses a carbon footprinting tool to identify areas of carbon hotspots across their value chain.
Paper 3 Appendix C	Highway Routine Maintenance Carbon Dioxide Emissions Assessment	Institution of Civil Engineers (ICE): Journal of Engineering Sustainability (2012)	Accepted (Journal) Peer Reviewed	This paper describes the business implementation and results of the process-based PAS2050-compliant methodology framework
Paper 4 Appendix D	Development and Implementation of a Life Cycle Carbon Evaluation Tool for Highway Maintenance	American Society of Civil Engineers (ASCE): Journal of Transportation Engineering (Forthcoming)	Under Review (Journal) Peer Reviewed	This paper describes the development and business application of the process-based PAS2050-compliant carbon evaluation tool for carbon footprinting and business decision-making support

1.9 SUMMARY

This chapter provides a general introduction to the EngD research and the subject domain. The need for the research is justified and the research is set in an industrial context. The research scope, aim, objectives and structure of the thesis including the synopsis of each of the published papers are also provided. Chapter Two details the review of the related work to provide background to the research and establishes the need for the EngD research.

2 CHAPTER TWO: REVIEW OF RELATED WORK

2.1 INTRODUCTION

This chapter summarises and presents the findings from a review of the literature undertaken in order to provide a knowledge framework (Appendix A, EngD paper 1) that can be used as an information source by the civil infrastructure sector to develop a corporate strategy for carbon emissions performance. The carbon emissions performance issues associated with civil infrastructure and highway maintenance sector were further explored. The intention is to create a deeper understanding of current carbon management practices within highway infrastructure maintenance, challenges and associated opportunities for emissions assessment and reduction.

This review forms part of the EngD research-related work, and it establishes the need for the research and presents available carbon emissions evaluation tools and approaches supporting the low-carbon agenda in infrastructure. The chapter further sets the EngD research project in the context of the existing and emerging studies within the subject domain and Life Cycle Assessment concepts. In accordance with the research background set out in Chapter One of this thesis, this research primarily focuses on the concepts of carbon footprinting from highway maintenance planning and operations; following the LCA methodology presented by the UK's Publicly Available Specification (the PAS2050:2011) protocol, which specifies the requirements for assessing the life cycle GHG emissions for goods and services (British Standards Institution, 2011). Building on this context, the EngD research-related work is presented as follows:

(1) A state of the art literature review into organisations' carbon emissions performance and the UK's highway maintenance sector was undertaken within the context of the regulatory and non-regulatory policy drivers. The existing and emerging initiatives at national and industrial levels supporting the low-carbon agenda, and opportunities and challenges inherently presented by the civil infrastructure and highway maintenance sector for carbon emissions performance were further explored (section 2.2).

(2) An overview of indicators for assessing and benchmarking environmental impacts of infrastructure systems and the concept of LCA methods and models are presented. A summary of further literature review then focuses on LCA studies that employed the process-based method discussed. Prior and emerging studies on carbon emissions assessment methodologies and carbon evaluation tools are provided. Additional literature review of road materials-embodied carbon reduction studies and emissions data collection approaches is explored (section 2.3 and 2.4).

(3) Highlight of the EngD research novelty (section 2.5).

The review into organisation carbon emissions performance and UK's highway maintenance sector are detailed in Appendix A (EngD paper 1), while the summary of findings from LCA studies reviewed and the key conclusions are outlined in section 2.2. Appendix B (EngD paper 2) provides a detailed review into prior and emerging studies on LCA methodologies, while section 2.4.1 of this chapter summaries the findings from the review. Appendix C (EngD paper 3 sections 2.1) detailed the review into LCA studies that employed the process-based LCA method to compare the environmental footprints of different materials used for road maintenance work and section 2.4.2 summarises the findings from the review. Details of the review into studies on materials-embodied carbon reduction and emissions data collections are presented in sections 2.4.3 and 2.4.4. Appendix D (EngD paper 4) provides the details of literature review into international and the UK-based carbon evaluation tools, while the review findings are summarised in section 2.4.5 of this chapter, and section 2.5 presents the novelty of the EngD research project.

2.2 STATE OF THE ART LITERATURE REVIEW

This section presents a summary of a state of the art literature review that focuses on carbon emissions performance and the UK's highway maintenance sector (as detailed in the EngD paper 1 (see Appendix A)). The review presents existing and emerging international and UK-based policy frameworks driving the low-carbon agenda. These policy frameworks were further discussed within the context of their regulatory and non-regulatory stringency requirements, and capacities of their environmental effectiveness, cost-effectiveness and institutional feasibility. This provides a deep understanding on how these policy frameworks might impact on businesses in general and the highway maintenance sector in particular, and highlights the UK's government current and future thinking on carbon emissions and climate change.

The key findings and conclusions from the literature review are outlined below.

- It was revealed that there is momentum at an international, national, industrial and organisation levels driving carbon emissions assessment and reduction through policy frameworks. However, it was argued that these policies have been greatly criticised for not being able to drive the required innovation and growth to achieving the expected emissions reduction targets (Halcrow Limited, 2011). The reason has being that majority of these policies are voluntary in nature, and varied considerably in scope and regulatory stringency requirements.

- The existing and emerging civil infrastructure and highway maintenance emissions initiatives promote both direct and indirect carbon assessment and reduction. This suggests life cycle methodology across the infrastructure value chain. The relevance of energy, materials and waste efficiency for infrastructure carbon emissions performance was emphasised. The inability of existing and emerging carbon emissions initiatives to provide adequate guidance, or to define a wider scope for emissions assessed and system boundary are barriers for the infrastructure sector to develop corporate strategy for emissions reduction performance.

- The infrastructure maintenance sector can influence significant carbon emissions reduction through effective design. This suggests that the greatest opportunity to influence and manage carbon exists at pre-design and design stages of an infrastructure maintenance project. Quantifying carbon emissions at the early stages of infrastructure project's life cycle can support design, option appraisal, procurement and low carbon construction method decision-making.

- The materials consumed during highway infrastructure maintenance have significant embodied emissions impact across its production and delivery process. The actual scope of emissions the design process can influence depends on the impacts it has on infrastructure in-use phase, materials selection and option appraisal stages.

- For organisations to enhance carbon emissions performance, EngD paper 1 argued that a robust knowledge framework that can be used as information source is essential. This can support the organisation to develop efficient corporate strategy for carbon emissions performance.
- From a highway maintenance service perspective, EngD paper 1 highlights the importance of the highway maintenance sector in having a deeper understanding of its business processes, materials production and delivery. The paper further suggested that a robust strategy on carbon performance should include a carbon evaluation tool, underpinned by a robust methodology and complementary studies outputs to validate and justify emissions performance claims supported by a robust carbon data and collection approach. These issues are further discussed in subsequent sections of this chapter.

2.3 REVIEW OF LIFE CYCLE ASSESSMENT METHODS AND MODELS

This section presents an overview of Life Cycle Assessment (LCA) methods and models within the context of their underlying principles and concept. The intention is to provide a deeper understanding of LCA methods that can facilitate its adoption and application for highway maintenance process, carbon footprinting. Huang *et al* (2012) argued that the adoption of a standard methodology for highway maintenance life cycle studies can assist in the transparency of results and decision-making process.

2.3.1 LIFE CYCLE ASSESSMENT METHODS

Currently, environmental and carbon emission impacts on the earth's climate are priority issues impacting on government policy, legislation and project procurement decisions particularly for infrastructure investment decision-making (Athena Institute, 2006 Halcrow Limited, 2011 HM Treasury, 2011 ICE, 2010). The sustainability implications of infrastructure have led to the increasing demand for low-impact infrastructure (low-carbon infrastructure) by its stakeholders (Muench *et al.*, 2009). Therefore, it is important that investment decisions on infrastructure be assessed not only from financial and technical perspectives, but also from environmental perspective (Muench, 2010). As such, a number of tools and indicators for assessing and benchmarking environmental impacts of infrastructure have been developed (Finnveden *et al.*, 2009). This includes:

- Life Cycle Assessment (LCA)
- Environment Impact Assessment (EIA) and,
- Strategic Environmental Assessment (SEA) e.t.c.

Within the context of this chapter, LCA methodology is further discussed given its capacity to support business decision-making and highway pavement embodied carbon evaluation (Hoang *et al.*, 2005). The three methods commonly employed in life cycle studies (Muench *et al.*, 2009 Santero *et al.*, 2010) are outlined and discussed below:

(a) Process-based LCA method.

(b) Input-Output LCA (IO-LCA) method.

(c) Hybrid LCA method.

(a) Process-based LCA method

The process-based life cycle employs the principles refined by the Society of Environmental Toxicology and Chemistry (SETAC) and the United States Environmental Protection Agency (Santero *et al.*, 2010). It provides a transparent bottom-up approach for assessing process-based environmental contributions (e.g. carbon emissions) within the defined boundary. Employing this approach allows each process that comprises the system boundary to be discretely and specifically assessed (Muench, 2010). Although the method offers a straight forward and transparent approach, the data collection approach can be cumbersome and expensive due to the activities and tasks involved. As such, the tendency to exclude relevant activities from the process (e.g. upstream supply chain emissions) is high. This exclusion can introduce a truncation error (Lenzen and Dey, 2000): a common error when using the process-based life cycle method. This error can be addressed by increasing the system boundaries, although Lenzen (2001) argued that increasing the system boundaries may not significantly reduce the truncation error.

(b) Input-Output LCA (IO-LCA) method

The IO-LCA method employs a top-down approach to critically relate the production inputs of goods and services to the production outputs of other sectors of an economy. It has the capacity to analyse entire supply chains' environmental contributions and eliminate truncation error. It traces all direct and indirect economic inputs required to produce a unit of output from a given economic sector (Santero *et al.*, 2010). This life cycle method does not require a system boundary for its analysis. However, Lenzen (2001) identifies three significant types of error associated by the method, which include: aggregate error - due to grouping different establishments into a single entity, allocation error - due to the grouping of different products into a single unit and data source error - due to data collection, sampling and reporting. These errors are significant enough to undermine the methods credibility when used as a standalone LCA method. However, the method has demonstrated usefulness as a complementary approach to the conventional bottom-up process-based life cycle, due to its potential to address the truncation error associated with the process-based approach (Chang *et al.*, 2010 Lenzen, 2001 Santero *et al.*, 2010).

(c) Hybrid LCA method

This method combines the process-based and IO-LCA approaches in a manner that exploits the strength and minimises the limitations associated with the two LCA methods. A hybrid analysis approach enhances the value of each life cycle method (Process-based and IO-LCA) to provide an improved and more certain outcome. Santero (2010) suggested that the hybrid method can best be employed by using the process-based LCA method to analyse the most direct processes and the IO-LCA for the indirect upstream processes within the product or service life cycle. It is important to note that the process-based LCA and IO-LCA approaches are not rivals, but present comparative advantages (Hendrickson *et al.*, 2006). By using the hybrid approach, the limitations and errors of using the conventional methods (process-based LCA and the IO-LCA) are reduced (Crawford *et al.*, 2003), and the specificity and comprehensiveness of the conventional approaches are exploited, whilst filling the analytical gaps associated with the approach (Treloar *et al.*, 2004).

2.3.2 LIFE CYCLE ASSESSMENT MODELS

A number of highway pavement-specific LCA models have been developed to assess highway pavement environmental contributions and subsequent impacts. These models include (1) ROAD-RES (2) PaLATE (3) The UK-based LCA Model. These models employ the LCA methods discussed above. Therefore, an overview of the LCA models and their concepts outlined in this section will focus on the emissions assessment scope, LCA method employed and analytical drawbacks presented by the models.

(1) ROAD-RES model

The ROAD-RES model is a process-based LCA tool for road construction and disposal of residue waste developed at the Technical University of Denmark (Birgisdottir *et al.*, 2007 Birgisdottir *et al.*, 2006 Santero *et al.*, 2010). The tool facilitates and compares the environmental impacts associated with the use of virgin and waste products as highway construction materials. Within this model, eight environmental impact categories (e.g. Global warming, acidification, stratospheric ozone depletion, photochemical ozone formation, human toxicity, eco-toxicity) can be assessed (Birgisdottir *et al.*, 2007) through the road materials production, construction, maintenance and end-of-life phases (Huang *et al.*, 2009).The specific nature of the assessment results based on the model, and the possible introduction of truncation error are seen as the model's major drawbacks.

(2) PaLATE model

The PaLATE model is a four-phased Excel-based LCA tool which combines both the IO-LCA and process-based approaches to create a hybrid LCA model (Santero, 2009). The model estimates the environmental and economic burden associated with highway pavement maintenance projects (Natham *et al.*, 2009 Santero *et al.*, 2010). The model has the capacity to estimate the environmental burdens associated with highway pavements through the raw material acquisitions, manufacturing, construction, maintenance and end-of-life management (Treloar *et al.*, 2004). The environmental burdens commonly considered using the PaLATE model include energy and water consumption, Global Warming Potential (GWP), pollution, hazardous waste and human toxicity (Horvath, 2003). The model provides the inventory information of the burdens rather than impacts, thus making the model a Life Cycle Inventory (LCI) tool rather than Life Cycle Impact Assessment (LCIA). Although the model is data quality-sensitive, it has demonstrated the capacity to minimise truncation and aggregate errors, and drawbacks associated with conventional LCA methods. The model has been criticised for employing outdated data in its analysis (Anderson and Muench, 2010 Natham *et al.*, 2009). However, Anderson and Muench (2010) indicate that the Greenroads Rating System, a point based sustainability rating system, recommends the modified version of the PaLATE model as the most adequate tool to justify any service or system environmental impacts.

(3) The UK-Based LCA model

Due to different highway pavement materials, method of construction and data validity and applicability, a LCA model from one country cannot be applied to another (Huang *et al.*, 2009) since different data sets are required. In addition, issues around model relevance, adaptability, scope, compliance and availability have been observed to be major reasons why existing pavement LCA models are inadequate (Huang *et al.*, 2009 Santero *et al.*, 2010). With this in mind, a LCA model to estimate the environmental impact of asphalt pavement used in the UK's road construction was developed (Huang *et al.*, 2009) based on materials use, construction activities, maintenance and recycling practice in the road industry, excluding the use phase. The model created a process-based framework that can evaluate eleven environmental impact categories associated with asphalt pavement. These include: materials and fossil fuel depletion, stratospheric ozone depletion, acidification, GWP, photo oxidant formation, eco-toxicity, human toxicity, eutrophication, noise and depletion of landfill space (Santero *et al.*, 2010). The complexity of the impact categories considered and related data demands suggest that the model should be carefully reviewed in order to enhance its life cycle assessment results.

2.4 FURTHER LITERATURE REVIEW

2.4.1 PRIOR STUDIES ON CARBON EMISSIONS METHODOLOGIES

This section presents a summary of the literature review on prior studies on emissions assessment methodologies reviewed as detailed in Appendix B (EngD paper 2). The literature review revealed the complexities that exist in business carbon emissions assessment. These complexities are compounded following issues around emissions allocations; lack of robust accepted methodologies, emissions assessment standards and relevant industrial data. The insufficient analytical rigor on carbon demonstrated by existing approaches is another major barrier frustrating organisations efforts on carbon footprinting. The studies indicate the adoption of a robust methodology, more sustainable practices and materials in the business process and its value chain will have a profound impact on its carbon reduction and subsequent performance. The studies recommended the adoption of Life Cycle Assessment (LCA) methodology (and its integration into highway maintenance process decision-making) since the methodology has been widely applied in many areas including product environmental footprint due to manufacturing processes, business decision-making, and highway maintenance work (Hoang *et al.*, 2005).

2.4.2 HIGHWAY MAINTENANCE CARBON EMISSIONS ASSESSMENT

The literature reviewed in EngD paper 3 (Appendix C section 2.1) is summarised in this section. The review compares the environmental footprints associated with asphalt and concrete materials used for road maintenance work. The studies that employ the process-based LCA method discussed in section 2.3.1 of this chapter were considered. The scope and focus of each study were explored and the limitations discussed. The intention is to provide useful and constructive assessment of the application of life cycle methodology in the field of engineering enquiry. This then highlights possible research scope to advance the state of knowledge of the process-based LCA methodology implementation in highway maintenance planning and operations.

The inability of the existing studies reviewed to provide a comprehensive representation of the highway infrastructure system in life cycle terms is attributable to limited understanding of the system, the knowledge gaps in the study domain, and absence of accepted industrial methodology for life cycle studies. These drawbacks are compounded, given the lack of credible data and their collection approach. The issues around relevance, compliance, scope, adaptability, data credibility and representativeness are other reasons are cited by Huang et al (2009a) as to why the existing LCA studies are inadequate as an information source or as a standalone highway maintenance service environmental footprints appraiser. In addition, there was little or no attention paid to environmental footprints attributable to other aspects of the highway infrastructure system, namely: traffic delay, the use phase, pavement making, lighting and vegetation clearance.

2.4.3 STUDIES ON ROAD MATERIALS' EMBODIED CARBON REDUCTION

In this section, additional literature reviewed on road materials embodied carbon assessment and reduction studies is presented. The studies on road maintenance process environmental footprint assessment revealed that materials' production is an energy and carbon-intensive operation and can be reduced by using recycled and secondary materials in place of virgin materials. These studies include the work by Mroueh et al. (2001), which recommends the use of slag and crushed concrete in place of virgin aggregates for road maintenance. The case study results showed a significant decrease in the environmental burden in terms of energy consumption, emissions, pollution, leaching, and natural resources consumption. A similar study by Roth and Eklund (2003) suggests that the decisions to use these secondary materials are largely dependent on value choices, but recommends that extended system boundaries in road LCA will improve the basis of decision-making with regards to the use of secondary materials. In addition, Carpenter et al. (2007) suggests that the use of furnace bottom ash can significantly lower energy consumption, emissions, soil and water pollutants (Carpenter *et al.*, 2007 Mroueh *et al.*, 2001 Roth and Eklund, 2003). The life cycle studies undertaken by the UK's Waste Resources Action Programme (WRAP) to promote emissions reduction through the use of recycled and secondary aggregates in construction, and enhanced resource efficiency in the UK, concluded that choosing less energy-intensive construction techniques, selecting sources of aggregates closer to site, opting for green transport, and the use of recycled and secondary aggregates can reduce carbon emissions, conserve natural resource consumption and minimize waste (Durucan and Korre, 2009 Hammond and Jones, 2011 Transport Research Laboratory Limited, 2010) . Recently, an extended WRAP life cycle emissions assessment methodology was developed by Thomas et al. (2009) aimed at assessing construction materials sourcing options and evaluating emissions impact of previously unconsidered factors such as materials quality and local conditions (e.g. road transport congestion) in the initial methodology. The study revealed that emissions associated with construction materials sourcing do not only depend on material type, but also on local conditions (Thomas *et al.*, 2009). This agreed with the findings of Thenoux et al. (2006) in their life cycle study which concluded that the materials' haulage distance is a sensitive factor in energy consumption during materials sourcing for road construction and maintenance (Thenoux *et al.*, 2006).

LCA studies have placed huge emphasis on highway materials' efficiency and their environmental relevance, and demonstrated how recycled and secondary materials can reduce material and energy consumption and related carbon emissions (Athena Institute, 2006 Durucan and Korre, 2009 Zapata and Gambatese, 2005). However, the studies paid no attention to carbon emissions arising from road maintenance site activities only, following the claim that the life cycle energy and carbon inputs from road maintenance activities are negligible when compared with materials production and the delivery process (embodied carbon). In addition, the lack of a standard methodology for data collection during the site activities is another contributing factor to this lack of assessment.

2.4.4 EMISSIONS DATA COLLECTION AND STANDARDISED APPROACHES

Most recently, in the United States, a number of consolidated complementary carbon emissions inventory studies were undertaken to develop construction vehicle and equipment emission inventories over their duty cycle during road maintenance activities. These included the work of Lewis et al (2009) and Rasdorf et al (2009), aimed at developing a methodology for construction vehicles emission inventory that can inform a reduction strategy (Lewis *et al.*, 2009 Rasdorf *et al.*, 2009) . The methodology provides fundamental standard procedures for capturing fuel use by construction fleets and a management strategy to inform emissions reduction decisions. Similarly, in the UK, the Strategic Forum for Construction (SFfC) in 2010 commissioned a study with the intention of developing an action plan for carbon emission reduction targets set by the UK's Strategy for Sustainable Construction. This included a reduction of 15% in carbon emissions from all construction processes and associated transport by 2012 compared to 2008, a reduction in all construction and demolition waste sent to landfill by 50% by 2012 (compared to 2005 levels) and zero waste to landfill by 2020. The study primarily focused on carbon emissions associated with the construction process (Department of Business Innovation and Skills, 2008 Joan, 2010); given that the construction process emissions were identified as a gap by the SFfC from emissions studies within the public domain. The study identified the need to drive carbon emissions improvement in construction processes. The scoping study defined construction processes as those activities and proposed a boundary on emissions sources and data to be included within the scope to achieve the emissions reduction targets. This suggests exclusion of data from construction indirect inputs, outputs and product emissions (for example, from the materials manufacturing sector, waste sector and asset owners and users emissions) in the assessment. However, these data are relevant in developing a robust construction industry life cycle carbon footprint for improvement. The studies reviewed above do not consider carbon emissions assessment over the highway system defined by SERI such as: highway lighting, vegetation clearance and pavement marking in their life cycle studies. It is important to know that these processes also contribute considerably to the highway life cycle carbon impact. The inability of existing studies to develop a comprehensive representation of a life cycle assessment for highway maintenance systems are major drawbacks that are creating barriers for life cycle studies. Addressing these drawbacks and barriers in the highway maintenance process carbon footprinting will require a standardised methodology that can assess both materials and energy flow across the highway system value chain.

2.4.5 REVIEW OF EXISTING CARBON EVALUATION TOOLS

This section presents a summary of the literature reviewed into the existing carbon calculation tools detailed in Appendix D (EngD Paper 4 section1.1). The intention was to understand the state of practice on carbon emissions assessment and reduction, and identify the best available techniques and tools in the public domain supporting the agenda. Table 2.1 presents a summary of the review of existing carbon calculation tools that are available in the public domain. The emphasis was to examine the analytical capacity of the existing tools against the research carbon evaluation tool design concept requirements.The review focuses on tools system boundary definition, carbon assessment focus, sources and functionality of the tools. The review presents consistent carbon analytical drawbacks in that majority of the existing carbon tools are not closely aligned with carbon assessment standards that specify "Data Quality Rules" and systematic data collection approach. Further weakness was showed in the tools capacity to identify carbon "Hotspots" across highway maintenance system (defined by SERI, see Chapter One, section 1.2), perform sensitivity analysis to identify opportunities for reduction and establish carbon reduction hierarchy to support reduction investment decision-making. However, these drawbacks are key requirements for the research carbon evaluation tool development and implementation process. The increasing demand for life cycle carbon information and its integration into business investment decision-making presents an obvious need for a robust carbon evaluation tool to be developed. The tool development and implementation process should be underpinned by a robust life cycle methodology, and outputs from complementary studies. This will enable organisations to produce credible life cycle carbon emissions inventory to support reduction investment decision-making, and allow emissions reduction efforts to be prioritised.

Table 2.1 Summary of Review of Existing Carbon Calculation Tools

Existing Carbon Calculation Tools	Boundary Condition		Calculate Emissions From:					Carbon Emissions Sources:				Functionality:							
	Cradle to Grave	Cradle to Gate Or Cradle to Site	Highway Design Phase	Highway Construction Phase	Highway Maintenance Phase	Highway in-Use phase	Highway Decommissioning Phase	Site Utilities	Plant and Transport	Materials (Embodied carbon)	Aligned with PAS2050 Protocol	Allows Design and construction stages carbon emission estimates	Systematic Data Collection Approach	Allows Highway System (see SERI definition)	Allows Sensitivity Analysis	Allows End-of-life Treatment (Recycling)	Allows "Hotspot" Analysis	Supports Reduction Decision-making	Allows Supply Chain Emissions
IRL (CHANGER)	×	√	×	√	×	×	×	√	√	√	×	×	×	×	×	×	×	×	×
HA/TRL asPECT	×	√	×	√	√	×	×	×	√	√	√	×	√	×	×	×	×	×	×
HA Carbon Calculation Tool	×	√	×	√	√	√	×	√	√	√	×	×	√	×	×	×	×	×	×
EA Carbon Calculator	×	√	×	√	×	×	×	√	√	√	×	×	√	×	×	×	×	×	×
Transport Scotland Carbon Mgt.System	×	√	√	√	√	×	×	√	√	√	√	√	√	×	×	×	√	√	×
DEFRA/DECC GHG Conversion Factor	×	×	×	×	×	×	×	√	√	×	×	×	×	×	×	×	×	×	×

Summary of review of existing carbon calculation tools against this research carbon evaluation tool. The review focuses on the system boundary, carbon calculation focus, sources and functionality (adapted from Fox *et al.* (2011). Proceedings of the Institutions of Civil Engineers (ICE): Transport, Vol 164, Issue TR3).

2.5 NOVELTY OF THE RESEARCH WORK

Despite the strong scientific evidence (IPCC, 2007) that linked business and human activities with increasing carbon emissions, only a few narrowly focused and unstructured approaches have been developed to allow businesses to measure and decarbonise their activities, and this is evident in the construction industry and its infrastructure sector. The fragmented nature (Egan, 1998) of the industry and the complexity of its infrastructure are issues needed to be tackled by the industry and its supply chain. The "state of the art" review presented the policy frameworks and industrial initiatives and guidance driving the carbon emissions reduction. It explores the principles and requirements of the policies regulatory and non-regulatory driver. The intention is to provide businesses with a knowledge framework that can be used as an information source to understand their carbon contributions, and develop a robust strategy to reduce them (e.g. carbon footprints).

Furthermore, highways infrastructure providers are responsible for providing well maintained highways to enhance public safety and support economic growth within a constrained budget. This responsibility is complicated following the significant risks (hotter summer, wetter winter, more intense rainfall and raising sea level respectively) climate change poses on existing infrastructure (Arkell and Darch, 2006 DECC, 2010). As such, these risks are changing the way infrastructure is being designed, constructed, planned and procured. In the UK, highway infrastructure customers are increasingly demanding from their supply chain an integrated highway maintenance service delivery. Along with this demand, supply chains are expected to address climate change, related energy and emission inputs through: The Climate Change Act (2008), Carbon Management Plan (2009) and Sustainable Procurement Policy (2007).

To meet this customer expectation from a highway maintenance service delivery perspective requires accurate understanding of the service emissions inputs and their interaction with the supply chains. In the past, businesses that begun to understand the relationship that exists between their carbon emissions and business activities have done so by focusing on activities within their control. Whilst this approach is appropriate in its own concept and scope, more recently business customers are now demanding emissions information across the business value chain (British Standards Institution, 2008). This demand presents a huge challenge for sectors, businesses and their supply chain. In the UK, this challenge is further compounded given that carbon emissions reduction and other sustainability performance issues are considered as a major part of the tender selection criteria, and a major contractual requirement(Itoya *et al.*, 2012) . The absence of a consistent and transparent industrial methodology standard that focuses on carbon emissions assessment, and non-availability of credible baseline data for emissions benchmarking are seen as major drawbacks plaguing the highway maintenance business carbon footprinting studies.

The Swedish Environmental Research Institute (SERI) defined the highway infrastructure as a system that consists of not only the highway pavement itself, but also the traffic control system, street lighting, pavement marking and road signs operation (Stripple, 2001). It is important to note that emissions assessment over this system is an enormous task and complicated. It requires an in-depth knowledge of the entire system and their interactions with their value chain. This promotes holistic and integrated approaches to carbon emissions assessment. . However, there is little or no evidence that such a holistic and integrated life cycle approach exists to support the agenda in highway infrastructure maintenance service delivery; with such vast scope as defined by SERI. The majority of the studies reviewed completely overlooked emissions from the highway infrastructure system that are not directly related to the pavement itself. To meet highway customers' carbon emission expectations, that is accounting for highway infrastructure system carbon emissions across its supply chains, and integrating the information into the maintenance investment decision-making, there are calls for a consistent and project-focused life cycle methodology.

LCA methodology is being accepted by the road industry to measure its key environmental contributions and impacts (Huang *et al.*, 2009), given its capacity to provide businesses with consistent, representative, transparency and credible information to support business decision-making (Huang *et al.*, 2012). Adopting a standard LCA methodology for highway maintenance emissions assessment can improve decision-making and transparency of emissions reduction claim. The life cycle methodology described by the PAS2050 protocol has added more significant direct and innovative guidance (Sustain Limited, 2010) that can allow organisations to undertake a comprehensive life cycle study. This guidance presented a unique and practical guideline that simplifies the protocol implementation as a default approach to highway maintenance carbon emissions assessment (Sinden, 2009). The step-by-step iterative approach presented by the PAS2050 protocol will allow the study system boundary to be undertaken, provides a specific approach to data acquisition, and robust treatment of the system defined and provides a specific approach to data acquisition. The protocol refinement of the existing international guidance on emission allocation has further strengthened its capacity to create standardisation and representative emissions life cycle assessment across different product types.

This research presents a unique and practical project-focused life cycle methodology based on PAS2050:2011 (discussed in Chapter One) that can allow highway maintenance service providers and their supply chains to accurately evaluate their emissions holistically across their value chain. The methodology employs a process-based life cycle approach, which allows the energy and materials flow across selected core highway maintenance processes to be assessed. Since the protocol publication in 2008 by the British Standards Institution (British Standards Institution, 2008), this is the first time, project-specific and process-based methodology framework has been developed based on the PAS2050 protocol. The framework will allow the carbon emissions associated with core highway maintenance processes to be assessed across the business value chain. The core maintenance processes selected for emissions assessment within the context of this study include highway pavement resurfacing, pavement marking, bulk lamp change and grass cutting. The carbon footprints associated with these processes were assessed through their raw material acquisition, material manufacturing, transportation, and on-site activities to the end-of-life management.

In summary, this research advances the body of knowledge on business carbon footprinting, and demonstrates innovation in the application of PAS2050 life cycle methodology (which was originally designed for the retail industry) for carbon footprinting associated with integrated highway maintenance service delivery. The approach has the capacity to identify emission hotspots across the core highway maintenance processes value chain, and provides credible carbon information that can support the highway maintenance investment decision-making. It presents a step-by-step and practical guidance to support business efforts on carbon footprinting and reduction. A hierarchy of reduction is developed based on the analysis of the results to allow reduction efforts to be prioritised. This research provides significant progress in the application of LCA and PAS2050 methodology. The methodology is unique and specific in nature, which demonstrates the EngD research novelty.

2.6 SUMMARY

This chapter has provided a summary of the “state of the art” review and additional literature review detailed in Appendices A, B, C and D (EngD papers 1, 2, 3 and 4) within the research subject domain. The review indicates that the policies driving the low-carbon agenda present business challenges and opportunities, which can be poorly understood by highway maintenance stakeholders. It further suggests a knowledge framework that can be used as an information source by organisations to develop a corporate strategy for carbon performance. The strategy should include a carbon evaluation tool underpinned by a robust methodology and outputs from complementary life cycle carbon assessment studies, credible carbon data and collection approach. These inclusions were found to be crucial for organisations to enhance their carbon footprinting and reduction performance. In addition, the existing and emerging LCA studies and methodologies were explored to identify carbon performance issues, which then revealed the complexities that exist for organisations to undertake efficient carbon footprinting and reduction program.

3 CHAPTER THREE: RESEARCH METHODOLOGY

3.1 INTRODUCTION

The research methodology adopted for any research has a significant impact on the study results. This implies that the success and validity of any study are essentially dependent on the appropriate research methods selected (Fellows and Liu, 2003 Steele, 2000). This chapter discusses the types of research, research methods and methodological approaches that are available. It also briefly outlines the research process, specific research methods and methodological approaches employed in this study. It further explains and maps the adopted approaches against the research objectives, related tasks and expected outputs, and justifies the reason behind the research approaches selected for this study.

3.2 TYPES OF RESEARCH

The word research describes a careful search, methodical investigation and patient study in some subject area to increase the sum of knowledge (Fellows and Liu, 2003). It is commonly undertaken to establish facts or principles through a structured inquiry that employs accepted scientific methodology to solve the problems under consideration, and creates new knowledge that is widely applicable (Grinnell and Unrau, 2007). Research is not a closed system, but a learning process commonly executed in context of the problem under investigation. From a business perspective, Sakaran (2003) defined research as “an organised, systematic, data-based, critical, objective, scientific inquiry or investigation into a specific problem undertaken with the purpose of finding solutions”. Therefore, it is imperative that the researcher always considers the contextual factors and environmental variables that might impact on the research process and data recorded (Fellows and Liu, 2003). This suggests the importance of having a deeper knowledge of the research application, objectives and type of information sought. According to Kumar (2011), research can be classified into three major categories from application, objectives and types of information sought perspectives. Figure 3.1 presents a modification of Kumar’s research categories based on these perspectives.

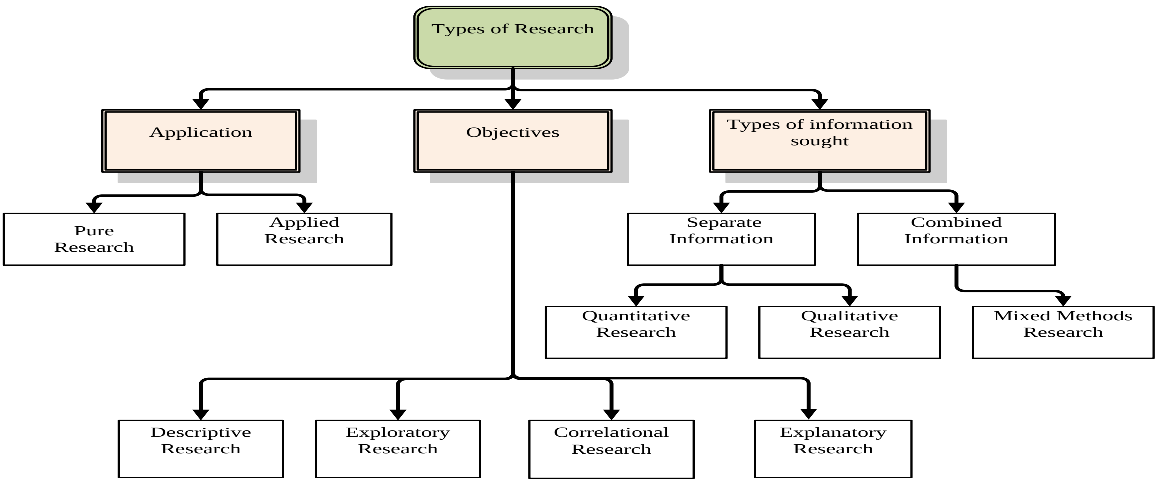


Figure 3.1 Types of Research

(Source: (Kumar, 2011))

Figure 3.1 indicates that two types of research exist from an application perspective, pure research and applied research. The pure research (Sekaran, 2003) is academic in nature and seeks to advance a fundamental knowledge in various functional areas of endeavour that may or may not have immediate application. The knowledge generated is commonly applied for problems solving in the future (Sekaran, 2003). This type of research is usually applied by researchers to support or refute theories (Neuman, 2011). In contrast, any research undertaken with the intention to applying the results to a specific problem (Sekaran, 2003) or brings a change to a situation; program or phenomenon (Neuman, 2011) currently being experienced is applied research. This type of research demands a timely solution to immediate problems (Sekaran, 2003).

In addition, from an objective point of view, four types of research are defined , namely descriptive, correlational, explanatory and exploratory. The descriptive research seeks to describe and provide a background or context of a situation, phenomena, problem or issue (Neuman, 2011). Correlational research is used to establish or explore a relationship between two or more variables through three outcomes namely: a positive correlation, a negative correlation, and no correlation. Explanatory research primary focus is to provide an explanation on why certain phenomena or situation happen the way they do, while exploratory research aimed at providing insight into a phenomenon or problem under investigation, formulates precise research questions and examines the feasibility of conducting a study (Neuman, 2011). Furthermore, from an information view point, two types of research exist. These include: quantitative and qualitative research or combination of both research. Following these arguments, the current EngD research can be categorised as applied and exploratory research that employs mixed methods of enquires. Table 3.1 presents detail of the EngD research categorisation and defines the research in the perspective of the methodological orientation.

Table 3.1 The Categorisation of the EngD Research Project

Perspectives	Type of Research	Reason(s)
Application	Applied research	• Following the industrial sponsor's business immediate business need, the purpose of the EngD research and its deliverables were jointly defined by the research team. • The intention is to provide the industrial sponsor with a project-focused carbon footprinting methodology to meet its immediate carbon emissions assessment and reduction challenges, and enhances its business competiveness and long-term success
Objectives	Exploratory Research	• The EngD research seeks to provide an insight into the sponsor's business carbon emissions assessment and reduction from life cycle perspective. • It seeks to explore ways to embed the project-focused carbon footprinting methodology and resulting emissions information into the stakeholder's business decision-making process.

Information Sought	Mixed Method Research	• The EngD research requires a combination of quantitative and qualitative data sets. In this case, the qualitative research findings are required to justify and validate findings from the quantitative research.

3.3 RESEARCH METHODS

A research method is a systematic and orderly approach taken towards the collection of data so that information can be obtained (Jankowicz, 2005). Therefore, the choice of a robust research method is important to assist the researcher in identifying all relevant research variables, their mechanisms and impacts. In any type of research, the methods for collecting data will impact upon the analysis which may be executed and, hence, the results, conclusions, values and validity of the study (Fellows and Liu, 2003). Jankowicz (2005) argued that the choice of a research method depends on the nature of problem under investigation, scope, sources of the data, purpose for the data, the amount control the researcher has over the data collection, and the assumptions in analysing them. By employing different research methods, different types of research data can be acquired about a problem investigated which can either be quantitative or qualitative, and or a combination of both. The section below discusses the basic distinctions between quantitative and qualitative research methods, and mixed methods of research.

3.3.1 QUANTITATIVE METHODS

Quantitative methods of research seek to gather factual data in order to study relationships between facts and how such relationships and facts accord with theories and findings of research previously undertaken. The research approach is objective (follows the positivist or realist standpoints) in nature and employs scientific techniques of problem solving (Fellows and Liu, 2003). It involves investigation into and identifies a problem based on theory tested, measured by numbers and analysed using statistical techniques. The conclusions drawn from the interpretation of the results is based on the facts of the findings derived from the actual data analysed, rather than others' subjective views and experiences or emotional values (Sekaran, 2003). Some widely used quantitative data collection techniques are outlined in Table 3.2 below:

Table 3.2 Quantitative Research Data Collection Techniques

Technique	A brief description
Experiments	Characterised by random assignment of subjects to experimental conditions, and the use of experimental controls so that the outcome is valid, objective and replicable (Gill and Johnson, 2002). The approach is best suited for 'bounded' studies or issues in which the variables involved are known (Fellows and Liu, 2003)
Quasi-Experiments	The primary aim of quasi-experiments is to analyse causal relationships between independent and dependent variables (Gill and Johnson, 2002) of any study. It shares almost all the features of experimental study design except that they employ non-randomised assignment of subjects to experimental conditions.

Surveys	Uses questionnaires or interviews (structured, semi-structured and unstructured) for data gathering from a smaller sample of a large population of interest to the researcher. The intention is to produce an estimate of the characteristics of the large population. The data collected is analysed using statistical techniques and the outcomes displayed in the form of tables, charts or graphs. These outcomes reveal the relationships that exist between the facts and how these relationships are in agreement with existing theories and findings from previous studies.

3.3.2 QUALITATIVE METHODS

Qualitative research is an exploratory study that seeks to gain insights and understanding of phenomena under investigation, and describes the variations that exist. It is commonly used for subjective inquiry and emphasise meaning, experience, description and perception of the situations, events, peoples, interaction and behaviour (Naoum, 2002 Patton, 2002). This method reflects the constructivist or interpretative viewpoints. The techniques in this type of research include action research, direct observation, and focus groups etc. An overview of action research and direct observation techniques are provided below.

(a) Action Research: This requires active participation in the research process by the researcher. The intention is to identify, promote and evaluate the research problems and potential solutions (Fellows and Liu, 2003) within the scope of the study.

(b) Direct Observation: This refers to careful observing and studying of those participating in research to enhance the success of the method employed and determine the validity of the research findings.

3.3.3 MIXED METHODS

The nature and objectives of any research, together with the nature of the data required determines the research methods to be employed, which classifies whether the study will be quantitative or qualitative research (Fellows and Liu, 2003) or a combination of both (mixed methods). In practice, mixed methods integrate quantitative and qualitative research techniques (combining methods) or produce knowledge from a social enquiry by analysing data from different sources (primary and secondary data types). According to Johnson and Onwuegbuzie (2004), the mixed methods are defined as “the class of research; where the researcher mixes or combines qualitative and quantitative techniques, methods, approaches, concepts or language into a single research”. It employs a pragmatic and system of philosophy (Johnson and Onwuegbuzie, 2004 Maxcy, 2003) that can allow certain complex social phenomena to be usefully understood which ordinarily cannot be addressed by one specific, standalone research approach. An overview of the context and applications of the mixed methods of research are discussed in section 3.5 of this chapter.

3.3.4 ADVANTAGES AND DISADVANTAGES OF THE RESEARCH METHODS

This section presents the advantages and disadvantages of quantitative, qualitative and mixed methods of research within the context of their methodological standpoints, types of data required and collection approaches, analysis and suitability for specific problem solution.

Table 3.3Advantages and Disadvantages of Research Methods

Methods	Advantages	Disadvantages
Quantitative	• It offers the advantage of undertaking cross-sectional and large-scale studies and secures objective knowledge. • Its main strength lies in precision and control of the studies (Burns, 2000). • Deals with large sample sizes and provides a firm basis for generalisations.	• Inability to explain or provide a deeper understanding of identified patterns in datasets or totally ignores the cultural and social construction of the variables investigated. • It is generally considered to be unsuitable for “unbounded” problem in which the variables are unknown (Fellows and Liu, 2003).
Qualitative	• It provides richness of data and deeper insight into the phenomena investigated. • It offers the opportunity to study and understand the beliefs, experiences and views of research stakeholders of the research subject matter. • It offers the researchers the scope to gain insider’s views and reveals subtleties and complexities that could have go undetected through quantitative measures.	• Problem of adequate validity and reliability of data collected due to it subjective nature and relatively small sample sizes (Burns, 2000). • Data collection is time consuming and unstructured. Analysing these data tends to be difficult, requiring a lot of filtering, sorting and other possible ‘manipulations’ (Fellows and Liu, 2003). • Sometimes data might be unreliable, impressionistic and not objective enough.
Mixed	• It presents ability to answer simultaneously confirmatory and exploratory questions that other approaches cannot answer. • Provides divergent findings from an expression of differing viewpoints. • Provides stronger inferences through depth and breadth answer to complex social questions (Tashakkori and Teddlie, 2003).	• Requires the researchers to study multiple methods and understand how they can be mixed appropriately. • May require a research team, particularly if two or more approaches are expected to be employed, hence can be more expensive and time consuming. • The methodologies that underpin the mixing process are still unbalanced and unclear.

3.4 ADOPTED RESEARCH APPROACH

The purpose of any study, the type of data and availability of information required in such studies are decision-making criteria on the research approach (Naoum, 2002) to be adopted. It is crucial the researcher has in-depth understanding of the type of research questions (Who? Why? What? Where? How?), the research is trying to address, and the degree of control the researcher will have over the research process. According to Barbour (2008), the key to a successful research design depends on the capacity to have an appropriate link between the research question, aim and approach to be employed. It is important to know that research is not strictly a linear process; it may flow in several directions before reaching an end. Neuman (2011) suggests that research does not abruptly end, but an on-going process, the end of one research often stimulates new thinking for further research work (Barbour, 2008 Neuman, 2011). With this in mind, the five research strategies highlighted by Yin (2003), and related questions the research is trying to address are detailed in Table 3.4, which provides a useful categorisation for selecting the most appropriate research method.

Table 3.4 Relevant Situations for Different Research Strategies (Yin, 2003)

S/N	Strategy	Form of research question	Requires control over behavioural events?	Focuses on contemporary events?
1	Experiment	How? Why?	Yes	Yes
2	Survey/ Questionnaire	Who? What? Where? How many? How much?	No	Yes
3	Literature Review	Who? What? Where? How many? How much?	No	Yes/No
4	History	How? Why?	No	No
5	Case Study	How? Why?	No	Yes

As stated in Chapter One (section 1.6.3), the sponsor has not been able to identify a practical means of maximising its potential carbon reduction initiatives within its highway maintenance planning and operation in order to enhance its business competitiveness and retain its market position., The primary aim of the EngD research is to develop a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool, to support carbon management decision-making in the sponsor’s highway maintenance planning and operation. The research objectives defined to meet this primary research aim gave a clear perspective of how the research would be approached. It also defined the scope, the data type required and appropriate research method to be employed. To this end, the research methodology employed then divides the entire project into three phases and related stages following the Morse (1984) technique (see Table 3.5). These phases include: investigation, synthesis and application. The investigation phase involves the stakeholder’s engagement (industrial sponsor’s internal and external stakeholders) and the state-of-the-art literature review to provide in-depth understanding of the subject matter (carbon optimisation for highway maintenance planning and operation), gathering of preliminary information for research definition; establishing the research questions and developing the research data collection instruments.

As soon as the investigation stage is completed, the synthesis phase presents the research objectives and tasks that contribute towards achieving the research aim. At this phase, a process-based life cycle methodology framework specific to highway maintenance service delivery and a carbon evaluation tool based on PAS2050 protocol were developed. This is to ascertain the potential and the use of LCA methodology for highway maintenance life cycle carbon emissions assessment and reduction decision-making process. As part of this research phase, four core highway maintenance processes were then selected for carbon emissions assessment based on the tool developed and data collected. At the end of this phase, the research then entered into the application phase which involves the dissemination and implementation of the research carbon evaluation tool and data in the sponsor's business operations, critical evaluation of the research to identify its limitations to inform recommendation for future research for improvement.

Table 3.5 Research Phases and Stages

Phases	Stages
Investigation	- Preliminary Information Gathering
Synthesis	- Stakeholder (see Table 3.6) engagement process - Primary Data Gathering using questionnaire survey - Secondary Data Gathering. - Develop a process-based life cycle methodology framework specific for highway maintenance operation. - Develop a "Carbon Evaluation Tool" for the methodology framework implementation - Primary data analysis (Quantitative Data Analysis) from 48 different site locations using the methodology framework and carbon evaluation tool developed.
Application	-The use of the research approach and data for the sponsor business operations. - Critical evaluation of the research to identify limitations that can inform recommendations for future work for improvement. - Produce and implement the carbon evaluation tool dissemination strategy to allow for the tool improvement and adoption.

(Based on(Morse, 1984))

3.5 METHODOLOGY ADOPTED FOR THIS RESEARCH

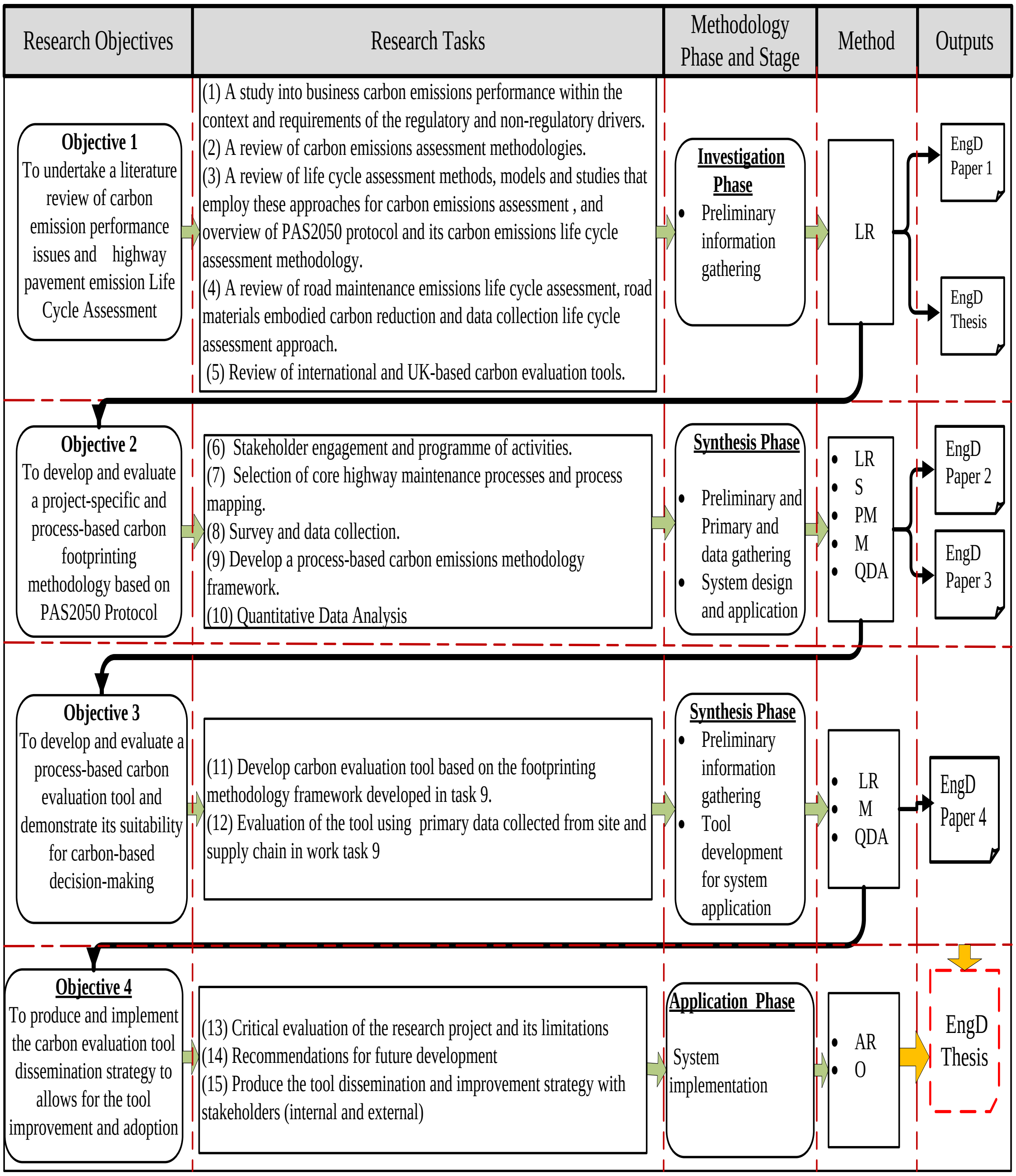
The philosophical choices underlying the research methods applied can have a significant impact on the quality and research outcomes. The methodology presents the principles and procedures of logical thought processes that are applied to scientific investigation (Fellows and Liu, 2003). To define appropriate research methodology, Yin (1984) suggested four key issues to be considered. These include: what questions to study and in what context, what data is relevant; what data to collect; and how the data will be analysed. Addressing these research questions, it is important to explore the benefits and limitations of the five research strategies (see Table 3.4) commonly employed (Yin, 1984), so that the validity of the study, and its results and conclusions can be appreciated (Fellows and Liu, 2003). As mentioned earlier in Chapter One, the overall aim of this study is to develop a project-focused carbon footprinting methodology that includes a decision-support and carbon management tool that can support decision-making in highway maintenance planning and operation. By taking a critical look at the nature and goal of the research aim from the sponsor's business perspective, it is apparent that the research aim presents both objective and subjective views of the study. In this context, the mixed methods of research are presented in this study to seek convergence, corroboration, and correspondence of research findings from both quantitative and qualitative methods standpoint, whilst providing a more complete picture or enhance coverage of the research focus. Table 3.6 presents the research map, which provides the overall research methodology, and indicates where the research methods were employed during the different stages of the research. Figure 3.2 also presents the research objectives identified, research information flow, research work tasks against the phases and stages of the research methodology. It also identifies which portfolio of research methods employed at each stage and related outputs.

Therefore, when combining research methods, it is important to have a well thought-out rationale and a good understanding of the various assumptions that underpin the various methods, their potential and limitations (Barbour, 2008). The sections (sections 3.5.1 to 3.5.7) below discuss the concept of various research methods (mixed methods) within the context of the current EngD research project aim and objectives, and the methodology that underpinned its implementation. This comprises a literature review, process mapping, questionnaire survey, quantitative data analysis, modelling, action research and direct observation. An overview of these research techniques and their implementation within the scope of EngD research are discussed, the rationale for their adoption explained.

3.5.1 LITERATURE REVIEW

The literature review is the most efficient means of initial information gathering and initiates the research investigation (Steele, 2000). The literature that falls within the subject matter of this research project spanned across existing and emerging government policy reports, industrial, sectors and academic studies that focus on carbon emissions assessment and reduction (see Tasks 1-5, Figure 3.2). The review was particularly useful in achieving the goals of the research objectives through the related research work tasks outlined in the research map (see Figure 3.2). It was also used to inform and refine the research objectives' scope and keeping up-to-date with highway maintenance sector developments and emerging knowledge on the low-carbon agenda, and allowd the current EngD research findings to be justified and validated from an industrial context. The knowledge gaps in business carbon emissions assessment and reduction were identified, and the areas requiring research highlighted. In effect, the literature review was very important throughout the EngD research project, since it provides the knowledge framework (see Figure 4.2) in which the EngD research is based . The outcomes of the state of the art review and additional literature reviewed during the course of this research project are discussed and presented in Chapter Four .

Overall Aim: Aim: To develop a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool, to support carbon management decision-making in highway maintenance planning and operation.



Key : LR: Literature Review , S: Survey, PM: Process Mapping , M : Modelling , QDA : Quantitative Data Analysis
AR : Action Research, O : Direct Observation

Figure 3.2 Research Map

3.5.2 STAKEHOLDER ENGAGEMENT PROCESS

Table 3.6 outlined the various activities (1-9) that explain the research stakeholder engagement process (see Figure 3.2, Task 6). The activities facilitate the implementation of the PAS2050-compliant methodology framework (see steps 1-4 in Figure 4.6). The stakeholder engagement process was crucial for the Research Engineer (RE) to understand BB-HST's highway business carbon emissions inputs, and the interface that exist between the business and its supply chain. The stakeholder engagement process was a continuous process throughout the EngD period in order to ensure stakeholder (see Table 3.6) views are reflected in the research outcomes. The launch event and focus group workshop discussed in Chapter Four (section 4.2.2) are important to capture the stakeholder's views on the carbon evaluation tool, establishes its improvement and adoption process within the sponsor's business operation and its supply chain. A postscript that describes the launch event undertaken at the sponsor's business premises (as part of the tool dissemination process) is included in Appendix G.

Table 3.6 Stakeholders Engagement Process

Stakeholders Engagement Activity	Who were involved?	When?	Purpose and How
Activity 1: Select highway maintenance processes to be interrogated in carbon terms.	Research Engineer and industrial supervisor.	2009	• Determines carbon expenditure to PAS2050 across different contract environments in the UK. • Understands the differences in carbon terms of using different materials and processes.
Activity 2: Identify and select BB-HST's business internal and external stakeholders (see Chapter One, Table 1.3).	Research Engineer and industrial supervisor.	2009	• Ensure representative carbon data are collated from the right sources for analysis. Stakeholders were selected from BB-HST's employees and supply chain information database (SharePoint).
Activity 3: Develop the EngD project brief (see Appendix F).	Research Engineer and industrial Supervisor.	2009	• Educates the selected stakeholders (see Table 1.3) on the research background, scope and focus. • Collates stakeholders specific contact details (highway maintenance process managers, suppliers and supply chain representative). The EngD project brief was sent to all stakeholders via emails (from the BB-HST's emails address book).

<u>Activity 4</u>: Develop and implement a knowledge framework to educate stakeholders on the need for the research.	Internal and external stakeholders (see Table 1.3).	2009	• Educate stakeholders on the research need, business benefits, approach and justification of the approach. • Establish stakeholder's business carbon need, views on the research approach, the selected core highway maintenance processes (Activity1) and data variability (availability and reliability). • Define stakeholder responsibilities within the context of the research. • Produce a programme for action. Activity 4 was undertaken by PowerPoint presentation and open discussion section across five BB-HST's contracts considered.
<u>Activity 5</u>: Work with highway maintenance process managers or owners.	Process Managers and Research Engineer.	2009	• Provides in-depth knowledge of the core highway maintenance delivery process they are responsible for. • Map the core highway maintenance process to PAS2050 protocol (see section 3.5.3 and Figure 4.3). • Collate additional information that can support site data collection templates development (see appendix E). • Produce a programme for site data collection, agree number of site visits and address issues around site safety and confidentiality. Activity 5 was undertaken in two days for each BB-HST's contacts (five contracts were considered): working one-on-one with process managers.

Activity 6 : Work with Supply chains (Material manufacturers, Suppliers and Waste Management Companies).	Supply chain representatives and Research Engineer	2009	• Seeks knowledge on the existing supply chain carbon emissions assessment approach. • Introduces the PAS2050 life cycle carbon emissions assessment approach and related benefits. • Identifies material types, manufacturer locations and mode of delivery. • Identifies BB-HST's waste streams, types and processing techniques. • Addresses issues around IPR agreement and confidentiality. Activity 6 was carried out in two days for each BB-HST's contacts (five contracts were considered in total): working one-on-one with the supply chain representatives.
Activity 7 : Develop Data collection Templates (see appendix E)	Research Engineer	2010	• Provide consistent and formalise approach on data collection across BB-HST's and supply chain business operations.
Activity 8: Collect Data based on the Templates develop in Activity 7	Research Engineer and Supply chain	2010	• Supports data collection and management. Activity 8 was undertaken by visiting highway maintenance sites (48 sites), three product manufacturers and three waste management companies in the UK.
Activity 9: Disseminate research deliverables and strategy for improvement	Research Engineer and stakeholders	2013	• Undertake a launch event (presentation research outputs) • Undertake a focus group workshop. (see Chapter Four , section 4.2.2)

3.5.3 PROCESS MAPPING

Process mapping is a concept commonly used to describe a business process in a step-by-step manner, using visual workflow diagrams with supporting text. It allows all vital activities and tasks within the business process to be clearly identified. According to Anjard (1998), a process map is a visual aid for picturing work processes that defines how inputs, outputs and tasks within each process are linked. However, developing a business process map is a continuous and iterative process (British Standards Institution, 2008). One major advantage of using process mapping is that, it allows the user to gain a better understanding of current processes and simplifies those that required changes, tasks and problems that are faced within the business (Hunt, 1996 Peppard, 1999). Karhu (2000) presented six commonly used methods of process mapping : IDEF0, IDEF0v, IDEF3, Petri Nets, Scheduling method and simple flow. However, Koskela (1992) explained that to model a complex scenario of real-world problems, the Integrated Definition Language (IDEF0) and Process Decomposition (PD) techniques are commonly employed (Anjard, 1998 Karhu, 2000 Koskela, 1992). In view of the nature of research objective 2 (see Chapter One, section 1.6.2) and Tasks 6, 7& 8 (Figure 3.6), the PD technique is employed in this study to identify and define the activities, tasks and associated emissions data inputs (items of energy and materials consumption) across the sponsor's highway maintenance process supply chain. Although the PD technique lacks the sophisticated representation found in other techniques, the PD technique was adopted in this study because it was straightforward and easy to use. It identifies and defines the key stakeholders across the EngD research sponsor's business supply chain. More details of the process mapping activities, approach employed and outcome are provided in Chapter Four.

3.5.4 SURVEY

It is essential at the initial stage of any research to investigate the nature of the data required and collection approaches to be employed in order to identify the limitations of the data and their variability (validity and availability). The restrictions commonly encountered in research data collection are mainly due to availability, ease of collection, provision, cost, time and confidentially issues (Fellows and Liu, 2003). To enable Task 8 (see Figure 3.2) to be undertaken in this study, self-completed structured data gathering proforma was developed to enable quantitative data (for example, quantity of materials, fuel consumed and distance travel) to be collected from selected core highway maintenance processes selected in Task 7 and their supply chain. The data gathering proforma (see Appendix E) were designed to capture the research data. . Although the approach was time consuming and prone to bias, due to high control the researcher has on the survey process, the issues around response rate, skills require to administer the survey proforma and opportunity to collect supplementary information were adequately addressed... Details of the quantitative data gathering activities are summarised in chapter Four .

3.5.5 MODELLING

At the synthesis phase of the EngD research (Objectives 2 & 3), a process-based modelling technique was employed to develop a highway maintenance project specific carbon footprinting methodology (Task 9) following the life cycle methodology described by the PAS2050 protocol on carbon emissions assessment. At the later stage of the research, a carbon evaluation tool (Task 11) was developed based on the principles and requirements of the carbon footprinting methodology developed in (Task 9) and evaluated (Task 12) using carbon data collected in Task 8. The need for these developments was to support the quantitative data analysis (Task 10), whilst providing a consistent, project-focused carbon assessment tool, underpinned by a robust methodology that can analyse and account for emissions holistically. This will support highway owners, designers, managers and maintainers to produce and integrate credible emissions information into highway maintenance decision-making processes.

3.5.6 QUANTITATIVE DATA ANALYSIS

At this stage, the raw data collected using the proforma can then be manipulated, and analysed quantitatively using statistical techniques (commonly used for analysing quantitative data) in order to meet the goal of the research Task 10. The analysis of results is expected to provide a condense picture of the study variables displaced in the form of tables, charts and graphs. These outputs reveal the relationships that exist between the research variables, summarise and interpret or give theoretical meaning to the results (Neuman, 2011). In this study, these relationships coupled with the interpretation of the results, are used to support and inform generalisation of research findings. Although, this analysis approach provides an objective view of the research aim, the results might not represent the general views of the research stakeholders defined in Table 1.3, since their shared views and perceptions cannot be elicited by the approach.

3.5.7 DIRECT OBSERVATION

This is a careful observation and the studying of research participants in order to enhance the success of the method, and determines the validity of the findings. This approach is commonly employed when data collected based on other means are difficult to validate or can be of limited value (Hancock, 1998). The observation technique (Ackroyd and Hughes, 1992) employed in this research follows the “participant as observer” role defined by Ackroyed and Huges (1992). The “Research Engineer (RE)” was closely embedded within the sponsor’s business environment for most of the four years period. This allowed the RE to gain an in-depth understanding of the sponsor’s organisation’s culture and business operations. This helped to refine the research to align with the sponsor’s immediate business need (on carbon emissions reduction) and recommend areas requiring further research work(Tasks 13 and 14). Chapter Four presents details of the carbon footprinting methodology and evaluation tool developed.

3.5.8 ACTION RESEARCH

Fellows and Liu (2003) described action research as a style of study that requires active participation by the researcher in the research process in order to identify, promote, and evaluate problems and potential solutions. The solutions are then implemented, in the knowledge that there may be unintended consequences following such implementation. In this case, the effects are evaluated, defined and diagnosed, and the study continues on an on-going basis until the problem is fully resolved (Sekaran, 2003). Bryman (2004) argued this research approach allows the researcher and a client to collaborate in the analysis of a problem and development of solution following the analysis. According to Avision et al (1999), the supporters of action research argued that to make academic research relevant, the researchers should try their theories with practitioners in real life situations and real organisation environments (Avision *et al.*, 1999 Bryman, 2004). This view aligns strongly with the EngD goal, which involved practical research work undertaken within an industrial business environment. Furthermore, the EngD project was embedded within the sponsoring organisations, and the researchers (in collaboration with the sponsor) were deeply involved in the EngD research scope definitions and the methodology to be employed. The RE promotes the EngD research needs, problems and possible solutions to address the problems through formal research stakeholder consultations. In general, action research allows the researchers to put into action the concept that the PAS2050 life cycle methodology can be used for highway maintenance carbon footprinting and support reduction investment decision-making (Task 15). The close involvement of the RE within the sponsor's business operations had the potential to introduce an element of subjectivity and bias in the assessment of the applicability of the PAS2050 protocol for business carbon footprinting and decision-making process. This was largely overcome by working closely with the sponsor and others (e.g. potential end-users) in the implementation of the research approach, outputs and data across the sponsor's internal and external business operations (Task 15).

3.6 JUSTIFICATION OF THE ADOPTED RESEARCH APPROACH

This research seeks to develop a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool to support carbon management decision-making in highway maintenance planning and operation. Given the nature of these business needs, the research objectives and related tasks (see Figure 3.2 identified to achieve the research aim present specific research question that a mono-methods approach cannot answer.. This then introduces elements of objectivity and subjectivity to the research aim, using approaches drawn from both quantitative and qualitative tradition (Creswell, 2003). A deeper understanding of the key issues affecting highway maintenance carbon footprinting and reduction across its value chain is essential. As such, it is important to work closely with the highway business stakeholders (internal and external) to accurately understand the business challenges and benefits of undertaking business carbon footprinting and reduction agenda. This requires capturing the opinions, views and perceptions of the research stakeholders to support a robust carbon evaluation system to be developed that can support inform business decision-making.

To this end, a mixed methods approach was applied to meet the research aim and objectives, since it has the capacity to answer certain types of research questions that can only be addressed by combining quantitative and qualitative studies (Bryman, 2006). The methods are often employed in order to compensate for the perceived shortcomings of stand-alone methods and provide a more complete picture or enhanced coverage of the issues under investigation (Barbour, 2008). Mason (2006) argued that employing mixing methods in research provides researchers with the opportunity to access multiple perspectives and dimensions of the research issues, since social phenomena and realities are multi-dimensional; also good understandings of the phenomena can be hindered, if viewed only along a single continuum (Mason, 2006). This position justifies the use of mixed methods in this study, since it can provide parallel insights into the experiences of the different highway maintenance stakeholders including the customers. Fellows and Liu (2003) argued that by combining research methods, the richness and complexity of research issues can be explained in more detail, and provide the opportunities for the issues to be studied from more than one viewpoint. This approach can provide a more enhanced coverage of the issues researched and compelling views of the experiences and perception of related multi-dimensional stakeholders (Barbour, 2008). Bryman (2006) recommends that this research approach should not be seen as a universally superior research strategy, but like every other research method, presents its own advantages and disadvantages which were highlighted in Table 3.3.

3.7 SUMMARY

This chapter has discussed types of research from application, objectives and information sought point of views. It has also briefly discussed the main research methods and related methodological approaches available and highlights the advantages and disadvantages of employing specific research methods for an enquiry. The EngD adopted research process, research map and stakeholders engagement process that outlined the overall research methodology were also presented. An overview of the specific research methods and approaches employed in this study and justification of the approaches adopted were provided as appropriate.

4 CHAPTER FOUR: RESEARCH UNDERTAKEN

4.1 INTRODUCTION

This chapter describes the research undertaken to meet the research aim and objectives outlined in Chapter One. The research undertaken is detailed in such a way as to demonstrate its relevance to the realisation of the research objectives. These tasks were vigorously pursued in accordance with the research methods and methodologies described in Chapter Three (sections 3.3 and 3.5). This chapter further describes the overall research process based on the scope and focus of the research aim. It is essential to note that where references are made to the appended relevant papers in this thesis, readers are expected to read each paper in its entirety and then return to the discourse.

4.2 RESEARCH OBJECTIVES AND PROCESS

The research map presents the tasks undertaken, information flow, methodology and methods employed at each phase and stage, and expected outputs based on the aim, objectives and the methods detailed in chapter three. Figure 4.1 presents the overall research process through which the objectives were achieved. It builds on Table 3.5, and provides industrial/sector developments (contextual) promoting carbon footprinting and reduction. It then links the developments to the study objectives, research phases and expected outputs. These developments form part of the preliminary information gathering tasks that were used to define and establish the EngD research project. This forms the basis to validate and justify the relevance of the EngD research project from an industrial context.

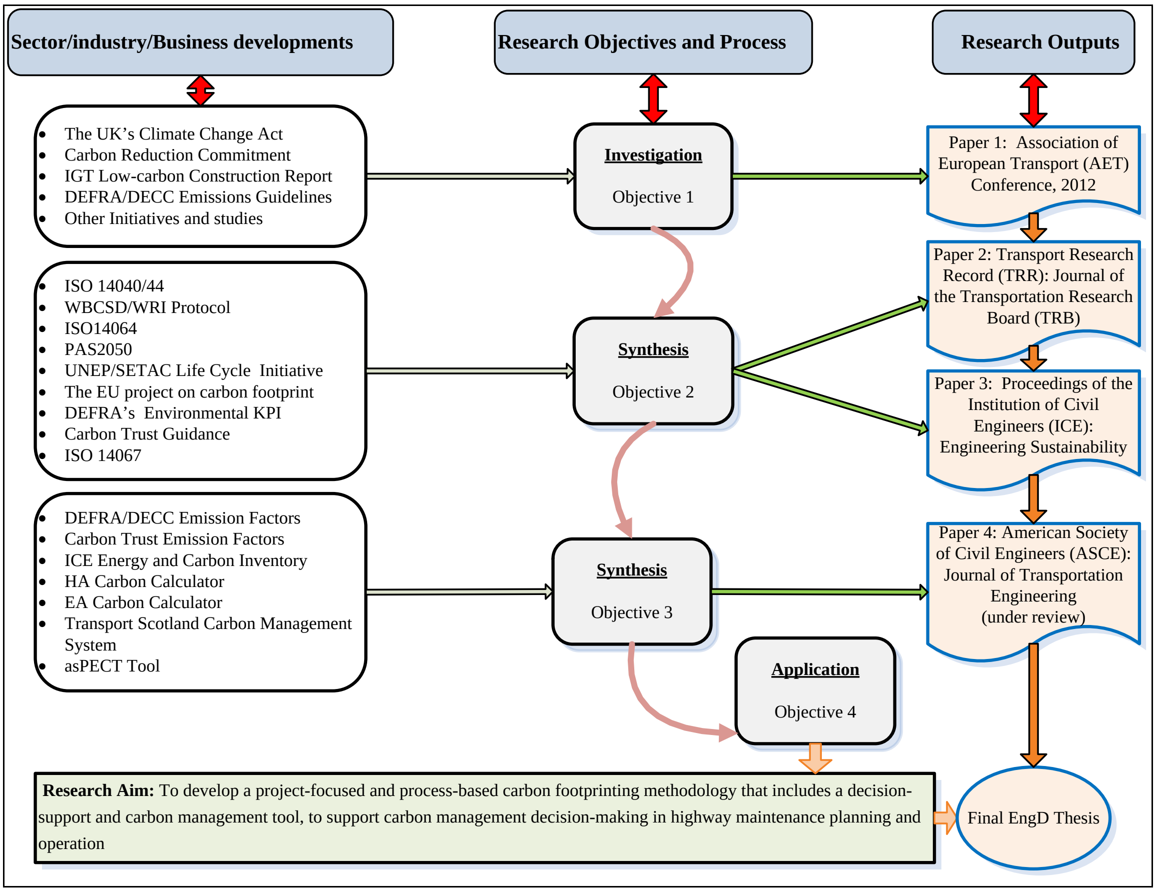


Figure 4.1 Industrial/Sector Developments, Objectives and Process, and EngD Outputs

4.3 THE RESEARCH INVESTIGATION AND SYNTHESIS PHASES

This section presents the research activities undertaken to meet the goals of objectives 1, 2 & 3. This includes the literature review and quantitative aspect of the EngD research methods adopted. The research objectives and related work tasks to achieving each of the objectives are discussed below. The research approach employed and expected outcomes are also discussed.

4.3.1 OBJECTIVE 1 (RESEARCH WORK TASKS 1-5)

This is the investigation phase (see Figure 3.2), and it involved the preliminary information gathering stages where an initial state of the art literature review into business carbon emissions performance (see Appendix A, EngD Paper 1) was undertaken to identify:

- the contents and requirements of the regulatory and non-regulatory policy frameworks driving carbon footprinting and reduction;
- the opportunities and challenges inherently presented by the civil infrastructure and highway maintenance sector in promoting carbon performance; and ,.

- carbon footprinting and reduction issues, knowledge gaps in the state of practice and research opportunities to minimise the impact of these issues at business and project levels.

It was important to explore these areas so that a better understanding of the infrastructure and its highway maintenance sector carbon footprinting and reduction performance were consistent with the policies driving the agenda (Work Task 1), and how the challenges presented by the sector can be addressed in highway maintenance planning and operation.

The EngD Paper 1 (Appendix A) documents the findings of the state of the art literature review into the regulatory and non-regulatory frameworks driving carbon footprinting and reduction performance. The paper concluded with a conceptual knowledge framework (see Figure 4.2) that can be used as an information source by businesses to develop a robust corporate strategy for carbon emissions performance. This conclusion promotes project-focused and process-based carbon footprinting and a reduction approach across the organisation value chain. It was recommended within the paper that an efficient corporate strategy for carbon performance should include the following elements: a carbon evaluation tool underpinned by a robust methodology, outputs from complementary studies and credible carbon data and collection approach, as detailed in Figure 4.2 (see the EngD paper 1 for detail). Following this conclusion, an additional literature review was initiated to explore the elements outlined above. The additional literature review is documented in Chapter Two .

The EngD paper 2 (Appendix B) detailed a review into prior studies on carbon emissions methodologies from a life cycle perspective. Chapter Two presents a brief summary of the review (see section 2.4.1). This represents the research work task 2 (see Figure 3.2).

Chapter Two (section 2.3) provided an additional literaturereview of the Life Cycle Assessment methods and models. The EngD paper 3 (Appendix C, section 2.1) provided details of the review of studies that employed a process-based life cycle approach for highway maintenance carbon emissions assessment. Section 2.4.2 provided a summary of the review. This additional literature review represents the EngD research work task 3 (see Figure 3.2).

Chapter Two (sections 2.4.3 and 2.4.4) provides details of a literature review into studies on road material (asphalt) embodied carbon and reduction, emissions data collection and standardisation approaches. The emphasis is on studies for construction vehicles and equipment emissions inventory. This represents the research work task 4 (see Figure 3.2).

The EngD paper 4 (Appendix D) presented details of the literature review into existing carbon evaluation tools developed at international and national levels to support the carbon footprinting and reduction agenda. Section 2.4.5 provides a summary of the review undertaken in work task 5.

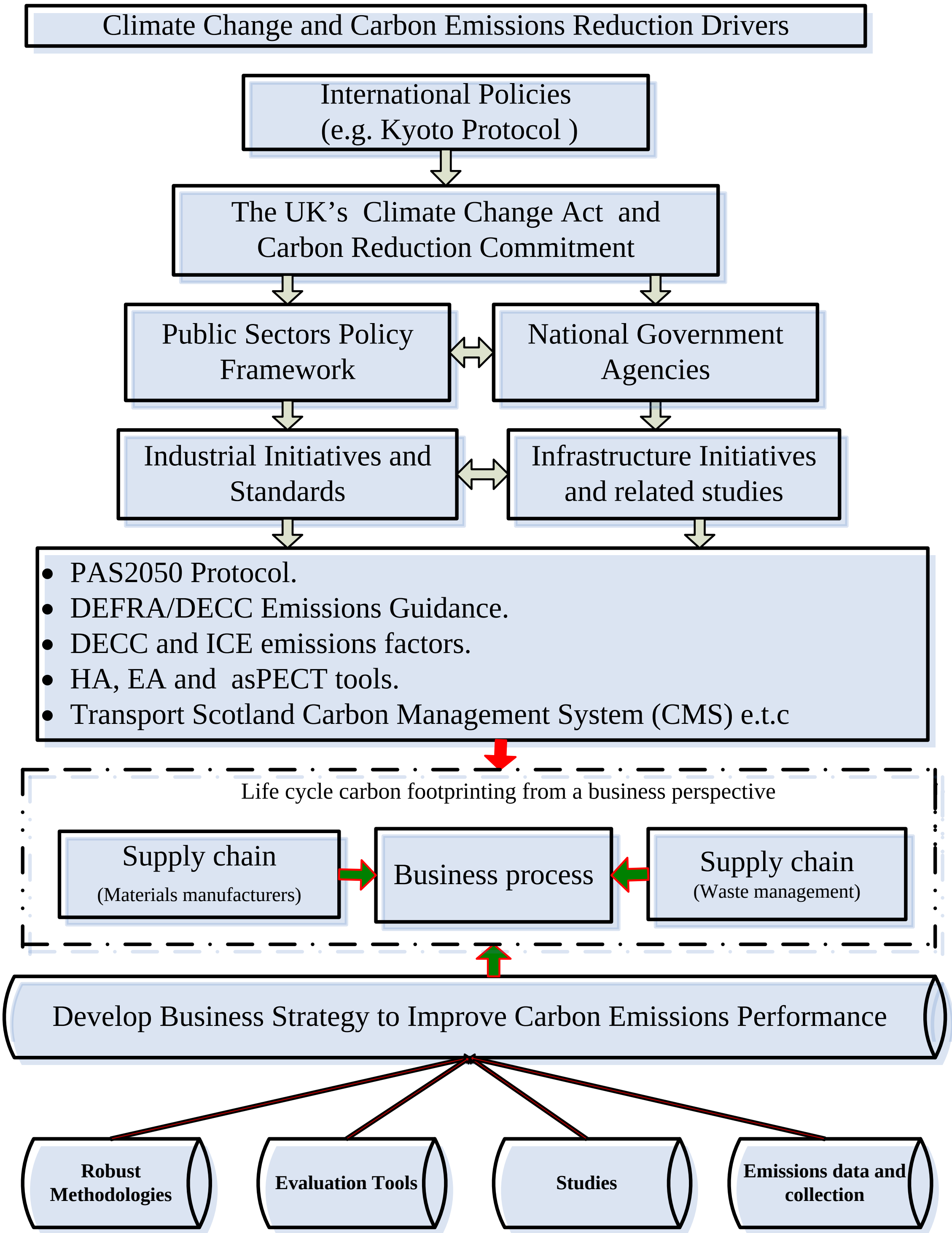


Figure 4.2 A Conceptual Knowledge Framework for Carbon Emissions Performance

Following the state of the art literature review, it was evident that there is a strong momentum at the international, national, industrial and business levels driving carbon emission performance. The absence of an accepted industrial methodology standards for carbon footprinting, overarching policies focusing on carbon footprinting, analytical drawbacks presented by existing studies and evaluation tools are issues constantly frustrating organisational efforts to undertake credible carbon footprinting and reduction.

These issues present organisations with challenges, risks and business opportunities yet to be understood by business stakeholders.

Following the study aim within the context of the sponsor's business need, two additional research objectives (Objectives 2 and 3) were identified.

4.3.2 OBJECTIVE 2 (RESEARCH WORK TASKS 6-10)

To explore the potential of the PAS2050 protocol and to gain an insight as to how it can be implemented for carbon footprinting to support carbon reduction decision-making in highway maintenance processes, a project-specific and process-based methodological framework based on the protocol was developed. Its application is illustrated in Objective 2. This forms the beginning of the synthesis phase (see Figure 3.2) of the EngD research. The details of the research Objective 2 and outcomes are documented in the EngD Papers 2 and 3 (see Appendices B and C). Task 6 focuses on the research stakeholders engagement process and programme of activities. The selection of identified core highway maintenance processes and process mapping were undertaken in Task 7. The stakeholders' engagement process undertaken in Task 6provided a deeper understanding of the selected core highway maintenance processes. This supports site data collection (quantitative data) approach in research *Task 8*. The detail of the project-specific and process-based carbon footprinting methodology framework developed is presented in research *Task 9* and the business implementation process illustrated in *Task 10*.

4.3.2.1 Stakeholders Engagement Process (Task 6)

The research stakeholders' (internal and external) engagement process was a key component of Objective 2, and was a continuous process throughout the EngD programme. As part of this, a framework was developed enabling the research need, aim, objectives, scope and focus to be explained to stakeholders including the supply chain. This offers the opportunity to work closely with the highway process managers, maintainers and supply chain. It allows relevant energy and carbon-intensive activities and tasks (major carbon emissions sources) within the selected core highway maintenance processes to be clearly identified which allows representative core highway maintenance process mapping to be developed. The stakeholders then provided suggestions to refine the research data collection approach to minimise data error. The research task offers the RE the opportunity to address issues around site safety (during data collection), legal, commercial and confidentiality. It also allows relevant data and the collection approach to be defined, whilst assigning responsibility among stakeholders and developing a workable programme for action. Section 3.5.2 and Table 3.6 (see Chapter Three) provide a more fulsome description of the on-going stakeholder engagement process. It describes who was involved, when and how the engagement process was undertaken. **4.3.2.2 Process Mapping (Task 7)**

Building a business process map is a continuous and iterative process (British Standards Institution, 2008). The initial stakeholder engagement provided useful information to understand the core highway maintenance processes selected for carbon footprinting. Section 3.5.2 explained the process mapping technique applied in this study. Figure 4.3 presents the process map developed as part of this study specific to highway maintenance operations. It outlines the selected highway maintenance process activities data (e.g. material, energy used, waste generated, etc.) relevant within the defined system boundary. It allows the carbon emissions interface that exists between the sponsor and its supply chains to be clearly defined.

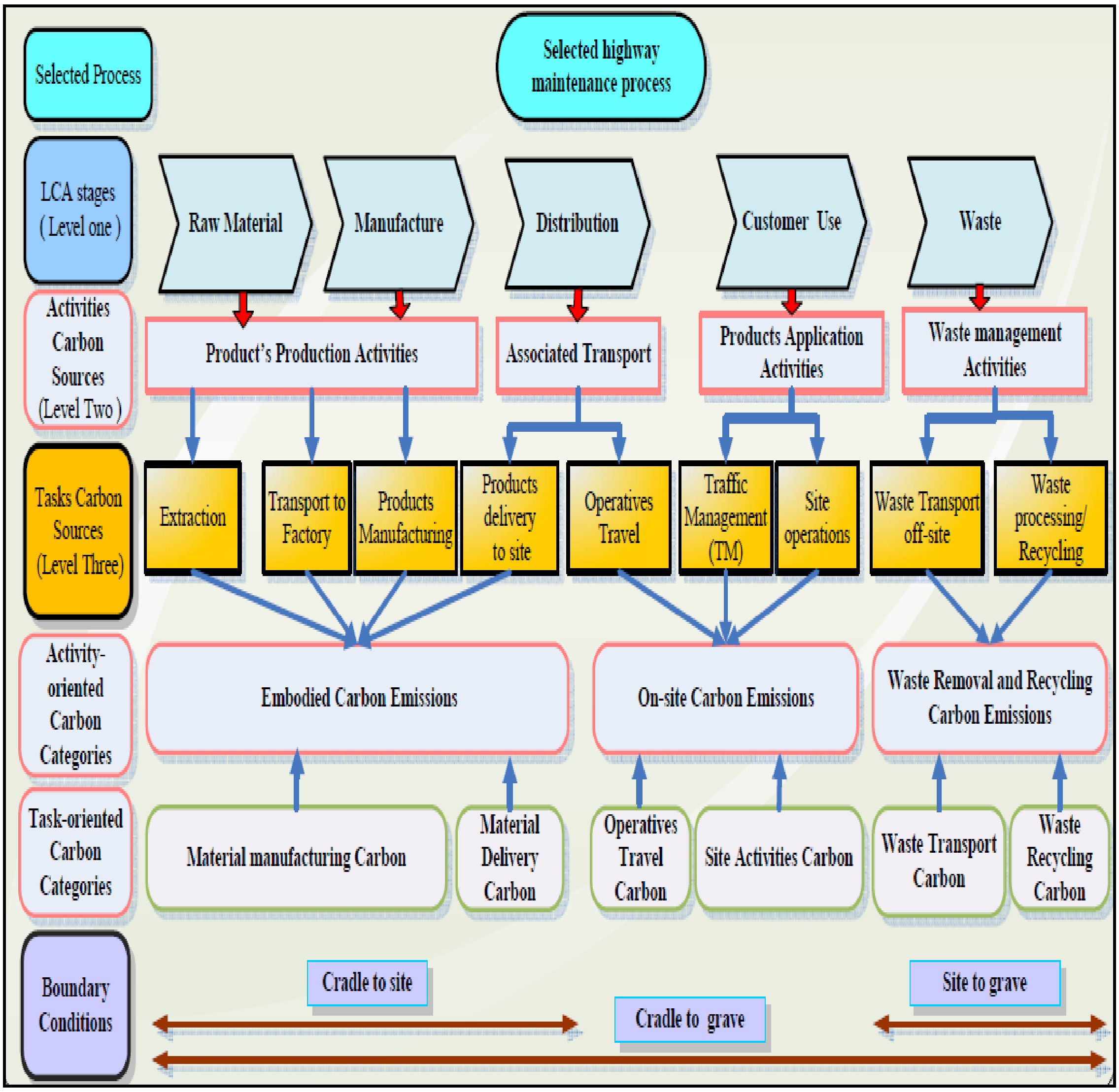


Figure 4.3 Process Map Specific to Routine Highway Maintenance Processes

4.3.2.3 Survey and Data Collected (Task 8)

The PAS2050 approach recommends that activities data, including that from the supply chain and standard emission factors are required to calculate life cycle carbon emissions associated with products and services (British Standards Institution, 2011). The process map helps define the activities data types required for the study, and provided useful guidance on the data collection approach. During this task, quantitative data (secondary and primary) were collected across core highway maintenance processes identified during the stakeholder engagement exercise. A data gathering proforma was developed and used to collect the carbon activities data (mainly energy-based data) required for the analysis. The data collected include standard emission factors from publicly available databases (in appropriate units), scale of work completed on site, quantity of materials (e.g. asphalt) and energy (e.g. fuel used by plant/equipment) consumed, waste generated and waste recycling processes. This data was collected across urban, semi-urban and rural site environments. Tables 1a, b (EngD Paper 3 Appendix C) present the energy-based activities data collected from selected core highway maintenance processes namely: pavement resurfacing, pavement marking, lamp replacement and grass cutting across urban, semi-urban and rural site locations. These data were collected from fourty eight highway maintenance site locations across urban, semi-urban and rural environments, three product (Asphalt, Thermoplastic paint and Lamps) manufacturers and two waste (Road Planings and lamp recycling) management companies,.EngD Paper 3 (see Table 2) presents the fuel-based emission factors from publicly available databases, materials manufacturing and waste recycling companies. Figures 4.3 and 4.4 define and provide the energy-based activities data sources associated with the core highway maintenance process across its value chain, while Figure 4.5 provides a methodology flowchart to formalise the data collection and ensure consistency of approach.

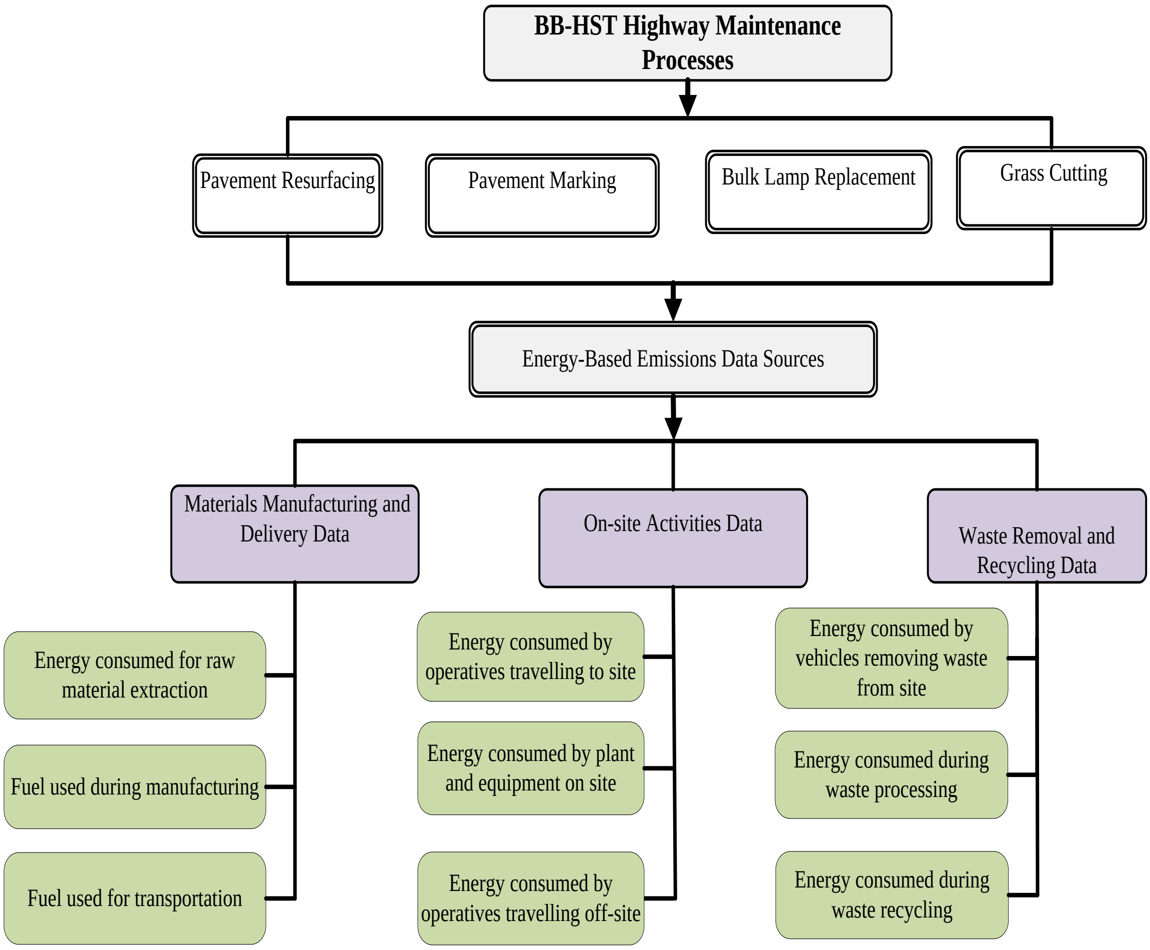


Figure 4.4 Energy-Based Emission Data Sources from Highway Maintenance Processes

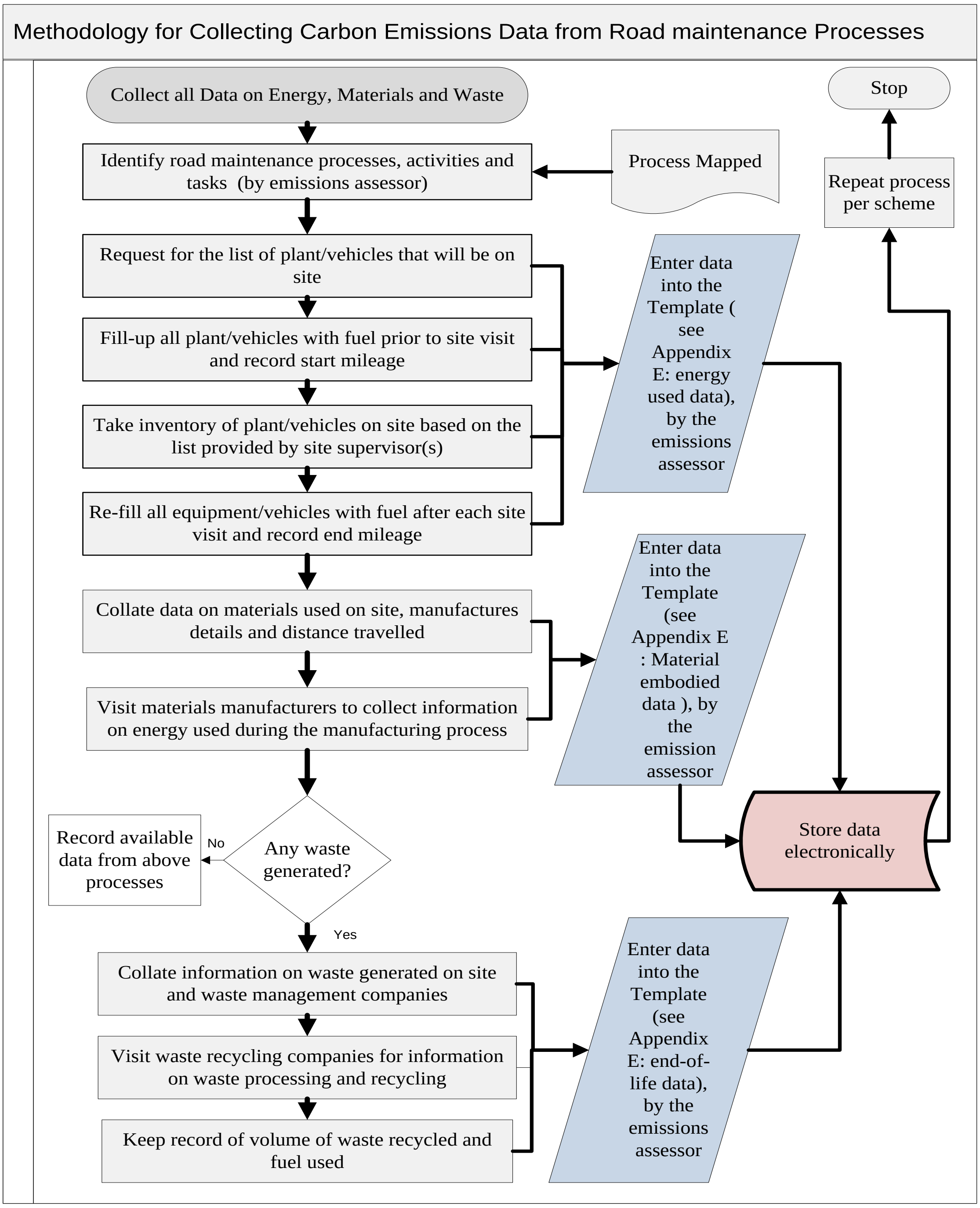


Figure 4.5 A Methodology Flowchart for Quantitative Data Collection

Data Bias

The approach employed in data collection and compilation may introduce bias in the data (Choudhury, 2002). In this study, measurement, sample selection and the survey questionnaire are the main sources of bias in terms of data collected:

(a) Measurement Bias: This type of bias is introduced due to the tendency of the study stakeholders to provide "socially desirable" information. In this study, the material embodied carbon data (e.g. asphalt) was estimated and provided by the product manufacturers. The tendency for the manufacturers to provide sustainable desirable data is very high in order to promote their environmental and sustainability commitments.

(b) Sample Selection Bias: The fuel emission factors (e.g. Diesel) used in the carbon footprinting represents the energy calorific-value, since the "Well-to-Wheel" data (life cycle perspective) are currently unavailable in the public domain.

(c) Questionnaire Bias: This type of bias is introduced from the way the survey questions and the entire questionnaire are designed and administered (Choi and Park, 2005) for data collection. In this study, the questionnaire seeks to explore and interrogate existing highway maintenance processes that the sponsor and its supply chains operate in terms of carbon (commercially sensitive information). This created "underreported" information particularly from materials manufacturers, since the majority of the information are commercially sensitive. Table 4.1 provides the emissions data types, collection approaches and sources..

Table 4.1 Emissions Data Types and Sources

Data Types	Collection approaches/sources	Comment
(a)Emission factors	• University of Bath: Inventory of Carbon and Energy (ICE)", • "2010 Guidelines to DEFRA/DECC's Greenhouse Gases Conversion Factors for Company Reporting and UK-based company and company-based emission factors (DECC, 2010)	These are fuel-based emission factors to be used in the UK for carbon emissions calculations
(b) Scale of work completed	Measured directly on site or estimated from the highway designers working drawings (CAD drawings and BoQ)	Required inputs from the site supervisors
(c) Quantity of material used and waste generated on site	• Material supplier's delivery tickets. • Measured directly from site, estimated from the highway designer's specification drawings. • Site waste transfer notes	Required inputs from site supervisors and waste management company
(d) Distance covered	• Materials (Plant-to-site). • Operatives (Depot-to-site). • Site waste (Site-to-recycling)	Return journey should be included
(e) Fuel consumed	• Material production. • Operative travel. • Site plant/equipment. • Waste transport off-site. • Waste processing and recycling	Measured data follows the methodology flowchart detailed in Figure 4.5

Data Quality Assurance

PAS2050 recommends that the primary and secondary data required for carbon footprinting of goods and services must meet its “Data Quality Rules”. This is to ensure that the carbon footprinting process employed data with reduced bias and uncertainty as far as practicable in order to produce accurate, reproducible and more comparable and representative carbon footprints(British Standards Institution, 2011). Table 4.2 presents the PAS2050 “Data Quality Rules”, and how the data employed in this study comply with the quality rules set by the protocol. It also presents the quality control measures employed to minimise errors, and enhances the data quality.

Table 4.2 Carbon Emissions Data Quality Assurance

PAS2050 Data Quality Rules	How the Data used in this Research meets the PAS2050 Data Quality Rules	Data Quality Control Measures
Completeness	• Core highway maintenance processes (pavement resurfacing, line marking, street lighting and grass cutting) specific to the UK highway sector were selected for carbon footprinting. • The six Greenhouse Gas (GHG) emissions defined by the IPCC and Kyoto Protocol were considered for the study expressed in carbon equivalent (CO_2e).	• Ensure relevant stakeholders are appropriately engaged. • Develop a process map to support the data collection process.
Consistency	• Data collection template (see Appendix E) and methodology flowchart (Figure 4.5) were developed to formalise the data collection approach and enhance consistency. • Ensure the data collection approach does not interrupt the daily operative’s productivity rate. • Number of site visits per process per site location were agreed prior to site visit. Ensure all data collection complies with site safety rules.	• Figure 4.5 provides consistent approach to the data collection process. • Where the data collection failed to meet the approach defined, such activities were removed from the data collection.
Reproducibility	• The carbon footprints’ information was compared across urban, semi-urban and rural site locations.	• Consistent system boundary employed across different site locations.
Accuracy	• Highway maintenance process specific data gathering proforma was developed for data collection across different site locations.	• Data that fails to meet the data quality rules was discarded.

Data Sources	• All primary data was measured directly from site across urban, semi-urban and rural site environments, and from supply chain operations. • All secondary data (e.g. emission factors) were collected directly from publicly available databases.	• Both direct and indirect data sources were used. • Updated versions of the databases were employed.

4.3.2.4 Framework for Carbon Emissions Evaluation (Task 9)

This section presents a summary of the development and evaluation process of a project-specific and process-based methodology framework based on the Publicly Available Specification (PAS2050) standard for carbon footprinting. The framework developed is specific to highway maintenance planning and operation.. It presents a life cycle approach that can allow businesses to identify areas of carbon hotspots, opportunities for reduction and establishes a reduction hierarchy to allow reduction efforts to be prioritised through informed decision-making. Within the scope of this research task, the framework development process, the theoretical concept that underpinned the framework development and its implementation using preliminary data are detailed in EngD paper 2 (Appendix B). The EngD paper 2 has been published as part of the Transportation Research Record (TRR)- a journal (No.2292) of the Transportation Research Board (TRB) of the National Academies Washington, DC.The paper suggests that the PAS2050 methodology has the potential to identify areas of carbon hotspots associated with highway maintenance process and opportunities for reduction. The paper then concludes that asphalt production and its delivery for highway maintenance work present most environmental burdens from a life cycle perspective. The paper further outlined the challenges and complexity that exist when undertaking highway maintenance life cycle carbon footprinting. The methodology framework offers the highway maintenance sector the potential to make informed decisions in carbon terms, by identifying areas of carbon hotspots and prioritising potential emissions reduction efforts. Figure 4.6 presents the methodology framework developed and Figure 4.7 presents a flowchart which provides a step-by-step approach on the methodology framework application process.

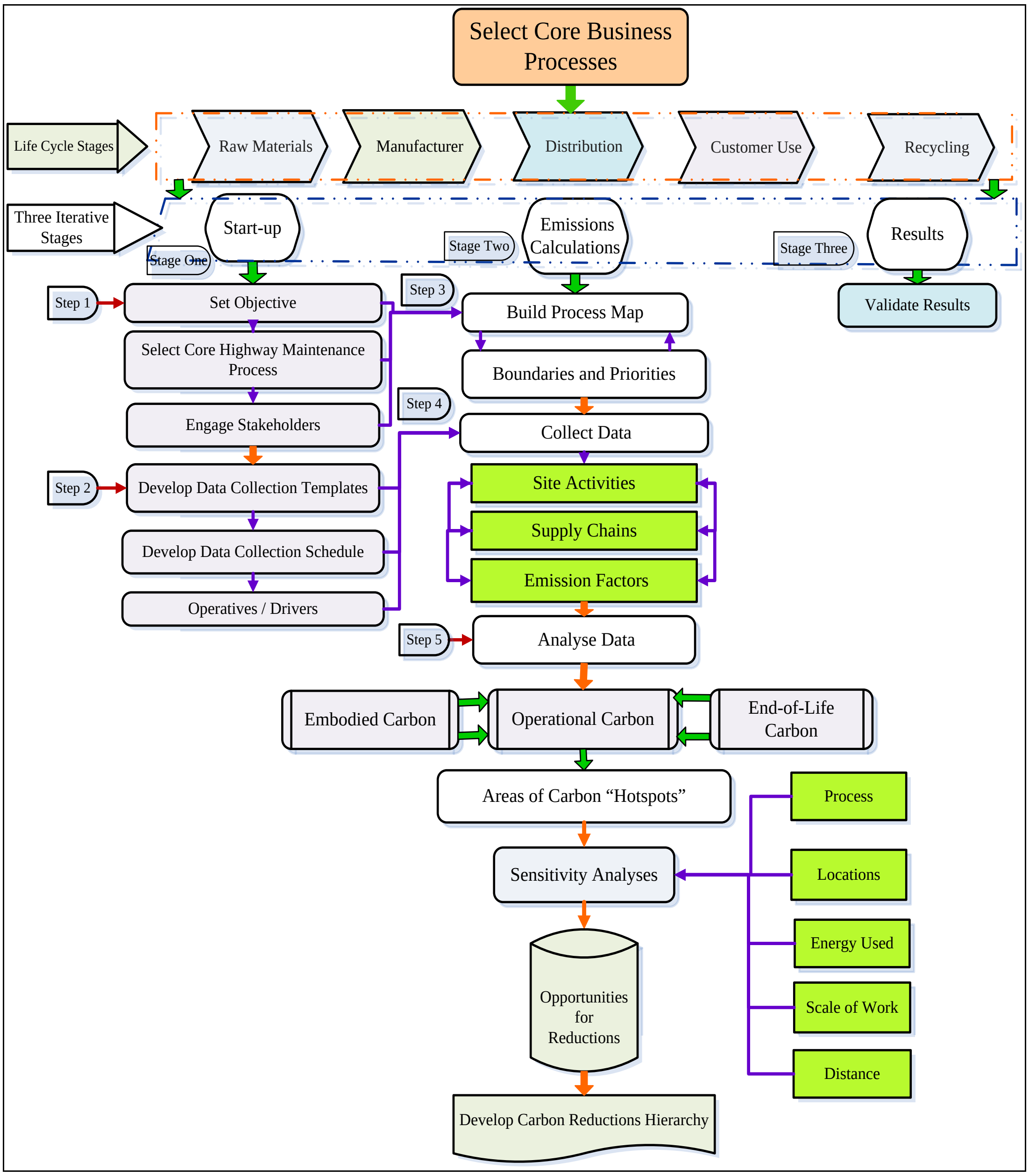


Figure 4.6 Life Cycle Methodology Framework for Business Carbon Footprinting

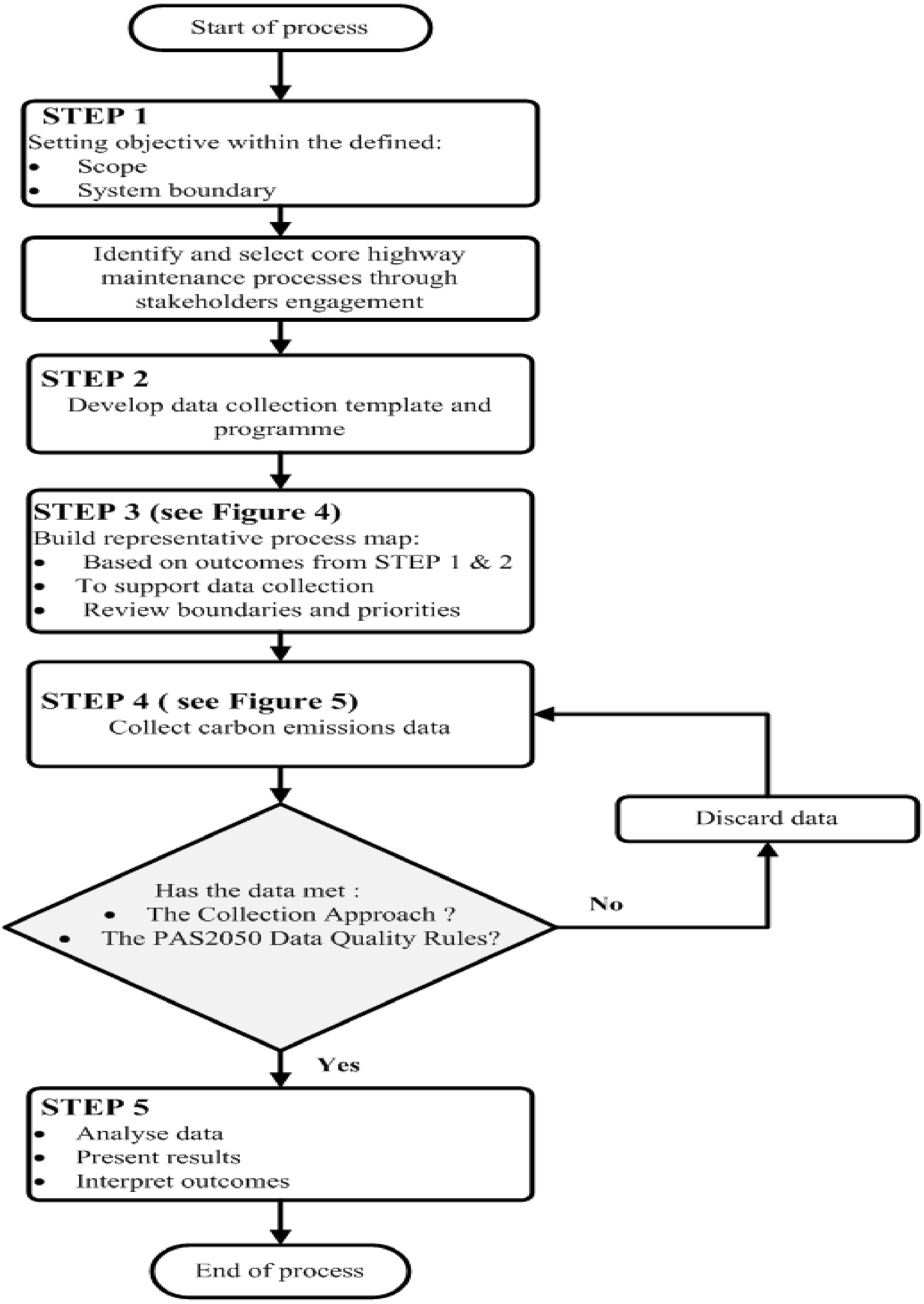


Figure 4.7 A Flowchart for the Application of the Methodological Framework

- **Step 1** involved selecting core highway maintenance process and locations through the stakeholders' engagement (see Chapter One) in order to adequately define the study scope and system c boundary.

- **Step 2** involved producing a data collection method that will allowed a work study to be undertaken for the maintenance processes evaluated. This incorporated assessment of material embodied carbon from suppliers and site work to measure the carbon footprint used (via fuel consumption) in the transport, plant/operations required to place materials and dispose of materials within the activity.
- **Step 3** involved building a process map to allow the method in Step 2 to be undertaken.
- **Step 4** was the site work to collect field data and review it in the context of the PAS 2050 approach from step 3.
- **Step 5** involves the analysis of the data collected (converting the data collected to their corresponding carbon footprint using appropriate emission factors) and presents the results for interpretation.

4.3.2.5 Quantitative Data Analysis (Task 10)

The data analysis stage presents industrial implementation and results of the process-based life cycle methodology framework developed in Task 9 (See Figure 4.6). The carbon footprints associated with highway pavement resurfacing, pavement marking, bulk lamp change and grass cutting operations were assessed across urban, semi-urban and rural site locations using the framework and data collected in Task 8. The intention is to identify areas of carbon hotspots and related opportunities for reduction, not least developing a reduction hierarchy, so as to ensure potential carbon emissions reduction efforts are adequately focused and prioritised across the highway maintenance process value chain. The details of the data analysis approach and results are documented in EngD Paper 3 (Appendix C), which include the exploratory analysis undertaken based on the site variables identified. This approach offers the highway maintenance sector a holistic life cycle carbon footprinting framework that can assess the sector carbon emissions performance in life cycle terms. The results indicate that the PAS2050-compliant methodology framework presents a robust analytical rigour and provides the largest potential for carbon emissions reduction across the value chain.

4.3.3 Objective 3 (Research Work Tasks 11 and 12)

This is a continuation of the synthesis phase of the EngD research project (see Figure 3.2).The primary focus of this objective is to develop a life cycle carbon evaluation tool (section 4.3.3.1). The carbon evaluation tool development process and full description on how the tool was developed and changed from initial version to the current version (from version 1 to version 19) are discussed. The business evaluation of the tool was also illustrated to justify and validate the credibility and overall value of the carbon information generated by the tool (see section 4.3.3.4).

4.3.3.1 Carbon Evaluation Tool Developed (Task 11)

The research task presents the development process of a carbon evaluation tool based on the principles and requirements of the PAS2050-compliant process-based methodology framework developed in research Objective 2 (Task 9). The intention is to provide the sponsor with robust carbon evaluation tool that can support its business decision-making in carbon terms. To enhance the carbon evaluation tool development process and application for use within the sponsor and its supply chain business operation , Microsoft Excel and Visual Basic Application (VBA) were employed to ensure the tool was user-friendly. Section 4.3.3.2 discussed the rationale for choosing the tool development environment (Excel and VBA). A full description of changes (from version 1 to version19) that occurred during the tool development process is detailed in section 4.3.3.3. . The details of the tool development process, its scope and structure, data requirements and business implementation for carbon footprinting at design and construction stages of a project life cycle are documented in EngD Paper 4 (Appendix D). Figure 4.8 below presents a screenshot of the carbon evaluation tool. The tool is a Balfour Beatty business focus tool. It should not been seen as direct competitor to existing highways carbon tools reviewed in Chapter Two (see Table 2.1), but complements the existing highway tools.

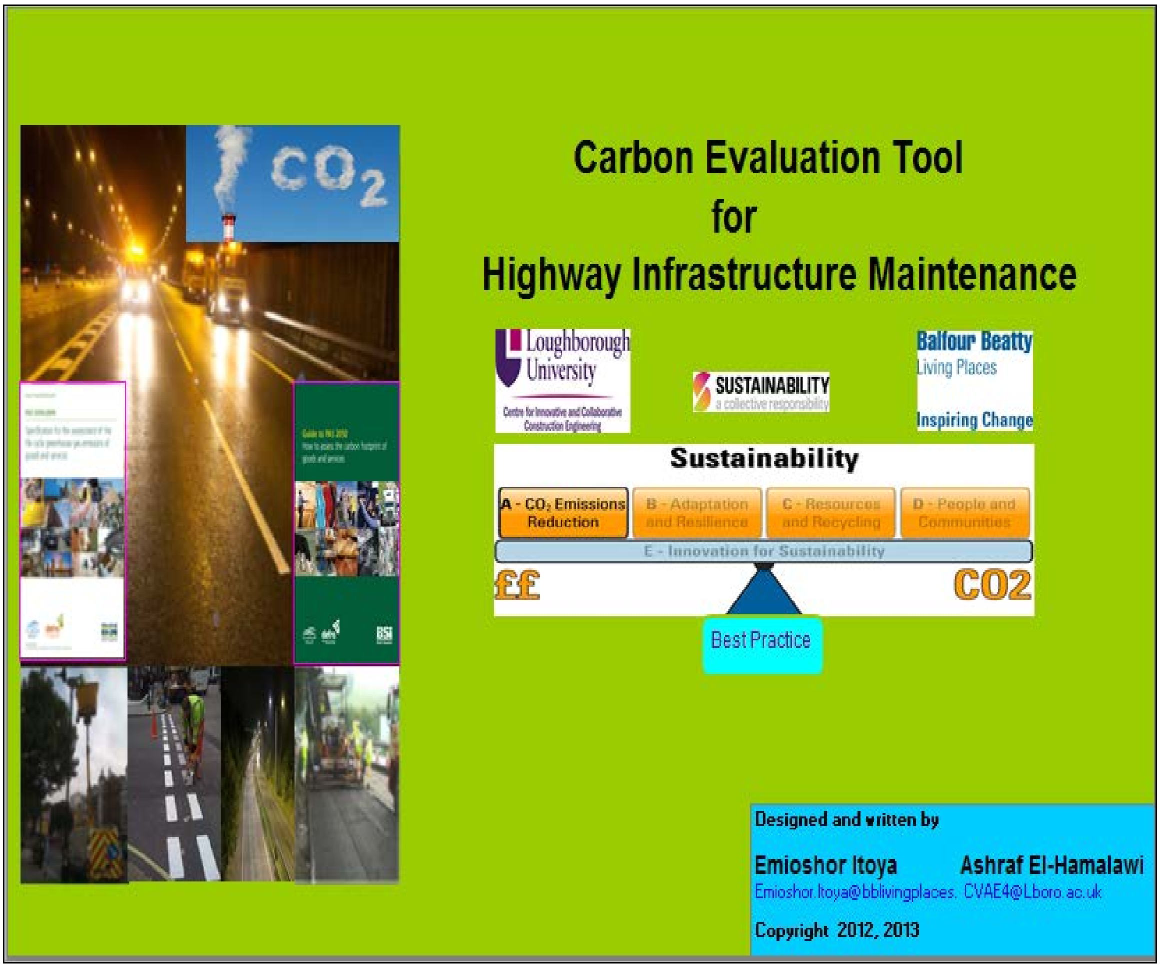


Figure 4.8 A Screenshot of the Carbon Evaluation Tool Developed

4.3.3.2 Rationale for Choosing the Tool Development Environment

The development of the carbon tool took about four months and required the help of my supervisor, Dr Ashraf El-Hamalawi, who is proficient at software programming. The initial challenge was which options author should take to develop the tool within:

1) a mathematical shell environment such as Matlab/Mathcad,
2) a commercially available software that is commonly used in most workplaces such as Microsoft Office (e.g. Excel), or
3) a standalone software.

The first option, although would have made the tool development much easier as a lot of the basic mathematical algorithms and graphics are already incorporated within the toolboxes and libraries of software such as Matlab and Mathcad, which would have also be problematic for typical tool users, since Matlab and Mathcad are mainly used in academia, and at research development sections of companies, so would not be readily available for most typical users such as engineers, managers and maintainers within highway maintenance sector, and the construction industry.

The second option was the use of Microsoft Office, with Excel being the component to be employed. The advantage of writing macros within the Excel would have been the simplicity of use for the tool users, as almost all engineers and managers have a basic knowledge of Excel, while at the same time, the familiarity of the software and ease with which data can be used in graphs is highly attractive. In terms of future further development, the ease of importing and exporting data with other packages and in text-readable format makes it an even more attractive option.

The final option was a standalone programme which would have been difficult to develop in the time available for the EngD. This requires a high level of programming skill, with possible lack of platform portability. It was therefore decided to go for the second option, with a bit of extra programming to enable the third option to be taken in future, but with minimal portability issues across different operating systems. The initial basic analysis module was done within Excel where the equations for carbon analysis were included and the automation stage undertaken using Visual Basic and macros within the Excel, and the Visual Basic shell environment. This provides a user-friendly interface visible to the users.

4.3.3.3 Description of the Tool Development Stages and the Changes that Occurred

A list of stages the tool would cater for was created, including the processes involved, and the required outputs. The initial stages covered include embodied, operational and end-of-life carbon emissions assessment. A front page was also needed to show the tool focus. Based on the latter, the Excel spreadsheet was split into seven interfaces “sheets” which includes: Front, Data Input, Options, Embodied, Operational, End-of-life and Summary/Results. The next stage then involved creating the various formulae for the carbon calculations tool within the Excel spreadsheet, and entering the various emission factors. This was done at various stages and version 3 was produced..

The basic spreadsheet was then evaluated by the research team (including academic and industrial supervisors), who then suggested that output results could be clearer by including the graphical format, and also including an extra page of scenario analysis (sensitivity analysis). These extra stages were included in the spreadsheet and a fully functional version 7 was created. The project team deemed the output suitable, but further suggested that the data input needed to be improved and graphical interface changed. Since the author has no experience of programming in Visual Basic and macros within Excel, a member of the project team (Dr Ashraf El-Hamalawi) started including the improvement from version 7 onwards. Ashraf and the author jointly checked all data formats and assessed whether data are being processed correctly within the spreadsheet, cell by cell, of which several formulae were needed to be corrected. It was then decided that the spreadsheet would be more efficient, if all data could be entered in one sheet "Input Data sheet", which would then be passed "globally" across all the other sheets within the spreadsheet, without users having to re-enter the same type of data in several places. This would save the user a lot of time during the data entry stage..

Changes were further made to the graphical interfaces by Dr El-Hamalawi, where code were written to allow the graphs to automatically update themselves and show pre- and post-updated statuses of the graphs whenever an input value was changed. This would allow the user to easily perform parametric studies, where the effect of either one parameter, or a multitude of parameters, could be seen on the rest of the processes. These changes were done in versions 8 up to 11, with each version entailing one of the above changes. The passing of parameters within the spreadsheet takes a week of solid work and programming, and the spreadsheet was tested on various cases to ensure that the data was being passed correctly, the graphs were being updated with no compatibility issues, and the output results were realistic.

Versions 12 and 13 were made to allow the empirical factors that had been previously defined as "static numbers", to become "dynamic variables"; this was accompanied by the grouping of emission factors in one "sheet". This means that changes of emission factors were easily made in the "factors" sheet page. The visibility of the graphs was also improved within version 13. Version 14 involved improving the inter-linking of data, and the way data are calculated. This was also made more efficient by allowing more options to be entered. This was done by introducing drop-down menus for cells with options.

The final major decision during the tool development process was to automate the data input process. Previously, the user needs to start the spreadsheet, and then enter the data in the "Data input" page, and results would be displayed in the "Summary&results" page. The user would have had to know which of the Excel cells the data need to be entered in the "Data input" page, and then go to the "Summary&results" pages to see the results at different scenarios. With the new Visual Basic programming effort undertaken in versions 15 to 17, a front end screen automatically appeared when the spreadsheet is running, followed by menus that allowed the user to enter the data, with drop-down menus in places, where required data are needed are clearly defined. These data are then passed instantaneously into the relevant Excel cells within the spreadsheet. Results were also automatically being calculated within the "Summary&results" page as data are being entered into the "data input" page.

Version 18 involved programming in Visual Basic by Dr El-Hamalawi to allow the data to remain in the spreadsheet, while the data are being entered as explained above, in case the user decided to exit and continue the data input at a later stage, or in case of a computer crash the data entered would be saved.

A final version (version 19) was where error checks were introduced across all cells, to prevent input of either non-numeric values in numerical fields or vice-versa, or entering unrealistic values, in addition to other data checks. Graphs in the "Summary&results" page were also made to appear as standalone graphs next to the input data, but this stage has not been completed yet. In future, this and other changes will be included in the tool to make the interface more user-friendly (see Appendix G for detail).

The effort of producing the basic spreadsheet interfaces with all the equations for carbon calculation and input/output data was part of the author's thesis work. The author received assistance from his supervisor (Dr A. El-Hamalawi) in checking the spreadsheet for any mistakes and validation process, updating the fields and allowing data to be passed across the fields and sheet pages and reducing the data entering effort by users. Dr El-Hamalawi undertakes the Visual programming of all the tool interfaces, drop-down menus and graphics to provide a full working carbon tool for evaluation.

4.3.3.4 The Tool Evaluation (Task 12)

Initial carbon assessment (hand calcualation) based on the methodology framework (see Figure 4.6: the methodology that underpins the carbon evaluation tool implementation process) was undertaken using preliminary data from pavement resurfacing work carried out in an urban location. Details of results of the hand calculation are documented in EngD Paper 2 (see appendix B).

The next stage of the carbon tool evaluation process focuses on using specific primary data collected from pavement resurfacing works undertaken in an urban environment. The data collected from pavement resurfacing works were used to evaluate the carbon footprint at the design and construction stages. This carbon information is essential to support the pavement material selection, delivery option, and project procurement decision-making.

The results and findings from the quantitative data analysis (system evaluation) based on the initial hand calculation and carbon evaluation tool demonstrate that the tool presents a robust analytical capacity that can create credible carbon footprint information to support carbon emissions reduction associated with highway pavement resurfacing works, , whilst identifying areas of potential carbon hotspots and opportunities for reduction. This can inform a reduction hierarchy that can allow carbon reduction efforts to be adequately prioritised. Details of the carbon tool evaluation results and related discussions are documented in EngD Paper 4 (Appendix D). Figures 4.9 and 4.10 provide screenshots of the data input interface (Estimated and Measured data) of the carbon evaluation tool. They provide the input data interface required to assess the pavement materials embodied carbon during design (estimated) and construction (measured) stages. Using these data sets both the activity-oriented (Embodied carbon, Operational carbon and End-of-life carbon) and task-oriented emissions (material manufacture, delivery to site, operative transport, site activities, waste transportation and recycling) are evaluated. Figure 4.11 presents a screenshot of a carbon reduction hierarchy based on the pavement estimated and measured data sets. It indicates where the biggest carbon reduction efforts can be focused within the pavement resurfacing process and provides emissions information that can support highway designers, managers' and maintainers reduction decision-making.

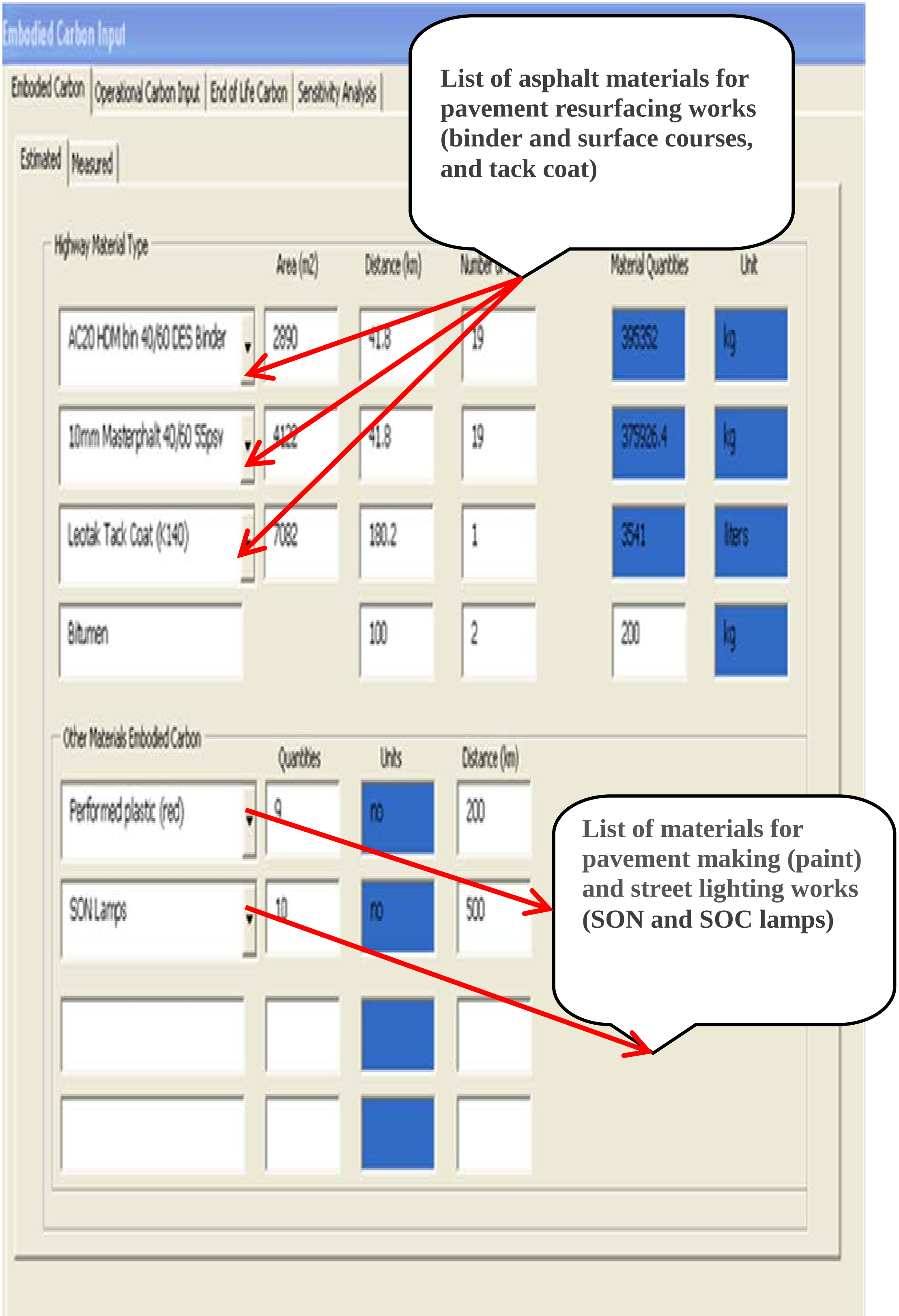


Figure 4.9 Estimated Embodied Carbon Input Interface

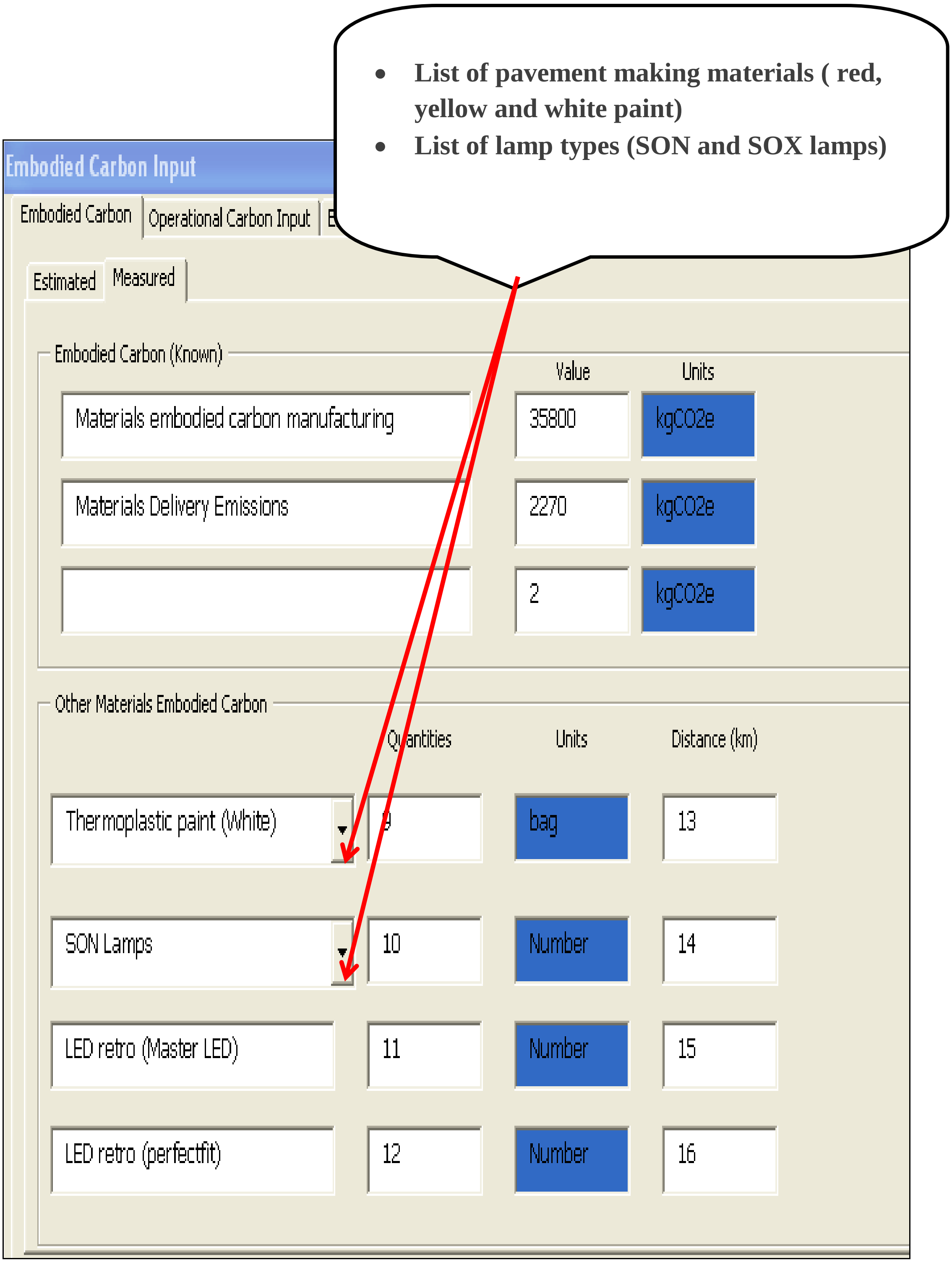


Figure 4.10 Measured Embodied Carbon Input Interface

Figure 4.11 further indicates that the pavement material embodied carbon accounts for on average 79.01% and 75.15% of the total process Carbon Footprint (CF) based on estimated and measured data sets. The materials manufacturing process and their delivery to point of use account for on average 71.05% and 75.65%, 3.85%, 6.07%, respectively. The results suggest that for pavement resurfacing, the material manufacture in particular and their delivery (embodied carbon emissions) to a less extent is emission-intensive and important sustainability elements to consider when decisions on reducing carbon are taken. Focusing on these areas is crucial in order to deliver a low-carbon pavement resurfacing works.

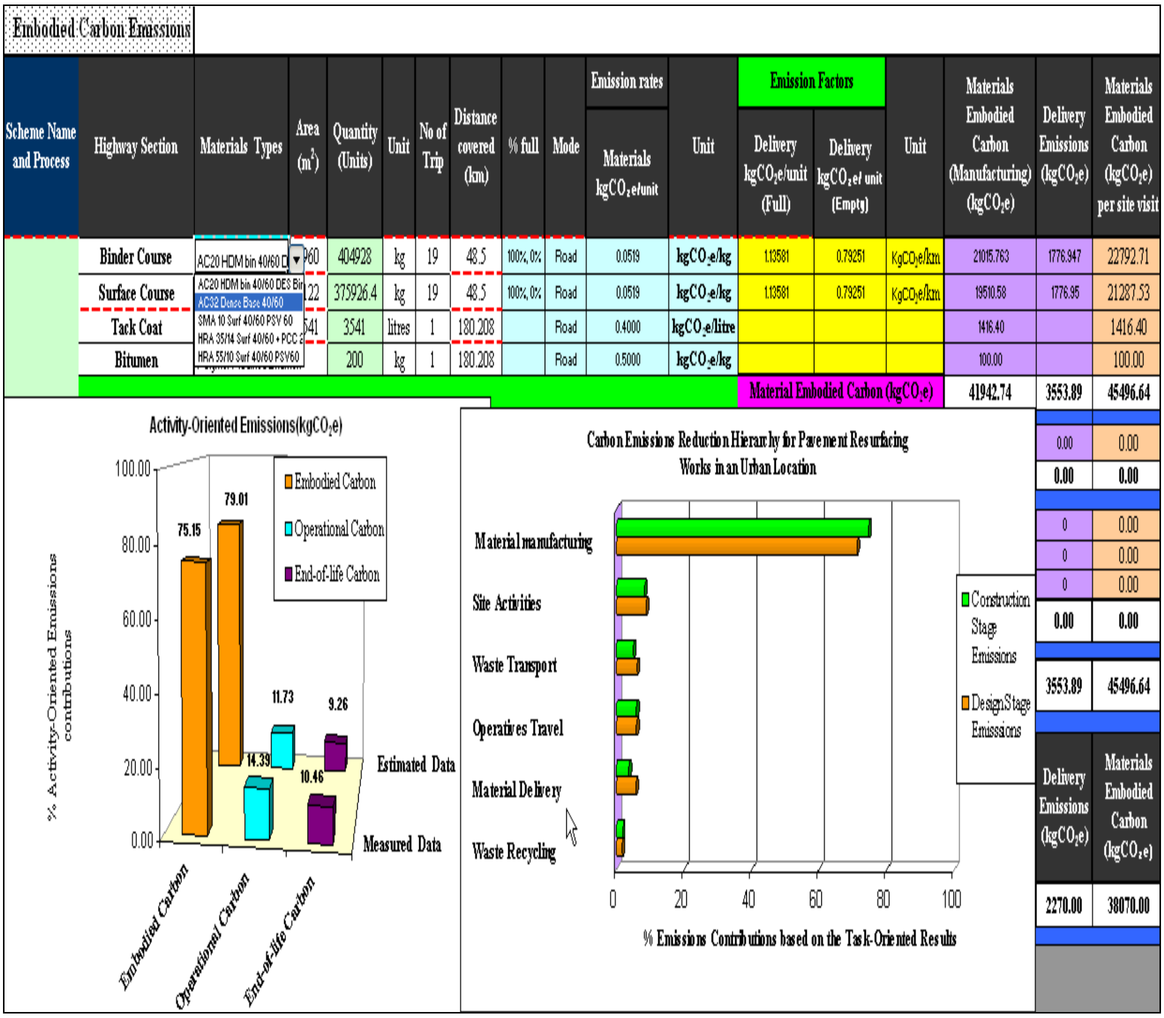


Figure 4.11 Carbon Reduction Hierarchy Based on Estimated and Measured Data

4.3.3.3 Sensitivity Analysis

The carbon evaluation tool provides an interface to allow users undertake sensitivity analysis based on carbon emission variables in order to identify opportunities for carbon reduction. Within the context of this study, energy type, distance to site (km) and design life of asset are emission variables considered for the sensitivity analysis (see details in EngD Paper4, Appendix D).

The quantitative data analysis indicates that material embodied and transportation emissions have been identified as areas of emission hotspots and emission reduction priority areas to deliver low-carbon pavement resurfacing following Figure 4.11. However, this study has argued that the increase in embodied carbon due to material manufacturing and delivery is attributable to the type of energy consumed during the manufacturing process and delivery. Figure 4.12 presents a screenshot of emission results associated with different types energy (100% mineral diesel, diesel blended biofuel, 100% biodiesel, 100% mineral petrol and petrol blended biofuel) used for material (asphalt) manufacturing and delivery process. It was observed that the emission rates for each unit of asphalt material produced decreases directly with fuel type used.. The results indicate that the emission rates can be influenced by using alternative fuel types during the asphalt manufacturing process .The results suggest that biofuels are far less carbon-intensive when compared to other fuel types considered. However, the technological question on using biofuel fuel for asphalt manufacturing and delivery at commercial scale remains an open question.

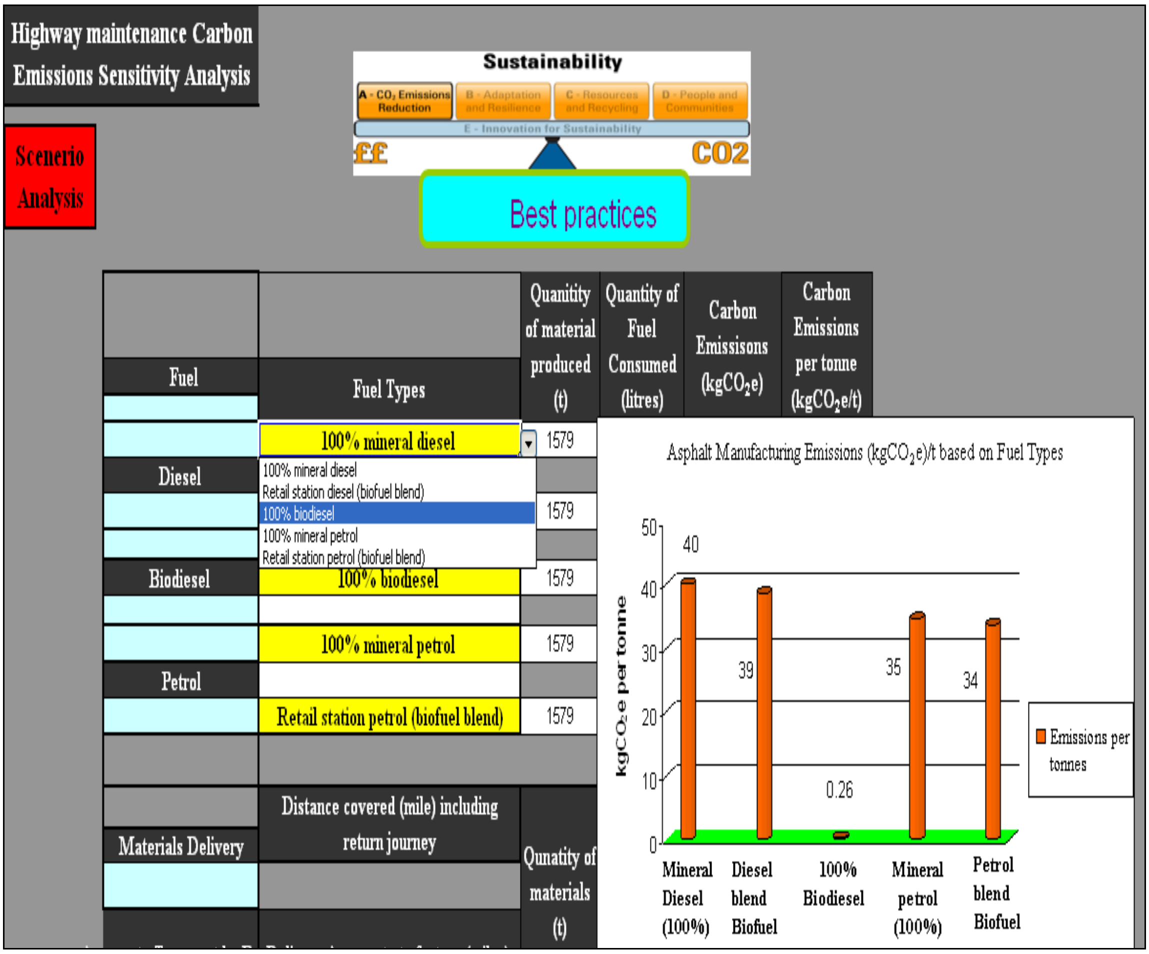


Figure 4.12 Material Manufacturing Emissions using Fuel Types

In Figure 4.13 asphalt material delivery emissions (part of embodied carbon) was found to show a direct linear relationship with the distance to site. As expected, the emissions rate reduces with reduced distance to site. This indicates that the emission associated with material delivery to site has a direct relationship with the distance travelled. This suggests that material procured from sources closer to site (responsible sourcing) and delivered in bulk can significantly reduce the transportation emissions.

The sensitivity interface provides the tool users the capacity to identify carbon reduction opportunities (emissions variables) associated with highway maintenance process and establish a reduction hierarchy that can help highway owners, designers, managers and maintainers prioritise their carbon reduction efforts through informed decision-making.

					Road			
Materials Delivery	Distance covered (mile) including return journey	Trips	Qunatity of materials (t)	Total Distance covered (km)	Quantity of fuel consumed (litres)	Transport Emissions ($kgCO_2e$)	Transport Emissions ($kgCO_2e/t$)	Transport Emissions ($kgCO_2e/km$)
Aggregate Transport by Road	Delivery Aggregate to factory (miles)							
Articulated >33t & Distance to factory	1147	79	1579	291408.08		275131.48	174.24	0.94
			1579	145704.04		137565.74	87.12	0.94
			1579	72852.02		68782.87	43.56	0.94
Materials Delivery to site	Delivery of materials to site (miles)							
Tipper Wagon (Rigid >17t & Distance Travel	49	79						
		79						
		79						
Operatives Transport	Operatives Travelled (miles)							
Diesel van (1.74 to 3.5t) & Distance Travel	150							

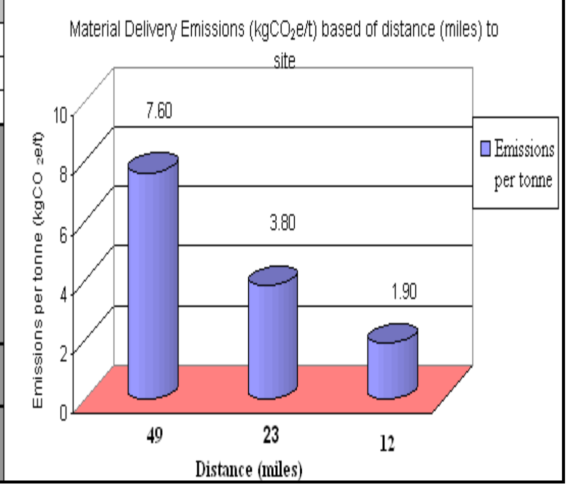


Figure 4.13 Material Delivery Emissions Based on Distance Travelled (km)

The maintenance requirement or the frequency of maintenance of an asset is a function of the design life. Figure 4.14 indicates the emissions impact of road maintenance with a design life of 10 years. With a two year maintenance cycle requirement (frequency of maintenance), the estimated emissions over the ten year period increased by 80%, compared to a 20% increase in emissions (including the initial construction emissions) for one-off maintenance over the ten year period. This result suggests that by reducing asset maintenance requirement, the emissions impact associated with the asset over its design life cycle can be reduced significantly.

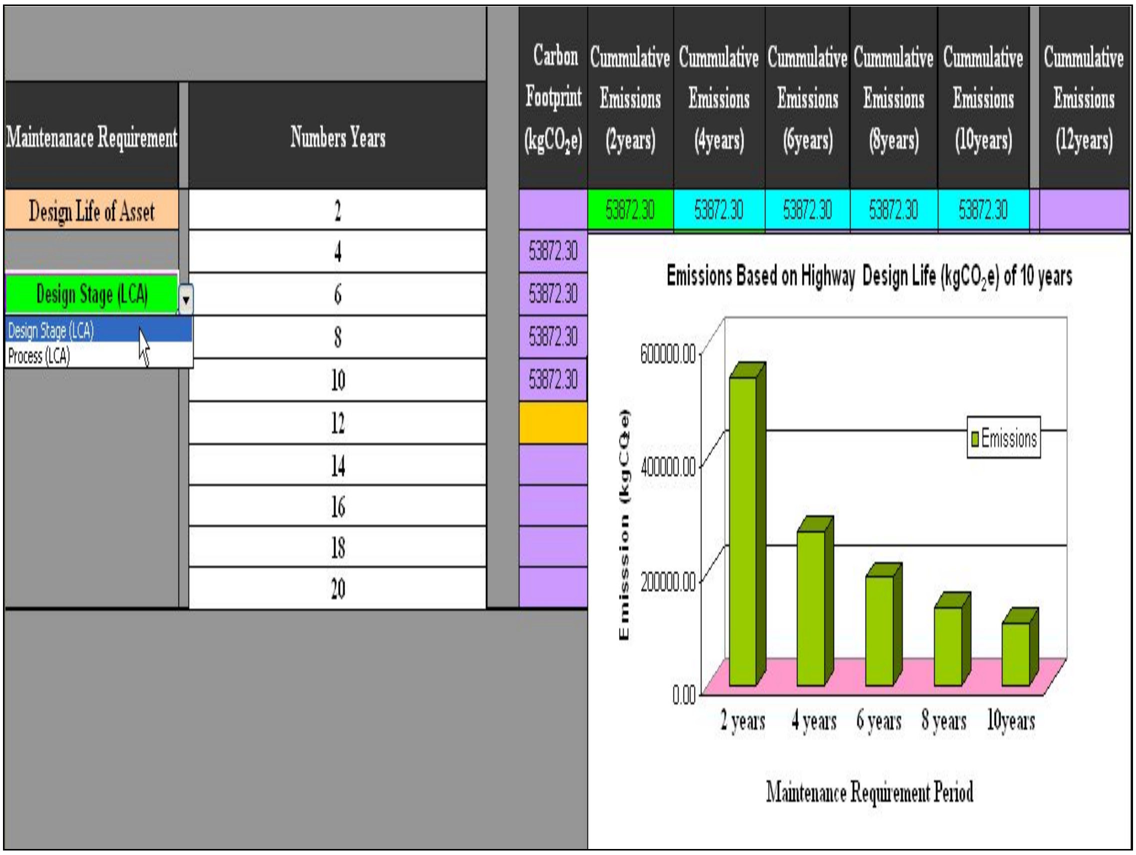


Figure 4.14 Design Life of a Highway Maintenance and Emissions Impact

4.4 APPLICATION PHASE

This research phase covers three main research tasks (see Figure 3.2) undertaken to achieve Objective 4. It describes the carbon evaluation tool dissemination strategy produced. This Chapter further explains the activities planned for the tool improvement and subsequent adaption, for use within the sponsoring company, clients and its supply chain business operation.

4.4.1 OBJECTIVE 4 (RESEARCH WORK TASKS 13, 14 &15)

This research objective requires critical evaluation of the research project to identify its limitations (task 13), make recommendations for future work (Task 14) and discuss the strategy produced to allow for the carbon evaluation tool's dissemination and improvement across the sponsor's business operation including its supply chain (Task 15). The intention is to understand the stakeholder views on the carbon evaluation tool and elicit recommendations for the tool improvement and adoption. The critical evaluation of the EngD research and recommendations for future work are detailed in sections 5.6 and 5.7. The impacts of the research work on the sponsor's business operation are also detailed in section 5.. It explains how the research and its outputs have influenced the sponsor's carbon assessment and reduction investment decision-making.. This illustrates the sponsor's commitment to address sustainability issues within its business and that of its customers. This has also shown that the EngD research implementation within the EngD sponsoring company business operation has started. It demonstrates how the research has been published among the sponsor's internal and external business stakeholders. However, the dissemination of the carbon evaluation tool developed among the business stakeholders (internal and external) is essential for the tool's implementation and improvement. The carbon evaluation tool is being made user-friendly (Visual Basic Application (VBA)), and its dissemination strategy developed and discussed next.

4.4.2 THE CARBON EVALUATION TOOL DISSEMINATION AND IMPROVEMENT STRATEGY

This section describes the dissemination and improvement strategy produced by researchers to enable the carbon evaluation tool to be disseminated and improved for use among research stakeholders (see Table 1.3) business operation. The dissemination and improvement of the carbon evaluation tool among the sponsor's business stakeholders is crucial to its implementation. The strategy (a launch event and focus group workshop) can provide the sponsor and its stakeholders with the business opportunities and benefits discussed in Table 4.3. This will provide the research stakeholders with the opportunity to understand how the carbon evaluation tool can be used for business carbon footprinting to support investment decision-making in terms of carbon. It will also provide the research stakeholders with the opportunity to provide recommendations for the improvements and adoption within the sponsor's business operation. The interaction between the workshop participants will provide a platform to explore and identify the participant's shared views and understanding of the carbon evaluation tool, which can create a deeper insight into the carbon evaluation tool business implementation process. This approach is important since it can offer the opportunity for the stakeholders to share their experiences, views and provide suggestions for the tool improvement in a collective manner. The activities within the strategy include:

(a) A one day launch event at the sponsor's business premises was undertaken. A postscript that describes the launch event, its outcomes (i.e. reactions from participants) and recommendations for the tool improvement are detailed in Appendix G. The event activities include:

- A presentation on the carbon evaluation tool functionality, structure, data requirements and methodology that underpins the tool implementation,
- Demonstration on the tool application for carbon footprinting using primary data, and
- Send questionnaire to participants (for feedback) via email

(b) A focus group workshop. The workshop activities include:

- Pre-workshop (e.g. workshop definition and formation).
- The workshop (participants understanding, empowerment and engagement on the carbon tool business implementation, whilst eliciting recommendations for the tool improvement and adaption).
- Post workshop (workshop information analysis for the tool improvement and adaption).

The focus group workshop could not be undertaken due to time constraint. This activity has been recommended for further work, since the workshop will offer the sponsor with opportunity to elicit suggestions from participants of different technical orientations and experiences. This will enhance the tool improvement and adoption within the sponsor’s and its supply chain business operation. However, as experience on the carbon tool increases within the sponsor’s business, new highway maintenance activities will be included in the carbon evaluation tool and relevant data collected using the same approach described in this study.

Table 4.3 Benefits associated with the Tool Dissemination and Improvement Strategy

Benefits and Opportunities	Discussion
Understanding	The strategy is to ensure the sponsor’s business stakeholders understand the carbon evaluation tool development process, its structure, the theoretical concept that underpinned its implementation, what the tool can achieve and how it could be operated. These can be achieved through the focus groups workshop.
Empowerment	It will offer the sponsor’s employees and supply chain with the opportunity to use the carbon evaluation tool for highway maintenance carbon footprinting based on actual data collected from a typical highway maintenance process, and how the results can be interpreted to support business decision-making in terms of carbon. This will also be achieved through the workshop.
Engagement	As soon as the sponsor’s business stakeholders have been empowered, and the understanding of the business implementation of the carbon evaluation tool established, an open discussion section will be undertaken facilitated by the researcher during the workshop. The interaction between the stakeholders (workshop participants) will help to elicit the stakeholders shared views and understandings of the carbon evaluation tool which will create a deeper insight into the tool business implementation process.
Improvement	The feedback and recommendations from the focus group workshop will be used to support the carbon evaluation tool improvement, refinement and adoption into the sponsor’s business operation and that of the supply chain.
Application	At this stage, the improved carbon evaluation tool will be disseminated for use across the sponsor and its customer’s business through launch event. The opportunities and business benefits discussed above will be reviewed periodically to support management decision-making in terms of carbon.

4.5 SUMMARY

This chapter has discussed the research undertaken to meet the aim and objectives of the EngD research project. It also highlighted the main aspects of the research process and details of the research undertaken to achieving each objective. The implementation of the EngD research deliverables in the sponsor's business operation was highlighted. The chapter then described the PAS2050-compliant carbon tool developed, it evaluation and dissemination and improvement strategy that can enhance the tool implementation and improvement.

5 CHAPTER FIVE: KEY RESEARCH FINDINGS AND CONCLUSIONS

5.1 INTRODUCTION

This chapter summarises the main research findings and discusses its contributions impact on the industrial sponsor and the implications for wider industry. The chapter critically evaluates the research; identifies the research limitations and offers recommendations and suggestions for future research. Finally, the overall conclusions of the four year research project are presented.

5.2 KEY FINDINGS OF THE RESEARCH

The key research findings presented in this section follow the adopted research process (see Figure 3.2) defined in Chapter Three. These include the initial investigation stage (literature review), synthesis stage (methodology framework and carbon evaluation tool development and business implementation) and application stage (The carbon evaluation tool dissemination and improvement strategy).

5.2.1 INVESTIGATION STAGE

The initial investigation was undertaken specifically to address three issues: lack of understanding of the "state of the art" of businesses' carbon footprinting and reduction within the context of the policy drivers, inherent challenges and opportunities and approaches. It also defined the scope and established the need for the EngD research project from the sponsor's business perspective. The main research findings from this initial stage (literature review) of the study are outlined below:

- The state of the art literature review revealed that there is a strong momentum (regulatory and non-regulatory policy drivers and low-carbon initiatives) at international, national and organisational levels driving carbon footprinting and reduction. The voluntary nature of these policies and their inability to define a wider scope, guidelines and defined system boundary for carbon emissions assessed are seen as major drawbacks. It was argued these policies and initiatives are not strong enough to drive innovation to support the Government's low carbon agenda Civil infrastructure including the highway maintenance sector presents opportunities that can promote efficient carbon footprinting and reduction, for example through innovative design. It was then argued that the actual scope of emissions that the design process has on civil infrastructure is inherent in the impact that design has on the materials selection and in-use phase of the asset.

- It was revealed that having a good understanding of highway maintenance carbon footprinting and reduction within the context of its drivers, approach and related benefits can offer highway stakeholders a knowledge framework that can be used as an information source to develop a robust corporate strategy for business environmental performance. It was revealed that an effective business strategy for carbon reduction performance should include: a carbon evaluation tool underpinned by a robust methodology and complementary studies' outputs, credible carbon data and a collection approach. This conclusion helps define the current research scope and direction from the sponsor's business perspective (see Chapter 4, Figure 4.2).

The initial investigation indicated the relevance of energy, materials, and waste efficiency across all sectors. This lead to the next phase of the research work which showed that:

- Carbon footprinting and reduction challenges and opportunities were imperfectly understood by highway stakeholders. These issues are compounded given the lack of an agreed industrial methodology standard and robust evaluation tools, knowledge gaps in the current approach, lack of credible emissions data and collection method. The absence of baseline information for emissions benchmarking was seen as another issue frustrating organisations' efforts on carbon footprinting and reduction.
- The investigation stage of the EngD research demonstrated that there are potential opportunities with the highway maintenance process that can reduce carbon emissions. These opportunities can be maximised through effective design and planning, and the consideration of carbon in investment decision-making.

5.2.2 SYNTHESIS STAGE

This research stage covered the methodology framework and carbon evaluation tool development based on the PAS2050 protocol, and development of its business implementation strategy. This study has demonstrated that the PAS2050 protocol can enhance the highway maintenance process carbon footprinting and reduction through informing decision-makingby providing:

- A robust life cycle methodology framework for carbon footprinting specific to highway maintenance planning and operations which can identify areas of carbon "hotspots" and related opportunities for reduction. This can inform a reduction hierarchy, supports decision-making and ensures carbon reduction efforts are adequately prioritised (see EngD Papers 2 and 3) across the highway maintenance process and its supply chain business operation.
- The capacity to define the carbon assessment scope, objective and system boundary from the beginning. This allows a comprehensive picture to be identified of the carbon data and analysis approach required within the scope defined. The stakeholder engagement and process mapped were found to be crucial for the data collection within the "Data quality rules" set by the protocol.
- A life cycle methodology which offers a step-by-step and iterative carbon footprinting approach that is consistent with the "cradle-to-grave" (Business-to-Consumer (B2C), and "cradle-to-site" Business-to-Business (B2B) boundary conditions. This allows the direct and indirect carbon information to be assessed. This revealed that the application of PAS2050 protocol can allow different datasets (primary and secondary data) to be analysed together rather than singularly. This indicates why the protocol is being considered as a default approach for product or service carbon footprinting across different product or service types.

The quantitative data analysis (assessing carbon footprint from pavement resurfacing work, pavement marking, bulk lamp replacement and grass cutting work: (see Tables 5.1, 5.2, 5.3, 5.4, 5.5 and 5.6) revealed that the:

- Majority of the sponsor's carbon footprint is attributable to the material used and energy consumed during highway maintenance operation and waste management. Material manufacturing and its delivery (embodied carbon: accounts for in excess of 70% of the average overall carbon footprint) are areas of maximum carbon usage and relevant sustainability decision points for highway designers, managers and maintainers to deliver a low-carbon service irrespective of the site location considered as indicated in Tables 5.1, 5.2, 5.3 and 5.4 for pavement resurfacing, pavement marking and Grass cutting works. The activity-oriented carbon emissions categories and task-oriented emissions "Hotspots" are presented. It was found out that the increase in the material embodied carbon is attributable to the energy type (e.g.fossil-fuel: 100% mineral diesel) used during the material manufacturing and delivery process (see Figure 4.12). The significant decrease in "Asphalt Delivery" (from 960kgCO2e to 698kgCO2e) emissions (see Table 5.2) of delivery approximately the same quantity of asphalt (294 tonne and 290 tonne) at the same site location (Urban) and distance (1400km and 1352km) is primarily due to poor data keeping from the material delivery company.
- The PAS2050-compliant tool has demonstrated its capacity to assess site locations carbon impact on the overall project carbon footprint. This provides a vivid picture that can support site operation decision-making. For example, the bulk lamp replacement revealed that the percentage contributions of the on-site carbon (excess of 80% and 70%) to the overall project carbon footprint in semi-urban and rural (see Table 5.3) site locations increase significantly compared to its embodied carbon contributions (11.90 % and 29%) respectively. This was found to be due to the type of Traffic Management (mobile TM was employed because of the safety critical nature of the site) used on site during the maintenance work. The majority of the works were carried out in site locations where the average vehicle speed is at national speed limit level (Excess of 60mph compared to 30mph in an urban site location).
- Analytical capacity of the PAS2050 protocol to assess highway maintenance process direct and indirect carbon at design and construction stages (on-site) to inform design, materials selection and procurement decision-making, whilst providing the biggest areas where carbon emissions reduction can be made relatively quickly and cheaply across the process value chain. Tables 5.5 and 5.6 present both the activity and task-oriented emissions modes for twelve (12) pavement resurfacing works undertaken in Urban, Semi-urban and Rural site locations at both the design and construction stages. The percentage emission contributions of both emission modes at design stage (based on estimated data) and construction stage (based on measured data) are further presented. These provide carbon information that can be used to cross check actual carbon production against the estimated, and offer vital learning to inform the pavement design, material procurement and operational decision-making in carbon terms.

Table 5.1Activity-Oriented Emissions Analyses and Carbon Emission Rates

Activity-oriented Carbon Emissions associated with Twelve Pavement Resurfacing Works across Different Site Locations															
Location	Asphalt Concrete Embodied Carbon (AEC) ($kgCO_2e$)	Asphalt Concrete Embodied Carbon per area resurfaced ($kgCO_2e/m^2$)	On-site Carbon Emissions (OCE) ($kgCO_2e$)	On-site Carbon emisions per area resurfaced ($kgCO_2e/m^2$)	Waste (Planings) Removal and Recycling Carbon Emissions (WCE) ($kgCO_2e$)	Waste (Planings) Removal and Recycling carbon per tonne of planings ($kgCO_2e/t$)	Carbon Footprint (CF) ($kgCO_2e$)	Average AEC ($kgCO_2e$)	Average OCE ($kgCO_2e$)	Average WCE ($kgCO_2e$)	Average CF ($kgCO_2e$)	Average Rate of AEC to CF	Average Rate of OCE to CF	Average Rate of WCE to CF
Urban	38070	12.93	7810	2.65	4570	7.62	50450	21778	3678	2083	27538	79.08	13.36	7.56
	23340	9.00	2870	1.11	1620	7.35	27830							
	11360	8.85	1924	1.49	1470	7.54	14754							
	11360	11.09	1924	1.88	674	7.48	13958							
Semi urban	40323	5.99	4970	0.74	1248	2.00	46541	26197	3311	746	30254	86.59	10.94	2.47
	24547	5.87	2889	0.69	601	1.67	28038							
	21557	5.64	2277	0.6	422	1.21	24256							
	18361	8.19	3108	1.39	713	2.16	22182							
Rural	19350	7.74	3345	1.34	347	2.89	23043	8961	1691	206	10859	82.52	15.57	1.90
	3838	6.02	1373	2.15	40	1.00	5251							
	6358	11.77	1129	2.09	91	0.91	7578							
	6300	15.75	917	2.29	347	8.68	7564							

Table 5.2 Task-Oriented Emission Analyses and Emission Rates

Task-oriented Carbon Emissions associated with Twelve Pavement Resurfacing Works across Different Site Locations

Location	Area (m^2)	Quantity of Asphalt Concrete (tonne)	Distance (factory to site) including return journey (km)	Asphalt Concrete Manufacturing Carbon ($kgCO_2e$)	Asphalt Concrete Delivery Carbon Emissions (AD) ($kgCO_2e$)	Asphalt Delivery Carbon Emissions rate ($kgCO_2e$/ trip)	Operatives Travel Carbon Emissions (OT) ($kgCO_2e$)	Site Activities Carbon Emissions (SA) ($kgCO_2e$)	Site Activities Carbon Emissions rate ($kgCO_2e/m^2$)	Operatives Travel Carbon Emission rates ($kgCO_2e$/ km)	Waste (Planings) Transport off-site Carbon Emissions (WT) ($kgCO_2e$)	Waste (Plaings) Recycling Carbon Emisions (WR) ($kgCO_2e$)	Waste (Planings) Carbon Emission rates ($kgCO_2e$/ tonne)
Urban	2945	758	3669	35800	2270	59.737	3108	4703	1.60	8.46	4168	401	7.62
	2593	294	1400	22379	960	64.067	1042	1828	0.70	4.22	1470	147	7.35
	1284	290	1352	13642	698	46.200	786	1320	1.03	5.68	1336	134	7.54
	1024	237	991	10818	542	49.273	556	1368	1.34	5.01	607	67	7.48
Semi Urban	6728	622	2594	37790	1170	37.742	1403	3568	0.53	7.78	828	420	2.00
	4184	399	1802	21960	1730	86.500	1534	1356	0.32	8.91	361	240	1.67
	3821	339	1641	18690	2100	123.529	858	1420	0.37	6.83	187	235	1.21
	2243	430	4248	11010	2600	118.182	1256	1852	0.83	6.79	441	273	2.16
Rural	2500	318	1905	16330	2520	157.500	1742	1603	0.64	5.82	267	80	2.89
	638	60	1101	3380	330	110.000	486	887	1.39	2.51	13	27	1.00
	540	110	463	5630	620	103.333	202	927	1.72	1.63	24	67	0.91
	400	109	521	5600	620	103.333	639	278	0.69	4.41	321	27	8.68

Note: **AD**: Asphalt Concrete delivery carbon emissions , **OT**: Operatives Travel carbon (depot to site) including the return journey , **SA**: Site Activities carbon based on plant equipment used during the pavement resurfacing works, **WT**: Waste Transport carbon (site to recycling plant including the return journey), **WR**: Waste (planings) processing and recycling carbon (crush and screen to type 2 aggregate).

Table 5.3 Activity-Oriented Emissions Model and Carbon Rates for Highway Maintenance work

Activity-Oriented carbon categories, CF and carbon emissons rate from Twelve pavement marking and lamps replacement works across urban, semi-urban and rural site locations

Location	Materials Embodied Carbon (MEC) ($kgCO_2e$)	Materials Embodied Carbon per bag ($kgCO_2e$/ bag)	On-site Carbon Emissions ($kgCO_2e$)	On-site Carbon Emissions (OCE) per bag ($kgCO_2e$/ bag)	Total Carbon Footprint (CF) ($kgCO_2e$)	Average CF ($kgCO_2e$)	Average Rate of MEC to CF	Average Rate of OCE to CF	Lamp Embodied Carbon (LEC) ($kgCO_2e$)	LEC per Lamp ($kgCO_2e$ /Lamp)	On-site Carbon Emissions (OCE) ($kgCO_2e$)	Waste (old lamps) Removal & Recycling Carbon (WRC) Emissions ($kgCO_2e$)	WRC Emissions rate ($kgCO_2e$/ lamp)	Total CF ($kgCO_2e$)	Average Rate of LEC to CF	Average Rate of OCE to CF	Average Rate of WRC to CF
Urban	673	48.0	126.18	6.49	799	646.32	81.4	18.6	117.03	2.1	32.0	0.929	0.016	102.61	68.00	31.46	0.54
	524	47.7	131.52	8.74	656				86.23	2.1	43.0	0.685	0.016				
	524	47.7	120.93	7.29	645				59.54	2.1	35.0	0.473	0.016				
	383	47.9	102.13	8.35	485				16.42	2.1	19.0	0.130	0.016				
Semi urban	11738	47.7	1194.95	11.65	12933	10923.01	86.0	14.0	148.48	2.3	858.0	1.292	0.020	823.67	11.09	88.81	0.10
	10205	47.7	1678.09	12.50	11883				82.24	2.3	764.0	0.715	0.020				
	10205	47.7	1728.27	16.36	11933				73.10	2.3	601.0	0.636	0.020				
	5446	47.8	1497.05	21.92	6943				61.68	2.3	703.0	0.537	0.020				
Rural	2859	47.7	343.48	9.72	3203	1334.30	80.4	19.6	101.71	1.8	321.0	0.628	0.011	289.02	29.00	70.76	0.18
	953	47.7	370.11	30.04	1323				81.73	1.8	75.0	0.505	0.011				
	477	47.7	334.82	50.38	811				76.28	1.8	187.0	0.471	0.011				
	0	0.0	0	0.00	0				76.28	1.8	235.0	0.471	0.011				

Note: MEC: Materials (Themoplastic Paint and Glass bead) embodied carbon, OCE: On-site activities carbon during pavement making and bulk lamp replacement , LEC: (carbon associated with Lamp manufacturing and delivery to site), WRC:(carbon associated with old lamps revoval from site, processing and recycling).

Table 5.4 Activity-Oriented and Task-Oriented Analysis of Highway Grass Cutting Operation

Activity-oriented and task-oriented carbon analysis of eight grass cutting operations across semi-urban and rural site locations											
Location	Distance Covered by Operatives (km)	Grass Cutting Completed (m)	On-site Carbon Emissions ($kgCO_2e$)	Total Carbon Footprint (CF) ($kgCO_2e$)	On-site Carbon Emission Rates ($kgCO_2e/m$)	Operatives Travel Carbon Emissions (OT) ($kgCO_2e$)	Operatives Travel per distance covered ($kgCO_2e/km$)	Site Acticities Carbon Emissions (SA) ($kgCO_2e$)	Site Activities per km of grass cutting ($kgCO_2e/km$)	Average Rate of OT to CF	Average Rate of SA to CF
Semi - urban	88.5	5800	83.69	83.69	0.01	72.14	0.82	11.54	0.0020	88.20	11.80
	104.6	5200	108.88	108.88	0.02	98.86	0.95	10.02	0.0019		
	113.8	3300	94.86	94.86	0.03	80.16	0.70	14.70	0.0045		
	99.8	3900	82.16	82.16	0.02	74.82	0.75	7.35	0.0019		
Rural	30.6	342	344.96	344.96	1.01	24.32	0.79	320.64	0.9375	4.43	95.57
	10.1	65	355.38	355.38	5.47	8.02	0.79	347.36	5.3440		
	17.7	370	347.63	347.63	0.94	13.63	0.77	334.00	0.9027		
	20.9	378	358.32	358.32	0.95	16.3	0.78	342.02	0.9048		
Note: OT : Operative Travel carbon emissions (from depot to site) including return journey , SA: Site Activities carbon emissions due to grass cutting operation.											

Table 5.5 Percentage Emissions by Activity and Task-Oriented Modes Based on Twelve pavement Resurfacing works (Estimated Data)

Location	S/N	% Material Embodied carbon	% Operational carbon	% End-of-life carbon	% Material production	% Material Delivery	% Operatives Transport	% Site Activities	% Waste Transport	% Waste Recycling
Urban	**1**	78.56	12.16	9.28	73.1	5.5	5.4	6.8	7.0	2.2
	2	72.58	19.15	8.27	66.8	5.7	7.3	11.9	6.3	2.0
	3	76.00	14.61	8.60	70.8	5.9	6.2	8.4	6.6	2.0
	4	79.60	15.08	5.32	73.5	6.1	6.4	8.7	4.1	1.3
	% Average	**76.69**	**15.25**	**7.87**	**71.05**	**5.80**	**6.33**	**8.95**	**6.00**	**1.88**
Semi-Urban	1	85.1	10.65	4.25	78.1	7.0	3.7	6.9	1.4	2.8
	2	84.84	10.93	4.23	77.9	6.9	5.6	5.4	1.3	2.9
	3	84.43	11.28	4.30	77.5	6.9	4.3	6.9	1.9	2.6
	4	78.46	19.31	4.23	69.1	7.3	10.2	9.1	1.4	2.8
	% Average	**83.21**	**13.04**	**4.25**	**75.65**	**7.03**	**5.95**	**7.08**	**1.50**	**2.78**
Rural	**1**	72.67	17.35	9.98	65.6	7.0	8.6	8.7	7.3	2.7
	2	65.60	31.65	2.75	59.3	6.3	11.3	20.4	0.3	2.4
	3	75.02	22.69	2.29	71.1	3.9	9.9	12.8	0.1	2.2
	4	73.27	21.46	5.27	65.0	8.3	8.6	12.9	4.1	1.2
	% Average	**71.64**	**23.29**	**5.07**	**65.25**	**6.38**	**9.60**	**13.70**	**2.95**	**2.13**

Table 5.6 Percentage Emissions by Activity and Task-Oriented Modes Based on Twelve Pavement Resurfacing work (Measured Data)

Location	S/N	% Material Embodied carbon	% Operational carbon	% End-of-life carbon	% Material production	% Material Delivery	% Operatives Transport	% Site Activities	% Waste Transport	% Waste Recycling
Urban	1	75.15	14.39	10.46	70.67	4.48	5.91	8.48	7.92	2.54
	2	79.94	13.6	6.46	76.65	3.29	4.36	9.24	4.85	1.62
	3	78.53	12.13	9.34	74.74	3.8	5.14	6.99	7.05	2.29
	4	80.22	14.29	5.49	76.39	3.83	4.99	9.3	4.13	1.36
	% Average	**78.46**	**13.60**	**7.94**	**74.61**	**3.85**	**5.10**	**8.50**	**5.99**	**1.95**
Semi-Urban	1	85.25	10.08	4.68	82.69	2.56	2.96	7.12	1.74	2.93
	2	86.02	9.92	4.06	79.74	6.28	5.35	4.56	1.26	2.8
	3	86.47	8.83	4.71	77.73	8.73	3.78	5.05	1.77	2.94
	4	77.27	18.55	4.18	70.55	6.71	10.58	7.97	1.42	2.76
	% Average	**83.75**	**11.85**	**4.41**	**77.68**	**6.07**	**5.67**	**6.18**	**1.55**	**2.86**
Rural	1	83.85	13.87	2.29	72.64	11.21	7.46	6.41	1.14	1.14
	2	71.46	26.66	1.88	65.11	6.36	9.07	17.59	0.22	1.65
	3	78.96	18.04	3	71.13	7.83	5.2	12.84	0.29	2.71
	4	71.63	14.93	13.43	64.49	7.14	7.08	7.85	3.56	9.88
	% Average	**76.48**	**18.38**	**5.15**	**68.34**	**8.14**	**7.20**	**11.17**	**1.30**	**3.85**

It was observed that the carbon information presented in Tables 5.1, 5.2, 5.3, 5.4, 5.5 and 5.6 present the system (PAS2050-compliant methodology framework and carbon evaluation tool) capacity to provide direct and innovative guidance on business carbon footprinting and inform reduction decision-making. This presents unique and practical guidelines for businesses to undertake life cycle carbon footprinting and supports investment decisions through carbon hotspotting design, material procurement and operational (see Table 5.1, 5.2, 5.3, 5.4, 5.5 and 5.6) decision-making. However, effective stakeholders' engagement plan and implementation strategy are found to play a significant role to achieving the business benefits

5.2.3 Application Stage

A launch event was undertaken at the sponsor premises to understand the participant's (internal stakeholder) reactions on the carbon evaluation tool (see Figure 4.8), and elicits recommendations for improvement and adoption. The event forms part of the on-going research stakeholder engagement process (Table 3.6) and the carbon evaluation tool dissemination and improvement strategy (see Thesis Four, section 4.2.2).The event involved representatives from the sponsor's Asset Management and Sustainability Teams (internal stakeholders) responsible for overseeing and managing the sponsor's Asset and Sustainability strategies. Details of the event are documented in Appendix G.

The participants indicated that the sponsor's existing "Asset Management Strategy" tends to focus on whole life costing only. Using the current tool in its Asset value management exercise will enable the sponsor to review its carbon costs of all works (both financial and carbon costs - true costs of asset management) and offers the sponsor major selling point in its Asset management strategy and value engineering decision-making, whilst meeting customers' carbon reduction needs.

The participants agreed that the carbon evaluation tool's business logic is sound from the sponsor's business perspectives, but to enhance its adoption in the sponsor's and its supply chain business operation, the tool will require further improvements that focus on the followings:

- The tool interfaces need to be made users friendly (by completing the VBA front end of the tool) and cater for more highway maintenance works and activities (e.g. reactive works).
- More sensitivity analysis should be added to the tool to enable more carbon reduction alternatives to be investigated e.g. alternative vehicles, plant and materials options etc. This will offer users with more choice and options to reduce the carbon impact of their work.
- Develop guidance notes and toolkits for the tool implementation and roll-out programme to be carefully managed.

Following these recommendations, the tool future development, improvement and roll-out action plans have been initiated (see Appendix G for detail). A proposal has been developed and sent to the sponsor's "Operational Excellence Board (OEB)" for approval. The approval by OEB would provide a mandate for the tool immediate investment for improvement and adoption.

The application of the outputs of the EngD research in the sponsor's business operations has provided the sponsor the opportunity to demonstrate its:

- Potential to identify areas of carbon hotspots from highway maintenance planning and operation, opportunities of reduction and prioritising carbon reduction efforts based on the PAS2050 life cycle methodology standard, and credible carbon data obtained using standard data collection approach.
- Capacity to provide its customers with additional service scope, and innovative solutions to illustrate its sustainable credibility and alignment with the customer's sustainability strategic direction. This offers the opportunity to develop new business streams (e.g. Integrated Asset Management), whilst securing its market position as the leading UK's highway maintenance service provider.
- Commitment and potential to reduce both its business and customer's carbon footprint through effective planning, design and credible decision-making. This provides the sponsor with an opportunity to demonstrate energy, material and waste efficiency in all aspects of its business, whilst enhancing its competitive advantage.
- Sustainability leadership, influencing its customer and supply chain perceptions on carbon footprint and reduction, and optimising its business stakeholder relationships.

Details of the research impacts on the sponsor's business operation are discussed further in section 5.3. It provides how the research has been used to influence the sponsor's sustainability investment decisions.

5.3 REALISATION OF RESEARCH AIM AND OBJECTIVES

The research has made useful contributions to knowledge and practice in the field of highway maintenance planning and operation carbon footprinting. Table 5.7 outlines and discusses how the research aim and objectives (defined in Chapter One, section 1.6.2) have been realised.

Table 5.7 Realisation of Research Aim and Objectives

<table>
<tr><td colspan="2">Aim: To develop a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool, to support carbon management decision-making in highway maintenance planning and operation</td></tr>
<tr><th>Research Objectives</th><th>Research Contributions to knowledge and Practice</th></tr>
<tr><td>Objective 1</td><td>A knowledge framework has been developed based on the review of the existing and emerging policy frameworks, initiatives and life cycle studies driving carbon emissions assessment and reduction (see EngD Paper 1, Appendix A). This framework can be used as an information source to develop a robust corporate strategy for an organisations carbon emissions performance. .</td></tr>
<tr><td>Objective 2</td><td>The study has presented a methodological framework based on the PAS2050 life cycle methodology specific to highway maintenance planning and operations (see EngD Paper 2, Appendix B). Carbon footprinting analytical potential of the framework demonstrated using preliminary data. It offers a robust approach that can allow businesses to accurately understand their carbon expenditure and inform the development of a carbon reduction strategy.
The business implementation of the methodological framework illustrated using selected four core highway maintenance processes (pavement resurfacing, pavement making, bulk lamp replacement and grass cutting) across different site locations (urban, semi-urban and rural). The results indicate the capacity of the framework to assess credible carbon information for business decision-making in carbon terms (see EngD paper 3, Appendix C).</td></tr>
<tr><td>Objective 3</td><td>The study further developed and implements a project-specific and process-based carbon evaluation tool based on the principles and requirements of the methodological framework developed in Objective 2. The tool was evaluated using data from pavement resurfacing projects at design and construction process stages (see EngD Paper 4, Appendix D). The results demonstrate the tool analytical capacity to support business decision-making in carbon terms. This provides the sponsor with a practical means that can assess its business carbon footprints, identify hotspots, established a reduction hierarchy and support reduction decision-making.</td></tr>
</table>

	It is important to note that the research carbon evaluation tool is a Balfour Beatty business focus tool. It should not been seen as direct competitor to existing highway tools reviewed in Chapter Two (see Table 2.1), but the tool complements the existing highway tools.
Objective 4	A strategy to enhance the carbon evaluation tool (developed in Objective 3) dissemination, improvement and adoption within the sponsor's and supply chain business operation has been developed (see Chapter Four, section 4.2.2). The strategy (includes launch event and focus group workshop) can provide the sponsor and its stakeholders with the business opportunities and benefits discussed in Table 4.3. A launch event undertaken at the sponsor's business premises creates an opportunity for the research stakeholder (internal) to understand the tool and its business implementation. This offers the opportunity to elicit recommendations for the tool improvement and subsequent adoption (see Appendix G for detail).

5.4 IMPACTS ON THE SPONSOR

The legal obligation imposed on all sectors following the enactment of the UK's Climate Change Act and Carbon Reduction Commitments cannot be ignored by the sponsor. It was therefore necessary for the sponsor to identify a pragmatic means of maximising potential opportunities of carbon reduction initiatives associated with its business operations which is critical to the success of the service it provides to clients. This will allow carbon optimum reduction opportunities that can inform reduction efforts to be prioritised. BB-HST (the Industrial sponsor) is a leading UK provider of integrated highways and transportation solutions for both the Local Authorities (LA) and Highway Agency (HA) in the UK. Its business operation covers highway management and maintenance and civil engineering works, together with related design, consultancy and specialist services. The sponsor has recognised the need to meet its highway client's demand on business sustainability and carbon footprint reduction in order to consolidate its market position and improve its competitive advantage, whilst enhancing its green and sustainability credentials. As such, a sustainability action plan (BBLP Limited, 2012) has been developed by the sponsor as a strategic response to the ambitious sustainability vision (2020 vision) set by Balfour Beatty group (BB Group, 2012). The action plan clearly sets out the objectives and actions that all BB group operating companies including the industrial sponsor need to undertake in all aspects of their business operations to meet the targets set by the vision. The focus is to design, manage and deliver a low-carbon highway infrastructure service, and create a profitable business, healthy communities that can assist organisations and individuals to live within environmental limits, whilst adding value and generating new business opportunities.This research has been published in the action plan to demonstrate the sponsor's commitments to sustainability issues and challenges presented by the 2020 vision.

Part of the sustainability agenda set by the action plan (BBLP Limited, 2012) focuses on: supply chain engagement; climate change/carbon emissions mitigation; sustainable materials consumption; waste reduction and meeting customers need. As a leading UK provider of integrated highways and transportation solutions, the sponsor has recognised the importance of understanding its business operations and client's climate change contributions and related impacts, and the importance of working closely with the business stakeholders. The key issues discussed below provided the EngD research contributions toward the sponsor's sustainability targets set within the action plan..

(a) Supply chain

The EngD research project provided a knowledge framework that was used as a strategic resource to engage the sponsor's business supply chains at all levels in terms of carbon. It interrogates existing core highway maintenance processes which the sponsor operates at various contract locations across the UK, and further helps explore the supply chains' alignment with the sponsor's carbon footprinting and reduction agenda. The EngD research has provided an approach to engage the sponsor's supply chains and ensured credible carbon data are collected in order to identify the carbon interface that exists between the sponsor and the supply chains to avoid double carbon counting (see Chapter 4, Figures 4.3 and 4.6). The sponsor now requires all supply chains to provide embodied carbon information for materials used, and the energy expended during highway maintenance service delivery using the data collection approach presented by the EngD (see Chapter 4, Figures 4.4 and 4.5). This information is used to support the sponsor's sustainable material procurement decision-making process and its strategy to promote the materials' responsible sourcing with environmental limits.

(b) Climate Change/Carbon Emissions

The sponsor has committed itself to a 50% normalised reduction of scope 1, 2 and 3 GHG emissions (direct and indirect emissions) by 2020 against a 2010 baseline through energy efficiency and alternative low-carbon solutions. Achieving this target requires an accurate understanding of its business and carbon interaction with its stakeholders. Therefore, the research has provided the sponsor with a unique project-specific and process-based life cycle methodology and carbon evaluation tool based on PAS2050 protocol (see Chapter 4, Figures 4.6, and 4.8). The approach presents an analytical capacity that can allow the sponsor to assess its business process carbon at design and construction stages, identify areas of carbon hotspots, and produce representative carbon information to support reduction decision-making across its supply chain. The approach has refined existing carbon assessment methodologies by adding more direct and innovative guidance. This strengthened the capacity of the approach to generate representative carbon information, whilst providing the biggest potential carbon emissions reduction across the sponsor's business value chain.

(c) Baseline Data

The EngD carbon data (e.g. materials: asphalt and fuel: diesel) were converted into their corresponding carbon footprints using emission factors obtained from the publicly available databases. The resulting carbon information has been used to change the sponsor's existing highway maintenance design, planning, options appraisal and procurement decision-making. In addition, a 25 year life cycle carbon budget has been developed based on the EngD data to support the sponsor's bid submission for new and renewal of the existing highway maintenance contracts under the Public Finance Initiative (PFI). This has facilitated the sponsor's competiveness and corporate social responsibility image, whilst offering credible baseline information for carbon benchmarking to validate and justify its carbon emission reduction claims.

(d) Waste

he sponsor has indicated its commitment to reduce waste sent to landfill, and has to managing waste as a resource in all aspects of its business. This requires the sponsor to innovate and deliver services with a minimum carbon and environmental impact. Thus, the innovative waste management project “asphalt Re-Heat project” has been initiated as part of the sponsor’s integrated waste management strategy. The intention is to meet its target on waste set by its sustainability action plan “reducing waste to landfill and managing waste as a resource”: at least 50% reduction of waste sent to landfill by 2012 and zero waste to landfill by 2020 against the 2010 baseline (BBLP Limited, 2012). This requires embedding zero waste thinking in all aspects of the business operations and that of the supply chain (BB Group, 2012). The project offers cost savings for using the recycled asphalt on highway maintenance from an economic sustainability perspective. There was, therefore a need to also identify the carbon savings associated with the project. The data collected during this research has been used to evaluate the carbon savings associated with the asphalt re-heat project in life cycle terms, and identify potential areas where maximum savings can be made quite quickly and cheaply.

(e) Customers

Business carbon footprinting and reduction, and other sustainability issues are currently becoming increasingly important to customers, particularly the highway maintenance sector. Thus, the Highways Agency (HA) in 2010 developed a new Strategic Alignment Review Toolkit (StART) to assess its supply chain alignment with its sustainability vision and strategic direction. StART focuses on leadership, supply chain management, cost, inclusion (skills and diversity) and sustainability respectively. The results of StART are expected to be employed by the HA in selecting future bidders or suppliers. The sponsor, as a major supplier to HA, has used the current EngD research project as an evidence-based case to demonstrate its strategic alignment with the HA’s strategic direction, best practice and value adding business initiative.

5.5 IMPLICATIONS FOR THE WIDER INDUSTRY

The EngD research project has several implications for the construction industry and the highway maintenance sector. The opportunities the construction industry presents to meet the goal of the low carbon agenda are emphasised in the strategic review of the UK’s construction industry capacity to meet the challenge of the low-carbon agenda. However, the industry has been faced with the lack of specific standards, formal carbon emissions requirements in project contracts, overarching policy focusing on carbon and relevant skills and knowledge gaps to support the agenda. These pitfalls within the industry are creating difficulties for organisations in undertaking credible carbon footprinting and reduction. These difficulties are compounded given the absence of an accepted industrial methodological standard, credible industrial data, robust evaluation tool, and baseline information to validate and justify carbon reduction claim. The business challenges presented by these difficulties are seen as major barriers facing the construction industry and its sectors in developing robust corporate strategies for carbon footprinting and reduction performance. In the past, organisations tended to assess their carbon footprint by focusing on carbon from activities within their control. Although this approach is appropriate in its own right, recently major construction clients are requesting carbon information across their supplier's value chain to support business decision-making. This suggests the adoption of a standard life cycle methodology to assist in transparency and the decision-making process. This provides a way for the industry to re-think its project design, investment and procurement decision-making process.

The highway maintenance specific carbon evaluation tool developed based on the PAS2050 protocol (see Chapter 4, Figure 4.8) is a Balfour Beatty business focus tool. It should not been seen as direct competitor to existing highways carbon tools reviewed in Chapter Two (see Table 2.1), but complements the existing highway tools. The tool will offerthe industry the capacity to undertake credible life cycle carbon footprinting, identify areas of carbon hotspots, opportunities for reduction that can inform a reduction hierarchy to allow reduction efforts to be prioritised. The carbon evaluation tool allows highway projects to be carbon footprinted at design and construction stages. This will allow areas of potential carbon hotspots to be identified at the early stage of the project, and ensure appropriate actions are taken, through project design change; materials selection; option appraisal and construction method. However,the research has also advanced the body of knowledge on carbon footprinting and demonstrates innovation in the application of the PAS2050 life cycle methodology. It presents a unique and practical life cycle approach (project specific) to plan, evaluate and manage construction business carbon footprint across its value chain. This will help the industry to facilitate life cycle carbon evaluation, and its consideration in the business decision-making process to improve its green credentials, CSR image and sustainability performance.

5.6 CRITICAL EVALUATION OF THE RESEARCH

As previously mentioned, the aim of this research has been to develop a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool, to support carbon management decision-making in highway maintenance planning and operation. This presents a challenge, considering the complexities associated with business carbon footprinting and reduction, the peculiarity of the highway maintenance sector and the limited time period (four years) required to complete the EngD project. A critical evaluation of the EngD research has been undertaken within the context of the research findings. This presents some limitations that focus on the research scope, time constraint, data and knowledge gaps that exist in the research area. These limitations are summarised below:

- The application of PAS2050 protocol for selected highway maintenance carbon footprinting has been undertaken across various site locations. The data analysis demonstrate the capacity of the protocol to identify areas of carbon hotspots and opportunities for reduction, whilst prioritising reduction efforts in life cycle terms. However, the approach can only assess carbon emissions responsible for Global Warming potential (GWP). Assessing other environmental impacts such as acidification, toxicity, biodiversity, and ecological formation are completely outside the scope and capacity of the protocol. Therefore, business decisions made on the basis of a single impact (GWP only) are incomplete and might be disruptive, since some services may have relatively low impact in terms of GWP, but have a high toxicity impact which is ignored by PAS2050.

- The data analysis results clearly show that the material used presents significant environmental burden (embodied carbon) and represents the area of carbon hotspots requiring attention. However, the energy-based embodied (total energy consumed to extract raw materials, processed, and manufactured and transport the finished product to customers) are considered in the carbon footprinting discussed in this study (see Chapter 4). The non-energy-based embodied carbon (the ecological footprint for using a specific natural resource) is excluded because the data could not be collected as part of this study. Furthermore, the fossil fuel used to assess the vehicles and plant/equipment carbon footprints has embodied carbon value (“Well-to-wheel”) due to the crude oil extraction, production and distribution. However, this embodied carbon information is not considered in the carbon footprint results (see Chapter 4)because it is currently not available in the public domain. The calorific values of the fossil fuel (e.g. diesel) are considered only..
- The significance of asphalt’s material embodied carbon has been emphasised by the case study results (see the EngD Paper 3, Appendix C). It accounts for on average 70% of the total maintenance process carbon footprint (CF) across all site locations (urban, semi-urban and rural) considered. However, an initial life cycle study by Zapata and Gambatese (2005) suggested that asphalt material embodied carbon is attributable to the energy expended for the aggregate drying and asphalt mixing processes. Similar studies by the Athena Institute (2006) and Durucan and Korre (2009) also suggest that the material embodied carbon is as a result of the feedstock energy in the bitumen used for asphalt production. However, this study argued that the asphalt material embodied carbon is dependent on the type of energy (e.g.100% mineral diesel) used during the material manufacturing and delivery process. Therefore, a good understanding of the extent to which these complementary views agreed can support investment decisions-making on asphalt material embodied carbon reduction. The construction industry is traditionally conservative in the adoption of new approaches and the highway maintenance sector is reflective of this. Poor record keeping by many of the supply chain (e.g. subcontractor) hindered the effective collection of site data, despite the initial assurance to all stakeholders that the data collected during the research will be subject to the IPR agreement and strict confidentiality rules. Majority of the supply chain provided carbon information in order to promote their green credentials (introducing possible measurement bias in the carbon data).
- This study presented the environmental burden associated with business carbon footprinting in terms of GWP only, but excludes the social and economic impacts. In addition, due to the time constraint, the carbon evaluation tool could not be developed further to include these impacts. . However, the carbon tool dissemination and improvement strategy has been produced (discussed in section 4.4.2). A launch event within the strategy has been undertaken, and the outcomes and recommendations from participants are documented in Appendix G.

5.7 FURTHER RESEARCH

The EngD research described in this thesis has successfully demonstrated the carbon analytical and decision-making potential of the PAS2050 life cycle methodology for highway maintenance planning and operations carbon footprinting. Following the research findings and the limitations discussed above a number of areas are recommended for future research .

- Further research work is required into the PAS2050 application for other environmental impact assessments. As such, the PAS2050-compliant carbon evaluation tool developed as part of this study can be expanded to include its capacity to assess other environmental impacts (toxicity, ecological formation, acidification and ozone formation) associated with the highway maintenance process currently not considered in this study. This will provide highway managers, designers and maintainers with robust environmental impact information for credible business decision-making and to address the impacts in a holistic manner.
- Material production accounts for the largest amount of carbon (embodied carbon) within the highway maintenance process. Despite the significance of the material embodied, the ecological footprint due to the use of the material is not considered in this study. This offers additional research scope into how ecological footprints associated with using a specific material can be assessed and included in its embodied carbon information.
- Studies have shown that asphalt material embodied carbon is attributable to the feedstock energy in the bitumen and the energy consumed during aggregates drying and asphalt mixing. However, the current study found that the asphalt embodied carbon is due to the energy type used during the material production and distribution process. Therefore, additional study is required to investigate the extent to which these complementary views agree.
- To improve the data collection process, it is recommended for a sector wide framework to be developed to support data collection process, and set a common basis for responsibility allocation, IPR definitions and legal confidentiality agreements. This offers additional research scope to identify how best this can be implemented.
- Focus group workshop (that will include both internal and external stakeholders) is recommended. The interaction between the workshop participants (participants with different experiences, technical orientation and management background,) will provide a platform to explore and identify the participant's understanding and shared views on the carbon evaluation tool. This will create an opportunity to elicit recommendations on the tool improvement, implementation and adoption in a collective manner.

5.8 RECOMMENDATIONS

Based on the research findings and limitations, the following recommendations are submitted for consideration to enhance business carbon footprinting and reduction:

- If the PAS2050 protocol is to be more widely used for life cycle carbon footprinting and reporting standards across the industry, there is a need to better understand how the construction industry in general and the highway maintenance sector in particular will decide on what data to collect and records to keep.

- An effective business stakeholder engagement strategy is crucial to developing a representative process map for site data collection. These allow the carbon interface that exists between the sponsor and its supply chain to be clearly identified, and avoid double carbon counting.
- Business carbon footprint is commonly calculated from activities data (material and energy consumed). The calculation process is relatively simple and direct, but the key challenge lies in the data credibility and interpretation of results to support reduction decision-making. Therefore, a structured and consistent data collection approach is recommended (meet standard data quality rules) to minimise data error and enhance their credibility.

5.9 SUMMARY AND CONCLUSIONS

This chapter has highlighted the main EngD research project findings, impacts on the industrial sponsor and the wider construction industry. Critical evaluation of the research was further presented in this chapter, which also discussed the research limitations and suggested recommendations for future research work. The research contributions to knowledge and practice in highway maintenance carbon footprinting were further highlighted. This thesis together with the supporting documents (see Appendices) provides essential evidence (see Table 5.7)to suggest the achievement of the EngD research aim and objectives highlighted in section 1.6.2. As earlier mentioned, the main aim of this EngD research was “To develop a project-focused and process-based carbon footprinting methodology that includes a decision-support and carbon management tool, to support carbon management decision-making in highway maintenance planning and operation”. In order to achieve the EngD project aim using a series of research methods, four specific research objectives were identified:

1. To undertake a literature review of carbon emission performance issues and highway pavement emission Life Cycle Assessment;

2. To develop and evaluate a project-specific and process-based carbon footprinting methodology based on PAS2050 Protocol;

3. To develop and evaluate a process-based carbon evaluation tool and demonstrate its suitability for carbon-based decision-making; and

4. To produce and implement the carbon evaluation tool dissemination strategy to allows for the tool improvement and adoption.

These objectives have been achieved as detailed in Table 5.7. .

From these main contributions and the research impacts on the sponsor, it can be seen that the primary research objectives above were satisfied. In addition to this, the following conclusions can be drawn from the research:

- A good understanding of the policy frameworks and initiatives driving the carbon reduction agenda within the context of their regulatory and non-regulatory requirements can assist businesses in developing a robust corporate strategy to manage the risks and opportunities businesses are expected to manage now and in the future.

- The PAS2050 protocol has demonstrated its ability to identify areas of carbon hotspots and opportunities for reduction across a business value chain. This has provided a picture of the overall carbon burden for the business, and outlined areas within the business where reduction efforts can be prioritised providing for the biggest reduction potential opportunity.
- An effective stakeholder engagement strategy can support data collection and allow businesses to identify the carbon interface that exists between the business and its supply chain, and avoid double carbon counting .
- The case study results revealed that material production and its delivery to site are the main areas of maximum carbon usage across the highway maintenance process irrespective of the site location. This presents important sustainability decision points for highway maintenance stakeholders.

This research has advanced the body of knowledge in carbon footprinting and demonstrated innovative application of the PAS2050 life cycle methodology in business carbon assessment. The carbon evaluation tool developed is unique in the highway maintenance planning and operations, hence the novelty of the EngD research project. In addition, the adoption of the life cycle carbon evaluation tool can yield carbon performance benefits for the wider construction industry and its infrastructure maintenance sector. The final implementation phase however should include an understanding of stakeholders' shared views on the carbon tool, and how it can be embedded in the business decision-making process in carbon terms to ensure a positive and beneficial outcome.

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APPENDIX A : ENGD PAPER 1

Itoya et al (2012), E., Ison, S., Frost, M.W., EL-Hamalawi, A. and Hazell, K. (2012). Carbon Emissions Performance and the UK's Highway Maintenance Sector: Review of the Issues. In: proceedings of the 40th European Transport Conference (ETC), Association of European Transport (AET), Glasgow, Scotland.

CARBON EMISSIONS PERFORMANCE AND THE UK's HIGHWAY MAINTENANCE SECTOR: REVIEW OF THE ISSUES

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ABSTRACT: Currently in the UK, carbon emissions performance and other sustainability issues are being considered as part of project's contractual requirements and a major part of the tender selection criteria for highway construction and maintenance, with the intention of delivering a low-carbon service. This inherently presents business opportunities and risks; which can be poorly understood by the highway maintenance stakeholders including their supply chain. Having an in-depth understanding of the carbon emissions performance from highway maintenance operations within the context of their drivers, approach and business benefits can provide highway providers, managers, designers, maintainers and contractors with a robust knowledge framework to support business investment decision-making. This can also support businesses in developing a robust corporate strategy to manage the risks and opportunities that businesses are expected to manage and meet the objective of the low-carbon agenda, whilst enhancing business competiveness. The purpose of this paper is to provide a knowledge framework that can facilitate carbon emissions performance, and promotes project-based carbon footprinting methodology for carbon consideration in highway maintenance decision-making processes. The paper presents key definitions of highway maintenance carbon emissions assessment and performance, a review of regulatory and non-regulatory drivers focusing on the existing and emerging international and UK-based policy frameworks and initiatives on climate change and carbon footprinting. The carbon emissions reduction guidance, opportunities and inherent issues presented by civil infrastructure including the highway maintenance sector are explored. A brief overview of pavement materials embodied carbon sources, and discussion on carbon emissions reduction issues are also provided. The paper concludes that the availability of a carbon evaluation tool underpinned by sound methodology and complementary study outputs, and emissions data and collection approach are essential for organisations to develop a corporate strategy to enhance carbon emissions performance. Although, emphasis within the paper focuses on the highway maintenance business sector, the knowledge framework can also be utilised by other sectors within the built environment as an information source to improving their carbon emissions performance.

Key Words: Emissions Reduction; Policy Drivers; Infrastructure; Emissions performance

1. INTRODUCTION

There is generally a consensus that the current mode of economic development is unsustainable and exposes human life to the risk of climate change, which is attributable to the increasing greenhouse gas (GHG) emissions from business activities and associated natural resource and energy consumption, and consequent emissions (IPCC, 2007). There will clearly be little or no economic activity without infrastructure (ICE, 2009), and transport for example is increasingly being highlighted as a sector that consumes emission-based fuels, accounts for 13% of global greenhouse gas emissions, and has contributed least to the emissions reduction agenda (Hickman et al., 2008 Kok and Gille, 2009 Lopez-Ruiz and Crozet, 2009).

Currently in the UK, highway maintenance investment decision-making is examined not only from an economic and technical perspective, but also from an environmental perspective (Hoang et al., 2005 Zhang et al., 2008). The increasing emphasis on environmental and carbon emissions performance by highway stakeholders is placing responsibility on the sector to re-think its business activities within environmental, economic and social limits across its operation value chain. This emphasis presents risks and business opportunities, which can be poorly understood by the stakeholders given that the majority lack a good understanding of the policies driving the agenda, of areas within the sector on which to focus carbon emissions reduction efforts, and of how to ensure that operational and strategic decisions are appropriately linked. This knowledge gap is creating a barrier for the sector to develop a robust corporate strategy in order to meet its carbon emissions performance and enhance its business competiveness. This suggests and justifies the need to provide highway maintenance stakeholders with a robust knowledge framework. This will allow for an in-depth understanding of their carbon contributions and allow them to develop a strategy in order to manage the risks and opportunities expected both now and in the future. It also offers businesses an efficient carbon management and value adding opportunity to service delivery, whilst enhancing continued business success and competiveness.

The aim of this paper is to provide a knowledge framework that can facilitate carbon emissions performance (see Figure 1), and promote a project-based carbon footprinting methodology for carbon consideration in the highway maintenance decision-making process. This requires a consistent system-based and business-specific carbon management approach that ensures highway maintenance strategic and operational decisions are appropriately linked. The paper presents key definitions of highway maintenance carbon emissions assessment and performance from life cycle and business perspectives. A state of the art review is presented focusing on existing and emerging international and UK-based policy frameworks and initiatives; driving climate change mitigation, carbon footprinting and emissions reduction, within the context of their regulatory and non-regulatory requirements.

The carbon emissions reduction initiatives and guidance, and inherent issues associated with civil infrastructure and highway maintenance sector are explored to support the sector-specific knowledge framework developed. The opportunities offered by the sector to promote efficient carbon management, whilst addressing the expected risks and business co-benefits are also examined.

The study also presents a brief overview of pavement materials embodied carbon sources and discussion on carbon emissions reduction opportunities and issues identified from the review. It is expected that the knowledge framework will allow businesses a snap-shot of their current carbon impact, and sign-post of possible future emissions reduction; whilst opening new research direction to enhance business improvement, opportunities and competitiveness in carbon terms. The approach argued in this paper is fundamental to ensuring that carbon performance is given an appropriate profile in the business decision-making process. This promotes business life cycle thinking for carbon consideration. This shift in business decision-making is a direct response to the increasing demand and attitude of business stakeholders towards a low-carbon service and greater transparency on sustainability and environmental accountability, and business capacity to reduce both direct and indirect carbon from their value chain. Although emphasis within the study focuses on infrastructure and the highway maintenance business sector, the knowledge framework can also be utilised by other sectors within the built environment as a guide to understand and improve their carbon emissions performance, and enhance business competiveness based on researched propositions.

2. KEY DEFINITIONS

This section presents the definitions of highway maintenance carbon emissions assessment (or carbon footprinting) and performance from life cycle and business perspectives. Carbon footprinting is defined as a methodological approach commonly used to describe the total amount of CO2 and other Greenhouse Gas (GHG) emissions defined by the Kyoto Protocol and the Intergovernmental Panel on Climate Change (IPCC) over the full life cycle of a product or service for which an individual or business is responsible for (ADB, 2010). It is often used to estimate global warming potential of carbon emissions associated with product or service life cycle (Huang et al, 2012). Carbon emissions or footprint can be evaluated at business, process, activity, task, and product level. In this context, this study defined the highway maintenance carbon footprint as the total amount of CO2 and other GHG emissions (both direct and indirect emissions) emitted over the full life cycle of the maintenance process, including the supply chain.

In view of these definitions, this study defined carbon emissions performance as a business improvement strategy to identify, assess, reduce and report business direct and indirect carbon emissions, whilst harnessing the environmental, economic and social benefits through energy and resource efficiency across the business value chain. This requires giving carbon emissions information appropriate profile in business decision-making process. These definitions provide the scope and system boundary for businesses to apply in order to enhance their emissions performance and promote environmental sustainability through materials and energy conservation. A good understanding of inherent business challenges and benefits, and the policies and standards driving the agenda is crucial for businesses to achieve the expected carbon emissions performance so as to tackle climate change impacts. The ability for businesses to improve their emissions performance do not simply depend on the application of comprehensive assessment methodology, but also having an in-depth knowledge of the carbon intensive operation that comprises the business process and activities life cycle (Santero, 2009). This provides the fundamentals for businesses to focus their carbon emissions reduction efforts in areas with high-impact, since a small change in these areas will produce significant reduction. This presents a huge challenge for businesses including the highway maintenance sector, given the complex nature and activities involved.

3. STUDY APPROACH

The approach employed in this study essentially relies on three inter-dependent sources of information. The intention is to provide a knowledge framework (see Figure 1) to enable businesses to develop a corporate strategy to cope with the risks and opportunities, which businesses are expected to manage in order to enhance their carbon emissions performance and continue business success. The study not only focuses on current information sources, but also on historic information, so that any change in the future could also be appropriately described and documented.

First, a comprehensive state of the art review of both the international and UK's national policy frameworks promoting carbon emissions assessment and reduction was undertaken, within the context of their regulatory and non-regulatory drivers. These policy frameworks were analysed and discussed within the context of their environmental effectiveness, cost-effectiveness and institutional feasibility. Essentially, the analysis process provided in-depth understanding and background information to explore and evaluate how these policies are likely to impact on the business environment in general and highway infrastructure maintenance sector in particular.

The second source of information is the review of the opportunities inherently presented by the UK's civil infrastructure and highway maintenance sector that can promote a carbon management and system-based approach for carbon emissions consideration in business decision-making processes. The absence of an accepted industry methodological approach and standard, data collection approach and robust evaluation tools, to support the agenda presents carbon assessment and reduction challenge for businesses.

Third, it was observed that the information sources described above collectively promote the need for efficient carbon management and performance at sector and business levels, but they fall short of the potential to provide a comprehensive emissions assessment and reduction guidance for businesses to understand carbon expenditure, and develop a corporate strategy for reduction. The analysis of the identified shortfall presents issues associated with carbon emissions performance, gaps in the state of practice and research opportunities to address the shortfalls with infrastructure maintenance sector.

4. CLIMATE CHANGE AND CARBON EMISSIONS REDUCTION DRIVERS

4.1 International and UK's Policies Perspective

Climate Change has been recognised as a global problem (attributable to human activities) that requires a global solution(DECC, 2009a DEFRA, 2006a, 2007a, 2009 Townsend, 2005). Although some authors argued that human-made climate change does not exist (Byatt et al., 2006 Carter et al., 2006), but the threats and challenges imposed by the changing climate are real. There has been increasing international, scientific and global efforts to address the impacts of climate change (Ikhrata et al., 2012). The Intergovernmental Panel on Climate Change (IPCC) provides the scientific, technical and socio-economic information relevant to understand the risk of climate change, its potential impacts, and options for adaptation and mitigation (DEFRA, 2007a IPCC, 2007). The IPCC's fourth Assessment Report provides a comprehensive and up-to-date assessment on climate change and its potential impacts. The report concluded that the science of climate change is real and requires urgent international agreements to tackle (IPCC, 2007). The mechanism under which this can be met depends on a comprehensive understanding and accurate knowledge of climate change impacts, trends and collective efforts that can alter these trends. To this end, the United Nations Framework Convention on Climate Change (UNFCCC) was assigned the responsibility to coordinate global efforts to tackle climate change impacts and stabilise CO2 and other Greenhouse Gas (GHG) concentrated in the atmosphere at a level that could prevent dangerous interference with the climate system (DEFRA, 2006a Wang and Watson, 2007).

2005, saw the introduction of a legally binding international treaty (Kyoto Protocol (KP)) aimed at reducing carbon emissions and tackling climate change impacts at national levels, particularly from industrialised nations like the UK. It presented these countries with a system that can measure, reduce and report their total GHG emissions they are responsible for. The international emissions trading system (e.g., European Union Emissions Trading System (EU-ETS) and the flexible mechanisms, the Clean Development Mechanism (CDM) and Joint Implementation (JI) programme, are 3 market-based mechanisms introduced by the protocol to achieve its emissions reduction objective (UNFCCC, 2007).

The European Union (EU) and its member states committed under the Kyoto Protocol to reduce all GHG emissions by 8% below 1990 levels by 2008-2012 (EU, 2009). Keppo and Rao (2008) argued that delay and non-participation in global efforts to tackle climate change can affect global climate change mitigation efforts in terms of feasibility, costs, timing, magnitude and nature of the long-term mitigation response (Arnulf et al., 2006 Keppo and Rao, 2008). Currently, the question about timing, forms and levels of mitigation that can replace the Kyoto Protocol when it expires in 2012 has occupied the centre stage of international forums on climate change (Baker, 2008 Corfee-Morlor and Hohne, 2003 UNFCCC, 2010, 2011 Wang and Watson, 2007). Corfee-Morlor and Hohne (2003) suggested that securing a realistic global agreement that takes into account long-term climate change risk is crucial to design the post Kyoto Protocol.

The UK government has introduced stringent policy measures to reduce its GHG emissions under the Kyoto Protocol and the “EU Member States” Burden-Sharing agreement (DEFRA, 2006b, 2007b). In 2008, the UK’s Climate Change Act (CCA) was enacted. This moves carbon emissions from policy requirements to legal responsibility across all sectors, and provided the framework to facilitate all UK’s based carbon emissions reduction initiatives and agenda. The Act commits the UK to reduce all GHG emissions by at least 80% below 1990 levels by 2050, and by 34% below 1990 levels by 2020 through a system of five-year carbon budgeting periods (DECC, 2009a). This effectively makes the UK the first country to put carbon emissions reduction targets into law. However, the wider strategy to implement the act has been recognised to reach deep into every aspect of the UK’s economy. For the UK’s government to achieve its emissions reduction targets and transit into a low-carbon economy, a number of initiatives have been introduced. These include:

(1) the UK’s Low-Carbon Transition Plan (DECC, 2009b) published in 2009, which set out a route-map for the UK to meet its 34% emissions reduction target by 2020 (DECC, 2009b),

(2) the “2050 Pathways Analysis” (DECC, 2010b) published in 2010, which detailed the changes that must occur in the UK’s sectors to achieve the 80% emissions reduction targets by 2050,

(3) the Carbon Plan (DECC, 2011), which provided specific practical responsibility, cross-government and UK’s sectors to meet the carbon budgets set under the Climate Change Act (DECC, 2009b, 2010b, 2011).

Although, it has been argued that given the ambitious nature of the UK's policies on GHG emissions reduction, innovation and economic regulatory policies are essential to stimulate innovations, investment and the much-needed change towards energy and materials efficiency (DECC, 2008).

In addition, the concept of the UK's transition into a low-carbon economy is underpinned by the Carbon Reduction Commitments (CRC);a cap and trade scheme, similar to the EU-ETS (DECC, 2010a DEFRA, 2008a). It requires organisations to measure and report their annual emissions. This overreaching regulatory framework provided by the CRC further strengthens the legal obligations on large and process-based sectors, including the infrastructure sector, to measure and report their emissions. The initiative was designed to set the UK on the path to achieving the 2050 emissions reduction target by focusing on energy and carbon intensive sectors. Similarly, the National Indicators (NI 185: Percentage CO2 reduction from LA operations, and NI 186: per capita CO2 emissions in the LA area) introduced in 2008, places legal requirements on all UK's Local Authorities (and their supply chain in the UK) to measure and report their GHG emissions annually, as part of the Carbon Reduction Commitment (CRC), defined under the UK's Climate Change Act (DEFRA, 2007b, 2008a, 2008b).

The UK's government recognises the need for appropriate guidance to enable organisations to take the right action on GHG emissions assessment and reduction. This led the government to publish a document, which offers guidance on how organisations can measure and report their GHG emissions. However, organisations which use the guidance to assess emissions are not required to submit the information as part of the national emissions inventory (DEFRA, 2009). This voluntary approach has been observed as a major drawback that weakens the general uptake of the guidance as an organisations GHG emissions assessment and reporting standard.

Furthermore, the importance of energy and materials efficiency is reflected in the debate and demands for a low-carbon service from organisations (Waddell, 2008). The "Waste Resources Action Programme (WRAP)" was initiated in 2008 to promote and enhance materials and resource efficiency in construction operation across the UK, and encourage innovation across industry so as to achieve its waste and emissions reduction targets set under the "Strategy for Sustainable Construction" (BERR, 2008 WRAP, 2008) - a 50% waste reduction sent to landfill by 2012 compared to 2005 and zero waste by 2020. The initiative promotes material and energy efficiency, and to achieve this, sets the "Landfill Tax" (currently at £64 per tonne of waste, and increases to £72 by 2013) and the "Aggregate Levy" (£2.40 per tonne of waste, and increases year on year (HM Treasury, 2011)).

The review has shown that the existing and emerging international and UK's carbon emissions reduction policies and initiative frameworks reflect the relevance of energy, materials and waste efficient across all sectors. The voluntary nature of some of the policies and initiatives offers non-regulatory drivers on carbon emissions reduction. In addition, their inability to define a wider scope and system boundary for emissions assessed presents a huge challenge for organisations. The policies and initiatives currently offer introductory guidelines and guidance for organisations to understand their emission inputs, and the government's current and future thinking on carbon emissions reduction and impacts on climate change. Therefore, this study argued that the existing carbon emissions reduction policies and initiatives are not strong enough to drive the low-carbon agenda; since the majority of these policies and initiatives lack the specific regulatory drivers and standards for organisations to apply and develop a credible emissions reduction strategy. This view suggests the need for a practicable carbon management action plan (e.g. the "Zero Waste

Scotland" and Resource Efficiency Plans by WARP) that can promote a project-specific approach to carbon management across all sectors, and provide organisations with a pragmatic means to prioritise emissions reduction efforts, whilst ensuring that organisation strategic and operational decisions are adequately linked.

The civil infrastructure sector presents the opportunities that can promote a project-specific carbon management approach, given the materials and energy-based processes involved. Within the context of this study, these opportunities and associated carbon emission issues are reviewed and discussed below.

5. THE INTRASTRUCTURE AND CARBON MANAGEMENT

This section presents an overview of UK-based carbon management frameworks focusing on the civil infrastructure sector including highway infrastructure maintenance operation. The opportunities presented by the sector that can enhance efficient emissions assessment and reduction are examined. The intention is to understand the sector's current carbon management practices, and associated emissions performance, within the context of the opportunities to promote a life cycle and business-specific carbon management approach.

5.1 The Civil Infrastructure and Carbon Management

Infrastructure exists to meet the economic, social and environmental needs of any society. There will be little or no economic activities without infrastructure (ICE, 2010). The stress placed on ageing infrastructure by the growing population, booming economic activities and demands for new infrastructure to accommodate this growth are critical issues for the UK's infrastructure to address in order to enhance performance. These suggest the demand for new or well-maintained infrastructure to accommodate this growth (ADB, 2010 BIS, 2010a). Consequently, this situation calls for a considerable financial investment, but poses a significant environmental and sustainability implication (Lopez-Ruiz and Crozet, 2009 Muench, 2010), considering the materials and energy inputs and associated GHG emissions involved. In practice, this suggests effective carbon management and other sustainability issues (Whalley, 2011), which present challenges for the sector given that existing management systems do not consider carbon management (Halcrow Limited, 2011). The "State of the Nation's Infrastructure" (ICE, 2009) report published by the Institution of Civil Engineers (ICE, 2010) recommended that the development of a system-based approach to manage carbon impacts associated with infrastructure is essential. In 2011, the UK's "National Infrastructure Plan" published a similar report, which set out a new strategy for the UK to meet its infrastructure performance and economy needs within environmental, economic and social limits (HM Treasury, 2011). Recently, Halcrow Ltd has undertaken a questionnaire survey to gain insight into carbon considerations in infrastructure project investment, planning, design and maintenance. The study focuses on major infrastructure delivery organisations in the UK, and the objective was to identify the key policy drivers and barriers for carbon emissions consideration in infrastructure development and management, and the success factors in terms of carbon reduction over the infrastructure life cycle.

The then study concluded that carbon management is moving towards becoming part of infrastructure projects but suggests that an organisation's internal or external policies and standards, not regulation, are the main driver for carbon consideration in infrastructure. The reason is that existing regulations are not strong enough to provide a comprehensive low carbon approach. The study further suggests that there is a lack of an overarching policy that focuses on carbon, and the availability of relevant skills and knowledge to support the agenda. These are seen as major drawbacks and barriers for organisations to design and deliver low-carbon infrastructure. To address these drawbacks and barriers, and bring about the desired step change in carbon management approach in infrastructure, this study suggests a system-based approach that can facilitate holistic carbon management over infrastructure life cycle, since the approach has the potential to ensure that an organisation's strategic and operational investment decisions on infrastructure delivery process are adequately linked (Halcrow Limited, 2011). However, these views from the participating organisations might not reflect the general view of all infrastructure delivery organisations, since only fifteen organisations participated in the survey.

5.2 Highway Infrastructure Maintenance and Carbon Emissions

The transport sector and its supporting infrastructure emissions have risen by 10% since 1990, and currently account for 24% of the UK's domestic emissions. Overlooking the carbon emissions from this sector will undermine the UK's efforts to meet its emissions reduction commitments (BERR, 2008). Thus, the transport system including its supporting infrastructure are required to play a significant role towards meeting the UK's emission reduction targets (DfT, 2008). In this context, the UK's Highways Agency (HA), in a desire to extend carbon management across its business activities, has initiated the development of a practical carbon management framework based on the principles existing in project management systems, under the Forum for the Future Engineers 21st Century (e21C) programme. The framework sets out guidance for businesses to estimate the lifecycle carbon impacts of infrastructure assets at the project level, whilst examining how carbon from major infrastructure projects can be managed and influenced (Forum for the Future, 2009). The framework builds on carbon emissions assessment and reporting methodology provided by the Greenhouse Gas (GHG) Protocol (WRI/WBCSD, 2011), Publicly Available Specification (British Standards Institute, 2008), Carbon Reduction Commitment (CRC) Energy Efficiency Scheme (DECC, 2010a DEFRA, 2008a), the Department for Food and Rural Affaires' (DEFRA) guidance on how organisations can measure and report their emissions (DEFRA, 2009), and the carbon emissions calculation principles and approaches provided by the UK's Environment Agency (Environment Agency, 2007) and Highways Agency (Highway Agency, 2009). The study concluded that life cycle carbon emissions from infrastructure projects can be influenced through effective design (BERR, 2008). This conclusion suggests that the greatest opportunity to influence and manage carbon exist at pre-design and design stages of the project. This indicates that quantifying carbon emissions at early stages of a project's life cycle can support design, option appraisal, procurement and sustainable construction method decision-making.

Furthermore, the Innovation and Growth Team (IGT) has undertaken a strategic review of the UK's construction industry capacity to meet the challenge of the low-carbon agenda on behalf of the UK's Department of Business, Innovation and Skills (BIS, 2010a). The review recognises the opportunities within the construction process needed to drive innovation and growth to meet the UK's legally binding emission reduction targets. The review further presents a holistic view of the emissions the industry and its infrastructure sector have the capacity to influence. This view suggests the development of a new life cycle carbon emissions assessment approach that reflects the inclusion of emissions information as a primary construction design constraint (BIS, 2010a). However, a comprehensive study by the UK's Department of Business, Innovation and Skills (BIS) suggests that the in-use phase of asset lifecycle accounts for 80% of the total emissions (e.g. tail-pipe emissions), while the construction material manufacturing (embodied carbon) process accounts for the largest amount of emissions from the asset delivery process (BIS, 2010b). Therefore, the actual scope of emissions that the design process can influence is inherent in the impacts the design has on the in-use phase, materials selection and construction methods (BIS, 2010b Forum for the Future, 2009). Although, the Forum for the Future infrastructure framework tends to promote carbon management and reduction over infrastructure life cycle, it presents drawbacks by failing to provide guidance on how carbon management can be considered as formal requirement in projects. In addition, since the framework was developed as a separate generic process, it needs to be embedded into existing project management systems for effective implementation in infrastructure delivery.

The material consumed during highway construction and maintenance has significant embodied carbon impact across its production and delivery processes. Therefore, an overview of major sources of highway pavement materials embodied carbon is explored.

5.3 Pavement Materials Embodied Carbon

Highway pavement material production and transportation are energy and carbon-intensive, and produce the most significant impact on highway carbon footprint from a life cycle perspective (Athena Institute, 2006 Chan, 2007 Durucan and Korre, 2009 Fox et al., 2011 Muench, 2010 Nisbet et al., 2001 Stripple, 2001).However, Stipple et al (2001), Athena Institute (2006) and Chen (2007) argue that energy consumption and associated carbon emissions due to asphalt materials manufacturing is attributable to bitumen feedstock energy. The initial life cycle study by Zapata and Gambatese (2005) concluded that asphalt mixing and the aggregates drying processes during asphalt materials production are mostly responsible for the energy consumption and associated carbon emissions (Zapata and Gambatese, 2005). This conclusion suggests the use of renewable energy (e.g. Biodiesel) for asphalt materials production. However the use of this energy type at a commercial scale presents an obvious challenge for asphalt material manufacturers. It is essential to know that the impact of highway pavement materials on the environment does not only occur during the production process, but also through rolling resistance of the materials, traffic delay, the urban heat island effect and other impact mechanisms (Santero, 2009).

The above review has revealed that the infrastructure delivery process presents opportunities and challenges for effective carbon management if properly designed and executed. The key challenge has been that existing management practices in infrastructure are fragmented and unbalanced. Some of the existing and emerging infrastructure initiatives/frameworks reviewed in this study emphasise the need for practical carbon management systems that can promote a system-based carbon assessment and reduction approach, whilst giving carbon emissions information appropriate profiles in infrastructure delivery investment, planning and design decision-making.

Halcrow (2011) has revealed the challenges associated with carbon emissions consideration for infrastructure delivery that are creating drawbacks and barriers for businesses to design and deliver low-carbon infrastructure. Furthermore, the need for carbon management in highway infrastructure maintenance is emphasised. It was emphasised that the greatest opportunity within infrastructure delivery to effectively manage carbon emissions over its life cycle exist at design, option appraisal, procurement and sustainable construction method decision-making. To efficiently evaluate this carbon emission impacts and optimise the emissions across the business value chain, there is a need to develop a robust corporate strategy that can improve carbon emissions performance.

In summary, the above state of the art literature review revealed that the lack of a practical carbon management framework has been the greatest barrier that prevents a business strategy to be developed by organisations and enhance their business emissions performance. It is important that the strategy should include a carbon evaluation tool underpinned by a robust methodology and credible emissions data and collection approach for implementation. This will allow businesses to assess and optimise carbon emissions across their business delivery processes including materials production and delivery. Benchmarking the emissions results based on the corporate strategy developed and emissions outputs from existing and emerging complementary carbon emissions studies can offer organisations the fundamental basis to justify and validate their emissions performance claim.

5.4 A Knowledge Framework for Carbon Emissions Performance

This paper has examined the policy frameworks driving carbon emissions management within the context of their requirements and principles. The opportunities and challenges presented by civil infrastructure, particularly the highway maintenance delivery, have been explored. The study has argued that a knowledge framework that can support businesses to develop a corporate strategy for carbon emissions performance and promote project-focused carbon footprinting methodology across its value chain is essential. This strategy should be able to address the carbon emissions assessment and reduction challenges identified. Figure 1 below presents the knowledge framework for carbon emissions performance specific to the highway maintenance sector. The framework presents a combination of top-down and bottom-up carbon management approaches. The intention is to ensure that organisations are able to develop a robust strategy for emissions performance that meets the principles and requirements of relevant policy drivers. The top-down approach presents the policy frameworks, standards, initiatives and sector developments driving business emissions performance, while the bottom-up presents a life cycle approach that can support businesses to facilitate business carbon emissions performance across its value chain through informed decision-making, whilst meeting the policy driver's principles and requirements.

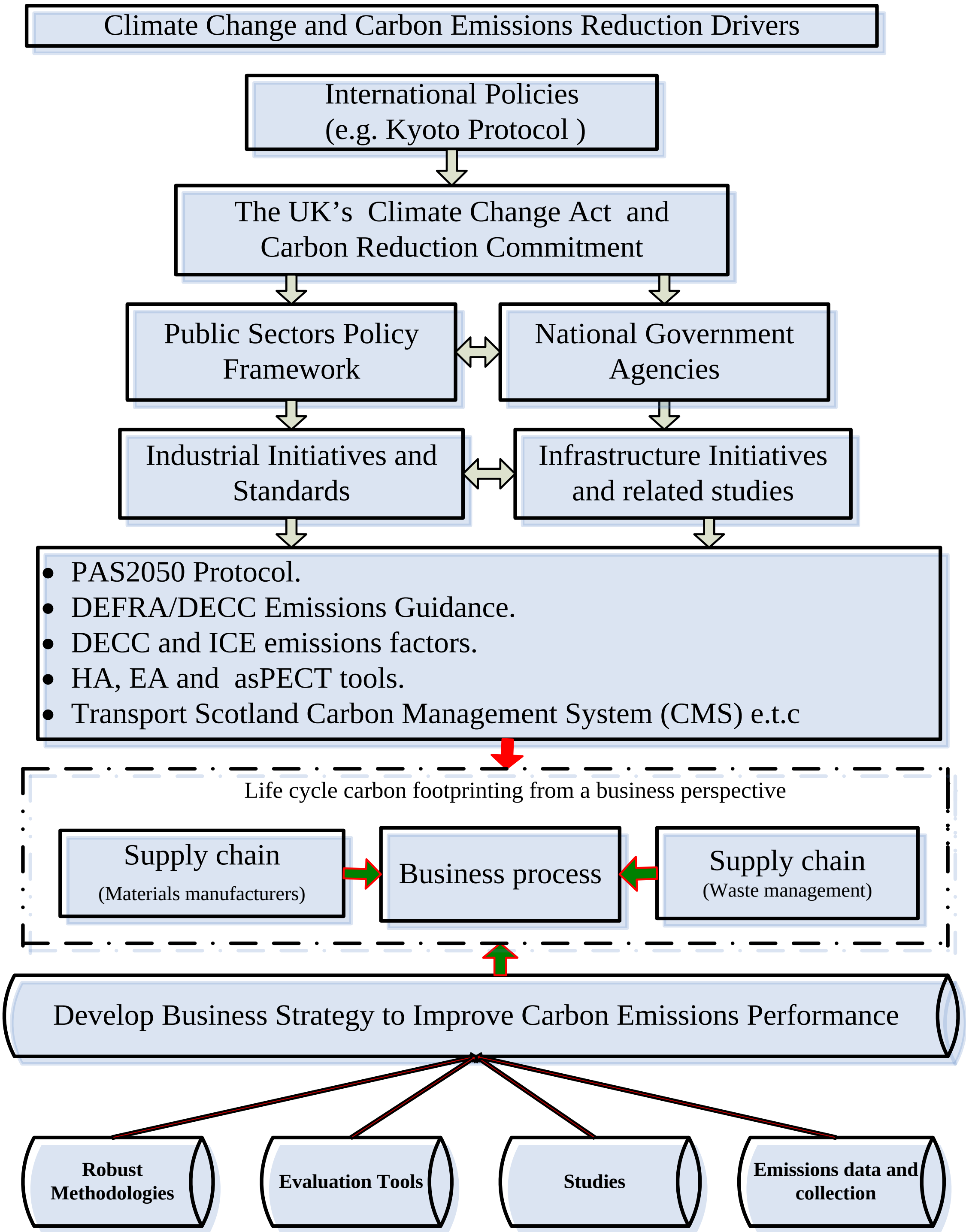

Figure 1: A knowledge Framework for Carbon Emissions Performance

Figure 1 suggests a business strategy that employs a life cycle methodology for carbon emissions assessment and reduction across the business process and its supply chain, and promotes carbon consideration in the decision-making process. Performing a highway carbon emissions life cycle assessment and integrating the information into the highway maintenance decision-making process is an enormous task. The Swedish Environmental Research Institute has defined the highway infrastructure as a system which consists not only of the highway pavement itself, but also of the traffic control system, highway lighting, pavement marking and road signs operation (Stripple, 2001). Assessing carbon emissions across these various systems from a life cycle perspective requires an in-depth knowledge of the entire system including the supply chain's emissions interaction with the highway system. This approach to carbon emissions performance inherently presents a range of issues which are discussed below.

6. DISCUSSION

This state of the art review presents issues associated with organisation's carbon emissions performance. These issues range from the stringent nature of the regulatory and non-regulatory policies framework, the UK-based carbon emissions assessment and reporting initiatives to guidance developed by national government agencies, industry and private organisations within the civil infrastructure and highway maintenance sector. Although the review had revealed the changes taking place at the international, national, industrial and organisation level driving carbon emission management, the lack of an agreed industrial methodology standard and the difficulties presented by existing carbon management practices are issues that frustrate organisation efforts on carbon emissions performance.

6.1 Emissions Reduction Policies Framework Issues

An overview of carbon emissions assessment and reduction policies within the context of their regulatory and non-regulatory requirements and their capacity to promote environmental and cost-effectiveness and institutional feasibility are presented. The review has provided in-depth information on the aspiration of existing policy frameworks towards tackling climate change and promoting the low-carbon agenda through global efforts. The literature has revealed the level of certainty on emissions that the regulatory policies can address. The review suggested that the policies environmental effectiveness, cost-effectiveness and institutional feasibility are reflected in their regulatory power, distribution, knowledge and structure of targeted organisations. In addition, Halcrow Limited (2011) argued that existing policies on carbon emissions reduction have been greatly criticised for not being able to drive the required innovation and growth to achieve the reduction targets (Halcrow Limited, 2011). The reason had been that the majority of these policies are voluntary in nature, and varied considerably in scope and stringency. In most cases, these voluntary policies are simply an agreement between the government and industry to drive and encourage energy efficiency in organisations. The review further argued that these voluntary policies are cost-effective, but lacked the required level of certainty on the scope and amount of emissions they have the capacity to reduce. Although, the review indicates that the non-regulatory emissions policies present opportunities for businesses to develop emissions reduction initiatives internally and stimulate sustainable practice. However, both the regulatory and non-regulatory policies present the need to drive emissions improvement across all sectors, and provided the policy frameworks with which existing, current and emerging emission reduction initiatives and guidance are established.

6.2 Emissions Reduction Initiatives and Opportunities Issues.

The existing UK-based national policies present the requirements for UK's regional, industrial and private sector initiatives to drive the low-carbon agenda. These initiatives are developed to influence the public sector's actions, strategic response to stakeholder's environmental concerns, create and add value and enhance organisations' business competiveness. The review revealed that these initiatives are promoting direct and indirect carbon assessment and reduction, stimulating innovation and integration of sustainable solutions across businesses. However, the initiatives demonstrate consistent weakness within the context of their emissions assessment scope, analytical rigour and ability to independently reduce carbon emissions. Although, the initiatives indicate the relevance of energy, materials and waste efficient across all sectors, their inability to define a wider scope and system boundary for the emissions assessed present implementation challenges for organisations. The majority of these initiatives simply offer introductory guidance and information towards a carbon management approach. This further suggests the need for an efficient and practicable carbon management action plan that can promote a system-based approach across an organisation's value chain. This approach will provide a life cycle methodology framework that can support an organisation's ability to connect both the strategic and operational decisions across its value chain. This further suggests the integration of carbon emissions information into the organisation's decision-making process.

In practice, undertaking carbon emissions assessment and integrating the information into the business decision-making process is a complicated task as earlier mentioned, given that it is likely to require trade-offs between many conflicting variables. These complexities are compounded due to a lack of specific standards focusing on carbon management, absence of formal requirements of carbon management in project contracts, and knowledge and skill gaps to drive carbon management. The complexities are further compounded given the lack of robust and an agreed carbon emissions assessment methodology, credible industrial emissions data, and baseline information for benchmarking. The challenge imposed by these complexities has been seen as major barrier for organisations to developing a robust business strategy that focuses on carbon emissions assessment and reduction. To address the challenge and barriers in the face of these complexities within the infrastructure and highway maintenance sector, Figure 1 has presented a knowledge framework that can facilitate organisation efforts to develop robust corporate strategy that focuses on carbon management performance through an informed decision-making process. In this context, it is important to balance both the capital and operational carbon costs (Whalley, 2011) across the value chain, whilst still meeting the fundamental objective of the low-carbon agenda. The framework will provide infrastructure and highway practitioners with a practical means of identifying and maximising potential carbon reduction initiatives within their business, and develop a cooperate strategy that includes a robust methodology for carbon hotspotting and opportunities for reduction. This will inform the development of an emissions reduction hierarchy to allow businesses to focus and prioritise their emissions reduction efforts. This presents a research opportunity that can offer businesses the capacity to improve their carbon emissions performance, enhance their competiveness and long-term business success.

7. CONCLUSIONS

This paper has presented a state of the art literature review to provide a knowledge framework (Figure 1) to be used by organisations as an information source, particularly the highway maintenance sector, to develop a robust corporate strategy that can facilitate carbon emissions performance and promote a business lifecycle approach to carbon assessment and consideration in the business decision-making process within the context of internal and external drivers. This will allow businesses to effectively manage the risks and opportunities to enhance business competiveness. The study focused on the trend and context of existing international and national (UK) policy frameworks, UK-based and industrial initiatives within the infrastructure sector driving carbon emissions assessment and reduction. The primary sources of pavement materials embodied carbon and an overview of knowledge framework developed for carbon emissions performance are other areas the study considered. The findings and associated carbon performance and management issues have been discussed to pave the way for research to improve businesses' environmental footprint.

This paper has argued that the key step towards efficient carbon performance from business operation is at first to get a good understanding of the carbon systems and expenditure. However, existing research on carbon management and performance, and carbon consideration in the infrastructure decision-making process are vague and unbalanced, thus, cannot provide the knowledge framework required for improvement. In addition, this study seeks to provide a knowledge framework that can be used as information sources by businesses to understand the risks and opportunities presented by existing policy frameworks, initiatives and guidance. They offer introductory guidelines and guidance for businesses to understand their emission inputs, and are not strong enough to drive the low-carbon agenda; they simply provide government current and future thinking on carbon and climate change since the majority of these policies and initiatives lacked the specific regulatory stringency to drive innovation for improvement. This conclusion suggests the need for a practicable carbon management action plan that can promote a holistic and project-focused life cycle approach, and provide organisations with a pragmatic means to focus and prioritise emissions reduction efforts sustainably. Following this conclusion, this study recommends a project-focused and process-based carbon footprinting approach that can support carbon management decision-making, and identify area emission hotspots and opportunities for reduction. These areas of emission hotspots and reduction opportunities can inform a reduction hierarchy that can allow businesses to focus and prioritise emissions reduction efforts. Prioritising emissions reduction efforts on business activities with a potentially large impact can significantly improve its emissions performance. Achieving this desired carbon performance from a highway maintenance process perspective suggests a knowledge framework to be employed as an information source to support a robust business strategy to be developed, whilst facilitating life cycle carbon emissions performance and promoting project-focused carbon footprinting methodology that includes a decisions support tool to manage carbon across the process value chain. This paper concludes that an efficient business strategy for an organisation carbon emissions performance should include a carbon evaluation tool, underpinned by a robust methodology and complementary studies outputs, and credible emissions data and collection approach.

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APPENDIX B : ENGD PAPER 2

Itoya,et al (2012) E., Hazell, K., Ison, S.G., EL-Hamalawi, A. and Frost, M.W. (2012). Framework for Carbon Emissions Evaluation of Road Maintenance. In Transportation Research Record (TRR): a Journal of the Transportation Research Board, No. 2292, Transportation Research Board of (TRB) of the National Academies, Washington, D. C. pp. 1 - 11

FRAMEWORK FOR CARBON EMISSIONS EVALUATION OF ROAD MAINTENANCE

Emioshor Itoya, Katrina Hazell, Stephen Ison, Ashraf El-Hamalawi and Matthew W. Frost

Currently in the UK, carbon emissions associated with businesses activities has moved from policy requirements to definitive legal responsibilities following the UK's Climate Change Act (CCA) in 2008. Real and pressing need exists for a flexible and easy to use technique to enable businesses to assess their carbon emissions; following recent changes in legislation and regulations on environmental impacts of construction activities. The aim of this paper is to develop a methodology that can offer businesses a carbon Life Cycle Assessment (LCA) tool to identify emissions "hotspots" across its value chain, and inform a carbon reduction hierarchy.

The approach employed is based on the methodology described in the Publicly Available Specification (PAS2050) protocol. The objective of the method is to identify where the largest production of emissions exists and provides for the biggest potential reduction within routine highway maintenance processes. The developed methodology framework offers businesses the potential to make informed decisions in carbon terms, by identifying and prioritizing areas of potential emissions reduction.

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INTRODUCTION

There is a growing consensus that human activities contribute significantly to the increasing concentration of carbon emissions in the atmosphere. These activities cover both individual and industrial activities and their associated energy use *(Dlugolecki, 2003 United Kingdom, 2008).* This has raised a greater awareness and understanding of the environment, and has also called for a change in energy use and other activities that emit carbon; to ensure that future economic development is achieved within economic, social and environmental limits. This is reflected in the UK by a legislative commitment to reduce Greenhouse Gas production (GHG) by at least 80% by 2050 from 1990 levels *(Transport Research Laboratory Limited, 2010 United Kingdom, 2008).* This places legal obligations on all sectors (including construction) to reduce their emissions, and defines strategies to meet this obligation. Reducing carbon emissions in construction processes is highly desirable given their impact.

Furthermore, carbon emissions reduction is now becoming a contractual requirement and a major consideration in tender selection in both the UK and internationally, particularly for public sector clients. This emerging Key Performance Indicator (KPI) for new projects has placed the construction industry under pressure, particularly the civil infrastructure maintenance sector, to assess and reduce emissions. In the past, businesses wanting to assess their emissions have usually done so by focusing on activities under their immediate control, but recently, customers have required businesses to assess their emissions across their value chain. This is driven by the increasing demand for low-carbon goods and services, and the need to make cost-effective investment decisions in carbon terms. The broader strategy by which this demand can be met in construction reach deep into every aspect of the built environment. This presents the construction industry with great business opportunities as well as challenges not simply in terms of immediate business opportunities, but also on long term business standing. The shift in the emissions assessment paradigm promotes the emissions Life Cycle Assessment (LCA) approach that will allow businesses to make an informed decision on emissions reduction.

The Innovation and Growth Team (IGT) – (a team drawn from across the UK's construction industry and public sector) was commissioned by the Department for Business, Innovation and Skills (BIS) to undertake a strategic review of the UK's construction industry and its capacity to rise to the challenge of the low carbon agenda. Key conclusions from the review suggested that the development of a new construction design paradigm supported by new carbon evaluation tools/methodologies that can account for emissions across the construction supply chain is essential *(United Kingdom, 2010).* The lack of accurate construction emissions inventories, consistent methodology and relevant industrial data have thus been seen as a key challenge to developing any robust carbon emission evaluation methodology *(United Kingdom, 2010).*

The need to adequately meet legal and clients' requirements, and other broader issues around energy, and materials efficiency in construction to deliver low-carbon services is a long term but pressing issue, and there is a need to develop an emissions LCA methodology that can inform cost-effective investment decisions on emissions reduction. A review of the existing carbon emissions assessment methodologies demonstrate that there is little or no evidence that such an overarching methodology exists within the civil infrastructure maintenance sector**.** Therefore, the purpose of this paper is to develop a framework methodology that can offer a Life Cycle Assessment (LCA) technique to identify areas of emissions "hotspots" and opportunities for carbon reduction and inform a reduction hierarchy. A LCA methodology based on the Publicly Available Specification (PAS2050) standard is presented. The methodology is specific to road maintenance (e.g. Road Resurfacing).

This paper provides a literature review, scope, definitions and system boundaries for the life cycle emissions assessment study, and subsequent development of the integrated methodology based on the British PAS2050 standard (an independent standard) specific to civil infrastructure maintenance. A case study is undertaken to demonstrate the implementation of the methodology, using data collected from road resurfacing schemes carried out in an urban environment. Although, emphasis within the paper is on civil infrastructure maintenance services delivery processes, the methodological approach can also be applied in other sectors within the built environment for emissions assessment purposes.

PRIOR STUDIES ON EMISSIONS ASSESSMENT METHODOLOGIES

Previous studies on construction emissions inventories have been on construction materials and waste management. This was primarily due to the growing debate on materials efficiency *(Waddell, 2008)*. Currently, in the UK's construction sector, the methodology commonly used to estimate materials embodied carbon is the Inventory of Carbon and Energy (ICE) methodology produced by Bath University (UK) in collaboration with the Carbon Trust *(Hammond and Jones, 2011 Transport Research Laboratory Limited, 2010)*. The approach defines a material's embodied carbon as an estimated value of the quantity of emissions expressed in kgCO_2e per kg of the material, associated with raw materials extraction; processing and manufacturing, and transportation. The methodology promotes a life cycle emissions assessment technique with boundary conditions consistent with ''Cradle-to-gate''. The inventory introduces data sets that can estimate embodied carbon associated with construction materials used in the UK. However, it was argued that the data sets need review with specific data; if the outputs are to be relied upon within the construction industry *(Hammond and Jones, 2011 Muench et al., 2009)*.

A number of complementary inventory studies have been conducted to develop construction vehicle and equipment emission inventories over their duty cycle. These include the works by Lewis et al (2009) and Rasdorf et al (2009) *(Lewis, 2009 Rasdorf, Jun. 2009)*, aimed at developing a methodology for construction vehicles emissions inventory that can inform a reduction strategy. Although, the methodology provides foundational standard procedures for capturing fuel use by construction fleets and management strategy to inform emissions reduction decisions, the methodology excludes emissions data from materials suppliers; thus failing to promote the full emissions LCA approach.

The UK government and industry-led initiative "Strategy for Sustainable Construction" has set targets to reduce emissions from construction activities by 15% compared to 2008 by 2012, and reduce all construction and demolition waste sent to landfill by 50% by 2012, compared to 2005 levels, and zero waste to landfill by 2020 *(United Kingdom, 2008)*. To contribute towards meeting these targets, the Strategic Forum for Construction (SFfC) commissioned a carbon subgroup in 2010 to undertake a study and develop an action plan for emissions reduction from construction activities and associated transport.

The study primarily focused on emissions associated with: On-site activities and accommodation, transportation and corporate offices *(Joan, 2010)*, but said nothing on emissions associated with construction materials, waste management and project owners/user. However, these emissions categories are fundamental to the ideals of a true and accurate LCA emissions assessment. Other contributing works to meeting these targets include studies by the UK's Waste Resources Action Programme (WRAP), commissioned to promote emissions reduction through the use of recycled and secondary aggregate in construction, and enhance resource efficiency *(United Kingdom, 2010)*. These studies showed that choosing less energy intensive construction techniques, selecting sources of aggregates closer to site, opting for green transport, and the use of recycled and secondary aggregates can reduce emissions, whilst conserving natural resources and minimizing waste *(Durucan and Korre, 2009 Hammond and Jones, 2011 Transport Research Laboratory Limited, 2010)*. An extended WRAP LCA emissions assessment methodology has been developed by Thomas et al *(Thomas et al., 2009)* to assess construction materials sourcing options in carbon terms, and evaluate the emissions impact of previously unconsidered factors such as materials quality and local conditions (e.g. road transport congestion) in the initial WRAP methodology. The study revealed emissions from construction materials sourcing do not only depend on material type, but also local conditions *(Thomas et al., 2009)*. This conclusion concurred with the outcome of a life cycle study conducted in Finland by Mroueh et al *(Mroueh et al., 2001)* on road construction materials characterization; which indicates that construction materials production and transportation produces the most significant environmental burden.

A review of existing studies on life cycle emissions assessment methodologies demonstrates that complexities exist in business emissions assessment. These complexities are further compounded following issues around emissions allocations; lack of robust methodologies and relevant industrial data, and the insufficient analytical rigor showed by the above studies to support businesses in making an informed decision and develop an emissions management strategy across the supply chain. However, the existing studies do indicate that the use of more sustainable practices and materials in the construction process and products has a profound impact on emissions reductions.

The Publicly Available Specification (PAS2050) LCA methodology standard developed by the British Standard Institute (BSI) in 2008; in collaboration with the Department for Environment, Food and Rural Affairs (DEFRA) and the Carbon Trust has shown sufficient analytical rigor to address the above complexities associated with business emissions assessment. *(British Standards Institute, 2008)*. It's robustness is inherent in the significant inputs received from international stakeholders, experts across academia, businesses, government and non-governmental organizations (NGOs), through formal consultations and multiple technical working groups *(British Standards Institute, 2008)*. The approach has been tested through diverse business streams and has proved to be robust. To widely integrate this LCA concept into construction processes and its value chain, the development of a new and integrated emissions assessment methodology framework within construction is imperative; this paper now presents the framework development process based on this PAS2050 LCA and its application in road maintenance works in an urban environment.

THE FRAMEWORK DEVELOPMENT PROCESS

This section presents the background to PAS2050 standard, the LCA methodology framework and scope definitions and system boundaries. The three stages and five basic steps to implement the LCA methodology framework defined in Figure 1 are further discussed.

Background to PAS2050

PAS2050 was developed by British Standard Institute (BSI) *(British Standards Institution, 2011 Sustain Limited, 2010)* to produce a consistent and robust method of assessing life cycle emissions for goods and services. It forms an independent standard, enhancing methods created in the ISO14040 and ISO14044 LCA protocols *(British Standards Institution, 2011)*.

It offers an iterative process where the scope and objectives of the assessment are defined, relevant data are collected these are analyzed and interpreted within the scope and system boundary and data quality defined by the standard.

The Methodology Framework

The framework presented is divided into the life cycle stages and an iterative three stage process. The life cycle stages help users to define and build a representative process map for emissions assessment, while the iterative element (Start-up, Service emissions calculation and Results) defines and outlines the five steps to enable the service to be evaluated in carbon terms. Figure 1 presents the LCA methodology framework developed which is specific to civil infrastructure maintenance operations (particularly for highways).

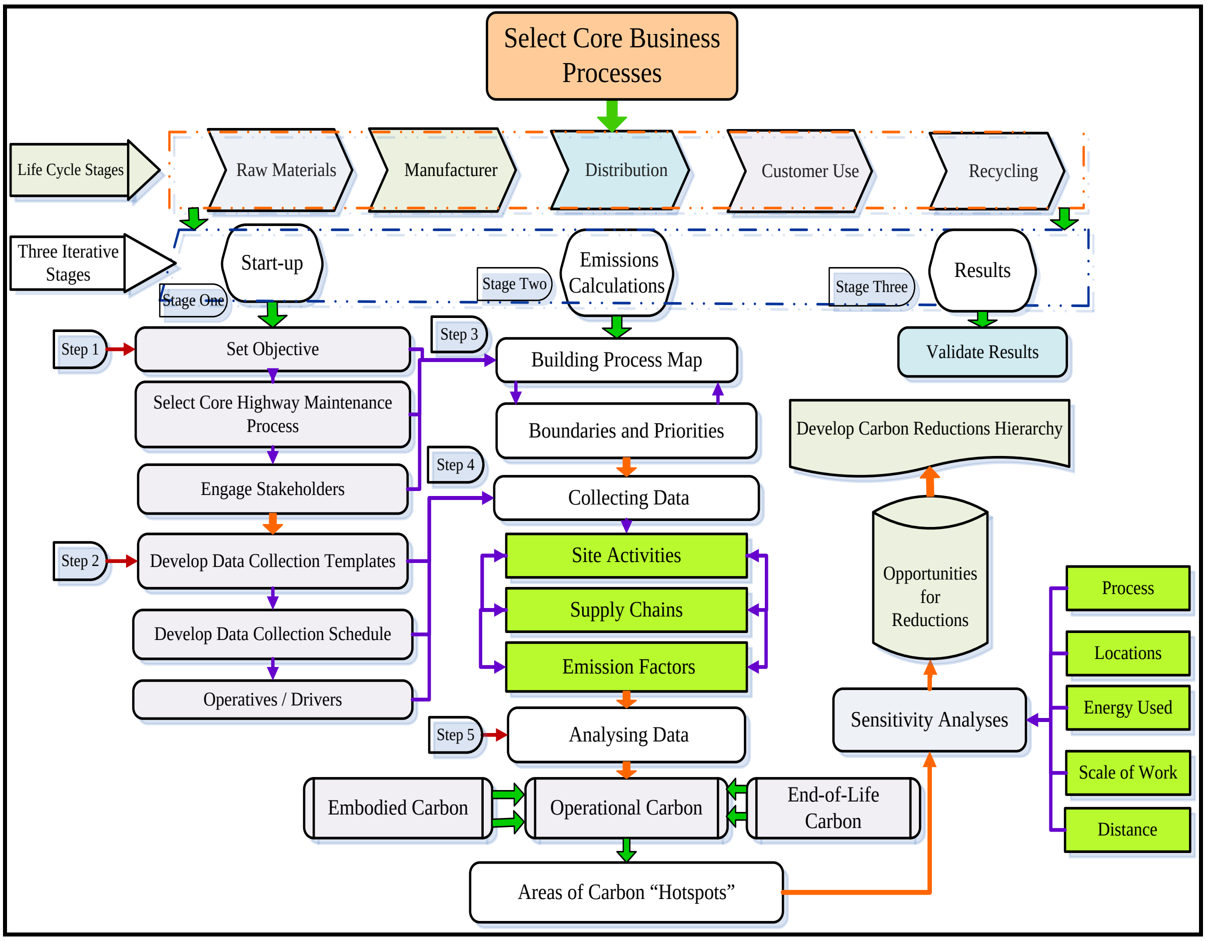


Figure 1 LCA methodology framework to evaluate road maintenance emissions inventory

Scope Definitions and System Boundaries within the Model

Defining system boundaries and the scope of emissions assessment have been key challenges when developing emission frameworks. Within the PAS2050 approach, these challenges have been addressed through the definition of two types of model for LCA studies, namely: the Business-to-Customer (B2C) model – where the customer is the end user of the product (this model is consistent with the "Cradle-to-Grave" boundary condition), and the Business-to-

Business (B2B) model - where the customer is another business using the product as input into its own process. This model is consistent with the “Cradle-to-Gate” boundary condition *(British Standards Institute, 2008)*. The application of PAS2050 LCA methodology to both models in service emissions assessment covers both direct and indirect emissions which include embodied, operational and end-of-life carbon emissions.

The embodied carbon defines the energy consumed in raw material extraction, transportation to the factory, the product manufacturing process and transportation to the customer’s gate (B2C model). Operational carbon category defines the energy consumed (e.g. fossil fuel) by operatives travel and site operations, while the end-of-life carbon accounts for the energy consumed during waste transportation, processing and recycling. The summation of these carbon emissions categories from a life cycle perspective is referred to as the service Carbon Footprint (CF).

Stage One: Start-up within the Framework

Step 1

Setting Service Objectives - Defining and agreeing specific objectives prior to commencing the emissions assessment agenda can create direction with respect to the scope, boundaries and data required for assessment *(British Standards Institute, 2008)*. Adequate stakeholder engagement is imperative to define the objectives, processes to be assessed, data type required, data collection and a programme of action.

Selecting Core Highway Processes - Core highways maintenance and management processes can be selected across various locations for emissions assessment. These include, but not limited to: road resurfacing works, bulk lamp/lantern change, line marking, patching and grass cutting/ litter picking.

Engaging Stakeholders - Adequate stakeholder engagement is crucial to understanding business service emissions and the interface that exist between the service and its supply chains. Conventionally, a stakeholder (internal and external) engagement plan is required early to define objectives, scope, expected business benefits and allocate responsibilities to enhance the data collection process and address issues around safety/legal/commercial confidentialities.

Step 2

Developing Data Collection Templates and Schedule - Both quantitative and qualitative data collection templates are useful to ensure a consistent and formalized data collection approach. The quantitative templates should focus on data around site locations, materials inputs and suppliers, fuel consumed by vehicles and equipment, (during waste processing and recycling), while the qualitative templates should focus on capturing expert’s opinions on the emissions agenda within the context of their day-to-day jobs. This data set can be used as a basis to compare and justify results. Prior to site data collection, it is crucial to assure those involved of the following:

- Data collection procedures will not interrupt the daily operatives’ productivity.
- Number of site visits per process per location should be specified and agreed.
- Site safety rules and requirements will be obeyed.

Operatives - Site operative's cooperation will help with the daily site specific information particularly on materials inputs; waste generated and amount of fuel consumed on site per scheme.

Stage Two: Service Emissions Calculations

Step 3: Building Process Map, and Review Boundaries and Priorities

The aim of this phase is to identify all processes, activities, tasks and associated data inputs that are relevant to undertake emissions assessment in life cycle terms. To model complex scenarios of real-world problems, the Integrated Definition Language (IDEF0) and process decomposition techniques are employed *(Koskela, 1992).* These techniques are employed within this paper, and involve breaking down selected business processes into levels of granularity, where the lower–levels define corresponding upper-level processes *(Cooper R. et al., 2005).* Road resurfacing was selected as an example; as part of a wider study to produce carbon emissions inventory for routine highway works. This activity was divided into its life cycle stages, activities and tasks levels in order to evaluate its emissions in life cycle terms. The embodied, operational and end-of-life carbon categories were estimated, which help to identify areas of emissions hotspots across the predefined boundary condition (Cradle to end-of-life). Figure 2 below presents the road resurfacing process map that fits the framework defined in Figure 1.

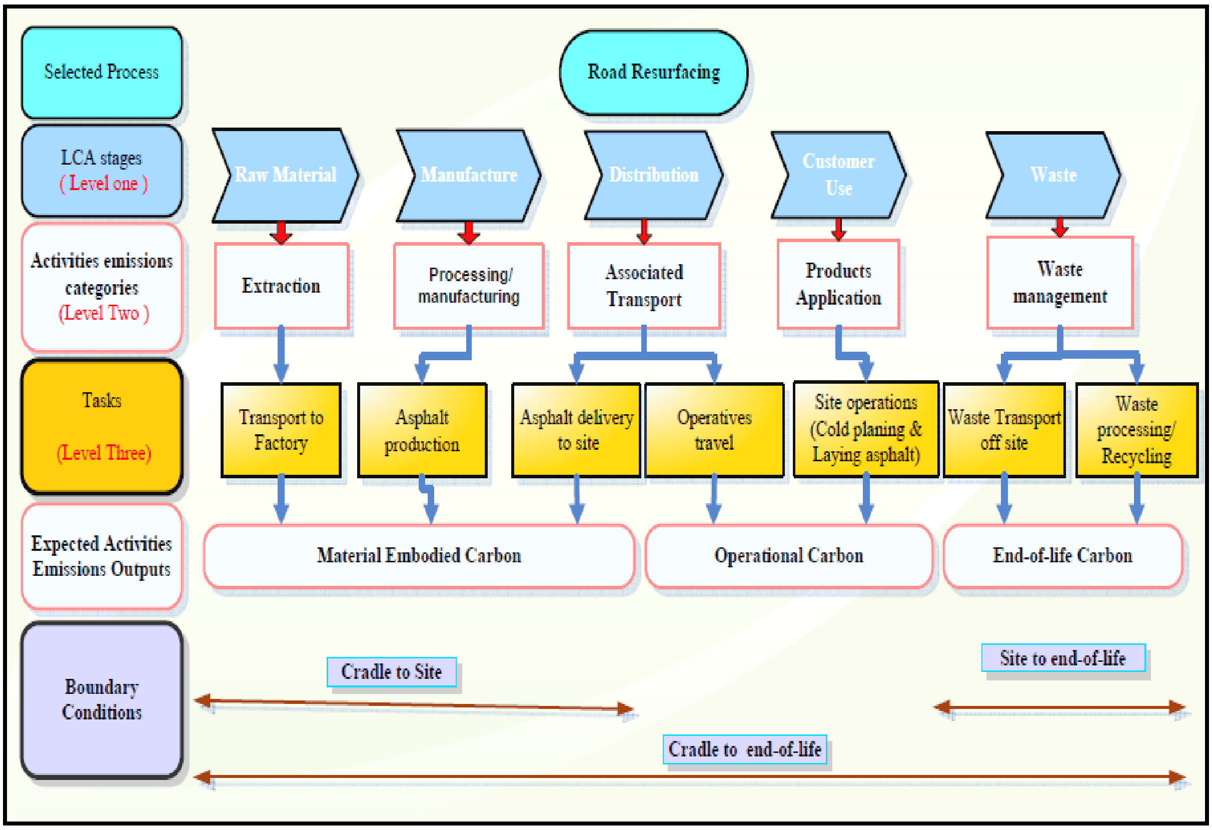


FIGURE 2 process map for road resurfacing process.

The process map is structured into three different levels, expected outputs and boundary conditions.

- **Level One**: Outlines the life cycle stages for the selected service process (road resurfacing work) to enable a full emissions life cycle assessment to be undertaken.
- **Levels Two and Three**: Defines the various activities and tasks relevant to assess the life cycle stages in carbon terms. Level two indicates the activity-oriented data to evaluate the various emissions categories (Embodied carbon, Operational carbon and End-of-life carbon), while level three allows the expected emissions outputs of the emissions categories to be analyzed to identify areas of emissions hotspots across the road resurfacing process value chain.
- **The expected emissions outputs and boundary conditions** define the emissions assessment results and the boundary conditions that underpin the assessment.

Step 4: Data Type, Collection Procedures and Quality Assurance Measures

The PAS2050 emissions assessment approach recommends that primary activities data and emission factors are required to calculate the service or product Carbon Footprint (CF) *(British Standards Institute, 2008).* Within this case study, data, in its appropriate units in terms of materials used (one kilogram of material) and fuel (liters) consumed by vehicles (for both outgoing and return journey), site equipment, waste processing and the recycling process were collected.

The scale of work undertaken was measured directly on site and the design specification of material types identified. The total daily materials deliveries and distance covered from the manufacturing plant; including return journey were obtained from the suppliers' delivery tickets. Figure 3 presents an approach that enables the daily amount of fuel consumed to be accurately measured. Site waste transfer notes provide information on total waste (planings) generated on site in tonnes, and distance covered from site to recycling plant including return journey. These data sets were entered into the quantitative data templates and later transferred into an Excel Spreadsheet. Material manufacturers and waste recycling companies provided information on the embodied energy and carbon associated with materials manufacture, their delivery to customer's gates, and energy use for waste processing and recycling.

Fuel-based emission factors were selected from publicly available emission factors databases *(7, 20).*

During field data collection, measures were taken to ensure PAS2050 data quality rules are met with concern given to their completeness, consistency, reproducibility and source *(British Standards Institution, 2011)*, whist minimizing data errors such that:

- The recorded volume of materials (e.g. asphalt) used on site were compared with the quantities from contract documents and invoices.
- Materials manufacturers were allowed to collect primary data, and estimate their embodied carbon based on the quantity of material supplied to site.
- For limited cases where operatives failed to follow the data collection approach presented in figure 3, particularly site fuel usage; such operations were excluded from the data collection exercise.
- Accompanying each data sets are the names of the road maintenance schemes, site locations and nature of work undertaken.

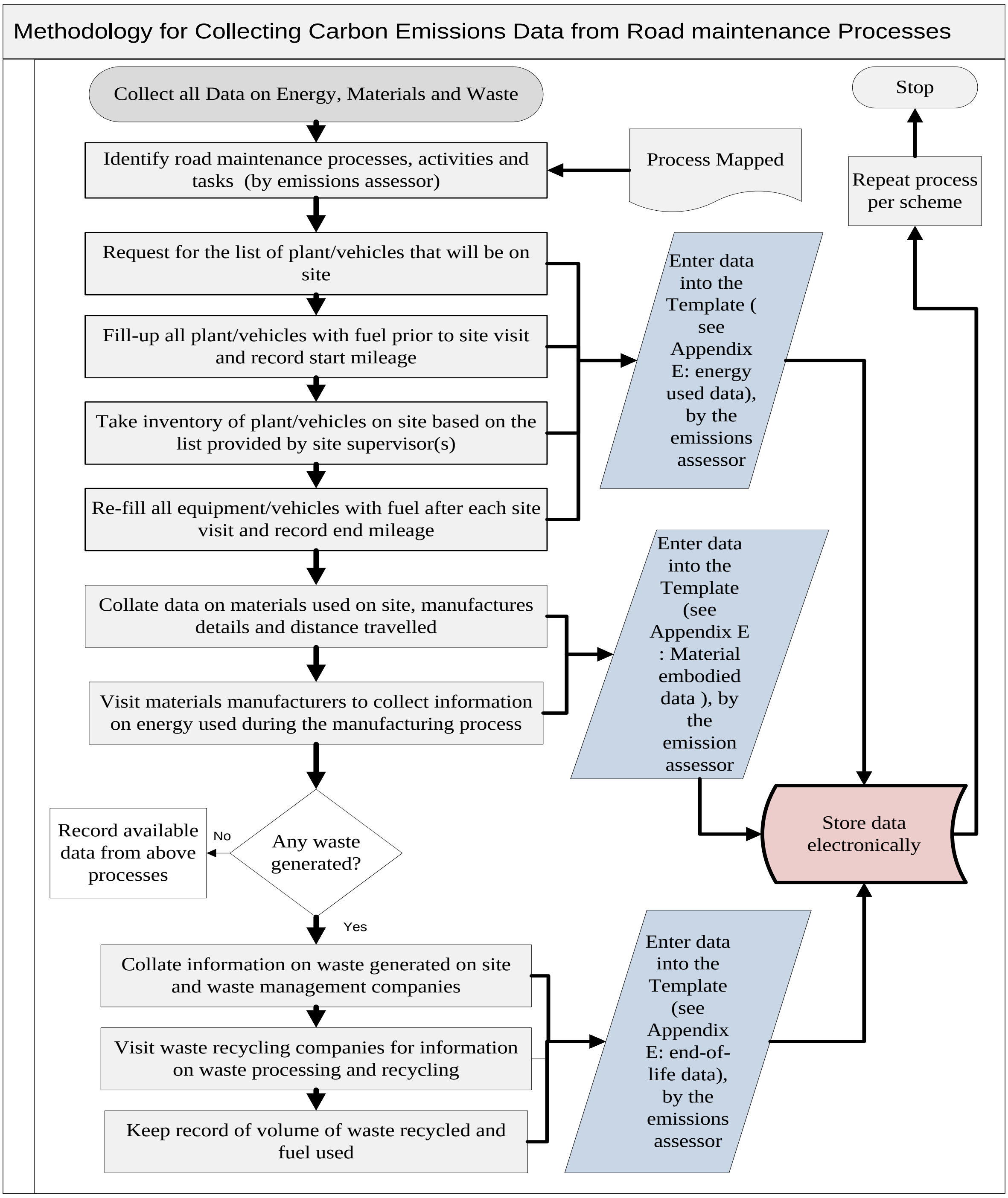


Figure 3 presents a field data collection methodology flowchart to ensure that the data quality rules are met.

Step 5: Data Analysis

Equations 1, 2 and 3 can be employed to calculate embodied, operational and end-of-life carbon emissions associated with construction activities.

$$\text{Embodied carbon}\,(\Phi) = \sum_{i=1}^{i=w} [\mathrm{E}]iw \times \mu \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathit{(1)}$$

$$\text{Operational carbon}\,(\Omega) = \sum_{j=1}^{j=n} [\mathrm{H}]jn \times \lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathit{(2)}$$

End-of-Life carbon $(\Psi) = \sum_{k=1}^{k=z} [\Pi] kz \times \lambda$ ……………………....................................... *(3)*

Total Carbon Footprint $(CF) = (\Phi) + (\Omega) + (\Psi)$…………………………….…….. (*4)*

$\sum[\mathrm{E}]$ = Sum of i^{th} energy consumed during raw materials acquisitions, materials manufacturing, transportation to w^{th} customers gates.

μ : The appropriate emission factors from publicly available databases.

$\sum[\mathrm{H}]$= Sum of total energy consumed by n^{th} equipments and vehicles during their duty cycle on j^{th} sites.

λ : The appropriate emission factors from publicly available databases.

$\sum[\Pi]$ = Sum of total energy consumed to transport, processed and recycled z^{th} tonnes of waste generated from k sites.

(CF): The sum of emissions categories outputs. This represents the total Carbon Footprint (CF) per project.

CASE STUDY: ROAD MAINTENANCE WORKS

As part of the framework development and improvement a case study was undertaken. The aim was to demonstrate industrial implementation of the methodology developed. Four road resurfacing schemes of different areas and site locations were selected in an urban environment to allow comparability of emissions assessed and identify where emissions hotspots exist within the highway routine maintenance process. The road resurfacing activities within the four schemes included: planing-off of existing road surfaces to a nominal depth of 100mm and reinstating the planed surfaces with a thin layer of tack coat (K140), 60mm AC 20 HDM BIN40/60 DES binder course and 40mm surface course. Table 1 provides a brief overview of the selected road maintenance schemes, the nature and scale of work undertaken.

TABLE 1 Brief Overview of Selected Road Maintenance Schemes.

Location	Nature of work	Depth (mm)	Total area (m^2)	Quantity of Asphalt (tonnes)	Distance to site (a trip) (miles)	Number of trip (19.99 tonnes per trip)	Quantity of Tack Coat K140 (Liters)	Quantity of Polymer Modified Bitumen (kg)	Total Waste generated (tonnes)
Urban	Deep planing/inlay	100/40	2945	758	60	38	2062	200	600
	Deep planing	100	2593	294	58	15	1493	125	220
	Deep planing	100	1284	290	57	15	642	25	195
	Deep planing/inlay	100/40	1024	237	56	12	512	25	90

Data Analysis

To ensure clarity of results associated with the case study data analysis, two analysis modes were developed: the activity-oriented and task-oriented mode. The activity-oriented mode defines the Embodied Carbon, Operational Carbon and End-of-Life Carbon, and the task-oriented mode defines asphalt production and transportation to the customers' gate, operatives travel, site operations, waste transport off-site, waste processing and recycling. (see Figure 2). By using equations 1, 2 and 3, (above) emissions were evaluated quantitatively in terms of carbon. The fuel-based emission factors selected from the publicly available databases (2.6720kgCO_2e per liter and 2.71780kgCO_2e per kg) were used to convert the primary data (e.g. tonnes of materials and waste, liters of fuel consumed) into their corresponding kilogram of carbon dioxide equivalent, expressed in kgCO_2e *(Hammond and Jones, 2011 United Kingdom, 2010)* Fuel-based emission factors were selected instead of time-based emission factors since they are less sensitive to site variables *(Frey et al., 2008)*. A sensitivity analysis was further undertaken during the case study to identify relevant exploratory variables for emission rates that can inform emissions reduction decisions. Variables identified were material haulage distance to site (miles), congestion, and number of deliveries to site, average distance travelled by operatives (miles) and scale of work undertaken. This approach allowed emission hotspots to be identified within the case study in terms of life cycle and associated opportunities for a reduction to inform a reduction hierarchy

RESULTS AND DISCUSSION

In terms of the four roads maintenance schemes based on the framework methodology developed the results are summarized into the activity-oriented mode analysis, task-oriented mode analysis and exploratory analysis (sensitivity).

Activity-Oriented Data Analysis

This analytical approach allows the embodied carbon, operational carbon and end-of-Life carbon associated with the four schemes to be estimated. Site activities and tasks carbon emissions analyses are presented in Table 2. The percentage averages of each activity-oriented mode compared to the overall Carbon Footprint (CF) is presented in Table 2a. These results indicate that materials embodied carbon accounts for on average 79.08% of the total CF, irrespective of the scale of work undertaken and material supplier, whilst operational carbon and end-of-life carbon accounts for an average of 13.36% and 7.56% respectively. These results suggest that embodied carbon value is not just a function of the material type (quality), but also materials quantity, haulage distance and local conditions (e.g. consequential congestion).

Task-Oriented Data Analysis

The task-oriented analysis approach allows the road scheme activities emissions to be further analyzed to identify areas of emissions hotspots that can inform the emissions reduction decision and prioritized reduction efforts. Asphalt production was found to account on average for 98% of the total materials embodied carbon and its transportation with other materials accounting for the 2% of the embodied carbon. Analysis of Table 2b reveals that asphalt production accounts for 75%, Site operations: 8.4%, waste transportation: 6.9%, operatives travel: 5%, asphalt delivery: 4%, waste processing and recycling (into secondary aggregate) produces 0.7% respectively compared to the schemes total Carbon Footprint (CF): 27538kgCO_2e. These results confirm the key findings of Durucan and Korre's *(Durucan and Korre, 2009)* LCA study on road construction materials characterization; which conclude that construction materials production and transportation produce the most significant environmental burden.

Exploratory Analysis

An interpretation of the case study results indicate that there is a significant increase in emission rates per mile travelled for vehicles carrying load (e.g. Delivering materials or equipment to sites) compared to vehicles not carrying a load. This increase in emission rates is attributable to the fuel type (diesel) used to estimate the schemes transport emissions. Diesel produces a significant increase in emission rates at high engine combustion rates due to loading and congestion.

Table 2c shows that an increase in emission rates has a significant correlation with an increase in distance to site, materials haulage distance and numbers of material deliveries to site, particularly in an urban environment. This correlation is primarily due to the fuel type (diesel) used for the emissions assessment and the impact of congestion. For example, the asphalt delivery to site and waste transport off-site produces emission rates of an average of 19.1kgCO_2e/trip and 23.9kgCO_2e/mile for a mile increase in distance between sites, and 0.003kgCO_2e per tonne of asphalt per mile and 0.0823kgCO_2e per tonne of waste transported off-site while operatives' travel produces average emission rates of 9.84kgCO_2e/mile for an average distance (128miles) travelled.

TABLE 2 Carbon Analysis of Tasks

Table 2a: Analysis of Activity-oriented mode contributions to road maintenance total Carbon Footprint (CF)

Activity-oriented mode analysis to calculate each emissions categories and total CF															
Area (m^2)	Quantity of asphalt (tonnes)	Quantity of Tack Coat K140 (liters)	Polymer Modified Bitumen (kg)	Materials Embodied Carbon (MEC) ($kgCO_2e$)	Operational Carbon (OC) ($kgCO_2e$)	End-of-Life Carbon (ELC) ($kgCO_2e$)	Carbon Footprint (CF) ($kgCO_2e$)	A-MEC ($kgCO_2e$)	A-OC ($kgCO_2e$)	A-ELC ($kgCO_2e$)	Average (CF) ($kgCO_2e$)	% A-MEC to CF	% A-OC to CF	% A-ELC to CF
2945	758	2062	200	38070	7810	4570	50450	21778	3678	2083	27538	79.08	13.36	7.56
2593	294	1493	125	23340	2870	1620	2783							
1284	290	642	25	11360	1924	670	13954							
1024	237	512	25	11360	1924	670	13984							

Note: **A-MEC**: Average Materials Embodied Carbon, **A-OC**: Average Operational Carbon, **A-ELC**: Average End-of-Life Carbon: **CF**: Carbon Footprint

Table 2b: Task-oriented mode analysis to identify areas of significant emissions

Task-oriented mode analysis to evaluate areas of emissions Hotspots													
Area (m^2)	AP emissions ($kgCO_2e$)	AD emissions ($kgCO_2e$)	Tack coat K140 & Bitumen emissions ($kgCO_2e$)	OT emissions ($kgCO_2e$)	SO emissions ($kgCO_2e$)	WT emissions ($kgCO_2e$)	Waste processing & Recycling emissions ($kgCO_2e$)	% Average AP emissions to CF	% Average AD emissions to CF	% Average OT emissions to CF	% Average SO emissions to CF	% Average WT emissions to CF	% Average of waste (P&R) emissions to CF
2945	35800	2270	472	3108	4703	4168	401	75	4	5	8.4	6.9	0.7
2593	22379	960	336	1042	1828	1470	147						
1284	13642	698	136	786	1320	1336	134						
1024	10818	542	120	556	1368	607	67						

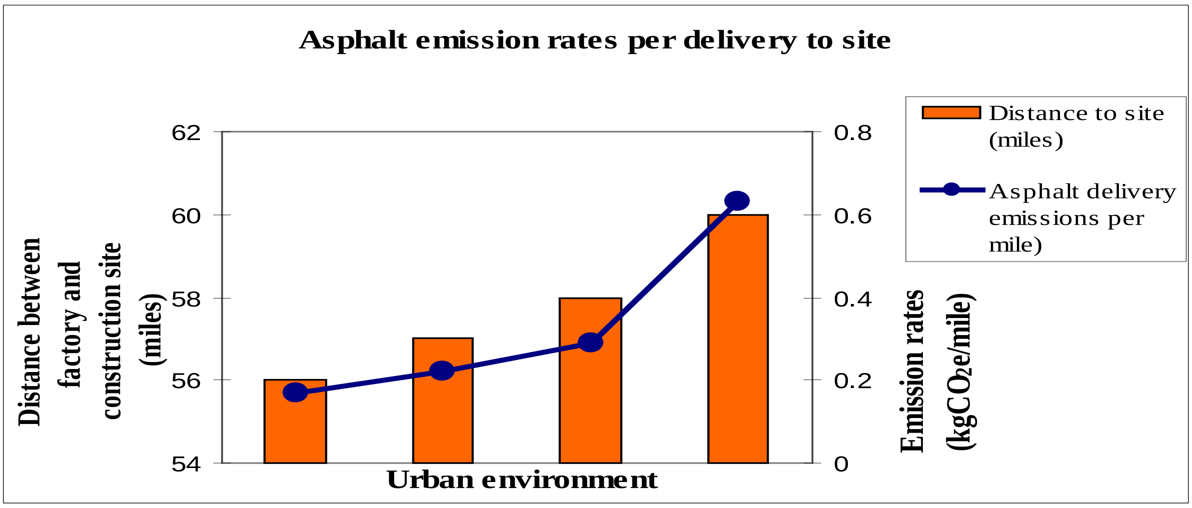
AP: Asphalt production, **AD :** Asphalt Delivery, **OT :** Operatives Travel , **SO:** Site Operations, **WT :** Waste Transport, **P&R :** Processing and Recycling, **CF:** carbon Footprint

Table 2c : Evaluations of Emission rates associated with the task-oriented mode

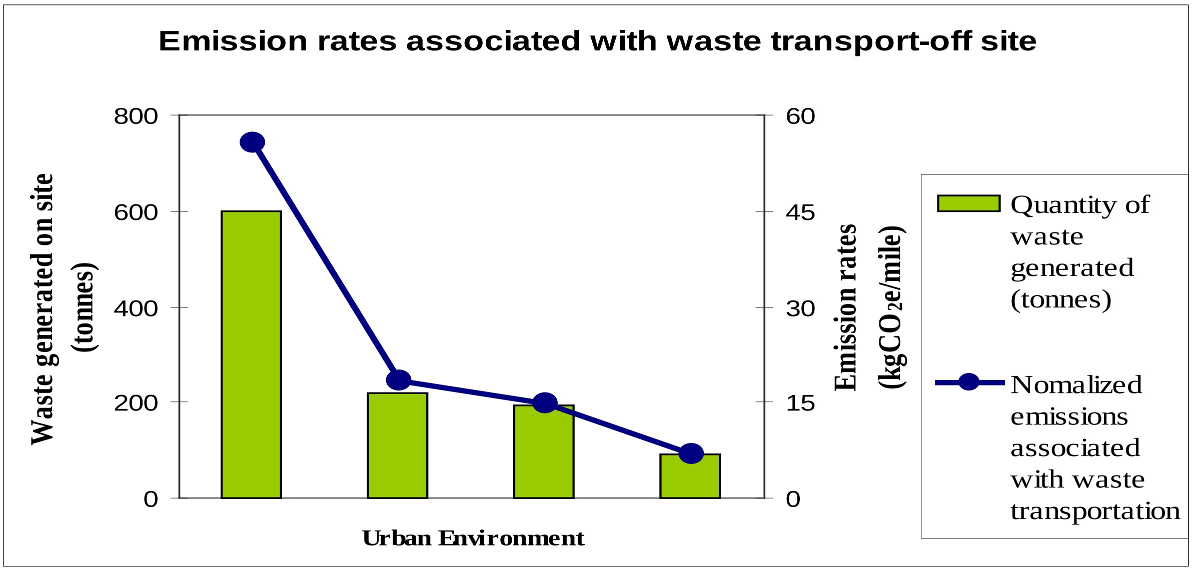
Exploratory analysis of emissions categories to produce emission rates																
Area (m^2)	Quanity of asphalt delivered (tonnes)	Distance per trip (miles)	Number of trips	Total distance covered by asphalt (miles)	AD emissions ($kgCO_2e$)	AD emission rates ($kgCO_2e$/trip)	AD emission rates ($kgCO_2e$/tonne)/mile)	Average OT (miles)	OT emissions ($kgCO_2e$)	OT emission rates ($kgCO_2e$/mile)	Road planing emissions ($kgCO_2e$)	Road planing emission rates ($kgCO_2e/m^2$)	Waste (tonnes)	Average distance covered by waste (miles)	WT emission rates ($kgCO_2e$/mile)	WT emission rates ($kgCO_2e$/tonne)/mile)
2945	758	60	38	2280	2270	37.83	0.001	217	3108	14.32	1015.40	0.35	600	75	55.6	0.093
2593	294	58	15	870	960	16.55	0.004	146	1042	7.14	454.24	0.18	220	80	18.4	0.084
1284	290	57	15	855	698	12.46	0.003	83	786	9.47	390.11	0.30	195	90	14.8	0.076
1024	237	56	12	684	542	9.51	0.003	66	556	8.42	240.48	0.24	90	89	6.8	0.076

AD: Asphalt delivery to site (including return journey); **OT:** Operatives Travel and **WT:** Waste transport off site (including return journey)

These results tally with key conclusions from Thomas et al (2009) LCA study *(Thomas et al., 2009)* which aimed to assess aggregates sourcing options. It revealed that emissions associated with construction materials sourcing do not only depend on material type, but also local working conditions. In addition to the above examples, Figures 4a & 4b reveal that emission rates associated with construction material delivery or waste transportation off site, increases with an increase in distance between site and material manufacturing plant, and waste recycling facilities and the site. Further exploratory analysis on the scale of work impact on site operations emission rates, in Table 2c reveals that road planing emission rates (average of 0.268kgCO_2e/m^2 and 1962 m^2) increases as expected; with an increase in the scale of work (increase in areas and depth of road surfaced planed).



(4a)



(4b)

FIGURE 4 Transport emission rates

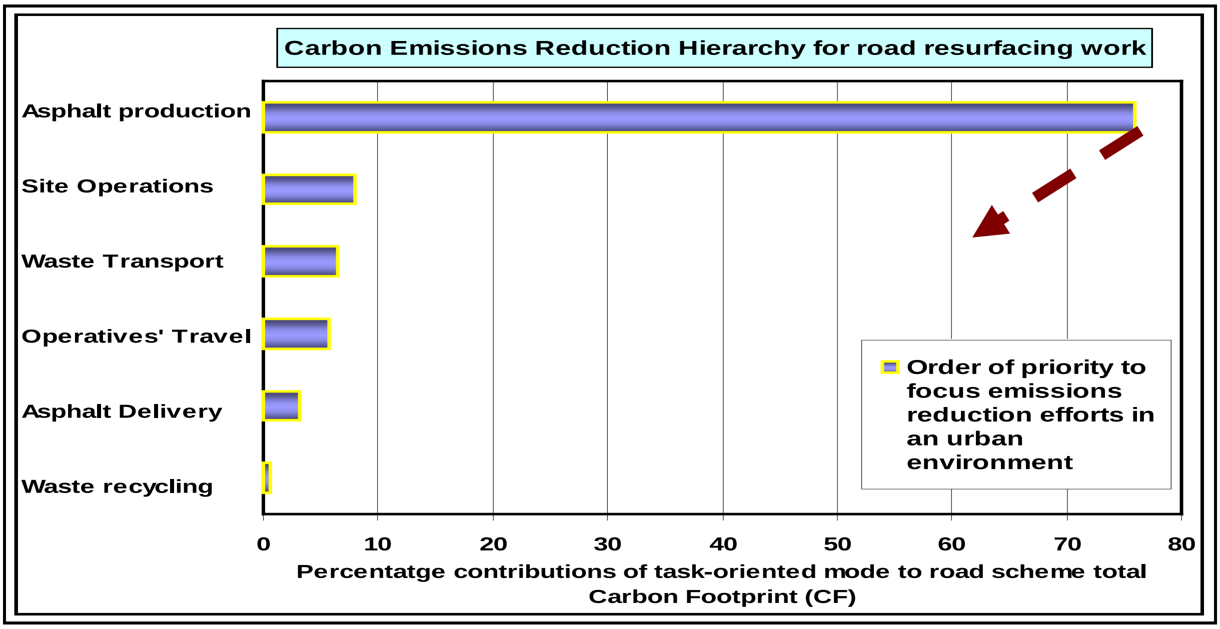


FIGURE 5: Emissions Reduction Hierarchy for road maintenance in an urban location

Carbon Emissions Reduction Hierarchy

Detailed assessment of the data analyses and discussions above provide the basis upon which the carbon emissions reduction hierarchy in Figure 5 is developed. The hierarchy of reduction is expected to provide road designers, managers and planners the knowledge framework to support emissions reduction investment decision-making, and enable efforts to be prioritized. The emissions reduction hierarchy presented in this paper is specific to road resurfacing work carried out in an urban environment. The order of priority - where to focus emissions reduction efforts may change slightly if a similar scale of work is carried out in a different environment (such as rural or semi-urban location).

CONCLUSIONS AND RECOMMENDATIONS

This paper has presented the development of a framework based on LCA methodology described in PAS2050. Although, the application of the framework methodology developed in this paper relates to road maintenance, the approach can also be used for other highway construction schemes so as to identify areas of emissions hotpots and develop a reduction hierarchy.

This study has aimed to address significant gaps in the current body of knowledge in relation to business emissions assessment methodology. It presents a methodology that can provide the civil infrastructure maintenance sector with a LCA tool to assess their business environmental performance to inform decision-making across its whole value chain in turn. To enhance comparability of emissions assessed, the area of emissions hotspots and associated emissions reduction hierarchy for four road maintenance schemes carried out in an urban location have been presented.

The process map developed allows the activity-oriented and task-oriented emissions modes to be evaluated. The case study results reveal the methodology has the potential to identify areas of emissions hotspots, and opportunities for reduction. It offers a robust tool that can allow businesses to accurately understand their carbon expenditure, and inform an emissions reduction strategy to enhance their competitiveness. The case study reveals that asphalt production (site operations, waste transportation, operatives travel and asphalt delivery are relatively minor) is the sole area of maximum carbon usage, and important aspects in sustainability decisions for road designers, managers and maintainers, to enable them to priorities emissions reduction.

Energy efficiency in material production, selecting less energy intensive construction methods and adequate site logistic planning are critical for highway maintenance to meet both environmental and business risks, and opportunities to manage competitiveness in a "carbon conscious" business environment.

Recommendations below are informed following the experience gained during the site data collection. These include:

- An effective business stakeholder engagement strategy to develop a representative process map to support field data collection, and allow businesses to accurately understand the emissions interfaces that exist between the businesses and avoid double carbon emissions accounting.
- To adequately improve site carbon emission data gathering, it is crucial to allocate responsibilities across the business value chain to prevent data quality problems, and ensure that representative emissions data are collected to build a robust emissions information for business sustainable procurement decision-making.
- Emission factors convert measured and estimated quantities (data) into their corresponding emissions value. Fuel-based emission factors are recommended where available for process emissions evaluation. These factors are less sensitive to site variability compared to time-based emission factors.

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APPENDIX C : ENGD PAPER 3

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Highway Routine Maintenance Carbon Emissions Assessment

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Abstract: Civil infrastructure, including the highway maintenance sector is under increasing pressure to deliver low-carbon services, since the sector consumes a significant amount of resources, is energy intensive and is a large Greenhouse gas (GHG) emitter. As such, reducing the carbon footprint from this sector can help contribute towards meet the reduction targets set under the Kyoto Protocol. The enactment of the UK's Climate Change Act, carbon emissions reduction is now a legal requirement, and as such infrastructure customers now require its supply chains via contractual obligations to provide carbon footprint information relating to work done or being tendered for. Carbon footprint consideration and reduction in business decisions is attracting growing attention. There is a real and pressing need for a new, more holistic project specific carbon footprinting approach that can account for carbon in an integrated manner (including carbon from supply chains), identifying areas of carbon hotspots and developing a reduction hierarchy to support business decision-making.

This paper presents the application and results of a process-based carbon footprinting framework based on the PAS2050:2011protocol. The results of case studies (focusing on the carbon footprint) of 'typical' UK highway maintenance processes are presented namely: pavement resurfacing, pavement marking, bulk lamp change and grass cutting. These processes were selected across urban, semi-urban and rural site locations in order to investigate the significance of these locations on the carbon footprint. The results indicate the robustness of the PAS2050-complaint framework for highway maintenance carbon footprinting; identifying areas of carbon hotspots and related reduction opportunities that can inform the reduction hierarchy across the processes value chain. The research presented in this paper can be used as a framework to plan, evaluate and manage highway maintenance programmes, and carbon budgets over the maintenance processes value chain.

Keywords: Highway; Maintenance; Carbon Footprinting

1. Introduction

In today's environmentally conscious world, no industry can afford to ignore its ecological impacts and contribution to climate change (Zammataro, 2010). Within the context of the UK's Climate Change Act and the Carbon Reduction Commitment carbon emissions accounting, and reduction from the construction industry, encompassing the civil infrastructure sector will be a major consideration. The construction industry and its sectors have engaged with sustainability issues, and highway maintenance decisions are now being examined, not only on economic and technical grounds, but also from an environmental performance perspective (Hoang *et al.*, 2005 Zhang *et al.*, 2008) with a remit of delivering low-carbon highway maintenance. In the UK, carbon emission reductions are now being considered as contractual requirement and a major part of tender selection criteria particularly by public sector clients. In addition, highway owners are now looking for ways to include mandatory life cycle carbon emissions assessments in highway design, construction and maintenance projects (for example, the UK's Highway Agency and Local authorities). This emerging Key Performance Indicator (KPI) is putting the construction industry and the highway maintenance sector including their suppliers, under increasing pressure to measure and reduce their carbon emissions, given the associated business and Corporate Social Responsibility (CSR) image impacts.

As result of the increase in importance of carbon emissions assessment and reduction, the Life Cycle Assessment (LCA) methodology has been considered by the highway sector as a methodological approach (i.e. cradle-to-grave) that can measure its environmental aspects and potential impacts such as global warming, toxicity, acidification, and ozone formation respectively. As a subset, the Carbon Footprinting approach is often used to accounts for life cycle carbon assessment responsible for global warming impact only (Huang et al., 2012). The lack of a consistent and transparent industrial standard life cycle methodology has been a major challenge for highway owners, contractors, designers, managers and maintainers to assess the carbon footprint information associated with highway design, construction and maintenance in order to inform a credible reduction strategy.

Furthermore, a strategic review of the UK's construction industry and its capacity to meet the challenge of the low-carbon agenda, undertaken for the UK's Department of Business, Innovation and Skills (Department of Business Innovation and Skills, 2010) suggests a vigorous shift in the design of construction projects, and recognises the opportunities within the construction industry to drive innovation and growth that can meet the government's legally binding carbon reduction targets. These opportunities suggest a project-focused and process-based life cycle methodological approach should be developed, whilst complementing existing carbon calculation methodologies such as the Highways Agency (Highway Agency, 2008) and Transport Scotland (Fox et al., 2011) carbon calculation methodologies. This approach will ensure that relevant carbon sources (e.g. energy, materials, waste respectively) within the highway maintenance process are considered holistically and in an integrated manner within the carbon footprint, so as to inform transparent and effective business decision-making. A review of existing life cycle carbon analysis and studies on highway maintenance operation reveals little or no evidence that such an overarching methodology exists within the civil infrastructure maintenance sector. This creates difficulties for reliable and robust carbon emissions information to be assessed from highway system maintenance works. To this end, this paper presents the application and the results of a project-focused and process-based life cycle methodology framework (Itoya et al., 2012) based on the Publicly Available Specifications (PAS2050) protocol, developed by the author specific to highway maintenance works within the UK. The case study (focusing on carbon footprinting) results of 'typical' UK highway maintenance procedure based on the framework are presented. This approach aims to identify areas of carbon emission "hotspots" and associated opportunities for reduction, not least in developing a reduction hierarchy across the highway maintenance value chain, so as to ensure that carbon reduction efforts are adequately focused and prioritised. The approach also helps identify the energy, materials and carbon emissions input that exist between the highway maintenance providers and their supply chains. The results presented in this paper represent the carbon footprint information expressed in CO_2 equivalent (CO_2e) associated with highway maintenance works undertaken at various site locations within the UK.

The paper provides a literature review of existing process-based LCA studies, a brief description of the PAS2050 life cycle methodology employed in the study, and outlines the outcomes of the case studies in order to demonstrate the analytical capacities of the methodology framework. An exploratory analysis has been undertaken based on the primary data collected across various site locations, which then inform the carbon reduction hierarchy, whilst prioritising carbon reduction efforts. The approach presented in this paper can offer highway owners, agencies and contractors a framework to aid in planning their highway maintenance programmes and evaluates the expected carbon budgets over the infrastructure service life. Although the methodology focuses on carbon emissions assessment only from highway maintenance, the methodology focus can also be expanded from simply a carbon emissions assessment methodology to consider full LCA environmental impacts such as acidification, toxicity and ozone formation associated with highway maintenance works.

2. Literature Review

The literature review focuses on studies that employ process-based Life Cycle Inventory (LCI) analysis for highway maintenance carbon emissions assessment and identify limitations with respect to current practice.

2.1. Highway Maintenance Carbon Emissions Assessment

In 2001 the Swedish Environmental Research Institute (SERI) collaborated with the Swedish National Road Administration to undertake a preliminary Life Cycle Inventory (LCI) study of a highway system including: pavement layers, a traffic control system, highway lighting, road signs respectively (Stripple, 2001). The study focused on carbon emissions assessment from raw material acquisition, material production, maintenance and operation life cycle phases, but excluded the end-of-life phase. The study employed a process-based life cycle methodology in which the life cycle phases were broken down into smaller processes to evaluate the energy, and materials consumption and related carbon emissions, following the International Standard Organisation (ISO) life cycle methodology principles and guidelines (International Organisation for Standardisation, 2006). The life cycle inventory model which resulted from the study was used to compare the energy and related carbon emissions from asphalt and concrete pavements. It was found that without the feedstock energy of the bitumen, concrete pavements consumed considerably more energy, and emitted higher carbon when compared with the asphalt pavement (Stripple, 2001). Similar LCA studies undertaken in the United States, exclude the use phase (Nisbet et al., 2001), maintenance and end-of-life phases (Zapata and Gambatese, 2005) in the studies life cycle phases. However, the Zapata and Gambatese (2005) life cycle study revealed that concrete materials' energy consumption is mostly affected by cement manufacturing, while asphalt materials' energy consumption is affected by the asphalt mixing and drying of the aggregates (Zapata and Gambatese, 2005).

In 2006 the Cement Association of Canada commissioned the Athena Institute (AI) to undertake a life cycle study to compare energy consumption and global warming potential of asphalt and concrete pavements (Athena Institute, 2006). The study examined the materials (Concrete and Asphalt) production (included the raw material extraction and manufacturing), construction and maintenance phases, but excluded the use and end-of-life phases of the life cycle. The results of the study heavily favoured concrete materials in terms of energy consumption, but revealed that the asphalt materials consume two to five times more energy over materials production and maintenance phases if the bitumen feedstock energy is included. The study further confirmed that excluding the feedstock energy, asphalt materials still consume more energy (Athena Institute, 2006).These studies however demonstrate limited scope and system boundary definition when viewed from a life cycle perspective. In addition, the studies said nothing specifically on carbon emissions from highway design, operation and related on-site activities. This carbon emissions information is fundamental to the ideals of complete and accurate life cycle carbon assessment that can support credible reduction investment decision-making.

In the UK, a number of complementary carbon emissions assessment studies have been undertaken to strategically respond to the increasing demands on carbon emissions assessment and reduction from highway construction and maintenance processes. The studies include the Carbon Accounting Framework (Highway Agency, 2008) developed by the Highways Agency (HA). The HA has developed a highway construction and maintenance carbon accounting tool as part of its Sustainable Development Action Plan (SDAP), in response to the UK government’s legally binding carbon reduction commitments (Highway Agency, 2008). The tool primarily focuses on evaluating the agency’s direct and indirect carbon within the remit of its business operations; with particular emphasis on materials, on-site activities and associated waste; enabling works and associated transport (these carbon emission areas are also included in this paper). However, the HA carbon tool excludes the carbon information from the Traffic Management (TM) system used on-site in the assessment. Within the scope of this paper the carbon emissions from the TM system used on-site are considered. The paper also presents an approach that can be used by the highway authorities and their supply chains to assess their business carbon emissions, identifying areas of carbon hotspots and understanding the impact of site locations (urban, semi-urban and rural site locations) on the carbon emissions assessed.

Similarly, Halcrow (2010) in conjunction with Transport Scotland developed a Carbon Management System (CMS) aimed at enabling highway designers to integrate carbon analysis into highway design processes, and informed carbon optimisation through design and construction processes in the life cycle term. The study produced and presented a range of carbon accounting tools called CMS (Fox *et al.*, 2011). The case studies undertaken using the CMS demonstrate the analytical capabilities of the approach for highway carbon emissions assessment (Fox *et al.*, 2011), but excludes the end-of-life treatment emissions. The carbon information using the CMS is expressed in CO_2 equivalent (CO_2e) - a standard way of showing that the carbon emissions analysed includes all the six Greenhouse Gases (GHGs) defined by the Kyoto Protocol and the Intergovernmental Panel on Climate Change (IPCC). In this paper, the carbon information presented is expressed in carbon equivalent (CO_2e).

Although the HA and CMS carbon accounting tools tend to promote the life cycle carbon assessment approach, but the tools lacked the analytical capacity to produce complete life cycle carbon information to support carbon management and business decision-making. Hence, the tools have not be adopted as a highway construction and maintenance carbon emissions assessment and reporting industrial standard.

To undertake a life cycle carbon emissions study and integrate the outcomes into the highway maintenance decision-making process is an enormous task, given the analytical scope and data required. The Swedish Environmental Research Institute has defined the highway infrastructure as a system which consists not only of the highway pavement itself, but also of the traffic control system, highway lighting, pavement marking and road signs operation (Stripple, 2001). Assessing life cycle carbon emissions across these various systems requires an in-depth knowledge of the entire system and supply chain's carbon interaction with the system carbon footprint.

A review of existing life cycle studies on carbon emissions assessment demonstrates the complexities and difficulties that exist when undertaking a life cycle carbon assessment for highway maintenance processes. These difficulties include carbon emissions allocation and a lack of relevant industrial data, scope and system boundary definitions, consistent functional units and insufficient analytical rigour which has the potential to affect the accuracy, consistency and valid comparisons between life cycle results. In addition, the studies reviewed do not include highway lighting, vegetation clearance and pavement marking in their life cycle carbon assessment studies. It is important to know that these maintenance processes excluded can also contribute considerably to highway maintenance life cycle carbon impacts. The inability of the existing studies to develop a comprehensive representation of a life cycle carbon assessment for highway maintenance is attributable to a lack of adequate industrial data availability and limited research, knowledge and skills in the subject area, which are major drawbacks and barriers to perform life cycle studies. Addressing these drawbacks and barriers in highway maintenance process carbon footprinting will require a holistic and standardised approach that can assess both materials and energy flow across the highway system value chain. A standardised life cycle methodology is desired to produce accurate and consistent results, and identify area of emission "hotspots" across the process value chain.

The independent Publicly Available Specification (PAS2050) life cycle methodology standard developed by the British Standard Institute (BSI) in 2008 and updated in 2011, in collaboration with the Department for Environment, Food and Rural Affairs (DEFRA) and the Carbon Trust (Transport Research Laboratory Limited, 2010) has shown sufficient analytical rigour to start addressing the above complexities and drawbacks in highway maintenance carbon footprinting. The protocol robustness is inherent in the significant inputs received from international stakeholders, experts across academia, businesses, government and Non-governmental Organisations (NGOs), through formal consultation and multiple technical working groups (British Standard Institute, 2011). The approach has been tested through diverse business streams and has proved to be robust in performing a holistic (Cradle-to-grave) life cycle carbon assessment including "cradle-to-gate" boundary conditions. This life cycle methodology has been developed by the author into an integrated and a process-based life cycle methodology framework that can holistically measure the carbon footprint from highway maintenance process and identify areas of emissions "hotspots" across the process value chain. The methodology framework is divided into five life cycle stages and a three iterative stage process. The life cycle stages help users to define and build a representative process map for the core highway maintenance process selected for carbon emissions assessment, while the three stage iterative process (start-up, service emissions calculation and results) defines and outlines the five steps to enable the highway maintenance carbon sources to be identified and evaluated across the process value chain.

3. A Life Cycle Framework for Highway Maintenance

This section presents the scope and system boundaries definition within the life cycle approach, definition of the two stages and five basic steps to implementing the PAS2050 methodology framework (Itoya *et al.*, 2012) within the context of highway maintenance process carbon footprinting.

3.1. Scope Definitions and System Boundaries

The literature review revealed that scope and system boundary definition has been a key challenge in undertaking life cycle studies. The PAS2050 life cycle methodology (British Standard Institute, 2011) has strategically addressed this key challenge through the definitions of two business models (British Standard Institute, 2008), the B2C (Business-to-

Customer) and B2B (Business-to-Business) models. These models are consistent with "cradle-to-grave" and "cradle-to-gate" boundary conditions. The B2C model covers materials, energy and carbon input from raw material extraction, product manufacturing, transportation, site operations, use and disposal/recycling of the product at the end-of-life, and whilst the B2B model covers materials, energy and carbon input from raw material extraction, product manufacturing and delivery to customers' gate (For example, the highway maintenance site). Depending on the scope and system boundary of the life cycle carbon information required and the purpose for the assessment, any of the models can be used to assess highway maintenance carbon emissions.

Within the scope of this paper, the application and results of a process-based life cycle methodology framework for selected highway routine maintenance processes based on the two boundary conditions ("cradle-to-grave" and "cradle-to-gate") defined above are presented. These include the assessment of the energy consumed and carbon inputs from raw material extraction, transportation, materials manufacturing, operatives travel (including the outbound and inbound journey), on-site activities and waste disposal/recycling from Pavement Resurfacing, Bulk Lamp Replacement, Pavement Marking and Grass Cutting. The carbon emissions from Traffic Management (TM) operations - an activity common to each of the selected core highway maintenance processes are also considered.

Assessing and considering carbon information in highway maintenance design and investment, will assist in transparency and the decision-making process (Huang *et al.*, 2012). This requires an in-depth understanding and evaluation of the material embodied carbon, on-site and waste removal and recycling carbon categories. The embodied carbon defines the energy consumed from raw material extraction, transportation to the factory, the product manufacturing process and transportation to the customer's gate (i.e. the highway maintenance site). On-site carbon defines the energy consumed (e.g. fossil fuel) by operatives travelling (this includes the outbound and inbound journey) and site activities (such as planing-off of the existing road pavement surface and reinstating the planed surface with new pavement material), whilst the waste removal and recycling carbon accounts for the energy consumed during waste removal from site (including return journey), waste processing and recycling processes. The summation of these carbon emissions categories for each of the selected highway maintenance processes assessed using the PAS2050 life cycle methodology framework are defined in this paper as Carbon Footprint (CF). The word “carbon” or “carbon emissions” or “Carbon Footprint” expressed in CO_2 equivalent (CO_2e) used interchangeably within this paper, represent the six Greenhouse Gases (GHG) defined by the Kyoto protocol and the Intergovernmental Panel on Climate Change (IPCC).

3.2 Stage one – The Framework Start-Up

The section explains the various stages that are critical to ensuring accuracy and reliability of carbon emissions results within the scope and system boundary defined for case studies undertaken.

Step1: Setting Objective, Selecting Processes and Stakeholder Engagement:-

Agreeing and defining a specific goal for the carbon emissions assessment agenda upfront is an important step to defining the scope, boundary and data required for the assessment (British Standard Institute, 2008). Therefore, the goal of this study is to assess the carbon footprint from highway maintenance processes based on PAS2050:2011 life cycle methodology. The highway maintenance processes selected for this study reflect ‘typical’ UK highway routine maintenance operations, namely:

- Pavement resurfacing process;
- Pavement marking process;
- Bulk Lamp replacement process;
- Grass Cutting.

These processes are selected across different supply chains (e.g. subcontractors) and site locations (urban, semi-urban and rural environments) so as to generate wider understanding of highway maintenance carbon footprinting, and related carbon from the supply chains. In this study, to facilitate data collection both the internal (e.g. Highway designers, managers and maintainers) and external (e.g. highway material manufacturers) stakeholders were consulted in order to identify and define the maintenance process activities and related carbon data required. This also allowed the data collection (e.g. sites and supply chains) responsibilities to be allocated and ensure relevant and representative carbon data was collected as required, whilst addressing issues around site safety, legal and commercial confidentialities. It is important to address these issues, since they have the potential to affect the quality of carbon data collection and the approach employed.

Step 2: Data Collection Template and Programme:- This step allows the data collection template and the programme of action to be developed so as to ensure that the data collection exercise is consistent and formalised across the process value chain, and to ensure that the data collection exercises do not interrupt operatives' daily productivity and site safety rules.

3.3. Stage Two – Service Emissions Assessment

Step 3: Process Map and Review of Boundaries and Priorities: Building a process map based on the PAS2050:2011 protocol helps to identify all materials, activities and energy consumed that contribute to the maintenance process's life cycle carbon. Although it is an iterative process, it provides a starting point for interviews and a graphical reference to guide both the data collection and the carbon calculation (British Standard Institute, 2008) approaches. Therefore, the process mapping should be adapted into current highway maintenance procedure, since it allows the maintenance processes, activities, and relevant data inputs needed for carbon assessment to be clearly identified. In this study, the process decomposition technique is employed in line with the PAS2050:2011 principles and guidelines. The technique breaks down the selected core highway maintenance processes into three levels of granularity (Cooper et al., 2005), which include the life cycle stages, activities and task levels. The lower levels defined the corresponding upper-levels. The detail of the process map developed and used in this paper is presented in **Figure 1**.

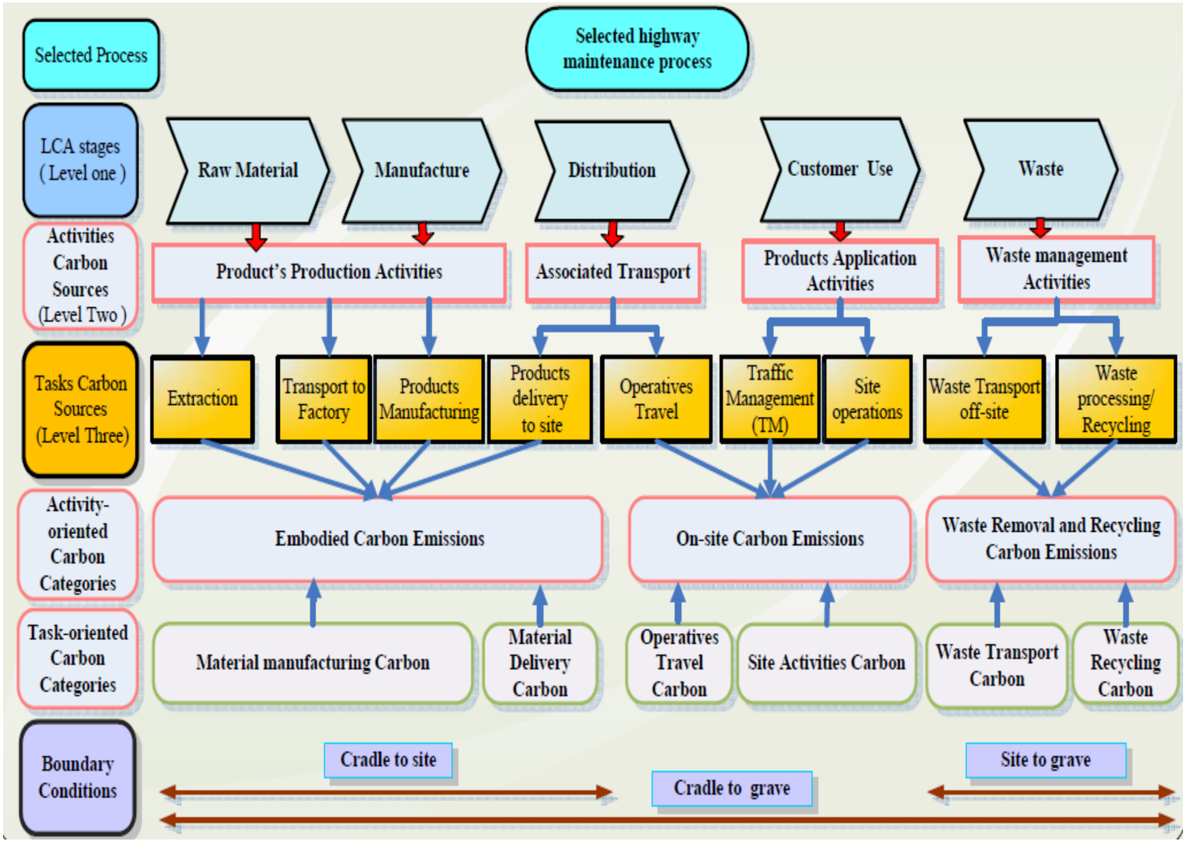

Figure 1. Process Map for Highway Maintenance Processes (adopted from Itoya et al., 2012)

Step4: Data Collected and Types: This step defines the carbon inputs data type, collection procedure and quality assurance measure employed. The materials and energy (litres of fuel, electricity and gas) consumed during raw material extraction, transportation, materials manufacturing, product delivery to site, operatives transport to site (including return journey), site activities (vehicles/equipment/plant energy consumption) and waste transportation off-site and the recycling process are considered as the data inputs for this study. These data types are collected from product manufacturing companies, product suppliers, and waste recycling companies and during on-site operations. The total materials (e.g. Asphalt concrete, Tack Coat (K140) and Polymer Modified Bitumen) daily deliveries, and the distance covered to site were obtained from the supplier's delivery tickets.

As a procedure, site operatives were allowed to fill-up their vehicles and plant with diesel at the start of each shift and re-fill at the end of the shift; with start and end mileages recorded. The materials input (e.g. tonnes, number of products) and fuel (litres) consumed by vehicles and plant for the site activities and the waste recycling process were collected and analysed in energy terms. This allows the materials design specifications to be transformed into equivalent energy units, and corresponding carbon emission values using fuel-based (see Table 2) emission factors from publicly available databases and products manufacturers, namely:

- the "University of Bath: Inventory of Carbon and Energy (ICE)" v2.0 (Hammond and Jones, 2011),
- the "2010 Guidelines to DEFRA/DECC's Greenhouse Gases Conversion Factors for Company Reporting" (Department for Energy and Climate Change, 2010),
- the "Carbon Trust Conversion Factors" (Carbon Trust, 2011) and,
- the UK-based product manufacturer factors, see Table 2.

Tables 1a and 1b summarise the data collected for each of the highway maintenance processes (see step1) selected for carbon assessment. Data on energy consumption from the Traffic Management (TM) system used for each of the processes were also included in the data collected.

3.3.1. Explanations of Highway Maintenance Processes Undertaken

Pavement Resurfacing Process: The work includes planing-off existing pavement asphalt surfaces to an average nominal depth of 100mm. The planed surfaces were reinstated with a thin layer of leotak tack coat (K140), 60mm AC 20 HDM BIN 40/60 DES binder, 40mm surface courses and polymer modified bitumen.

Pavement Marking Process: The pavement marking works involves the restriping of existing road line marking to enhance their reflectivity requirement.

Bulk Lamp Replacement Process: This is a localised highway lighting maintenance programme undertaken. During this operation existing lamps that have completed their nominal life expectancy are replaced with new ones, in order to maintain high standard highway illumination, keeping the energy consumption to the minimum and preventing the damage to the lightings control equipment (e.g. gear) within the street lighting network.

Grass Cutting Operation: To enhance safety and other environmental and visibility issues on roads, the grass cutting operation is undertaken as part of the highway routine maintenance programme. The strimmer and tractors were used on-site to carry out these operations. Tables 1a and 1b present a summary of the data collected from the core highway maintenance processes (pavement resurfacing, pavement marking, bulk lamp replacement and grass cutting operations) selected for carbon assessment.

Location	Total area (m^2)	Quantity of Asphalt Concrete (tonnes)	Distance (Factory to site) (km)	Number of trips (no)	Tack Coat K140 (Litres)	Polymer Modified Bitumen (kg)	Road Planings generated (tonnes)
Urban	2945	758	97	38	2062	200	600
	2593	294	93	15	1493	125	220
	1284	290	92	15	642	25	195
	1024	237	90	12	512	25	90
Semi urban	6728	622	84	32	3364	250	625
	4184	399	90	20	2092	50	360
	3821	339	113	17	1911	125	330
	2243	430	193	22	1947	100	350
Rural	2500	318	290	16	1250	0	120
	638	60	119	3	319	0	40
	540	110	77	6	270	0	100
	400	109	87	6	200	0	40

Table 1a. Summary of data collected from twelve pavement resurfacing works across different site locations.

Location	Pavement Marking			Lamps Replacement			Grass Cutting
	Bags of Thermoplastic paint used (no)	Bags of Glass bead (no)	Distance (Factory to site) (km)	Lamps installed (no)	Distance (Depot to site) (km)	Lamp Waste (no)	Grass Cutting completed (m)
Urban	14	1	74	57	106	57	0
	11	0.5	74	42	101	42	0
	11	0.5	51	29	105	29	0
	8	0.5	39	8	89	8	0
Semi urban	246	8	550	65	463	65	5800
	214	10	1492	36	161	36	5200
	214	10	1109	32	425	32	3300
	114	6	1369	27	428	27	3900
Rural	60	3	285	56	106	56	342
	20	1	180	45	71	45	65
	10	0.5	177	42	161	42	370
	0	0	0	42	113	42	378

Table1b. Summary of data collected from twelve pavement marking and lamp replacement, and eight grass cutting works across different site locations.

Step 5: Analysis of Data: Two models were developed namely: activity-oriented and task-oriented models to analyse the data collected. The activity-oriented defined the Embodied carbon, On-site carbon and Waste Removal and Recycling carbon categories associated with the highway maintenance processes. The task-oriented mode further breaks down the activity-oriented carbon categories into their corresponding task carbon, namely: Materials/products manufacturing and delivery to sites, operatives' travel (including return journey), site activities, waste transport off-site and waste processing and recycling. Table 2 presents fuel-based emission factors employed to quantitatively evaluate each carbon emissions model. An exploratory analysis was undertaken to interpret the results from the two models.

Fuel and Product Types	Distance covered by K140 and coldbond 50 (Source to site) (km)	K140 & Coldbond 50 Application Rate (litres/m^2)	Emission Factors (see units)	Units	Sources with references
Diesel	-	-	2.6720	$kgCO_2e$/litre	The UK's Department of Energy and Climate Change (DECC, 2010)
LNG	-	-	2.7178	$kgCO_2e$/kg	
Gas Oil	-	-	3.0212	$kgCO_2e$/litre	
Grid Electricity	-	-	0.5246	$kgCO_2e$/kwh	The Carbon Trust (Carbon Trust, 2011)
Secondary Glass	-	-	0.59	$kgCO_2e$/kg	The Inventory of Carbon and Energy (Hammond and Jones, 2011)
Tack Coat (K140)	80.5	0.5	0.1	$kgCO_2e/m^2$	The Colas Group (Colas Group, 2011) (A UK-based product manufacturer)
	321.8		0.1	$kgCO_2e/m^2$	
	804.5		0.2	$kgCO_2e/m^2$	
Coldbond 50	80.5	0.7	0.2	$kgCO_2e/m^2$	
	321.8		0.2	$kgCO_2e/m^2$	
	804.5		0.3	$kgCO_2e/m^2$	

Table 2: Fuel-based and Products emission factors employed in this study

4. Results and Discussion

The highway maintenance processes selected across different site locations (Urban, Semi-urban and Rural) were assessed in carbon terms using the PAS2050 life cycle methodology framework. The results of the carbon emissions assessment are summarised and discussed below.

4.1. Activity-Oriented Analysis

Employing this analysis technique, the embodied carbon, on-site and waste removal and recycling carbon categories for each of the selected core highway maintenance processes were calculated across the different site locations considered. Table 3a presents the average percentage contributions of each carbon category to the overall process carbon footprint from pavement resurfacing works. The materials embodied carbon accounts for in excess of 80% of the average of the overall carbon footprint (23079 kgCO_2e) for all locations considered, whilst on-site, and waste removal and recycling carbon account for 15% and 3% respectively, for the pavement resurfacing operation (see Table 3a).

Similarly, the carbon categories average percentage contributions to the overall carbon footprint associated with pavement marking and street lighting (lamp replacement) and grass cutting operations are highlighted in Table 4a and Figure 3a. For the pavement marking and lamps replacement works, the materials embodied carbon contributes an average of 82.6% and 36.03% to the overall carbon footprints (4301.21kgCO_2e and 405.1kgCO_2e), whilst the on-site and waste removal and recycling carbon account an average of 63.68%, 17.4% and 0.3% respectively across all locations. Table 4a indicates that on-site carbon for lamp replacement works in both semi-urban and rural locations increase significantly compared to the material embodied carbon input, primarily due to carbon inputs (59.40% and 35.38% of the CF) from the mobile Traffic Management (TM) system employed during the operation. The majority of the works were carried out in site locations where the average vehicle speed is at national speed limit level (Excess of 60mph compared to 30mph in an urban site location).

The results from this study indicate the materials embodied carbon usually contributes significantly to the overall process Carbon Footprint (CF) as indicated in Table 3a. However, Figure 4a does reveal that mobile TM systems used for the highway Street lighting maintenance can have a significant carbon impact, and is likely to a key sustainable decision point during the highway maintenance planning.

4.2. Task-Oriented Analysis

This analysis technique allows the activity-oriented carbon categories to be analysed further to identify areas of carbon "hotspots" from each of the core highway maintenance processes considered. The aim is to establish a reduction hierarchy that can prioritise carbon reduction efforts. Table 3a and Figure 2 indicate that asphalt manufacturing, site activities, asphalt delivery to site, operatives' travel, and waste transport off-site and waste recycling respectively are in order of priority, the areas where carbon reduction efforts can be focused for pavement resurfacing work across urban, semi-urban and rural locations. Tables 4b, 4c and Figures 3b, 3c and 3d present the carbon emission rates, areas of carbon hotspots and carbon reduction hierarchies for pavement marking, bulk lamp replacement and grass cutting operations. The results from Tables 3b, 4b and 4c, and Figures 2, 3b, 3c and 3d suggest that carbon reduction investment decision-making associated with highway maintenance operations should include the materials (e.g. asphalt, pavement marking materials, and street lighting lamps) manufacturing and delivery, site activities and operatives' travel.

The outcomes from the above analyses tally with the key findings from Stripple et al (2001), Nisbet et al (2001), Athena Institute (2006) and Durucan and Korre (2009) life cycle assessment studies. These studies concluded that construction materials production and delivery to site are energy intensive, and produce the most significant carbon impact compared to other activities (Athena Institute, 2006 Durucan and Korre, 2009 Nisbet *et al.*, 2001 Stripple, 2001). Following this conclusion, Stipple et al (2001), Athena Institute (2006) and Chen (2007) further argued that energy consumption and the carbon burden from asphalt materials manufacturing process is attributable to the feedstock energy in the bitumen used (Athena Institute, 2006 Stripple, 2001). However, an initial life cycle study by Zapata and Gambatese (2005) concluded that the energy consumption and carbon emissions impact associated with asphalt materials production are mostly affected by the asphalt mixing process and drying of the aggregates (Zapata and Gambatese, 2005). These views could not be confirmed within the remit of this study since the materials embodied carbon data employed in the carbon assessment were provided by the products manufacturing companies. However, these views provided a knowledge framework that can help identify relevant areas, where carbon reduction efforts can be focused most productively to reduce the embodied carbon from highway materials production and delivery.

Similar life cycle studies by Carpenter (2007) and Haung et al. (2009) on pavement maintenance carbon assessment suggest that the carbon emissions associated with highway pavement materials embodied carbon can be reduced significantly, if secondary materials are used in place of virgin materials (Carpenter *et al.*, 2007 Huang *et al.*, 2009). Roth et al.(2003) argued that the decision to use secondary materials in pavement maintenance is largely based on value choices (Roth and Eklund, 2003).

Activity-oriented Carbon Emissions associated with Twelve Pavement Resurfacing Works across Different Site Locations															
Location	**Asphalt Concrete Embodied Carbon (AEC) ($kgCO_2e$)**	**Asphalt Concrete Embodied Carbon per area resurfaced ($kgCO_2e/m^2$)**	**On-site Carbon Emissions (OCE) ($kgCO_2e$)**	**On-site Carbon emisions per area resurfaced ($kgCO_2e/m^2$)**	**Waste (Planings) Removal and Recycling Carbon Emissions (WCE) ($kgCO_2e$)**	**Waste (Planings) Removal and Recycling carbon per tonne of planings ($kgCO_2e/t$)**	**Carbon Footprint (CF) ($kgCO_2e$)**	**Average AEC ($kgCO_2e$)**	**Average OCE ($kgCO_2e$)**	**Average WCE ($kgCO_2e$)**	**Average CF ($kgCO_2e$)**	**Average Rate of AEC to CF**	**Average Rate of OCE to CF**	**Average Rate of WCE to CF**
Urban	38070	12.93	7810	2.65	4570	7.62	50450	21778	3678	2083	27538	79.08	13.36	7.56
	23340	9.00	2870	1.11	1620	7.35	27830							
	11360	8.85	1924	1.49	1470	7.54	14754							
	11360	11.09	1924	1.88	674	7.48	13958							
Semi urban	40323	5.99	4970	0.74	1248	2.00	46541	26197	3311	746	30254	86.59	10.94	2.47
	24547	5.87	2889	0.69	601	1.67	28038							
	21557	5.64	2277	0.6	422	1.21	24256							
	18361	8.19	3108	1.39	713	2.16	22182							
Rural	19350	7.74	3345	1.34	347	2.89	23043	8961	1691	206	10859	82.52	15.57	1.90
	3838	6.02	1373	2.15	40	1.00	5251							
	6358	11.77	1129	2.09	91	0.91	7578							
	6300	15.75	917	2.29	347	8.68	7564							
AEC: Asphalt Concrete Embodied Carbon**, OCE:** On-site Carbon Emissions **, WCE:** Waste Removal and Recycling Carbon Emissions														

Table 3a. Activity-Oriented model analysis to evaluate carbon emission categories, Carbon footprint and associated carbon emission rates

Task-oriented Carbon Emissions associated with Twelve Pavement Resurfacing Works across Different Site Locations

Location	Area (m^2)	Quantity of Asphalt Concrete (tonne)	Distance (factory to site) including return journey (km)	Asphalt Concrete Manufacturing Carbon ($kgCO_2e$)	Asphalt Concrete Delivery Carbon Emissions (AD) ($kgCO_2e$)	Asphalt Delivery Carbon Emissions rate ($kgCO_2e$/trip)	Operatives Travel Carbon Emissions (OT) ($kgCO_2e$)	Site Activities Carbon Emissions (SA) ($kgCO_2e$)	Site Activities Carbon Emissions rate ($kgCO_2e/m^2$)	Operatives Travel Carbon Emission rates ($kgCO_2e$/km)	Waste (Planings) Transport off-site Carbon Emissions (WT) ($kgCO_2e$)	Waste (Plaings) Recycling Carbon Emisions (WR) ($kgCO_2e$)	Waste (Planings) Carbon Emission rates ($kgCO_2e$/tonne)
Urban	2945	758	3669	35800	2270	59.737	3108	4703	1.60	8.46	4168	401	7.62
	2593	294	1400	22379	960	64.067	1042	1828	0.70	4.22	1470	147	7.35
	1284	290	1352	13642	698	46.200	786	1320	1.03	5.68	1336	134	7.54
	1024	237	991	10818	542	49.273	556	1368	1.34	5.01	607	67	7.48
Semi Urban	6728	622	2594	37790	1170	37.742	1403	3568	0.53	7.78	828	420	2.00
	4184	399	1802	21960	1730	86.500	1534	1356	0.32	8.91	361	240	1.67
	3821	339	1641	18690	2100	123.529	858	1420	0.37	6.83	187	235	1.21
	2243	430	4248	11010	2600	118.182	1256	1852	0.83	6.79	441	273	2.16
Rural	2500	318	1905	16330	2520	157.500	1742	1603	0.64	5.82	267	80	2.89
	638	60	1101	3380	330	110.000	486	887	1.39	2.51	13	27	1.00
	540	110	463	5630	620	103.333	202	927	1.72	1.63	24	67	0.91
	400	109	521	5600	620	103.333	639	278	0.69	4.41	321	27	8.68

Note: **AD**, Asphalt Concrete delivery carbon emissions , **OT**: Operatives Travel carbon (depot to site) including the return journey , **SA**: Site Activities carbon based on plant/equipment used during the pavement resurfacing works, **WT**: Waste Transport carbon (site to recycling plant including the return journey), **WR**: Waste (planings) processing and recycling carbon (crush and screen to type 2 aggregate).

Table 3b. Task-Oriented analysis to identify areas of carbon "Hotspots" and associated emission rates for pavement resurfacing works.

Activity-Oriented carbon categories, CF and carbon emissons rate from Twelve pavement marking and lamps replacement works across urban, semi-urban and rural site locations																		
Location	**Materials Embodied Carbon (MEC) ($kgCO_2e$)**	**Materials Embodied Carbon per bag ($kgCO_2e$/ bag)**	**On-site Carbon Emissions ($kgCO_2e$)**	**On-site Carbon Emissions (OCE) per bag ($kgCO_2e$/ bag)**	**Total Carbon Footprint (CF) ($kgCO_2e$)**	**Average CF ($kgCO_2e$)**	**Average Rate of MEC to CF**	**Average Rate of OCE to CF**	**Lamp Embodied Carbon (LEC) ($kgCO_2e$)**	**LEC per Lamp ($kgCO_2e$/ Lamp)**	**On-site Carbon Emissions (OCE) ($kgCO_2e$)**	**Waste (old lamps) Removal & Recycling Carbon (WRC) Emissions ($kgCO_2e$)**	**WRC Emissions rate ($kgCO_2e$/ lamp**	**Total CF ($kgCO_2e$)**	**Average Rate of LEC to CF**	**Average Rate of OCE to CF**	**Average Rate of WRC to CF**
Urban	673	48.0	126.18	6.49	799	646.32	81.4	18.6	117.03	2.1	32.0	0.929	0.016	102.61	68.00	31.46	0.54
	524	47.7	131.52	8.74	656				86.23	2.1	43.0	0.685	0.016				
	524	47.7	120.93	7.29	645				59.54	2.1	35.0	0.473	0.016				
	383	47.9	102.13	8.35	485				16.42	2.1	19.0	0.130	0.016				
Semi urban	11738	47.7	1194.95	11.65	12933	10923.01	86.0	14.0	148.48	2.3	858.0	1.292	0.020	823.67	11.09	88.81	0.10
	10205	47.7	1678.09	12.50	11883				82.24	2.3	764.0	0.715	0.020				
	10205	47.7	1728.27	16.36	11933				73.10	2.3	601.0	0.636	0.020				
	5446	47.8	1497.05	21.92	6943				61.68	2.3	703.0	0.537	0.020				
Rural	2859	47.7	343.48	9.72	3203	1334.30	80.4	19.6	101.71	1.8	321.0	0.628	0.011	289.02	29.00	70.76	0.18
	953	47.7	370.11	30.04	1323				81.73	1.8	75.0	0.505	0.011				
	477	47.7	334.82	50.38	811				76.28	1.8	187.0	0.471	0.011				
	0	0.0	0	0.00	0				76.28	1.8	235.0	0.471	0.011				

Note: MEC: Materials (Themoplastic Paint and Glass bead) embodied carbon, **OCE:** On-site activities carbon during pavement making and bulk lamp replacement , **LEC**: (carbon associated with Lamp manufacturing and delivery to site), **WRC**:(carbon associated with old lamps revoval from site, processing and recycling).

Table 4a. Activity-Oriented model to evaluate carbon emission categories, CF and related carbon rates for pavement marking and lighting maintenance works.

Task-Oriented model analysis to identify areas of emission ''Hotspots'' and evaluate emission rates for twelve pavement marking and lighting works across different site locations

Location	PM Carbon Emissions ($kgCO_2e$)	Paint Delivery Carbon Emissions ($kgCO_2e$)	TM Carbon Emissions ($kgCO_2e$)	Site Activities Carbon Emissions (SA) ($kgCO_2e$)	Site Activities Carbon Emission rates ($kgCO_2e$/bag)	LM Carbon Emissions ($kgCO_2e$)	LD Carbon Emissions ($kgCO_2e$)	LD Carbon Emission rates ($kgCO_2e$/km	TM Carbon Emissions ($kgCO_2e$)	Site Acrivities Carbon Emissions (SA) ($kgCO_2e$)	Waste (old lamps) Transport Carbon Emissions (WT) ($kgCO_2e$)	Waste Transport Carbon Emissions (WT) rates ($kgCO_2e$/km/ tonne)	Lamps Recycling Carbon Emissions (LR) ($kgCO_2e$)
Urban	656	1.44	0.00	126.18	9.01	115.48	1.55	0.011	0	32	0.57	0.158	0.36
	516	1.13	0.00	131.52	11.96	85.09	1.14	0.008	0	43	0.42	0.158	0.26
	516	1.13	0.00	120.93	10.99	58.75	0.79	0.006	0	35	0.29	0.158	0.18
	375	0.82	0.00	102.13	12.77	16.21	0.22	0.002	0	19	0.08	0.158	0.05
Semi urban	11535	26.45	614.40	580.55	2.36	142.03	6.46	0.047	596	262	0.88	0.158	0.41
	10034	23.01	366.70	1311.44	6.13	78.66	3.58	0.026	468	297	0.49	0.158	0.23
	10034	23.01	652.00	1076.3	5.03	69.92	3.18	0.023	385	216	0.43	0.158	0.20
	5345	12.26	368.70	1128.31	9.9	59.00	2.68	0.019	508	195	0.37	0.158	0.17
Rural	2813	1.61	120.20	223.24	3.72	70.67	31.04	0.037	160	160	0.28	0.158	0.35
	938	0.54	114.90	255.21	12.76	56.79	24.94	0.029	32	43	0.22	0.158	0.28
	469	0.27	80.20	254.66	25.47	53.00	23.28	0.027	53	134	0.21	0.158	0.26
	0	0.00	0.00	0	0	53.00	23.28	0.027	168	67	0.21	0.158	0.26

Note: PM :Paint Manufacturing, **PD**: Paint Delivery (factory to site), **TM:** Traffic Management used on sites, **SA** : Site Activities carbon emissions during pavement marking and lamp replacement, **LM**: Lamps manufacturing process, **LD:** Lamps Delivery (factory to depot), **WT**: Waste Transport carbon emissions (depot to recycling plant), **LR** : Lamps waste processing and recycling carbon emissions.

Table 4b. Task-Oriented model analysis of pavement marking and bulk lamp replacement works

Activity-oriented and task-oriented carbon analysis of eight grass cutting operations across semi-urban and rural site locations											
Location	**Distance Covered by Operatives (km)**	**Grass Cutting Completed (m)**	**On-site Carbon Emissions ($kgCO_2e$)**	**Total Carbon Footprint (CF) ($kgCO_2e$)**	**On-site Carbon Emission Rates ($kgCO_2e/m$)**	**Operatives Travel Carbon Emissions (OT) ($kgCO_2e$)**	**Operatives Travel per distance covered ($kgCO_2e/km$)**	**Site Acticities Carbon Emissions (SA) ($kgCO_2e$)**	**Site Activities per km of grass cutting ($kgCO_2e/km$)**	**Average Rate of OT to CF**	**Average Rate of SA to CF**
Semi - urban	88.5	5800	83.69	83.69	0.01	72.14	0.82	11.54	0.0020	88.20	11.80
	104.6	5200	108.88	108.88	0.02	98.86	0.95	10.02	0.0019		
	113.8	3300	94.86	94.86	0.03	80.16	0.70	14.70	0.0045		
	99.8	3900	82.16	82.16	0.02	74.82	0.75	7.35	0.0019		
Rural	30.6	342	344.96	344.96	1.01	24.32	0.79	320.64	0.9375	4.43	95.57
	10.1	65	355.38	355.38	5.47	8.02	0.79	347.36	5.3440		
	17.7	370	347.63	347.63	0.94	13.63	0.77	334.00	0.9027		
	20.9	378	358.32	358.32	0.95	16.3	0.78	342.02	0.9048		

Note: **OT** : Operative Travel carbon emissions (from depot to site) including return journey , **SA**: Site Activities carbon emissions due to grass cutting operation.

Table 4c. Activity-Oriented and task-oriented analysis to identify areas of carbon "Hotspots" of highway grass cutting operation

4.3. Exploratory Analysis

The exploratory analysis described here allows the results from the two analyses models to be interpreted to identify potential carbon reduction opportunities and emission rates associated with areas of carbon hotspots. Within the remit of this analysis, carbon emissions from highway material production, transportation and site activities have been identified as areas of carbon hotspots, and are sustainability decision areas to deliver a low-carbon highway maintenance service.

The carbon emissions rate increases for vehicle delivery materials, equipment/plant to site and transporting waste off-site. This is because the fuel type (diesel) used by vehicles during this operation produces a significant increase in carbon emission rates at higher engine combustion rates due to loading, distance covered (km) and congestion. For example, the average carbon emission rates (kgCO_2e/km/t) associated with asphalt delivering to site increases in semi-urban locations (0.06617 kgCO_2e/km/t) compared to urban (0.0479 kgCO_2e/km/t) and rural (0.0496 kgCO_2e/km/t) locations. This increase in carbon emission rates is attributable to higher average distance covered in semi-urban (2571 km) locations compared to urban and rural locations (1853 km and 998 km respectively). This result concurred with life cycle studies that concluded that materials haulage distance is a sensitive factor in terms of energy consumption for materials delivery (Thenoux *et al.*, 2006 Thomas *et al.*, 2009) . The above results mirror the findings of Mroueh et al (2001), which indicates that construction materials production and transportation produces the most significant environmental burden (Mroueh et al., 2001). This conclusion recommends that acquiring construction materials at a source closer to site can reduce transportation carbon and will impact on the overall embodied carbon, particularly when delivered in bulk. Conversely, the percentage contributions of on-site carbon (88.81% and 70.76%) to the overall carbon footprint for bulk lamp replacement in semi-urban and rural locations increases significantly when compared to embodied carbon contributions (11.90% and 29%) respectively. This increase is due to the type of traffic management system (mobile TM) used on site, given that the bulk lamp replacement operations were carried out in a high speed traffic area (excess of 60mph) of the road network compared to 30mph in a built-up area in an urban environment. This result indicates that site locations and selected TM system are also key sustainability priority decision points when undertaking bulk lamp replacement compared to embodied carbon of the material (lamp type). The embodied carbon rates for pavement marking was 47.9 kgCO_2e/25kg across all site locations considered.

4.4. Carbon Reduction Hierarchy

On the basis of the data analyses models and associated discussion, the carbon emission reduction hierarchies presented in Figures 2, and 3b, 3c, were developed. These hierarchies can offer businesses a decision support framework for carbon emissions reduction agenda, by allowing reduction efforts to be prioritised and targeted most productively at relevant points within the business value chain. Figures 2 and 3b, 3c, 3d reveal that the carbon reduction priority areas may vary slightly depending on the site location under consideration. The significant difference in operative transport emissions between semi-urban and rural locations for Grass cutting works is due to the allowable vehicle speed limits in the site locations. This variation suggests that there are other carbon emissions sensitive factors such as congestion and distance to site that are need to be considered when developing a business carbon reduction agenda. Therefore, it is crucial that the site locations, delivery materials in bulk (to reduce the number of trips) and materials haulage distance are included in the decision-making process by the highway designers, managers and maintainers.

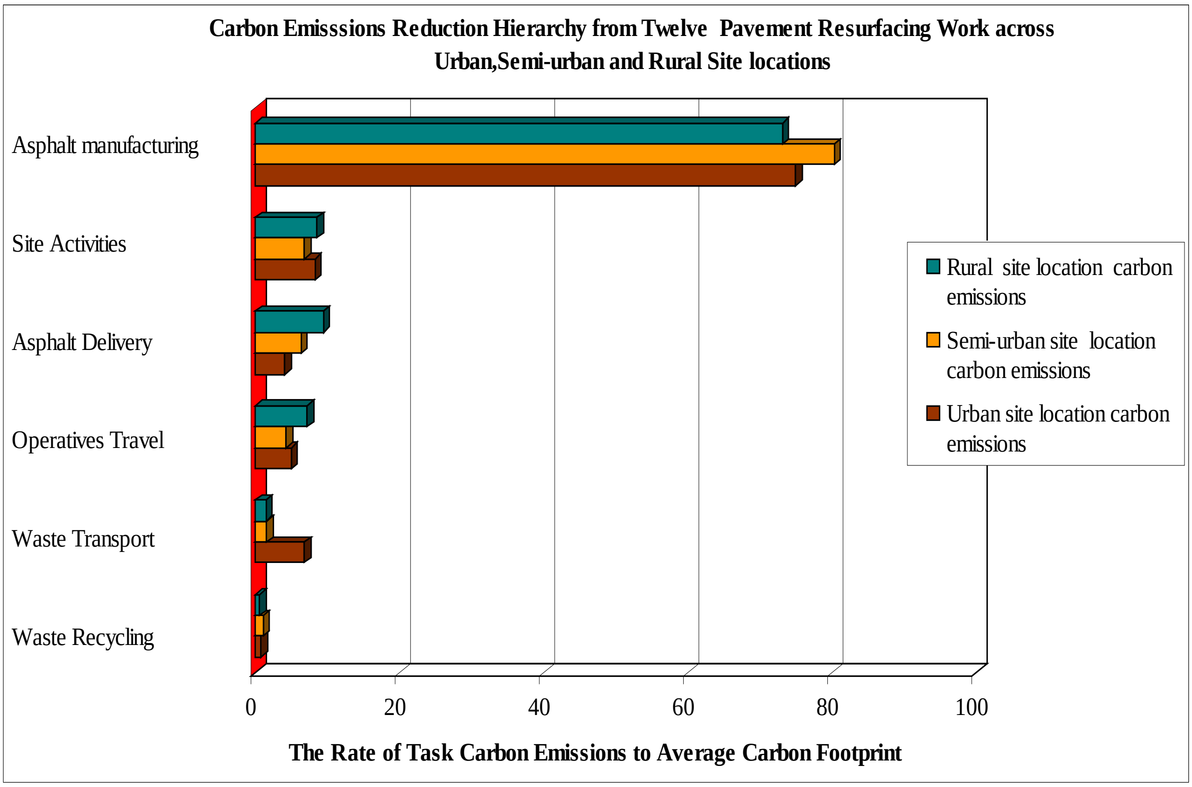

Figure 2. Carbon emissions reduction hierarchy for pavement resurfacing work

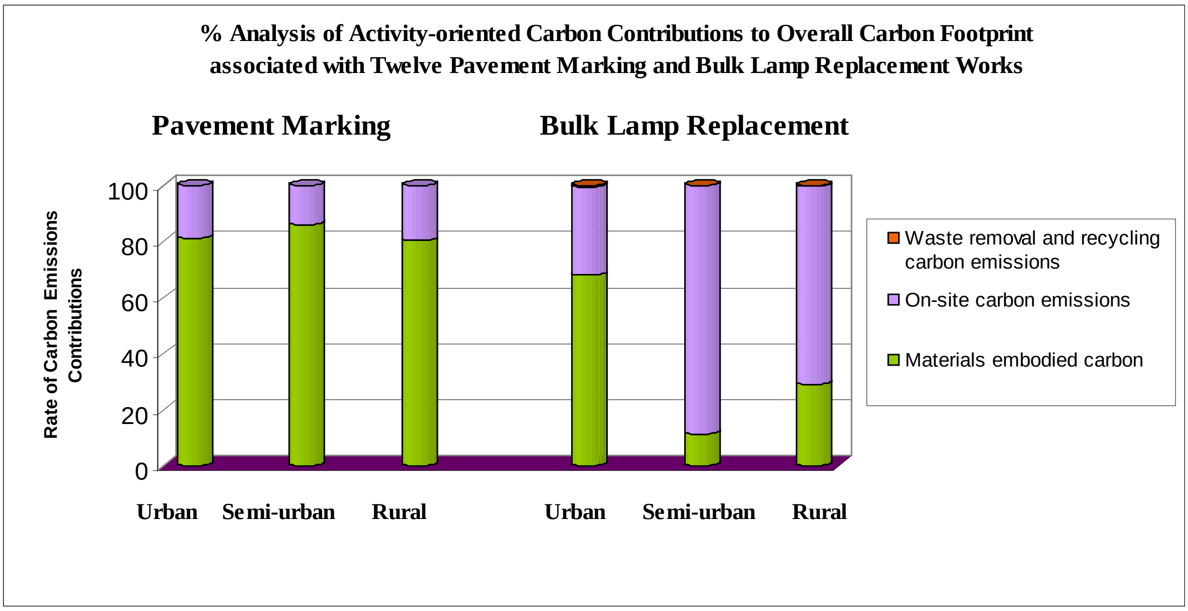

Figure 3a. Activity-oriented carbon from pavement marking and bulk lamp replacement works

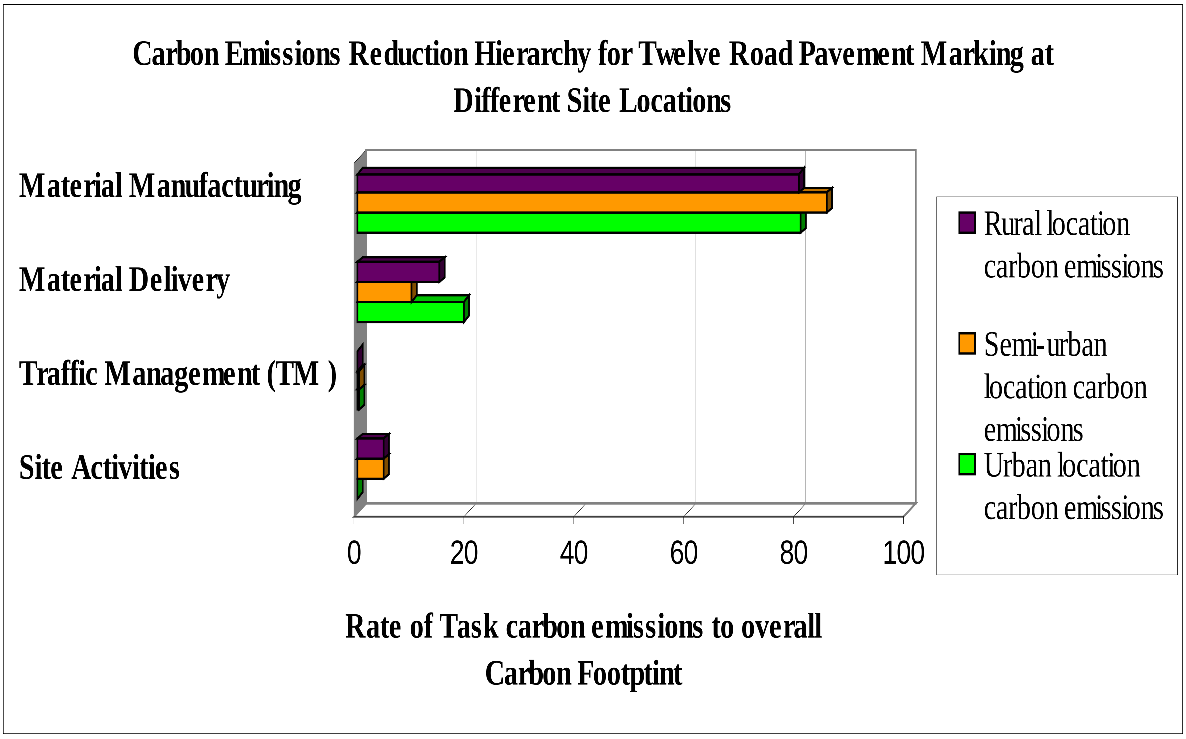

Figure 3b.Carbon reduction hierarchy for pavement marking

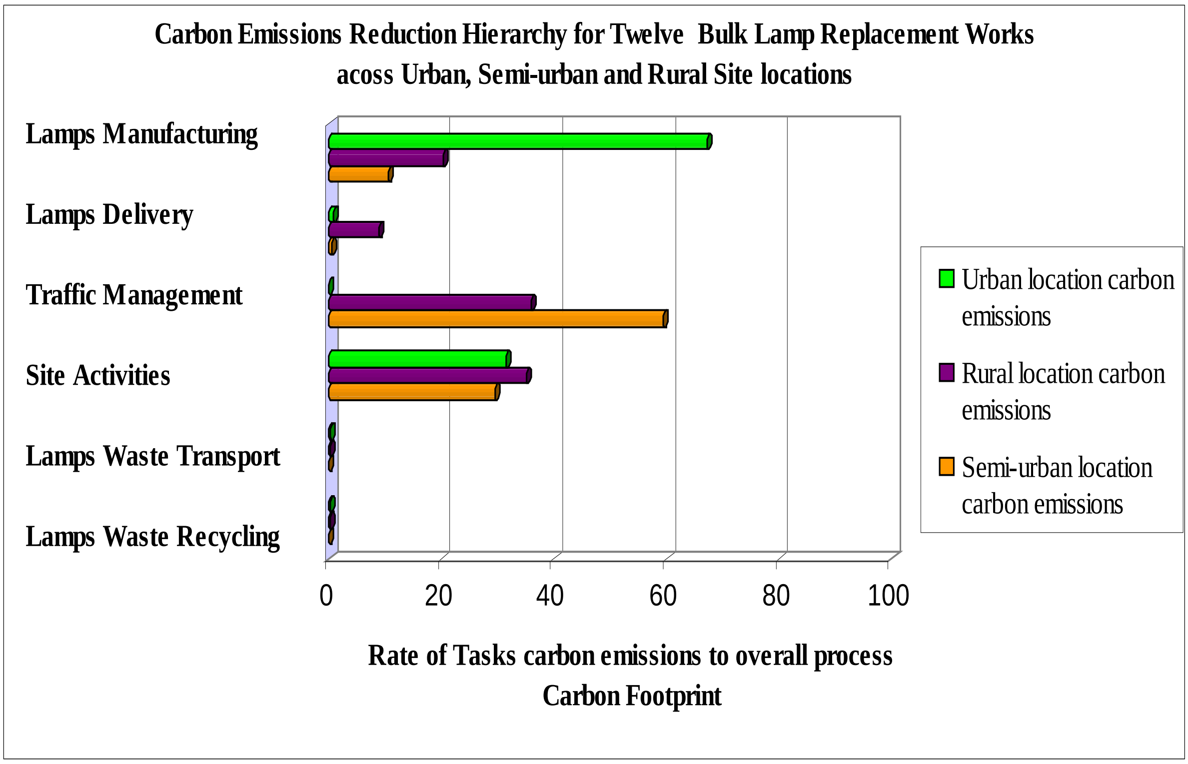

Figure 3c. Carbon emissions reduction hierarchy for bulk lamp replacement works

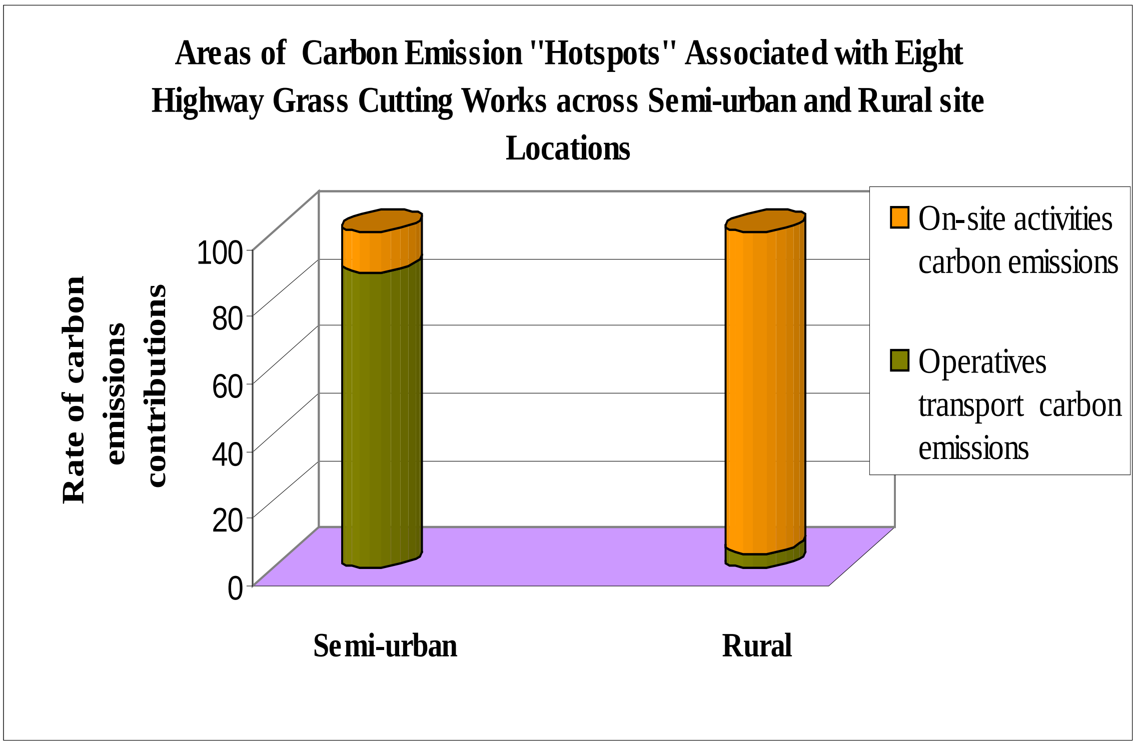

Figure 3d. Carbon emissions reduction hierarchy for highway grass cutting

5. Conclusions

Carbon footprinting provides opportunities for businesses to measure, manage, and accurately reduce carbon across their business value chain and provides customers with the chance to assess their project carbon performance in life cycle terms. To meet the legal obligation, the environmental stakes and business risks, and the opportunities that businesses need to enhance their competitiveness, it is crucial for highway designers, managers and maintainers to embrace and integrate the business opportunities presented by carbon footprinting.

This paper has presented a step-by-step application and results of a project-focused and process-based life cycle methodology framework based on PAS2050 protocol. This methodology offers the civil infrastructure maintenance sectors, particularly the highway maintenance sector a holistic life cycle carbon evaluation framework that can assess business carbon performance. The results of the carbon footprinting presented in this paper is specific to pavement resurfacing, pavement marking, bulk lamps replacement and grass cutting operations, undertaken at different site locations in the UK, namely: an urban, semi-urban and rural environment. The results indicate that the PAS2050 life cycle methodology can offer businesses a robust carbon evaluation framework that can identify areas of carbon hotspots and establish reduction opportunities and inform the development of reduction hierarchy, whilst providing for the biggest potential for carbon reduction.

The carbon emissions results reveal that materials production and their delivery to site are areas of carbon hotspots, which present an important aspect of sustainability decision for highway designers, managers and maintainers to deliver low-carbon service. This conclusion supports and promotes a less energy intensive or green construction materials manufacturing process i.e. using renewable energy sources (e.g. the use of Bio-Diesel (B20)) in place of carbon-intensive petroleum diesel or upgrading existing manufacturing facilities to be energy-efficient. In addition, long design life highway, the use of materials sourced and manufactured at source closer to site, the use of recycled and secondary materials sourced locally (closer to sites) and delivered in bulk can significantly reduce the overall embodied carbon. Therefore, it is crucial that the site location, materials haulage distance to site, and pavements design life are included in the decision-making process, when evaluating highway maintenance carbon reduction options. The approach implemented in this paper can also be used by highway authorities and contractors to identify areas of carbon hotspots and develop reduction strategy across their business value chain.

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APPENDIX D : ENGD PAPER 4

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Development and Implementation of a Life Cycle Carbon Tool for Highway Maintenance

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Abstract: The highway maintenance sector within the UK consumes considerable amounts of natural resources and accounts for a large amount of carbon emissions. The need to improve and enhance the environmental and emissions performance of the highway maintenance sector is crucial in helping the construction industry to meet the British government's desire for a low-carbon and sustainable infrastructure, and ultimately tackle the impacts of climate change as indicated in the UK's low-carbon transition plan. If this desire is to be realised, accounting for and reducing emissions contributions from this sector cannot be overlooked. This presents a challenge for highway designers, managers and maintainers, considering the associated business and Corporate Social Responsibility (CSR) image impacts. Thus, there is need for a consistent, project-focused carbon assessment tool, underpinned by a robust Life Cycle Assessment (LCA) methodology that can analyze and account for emissions holistically, and provide for emissions reduction across the core highway maintenance process value chain. This paper presents the development and business implementation of a project-focused and process-based life cycle carbon evaluation tool following the Publicly Available Specification (PAS) 2050 protocol. This is to identify areas of emission hotspots, opportunities for reduction, and then establish a reduction hierarchy that can allow emissions reduction efforts to be prioritized in life cycle terms. A life cycle carbon evaluation tool was developed to facilitate this. A case study was then undertaken and the results demonstrated the analytical capacity of the tool, and its potential to support highway owners, designers, managers and maintainers in order to produce and integrate credible emissions information into highway maintenance decision-making processes. Although, the implementation of the tool presented here is specific to road pavement resurfacing works undertaken at different site locations, the tool can also be used to account for emissions from other core highway maintenance processes, such as road marking, street lighting works and grass cutting, with potential for extension into other areas such as the evaluation of full environmental impacts (e.g. Toxicity, Acidification and Ozone formation) associated with highway maintenance processes.

Key Words: Highway Maintenance; Decision-making; Low-carbon emissions; Life Cycle Assessment tool; Carbon Measurement

1.0 Introduction

The commitment to reduce carbon emissions, in response to the concerns of climate change impacts from industrial processes; has become imperative for industrial sectors to deliver a low-carbon agenda (Escarameia, 2011), with the public sector setting specific emissions reduction targets to achieve this. Carbon emissions reduction is now a matter of legal (BIS, 2010 DECC, 2010) and financial responsibility across industrial sectors; particularly within the UK. This is supported by the emerging findings from the strategic review of the UK's construction industry capacity to meet the challenge of its low-carbon agenda, undertaken by the Innovation and Growth Team (IGT), on behalf of the UK government's Department of Business, Innovation and Skills (BIS, 2010), which emphases the industries responsibility. It further suggests the importance of a new construction design paradigm, supported by new carbon analyses and assessment methodologies that can account for emissions and other environmental issues holistically and support business decision-making across the business value chain.

The amount of carbon emissions from civil infrastructure (i.e. from construction and maintenance), and highways in particular, are largely unknown because of the complexity associated with its assessment. If emission reduction targets and the low-carbon agenda are to be achieved, accounting for and reducing emissions from this sector cannot be overlooked. As such, emissions reduction performance from highway infrastructure maintenance is now being considered as an integral part of tender selection criteria by highway clients (Fox et al., 2011).The intention is to integrate emissions accounting and reduction into the investment decision-making process. This presents a challenge for highway contractors, designers, managers and maintainers considering the business and Corporate Social Responsibility (CSR) image impacts. Thus, there is a need for a consistent, project-focused carbon assessment tool that can allow highway owners, designers, managers and contractors to analyze and account for emissions holistically across core highway maintenance operations such as pavement resurfacing, road patching, road marking, street lighting (Bulk lamp replacement) and grass cutting. This tool should be underpinned by a robust Life Cycle Assessment (LCA) methodology that can provide for the biggest potential emissions reduction across the highway maintenance value chain, by establishing emissions reduction hierarchies to support business decision-making.

The literature review of existing UK-based carbon evaluation tools within the civil infrastructure sector reveals that such tools with such overriding carbon assessment scope do not exist, given that the majority of the tools focus on assessing emissions from a specific core highway maintenance process only. In most cases, these tools show a lack of clear scope and system boundary definitions, fail to promote full life cycle emissions assessment and demonstrate insufficient analytical rigor in delivering comparable emissions from other processes. Thus, this paper presents the development and implementation of a project and process-based life cycle carbon evaluation tool based on the Publicly Available Specification (PAS) 2050 protocol. This tool is specific to core highway management and maintenance business operations.

The paper provides a literature review of existing international and UK-based carbon calculator tools for highway works, followed by a brief description of the tool produced and the methodology that underpinned its development process. Case studies are then used to demonstrate the business implementation of the tool for pavement resurfacing works undertaken in an urban environment. The paper further presents sensitivity analyses based on observed site variables (e.g. Fuel type, distance to site and mode of transport), and interpretation of the case study results to support business decision-making and prioritizing emissions reduction efforts across the operation value chain. Although the results presented by the tool are specific to carbon emissions expressed in carbon equivalent (CO_2e) associated road resurfacing works, but the tool can also be used to account for emissions from other specific core highway maintenance processes, such as: road marking, street lighting works and grass cutting.

1.1 A Review of Existing International and UK-based Carbon Evaluation Tools

The need to evaluate and reduce carbon emissions from infrastructure construction, management and maintenance as part of the government’s emissions reduction initiatives is well documented in the government’s emissions reduction agenda and policies (DECC, 2010 DEFRA, 2008).This section presents a review of existing carbon calculation tools in the public domain, aimed at identifying the best available techniques for business emissions assessment from industrial activities including highway construction and maintenance work.

The review focuses on the analytical capacity of the tools in life cycle terms, scope, system boundary definitions and associated drawbacks.

Carbon evaluation tools developed internationally and by the UK Government's national infrastructure delivery agencies (e.g. highway management and maintenance delivery agencies), and private businesses (contractors and suppliers) were areas of primary focus. The reasons for this is that majority of these tools were developed as a direct response to the need to accelerate efforts to reduce the increasing concentration of carbon emissions in the atmosphere, the UK government's national low-carbon agenda and the strategic response to the government's legally binding emissions reduction responsibilities provided by the UK's Climate Change Act and the Carbon Reduction Commitment (DECC, 2010 DEFRA, 2008).

In 2008, the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) convened a multi-stakeholder partnership across industries, government agencies, academia and non-profit making organizations to develop a product (goods and service) emission Life Cycle Accounting and Reporting protocol. The protocol provides international requirements and guidance for organizations to quantify and report their emissions inventory publicly and promotes global acceptance. The emissions protocol and resulting tools were expected to provide businesses with a robust framework to enable them to make an informed choice to measure, manage and report emissions associated with goods and services across their product life cycle (Bhatia et al., 2008). Although, the tools promote product emissions life cycle assessment, and its consideration in the business decision-making process, the tools depend on a products single environmental impact (global warming) for the decision-making process.

The transport system and the supporting infrastructure within the global economy have been conceived to have a clear scope and means to make a significant reduction in global emissions. The highway construction, operation and maintenance accounts for 13% of global carbon emissions and 23% of associated energy consumed (Zammataro, 2010). To this end, the International Road Federation (IRF) in conjunction with its global technical partners in 2010 developed a carbon evaluation tool specifically for road infrastructure construction projects, and fully compatible with the emissions assessment guideline provided by the Intergovernmental on Climate Change (IPCC). The tool provides a structured hierarchy for data input from materials production and transportation, pre-construction and on-site activities, so as to avoid data quality problem. The emissions associated with waste management are however excluded from the assessment (TRL, 2010 Zammataro, 2010). In the UK, similar study was undertaken Transport Scotland in 2010, which commissioned Halcrow Limited to develop a Carbon Management System (CMS) to enable highway designers integrate carbon analysis into the highway design processes, informed carbon analyses and optimization through design and construction processes. The study resulted in a range of carbon footprinting and assessment tools called CMS (Fox et al., 2011). The case studies undertaken using the CMS demonstrates the analytical capacities of the range of tools, although limited in scope, for example, does not consider end-of-life treatment emissions in its carbon assessment approach (Fox et al., 2011).

Furthermore, the Highways and Environment Agencies (HA and EA) developed carbon calculators, as part of their Sustainable Development Action Plan (SDAP) to meet the government's legally binding emissions reduction commitments, and reduce carbon emissions from infrastructure. The purpose of these tools is being to evaluate the agencies' emissions from construction and highways activities and associated transport within the remit of their business operations. These tools primarily focus on site activities, enabling works and associated transport carbon emissions. One major drawback observed is the tools' inability to produce emissions information that can support business decision-making across the business life cycle, since the emissions inputs from end-users of the construction products are excluded from the emissions assessed. In addition, their voluntary nature justifies why their general uptake and implementation within the construction industry is low. The tools simply offer an introductory approach to emissions calculations for construction and highway professionals during site operations (HA, 2008 Nisbet *et al.*, 2001)

Construction materials and construction techniques employed during construction process have significant impact on associated process emissions. An updated carbon emissions estimator tool has been developed by the Transport Research Laboratory in the UK (TRL, 2006) to estimate emissions savings from selected construction techniques and alternative construction materials e.g. aggregates (use of primary or recycled and secondary aggregates), whilst promoting emissions and costs benefits. A sensitivity analysis undertaken by TRL using the tool showed that the binder content of construction materials has significant impact on the embodied carbon, due to relatively high embodied energy associated with the construction material production. Employing specific UK data within the case studies, the results showed that emissions savings can be achieved through the use of more sustainable practices and materials in the construction process (TRL, 2010). However, emissions impact based on materials quality and local conditions (e.g. road congestion) were excluded from the emissions assessed. As such, a complementary study by Thomas et al (2009) produced an extension of the tool methodology to provide a decision support tool for emissions assessed from aggregate sourcing options, aggregate quality, transportation and local conditions, which were not considered in the initial TRL tool. The case study undertaken based on the tool shows a significant reduction in emissions in cases where site derived waste is reprocessed and reused. This study concluded that emissions associated with aggregate sourcing are not simply a function of the materials type, but also local conditions such as road speed, material haulage distance and congestion (Thomas et al., 2009).

Similar emissions evaluation tool developed by the Transport Research Laboratory (TRL) is the asphalt production embodied carbon evaluation tool. This tool represents the document Asphalt Pavement Embodied Carbon Tool called asPECT (TRL, 2009). The methodology that underpins the tool is consistent with the British Standard BS EN 14040: Environmental Management – Life Cycle Assessment: Principles and Framework, the PAS2050 protocol, and cradle-to-site boundary condition. The tool has created an industrial standard approach to evaluating life cycle embodied carbon associated with asphalt materials production and delivery to site. Tarmac and Midlands Quarry Products Limited (MQP), major asphalt manufacturers and aggregate suppliers in the UK, have adopted the asPECT methodology within their business operations, and developed project-focused embodied calculators for materials embodied carbon assessment, following the asPECT tool's capacity to account for emissions from conventional road pavement material and emissions levels of equivalent Low Energy Asphalt (LEA) products (MQP, 2008 Tarmac, 2008 TRL, 2009). Although these tools have been used extensively within Tarmac and MQP's business streams, a detailed assessment of the tools revealed no clear system boundary definition, and emissions assessed exclude site activities. The tool mainly focuses on emissions from asphalt production and delivery to site, which does not produce enough information to support adequate project life cycle decision-making.

Following the literature reviewed above, the lack of representative business emissions data, a structured data collection approach, limited knowledge and skills in the area, and lack of consensus on a single functional unit upon which highway emissions could be measured or estimated, have been seen as a challenge when developing a life cycle business emissions assessment tool and possible emissions reduction agenda. However, the increasing demands for life cycle emissions to be integrated into civil infrastructure management and maintenance investment decision-making present an obvious need to develop a life cycle carbon evaluation tool that can quantify and manage carbon emissions, by producing a credible business life cycle carbon emissions inventory to support emissions reduction investment decision-making, and allow emissions reduction efforts to be prioritized.

2.0 Highway Carbon Evaluation Excel Tool

The growing need for a carbon evaluation tool to integrate life cycle emissions into highway maintenance decision-making investment is becoming more urgent. This section of the paper presents the scope, system boundary definitions and the background to the PAS2050 methodology that underpinned the proposed carbon evaluation tool. The tool structure and data requirement definitions are also presented.

2.1 The Tool Scope and System Boundary Definition

The purpose of the carbon evaluation tool developed is to provide highway owners, managers, designers, maintainers, and contractors with a life cycle framework to produce a credible and representative highway maintenance emissions inventory. To achieve this, a project specific process-based life cycle carbon evaluation tool based on PAS2050 protocol (BSI, 2011) is presented specific to highway maintenance works. The protocol defines the methodology that underpins the emissions evaluation tool. The tool allows emissions from highway maintenance activity-oriented and task-oriented models to be accounted for at the design and construction stages for two business models: Business-to-Customer (B2C) and Business-to-Business (B2B). These models are consistent with the “Cradle-to-grave” and “Cradle-to-gate” boundary conditions. Both boundaries allow material, energy (e.g. fossil fuel) inputs from raw material acquisition, materials production, associated transportation, site activities and final disposal/recycling of associated waste to be assessed.

The core highway maintenance processes considered here include: - pavement resurfacing, bulk lamp/lantern replacement, grass cutting and pavement marking. The declaration for the life cycle carbon emissions assessed is expressed per scheme of the core highway maintenance process undertaken, which is the functional units adopted throughout the tool.

2.2 Background to PAS2050 Methodology

The proposed carbon evaluation tool accounts for emissions from core highway maintenance operations in a manner that complements the LCA approach based on the recommendations from the Society of Environmental Toxicology and Chemistry and the principles and framework provided by the International Organization for Standardization on environmental management (ISO, 2006). The LCA approach has being accepted by the highway industry as a methodological approach that can measure the key environmental impacts and emissions from materials and energy inputs (Huang et al., 2009), since its provides the sector with a system-based approach that promotes a methodology that can measure, manage and reduce emissions holistically, and supports business decision-making using quantitative data (Carbon Trust, 2011 Treloar *et al.,* 2004)

Within this study, the carbon evaluation tool capacity and its implementation process are underpinned by the life cycle methodology described in the Publicly Available Specification (PAS2050) standard (BSI, 2008, 2011). This is an independent Life Cycle Assessment (LCA) standard developed by the British Standard Institute (BSI) in 2008 (updated in 2010). The standard was built on existing ISO 14040 and 14044 LCA standards, but adds significantly more direct guidance to increase its emissions information accuracy and comparability of emissions assessed (Itoya *et al.*, 2012 Sustain, 2010). Its robustness is inherent in the significant inputs received from stakeholders (international and experts across businesses and academia), through formal consultation and multiple technical working groups (BSI, 2011). The approach presents a step-by-step iterative process-based life cycle approach following the scope and system boundaries defined. Based on the data quality rules recommended by the PAS2050 standard, the data collected is analyzed, and the results interpreted within the scope and system boundaries defined and the emissions results were expressed as carbon equivalent (CO_2e).

2.3 The Tool Structure and Data Requirement Definitions

The challenge to undertake business or process carbon accounting can be more complex, considering the length of time, quality of data, resources and skill required. Itoya et al. (2012) had developed a life cycle methodology framework based on the PAS2050 protocol specific to highway infrastructure maintenance. A carbon evaluation tool (an Excel tool) is designed following the principles and requirements of the life-cycle methodology framework. Previous studies by Itoya et al. (2012) have shown that implementing the framework for emissions assessment will offer highway owners and their supply chains, and designers a life cycle technique that can identify areas of emissions hotspots, and opportunities to prioritize emissions reduction efforts. Thus, the carbon evaluation tool is structured to account at design and construction stages, the activity-oriented and task-oriented emission categories from highway maintenance schemes.

2.3.1 The Design Stage

At the design stage, the carbon evaluation tool can estimate the expected carbon budgets (embodied, operational and end-of-life carbon emissions) associated with highway maintenance processes based on estimated quantities. Various methods can be employed by the designer to adequately collect these estimated data, which may include:

- Direct estimate of materials and waste quantities from CAD drawings, a bill of quantities or historical scheme data.
- Collation of vehicles and plant inventory, estimated fuel consumption and distance travelled to site.
- Expected hours of work on site and plant fuel consumption rates.

The embodied carbon from the anticipated materials and waste can also be estimated during the design stage. This will provide the highway owners, designers, managers and maintainers with relevant information to support design decisions, particularly in areas of materials selection, sourcing options and delivery to site; and the construction and waste management methods to be adopted. This is to ensure that materials selected are certified by sustainability criteria (responsible sourcing), whilst providing justification for the construction and waste management methods adopted (Sihabuddin and Ariaratnam, 2009).

2.3.2 Construction Stage

At this stage, the total energy inputs (Diesel, petrol, gas and electricity) from materials extractions, transportation to factory, through the product manufacturing, delivery to site, operatives transportation (including inbound and outbound journey), plant energy consumed on site, waste transported off-site and recycling processes are accounted for. These input energy values are measured directly where possible using the approach recommended by the authors (Itoya *et al.*, 2012) or from a suitable inventory. This approach requires the carbon assessor to ensure that all site vehicles and plant are filled up with fuel (for example diesel) before the site visit, and the start mileage recorded. At the end of each shift, the vehicles and plant are re-filled with fuel and a record made of the end mileage. These primary data are then converted to their respective carbon emissions using appropriate emission factors from publicly available databases provided by the UK government's Department for Environment, Food and Rural Affairs (DEFRA) and Department of Energy and Climate Change (DECC). This allows highway maintenance operation representative emission information to be evaluated and justified for future use in estimating.

2.3.3 Emission Factors

The publicly available databases provide the standard emissions factor data sets that can convert the measured or estimated data quantities (such as materials and fuel) into their respective carbon footprint. These standard emission factors are drawn from two main sources:

(a) University of Bath Inventory of Carbon and Energy (ICE) Version 2.0 (Hammond and Jones, 2011).

This is a publicly available database produced by the University of Bath in the UK. It provides life cycle emission factors that allow “Cradle-to-gate” emissions from business processes to be assessed. These emission factors can evaluate materials embodied carbon, which account for the total primary energy consumed and associated emissions from raw material acquisition, transportation, manufacturing and transportation to point of use(Hammond and Jones, 2011). A major update within the current ICE (version 2.0) database is the inclusion of emission factors that can convert tonnes of materials to its corresponding emissions equivalent (kgCO_2e) that were not in the previous versions.

(b) The 2011 Guidelines for DEFRA /DECC’s Greenhouse Gas (GHG) Conversion factors for Company Reporting (DECC, 2010). These emission factors allow businesses and individuals to calculate carbon emissions equivalent (kgCO_2e) from a range of activities for energy consumption. The Guidelines are developed by the UK’s Department of Energy and Climate Change (DECC) with the support from the Department of Environment, Food and Rural Affairs (DEFRA) in 2010 and updated in 2011.

It is important to know that the emission factors employed in this tool are UK specific, and represent the energy consumed calorific value only, which excludes “Well-to-Wheel” emission impacts. However, major changes have been included in the UK’s emission databases to reflect the UK’s actual emissions energy consumption. These changes include a reduction in the UK electricity grid average emission factors based on relative electricity imported, and fuel supplied at public refueling stations, which now have a national average proportion of biofuel blended in them. This allows a reduction on the average emission factors compared to 2009 and 2010 emissions factors (DECC, 2010).This however can easily be changed for different locations and countries.

3.0 The Tool Implementation

To use the Excel carbon evaluation tool and ensure that the emissions information are accurate, credible and representative of the highway maintenance process assessed, three basic iterative steps are required based on the PAS2050 methodology standard for life cycle emissions assessment. These three basic steps include:

(1) Start-up:- Setting objective, select core business process for assessment and engage relevant stakeholders.

(2) Emissions Calculation: - Service emissions calculation requires the building of a process map, collecting data and calculating the process carbon emissions within the scope and system boundary defined.

(3) Updating the system.

The three iterative steps are further developed into six emission assessment interfaces presented in Figure1.

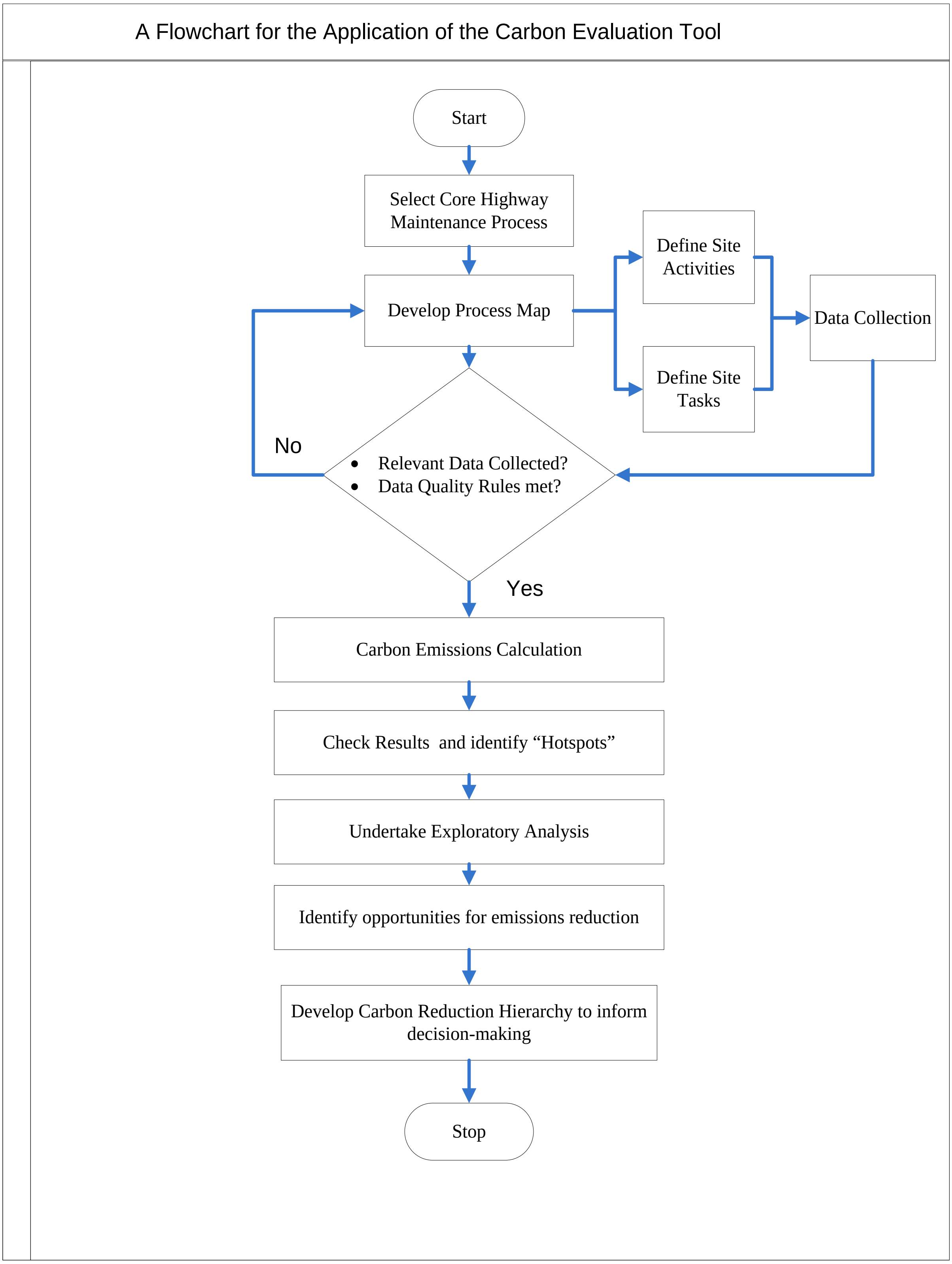


Figure 1. A flowchart for the application of carbon evaluation tool

3.1 Carbon Evaluation Tool Application

The tool allows the users to select and define core highway maintenance processes to be assessed, detail of the site location (urban, semi-urban and rural locations), material type, delivery distance to site (including return journey), mode of transportation, site plant inventory, type of waste transported off-site and distance covered using a pull-down menu. The material quantities, types and amount of energy consumed during materials production, transportation, and site activities energy use, waste transport and recycling are entered into the data input interface defined in the Excel tool. The tool is user friendly and introduces input and output Excel cells for each required data, and resulting emissions information. Pull-down menus have also been introduced within the worksheets to allow users select options for emissions evaluation. As soon as an option is selected the associated emission factors are obtained by the tool and multiplied by the relevant parameters. The tool requires both estimated and measured data sets that meet “Data Quality Rules” recommended by the PAS2050 standard (BSI, 2011) to ensure that the emissions assessed are accurate, reproducible and comparable.

The estimated activity and task-oriented emissions categories are evaluated using the distance-based method and estimated quantity of materials and waste from the contractor’s Bill of Quantities (BoQ), in addition to CAD drawings produced during the design stage.

The construction process activity and task-oriented emissions categories are evaluated using the fuel-based method based on direct measured data (e.g. Quantity of fuel consumed) from site activities. The fuel-based emissions factors are commonly recommended over time-based factors because they provide emissions information that is less sensitive to site emissions variability.

In areas where the materials embodied carbon emissions information are provided by the material manufacturers / suppliers, the tool allows such data to be entered into the calculator directly to assess the different emissions categories as required by the tool.

3.2 Activity-Oriented Emissions Category

The activity-oriented emissions category defines the embodied carbon, operational carbon and end-of-life carbon.

- **Embodied carbon:** Within the remit of the tool, this category accounts for the total energy consumed, and the resulting emissions inputs from materials production, which includes the raw materials extraction, the manufacturing process, and associated transportation (cradle-to-gate) customer's gate or to site depending on the system boundary defined.
- **Operation carbon:** This emissions category accounts for total energy consumed (e.g. liters of diesel consumed) and emissions input associated with site operatives travelled (including outbound and inbound journey) and subsequent energy consumed by plant during site operation.
- **End-of-Life carbon:** This emissions category accounts for the total energy consumed (e.g. fuel consumed in liters), and the associated emissions input from waste transportation off-site to the designated waste site. These emissions also include the waste recycling or disposal process energy consumption.

3.3 Task-Oriented Emissions

The task-oriented emissions model defines the corresponding upper-level activity-oriented emissions. This allow users to calculate the emissions from the selected core highway maintenance process and identify areas of emissions hotspots, and associated reduction opportunities that can inform a reduction hierarchy.

The sum of these emissions represents the highway maintenance process carbon footprint expressed as kgCO_2e (carbon equivalent).

3.4 Sensitivity Analysis

It is important to note that carbon emission results can be misleading, particularly where the methodology that underpinned the approach has no clear scope and system boundary definition, and the approach is not consistent. Therefore, the interpretation of emission results through exploratory analysis, based on identified emissions variables, are crucial in order to produce representative and credible emissions information to support business decision-making. Within the context of this study such an analysis approach was employed. This helps to identify areas showing emission hotspots to inform the development of a reduction hierarchy. The default highway maintenance process specific emissions variables, those considered within this study to date are:

- Energy types (e.g. Petroleum diesel, Biofuel blended diesel and biodiesel)
- Distance to site (km) – including inbound and outbound journey
- Mode of transportation (Road, Rail and Ship including supply of materials)
- Scheme design life and maintenance requirement

4.0 Case Studies

Twelve case studies on pavement resurfacing work across different site locations within the UK were undertaken, and the results are presented to demonstrate the analytical capacity of the tool, and it's potential to support business decision-making in carbon terms. The emissions evaluation processes for each of the pavement resurfacing schemes were carried out at the design and construction process stages for different site locations. In both stages, the activity-oriented (embodied, operational and end-of-life emissions) and task-oriented (materials manufacturing, material delivery, operatives transport, site activities, waste transport off-site and waste recycling) emissions categories were evaluated across the processes value chain.

The road pavement resurfacing activities include the planing-off of existing road surfaces to a nominal depth of 100mm and 40mm as shown in table 2 and reinstating the planed surfaces with a thin layer of tack coat (K140), binder course and surface course, or with surface course only. Tables 1 and 2 present a detailed description of the road resurfacing work undertaken across the urban, semi-urban and rural locations. In this study, an urban location is defined as a high density built-up area, where vehicles are allowed a maximum speed of 30mph due to congestion, and the semi-urban and rural locations are defined as low density less built-up areas, where vehicles are allowed speeds above 30mph.

4.1 Data

A detailed description of the case studies (road pavement resurfacing) considered for emissions evaluation and a summary of estimated data are summarized in Table 1, while Table 2 presents a summary of measured data (including total area road resurfaced, materials quantity, distance to site, number of trips and associated quantity of waste) during the pavement resurfacing process for different site locations.

Table1. A Summary of Emissions Data during the Pavement Design Stage

Location	Area (m^2)	Courses	Estimated Quantities During Scheme Design							
			Depth (mm)	Quantity of Asphalt (tonne)	Total Quantity (tonne)	No of Trips	Tack Coat (litres)	Polymer Modified Bitumen (kg)	Waste generated (tonnes)
Urban	4122	Binder Surface	60 40	404.9 375.9	781.0	39	3541	190	600
	2593	Binder Surface	60 40	53.8 236.5	290.0	15	1689.5	122	220
	1384	Binder Surface	60 40	138.6 126.2	264.8	14	1890	25	194
	1024	Binder Surface	60 40	140.1 93.4	233.5	11	1024	25	100
Semi urban	7628	Surface	40	695.7	613.6	31	3359	250	630
	4184	Surface	40	381.6	381.6	20	2092	50	362
	3821	Surface	40	348.5	348.5	18	1911	125	300
	1530	Surface	40	139.6	139.6	7	765	100	145
Rural	2500	Surface	40	228.0	228.0	12	1250	0	238
	638	Surface	40	59.0	59.0	3	319	0	60
	540	Binder Surface	60 40	73.9 49.3	123.0	6	270	0	93
	400	Binder Surface	60 40	54.7 37.0	92.0	5	200	0	40

Table 2. Summary of Data during Pavement Resurfacing Works

Location	Scheme Description	Measured Quantities						
		Total area (m^2)	Quantity of Asphalt (tonne)	Distance (km)	No of trips	Tack Coat K140 (litres)	Polymer Modified Bitumen (kg)	Waste generated (tonnes)
Urban	Planing-off existing surface to a nominal depth of 100mm and reinstated with AC 20 HDM BIN 40/60 DES and MasterPaver 10 SURF 40/60 40mm	4122	758	97	38	2062	200	600
		2593	294	93	15	1493	125	220
		1284	290	92	15	642	25	195
		1024	237	90	12	1024	25	90
Semi urban	Planing-off existng surface to a nominal depth of 40mm and reinstated with SMA wearing course type C (55PSV) to 40mm thick	6728	622	84	32	3395	250	625
		4184	399	90	20	2092	50	360
		3821	339	113	17	1911	125	330
		1530	140	97	7	765	100	140
Rural	Planing-off existing surface to a depth of 100mm and reinstated with SMA 40mm (inlay) or AC 20 HDM BIN 40/60 DES and MasterPaver 10 SURF 40/60 40mm	2500	318	85	16	1250	0	120
		638	60	119	3	319	0	40
		540	110	77	6	270	0	100
		400	109	87	6	200	0	40

5.0 Results and Discussion

The carbon evaluation tool can employ both estimated and measured data to evaluate activity and task-oriented emissions. This approach is consistent with the life cycle methodology described by the PAS2050 standard. The results of the application of the developed tool to road pavement resurfacing works across different site locations have been presented. The tool allows users to identify areas of emissions hotspots and associated opportunities for reduction at the design and construction stages, and ensures that emissions reduction efforts are prioritized across the process value chain.

5.1 Activity and Task-Oriented Emissions

Based on the estimated and measured sets of data, both the activity-oriented (Embodied carbon, Operational carbon and End-of-life carbon) and task-oriented emissions (material manufacture, delivery to site, operative transport, site activities, waste transportation and recycling) were calculated.

Tables 3 and 4 indicate the average percentage emissions contributions of each activity and task from the pavement resurfacing process across various site locations (urban, semi-urban and rural environment) considered in the case study. For all locations, using both estimated and measured data sets, the results indicate that the materials embodied carbon accounts for on average 76.69%, 83.21%, 71.64% and 78.46%, 83.75%, 76.48% respectively of the total process Carbon Footprint (CF), while the materials manufacturing process and their delivery to point of use account for on average 71.05%, 75.65%, 65.25% and 5.80%, 7.03%, 6.38%, and 74.61%, 77.68%, 68.34% and 3.85%, 6.07%, 8.14% respectively. These results suggest that for highway maintenance operations, the materials manufacture in particular and their delivery (embodied carbon emissions) to a lesser extent are emission-intensive and important sustainability elements to consider when decisions on reducing carbon are taken. Focusing on these areas is crucial in order to deliver a low-carbon highway maintenance service. This result agrees with the outcomes of initial life cycle assessment studies undertaken by the Athena Institute (2006) and Durucan and Korre (2009) on road pavement materials, which concluded that construction material production and their delivery processes are energy intensive, and produce the most significant emissions impact compared to other activities. These studies further suggest that the energy consumption and emissions impact associated with road pavement material manufacturing process are attributable to the feedstock energy in the bitumen used (Athena Institute, 2006 Durucan and Korre, 2009). However, a study by Zapata and Gambatese (2005) concluded that the energy consumed and emission impacts from asphalt material manufacture are mostly affected by the asphalt mixing process and drying of the aggregates (Zapata and Gambatese, 2005). However, this study argued that the increase in embodied carbon associated with asphalt material manufacture and delivery is attributable to the energy type (e.g.100% mineral diesel) consumed during the asphalt manufacturing process and delivery to point of use.

Table 3. Percentage Emissions by Activity and Task Oriented Modes based on Estimated Data

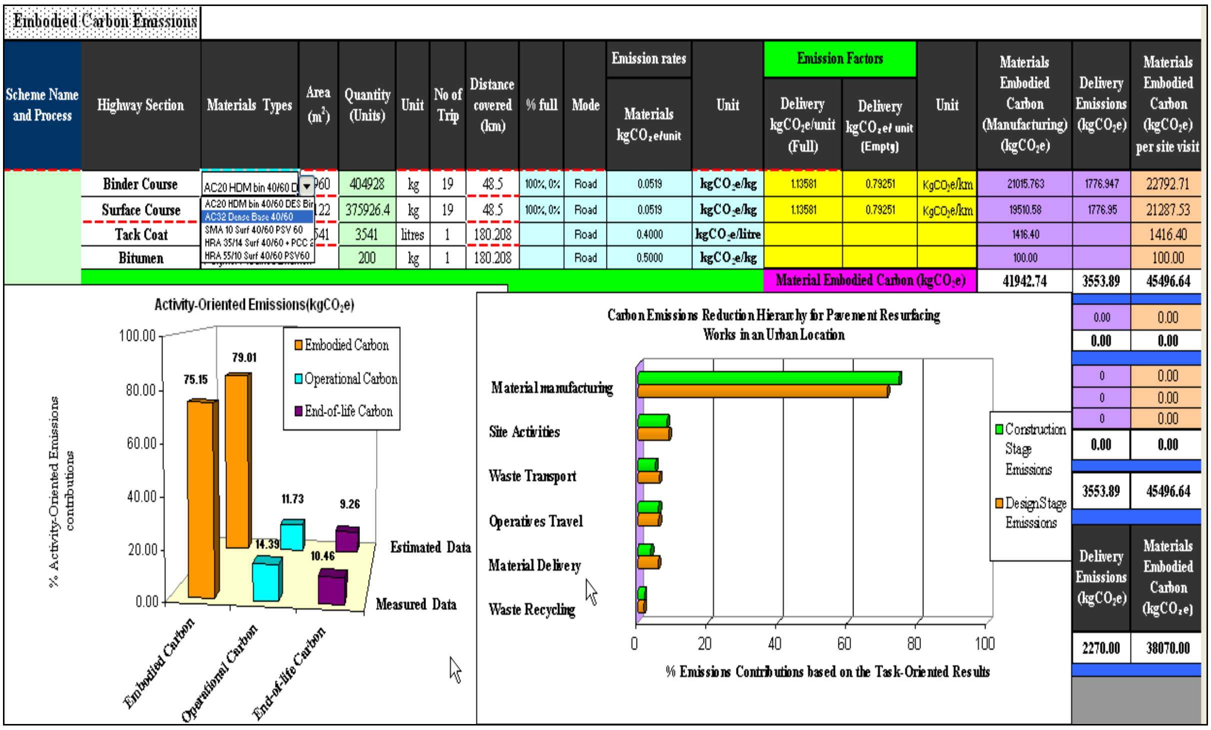
Location	S/N	% Material Embodied carbon	% Operational carbon	% End-of-life carbon	% Material production	% Material Delivery	% Operatives Transport	% Site Activities	% Waste Transport	% Waste Recycling
Urban	**1**	78.56	12.16	9.28	73.1	5.5	5.4	6.8	7.0	2.2
	2	72.58	19.15	8.27	66.8	5.7	7.3	11.9	6.3	2.0
	3	76.00	14.61	8.60	70.8	5.9	6.2	8.4	6.6	2.0
	4	79.60	15.08	5.32	73.5	6.1	6.4	8.7	4.1	1.3
	% Average	**76.69**	**15.25**	**7.87**	**71.05**	**5.80**	**6.33**	**8.95**	**6.00**	**1.88**
Semi-Urban	1	85.1	10.65	4.25	78.1	7.0	3.7	6.9	1.4	2.8
	2	84.84	10.93	4.23	77.9	6.9	5.6	5.4	1.3	2.9
	3	84.43	11.28	4.30	77.5	6.9	4.3	6.9	1.9	2.6
	4	78.46	19.31	4.23	69.1	7.3	10.2	9.1	1.4	2.8
	% Average	**83.21**	**13.04**	**4.25**	**75.65**	**7.03**	**5.95**	**7.08**	**1.50**	**2.78**
Rural	**1**	72.67	17.35	9.98	65.6	7.0	8.6	8.7	7.3	2.7
	2	65.60	31.65	2.75	59.3	6.3	11.3	20.4	0.3	2.4
	3	75.02	22.69	2.29	71.1	3.9	9.9	12.8	0.1	2.2
	4	73.27	21.46	5.27	65.0	8.3	8.6	12.9	4.1	1.2
	% Average	**71.64**	**23.29**	**5.07**	**65.25**	**6.38**	**9.60**	**13.70**	**2.95**	**2.13**

Table 4.Percentage Emissions by Activity and Task-Oriented Modes based on Measured Data.

Location	S/N	% Material Embodied carbon	% Operational carbon	% End-of-life carbon	% Material production	% Material Delivery	% Operatives Transport	% Site Activities	% Waste Transport	% Waste Recycling
Urban	**1**	75.15	14.39	10.46	70.67	4.48	5.91	8.48	7.92	2.54
	2	79.94	13.6	6.46	76.65	3.29	4.36	9.24	4.85	1.62
	3	78.53	12.13	9.34	74.74	3.8	5.14	6.99	7.05	2.29
	4	80.22	14.29	5.49	76.39	3.83	4.99	9.3	4.13	1.36
	% Average	**78.46**	**13.60**	**7.94**	**74.61**	**3.85**	**5.10**	**8.50**	**5.99**	**1.95**
Semi-Urban	**1**	85.25	10.08	4.68	82.69	2.56	2.96	7.12	1.74	2.93
	2	86.02	9.92	4.06	79.74	6.28	5.35	4.56	1.26	2.8
	3	86.47	8.83	4.71	77.73	8.73	3.78	5.05	1.77	2.94
	4	77.27	18.55	4.18	70.55	6.71	10.58	7.97	1.42	2.76
	% Average	**83.75**	**11.85**	**4.41**	**77.68**	**6.07**	**5.67**	**6.18**	**1.55**	**2.86**
Rural	**1**	83.85	13.87	2.29	72.64	11.21	7.46	6.41	1.14	1.14
	2	71.46	26.66	1.88	65.11	6.36	9.07	17.59	0.22	1.65
	3	78.96	18.04	3	71.13	7.83	5.2	12.84	0.29	2.71
	4	71.63	14.93	13.43	64.49	7.14	7.08	7.85	3.56	9.88
	% Average	**76.48**	**18.38**	**5.15**	**68.34**	**8.14**	**7.20**	**11.17**	**1.30**	**3.85**

In an urban location, Figure 2 presents the screenshot of the output from the tool of both the activity and task-oriented category results based on the estimated and measured data sets. This helps the tool users to compare emissions results from estimated data (during design stage) and measured data (during site operation). This carbon information is essential to support highway designers and manager's decision-making in terms of the material selection, delivery option, procurement and logistic planning. Figure 2 further presents areas of emission hotspots and emissions reduction hierarchy for both data sets, and provide emission information that can support highway designers, maintainers and managers' decision-making. This emission information will allow emissions reduction efforts to be focused and prioritised, particularly in area of materials selection and delivery options (and ensure that decisions on highway maintenance works are certified by sustainability criteria.

Figure 2. Emissions reduction hierarchy based on estimated and measured data

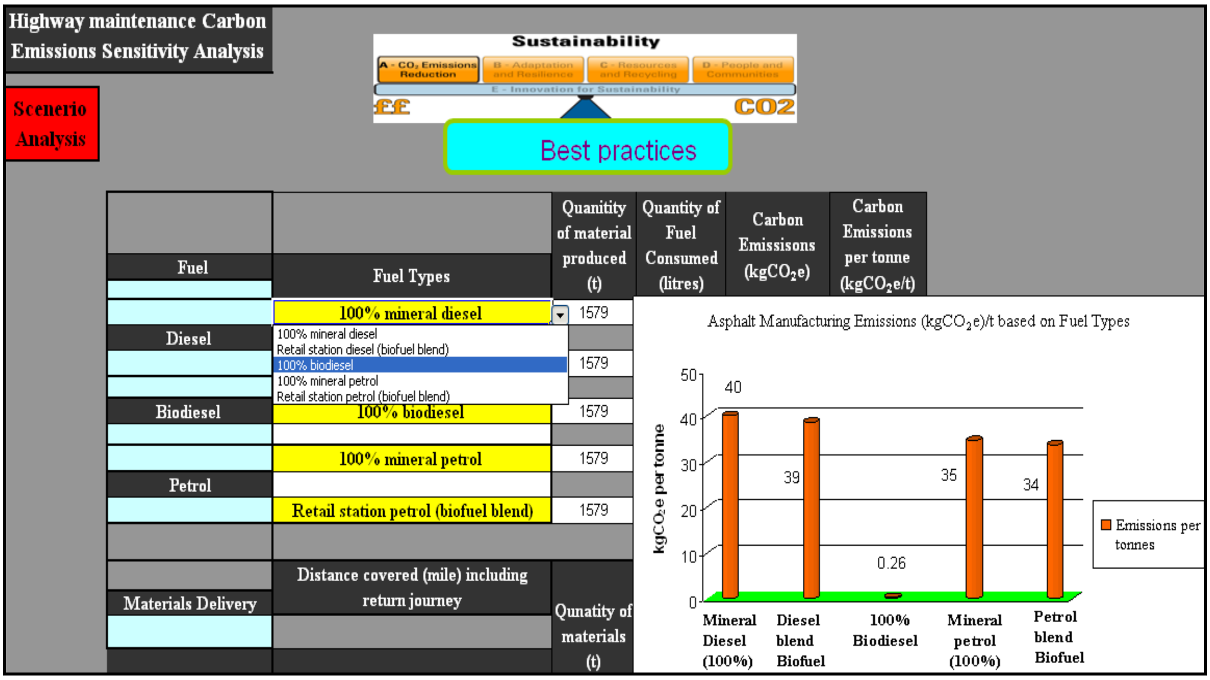


5.2 Sensitivity Analysis

Business decisions made without adequate understanding of the emission information results can be misleading and catastrophic. With this in mind, the tool provides an interface within the carbon evaluation tool to undertake exploratory analysis of the calculated emission results based on the identified emission site variables.

Within the case studies, material embodied carbon and transportation emissions have been identified as areas of emission hotspots and emission reduction priority areas to deliver low-carbon pavement resurfacing. However, this paper has argued that asphalt material manufacturing and delivery emissions are attributable to the energy type consumed during the manufacturing process (see Figure 3) and delivery. Figure 2 has showed that asphalt manufacturing emissions account for, on average 71.05% and 74.61% for both estimated and measured data sets in an urban location, whilst Figure 3 indicates that emission rates can be influenced by using alternative fuel types during the asphalt manufacturing process. By using the exploratory interface (scenario analysis) provided by the tool, and assuming the same quantity of 100% mineral diesel, diesel blended biofuel, 100% mineral petrol, petrol blended biofuel and 100% biodiesel as fuel consumed during asphalt manufacturing process, the emission rates of unit of asphalt produced decrease as follows: 40kgCO_2e/t, 39kgCO_2e/t, 35kgCO_2e/t, 34kgCO_2e/t and 0.26kgCO_2e/t respectively. The emission rates for each unit of asphalt produced decreases directly with fuel type consumed. This result suggests that biofuels are far less carbon intensive compared to 100% mineral diesel and petrol. The question of addressing the technological challenge of using this type of fuel at a commercial scale for asphalt production remains an open question among asphalt manufacturers.

Figure 3. Asphalt manufacturing Emissions using different fuel types



The asphalt delivery emissions and mode of transportation were found to show a direct linear relationship with the distance to site and transport mode. As expected the emissions rate reduces with reduced distance to site and transportation mode. These results are presented as output from the tool as indicated in Figures 4 and 5. The figures indicate that the emission associated with asphalt material delivery to site has a direct relationship with the distance and mode of transport. This suggest that asphalt materials procured from sources closer to site (responsible sourcing) and delivered in bulk can significantly reduce transportation emissions. Figure 5 indicates that shipping and rail transportation modes are low-carbon and sustainable transport options compared to road mass haulage.

Figure 4. Asphalt delivery emissions based on distance (km)

					Road			
Materials Delivery	Distance covered (mile) including return journey	Trips	Qunatity of materials (t)	Total Distance covered (km)	Quantity of fuel consumed (litres)	Transport Emissions ($kgCO_2e$)	Transport Emissions ($kgCO_2e/t$)	Transport Emissions ($kgCO_2e/km$)
Aggregate Transport by Road	Delivery Aggregate to factory (miles)							
Articulated >33t & Distance to factory	1147	79	1579	291408.08		275131.48	174.24	0.94
			1579	145704.04		137565.74	87.12	0.94
			1579	72852.02		68782.87	43.56	0.94
Materials Delivery to site	Delivery of materials to site (miles)							
Tipper Wagon (Rigid >17t & Distance Travel	49	79						
		79						
		79						
Operatives Transport	Operatives Travelled (miles)							
Diesel van (1.74 to 3.5t) & Distance Travel	150							

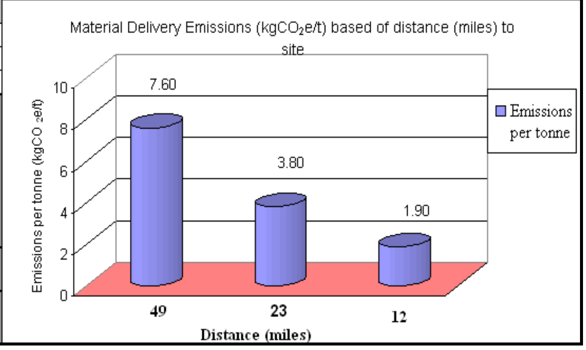
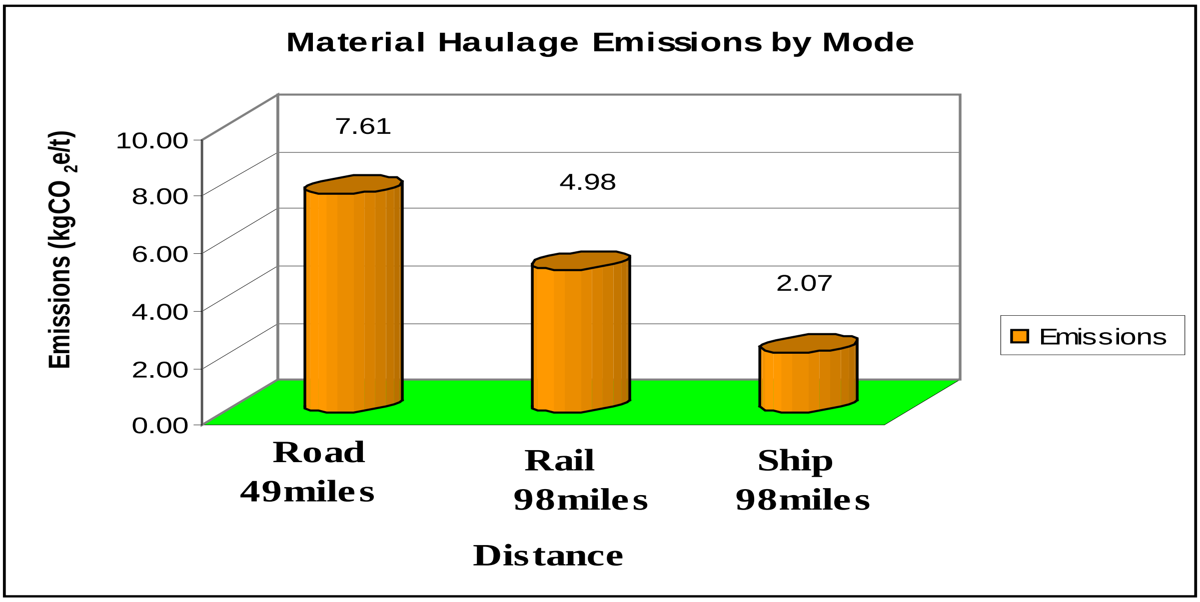
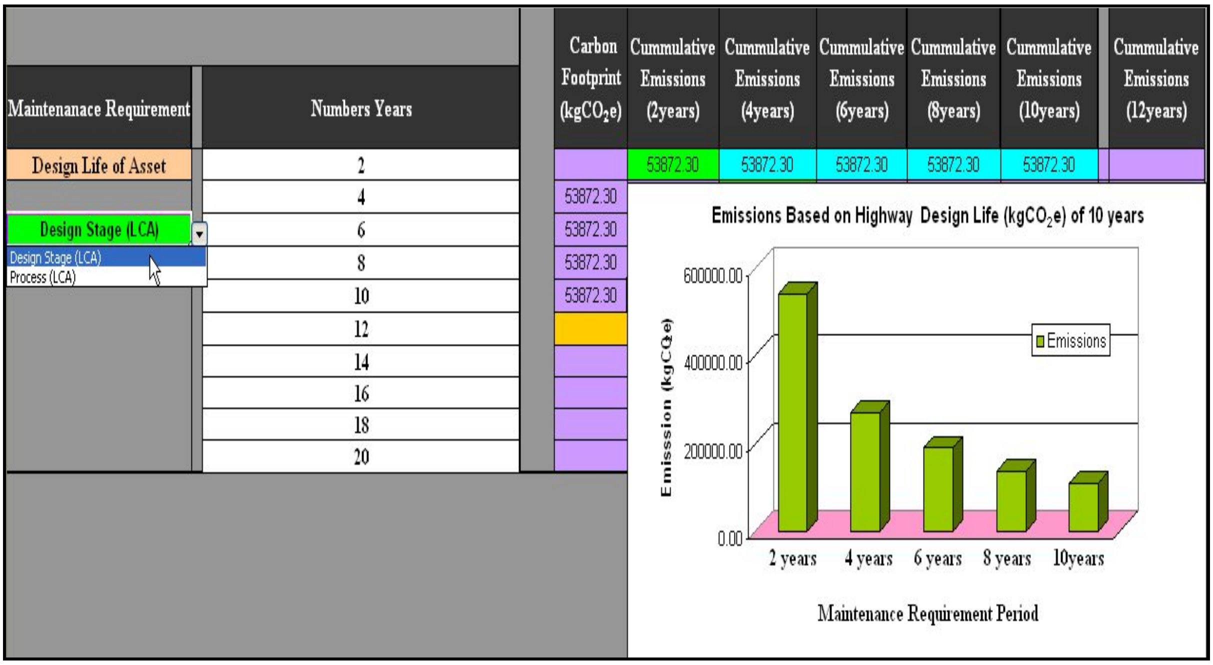


Figure 5. Materials Delivery Emissions based on Mode of Transport



The maintenance requirement or the frequency of maintenance of an asset is a function of the design life. Figure 6 indicates the emissions impact of road maintenance with a design life of 10 years. With a two year maintenance cycle requirement (frequency of maintenance), the estimated emissions over the ten year period increased by 80%, compared to a 20% increase in emissions (including the initial construction emissions) for one-off maintenance over the ten year period. This result suggests that by reducing asset maintenance requirement, the emissions impact associated with the asset over its design life cycle can be reduced significantly.

Figure 6. The Design Life of a Highway Maintenance and Emissions Impact.



6.0 Conclusions

Evaluating carbon emissions from highway maintenance processes is an important step in reducing its impact. This paper provides the development and implementation of a process-based LCA carbon evaluation tool based on the Publicly Available Specification (PAS) 2050 protocol specific to core highway maintenance processes. It accounts for emissions at design and construction stages, identifies areas of emissions hotspots and establishes reduction opportunities and a reduction hierarchy.

The carbon evaluation tool provides its users with project specific process-based life cycle emissions information which are partitioned into activity-oriented and task-oriented emission modes. By employing this approach, the materials embodied operational and end-of-life carbon emissions were accounted for. These emissions categories were further analyzed to obtain the material manufacturing and delivery, operatives transport, site activity, waste transportation and waste recycling emissions.

The case studies present the materials embodied carbon (≥ 70% of carbon footprint) and operational carbon (≤ 23% of the carbon footprint) as areas of emissions intensity across all site locations considered at both design and construction stages, while the materials manufacturing and site activities account for on average, in excess of 65% and less than 9% respectively of the embodied and operational carbon. In addition, previous studies concluded that asphalt embodied carbon is attributable to the feedstock energy in bitumen used for asphalt manufacturing. However, the results of the case studies indicate that embodied and operational carbon for pavement resurfacing works can be influenced by energy type (e.g., biofuels) consumed during the asphalt production and delivery to site. These results suggest that selecting the renewable energy type (e.g. biofuel) in the asphalt manufacturing, sourcing aggregates material locally (source closer to site), transporting the materials in bulk and considering less energy intensive site operations, can significantly reduce the embodied carbon and operational carbon. However, the challenges for asphalt manufacturers to use 100% biodiesel in place of 100% mineral diesel for asphalt manufacturing at a commercial scale, or sourced sustainable materials at distance closer to the point of use remain an open question among asphalt material manufacturers and suppliers.

A carbon emissions reduction hierarchy was presented that can help highway owners, designers, managers and maintainers make informative emissions reduction decisions, in addition to ensuring emissions reduction efforts are adequately prioritized at all relevant stages of the maintenance processes.

The case studies results have further demonstrated that the Excel carbon evaluating tool is user-friendly, unique and robust in its ability to provide credible LCA emissions information to support the highway maintenance sustainable decision-making process. However, the accuracy and reliability of the emissions information largely depends on the quality of the data employed. Therefore, effective stakeholder engagement and representative process map for the core highway maintenance process selected for emissions assessment are crucial in ensuring that the “Data Quality Rules” recommended by PAS2050 are adequately met for all data collected. Although, the implementation of the tool presented in this paper is specific to road pavement resurfacing works undertaken at various locations, the tool can also be used to evaluate carbon emissions associated with other core highway maintenance processes, which include road marking, street lighting works and grass cutting in any site environment.

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APPENDIX E : SURVEY TEMPLATES

• Pavement Resurfacing Work

1.0 Brief introduction

The lists of information below are in line with the contents of the project brief on Carbon Hierarchy and Whole Life Cycle Research Project (Attached), which was sent to all contracts by Katrina Hazell (Sustainability Manager) on the 27th February 2009. This information is important to enable Emioshor evaluate our carbon expenditure to PAS2050 within selected core highway processes, which we operate on different contracts in the UK.
This approach is a Whole Life Cycle technique and is aim to identify areas of maximum carbon usage within our processes. Please, note as stated in the project brief, all information provided /learned from this survey will be subject to strict confidentiality.

2.0 Programme.

To be efficient in the deployment of this project, Emi will work with process managers/owners from various contracts, visit site, and capture as much information as he can.
Below are some of the activities among others Emi will be involved with when he visits the various contracts.

- Safety Induction (To be decided by each contract)
- Meeting with process managers to understand the core processes of delivery.
- Meeting with supply chain representatives
- Site visit.

3.0 Detail activities/information for each initial areas of investigation

- **Pavement Marking**
- **Grass cutting**
- **Pavement Resurfacing**
- **Bulk Lamp and Lantern change**

- **Pavement Making Work**

Line Markings Whole Life Carbon Assessment Project Contract Name:-		
1	Type of contract and name of client:	
2	Nature of work undertaken:	
3	Safety Induction (When and with who):	Tel: Time: Location: Safety Officer:
4	Process manager/owner:	
A	**Traffic Management (TM).**	
5	Type of TM (including total units):	
6	Network type:	
7	Transport to/off site (Including Mode and Type):	
8	Operation of TM on site:	
9	• Type of Energy consumed :	
10	• Amount of energy consumed :	**Specify the quantity of energy below**

11	Electricity	
12	Gas	
13	Gas oil	
14	Petrol	
15	Diesel	
16	Fuel Oil	
17	Burning Oil	
18	Water	
19	Others (**Specify if any**)	
B	**Removal of Existing lining.**	
20	Existing lining removal techniques:	
21	Equipment use:	
22	Transport to/off site:	
23	Volume and type of Waste generated:	
24	Waste management techniques: • Recycled (Volume/percentage):	
	• Send to Landfill (Volume/percentage):	

25	**If recycled, quantity of energy consumed**?	
26	**Frequency of waste recycling or send to landfill**	
27	**% by volume of present waste to overall waste to landfill or for recycling.**	
28	**Distance covered (by waste from site to landfill or recycled plant)**	
29	• Type of Energy consumed (**Specify**) : • Amount of energy consumed :	 **Specify quantity of energy below**
30	Electricity	
31	Gas	
32	Gas Oil	
34	Petrol	
35	Diesel	
36	Fuel Oil	
37	Burning Oil	
38	Water	
39	Others (**Specify if any**)	

40	**Expected life of line material before removal:**	
C	**Application of line markings**	
41	• Application techniques:	
42	• Material (s) type :	
43	• Volume of material(s) used	
44	• Transport to /off site	
45	Volume and type of waste generated (**if any**)	
46	Waste management techniques	
47	• Recycled: (Volume/percentage)	
48	• Landfill(Volume/ percentage):	
49	• Reuse	
50	Type of Energy consumed (**Specify**):	
51	• Amount of energy consumed : **(Site Operations**)	**Specify the quantity of energy below**

52	Electricity	
53	Gas	
54	Gas oil	
55	Petrol	
56	Diesel	
57	Fuel Oil	
58	Burning Oil	
59	Water	
60	Others (**specify if any**)	
61	• Sources of site lightings	
62	Type and amount of energy consumed for site lightings	
63	**Expected Design Life of product (s):**	
64	**Expected Product (s) Life Warranty:**	

Summary

Line Markings : Whole Life Carbon Assessment Project Contract Name:-		
Materials		
1	❖ Total volume of material(s) used:	
	❖ Percentage from recycled source:	
Distance Travelled:		
2	❖ Total Distance travelled (materials, equipment, waste and workforce)	**Specify below as required.**
3	❖ From **contract to depot**:	
4	❖ From **depot to site**	
5	❖ From **site to back depot**	
6	❖ **Mode and Type of Transport**	
Waste:		
7	❖ Total waste generated	
8	❖ Total waste disposed to Landfill	
9	❖ Total waste recycled	
10	❖ **Distance covered by waste (Site to depot and then, to landfill or recycling site):**	

11	❖ **Mode and type of transport**	
12	**If recycled, type and quantity of energy consumed:**	
Energy consumed (Site Operations plus transport from depot to site (RTN))		
13	Total Electricity:	
14	Total Fuel :	
15	Petrol	
16	Diesel	
17	Water	
18	Gas	
19	Gas Oil	
20	Fuel Oil	
21	Burning Oil	
22	Others (**specify if any**)	
23	**NB: (Transport, TM, removal , applications , site lightings and others**	
24	Total number of workforce per shift:	
25	Volume of work completed per shift:	
26 **Information to be obtained form supply chain and manufacturer (materials extraction, manufacturing and transportation** **Boundary condition: Cradle to gate plus transportation.**		
27	Product type and manufacturer:	
28	Location of manufacturer:	
29	Contact details:	

30	Total energy consumed for extraction of raw materials plus transportation:	
31	Total energy consumed for product (s) manufacturing	
32	Additional energy to preserve product (s)?	
33	% of raw materials from recycled source(s):	
34	Total distance covered by product (s) to supply chain	
35	Total distance covered by product(s) from manufacturers to contracts.	
36	**Additional energy require to preserves the product(s) while in contracts?** : **If yes , what quantity:**	
37	Sum of energy consumed from materials extraction, manufacturing plus transportation to supply chain then to contracts	
38	**Expected Design life product (s)**	
39	**Expected product(s) Warranty**	

- **Grass Cutting Works**

Grass Cutting/Litter Picking Whole Life Carbon Assessment Project Contract Name:-		
1	Type of contract and name of client:	
2	Nature of work undertaken:	
3	Safety Induction (When and with who):	Tel: Time: Location: Safety Officer:
4	Process manager/owner:	
A	**Traffic Management (TM).**	
5	Type of TM (including total units):	
6	Network type:	
7	Transport to/off site (Including Mode and Type):	
8	Operation of TM on site:	
9	Type of Energy consumed :	
	Amount of energy consumed :	**Specify the quantity of energy below**

10	Electricity	
11	Gas	
12	Gas oil	
13	Petrol	
14	Diesel	
15	Fuel Oil	
16	Burning Oil	
17	Water	
18	Others (**Specify if any**)	
19	**Site work**	
20	Work arrangement	
21	Type of equipment (s)	
	Consumables (including herbicide)	
22	Transport to /off site (including equipment, materials and workforce)	
23	• Type of energy consumed (**Site Operations**)	
	• Amount of energy consumed	**Specify the quantity of energy below**
24	Electricity	
25	Gas	

26	Gas oil	
27	Petrol	
28	Diesel	
29	Fuel Oil	
30	Burning Oil	
31	Water	
32	Others (**Specify if any**)	
33	**Expected Design life of product** (I.e. how many times do you undergo grass cutting/litter picking per year?)	

Summary

Grass Cutting /Litter picking :Whole Life Carbon Assessment Project Contract Name:-		
	Materials	
1	❖ Total volume of materials used (including other consumables and herbicides):	
	Distance Travelled:	
2	❖ Total Distance travelled (materials, equipment and workforce	
3	❖ From **contract to**	

	depot:	
4	❖ From **depot to site:**	
5	❖ From **site to depot:**	
6	❖ **Mode and Type of Transport:**	
	Waste:	
7	Volume of : ❖ Green waste ❖ Litter waste (Percentage of) : Paper Plastic aluminium metals Cans Others	**Specify below**
8	❖ Total waste disposed to Landfill	
9	❖ Total waste recycled	
10	❖ Total waste Reuse	
11	❖ **Distance covered by waste (Site to depot and then, to landfill or recycling site):**	
12	❖ **Mode and type of transport**	
13	**If recycled, type and quantity of energy consumed:**	
14	**Frequency of waste recycling or send to landfill**	
15		

	% by volume of present waste to overall waste to landfill or for recycling.	
16	**Distance covered (by waste from site to landfill or recycled plant)**	
Energy consumed (Site Operations plus transport from depot to site (RTN)		
17	Total Electricity: (Transport, TM, Removal, applications, site lightings and others)	
18	Total Fuel : • Petrol	
19	• diesel	
	• water	
	• Gas	
	• Gas Oil	
	• Fuel Oil	
	• Burning Oil	
	• Others (Specify if any)	
	(Transport, applications, TM , waste, depot lightings and others)	
20	Total number of workforce per shift:	
21	Volume of work completed per shift:	
22 **Information to be obtained form supply chain and manufacturer (materials extraction, manufacturing and transportation** **Boundary condition: Cradle to gate plus transportation.**		
23	Product type and manufacturer:	
24	Location of manufacturer:	

25	Contact details:	
26	Total distance to contract	
27	Total energy consumed for extraction of raw materials plus transportation:	
28	Total energy consumed for product (s) manufacturing	
29	Additional energy to preserve product (s)?	
30	% of raw materials from recycled source(s):	
31	Total distance covered by product (s) to supply chain	
32	**Total distance covered by product(s) from manufacturer to contracts.**	
33	**Is additional energy required to preserve the product(s) while in contracts?** :	
	If yes , what quantity:	
34	Sum of energy consumed from materials extraction, manufacturing plus transportation to supply chain then to contracts	
35	**Expected Design Life of product(s)**	
36	**Expected product(s) Warranty**	

• Pavement Resurfacing works

Resurfacing and patching works Whole Life Carbon Assessment Project Contract Name:-		
1	Type of contract and name of client:	
2	Nature of work undertaken:	
3	Safety Induction (When and with who):	Tel: Time: Location: Safety Officer:
4	Process manager/owner:	
A	**Traffic Management (TM).**	
5	Type of TM (including total units):	
6	Network type:	
7	Transport to/off site (Including Mode and Type):	
8	Operation of TM on site:	
9	• Type of Energy consumed : • Amount of energy consumed :	 **Specify the quantity of energy below**
10	Electricity	

11	Gas	
12	Gas oil	
13	Diesel	
14	Fuel Oil	
15	Burning Oil	
16	Water	
17	Others (**specify if any**)	
B	**Preparation for resurfacing and patching works**	
18	Type of Equipment required	
19	Transport to/off site	
20	• Plane off existing road surface (techniques) : • Preparation for patching works:	
21	Volume and type of Waste generated	
22	Waste management techniques: • Recycled (Volume/percentage) • Landfill (Volume/percentage)	
	• Reuse	
23	**If recycled, type and quantity of energy consumed:**	

24	**Frequency of waste recycling or send to landfill**	
25	**% by volume of present waste to overall waste to landfill or for recycling.**	
26	**Distance covered (by waste from site to landfill or recycled plant)**	
27	• Type of Energy consumed (**Resurfacing or Patching) :** • Amount of energy consumed :	 **Specify quantity of energy below**
28	Electricity	
29	Gas	
30	Gas oil	
31	Diesel	
32	Fuel Oil	
33	Burning Oil	
34	Water	
35	Others (specify if any)	
C	**Relaying road surfaces/ patching works**	
36	• Material (s) type : • Volume of material(s) used	
37	Material processing	

	techniques	
38	Application techniques	
39	Transport to /off site	
40	Volume and type of waste generated.	
41	Waste management techniques	
42	• Recycled (Volume/percentage) • Landfill(Volume/ percentage)	
43	• Reuse	
44	• Type of Energy consumed : • Amount of energy consumed (**Resurfacing & Patching works**)	**Specify the quantity of energy consumed below**
45	Electricity	
46	Gas	
47	Gas oil	
48	Diesel	
49	Fuel Oil	
50	Burning Oil	
51	Water	

52	Others (specify if any)	
53	Sources of site lightings	
54	Type and amount of energy consumed on site lightings	

Summary

Resurfacing and patching works Whole Life Carbon Assessment Project. Contract Name:-		
	Materials	
1	❖ Total volume of material(s) used:	
	❖ Percentage from recycled source:	
	Distance Travelled:	
2	❖ Total Distance travelled (materials, equipment, waste and workforce)	**Specify below as required.**
	❖ From **depot to site**	
	❖ From **site to depot**	

	❖ From **batching plant to site:** ❖ From **site to batching plant**	
3	**Total numbers of trucks delivered to site**	
4	❖ **Mode and Type of Transport**	
5	**Waste:**	
6	❖ Total waste generated	
7	❖ Total waste disposed to Landfill	
8	❖ Total waste recycled	
9	**Distance covered by waste (Site to depot and then, to landfill or recycling site):**	
10	❖ **Mode and type of transport**	
11	**If recycled, type and quantity of energy consumed:**	
Energy consumed (Site Operations plus transport from depot to site (RTN))		
12	Total Electricity:	
13	Total Fuel :	
	• Petrol	
14	• diesel	
	• water	
	• Gas	
	• Gas Oil	

	• Fuel Oil	
	• Burning Oil	
	• Others (**specify if any**)	
15	**NB: (Transport, TM, removal , applications , site lightings and others**	
16	Total number of workforce per shift:	
17	Volume of work completed per shift:	
18 **Information to be obtained form supply chain and manufacturer (materials extraction, manufacturing and transportation** **Boundary condition: Cradle to gate plus transportation.**		
19	Product type and manufacturer:	
20	Location of manufacturer:	
21	Contact details:	
22	Total energy consumed for extraction of raw materials plus transportation:	
23	Total energy consumed for product (s) manufacturing	
24	Additional energy to preserve product (s)?	
25	% of raw materials from recycled source(s):	
26	**Total distance covered by product (s) from manufacturer to contracts.**	
27	**Additional energy required to preserve the product(s) while on site?** :	

	If yes , what quantity:	
28	Sum of energy consumed from materials extraction, manufacturing plus transportation to supply chain then to contracts	
29	**Expected Design life product (s)**	
30	**Expected product(s) Warranty**	

• Bulk Lamp /Lantern Change Replacement Works

Bulk Lamp /Lantern Change Whole Life Carbon Assessment Project Contract Name:-		
1	Type of contract and name of client:	
2	Nature of work undertaken:	
3	Safety Induction (When and with who):	Tel: Time: Location: Safety Officer:
4	Process manager/owner:	
5	Site Location:	
A	**Traffic Management (TM).**	
6	Type of TM (including total units):	
7	Network type:	
8	Transport to/off site (Including Mode and Type):	

9	Operation of TM on site:	
10	• Type of Energy consumed :	
12	• Amount of energy consumed:	**Specify the quantity of energy consumed below**
13	Electricity	
14	Gas	
15	Gas oil	
16	Diesel	
17	Fuel Oil	
18	Burning Oil	
19	Water	
20	Others (specify if any)	
B	**Removal of existing/old lamp**	
21	Type of equipment required	

22	Transport to/off site (equipments and workforce)	
23	**Lamps /lantern removal techniques**: NB: (evaluate energy used)	
24	Volume of waste generated.	
25	Type of Waste generated	
26	Waste management techniques: • Recycled (Volume/percentage) • Landfill (Volume/percentage)	
27	• % by volume of waste reuse	
28	**Frequency of waste recycling or send to landfill**	
29	**% by volume of present waste to overall waste to landfill or for recycling.**	
30	**Distance covered (by waste from site to landfill or recycled plant)**	
31	• Type of Energy consumed : • Amount of energy consumed (Waste management) :	 **Specify the quantity of energy consumed below**
32	Electricity	
33		

	Gas	
34	Gas oil	
35	Diesel	
36	Fuel Oil	
37	Burning Oil	
38	Water	
39	Others (specify if any)	
40	**Type and volume of consumables:**	
C	**Installations of new lamp**	
41	• Type product(s) plus accessories:	
	• Quantity of product(s) installed :	
42	Installation techniques and equipment used:	
43	Transport to /off site (Workforce, waste, equipment and others)	
44	Volume and type of waste generated (During installations) if any	
45	Waste management techniques	
46	Recycled (Volume/percentage) Landfill(Volume/ percentage)	

47	Type of Energy consumed :	
48	Sources of site lightings.	
	Amount of energy consumed:	

Summary

Bulk Lamp / Lantern Change Whole Life Carbon Assessment Project Contract Name:-		
Materials		
1	❖ Total numbers of Lamp /lantern changed:	
	❖ Percentage from recycled source:	
Distance Travelled:		
2	❖ Total Distance travelled (materials, equipment, waste and workforce)	**Specify below as required.**
	❖ From **contract to depot**	
	❖ From **depot to site**	

	❖ From **site to depot**	
3	❖ **Mode and Type of Transportation**	
Waste:		
4	❖ Total waste generated	
5	❖ Total waste disposed to Landfill	
6	❖ Total waste recycled	
7	❖ **Distance covered by waste (Site to depot and then, to landfill or recycling site):**	
8	❖ **Mode and type of transportation**	
9	**If recycled, type and quantity of energy consumed:**	
Energy consumed (Site Operations plus transport from depot to site (RTN))		
10	Total Electricity:	
11	Total Fuel : Petrol	
12	Diesel	
13	Water	
14	Gas	
15	Gas Oil	
16	Fuel Oil	

17	Burning Oil	
18	Others (**specify if any**)	
19	**NB: (Transport ,TM, removal , applications , site lightings and others)**	
20	Total number of workforce per shift:	
21	Volume of work completed per shift:	
Information to be obtained form supply chain and manufacturer (materials extraction, manufacturing and transportation **Boundary condition: Cradle to gate plus transportation.**		
22	Product type and manufacturer:	
23	Location of manufacturer:	
24	Contact details:	
25	Total energy consumed for extraction of raw materials plus transportation:	
26	Total energy consumed for product (s) manufacturing	
27	Additional energy to preserve product (s)?	
28	% of raw materials from recycled source(s):	
29	**Total distance covered by product (s) from manufacturer to our contracts.**	
30	**Additional energy required to preserve the product(s) while on site?** :	

	If yes , what quantity:	
31	Sum of energy consumed from materials extraction, manufacturing plus transportation to supply chain or to contracts	
32	**Expected Design life product (s)**	
33	**Expected product(s) Warranty**	

APPENDIX F : RESEARCH PROJECT BRIEF

Project Brief and Information Required

Introduction

After comprehensive study in Central Office and research at Loughborough University on our sponsored project we are conducting a 4 year research project into whole life cycle carbon emissions in the standard core processes we operate. Emioshor Itoya is our research Graduate working hard on this project. We are now at the stage where we need your help.

In the next few months we are commencing analysis on the processes we operate including where we engage supply chain providers and Emi will be seeking to work with your process managers and owners, and supply chain representatives on contract, to determine carbon expenditure to PAS2050 in 4 Core Areas across different contract environments. We aim to understand the differences in carbon dioxide equivalent terms of using differing particular materials, processes and standards. We will footprint, HA, LA, TS, and Urban processes.

The initial areas of investigation

1. White line, removal, application and associated TM in doing the work cradle to grave.
2. Grass Cutting associated litter picking including TM and waste and repeats
3. Resurfacing associated TM, and waste
4. Bulk Lamp/Lantern Changing associated waste and TM around the works

The scope of the project will widen as we get more confident with the robustness of our approach and investigation techniques.

What we need from you.

To be efficient in the deployment of this project we need some information from you quite quickly. This information needs to be sent to Emioshor at Emioshor.itoya@bbisl.com. He is also cc'd in the email.

If you could return the second & 3rd page of this request with completed information Emi will make contact with you independently to complete the work and investigation he needs to do before May.

What will happen with the information provided

This work is the subject of an IPR agreement and is market leading in it's approach. All information provided/learned will be subject to strict confidentiality rules. We hope by including the supply chain department/contact on your contract that this message will be reinforced with any supply chain members of our communities who may be concerned regarding their products and processes.

Ultimately we will be learning about the most appropriate materials and methods in carbon terms and identifying areas where Global Warming Gases could be stripped from the processes we deliver in partnership with our clients and customers.

Many thanks for your kind assistance in this endeavour and I look forward to hearing back from you with the detailed answers to the questions posed on the attached sheet.

Katrina Hazell
Sustainability Manager BBIS

27th February 2009

White Lines Whole Life Carbon Assessment Project Contract Name:-	
<u>Question 1</u> Who is the manager of the Routine Line markings Process on your contract	Note this contact should NOT be your sustainability rep as this requires direct engagement of the LINE MANAGER responsible for THIS PROCESS on your contract
Contact Details	Tel: Email: Location:
<u>Question 2</u> When does your routine line marking programme commence and finish	Programme Start: Programme End:
<u>Question 3</u> If you use a line marking supplier(s) which company(ies) do you use and who specifically do you liaise with?	Supplier/Provider Company details: Liaison Point:
<u>Question 4</u> Who is your supply chain Department representative	Name: Contact Details:

Grass Cutting Whole Life Carbon Assessment Project Contract Name:-	
<u>Question 1</u> Who is the manager of the Routine Grass Cutting Process on your contract	Note this contact should NOT be your sustainability rep as this requires direct engagement of the LINE MANAGER responsible for THIS PROCESS on your contract
Contact Details	Tel: Email: Location:
<u>Question 2</u> When does your routine grass cutting programme commence and finish	Programme Start: Programme End:
<u>Question 3</u> If you use a grass cutting supplier(s) which company(ies) do you use and who specifically do you liaise with?	Supplier/Provider Company details: Liaison Point:
<u>Question 4</u> Who is your supply chain Department representative	Name: Contact Details:

Resurfacing Whole Life Carbon Assessment Project Contract Name:-	
<u>Question 1</u> Who is the manager of the Routine Resurfacing Process on your contract	Note this contact should NOT be your sustainability rep as this requires direct engagement of the LINE MANAGER responsible for THIS PROCESS on your contract
Contact Details	Tel: Email: Location:
<u>Question 2</u> When does your routine Resurfacing programme commence and finish	Programme Start: Programme End:
<u>Question 3</u> If you use a resurfacing supplier(s) which company(ies) do you use and who specifically do you liaise with?	Supplier/Provider Company details: Liaison Point:
<u>Question 4</u> Who is your supply chain Department representative	Name: Contact Details:

Bulk Lamp/Lantern Change Whole Life Carbon Assessment Project Contract Name:-	
<u>Question 1</u> Who is the manager of the Bulk Lamp/Lantern Change Process on your contract	Note this contact should NOT be your sustainability rep as this requires direct engagement of the LINE MANAGER responsible for THIS PROCESS on your contract
Contact Details	Tel: Email: Location:
<u>Question 2</u> When does your routine Bulk Lantern/Lamp programme commence and finish	Programme Start: Programme End:
<u>Question 3</u> If you use a Bulk Lamp/Lantern change supplier(s) which company(ies) do you use and who specifically do you liaise with?	Supplier/Provider Company details: Liaison Point:
<u>Question 4</u> Who is your supply chain Department representative	Name: Contact Details:

APPENDIX G : THE LAUNCH EVENT, ITS OUTCOMES, RECOMMENDATIONS AND FUTURE ACTION PLAN

1. Event Background.

The postscript presents a one day lunch event undertaken in the EngD sponsor's business premises. The intention was to gain insight into the participants (sponsor's internal stakeholders) shared understanding and views on the PAS2050-compliant carbon evaluation tool developed. This postscript describes the lunch event, its outcomes, and recommendations for improvement and action for future developments. The event was attended by representatives from the sponsor's Asset Management and Sustainability Teams (internal stakeholders) responsible for overseeing and implementing the sponsor's Asset management and Sustainability strategies. The event involved the head of technical services, highway asset manager-technical services, sustainability manager and practitioner. The event activities include:(1) a presentation on the carbon evaluation tool functionality, structure, data requirements and methodology that underpins the tool implementation, (2) demonstration on the tool application for carbon footprinting using primary data, and (3) send questionnaire to participants (for feedback) via email. The questionnaire (attached) emailed to participants consist of six questions design to enable the participant reactions and recommendations on the tool to be elicited. Questions (Q1, Q2, Q3, Q4, Q5 and Q6) are used to capture the participant's reactions on the tool and recommendations for improvement (see Appendix).

2. Participant Reactions and Recommendations for Improvement

Tables 1 and 2 summaries the outcomes (Q1, Q2 & Q3) of the launch event (i.e. reactions from participants) and discusses recommendations (Q4, Q5&Q6) from participants on the tool improvement.

Table 1 Reaction from Participants.

Questions	Summary of Reaction from Respondents
(Q1)	• The respondents believed that Climate Change Act (2008), its Carbon Reduction Commitment and National Indicators (NI185 and NI186: Regulatory Drivers) present the sponsor and its supply chain with legal obligation to ensure they understand and reduce their carbon footprint. • Requirements of contract specifications and tender selection processes (Commercial Driver) are other reasons given by the respondents. • The respondents thought that carbon footprinting and reduction provides evidence that the sponsor is environmentally, socially and morally responsible. The respondents indicated that the highway customers now see carbon reduction as key project performance indicators that require the contracting partners to achieve. These indicators are linked to profit payments/ contract extensions particularly in public sector contracts.
(Q2)	• The respondents believed that the carbon evaluation tool can be used by the design and operational teams to complement their existing life cycle analysis process in carbon terms and inform credible carbon reduction decision-making. • Respondents indicated that the carbon evaluation tool will offer the

	sponsor with opportunities to evaluate the true cost of its maintenance activities, and aligned its carbon footprinting with Asset Management and "Value Engineering" best practices (analysis of highway life cycle plans, whole life cost assessments, predicted cost analysis including carbon hotpots, value management and analysis of highway maintenance priorities).
(Q3)	• The sponsor's existing "Asset Management Strategy" tends to focus on whole life costs. The respondents indicated that using the current carbon evaluation tool in Asset value management exercise will enable the sponsor to review its carbon costs from life cycle perspective. This will offer the sponsor a major selling point in its Asset Management strategy and "Value Engineering" decisions.

Table 2 Recommendations for Improvement and Adoption

Questions	**Summary of Reaction from Respondents**
(Q4)	The areas within highway maintenance process the respondents believed carbon savings can be achieved: • Choice of materials to be used and "Early Contractor Involvement (ECI)" stages. Increased usage of recycled materials and reducing emissions from product manufacturing. • Improved programming of works, optimising life cycle planning, operational techniques, route optimisation and improved forecasting of winter maintenance. Integrated work programmes-combining maintenance activities "Localism agenda" and alternative transport and logistics management
(Q5)	The respondents agreed that the tool requires the following improvements: • The interfaces need to be developed further to make its more users friendly (by completing the VBA front end) and cater for more highway maintenance works and activities (e.g. reactive works). More sensitivity analysis should be added to the tool to enable more carbon reduction alternatives to be investigated e.g. alternative vehicles and alternative plant options and materials etc. • More material types, plant and vehicle options should be included in the tool's database and input interface. This will offer users with more choice and options to reduce the carbon impact of their work. Develop guidance note for the tool implementation, and future development and roll-out programme should be carefully managed.
(Q6)	The current tool can offer the sponsor with a number of business benefits: • It helps to reinforce the sponsor's existing eco policies, whilst providing the right kind of resource for project teams to make informed business decisions in carbon terms.

	• It allows project whole life and cradle-to-gate and cradle-to-grave carbon impacts to be clearly understood, catered supply chain project deliverables and drive target improvements across all the scopes of emissions. • It can also support the sponsor's bid submissions and represents a major selling point in the sponsor's Asset Management Strategy and "Value Engineering" decision-making in whole life carbon terms. • The tool underpins the sponsor's commitments to reduce its carbon and that of its customers, and allows life cycle carbon review of highway maintenance works, so that lessons learnt can be taken forward to future projects.

3. Future Developments and Conclusions

Following the recommendations (Table 2), the tool future development and roll out programme within the sponsor's and its supply chain the participants have agreed the following actions:

- Funds to complete the tool development and roll-out in the business.
- Future management of the tool which requires regular updating with future industry changes, parameters and material improvements. Appoint an "Expert "to undertake a lead role, manage the tool improvement, and update the roll-out programme and workshops (for example a focus group workshop) to train potential users. This could be extended to other Balfour Beatty (BB) businesses (BB Utilities and BB Major Civil Projects).

The participants are currently having discussions with the sponsor's "Operational Excellence Board" on the carbon evaluation tool future development, and have produce a proposal for approval by the board. The event participants believed that active use of the tool in an "improved way" will send important messages within design, construction and more importantly highways management.

Appendix

Question 1(Q1): Why is carbon footprinting and reduction important to the business and its' customers**?**
Question 2 (Q2): How useful is the carbon evaluation tool developed to the business carbon footprinting and reduction commitment and responsibility?
Question 3 (Q3): To what extent does the tool represents an improvement to the existing practice?
Question 4 (Q4): Where in highway maintenance process do you believe carbon savings can be achieved, and how can it be implemented?
Question 5 (Q5): In what way(s) can the carbon evaluation tool be developed or its' interface be improved to accommodate these areas of carbon savings?
Question 6 (Q6): What benefit will this bring to the business carbon emissions reduction agenda or existing eco policies?