Life Cycle Carbon Footprint of the North-South Corridor Road Network

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Preface

Since its establishment in 2009, TradeMark Southern Africa (TMSA) has supported the COMESA-EAC-SADC Tripartite in developing and implementing its regional integration agenda. TMSA has provided this support by focusing on regional market integration to establish a free trade area in the Tripartite region, trade facilitation, infrastructure development and industrial development. One of the work areas under the infrastructure development pillar is TMSA's support for the design, upgrade and construction of regional transport corridors.

TMSA commissioned Camco Clean Energy and The Green House to undertake a study for estimating the carbon footprint of the North-South Corridor road network (NSC) according to international best-practice standards. This was done through a life-cycle analysis approach by determining the carbon footprint of individual road links forming part of the NSC in their respective construction, maintenance, rehabilitation and operational phases. Thereafter, the individual carbon footprints of NSC roads in different phases were added to determine and analyse the overall carbon footprint of the NSC.

The study is innovative by being the first of its kind to consider and determine the contribution of a wide variety of greenhouse gasses arising from road construction activities, equipment and materials over the entire life-cycle of roads. It is also innovative by determining the carbon footprint of a road corridor that spans across a number of countries. This innovative approach has been applied to the NSC as a pilot study.

The study is accompanied by the original data files for transparency and to enable other parties to replicate the calculations in similar activities. The study is also complemented by a related study which TMSA commissioned to consider climate change challenges in sub-Sahara Africa, the policy environment conducive to climate change and transport in the Tripartite region, mitigation and adaptation frameworks that can be used for the development of the regional transport/roads sector, available financing channels that could be used for the development of the regional transport/roads sector and how the carbon footprint of regional roads can be utilised to access finance or form part of climate mitigation/adaptation actions.

TMSA began to analyse literature related to estimating the carbon footprint of road projects in late 2012. It developed a concept note for internal dissemination and presented the findings to development practitioners and public and private sector participants as part of TMSA's regional integration research network. The response to the proposition for estimating the carbon footprint of roads was overwhelming and resulted in TMSA's appointment of Camco Clean Energy and The Green House in May 2013 to deliver the study.

The TMSA lead for this study was Deon Fourie, economist/economic research analyst, knowledge management and monitoring and evaluation. The study also benefitted from reviews and comments by the UK Department for International Development. TMSA would like to thank Deon Fourie, Lolette Kritzinger-van Niekerk, Alec Joubert, Camco Clean Energy and The Green House for their valuable contribution and hard work associated with this study.

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List of Acronyms

Acronym	Definition
AADT	Average annual daily traffic
AMGB	Asphalt mix on granular base
AMSB	Asphalt mix on stabilised base
AO	Asphalt Overlay
ASPASA	Sand Producers Association of Southern Africa
BSB	Bitumen Stabilised Base
BSI	British Standards Institute
CH_4	Methane
CNCI	Cement and Concrete Institute
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents
CRS	Crushed stone
CS	Cement Stabilised
COMESA	Common Market for Eastern and Southern Africa
DBSD	Double Bituminous Surface Dressing
DBST	Double Bituminous Surface Treatment
DEFRA	UK Department of Environment Food and Rural Affairs
EAC	East African Community
ETB	Emulsion treated base
GHG	Greenhouse gas
GM	Granular material
GWP	Global Warming Potential
HFC	Hydrofluorocarbons
HRA	Hot rolled asphalt
IRF	International Road Federation
ISO	International Organisation for Standardisation
JRCP	Joint reinforced concrete pavement
km	Kilometres
LCA	Life cycle Assessment
N_2O	Nitrous Oxide
NAMA	Nationally Appropriate Mitigation Action
NAP	National Adaptation Plan
NAPA	National Adaptation Programme of Action
NSC	North-South Corridor
PAS	Publicly Available Specification

Acronym	Definition
PFC	Perfluorocarbons
ROADEO	Road Emissions Optimisation calculator
SABITA	South African Bitumen Association
SADC	Southern African Development Community
SANRAL	South African National Roads Agency
SD	Surface Dressing
SF_6	Sulphur Hexafluoride
STGB	Surface treatment on granular base
STSB	Surface treatment on stabilised base
WBCSD	World Business Council for Sustainable Development

Executive Summary

The life cycle carbon footprint is the first deliverable of a wider set of services for TMSA rendered under a project to estimate the carbon footprint of the NSC road network. The aim of the life cycle carbon footprint study is to get a baseline of the carbon impact of the NSC road network, and to understand the relative importance of the different phases of a road (namely construction, operation, maintenance and rehabilitation).

To estimate the carbon footprint first required defining the system under study so that a model could be developed. The NSC road network is 10,696 km long, spans across eight countries in Sub-Sahara Africa[1] and is comprised of 117 road links, each identified with a specific road/pavement type, geometry and geographical location. The carbon footprint was defined as greenhouse gas emissions (in kg carbon dioxide equivalents) for the infrastructure and operation of the NSC road network for a period of 50 years. The time component of the functional unit is needed to incorporate the operation and maintenance phases of the road network into the carbon footprint. A 50-year time period was chosen to incorporate a number of periodic maintenance events, which typically occur at intervals of 3-15 years, and at least one partial reconstruction of the road, estimated to occur at a frequency of 15-40 years (depending on the particular road link).

The Carbon Footprint Model

The carbon footprint model developed in the study is built up as follows:

- **Construction**: This is the initial construction of the roads in the NSC road network. The basic building blocks in the model are the materials and fuels used in the construction of 1 km of a specific road and pavement type in a particular country. For example, 1 km of asphalt concrete surface (20 mm thick, 7m wide) on cement stabilised base, in Zambia. 34 unique road sections were identified for the NSC road network. The 1 km sections are multiplied by the specific lengths of the respective NSC road links to obtain the carbon footprint of each road link. The carbon footprint of constructing the roads that make up the NSC road network is then the sum of the individual road links.
- **Maintenance**: Routine maintenance in an on-going activity, and thus this phase is made up of the materials and fuels consumed on average in a year of routine maintenance on a specific road section. As for construction, this is calculated per specific road and pavement type in a particular country, and then multiplied by the specific lengths of the NSC road links to obtain the maintenance carbon footprint per year of each road link in the NSC. These annual figures for each road link in the NSC are then multiplied by 50 to get the carbon footprint of routine maintenance over the time period considered.
- **Rehabilitation**: The rehabilitation phase is made up of periodic maintenance events (e.g. resurfacing and partial reconstruction), as distinct from routine maintenance work covered in the maintenance phase. This phase is made up of the materials and fuels consumed per rehabilitation event on a specific road section. As for construction and maintenance, this is calculated per specific road and pavement type in a particular country, and then multiplied by the specific lengths of the NSC road links to obtain the carbon footprint per road rehabilitation event per road link of the NSC. This figure then needs to be multiplied by the total number of rehabilitation events estimated for that particular road link over the 50 year time period.
- **Operation**: The fuel consumption and emissions from the traffic operating on each section of the NSC road network constitute the operation phase. These are calculated

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[1] *Botswana, the Democratic Republic of Congo (DRC), Malawi, Mozambique, South Africa, Tanzania, Zambia and Zimbabwe*

first for the base year corresponding to the annual average traffic load data available for each road link. The base year values are then extrapolated for each subsequent year of operation of the NSC road network according to estimated increases in traffic loads. This time series is then summed to give the carbon footprint of 50 years of operation of the NSC road network.

The carbon footprint model uses data from a number of different data sources. The basis is the dataset on the NSC road links provided by TMSA that provided data on the pavement types, thicknesses, road geometries and annual average daily traffic (AADT), amongst other things. GHG emissions data on the production of materials, fuels and equipment, as well as on the combustion of fuels in construction equipment and in the various vehicle classes identified for the operating phase, were sourced from the ecoinvent database. Adaptations were made to this data to make it more representative of the Southern African context. Additional industry-specific and company-specific datasets were obtained for road maintenance, rehabilitation and bitumen products, and a large number of interviews conducted with road engineers, national road agency personnel and industry experts.

Life Cycle Carbon Footprint of the NSC Road Network

The carbon footprint of the NSC road network is estimated at 1,412 million tonnes CO_2e over a 50-year time period, with the road infrastructure carbon footprint estimated at 9.5 million tonnes CO_2e (i.e. for the construction, maintenance and rehabilitation of the roads). A breakdown across the countries is shown in Table 1.

Table 1: Country-level carbon footprint of NSC road network, million tonnes CO_2e over 50 years

	Overall	Construction	Maintenance	Rehabilitation	Operation
Botswana	63	0.19	0.03	0.52	62
DRC	13	0.03	0.01	0.22	13
Malawi	67	0.13	0.02	0.55	67
Mozambique	26	0.05	0.01	0.19	26
Tanzania	137	0.18	0.02	0.73	136
Zambia	234	0.55	0.05	2.4	231
Zimbabwe	110	0.25	0.04	0.89	109
South Africa	762	0.69	0.09	1.7	759
NSC Road Network Total	1,412	2.1	0.25	7.2	1,403
Percentage Contribution to Total Carbon Footprint	100%	0.15%	0.02%	0.51%	99.3%
Infrastructure Carbon Footprint	**9.5**	**2.1**	**0.25**	**7.2**	-
Percentage Contribution to Infrastructure Carbon Footprint	100%	22%	2.6%	75%	-

South Africa contributes the most to this carbon footprint, at 54%, with Zambia the next most significant at 17%. This is due primarily to the high traffic density on the South African road links, but also due to higher infrastructure impacts. These arise because the South African roads are more than double the carriageway width of most other road links on the NSC road network, and also are constructed with the more carbon intensive asphalt concrete (relative to surface-dressing type pavements). A further contributor is the higher carbon intensity of the South African fuel mix, because of the coal-based component of liquid fuels in South Africa.

Operation of the road network (the GHG emissions from the road traffic using the road network) is by far the greatest contributor to the carbon footprint (contributing on average greater than 99% if a 50-year time period is considered, and greater than 92% across every road link). Even if a shorter time period is considered (e.g. 20 years), the contribution of the infrastructure to the total carbon footprint (i.e. of construction, maintenance and rehabilitation) is on average less than 2% (and at most 13% considering the individual road links).

The next most significant is rehabilitation. With the GHG emissions of a partial reconstruction project equivalent on average to half the emissions of the initial road construction, and each road link predicted to need between 2-4 partial reconstructions and 6-20 resurfacings, it is clear why this phase is the most significant contributor to the infrastructure carbon footprint over a 50-year time period (accounting for 75% of the GHG emissions on average, and up to 88% of the GHG emissions for some road links). This also means that the frequency of rehabilitation works is the most influential variable in determining the carbon footprint of the road infrastructure. The construction phase contributes on average 22% to the infrastructure carbon footprint, with routine maintenance contributing relatively little (less than 3% on average).

The surface dressing pavement is the predominant pavement type on the NSC road network, and was found to have the lowest carbon footprint in its construction and non-routine maintenance. GHG emissions associated with the construction and rehabilitation of an asphalt pavement were found to be up to double those of the surface dressing pavement (both on granular base). This is because the surface dressing pavement is much thinner than typical asphalt pavements, and consequently much less bitumen is used per km of road constructed (resulting in lower GHG emissions associated with producing the bitumen). In other respects, the construction of the roads are similar, with a fairly equal split in GHG emissions between on-site emission, emissions arising from transporting materials to site, emissions associated with mining gravel and emissions associated with producing road materials.

Data Gaps and Uncertainty

Given that the operation phase contributes by far the most to the carbon footprint, variables that are influential in determining the operational phase emissions contribute most to the uncertainty of the carbon footprint as a whole. The growth rate assumed for road traffic is by far the most significant variable here. However, to a degree this is inherently uncertain, as growth models are by their very nature uncertain. Also contributing to the uncertainty of the operational phase are various key assumptions, including the fact that all vehicle classes grow at the same rate, and that the average annual daily traffic (AADT) can be considered representative for the entire length of a road link. Both these factors would tend to overestimate the road traffic and thus the carbon footprint.

The carbon footprint is considered to be as accurate and complete as current data sources allow. The emissions datasets used in the study are considered to be of good accuracy and completeness, and the best available, even though these were only partially representative of the Southern African context. Uncertainty in the results is thought to arise more from the activity data applied in the study. For example, assumptions had to be made for many of the road links as to their pavement type and thickness of the layers. Furthermore, many of the key activity data are inherently variable, such as the number of periodic maintenance works to take place over the next 20-50 years.

Conclusions and Recommendations

It is clear from the results that use of the road infrastructure is far more important in terms of carbon footprint than constructing and maintaining the road infrastructure. Thus measures that reduce operational emissions are of high importance rather than reducing construction impacts (although the latter are still important). Important avenues for future research are those that look at reducing the fuel consumption of vehicles, including different road designs and pavement types, and reducing traffic congestion. Also important is looking more holistically at transport corridors and the potential emissions reductions offered by modal shifts, e.g. road to rail migration. Measures to improve road durability also offer important improvement potential, as the high rate of rehabilitation required on the roads quickly amounts to more than the emissions of the original construction. Thus, building roads with a longer design period and with more frequent seals should be investigated. There are also a number of research initiatives that look at "greener" road materials, especially the use of a higher content of recycled materials in road construction. These also offer interesting improvement opportunities, but should be carefully assessed to be certain that the use of such materials does not cause the road to require more maintenance or negatively affect the fuel efficiency of the vehicles using the roads, as was found by this study to be where the majority of the road impact lies.

1 Introduction

This report is produced as a deliverable of a project to estimate the carbon footprint over the life cycle of road projects on the North-South Corridor (NSC), which spans across eight countries of the COMESA-EAC-SADC Tripartite region. Camco Clean Energy ("Camco") has partnered with The Green House ("TGH") as well as Mr Jeff Zingel (collectively, "the project team") in order to provide the following services to TradeMark Southern Africa:

1. Estimate the life cycle carbon footprint of North-South Corridor (NSC) road network in line with international best-practice standards;
2. Analyse how this carbon footprint can be used to contribute to, or form part of, Nationally Appropriate Mitigation Actions (NAMAs), National Adaptation Plans (NAPs) and other regional and national climate change initiatives, with a particular focus on the transport sector; and
3. Describe available and potential climate change mitigation and adaptation finance and incentive mechanisms and determine how the carbon footprint, as a base, together with NAMAs, NAPs and National Adaptation Programmes of Action (NAPAs), can enable access to climate change funding and incentive mechanisms

This draft report is the main deliverable in estimating the life cycle carbon footprint in that it provides the detailed methodology followed in calculating the footprint, and provides the draft results. Section 2 outlines the scope of the study, essentially providing a summary of the Scoping Report produced as an interim deliverable of this work. Section 3 provides a description of the life cycle models used to calculate the carbon footprint, and Section 4 provides a summary of the results. Detailed results and data tables are provided in an accompanying spreadsheet. The main conclusions and recommendations that can be drawn from the work are given in Section 5.

2 Scope of the study

This chapter provides an overview of the methodology followed in the life cycle product carbon footprint of the NSC road network. A detailed Scoping Report was produced as an interim deliverable of this project, and this section summarises the key points of this report. It starts with a brief discussion on applicable global standards for product carbon footprints and a short summary of similar projects in the literature. This is followed by the main items requiring consideration in the scoping of the study, according to the requirements of ISO 14040:2006 and the GHG Protocol product standard.

2.1 Overview of methodological approach

Product greenhouse gas (GHG) inventories, also commonly known as product carbon footprints, are a subset of life cycle assessment (LCA) because they focus only one of the many impact categories typically considered in an LCA[2]. The LCA method is standardized by the International Organization for Standardisation (ISO) under the 14040 series of life cycle assessment standards, which were updated in 2006[3].

Two main bodies have been active in developing standards specifically for product carbon footprinting. The British Standards Institution (BSI), in partnership with the UK Department of Environment Food and Rural Affairs (DEFRA) and the Carbon Trust, published a Publicly

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[2] *The climate change impact category is typically termed Global Warming Potential in LCA studies.*

[3] *International Organization for Standardization, 14040:2006, Life Cycle Assessment: Principles and Framework; and ISO 14044:2006, Life Cycle Assessment: Requirements and Guidelines. Geneva.*

Available Specification (PAS) for the assessment of life cycle greenhouse gas emissions of goods and services, known as PAS 2050[4]. More recently (in September 2011), the Greenhouse Gas (GHG) Protocol, convened by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), launched the GHG Protocol Product Life Cycle Accounting and Reporting Standard (referred to as the GHG Protocol Product Standard). Both of these standards are based on the methodology of life cycle assessment (LCA), and build on the 14040 series of life cycle assessment standards[5]. Whilst they are broadly consistent with each other, they each have a slightly different focus. The Product Standard was chosen as the most relevant to follow for this work in that it is the most recently published and captures developments in the LCA method that have occurred in the years since the publication of the ISO standards and PAS 2050. Its aims are also felt to be more in line with those of this work, i.e. the Product Standard is intended to support performance tracking of a product's GHG inventory and emissions reductions over time rather than to support claims regarding the overall environmental superiority of one product versus a competing product (which is the focus of PAS 2050).

Because of the very close alignment with the ISO LCA standards and the GHG Protocol product standard, the product carbon footprint of the NSC road network is in conformance with both of these two standards. The carbon footprint is also broadly in conformance with PAS 2050, although it is not explicitly conducted according to the requirements of PAS 2050.

2.2 Road studies in the literature

2.2.1 Road LCA studies

Roads have been a popular topic in LCA, since the transport of goods is common to nearly all product LCAs, and roads thus form an input into nearly all product LCA studies. It is generally the operation of the road (e.g. the diesel burned in the truck) where the majority of the road transport impact arises, but there have nonetheless been several LCA studies that focussed particularly on road construction and maintenance (Milachowski et al., 2010; Birgisdottir et al., 2007; Hoang et al., 2005, Mroueh et al., 2001; Stripple, 2001). Carlson conducted a review of European LCAs of roads and pavements made between 1996 and 2010 (Carlson, 2011). Her primary conclusion was that the results of the studies were not directly comparable because they included, amongst other things, differences in the life cycle stages covered, differences in road construction design and differences in the number of years for which impacts were estimated. This is despite the fact the studies reviewed followed the standardised approach to LCA, as specified in the ISO 14040 series of standards. Table 2 summarises these differences, which shows that only two of these studies included all road phases and all aspects of construction (as done in this study).

A common conclusion of road LCA studies is that each road section is unique due to various reasons, such as geotechnical conditions, traffic volumes etc. (Stripple, 2001; Mroueh et al., 2001; Hoang et al., 2005). The availability of data is cited as a common problem in constructing a representative LCA, whilst the uniqueness of roads means that calculations need to be done for each individual road construction if one wants a representative result.

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[4] *British Standards Institution et al. PAS 2050:2008: Specification for the assessment of life cycle greenhouse gas emissions of goods and services*

[5] *International Organization for Standardization, 14040:2006, Life Cycle Assessment: Principles and Framework; and ISO 14044:2006, Life Cycle Assessment: Requirements and Guidelines. Geneva.*

Table 2: **Key parameters of European LCA studies (from Carlson, 2011)**

Reference	Analysis period (years)	Functional unit	Life cycle stages			
			Construction		Maintenance	Use
			Earth works	Pavement		
Häkkinen & Mäkele (1996)	50	1 km pavement, motorway		X	X	X
Mroueh et al. (2001)	50	1 km motorway	X	X	X	X
Stripple (2001)	40	1 km road	X	X	X	X
Chappat & Bilal (2003)	30	1 m^2 pavement		X	X	X
Hoang et al. (2005)	30	1 km pavement, highway		X	X	
Olsson et al. (2006)	-	1 km road	X			
Birgisdottir et al. (2007)	100	4,400 tonnes ash (1 km road)	X	X		
Huang et al. (2009)	-	30,000 m^2 asphalt surface		X		
Sayagh et al. (2010)	30	1 km pavement		X	X	
ECRPD (2010)	25	1 km pavement, 4 roads		X	X	

2.2.2 GHG emissions of roads

Whilst all Road LCA studies include GHG emissions, a few studies have been conducted which focussed only on GHGs. The particular focus of GHG studies on roads found in the literature seem to be around GHG calculators. The International Road Federation (IRF) has designed a greenhouse gas calculator specifically tailored to road infrastructure projects[6]. However, it currently covers only pre-construction and pavements and does not include maintenance activities. The calculator is a simple activity-based model, and does not provide details on data sources or emission factors.

Another GHG gas calculator is the ROADEO (Road Emissions Optimisation) calculator developed specifically for Greenhouse Gas Emissions Mitigation in Road Construction and Rehabilitation for Developing Countries under the auspices of The World Bank (The World Bank, 2011). In this model,

- A first stage calculates quantities of items of road works based on general characteristics of the project. The output of this stage is a theoretical “bill of quantities”, and the work items are broken down into “work series” reflecting the types of works.
- A second stage calculates the GHG emissions generators, based on the number of road works items and on general characteristics of the project. These generators are broken down into materials, transport, equipment, and others.

As part of the development of the ROADEO calculator, this project undertook a thorough review of other existing calculators[7], and came up with the conclusion that all tools share the same principles, and consider:

- Processed materials that are produced from basic materials in a process that generates emissions;

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[6] *Calculator for Harmonised Assessment and Normalisation of Greenhouse-gas Emssions for Roads (CHANGER), http://www.internationalroadfederation.org/files-upload/pdf-files/CHANGER_Article_May2010.pdf*

[7] *including the Australian Victoria State tool (VicRoads), the Highways Agency carbon tool, the Technical University of Denmark tool (Road-Res), the IRF GHG calculator (CHANGER), the Egis infrastructure carbon tool, and the LCPC tool (Ecorce)*

- Transport at various stages of the construction process (supply of materials to the plants, supply of materials to the site, and transport on-site) that have emission factors; and
- Construction processes with emission factors in the form of equipment emissions.

Essentially all tools are simple calculation tools that consider these generators and sum the emissions from the various stages of the construction process and from various components of the works. However, whilst the bases of the calculators are very similar, there are large differences in emission factors applied in the calculators. None of the calculators explicitly mention the methodology followed, and lack of transparency in data sources was indicated for many of the calculators.

The carbon footprint model developed in this project is also built on these principles, and draws on emission factors from various sources, including the ROADEO calculator. A detailed spreadsheet of data sources is produced in this work to address the lack of transparency indicated in similar projects.

2.3 Scope of the study

The life cycle carbon footprint is the first deliverable of a wider set of services for TMSA rendered under this project, as listed in the introduction. The scope of the study, as laid out in this section, pertains particularly to the carbon footprint component of the work. The aim of the life cycle carbon footprint study is to get a baseline of the climate impact of the NSC road network, and to understand the relative importance of the difference phases of a road (namely construction, operation, maintenance and rehabilitation).

2.3.1 The functional unit

The system under study is the NSC road network. The NSC road network is 10,696 km long, spans across eight countries in Sub-Sahara Africa[8] and is comprised of 117 road links (see Figure 1). Each link is of a defined length, width, road/pavement type, and geographical location, and together these links comprise the road network. The functional unit (the unit of measurement for the carbon footprint) is the infrastructure and operation of the NSC road network for a period of 50 years. The infrastructure component is the sum of the individual road links of the NSC road network.

The time component of the functional unit is needed to incorporate the operation and maintenance phases of the road network into the carbon footprint. The choice of 50 years is somewhat arbitrary. By comparison, a wide choice of time periods have been used in road LCA studies (from 25 to 100 years). In the case of a road, it is not possible to define a product life, because the road is continually being renewed through rehabilitation. A 50-year time period was chosen to incorporate a number of periodic maintenance events, which typically occur at intervals of 3-15 years, and at least one partial reconstruction of the road, estimated to occur at a frequency of 15-40 years (depending on the particular road link). The results should be interpreted with the chosen time period in mind (e.g. the longer the time period, the greater the contribution of the operating phase to the life cycle carbon footprint of the road). To illustrate this, the carbon footprint results are also reported for a 20-year time frame.

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[8] *Botswana, the Democratic Republic of Congo (DRC), Malawi, Mozambique, South Africa, Tanzania, Zambia and Zimbabwe*

Figure 1: Map of the North-South corridor road network, showing road conditions (as at December 2012)[9]

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[9] *The map represents the road network that includes the North-South and Dar es Salaam Corridors and parts of the Trans-Kalahari and Nacala Corridors. The road conditions (as at December 2012) are based on visual inspections and information provided by National Road Agencies. Source: http://www.tripartitegis.org/*

The life cycle carbon footprint is reported according to the functional unit, but also for the individual reference flows from which it is comprised. These are essentially the building blocks that make up the carbon footprint, and are defined for each road phase as follows:

- Construction: 1 km of a road of specific road and pavement type (in a particular country)
- Operation: 1 year of operation of a specific section of the NSC Road network
- Maintenance: 1 year of maintenance of a km section of a specific road and pavement type
- Rehabilitation: Single rehabilitation project per km of a specific road and pavement type

In the calculation of the carbon footprint, each of the reference flows are broken down into the materials and services required to fulfil the function (see section 3 for an explanation of what is included in each phase). The four road phases are then combined into the functional unit as follows:

- **Construction**: This is the initial construction of the roads in the NSC road network. The basic building blocks in the model are the materials and fuels used in the construction of 1 km of a specific road and pavement type in a particular country. For example, 1 km of asphalt concrete surface (20mm thick, 7 m wide) on cement stabilised base, in Zambia. 34 unique road sections were identified for the NSC road network. The 1 km sections are then multiplied by the specific lengths of the respective NSC road links to obtain the carbon footprint of each road link in the NSC. The carbon footprint of constructing the roads that make up the NSC road network is then the sum of the individual road links.
- **Maintenance**: Routine maintenance is an on-going activity, and thus this phase is made up of the materials and fuels consumed on average in a year of routine maintenance on a specific road section. As for construction, this is calculated per specific road and pavement type in a particular country (for example, 1 km of asphalt concrete surface on cement stabilised base, in Zambia), and then multiplied by the specific lengths of the respective NSC road links to obtain the maintenance carbon footprint per year of each road link in the NSC. These annual figures for each road link in the NSC are then multiplied by 50 to get the total carbon footprint of routine maintenance over the time period considered, and then summed across the road links to get the carbon footprint of the NSC road network as a whole.
- **Rehabilitation**: The rehabilitation phase is made up of periodic maintenance events (e.g. resurfacing and partial reconstruction), as distinct from routine maintenance work covered in the maintenance phase. This phase is made up of the materials and fuels consumed per rehabilitation event on a specific road section. As for construction and maintenance, this is calculated per specific road and pavement type in a particular country (for example, resurfacing of 1 km of asphalt concrete surface on cement stabilised base, in Zambia), and then multiplied by the specific lengths of the respective NSC road links to obtain the carbon footprint per road rehabilitation event per road link of the NSC. This figure then needs to be multiplied by the total number of rehabilitation events estimated for that particular road link over the 50 year time period. The carbon footprint of rehabilitation of the NSC road network as a whole is then the sum across the individual road links.
- **Operation**: The fuel consumption and emissions from the traffic operating on each section of the NSC road network constitute the operation phase. These are calculated first for the base year corresponding to the annual average traffic load data available for each road link. The base year values are then extrapolated for each subsequent year of operation of the NSC road network according to estimated increases in traffic loads. This time series is then summed to give the carbon footprint of 50 years of operation of the NSC road network.

Building up the life cycle carbon footprint according to the reference flows is not only necessary for a transparent model structure, but also to aid interpretation and adaptability of the model.

2.3.2 The system boundary

The system boundary for the road network is shown in Figure 2, and is made up of the four phases of the road to deliver the functional unit of 50 years infrastructure and operation. The specific inclusions and exclusions for each road phase are explained in Section 3.2 to Section 3.5, along with the process map diagrams for each of the four road phases. The maintenance phase is defined to include only routine maintenance activities, whilst periodic maintenance activities are included in the rehabilitation phase, as shown in Table 3.

Table 3: Road works included in the "maintenance" and "rehabilitation" phases of a road[10]

Works category	Works type	Works activity/operation
Maintenance	Routine pavement	Patching, edge repair, crack sealing, etc.
Rehabilitation (periodic maintenance)	Preventative treatment	Rejuvenation
	Resurfacing	Surface dressing, slurry seal, cape seal, re-gravelling etc.
	Rehabilitation	Thick overlay, mill and replace, etc.
	Reconstruction	Partial reconstruction and full reconstruction

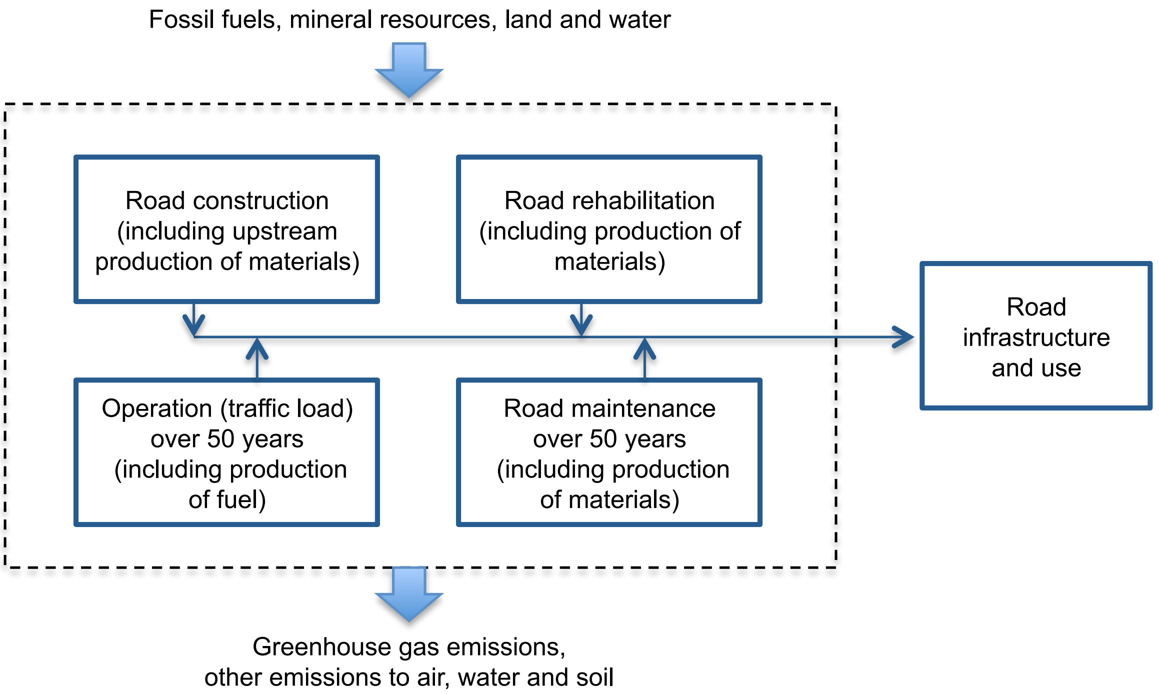

Figure 2: Road phases included in the inventory boundary of the NSC road network

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[10] *From Table D1.1 in HDM-4 Highway Development and Management Manual. Volume 4: Analytical Framework and Model Descriptions.*

The carbon footprint is calculated from an extensive inventory list of emissions to air that includes the six priority GHGs required by the GHG Protocol Product standard; namely, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs). This is because the ecoinvent database, used to provide the underlying emissions data for the carbon footprint model, considers a very comprehensive set of emissions (ecoinvent Centre, 2007). The ecoinvent database also includes emissions to water, emissions to soil and resource flows (fossil fuels and minerals). The focus of this study is on GHG emissions; however, because of the extensive data included in the ecoinvent database, the wider list of inventory flows are carried through the analysis.

Specific cut-off criteria have not been set in this study to determine exclusions, as these arise from lack of data rather than from a consideration of material contribution. The approach is rather to include processes wherever data can be found to characterise them, even if it is of a generic nature.

2.3.3 Allocation procedures

In product life cycles, processes that have multiple products for which it is not possible to collect data at the individual product level are frequently encountered. An oil refinery is a good example of such a process. In these situations, the total emissions from the common process need to be partitioned among the multiple products. The procedure by which this is done is referred to as allocation. A requirement of the GHG Protocol product standard is that the same allocation methods be applied to similar inputs and outputs within the product's life cycle. Thus, as the ecoinvent database (the primary source of data for secondary processes in the study) uses economic allocation, this is also the default method applied in the study. Economic allocation is a method whereby the inputs and emissions are allocated to the product and co-product(s) based on the market value of each when they exit the common process.

Emissions from the production of heavy equipment used in construction and rehabilitation is one area where economic allocation is not possible since economic information is not being collected for the road projects. Here, allocation is based on the estimated fraction of the total service life of the machine that the specific project represents.

2.3.4 Methodology of inventory analysis and calculation procedure to be used

Inventory analysis is the process whereby the GHG emissions for all the processes identified in the process map are quantified and compiled into an inventory table. In a subsequent step, the GHG emissions are multiplied by their global warming potentials (GWPs) to obtain the results in kg CO_2 equivalents (CO_2e)[11]. A simplified schematic of the calculation procedure for materials is shown in Figure 3. A similar procedure is followed for fuels, whereby the quantity of fuel is multiplied by an emission factor for the particular machine or vehicle in which it is burnt.

Once the inventory results are calculated for the individual materials and fuels, the results must be put on the same reference flow basis. For example, if the reference flow for road construction is 1 km, the inventory results must reflect the quantity of material or fuel required to construct 1 km of road. The results on the reference flow basis can then be summed together to calculate the total CO_2e/functional unit.

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[11] *For transparency, these are kept as two separate calculation steps so that the results are available on the individual GHG level and not just on the CO_2e level. Material production emission factors and GWPs are often combined into a single emission factor, which simplifies the calculation but loses the detail on the different GHGs emitted.*

The inventory calculations in this study are conducted in the life cycle assessment software SimaPro. This software ensures the integrity of carbon footprint calculations and allows for systemic and transparent handling of the large datasets involved.

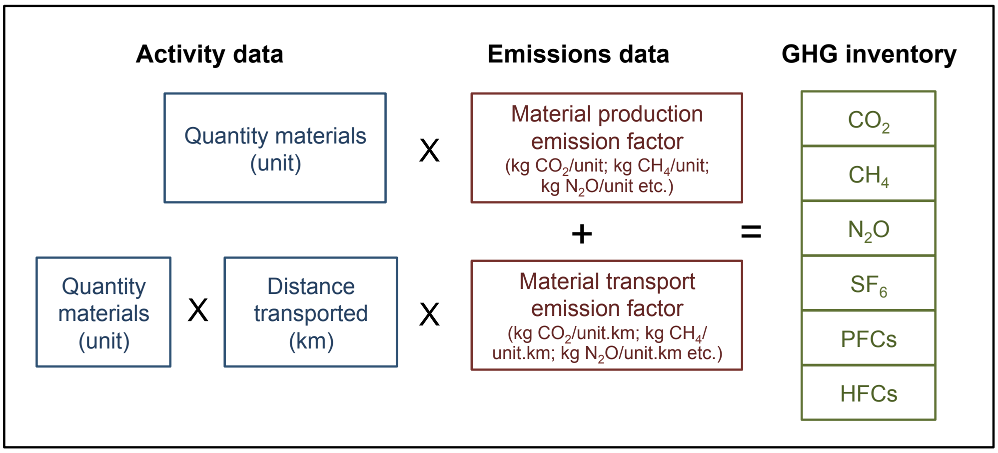

Figure 3: Schematic of inventory calculation

2.3.5 Methodology of impact assessment and subsequent interpretation to be used

Potential impact on climate change (or carbon footprint) is measured in carbon dioxide equivalence and is calculated by multiplying the amount of a GHG emitted by its global warming potential (GWP). The GWP is a measure of how much a given mass of a GHG is estimated to contribute to global warming (and by proxy, to climate change). It is a relative scale that compares the warming potential of a gas with the same mass of carbon dioxide. Emission factors used to convert GHG emissions to CO_2 equivalents are according to IPCC (2007) with a 100-year timeframe, and are listed in Table 22 in the Appendix.

While the carbon footprint is the focus of this study, other environmental impacts relevant to the road network can also be indicated because of the extensive inventory list included in the ecoinvent database. Results according to commonly applied life cycle impact assessment categories (CML 2001[12]) are thus also provided in the results spreadsheet accompanying this report.

2.3.6 Data requirements and data collection strategy

An overview of the approach taken to data collection is provided here; with Section 0 providing a detailed description of the data sources used in the life cycle models. Detailed data tables are also provided in the spreadsheet accompanying this report.

The project team were responsible for data collection, although responsibility for providing details on the NSC road network was the responsibility of TradeMark Southern Africa. Formulating the data requirements for this study therefore followed a 2-pronged approach:

1. Understanding the NSC road network and the data required to characterise this, i.e. road geometries, pavement types, etc.
2. Data required to characterise road construction projects and road operation more broadly

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[12] *The CML LCIA method is published in: Guinée et al. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, Dordrecht, 2002.*

TMSA provided a detailed dataset on the NSC road network[13], which informed the subsequent data collection needs (e.g. types of pavements to be considered). Wherever possible, the project team also sought input from TMSA wherever they have particular insight into the roads comprising the NSC network, and to leverage their expertise and experience so that the results could be as specific as possible the NSC road network.

Generic data requirements for estimating emissions from road construction, road maintenance and road operation were first formulated primarily through a wide array of carbon footprinting (and LCA) databases, literature reports and toolkits. The subsequent step in data collection was to populate the data tables with activity data as specific as possible to each section of the NSC road network. A list of potential data sources was compiled for each of the countries in the NSC, including relevant road construction and engineering companies, road operating agencies, government departments and road freight associations. Emails and phone calls were sent to attempt to establish a contact at the various companies, which was followed by further phone calls/emails aimed at explaining the project and the data request. A list of individuals and companies contacted with a request to provide input to this study is included in the data spreadsheet accompanying this report.

A relatively small number of company- and project-specific datasets were received (one routine maintenance, and two reconstruction projects). Generally there was a strong disinclination to provide quantitative information on materials. Secrecy around tenders/quotes was cited as a possible reason, as was the fact that each project is very different, so even if someone was willing to provide data, it was very difficult to do so at the level of information required for the study.

Road design manuals and toolkits were found to be a valuable source of information for road activity data, as these could be customised to the particular circumstances (e.g. climate). Industry associations were also found to be useful sources of information as they are less constrained by confidentiality concerns. The main sources of activity data form part of the description of the models of the different road phases in Section 3, with specific references given in the accompanying data spreadsheet.

Emissions data on the production of materials, fuels and equipment, as well as on the combustion of fuels in construction equipment and in the various vehicle classes identified for the operating phase, have been sourced from the ecoinvent database. The ecoinvent database is one of the few life cycle inventory databases that meet the requirements of consistency (e.g. in system boundaries and allocation procedures) and transparency, required by the GHG Protocol product standard. The ecoinvent database is therefore used preferentially in the study. The ecoinvent database is also unique in that it allows the production of “daughter” datasets, where the dataset can be partially updated to better reflect a particular geographical context, e.g. by swapping in the electricity grid mix of the particular country of production. The full list of ecoinvent processes applied in the study is given in the accompanying data spreadsheet.

2.3.7 Limitations of the study

A common theme of road LCA studies is that road projects tend to be unique (Carlson, 2011), with a large number of potential sources of variation (possibly even due to different practices of individual contractors). Thus there is an inherent limitation in any road study to get representative results, but especially one such as this covering a large number of different road projects across different geographies.

A road is not a product with a defined lifespan, as it tends to be renewed after a certain length of time. The time periods between major rehabilitations are likely to be highly variable

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[13] *TMSA/PPIU NSC Projects spreadsheet*

and influenced by a number of uncertain factors, for example, how heavily the road is used, how well it was constructed in the first instance, the climate it is in, whether extreme climatic events are experienced, whether maintenance schedules are adhered to etc. It is thus beyond the scope of a model such as this to predict all these factors, and the carbon footprint model must inevitably rely on the best estimates of the road experts that provided input to this study. Furthermore, the renewability of a road necessitates the choice of a long time period over which to assess the life cycle of the road (most commonly somewhere between 25 and 100 years is chosen). This then requires that certain aspects of the model must rely on forecasting, e.g. forecasting traffic volumes over the timeframe to model the operation phase. Models that predict the future are inherently uncertain even when based on sound modelling principles.

Specific data limitations for this study, and the consequent implications for the uncertainty of the carbon footprint results, are discussed in Section 4.3.

3 Description of life cycle models

This section describes the overall approach taken to modelling the life cycle carbon footprint, as well as providing descriptions of the models of each phase; construction, operation, maintenance and rehabilitation. The descriptions cover the approach taken, as well as highlighting the main data sources and assumptions. Data tables are provided in the accompanying spreadsheet.

3.1 Overview of the life cycle model

The challenge to modelling the carbon footprint of the North-South Corridor road network is that it is comprised of 117 individual road links spanning eight countries, resulting in a large variation of road types, road geometries, fuel mixes etc. This meant that is was necessary to construct the model at a high level of breakdown to accommodate all the variation, whilst trying to keep the resulting assessment as simple and transparent as possible. Figure 4 below illustrates the approach taken to modelling the carbon footprint of the North-South Corridor road network, using an example of the South African road links within the corridor. The approach to modelling each of the phases depicted in Figure 4 is as follows, with details provided in the following sections:

- Construction: The road links were grouped into like pavement types (e.g. AMGB, STGB) for each country. Where necessary, these groups are broken down further if the width of road section or thickness of base and surface layers are different. In this way the construction stages are set up per km of road into 34 unique road sections. The construction carbon footprint of each road link is then built up by linking to the relevant road type.
- Maintenance: Routine maintenance is modelled at the same level of road type as construction. The annual material and energy requirements for patching and pavement repair are applied per m^2 per km road. The variations in the geometry of the different road links are therefore captured, even though the same basic material and energy consumption dataset is applied throughout.
- Rehabilitation: The same approach is taken for periodic maintenance activities as for construction, and a single resurfacing, preventative treatment and rehabilitation intervention was developed for each pavement type in each country. The rehabilitation carbon footprint of each road link is then built up by multiplying each maintenance intervention with the number of times it is predicted over the time period of the study (50 years).
- Operation: The operation phase is modelled at the level of each road link because traffic load data was provided at this level. The operation phase includes emissions from all vehicles using the NSC over the full time period of the study (50 years).

The carbon footprint model is constructed in this way so that results can be provided at the level of the building blocks described above (termed reference flows), as well as at the road link and country level. This provides a good degree of transparency in the results, as well as flexibility in adapting and updating the model, should this be required.

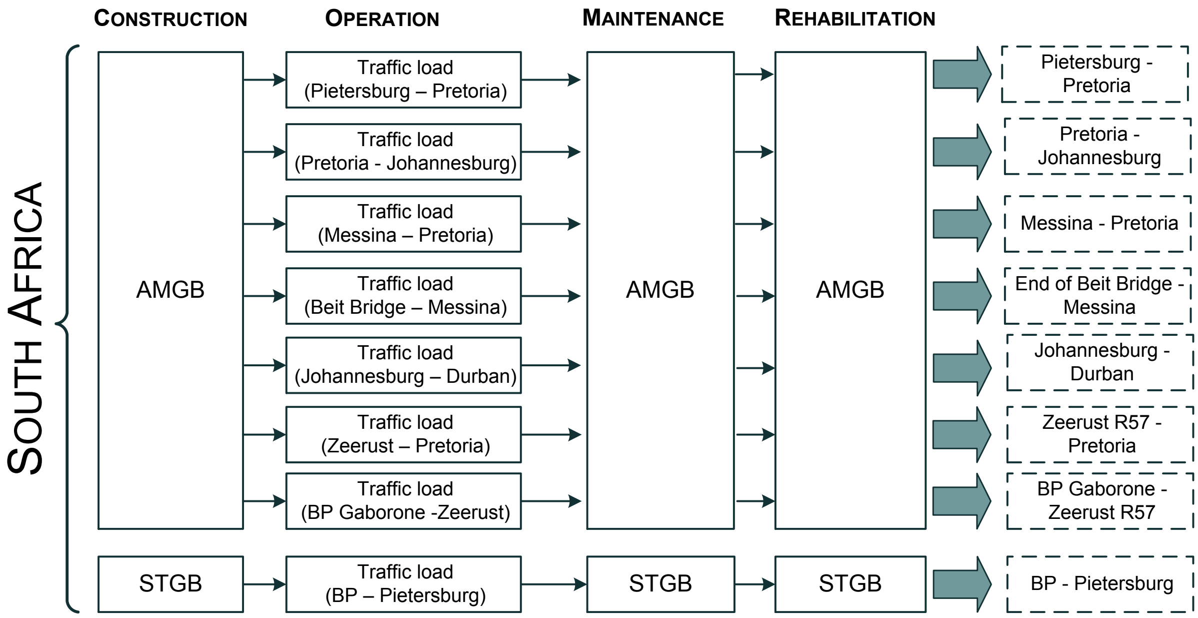

Figure 4: **Approach taken to the carbon footprint model, using South African road links in the NSC road network as an example.**

Table 4 gives an overview of the general data sources used in the carbon footprint model. These include databases, existing road LCAs, road design manuals and greenhouse gas emissions toolkits for road construction and rehabilitation. Data sourced through personal communication with construction companies and road agencies are detailed in the subsequent sections, and referenced as such in the accompanying data spreadsheet.

Table 4: **List of primary data from external sources**

Information type	Description	Data sources	Year
Road construction materials	Existing road LCAs (European)	Life Cycle Assessment for Road Construction and Use (Milachowski et al., 2010)	2010
	The Technical Recommendations for Highways series (TRH3 – TRH16)	South African National Roads Authority (SANRAL, 2013)	2013
	ecoinvent life cycle inventory database v 2.2	ecoinvent Transport Manual (Spielmann et al., 2007)	2007
Equipment and transport emissions	Road design and construction best practice manual for South Africa	South African Bitumen Association (Sabita, 2010)	2010
	Greenhouse gas emissions calculators and toolkits for road construction and rehabilitation	GHG Emissions Mitigation in Road Construction and Rehabilitation: A Toolkit for Developing Countries (ROADEO GHG calculator) (The World Bank, 2011) GHG Assessment Workbook for Road Projects (TAGG, 2011)	2011

3.2 Construction

Figure 5 gives the process map for the construction of a road with all the relevant processes that are included or excluded from the carbon footprint calculation for the construction phase. Included in the calculation are all relevant processes to construct the road infrastructure, including all the upstream processes to manufacture the materials, equipment and fuels used in the construction. Excluded from the calculation is the road "furniture", including barriers, signs, lights and traffic signals. These are assumed to be relatively low in number, given that the road network is comprised of highways rather than urban roads. Construction of drainage is also not included because insufficient information could be found on the design and material requirements of drains along the NSC road links. This exclusion is thought only to be significant to just over one-third of the road links that are indicated as having "hard" drains. Road "structures" such as tunnels and bridges were also excluded due to lack of data. The impact of these exclusions on the carbon footprint results are discussed in Section 4.3.

In the process map, any on-site electricity use is assumed to be produced by diesel generators on site, rather than purchased from the grid. Site offices and project management are excluded, as are light vehicles for transport of personnel. Fuel used to clear vegetation as part of site preparation is included, but the subsequent transport, use or disposal of the cleared vegetation is not included. An estimate of the loss of carbon storage due to land use change is reported separately, as is required by the GHG Protocol product standard.

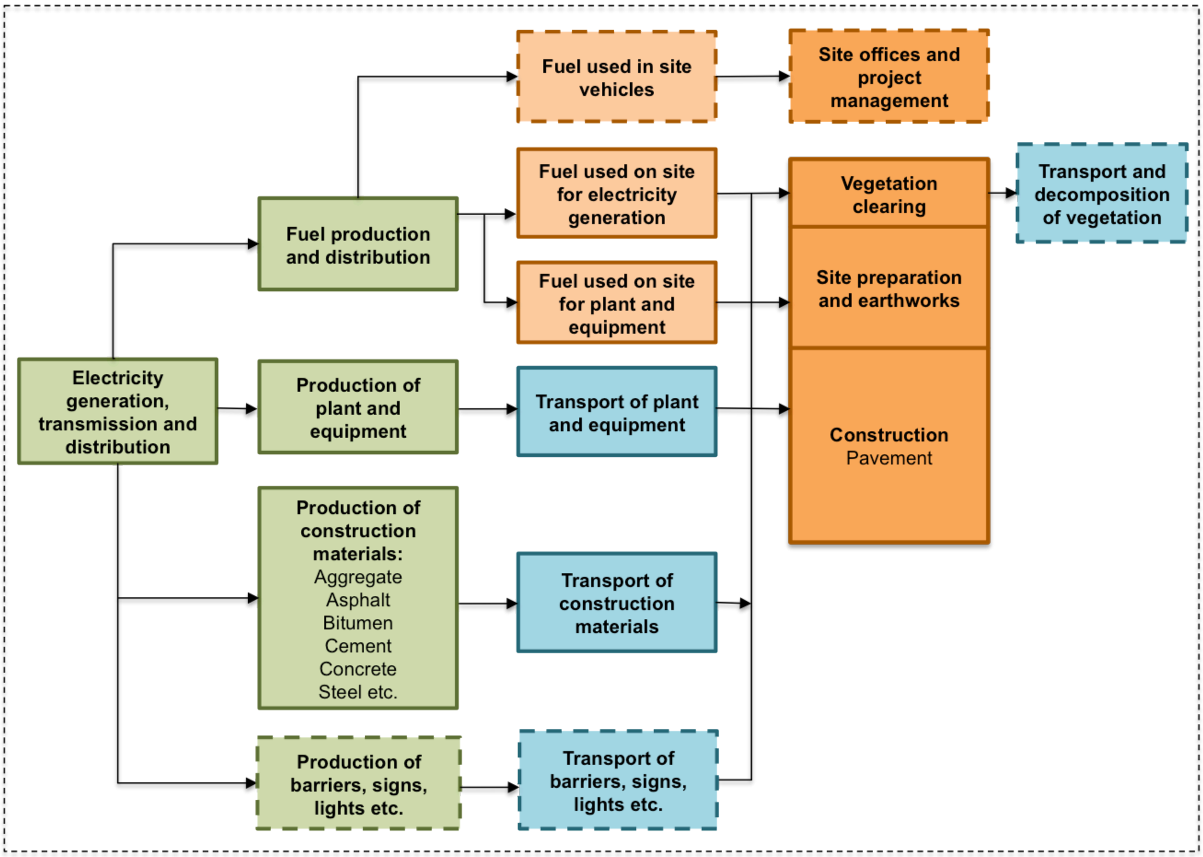

Figure 5: **Process map for the construction of a road**

The pavement types and associated materials for each of the road sections are a necessary starting point for estimating the emissions of construction, maintenance and rehabilitation. For the construction phase of the project the road links are grouped into like pavement types first, then into countries and finally into the pavement geometries (thickness of sub-base, base and surface layers, and width of carriageway). A total of 34 unique road sections were identified in this manner. The pavement types relevant to the NSC (and thus included in the carbon footprint model) are listed in Table 5. The surface and base materials that are used in these pavement types are described in Table 6 and Table 7, respectively. Table 8 assigns the different pavement types relevant to the NSC to the specific countries in which those unique road sections are located.

Details on the road links that make up the NSC road network were provided by TMSA[14], and include such information as section lengths, lane and shoulder widths, number of lanes, the thickness of the various layers and the pavement type of each section. Some of these details are reproduced in Table 23 in the Appendix (the full dataset used is provided in the accompanying spreadsheet). Importantly, for the model, each link needed to be assigned a base and pavement type (and thickness). Where specific details were not provided, estimates were made based on what was found to be most common for the corresponding pavement type or region. These instances are highlighted by the red text in Table 23. Based on this information for each road link, the resulting road links were grouped into the pavement types shown in Table 8.

Table 5: **Pavement types relevant to the NSC road network using HDM-4 pavement classification system (described in the subsequent tables) (Odoki & Kerali, 2006)**

Surface type	Surface material	Base type	Base material	Acronym for Pavement type	Description
AM	HMA	GB	CRS/ GM	AMGB	Asphalt mix on Granular base
		SB	CS	AMSB	Asphalt mix on Stabilised Base
ST	SBSD PM	GB	CRS / GM	STGB	Surface Treatment on Granular base
		SB	CS/ BSB	STSB	Surface Treatment on Stabilised Base
CP	JRCP	GB	CRS/ GM	JRCP	Joint reinforced concrete pavement

Table 6: **Description of surface material options relevant to NSC road network (Odoki & Kerali, 2006)**

Surface type		Surface materials		Description
AM	Asphalt mix	HMA	Hot mixed asphalt concrete	Mixture of bitumen (used as a binder) and mineral aggregate laid down on base layer and compacted.
ST	Surface treatment	SBSD	Single bituminous surface dressing	Also known as a “chip seal”, these are constructed by evenly distributing a thin base of hot bitumen onto an existing pavement and then embedding finely graded aggregate into it by rolling it into a smooth pavement surface.
		PM	Penetration macadam	Layers of coarse, open-graded aggregate (crushed stone, slag, or gravel) followed by the spray application and penetration of bitumen emulsion.
CP	Concrete pavement	JRCP	Joint reinforced concrete pavement	Contraction joints and reinforcing steel or steel mesh are used to control cracking in the concrete pavement

Table 7: **Description of base materials relevant to NSC road network (Odoki & Kerali, 2006)**

Base type		Base materials		Description
GB	Granular base	CRS	Crushed stone (calcrete)	Compacted aggregate layer of this sedimentary rock, a hardened deposit of calcium carbonate. Often supplemented with cement or pozzolan (siliceous or siliceous and aluminous material).
		NG	Natural gravel	Compacted aggregate layer of gravel. Can include sand and/or coal bottom ash/fly ash.
SB	Stabilised base	CS	Cement stabilised (CS)	Compacted mixture of aggregate and cement with possible additional pozzolanic materials.

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[14] *In the TMSA/PPIU NSC Projects spreadsheet*

Base type		Base materials		Description
		BSB	Bitumen stabilised base	Compacted mixture of aggregate and bitumous binder.

Table 8: Pavement types considered in the carbon footprint model

Pavement type	Description	Country/ border	Length [km]
AMGB **(Asphalt mix on granular base)**	Gravel surface on gravel base	DRC	176
	Asphalt concrete (40 - 50 mm) on gravel base	South Africa	1,722
		Zambia	256
	Asphalt concrete (100 mm) on gravel base	Malawi	116
		Tanzania	661
		Zambia	560
	Penetration Macadam (100 mm) on gravel base	Zambia	66
AMSB **(Asphalt mix on stabilised base)**	Asphalt concrete (100 mm) on cement stabilised base	Zambia	546
STGB **(Surface treatment on granular base)**	Surface dressing (15 mm) on calcrete base	Botswana	1,252
	Surface dressing (20 mm) on gravel base	DRC	224
		Malawi	960
		Tanzania	313
		Zambia	193
		Zimbabwe	2,058
		South Africa	179
STSB **(Surface treatment on stabilised base)**	SD (20 mm) on bitumen stabilised base	Zambia	64
	SD (15 - 20 mm) on cement stabilised base	Zambia	931
		Mozambique	412
JRCP **(Joint reinforced concrete pavement)**	Concrete pavement	Tanzania	7
			10,696

The individual components of construction considered in the carbon footprint model are explained in the following sections.

3.2.1 Site preparation

Site preparation includes the clearing of any vegetation, subsequent earthworks and subgrade preparation. Diesel consumed by the equipment used in these processes is estimated in the model. Diesel consumption varies according to the nature and quantity of the vegetation that requires clearing. The Greenhouse Gas Assessment Workbook for Road Projects (TAGG, 2011) identifies three broad types of vegetated areas that correspond to varying masses of vegetation that require removal, namely:

- grasslands;
- low shrubs; and
- high shrubs and medium dense trees.

Diesel consumption in litres per m^2 of area cleared for each of these three vegetation types are given in the TAGG workbook (2011), and are used in the carbon footprint model to estimate the diesel consumption of on-site clearing. To use these diesel consumption factors first requires the vegetation along the road links to be assigned to one of the three categories of vegetation listed above. Terrestrial mapping[15] was used to identify the type of vegetation occurring in the different regions through which the road links pass, and the corresponding diesel factor for clearing that vegetation type selected. Where there was a combination of vegetation type (e.g. grasslands and low shrubs), then an average of the applicable factors were applied. The area to be cleared was estimated as the width of the carriageway plus twice the width of the shoulder (to estimate the verge area).

For the earthworks, an estimate of diesel required per m^3 of earth removed (The World Bank, 2011) was used to estimate the diesel consumed in excavating the road base and transporting the removed material to the adjacent road reserve ("cut to spoil"), and was applied for all the road links. The volume of earth removed was assumed to simply be the total volume of the sub-base, base and surface, calculated using the thicknesses of the layers and the width of the carriageway per km stretch of road. It was assumed that the clearing and earthworks are conducted by conventional equipment such as graders and bulldozers. A dataset from the ecoinvent database, updated with the relevant country diesel mix, was used to estimate the emissions and materials associated with this diesel use (see section 3.6 for details on the country diesel mixes).

The preparation of the subgrade was assumed to include a motor grader, a water sprayer and a soil compactor. No treatment of the subgrade prior to the application of the pavement layer was assumed and the only material input into subgrade preparation in the model is therefore the diesel use of the equipment. As with site clearing, the diesel consumption is provided in litres of diesel per m^2 of area treated, which was multiplied by the width of the road to get the litres diesel consumed per km of road. As with the clearing and earthworks, a dataset from the ecoinvent database, updated with the relevant country diesel mix, was used to estimate the emissions and materials associated with diesel consumption in site equipment.

3.2.2 Sub-base pavement layer

Once the subgrade has been prepared, the sub-base, base and surface layers may be applied. The carbon footprint model includes both materials used to construct the pavement layers, and diesel consumed in their application.

According to the TMSA/PPIU NSC Projects spreadsheet, the sub-base layer is 150 mm thick for all the road links. The sub-base was assumed to be constructed from unbound granular materials, such as gravel, with a generic density of 2.4 tonnes per m^3 (Spielmann et al., 2007). To determine the volume of materials used, the thickness of the sub-base layer is multiplied by the width of the specific road to get the mass of gravel required per km of the particular road link.

The ROADEO GHG calculator (The World Bank, 2011) was used to estimate the diesel consumed in the equipment on site, and provided diesel consumption per m^3 of granular sub-base constructed. The equipment included a motor grader, a water sprayer and a soil compactor.

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[15] *Available online: http://www.uflib.ufl.edu/maps/mapafricamod01.html.*

3.2.3 Base pavement layer

There are two types of base layers; namely granular base course (GB) and stabilised base course (SB).

The granular base course is assumed to be gravel for all regions, with the exception of the road sections in Botswana, which are made up of calcrete, a calcium-rich duricrust[16]. It is assumed to be quarried in a similar manner to gravel. As for the sub-base, an estimate of the diesel consumed in the equipment used for the construction of a granular base is taken from the ROADEO GHG calculator (The World Bank, 2011).

Stabilised base (or sub-base) layers are pavement layers that are made up of a compacted mixture of aggregate and cementitious material (or binder). The binder material is usually cement or lime, with possible addition of a pozzolanic material (a siliceous or siliceous and aluminous material which, in the presence of water, reacts with calcium hydroxide to form compounds possessing cementitious properties, for example, coal fly ash). For a new construction, the mixing of the base materials with the binder and water can be done on site or at a plant. In the carbon footprint model, the stabilised base course is assumed to be gravel aggregate with a cement binder, with the cement stabilised base prepared on site, and subsequently graded and compacted. An estimate of the diesel consumed in the various equipment is taken from the ROADEO GHG calculator (The World Bank, 2011).

There is one road section in Zambia with a bitumen stabilised base, which entails the addition of bitumen emulsion into an aggregate, such as gravel or crushed stone, for the purpose of improving the engineering properties of the pavement. In the carbon footprint model, it is assumed that the bitumen stabilised base material is mixed at a plant and transported to the site, where it is graded and compacted with an asphalt compactor. Diesel consumed in equipment is estimated using the ROADEO GHG calculator (The World Bank, 2011).

3.2.4 Surface pavement layer

There are four types of surface layers considered in the carbon footprint model; a gravel surface, an asphalt mix (AM), a surface treatment (ST) and a concrete pavement (CP).

The road links in the NSC are predominantly made up of surface treatments (~62%). The default surface treatment was assumed to be a single surface dressing, which is constructed by spraying hot bitumen on the surface of the road and immediately rolling in chippings. Estimates of the diesel consumed in bitumen sprayers, aggregate spreaders and compactors were taken from the ROADEO GHG calculator (The World Bank, 2011).

Another kind of surface treatment is penetration macadam (PM), which is similar to a surface dressing but is made from layers of coarse, open-graded aggregate, such as gravel, followed by the spray application and penetration of bitumen emulsion. Only one road link in Zambia of ~66 km (Turnoff T1 – Mazabuka) was initially constructed with a PM surfacing. It is assumed that the PM surface is constructed using the same equipment as the surface dressing.

The next most common surface type on the NSC are the asphalt mix (AM) surfaces. The default AM surface was assumed to be constructed from hot mixed asphalt concrete (HMA), as HMA is still the most frequently used. Warm mixed asphalt (WMA) currently only makes up 4 – 5 % of asphalt production in South Africa[17]. The typical thickness of the HMA is 40 – 50 mm, which is typical for the bulk of the South African roads within the corridor and some sections in Zambia. In Malawi, Tanzania and Zambia the HMA surfaces are applied at 100 mm thickness. This is typical of pavement designs in Europe, and was presumably designed

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[16] *Duricrust is a hard layer on or near the surface of soil.*

[17] *Personal communication, Wagner, L., South African Bitumen Association (SABITA), email correspondence, September 2013.*

by European road design engineers[18]. As with the bitumen stabilised base, it was assumed that the HMA was mixed at the asphalt plant and transported to the site where it was subsequently applied with a paver and compacted. A fuel consumption 16.8 l/m^3 of asphalt mixed at plant was provided by a South African asphalt supplier, and was used for all countries. Estimates of the diesel consumption of the paver and asphalt compactor were taken from the ROADEO GHG calculator (The World Bank, 2011).

Only one road link in the DRC (Likasi – Kolwezi) was initially constructed as a gravel road, with a gravel surface of 50 mm on a granular base. An estimate of diesel consumed in the surfacing equipment (a motor grader and compactor) was taken from the ROADEO GHG calculator (The World Bank, 2011). The road section has subsequently been transformed into an asphalt mix (AM) surfaced road.

The corridor also consists of one 7 km concrete road section in Tanzania (Concrete Ikokoto - Concrete Kitonga Gorge) with a joint reinforced concrete pavement structure. The pavement uses contraction joints and reinforcing steel or steel mesh to control cracking in the concrete pavement. Dowel bars are typically used at transverse joints to assist in load transfer while the steel assists in load transfer across cracks. It is assumed that the concrete is cast at the plant, and therefore uses the same equipment as for joint plain concrete pavement (without reinforcement). Estimates for the diesel consumption of the batching plant, where the concrete is mixed, and the slip form paver were taken from the ROADEO GHG calculator (The World Bank, 2011).

3.2.5 Production of fuels and materials

Secondary datasets are used to estimate the emissions associated with the production of the materials, primarily the ecoinvent database (ecoinvent Centre, 2007). Where no dataset was found for the material in the ecoinvent database, this was built up from its constituents. For example, a dataset for asphalt concrete had to be constructed from its bitumen and aggregate components, as well as the energy required for heating and mixing prior to application. The composition and density were provided by a South African asphalt manufacturer and supplier. Secondary datasets applied in the carbon footprint model are listed in the accompanying data spreadsheet.

3.2.6 Transport of materials

Resources such as the Aggregate and Sand Producers Association of Southern Africa (ASPASA), Cement and Concrete Institute (CNCI) and the South African Bitumen Association (SABITA) were used to determine whether or not there were local materials available along the NSC corridor region. Default transport values for locally produced materials were then estimated for these materials (informed by guidelines given in the ROADEO GHG calculator (The World Bank, 2011).

Where materials were imported, then the relevant transport steps are included and the material manufacture in the country of origin. For example, South Africa is the only country within the NSC that produces bitumen. Bitumen used in road projects on the NSC is therefore assumed to be either imported from South Africa or the Middle East. In the case of the latter, it is assumed that the bitumen is transported via transoceanic ship to the nearest port (Dar-es-Salaam or Beira) and then transported to the site via road. Transport distances and modes are given in the data spreadsheet accompanying this report.

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[18] *Personal communication, Kannemeyer, L., Road Network Manager, SANRAL, September 2013*

3.3 Maintenance

Figure 6 shows the process map for the maintenance of a road with all the relevant processes that are included or excluded from the carbon footprint calculation for the maintenance phase. The maintenance phase includes routine pavement patching and repair work, such as edge-repair, crack sealing, spot re-gravelling etc. Only routine maintenance (patching and other repair) of the road pavement is included in the *Maintenance* phase, with periodic road works included in the *Rehabilitation* phase. The following activities were excluded from the maintenance phase:

- Drainage works (e.g. clearing drains, culvert repair, etc.), as insufficient data are available on the maintenance of drains to include it for the NSC road sections.
- Vegetation control and line marking, as their contributions to the GHG emissions of the maintenance phase are expected to be negligible (they contribute just 2.5% and 0.01%, respectively, to the GHG emissions in the maintenance of an average Swiss road[19]).

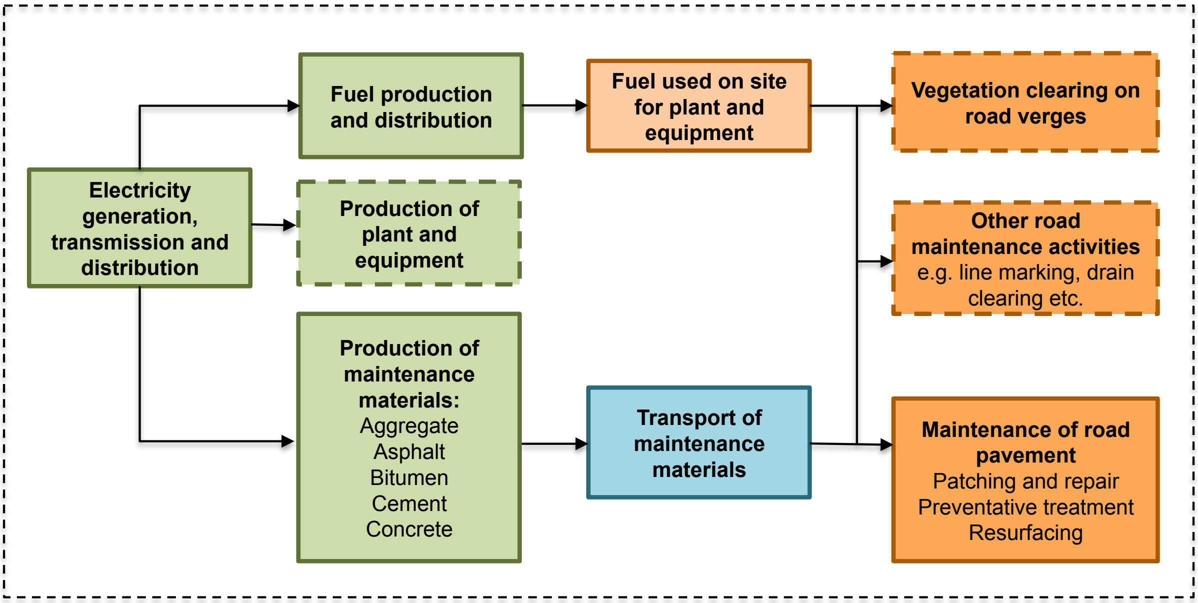

Figure 6: **Process map for the maintenance of a road**

Obtaining data on maintenance inputs was difficult as it is an on-going activity. The companies with contracts with SANRAL for maintaining sections of the NSC road network in South Africa were approached, but the response was poor with only one company providing information. This company provided data on the materials consumed in the routine maintenance of a 276 km stretch of the N11 over 34 months. These materials included the mass of asphalt concrete used for patching and edge repair (tonnes), the volume of emulsion treated base (ETB) for backfilling patching excavations (m^3) and the volume of aggregate for re-gravelling of the pavement shoulders (m^3). No fuel data was provided by the company. It was therefore assumed that the diesel consumption of the grader, paver and compacter used for the application of these materials is the same as that for a new construction (section 3.2).

The data provided was used to estimate the quantity of materials consumed on an average annual basis per m^2 of road maintained. This data was then applied to the particular road geometries of the road links of the NSC to calculate the maintenance inputs required per year. These are then multiplied by the time period of the study to obtain the total routine maintenance inputs over the 50-year time period. This assumes that maintenance activities

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[19] *Road/CH and Operation, Maintenance, road/CH, ecoinvent version 2.2 (Spielmann et al. 2007)*

remain more or less constant over the life of the road, which in turn assumes that resurfacing and reconstruction works occur at the necessary time intervals. The lack of any other data on routine maintenance required that the South African data formed the basis of estimates of maintenance inputs for all the non-South African sections of the road network, with the exception of the concrete road link in Tanzania.

Maintenance inputs for the concrete road link were assumed to be the same as that of the bituminous pavements. This assumption is based on the routine road repairs of rigid pavement as recommended in the Routine Road Maintenance Manual for South Africa (SANRAL, 2009).

3.4 Rehabilitation

Figure 7 shows the process map for the rehabilitation of a road with all the relevant processes that are included or excluded from the carbon footprint calculation for the rehabilitation phase. Rehabilitation includes the periodic road works maintaining the integrity of the road, including:

- Preventative treatment, such as a fog spray, is a thin film surfacing applied to improve surface integrity and waterproofing.
- Resurfacing (or restoration), such as a surface dressing, slurry seal, cape seal, re-gravelling etc.
- Rehabilitation and partial reconstruction, involving mill and replace of the base layer.

Rehabilitation includes many of the same processes as construction, and is governed by similar exclusions as those discussed above for construction. A difference from construction is that rehabilitation reuses some of the existing road material, which is assumed to be reprocessed on site. The different periodic maintenance activities are described in the subsequent sections, with the specific material and energy inputs provided in the spreadsheet accompanying this report.

The most challenging aspect of modelling periodic maintenance activities is estimating the frequency at which they occur. The dataset provided by TMSA had information for all road links on the year of last rehabilitation, year of last surfacing and year of last preventative treatment. These are used as the start of the maintenance period, i.e. the estimated frequency is applied from this date until 50 years from the base year of the study. Rehabilitation activities undertaken prior to the current year are therefore included in the carbon footprint model, as well as those predicted to occur in the coming 50 years. The approach to estimating the frequency of periodic maintenance and reconstruction works is discussed in the final sub-section below.

3.4.1 Preventative treatment

In the carbon footprint model a fog spray is considered as the default preventative treatment, which can be applied as a maintenance procedure on an existing bituminous surfacing to assist in retaining the aggregates in place, waterproofing the surface layer or to “rejuvenate” the surfacing when it is showing signs of dryness resulting from ageing or hardening of the bitumen (SANRAL, 1996).

The fog spray is essentially a bitumen emulsion (60% bitumen binder content) diluted with 50/50 water. An application rate of 1.0 litre per m^2 is typically used, which results in a residual binder application of approximately 0.3 litres per m^2 (SANRAL, 1996). The energy required for the application is estimated from the diesel requirements of a sprayer, taken from the ROADEO GHG calculator (The World Bank, 2011). It is assumed that the dilution of the fog spray occurs at the site and therefore the bitumen emulsion is transported to the site, either from South Africa or via the port of Dar-es-Salaam, from the Middle East.

3.4.2 Resurfacing (or restoration)

Resurfacing involves either asphalt or an asphalt seal, depending on the type of road. The thickness of the most recent surfacing was included in the data provided by TMSA for some of the road links, and in some cases the type of surfacing was specified. In the case where the type of surfacing was not specified, it was assumed that surfacing layers less than 30 mm thick are seals and those greater than 30 mm are asphalt overlays[20]. Furthermore, where no recent surfacing was presented, it was generally assumed that an asphalt pavement would generally require a periodic asphalt overlay and a sealed surface would require a periodic reseal.

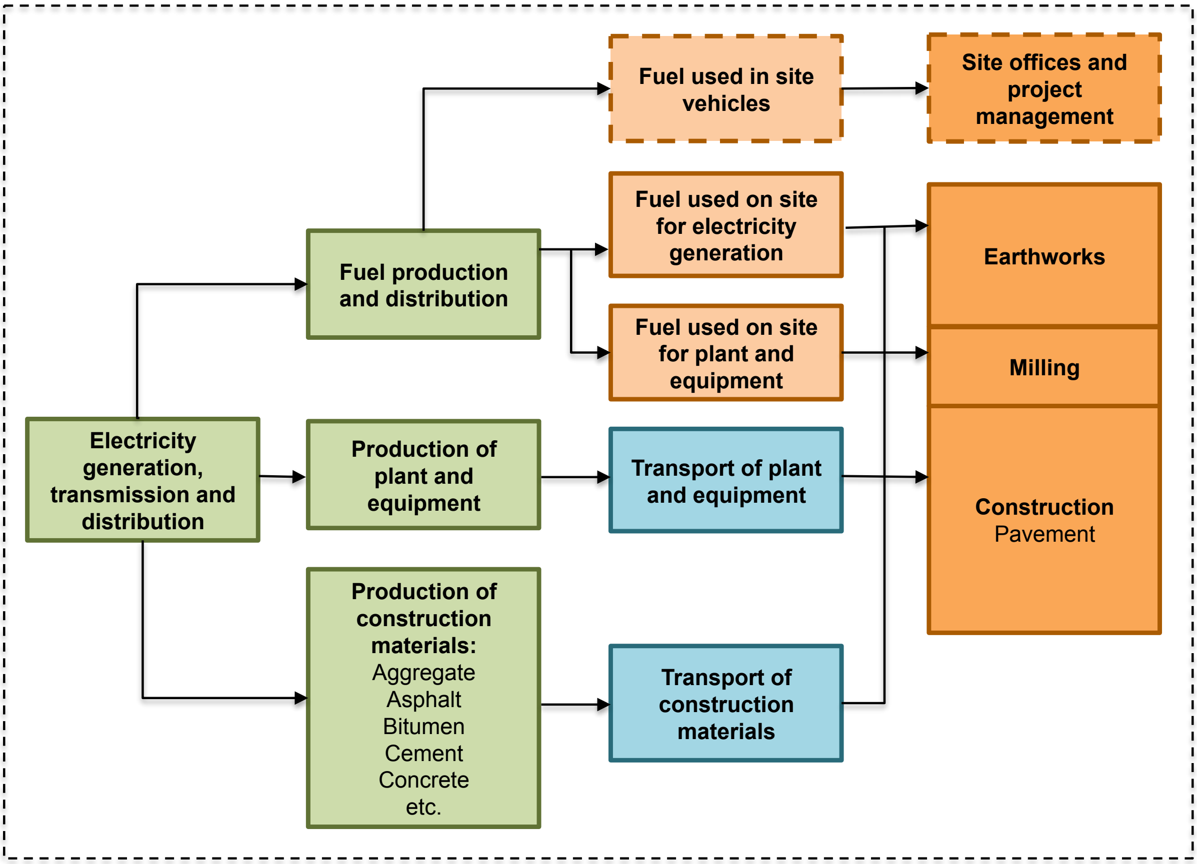

Figure 7: **Process map for the rehabilitation of a road**

For the application of an asphalt overlay (AO), a tack coat is first applied to the existing bituminous surface followed immediately by hot rolled asphalt (HRA). The tack coat is a 1:1 dilution of anionic bitumen emulsion with water.[21] The HRA used for the asphalt overlay is the same as that used during construction, and therefore requires the same material inputs and equipment for its application. The asphalt is typically applied to a thickness of 40 mm for South African road links.[22] For the remaining regions, a thickness of 50 mm is applied, which is consistent with the information provided in the TMSA dataset for some of the road links on thickness of the most recent asphalt overlay.

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[20] *Personal Communication. Abrahams, S., Civil Engineering Consultant (Stellenbosch University), email correspondence, 5 September 2013.*
[21] *Personal Communication. Labuschagne, M., Colas South Africa (Pty) Ltd, Interview, 2 September 2013.*
[22] *Personal Communication. Kannemeyer, L., Road Network Manager, SANRAL, Interview, 27 September 2013.*

The seals are constructed by running hot bitumen on the road surface and then immediately rolling in chippings of gravel, also known as a surface dressing (SD). In the case where two layers of bitumen and chippings are applied then it is called a double bituminous surface dressing (DBSD) or double bituminous surface treatment (DBST). The inputs for the surface dressing are assumed to be the same as those in new construction.

The dataset on the road links provided by TMSA indicated the most recent seal thickness to vary between 14-25 mm for the different regions. As with the asphalt overlay, it was assumed that the subsequent seals would be the same thickness as the most recent seal. For those road links that did not present a recent surfacing thickness, seals were assumed to be the same thickness of the seals of other links in the same country and of the same pavement geometry, i.e. with the same thickness of sub-base, base and surface layers.

3.4.3 Rehabilitation

For the rehabilitation of the roads a partial reconstruction was assumed, with a mill and replace of the base layer. This involves the on-site reworking of the existing top layers, typically the top 150-250 mm of the pavement, with up to 100% recycling of the materials milled to form a new sub-base[22]. Possible addition of a stabilising agent is carried out as well if the design requires it, i.e. cement (1.5% to 4.5%) and/or bitumen (1% to 3%). For the study however, it was assumed that no stabilising agent would be necessary. It is assumed that the amount of diesel combustion for milling and preparation of the sub-base is equivalent to that used in the new construction of a sub-base, as described in section 3.2.

The preparation of the sub-base is then followed by a new base and surfacing layer, the inputs of which are assumed to be the same as those in the construction phase (section 3.2). It is further assumed that the new base layer and surface layer would be the same as the first construction, i.e. the same type of base and surfacing, as well as the same thicknesses. An exception is the *Likasi – Kolwezi* road link in the DRC, which was initially constructed as a gravel road, but has subsequently been transformed into an asphalt pavement. The base will therefore be constructed in the same manner as before, but the surface will be reconstructed as an asphalt concrete layer.

Project specific data was provided for two partial pavement reconstruction projects currently being conducted by the Roads Division of Murray & Roberts[23]. These projects are fairly typical of reconstruction-type projects, and it is the considered opinion of the Murray & Roberts engineers that the material and fuel consumption data provided for these projects can be extrapolated for use in other rehabilitation projects on the NSC road network. Unfortunately, only aggregated data for the given road sections under construction were provided, with no differentiation between the worked layers, rendering the data less useful. However, the data provided a useful check against the total material and energy consumption of the rehabilitation phase estimated in carbon footprint model, which was found to correlate with the aggregated data provided by Murray & Roberts per km of road rehabilitated.

3.4.4 Frequency of rehabilitation works

The most significant challenge with periodic road works was estimating the interval at which they occur, i.e. the number of events to include in the 50-year time period. A large number of factors affect the interval between maintenance and reconstruction projects, including the original road design, construction practices, maintenance practices, traffic loads, climate etc.

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[23] *Along the N14 Route from Delareyville to Sannieshof (± 20 km completed), and along the N1 Route from Hammanskraal to Modimolle (± 22 km of 48 km completed).*

It has not proved possible to obtain data on maintenance cycles from the engineering companies approached for information because these are mostly one-off projects that go out on tender. The national road agencies are therefore a more appropriate information source and were approached for information. However, responses were only received from the national road agencies for South Africa, Botswana and Mozambique. These agencies provided a description of the types of maintenance actions carried out, i.e. routine maintenance, periodic maintenance and rehabilitation actions, which were found to vary slightly across the countries. For each maintenance action a minimum and maximum frequency in years was also provided, where the minimum corresponded to wetter regions and the maximum to dryer regions within the specified country.

For partial reconstruction works in South Africa, Botswana and Mozambique the frequency of the works for a particular road link was selected based on whether the climate of the region is dry, moderate or wet. For the remaining countries, the rehabilitation frequency was assumed to be the same as that of one of the adjacent countries with a similar climate. For example, the region in the DRC displays a similar climate to the wetter regions in Mozambique, and therefore it was assumed that the road links within this region would require rehabilitation at the same frequencies as those in Mozambique. Once the frequency was established, the number of times that the rehabilitation occurs over the 50-year period (2013 – 2063) was calculated from the year of the last rehabilitation (provided for every link in the dataset from TMSA).

The frequency of resurfacing was provided for dry, wet and moderate regions for South Africa, Botswana and Mozambique by the respective national road agencies. These were subsequently allocated to the different road links as done for reconstruction.

The “20 year work programme” in the HDM-4 North-South Corridor Efficiency study was used for the other countries. The document recommends an activity year and work type (seal or asphalt overlay) for the sections of the North-South Corridor over a period of 20 years. The frequency of the work type for the corresponding road links could thus be calculated from the work programme. Where data is not provided for a particular road link in the “20 year work programme”, the same frequency as a similar connecting road link was assumed, i.e. the same as a road link with the same type of pavement and geometry.

The number of resurfacings over the 50-year time period of the study could thus be estimated using these calculated frequencies. The resurfacing schedule was taken from the year of the most recent surfacing (obtained from the TMSA dataset), to 50 years from the current year. If the next resurfacing is found be to be scheduled prior to the current year (2013) then it is assumed that the road has been neglected and requires emergency treatment. It is further assumed that the road is not too damaged and would only require a reseal or asphalt overlay (as per the schedule). The remaining number of resurfacings for the 50-year period was then calculated from this point onwards, assuming that the works occur on schedule with no further delays.

In the information provided on prior treatments in the TMSA dataset, more often than not the last year that the preventative treatment was applied correlates with the last year of resurfacing. Therefore it is assumed that a fog spray is applied as part of resurfacing. In the case of an asphalt surfacing, the fog spray is applied prior to application of the asphalt overlay, whereas the fog spray is applied as the final layer of the surface dressing.

The only exception to this approach is Botswana, where fog spray application frequency was provided separately and differs from that of the resurfacing. Here the number of fog spray applications over the 50-year period is calculated in a similar manner to the resurfacing, i.e. from the year of last preventative treatment application. Likewise, if the scheduled fog spray was due before the current year (2013) then the first new treatment is assumed to be 2013, and the subsequent treatments calculated from that point onwards.

The frequency and resultant number of periodic maintenance works assumed for each road link are given in the accompanying spreadsheet. These include those carried out prior to 2013, as well as those to be carried out over the 50-year time period.

3.5 Operation

Figure 8 gives the process map of the operation of a road with all the relevant processes that are included or excluded from the carbon footprint calculation for the operations phase. This phase is comprised of the vehicles using the road and any processes occurring in the normal operation of the road (lighting in tunnels, street lights, traffic signals etc.). The latter are not included in this study, with the assumption that these are relatively minor inputs in a highway network. The only emissions considered in road operation are thus from fuel consumed in the various classes of vehicles using the NSC road network. Emissions from tyre and brake lining wear and road abrasion are not included, and neither is the manufacture of replacement vehicle components. The production of the vehicles themselves are also excluded because of the difficulty in attributing the vehicle to the particular section of the NSC road network (vehicles will drive on a large number of different roads over their lifetimes).

The traffic load data has been sourced from the updated RTFP HDM-4 Efficiency Study on the North-South Corridor Road Network. The annual average daily traffic (AADT) is provided for different vehicle categories for each road section in the NSC road network. An important assumption in using the AADT values is that these can be multiplied by 365 to get the annual traffic load. Even more important is the assumption that these are representative of the particular road link in its entirety. To calculate the carbon footprint of the particular road link the emissions per km are multiplied by the length of the road link. This essentially assumes that all vehicles in the count drive the entire length of the section (or as one vehicle leaves the section, another joins).

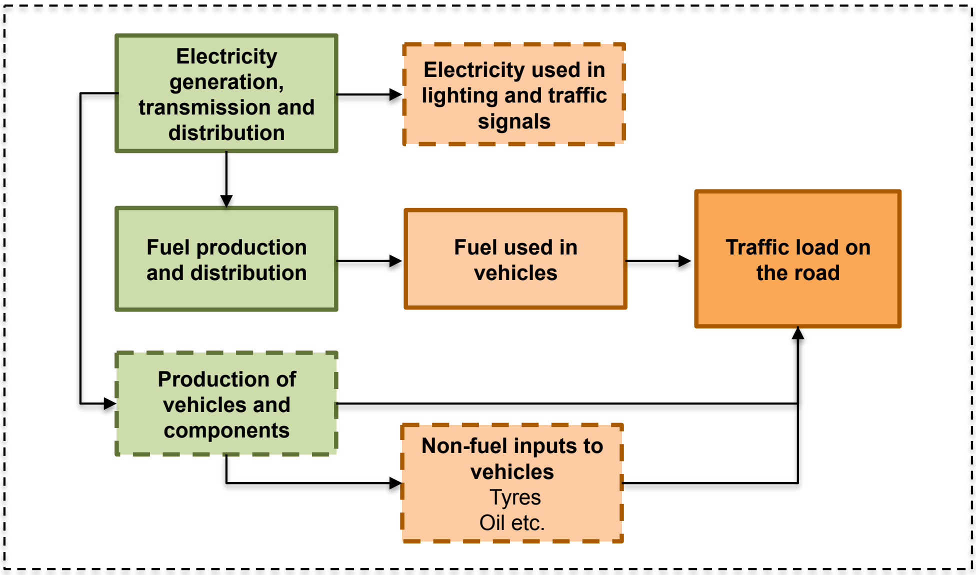

Figure 8: **Process map for the operation of a road**

3.5.1 Vehicle Emissions

Table 9 provides the breakdown of the categories into the corresponding vehicle types according to the HDM-4 model (Odoki & Kerali, 2006), along with the assumed fleet breakdown and the corresponding fuel type of the vehicle.

The ecoinvent database was primarily used as a source of models of the different vehicle types and their emissions (ecoinvent Centre, 2007). The ecoinvent dataset applied in the carbon footprint model and the fuel consumption for each of the vehicles is given in the accompanying data spreadsheet. Diesel production was adapted in the ecoinvent database to be representative of the individual country (see section 3.6 for the different country diesel mixes applied).

The fuel consumption of cars, light goods vehicles and buses are sourced from the ecoinvent Transport Manual (Spielmann et al., 2007) and the values applied are estimates of average fuel consumption for the corridor as a whole. The fuel consumption of medium and heavy goods vehicles were obtained through personal communications.[24,25] The fuel consumption of medium goods vehicles is estimated at 28 – 35 litres per 100 km, and the fuel consumption of heavy goods vehicles along the corridor is estimated at 48 – 68 litres per 100 km. These values are high compared with European sources, but take into account vehicle loadings, the older nature of the vehicles and terrain of the NSC road network. This is done at a fairly high level by assigning each of the road links into one of four possible fuel consumption categories spanning the ranges given above (see the data spreadsheet accompanying this report for a breakdown in fuel consumption per road link).

Table 9: Motorised vehicle HDM-4 classification and fuel type (Odoki & Kerali, 2006; Spielmann, et al., 2007)

Vehicle categories	% of fleet	Vehicle type and description	Fuel type
Car, 4WD, Pick-up	75%	Average passenger car	Petrol
	25%	Light delivery vehicle (panel van, utility or pickup truck)	Petrol (50%) Diesel (50%)
Light goods	50%	Light goods vehicle (very light truck for carrying goods, 4 tyres)	Diesel
	50%	Light truck (small two-axle rigid truck, <3.5 t)	Diesel
Mini bus	-	Mini bus (small bus based on panel van chassis, 4 tyres)	Petrol (50%) Diesel (50%)
Bus	100%	Large bus designed for long distance travel	Diesel
Medium goods	-	Medium truck (two-axle rigid truck, >3.5 t)	Diesel
Heavy goods	50%	Heavy truck (multi-axle rigid truck)	Diesel
	50%	Articulated truck or truck with drawbar trailer	Diesel

3.5.2 Growth in road traffic

The carbon footprint of a road has to be calculated over a long time period to incorporate maintenance and rehabilitation of the road over the years. A period of 50 years is chosen in this study. To calculate the carbon footprint of the operation of the road therefore requires road traffic to be estimated for the next 49 years, and not just for the base year of the study (2012). To do this the percentage growth in road traffic over the various road links of the NSC needs to be estimated.

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[24] *Curtis, B., FESARTA (Federation of East and Southern African Road Transport Associations), October 2013*

[25] *Campbell, J. Consultant and Chairman, Institute of Road Transport Engineers (IRTE), October 2013*

In 2011, the World Bank launched the *Definition and Investment Strategy for a Core Strategic Transport Network for Eastern and Southern Africa*, which among other things, describes the historic trade flows in the region and provides trade demand and trade flow projections for the Eastern and Southern African transport corridors (Nathan Associates Inc., 2011). The corridors that form part of the road network of this study include the North-South Corridor, the Nacala Corridor and part of the Dar-es-Salaam Corridor. The analysis involved initially determining the base year trade flows by trading partners (2009) and developing trade flow demand projections by trading partners for 2015 and 2030. A model was then developed to assign these trade flows to corridors (and sub-corridors), and to forecast potential induced traffic. Based on resulting capacity constraints, trade flows were reassigned to other sub-corridors, where possible, to arrive at base case trade flow forecasts by corridor for 2009-2015 and then 2015 -2030, as presented in Table 10.

However, the figures in Table 10 are for the overall freight volume growth of the corridors (i.e. road and rail), and not for roads in particular. To estimate the growth in road traffic, the split between road and rail for the base year (2009) and the forecasted years (2015 and 2030) was investigated. A traffic assignment model was used in the World Bank study to allocate traffic from landlocked countries to corridors and to railway and road modes, where the choices are based on various financial, logistical, or policy parameters, or simply on the basis of preferences for shipper connections (Nathan Associates Inc., 2011). Based on this model, the share of trade flow assigned to the road networks relative to rail will either remain the same or decrease for all corridors from 2009-2015, with an increase in share for the Dar-es-Salaam and Nacala corridors by 2030. However, the North-South corridor displays a marginal decrease in the road share of trade flows relative to rail (see Table 11).

Table 10: **Trade flow base case (2009) and forecasts for corridors to 2015 and 2030 (thousand tonnes) (Nathan Associates Inc., 2011)[26]**

Corridor	2009	2015	Growth 2009-2015	2030	Growth 2015-2030
Dar-es-Salaam	2,581	5,173	12.3%	14,449	7.1%
Nacala	1,181	2,262	11.4%	4,887	5.3%
North-South	25,354	49,228	11.7%	109,843	5.5%

Table 11: **Road corridor flows (thousand tonnes) and road share of overall flows for selected corridors (relative to rail) (Nathan Associates Inc., 2011)**

Corridor	2009	Road share in 2009	2015	Road share in 2015	2030	Road share in 2030
Dar-es-Salaam	1,830	71%	3,435	66%	10,068	70%
Nacala	1,051	89%	1,986	88%	4,341	89%
North-South	19,814	78%	38,226	78%	83,614	76%

Based on these flows, the annual traffic growth rate for the selected road corridors was calculated for the 2009- 2015 and 2015-2030 periods (Table 12). The growth rate for the period 2012-2030 was extrapolated from this data. This is applied as the road traffic growth rate in the carbon footprint model for the 20 years of operation from the base year of the study, where 2012 is taken as the base year of the study, as this is the year for which the most recent AADT data are available. It is clear from the World Bank Study that there is a decline in the growth rate during the latter period. Thus, growth is assumed to flatten towards 2030, and in the carbon footprint model, traffic volumes are assumed to remain constant for the last 30 years of the 50-year time period.

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[26] *Excludes domestic flows of coastal countries.*

Each road link along the road network is assigned to a particular corridor, and the corresponding annual growth rate shown in Table 12 was applied to calculate the annual traffic volumes for each of the 20 years from 2012. After this, it is assumed that traffic remains at these levels. No studies predicting growth rates in passenger vehicles were found, thus the growth rates in Table 12 were applied to all vehicles using the NSC. This probably results in an overestimate of overall road traffic on the corridor over the 50-year time period.

Table 12: **Annual growth rate for applicable road corridors[27].**

Corridor	2009 - 2015	2015 - 2030	2012 - 2030 (applied in footprint model
Dar-es-Salaam	11.1%	7.4%	7.2%
Nacala	11.2%	5.4%	5.7%
North-South	11.6%	5.4%	5.7%

3.6 Diesel and electricity data

To make the datasets taken from the ecoinvent database more representative of the particular country of production or operation, they are adapted with diesel and electricity data for the particular countries covered by the NSC road network. Table 13 and Table 14 respectively give the diesel and electricity generation mixes of the different countries used in the carbon footprint model. The electricity mixes were informed primarily by annual reports published by Eskom and the Southern Africa Power Pool (Eskom, 2011; SAPP, 2011), whilst the diesel mixes were informed by a World Bank study (Kojima, et al., 2010).

Adapting the diesel mix is especially important for South African diesel, where a component of the fuel is from coal-based synthetic fuels (with a much higher carbon footprint than diesel from crude oil sources).

The electricity grid mixes of the countries differ quite considerably, with those with a high hydroelectric component having a lower carbon footprint. However, the energy requirements of most of the road processes are met by liquid fuels rather than by electricity, so the electricity grid mixes do not play a large role in the carbon footprint results.

Table 13: **Electricity grid mixes of countries within the North-South Corridor road network (Eskom, 2011; SAPP, 2011; Tallapragada, et al., 2009)**

	South Africa	Botswana	DRC	Malawi	Mozambique[28]	Tanzania	Zambia	Zimbabwe
Hydroelectricity (generated)	0.1%	-	94.0%	99.9%	70.2%	50.6%	99.6%	46.8%
Coal (generated)	87%	10.2%	-	-	-	-	-	32.7%
Nuclear (generated)	4.8%	-	-	-	-	-	-	-
CCGT (generated)	0.1%	-	-	0.1%	-	6.8%	-	-
Hydroelectricity (pumped storage)	1.2%	-	-	-	-	-	-	-

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[27] *Calculated from data in Nathan Associates Inc. (2011)*

[28] *Electricidade de Moçabique (EDM) (2011) Statistical Summary 2011. Available online: www.edm.co.mz, accessed June 2013.*

	South Africa	Botswana	DRC	Malawi	Mozambique[28]	Tanzania	Zambia	Zimbabwe
Distillate (generated)	-	0.2%	-	-	-	0.7%	0.03%	-
Eskom electricity (imported)	-	76.6%	5.2%	-	29.8%	35.9%	0.3%	18.8%
Other electricity imported, majority hydro	6.8%	13.0%	0.8%	-	-	6.1%	0.05%	1.7%

Table 14: Diesel mixes of countries within the North-South Corridor road network

Country	Import of refined product	Domestic refining of imported crude	Domestic production of synthetic fuels	Primary sources of imported refined product	Primary land transport of refined product[29]	Primary source of imported crude	Primary land transport of imported crude
South Africa	4%	73%	23% (SASOL and PetroSA)	Middle East.	Pipeline	Middle East	Pipeline
Botswana	100%	0%	0%	South African refineries	Pipeline to Gauteng (SA)	N/A	N/A
DRC	100%	0%	0%	Middle East, South Africa, Tanzania, Kenya and Uganda	Pipeline and road and rail network	N/A	N/A
Malawi	20% 80%	0%	0%	South Africa Middle East	Road and rail	N/A	N/A
Mozambique	100%	0%	0%	Middle East	Road and rail	N/A	N/A
Tanzania	20% 80%	0%	0%	South Africa Middle East	Road	N/A	N/A
Zambia	50%	50%	0%	South Africa	Road and rail	Middle East	Pipeline
Zimbabwe	20% 80%	0%	0%	South Africa Middle East	Road and rail	N/A	N/A

3.7 Land use change

In road construction emissions of carbon dioxide also arise due to changes in land use, primarily from the cutting down of vegetation and converting it to sealed road and verge areas. This results in a loss of carbon storage in the vegetation. The effect is relatively small when grasslands are converted to sealed land areas, but can be very significant when forests are cut down.

The carbon impact of clearing vegetation for road construction was estimated in the model using the Tier 1 method and factors available in the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The area to be cleared is estimated as the area of the carriageway plus 2 x the area of the shoulder. Each road link was assigned a broad vegetation class from terrestrial mapping[30] and the most appropriate land use change factor chosen from the IPCC guidelines. The vegetation classes assumed and factors applied for

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[29] *To main consuming city, e.g. from refinery to city, or from port to city (in case of importing refined product).*

[30] *Available online: http://www.uflib.ufl.edu/maps/mapafricamod01.html.*

each road link are given in the accompanying data spreadsheet, with Table 15 providing the IPCC Tier 1 factors applied in the calculation. A number of assumptions had to be made where the IPCC Guideline (IPCC, 2006) did not provide default values, most notably for the carbon fraction of non-woody biomass and below-ground biomass. However, even when assuming the same carbon fraction as above-ground woody biomass (likely to result in an over-estimate) the land use change emissions from converting grasslands is found to be very small, and the only significant land use change emissions occur where forests are converted.

Table 15 **Tier 1 factors used in the calculation of CO_2 emissions due to land use change (IPCC, 2006)**

Vegetation Map Categories	IPCC 2006 Categories	Grasslands: total non-woody biomass (tonnes dry matter / Ha)	Forests: above-ground biomass (tonnes dry matter / Ha)	Forests: Ratio of below-ground to above-ground biomass	Carbon fraction of above-ground biomass [31]
East Africa coastal forest	Tropical rain forest	-	310	0.37	0.47
Deciduous forest-woodland savanna	Tropical - Dry	8.7	-	-	0.47
Brush-grass savanna	Warm temperate - Dry	6.1	-	-	0.47
Temperate grassland (veld) and mountain grassland	Warm temperate - Dry	6.1	-	-	0.47
Montane forest-tundra	Subtropical mountain systems	-	50	0.37[32]	0.47

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[31] *Value for above-ground biomass (tropical rainforest) applied throughout.*

[32] *No estimate provided in IPCC Emission Inventory Guideline (IPCC, 2006), so assumed same value as tropical rainforest.*

4 Results and discussion

Table 16 gives the high-level carbon footprint results of the NSC road network broken down into countries and road phases. It is clear from the table that the operation of the road contributes by far the most to the carbon footprint, contributing greater than 98% across all countries. The carbon footprint of the NSC road network over a 50-year time period is estimated at 1,412 million tonnes CO_2e. Road operations over the 50-year time period accounts for 99.3% of this total (1,403 million tonnes CO_2e). The road infrastructure carbon footprint (i.e. for the construction, maintenance and rehabilitation of the roads) is estimated at 9.5 million tonnes CO_2e or only 0.7% of the total.

Table 16: Country-level carbon footprint of NSC road network, million tonnes CO_2e over 50 years

	Overall	Construction	Maintenance	Rehabilitation	Operation
Botswana	63	0.19	0.03	0.52	62
DRC	13	0.03	0.01	0.22	13
Malawi	67	0.13	0.02	0.55	67
Mozambique	26	0.05	0.01	0.19	26
Tanzania	137	0.18	0.02	0.73	136
Zambia	234	0.55	0.05	2.4	231
Zimbabwe	110	0.25	0.04	0.89	109
South Africa	762	0.69	0.09	1.7	759
NSC Road Network Total	1,412	2.1	0.25	7.2	1,403
Percentage Contribution to Total Carbon Footprint	100%	0.15%	0.02%	0.51%	99.3%
Infrastructure Carbon Footprint	**9.5**	**2.1**	**0.25**	**7.2**	-
Percentage Contribution to Infrastructure Carbon Footprint	100%	22%	2.6%	75%	-

Even when a shorter time period is considered, for example, 20 years rather than 50 years, the operation phase still dominates, contributing greater than 96% to the carbon footprint across all countries making up the NSC road network.

Table 17 gives a comparative set of results to Table 16, but considers a 20-year time period instead of the 50-year time period. Over a 20-year time period, the overall carbon footprint of the NSC is estimated at 410 million tonnes CO_2e, with the infrastructure phases accounting for 5.3 million tonnes CO_2e or 1.3% of the total carbon footprint (see

Table 17). The carbon footprint does not increase linearly with time, because traffic growth is not linear. It is modelled with a simple compound growth model until 2030 (i.e. at a 5.7% increase per year for most road links). After 2030 traffic volumes are kept constant at 2030 levels. This approximates the “S” curve typical of most growth models. Furthermore, the shorter the time period, the greater the contribution from construction to the total carbon footprint. This is because the GHG emissions of construction are a fixed amount, whilst the GHG emissions from rehabilitation decrease with time as fewer maintenance works are required in the shorter time period.

Table 17: **Country-level carbon footprint of NSC road network, million tonnes CO2e over 20 years**

	Overall	Construction	Maintenance	Rehabilitation	Operation
Botswana	19	0.19	0.01	0.22	18
DRC	4	0.03	0.00	0.11	4
Malawi	19	0.13	0.01	0.23	19
Mozambique	8	0.05	0.00	0.08	8
Tanzania	38	0.18	0.01	0.31	37
Zambia	66	0.55	0.02	0.98	65
Zimbabwe	32	0.25	0.01	0.37	32
South Africa	224	0.69	0.03	0.84	222
NSC Road Network Total	410	2.1	0.10	3.1	404
Percentage Contribution to Total Carbon Footprint	100%	0.5%	0.02%	0.8%	98.7%
Infrastructure Carbon Footprint	**5.3**	**2.1**	**0.10**	**3.1**	-
Percentage Contribution to Infrastructure Carbon Footprint	100%	39%	2%	59%	-

South Africa accounts for 54% of the carbon footprint of the NSC road network over the 50-year time period, even though it accounts for only 18% of the road network (on a per km basis). This is due primarily to the high traffic density on the South African road links, but also due to high infrastructure impacts. High infrastructure impacts arise because the South African roads are more than double the carriageway width of most other road links on the NSC road network, and also are constructed with the more carbon intensive asphalt concrete pavement type (relative to surface-dressing type pavements, see Table 18 for the relative carbon footprint values of the different pavements and Section 4.1.1 for an explanation). A further contributor is the higher carbon intensity of the South African fuel mix, because of the coal-based component of liquid fuels in South Africa.

Zambia is the country with the next highest contribution to the carbon footprint at 17%, which is to be expected, since Zambia has the greatest share of the road network on a per km basis at 24%. All other countries contribute between 4% and 10% of the carbon footprint each, except for road links in the DRC and Mozambique, which contribute less than 2% each.

Table 24 to Table 31 in the appendix give the results per country broken down into the individual road links (both including and excluding the operation phase). These tables are shown for operation and maintenance of the road over a 20-year time period rather than the 50-year time period to show a greater resolution in the road phases. Full results on a per-link basis are provided in the results spreadsheet accompanying this report.

The contribution of the infrastructure to the total carbon footprint (i.e. of construction, maintenance and rehabilitation) is around 5% for most road links on the NSC over the 20-year time period. Where there are exceptions, this is predominantly due to relatively low emissions from the operation phase (e.g. low traffic volumes along these links, and/or a low percentage of trucks in relation to the passenger vehicles).

A further breakdown of the infrastructure carbon footprint (Figure 9) shows that the rehabilitation phase has the highest contribution (up to 80% for some road links). With major rehabilitation works required, on average, at least 3 times in the 50-year time period, and with the GHG emissions of each partial reconstruction equivalent to 50% or more of the GHG emissions of the original construction (see Table 18), this is clear why. The construction phase contributes 17–64% to the infrastructure carbon footprint across all road links on the NSC (excluding the one concrete road link), and 39% on average. Routine maintenance contributes relatively little (less than 2% on average, and up to a maximum of 4% across all road links). This trend holds for the majority of the road links, with the exception of the gravel and concrete roads, which are anomalous (as explained in the following section).

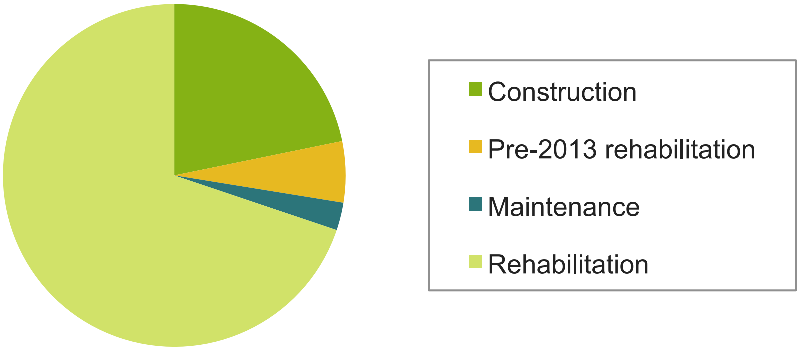

Figure 9: **Breakdown of the average carbon footprint of road infrastructure across all road links for a 50-year time period (excluding concrete and gravel links)**

The carbon impact of land use change (due to clearing vegetation when the road was constructed) was determined to be relatively small, and adds 482 thousand tonnes to the carbon footprint of the NSC road network as a whole (this is irrespective of time period as it occurs only during initial construction of the road). Whilst this is small in the context of the overall carbon footprint (less than 0.05% of the total carbon footprint and 5% of the infrastructure carbon footprint over a 50-year time period), it can be significant for individual road links if forest is cleared. For example, land use change is estimated to be of nearly half the magnitude of the infrastructure carbon footprint for two road links in Tanzania over a 50-year time period. However, for all the other road links it contributes only around 2% to the infrastructure carbon footprint over a 50-year time period.

4.1 Carbon footprint of road infrastructure

To understand the contributions to the carbon footprint of the road infrastructure, it is useful to look at these on a per km and per project basis, as shown in Table 18. These results are on the reference flow level, and are essentially the building blocks of the carbon footprint of the road infrastructure (as described in Section 3.2 to 3.4). The results in Table 18 also capture the differences between projects occurring in the different countries, as well as geometrical discrepancies within the countries (i.e. differences in the width of the carriageway and thickness of the pavement layer).

Table 18: Carbon footprint, in tonnes CO$_2$e per km, of construction, maintenance and rehabilitation at the reference flow level

Pavement type	Country (surface thickness, mm) (section width, m)	Construction tonnes CO$_2$e / km	Maintenance tonnes CO$_2$e / km.year	Rehabilitation tonnes CO$_2$e / km per project	Asphalt overlay[33] tonnes CO$_2$e / km per application	Reseal[34] tonnes CO$_2$e / km per application	Fog spray tonnes CO$_2$e / km per application
Gravel	DRC(50)(7)	90	0.33	159	69	-	-
Asphalt Concrete on Granular Base	RSA(40)(15.2)	371	0.89	175	108	-	-
	Zambia(50)(7)	156	0.39	87	66	-	-
	Malawi(100)(7)	228	0.35	152	67	-	-
	Tanzania(100)(7)	203	0.35	132	57	14	-
	Tanzania(120)(7)	226	0.35	154	57	-	-
	Zambia(100)(7)	226	0.39	151	66	-	-
Penetration Macadam on Granular Base	Zambia(100)(7)	201	0.39	126	66	-	-
Asphalt Concrete on Cement Stabilised Base	Zambia(100)(7)	304	0.39	229	66	-	-
	Zambia(100)(7.3)	317	0.41	229	69	-	-
Surface Dressing on Calcrete Base	Botswana(15)(7)	143	0.43	55	-	15	2
	Botswana(20)(7)	149	0.43	60	-	15	2
	Botswana(25)(14)	309	0.85	131	-	30	5
	Botswana(25)(7)	155	0.43	65	68	15	2
Surface Dressing on Granular Base	DRC(20)(6)	77	0.28	31	-	15	-
	DRC(20)(7)	89	0.33	36	-	17	-
	Malawi(20)(6.1)	100	0.31	40	-	16	-
	Malawi(20)(6.2)	101	0.31	41	-	16	-

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[33] *The asphalt overlay application includes an application of a tack coat (or fog spray) prior to the application of the hot mix asphalt.*

[34] *The surface dressing, "reseal", includes a fog spray application as well, with the exception of Botswana, which has separate application frequency for the fog spray.*

Pavement type	Country (surface thickness, mm) (section width, m)	Construction tonnes CO_2e / km	Maintenance tonnes CO_2e / km.year	Rehabilitation tonnes CO_2e / km per project	Asphalt overlay[33] tonnes CO_2e / km per application	Reseal[34] tonnes CO_2e / km per application	Fog spray tonnes CO_2e / km per application
	Malawi(20)(6.4)	105	0.32	42	-	17	-
	Malawi(20)(6.6)	109	0.33	44	-	17	-
	Malawi(20)(6.7)	109	0.34	44	-	17	-
	Malawi(20)(6.8)	108	0.34	45	-	18	-
	Malawi(20)(7)	113	0.35	46	-	18	-
	RSA(20)(15.2)	306	0.89	116	-	48	-
	Tanzania(20)(7)	101	0.35	38	-	14	-
	Zambia(20)(7)	113	0.39	46	-	26	-
	Zimbabwe(20)(7)	121	0.36	52	-	15	-
	Zimbabwe(25)(7)	127	0.36	57	-	15	-
Surface Dressing on Bitumen Stabilised Base	Zambia(100)(7)	207	0.39	140	-	26	-
Surface Dressing on Cement Stabilised Base	Mozambique(15)(7)	152	0.41	79	-	30	-
	Zambia(20)(6)	163	0.34	106	-	22	-
	Zambia(20)(6.1)	166	0.34	108	-	16	-
	Zambia(20)(7)	190	0.39	124	-	26	-
Concrete	Tanzania(250)(7)	2280	0.35	2204	57	-	-

4.1.1 Construction

The bulk of the NSC road network consists of pavements constructed with a surface dressing on a granular base, and is the predominant pavement type in the DRC, Malawi, and Zimbabwe. Surface dressing on a calcrete base is the pavement type used in Botswana. The carbon footprint of these pavement types is between 2-4 times lower than the asphalt pavement, with respect to the construction stage.

There is some difference between the same pavement types for different countries, which arises because of the different fuel sources of the different countries. For example, Botswana imports its diesel from South Africa, and South African diesel has a higher carbon footprint than the diesel used in the other countries due to the synthetic fuels component of the fuel (coal-based). The construction of a road pavement of a particular type in Botswana therefore has a higher carbon footprint than the construction of the same pavement type in the DRC, where the diesel mix is mainly crude oil based.

The use of a stabilised base instead of a granular base, for either a surface dressing or asphalt concrete surface, results in an increase in the carbon footprint per km of road section. This is due to the cement used in the stabilised base, where cement is a material with a high carbon footprint. Figure 10 and Figure 11 provide a more detailed breakdown in the GHG emissions arising from the construction of a pavement with an asphalt surface and that with a surface dressing on a granular base, respectively.

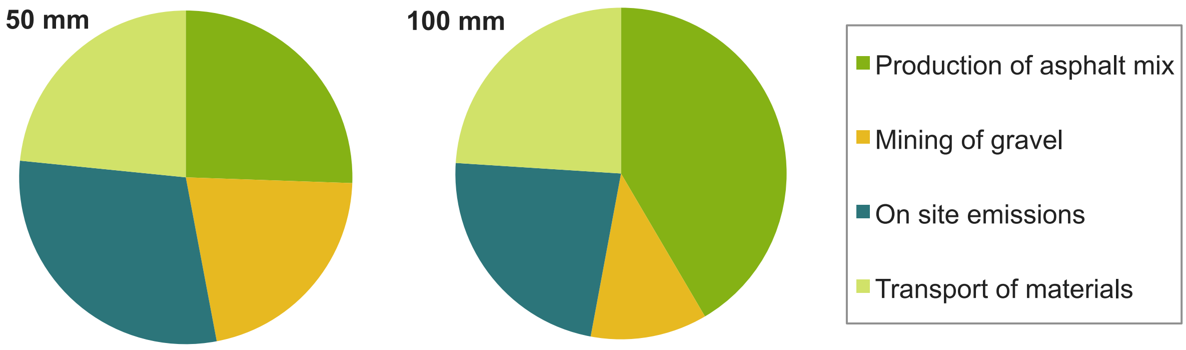

Figure 10: **Relative contribution to construction GHG emissions per km of asphalt pavement on granular base, with 50 mm surface (left) and 100 mm surface (right)**

For a typical asphalt pavement, with a thickness of 40-50 mm, diesel use on site is the highest source of GHGs. The diesel used on site is primarily for site preparation (accounting for around 90% of the total diesel use on site) and then construction of the pavement layers. The transport of materials, such as asphalt and gravel, accounts for nearly 25% of the construction phase GHG emissions. The remainder arise in asphalt production (approximately 25%) and gravel quarrying (approximately 20%). For a thicker asphalt surface (i.e. 100 mm), the asphalt production dominates the GHG emissions, contributing around 40% of the construction emissions, followed by the transport of materials (24%) and diesel used for equipment on site (23%).

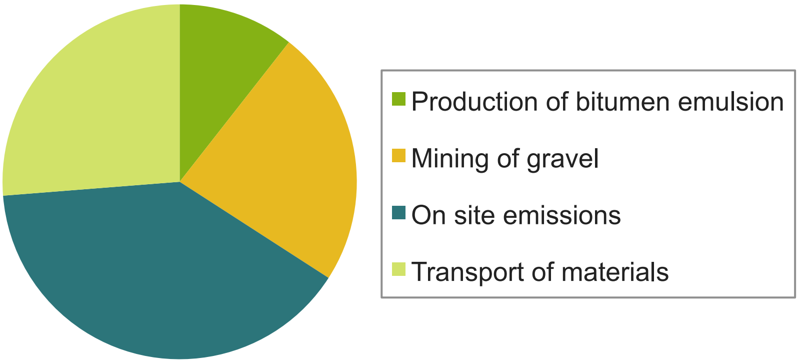

Figure 11: **Relative contribution to construction GHG emissions per 1 km of a 20 mm surface dressing on a granular base**

Construction of a surface dressing pavement follows a similar profile to the asphalt pavement. Diesel consumed in on-site equipment contributes most of the GHG emissions associated with construction (40%), followed by the transport of materials to site (approximately 25%), and gravel quarrying (approximately 25%). However, for the surface dressing, the GHG emissions associated with producing the materials for the road are considerably lower. This is because the surface dressing pavement is much thinner (15-25 mm) than typical asphalt pavements (40-100mm) and consequently uses much less bitumen per km of road constructed. Hence, it would appear that surface dressing on a granular base contributes the least to a road's carbon footprint in the regional context than alternative pavement and base mix options.

As expected, the construction of a gravel road has the lowest carbon footprint per km, due mainly to the absence of bitumen. Although the concrete road is shown to have a very much higher carbon footprint, this is of low significance to the carbon footprint of the NSC road network as a whole, as there is only one 7km road link in Tanzania constructed with a concrete surface.

The carbon footprint of the concrete road is very much higher than the other pavement types. This is consistent with what has been shown in other studies, where concrete has been shown to have as much as double the GHG emissions of the asphalt pavement (Milachowski et al., 2010). In this study, the construction of a concrete pavement was estimated to have 6–15 times the carbon footprint of the asphalt pavement on a per km basis because of the lower GHG emissions estimated for the asphalt pavements. This is because of structural differences in the asphalt pavements constructed in Southern Africa relative to those in Europe. In European roads the surfacing is typically constructed on an asphalt binder layer (around 80 mm) and an asphalt base layer (around 220 mm), whereas Southern African roads typically apply the bituminous surfacing directly onto a granular base, due to the abundance of aggregate materials. This results in the use of less bitumen, and therefore a much lower carbon footprint per km. This trend is also evident in countries such as Tanzania and Zambia where the roads have higher carbon footprints per km due to the use of thicker asphalt surfaces (around 100 mm).

4.1.2 Maintenance

Maintenance has a fairly small contribution to the carbon footprint of the NSC road network, contributing around 3.5% to the infrastructure carbon footprint for most road links, at an average of 0.4 tonnes CO_2e per km road maintained. This low contribution is mainly due to how the road phases have been defined in this study, with the maintenance phase including only on-going patching and crack sealing. The bigger, periodic maintenance works are included in the rehabilitation phase. Furthermore, the annual material requirements for on-going routine maintenance are taken from a single dataset, and applied for all road links in the NSC road network. The only variation captured between the road links is thus due to different road geometries (e.g. the wider South African roads have a higher maintenance material requirement per km maintained, see Table 18).

Figure 12 provides a breakdown in GHG emissions arising from the routine maintenance of pavements in the NSC road network. The major source of emissions, accounting for just over half of the maintenance carbon footprint, is the production of materials used in the routine maintenance processes, including bitumen, gravel and cement. The next most significant source of GHG emissions is diesel burnt in on-site equipment (including mixer, grader, paver and compactor), whist the transport of materials to site contributes just over 10%.

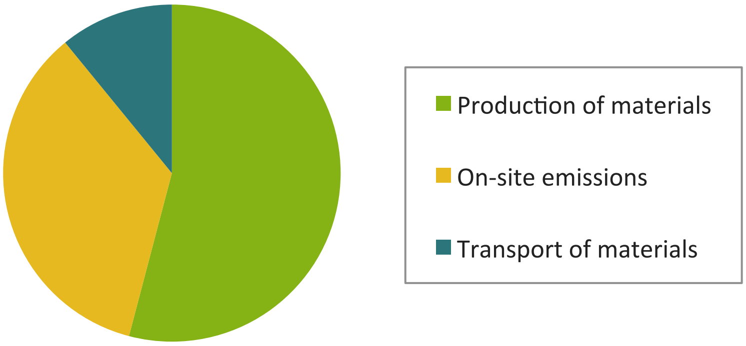

Figure 12: **Relative contribution to maintenance GHG emissions per km of asphalt pavement maintained**

4.1.3 Rehabilitation

Rehabilitation includes the milling of the existing top layers (150–250 mm) and then reconstruction of the base and surface layers. The GHG emissions arising from partial reconstruction of an **asphalt concrete pavement on a granular base** are equivalent to 50-70% of the GHG emissions from the original construction, and on a **stabilised base** equivalent to up to 75% of the original construction. GHG emissions arising from partial reconstruction of a **surface dressing pavement on a granular base** are lower than those of an asphalt pavement, and are equivalent to less than 40% of the initial road construction. The GHG emissions of a partial reconstruction of a pavement with **surface dressing on a cement stabilised base** are of similar magnitude to those of partial reconstruction of an asphalt concrete surface, and are equivalent to between 50-70% of GHG emissions of the original construction. It is therefore not surprising that the rehabilitation phase shows the highest contribution to the infrastructure carbon footprint as a whole, considering that partial reconstruction is required up to 4 times over the 50-year time period for some road links.

In general, the pavements are reconstructed to the same specifications as their original construction, with the exception of the gravel road in the DRC, which was transformed to an asphalt concrete surface of 100 mm on a granular base (prior to 2013). This explains the rehabilitation having carbon emissions higher than the initial construction. The concrete pavement is also anomalous, where the GHG emissions of the partial reconstruction are almost the same as the original construction. This is because the GHG emissions of the construction phase are dominated by those associated with the concrete surface, and the rehabilitation essentially entails the reconstruction of the entire 250 mm concrete surface. It should be noted, however, that rehabilitation of the concrete pavement is required much less frequently than for the bituminous pavements (estimated at only once over the 50-year period). Whereas, for the bituminous pavements, partial reconstruction is carried out 2 to 4 times over the 50-year period, depending on the particular region and its climate (although even taking this into account the concrete pavement still has much higher GHG emissions from the rehabilitation phase).

Figure 13 and Figure 14 provide a detailed breakdown of the GHG emissions associated with the rehabilitation of an asphalt surface pavement and a surface dressing pavement on a granular base, respectively.

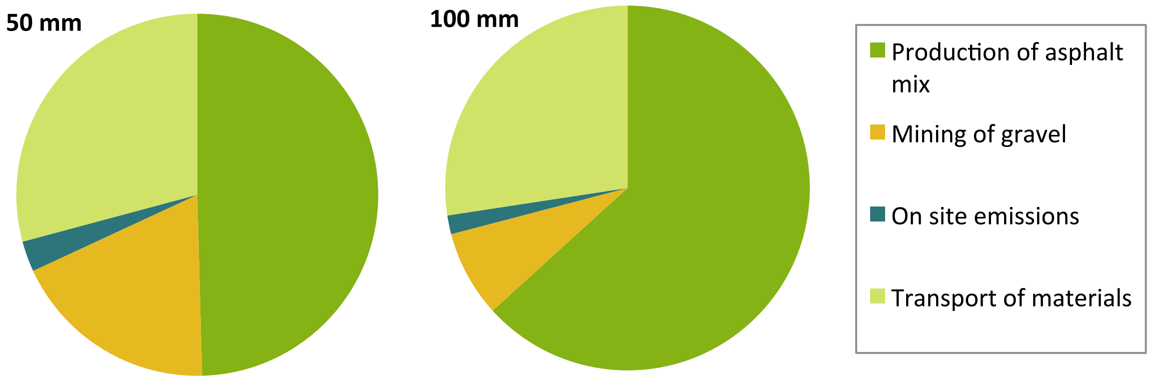

Figure 13: **Relative contribution to rehabilitation GHG emissions per km of asphalt pavement on granular base, with 50 mm surface (left) and 100 mm surface (right)**

Unlike the construction of an asphalt pavement, where diesel use on-site accounts for the bulk of GHG emissions, the largest source of GHG emissions arising during the rehabilitation of an asphalt pavement is the production of materials used in the road repair. On-site emissions from diesel use do not contribute as significantly because rehabilitation does not require the extensive site preparation of the initial road construction. It also requires less material to be transported to site as it reuses the existing pavement as a sub-base once milled. The production of the materials therefore dominate the GHG emissions, where asphalt production accounts for 50–60% and gravel mining 8-20%, depending on the thickness of the asphalt layer (Figure 13). This is followed by the transport of materials to site, which accounts for just under 30% of the total GHG emissions.

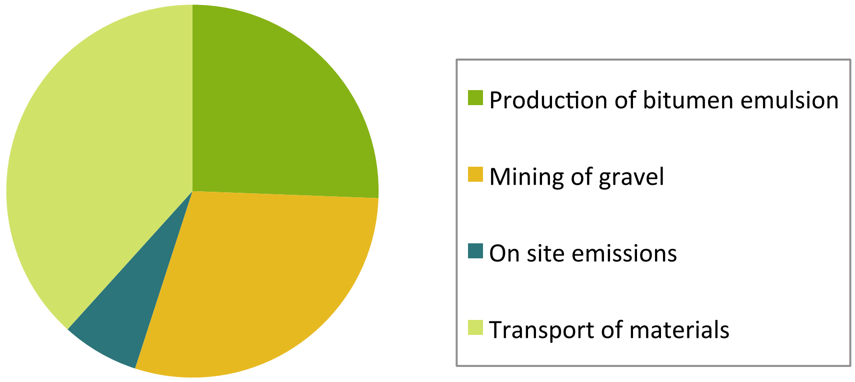

Figure 14: **Relative contribution to rehabilitation GHG emissions per 1 km of a 20 mm surface dressing on a granular base**

The rehabilitation of a surface dressing pavement follows much the same profile as an asphalt pavement in that the on-site emissions of the diesel are considerably lower than during the initial construction. However, in the case of the surface dressing pavement, the transport of road materials to the construction site contributes the most to the GHG emissions of the rehabilitation phase (at 38%). This is not because the rehabilitation of a surface dressing pavement has higher transport emissions than an asphalt pavement, but rather because of the lower relative share of the emissions from producing the materials (i.e. in the asphalt pavement the emissions associated with producing the asphalt are higher than those arising from transport, but in the bitumen pavement, the emissions associated with producing the bitumen are lower than those arising from the transport of materials.

The GHG emissions of an asphalt overlay is fairly consistent across the different regions, and varies between 60-70 tonnes CO_2e per km of road, with the exception of the road sections in South Africa. This is because these sections are more than twice the width of the other sections and therefore would require twice as much asphalt concrete per km.

As with the asphalt overlay, the GHG emissions of the reseal are quite consistent across the different countries (at 15-30 tonnes CO_2e per application). For all sections, except Botswana, a fog spray was included as part of the reseal application, as an additional layer to the seal. In the case of Botswana however, a separate maintenance plan was provided for the fog spray, which amounted to 2.5 tonnes CO_2e per km of road.

4.2 Carbon footprint of road operation

The GHG emissions intensity of the operation of the various vehicles using the NSC road network are given in CO_2e per vehicle per km driven in Table 19. The emissions intensity of the different vehicle classes are a function of fuel efficiency of the vehicles, and are kept constant over the 50-year time period (no allowances are made for changes in engine technology over the 50-year time period). Trucks (medium and heavy goods vehicles) and buses have a much higher emissions intensity than the passenger vehicles because of their higher fuel consumption. The differences between the countries arise primarily from the different diesel mixes of the countries, with passenger vehicle emissions assumed to be the same across all countries. The higher GHG emissions intensity of South Africa's fuel mix is clear, resulting from the higher GHG emissions associated with producing liquid fuels from coal-based sources, relative to producing them from crude-oil sources. The range across the other Southern African countries is primarily related to the amount of diesel they import from South Africa, with Botswana importing 100% of its diesel from South Africa, and Mozambique importing none. In medium and heavy goods vehicles, some of the variation between the different countries is also due to variation in the fuel consumption of the trucks estimated for the different road links (taking into account vehicle loading, terrain and road conditions, at a fairly high level).

Table 20 and Table 21 give the annual total and average GHG emissions per vehicle type, respectively. Annual GHG emissions per road link are calculated from the individual vehicle GHG emissions intensities of the vehicles (per vehicle per km, see Table 19) multiplied by the respective number of vehicles using the road link in that particular year (2012, in the case of Table 20) and the length of the road link. The country totals are summed from the GHG emissions calculated for the individual road links. Results on the level of road link are available for the base year (2012), as well as for the year 2020, in the spreadsheet accompanying this report.

The annual average GHG emissions per vehicle type are provided for the base year (2012) in Table 21, and are calculated from the annual totals divided by the length of road. E.g. for Botswana, the GHG emissions from passenger vehicles using the NSC road network was 1,604 tonnes CO_2e in 2012. The NSC road links in Botswana cover 1,252 km, giving an annual average per km emission of 1.3 tonnes CO_2e/km. Tanzania is found to be the country with the highest GHG emissions per km (due to high emissions from heavy goods vehicles), followed by South Africa, where passenger vehicles account for the highest share of GHG emissions.

Table 19: **GHG emissions per vehicle per km driven of the different vehicle classes using the NSC road network (kg CO_2e per km driven)**

Country	Passenger vehicles			Goods vehicles		
	Car, 4WD, Pick-up	Mini bus	Bus	Light goods	Medium goods	Heavy goods
Botswana	0.27	0.37	1.3	0.38	1.3 - 1.4	2.4 - 2.5
DRC	0.26	0.32	0.98	0.28	1.1	1.9
Malawi	0.26	0.35	1.2	0.33	1.2 - 1.3	2.2 - 2.3
Mozambique	0.25	0.32	0.94	0.27	0.9	1.7
Tanzania	0.26	0.33	1.1	0.30	1.1	1.9 - 2.1
Zambia	0.26	0.35	1.2	0.33	1.1 - 1.3	2.0 - 2.4
Zimbabwe	0.26	0.33	1.0	0.29	1.0	1.9
RSA	0.40	0.47	1.3	0.37	1.3	2.3 - 2.4

Table 20: **Annual GHG emissions per country and vehicle classes, in tonnes CO_2e for the base year (2012)**

Country	Passenger vehicles			Goods vehicles			All vehicles
	Car, 4WD, Pick-up	Mini bus	Bus	Light goods	Medium goods	Heavy goods	
Botswana	1 604	74	279	83	95	839	2 975
DRC	1.5	7.1	3.8	0.8	6.0	326	345
Malawi	1 017	508	279	135	425	883	3 247
Mozambique	142	104	85	29	56	347	763
Tanzania	716	182	1 001	150	484	1 695	4 227
Zambia	686	346	616	574	1 571	4 281	8 074
Zimbabwe	557	139	139	51	171	1 009	2 065
RSA	3 411	1 113	523	83	392	1 589	7 111
NSC road network	8 134	2 473	2 926	1 105	3 200	10 969	28 807

Table 21: **Annual average GHG emissions per km for the different countries and vehicle classes, in tonnes CO_2e per km for the base year (2012)**

Country	Passenger vehicles			Goods vehicles			All vehicles
	Car, 4WD, Pick-up	Mini bus	Bus	Light goods	Medium goods	Heavy goods	
Botswana	1.3	0.06	0.22	0.07	0.08	0.67	2.4
DRC	0.004	0.02	0.01	0.002	0.02	0.81	0.9
Malawi	0.95	0.47	0.26	0.13	0.39	0.82	3.0
Mozambique	0.34	0.25	0.21	0.07	0.14	0.84	1.9
Tanzania	0.73	0.19	1.0	0.15	0.49	1.7	4.3
Zambia	0.26	0.13	0.24	0.22	0.60	1.6	3.1
Zimbabwe	0.27	0.07	0.07	0.02	0.08	0.49	1.0
RSA	1.8	0.59	0.28	0.04	0.21	0.84	3.7
NSC road network	0.76	0.23	0.27	0.10	0.30	1.0	2.7

Goods vehicles account for just over half of the operating emissions of the NSC road network, even though passenger vehicle numbers are three times higher than goods vehicle numbers. This is because a heavy goods vehicle has nearly ten times the GHG emissions per km driven than a passenger car (see Table 19). Because of this, medium and heavy goods vehicles account for a high share of GHG emissions on most of the road links, other than those road links around cities where the passenger vehicle share is very high. An example of this is shown in Figure 15 for five road links in Botswana (*BP Kazungula to Sebina junction*). Here goods vehicles account for less than 20% of the traffic volume, but contribute just over 50 % of the emissions.

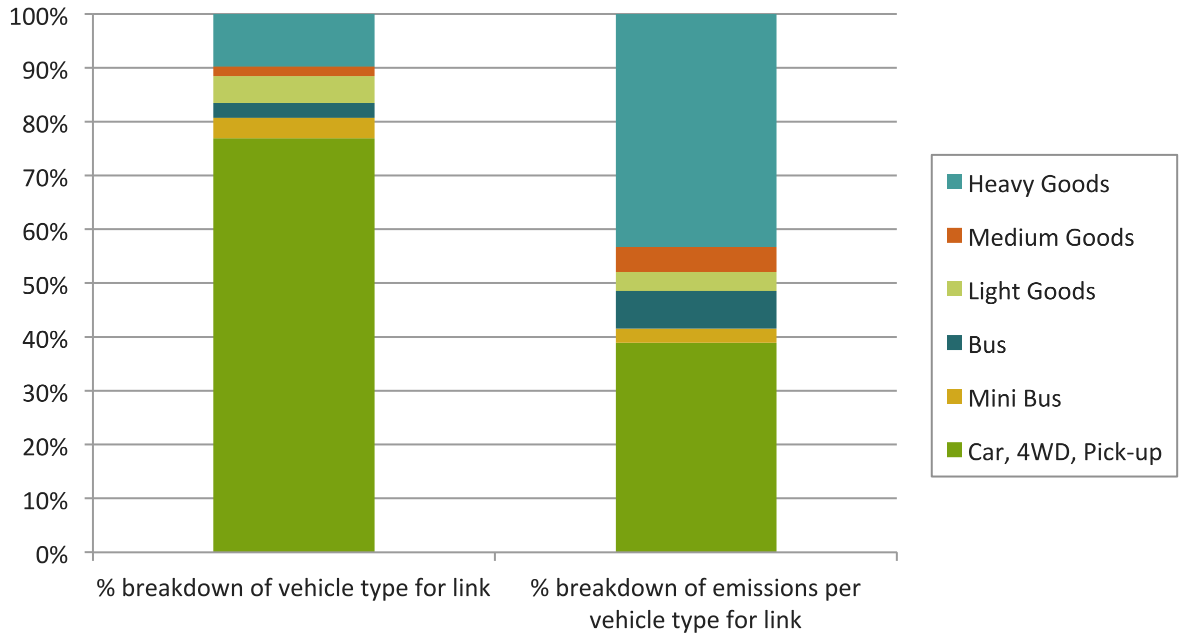

Figure 15: **Vehicle breakdown in traffic share and share of GHG emissions for five road links in Botswana (BP Kazungula to Sebina Junction)**

A general trend evident across the countries is that the passenger vehicle share of traffic is highest around the cities, with the volume of traffic and the percentage of passenger vehicles decreasing as you move further away from the cities. Other general trends across the countries are as follows:

- The highest volume of traffic in Botswana occurs around Gaborone at 7,500 – 10,000 vehicles per day (AADT), followed by Francis Town with approximately 5,300 vehicles. The passenger vehicles amount to greater than 90% of traffic volume around the cities, and contribute around 75% of the operational GHG emissions for these road links. Overall, passenger vehicles account for two-thirds of emissions from vehicle operation on the NSC road network in Botswana.
- In Malawi, the vehicle count is high around Lilongwe city near the airport at around 20,000 vehicles per day (AADT), with passenger vehicles making up 75% of the total traffic volume. There is also a high percentage of passenger vehicles around Blantyre and Mzuzu (2,000 – 5,500 vehicles per day), which decreases as you move further away from the cities. Overall, passenger vehicles dominate the vehicular emissions on the NSC road network in Malawi, accounting for 56% of GHG emissions.

- In Mozambique, the highest traffic count is around Moatize, with around 7,000 vehicles per day (AADT), the majority of which is passenger vehicles (approximately 80%). The remaining links however, have about a 50/50 split between passenger and goods vehicles, and with low vehicle totals compared to the other countries (below 3,500 per day).
- In Zimbabwe, the bulk of traffic occurs around Harare at 3,500 – 5,500 vehicles per day (AADT). Passenger vehicles account for the bulk of GHG emissions on the road link with Mozambique. However, for the link from South Africa leading towards Harare, goods vehicles dominate the emissions, resulting in goods vehicles accounting for 60% of vehicular emissions overall.
- South Africa has by far the highest vehicle count, with the bulk of the traffic on the Pretoria to Johannesburg link, at 46,000 vehicles per day (AADT), followed by the Johannesburg to Durban link at 26,000 vehicles per day. The other South African road links are still high in comparison with the non-South African NSC road links at 4,500 – 8,000 vehicles per day (AADT). On the South African road links passenger vehicles dominate both traffic share and emissions, accounting for 70% of the GHG emissions from vehicles operating on the NSC road network in South Africa.
- The Tanzanian road links have low vehicle counts in general (below 2,500 vehicles per day), with 70% passenger vehicles contributing 45% of emissions. The exception is the road links around the port of Dar-es-Salaam with 24,000 vehicles per day (AADT), and where 60% of emissions are due to passenger traffic.
- In Zambia, goods vehicles dominate the traffic volume, typically making up 60% of the vehicle share and 80% of the emissions. Zambia's highest vehicle count is along the Luanshya – Kitwe – Chingola links along the border with DRC at 6,000 vehicles per day, followed by the links around Central Lusaka at 4,500 vehicles per day. As in other countries, the vehicle count decreases as you move away from the cities.
- In the DRC, goods vehicles make up a large percentage of the overall traffic volume, up to 90% on some road links, and therefore make up most of the emissions (greater than 95%). However, total traffic volumes are very low in relation to the other regions (at an average of less than 500 vehicles per day).

4.3 Data gaps and uncertainty

A very large amount of data is applied in the estimate of the carbon footprint. Whilst the best data available has been used in the calculations, there are inevitably a number of gaps and uncertainties to consider.

The most important contributor to the uncertainty in the overall results is uncertainty in key activity data inputs. Assumptions had to be made for certain road links as to their pavement type and thickness. Obviously this choice underpins all materials and fuels required for the construction and maintenance of the road, and the model cannot provide accurate results without an accurate starting point.

Other key activity data, with a very high degree of influence on the results, are the assumptions regarding the frequency of periodic maintenance works, as well as the particular processes applied. Considerable effort was applied in finding reasonable estimates for these. Nonetheless, even where primary data sources were found (e.g. maintenance schedules from the national road agencies) there are, at best, plans that may or may not be applied on schedule in the actual regional context.

The operation phase considerably dominates the carbon footprint, and so it stands to reason that data inputs determining the emissions from operation have the highest influence on the certainty of the results. Here the most significant variable is the estimate of growth in road traffic over the timeframe of the study. Especially significant is the assumption that the same growth occurs in all vehicle classes; whereas the studies, from which the estimates of road traffic growth rates are extracted, are based on freight traffic. Also highly influential in the estimate of road traffic emissions is the assumption that the AADT data is representative of the entire road link (i.e. that it can be multiplied by 365 and the length of the road link to get the annual kilometres travelled on the road). These factors are judged to have greater influence on the uncertainty of the results than on the fuel efficiencies applied in the model for the various vehicle classes.

The carbon footprint of the infrastructure is incomplete in that it does not include bridges on the NSC road links and the construction of drainage on the roads. It is difficult to judge the significance of these omissions, because no information could be found on the number of bridges on the NSC road links (and thus how important it is that they are not included). However, concrete is shown to be a material with a high carbon impact in the carbon footprint model, e.g. a steel and concrete road has 8 to 10 times the GHG emissions per km constructed of an asphalt road, so the significance of omitting bridges could be high if together they make up a fair length of the road network.

The construction of drains might also be a significant source of emissions if these are constructed out of concrete. However, the majority of road links are indicated as having “soft-drains” that are assumed not to require concrete or steel in their construction. Thus, excluding the construction of drains is only relevant to just over one-third of the road links. Furthermore, of the road links with hard drains, only 5 are indicated to have drains that are “fully-lined”. Where existing soils and vegetation do not provide a stable enough surface or in mountainous terrain, where road gradients reach 8 to 10 percent, lining the side drains with concrete, stone or bricks can considerably assist in controlling erosion and silting, a big challenge in maintaining a good quality drain. The overall significance of not including the construction of drainage on the infrastructure carbon footprint is therefore estimated to be low, but as the materiality of this assumption could not be tested, drainage is flagged as a high source of uncertainty, and an area for future improvement of the infrastructure carbon footprint.

The use of a single data source on routine maintenance is a weakness in the study. Furthermore this source is from a South African company, but applied as representative of the whole Southern African region. Routine maintenance is found to contribute relatively little to the overall carbon footprint, which is consistent with the findings of other road studies, but this finding is unable to be verified as it is based on a single data source.

The secondary data applied in the study (primarily the ecoinvent database) is judged to be of a high degree of accuracy and completeness, as well as of fair technological relevance (with the processes applied, such as quarrying, bitumen production and concrete production fairly global in their technology). The geographical relevance of the secondary datasets was improved by adapting them to the African context with relevant electricity and fuel data. Thus, the use of secondary datasets is deemed be a relatively low source of uncertainty in the results.

The carbon footprint model also relies quite substantially on data extracted from the ROADEO GHG calculator (The World Bank, 2011), especially for on-site fuel consumption in road construction and rehabilitation. Although not specific to the African context, this calculator is specific to a developing country context (albeit Asian). The calculator was also developed as part of a very extensive methodological project and is deemed to be of high standard. Furthermore, data from the calculator was found to correlate reasonably well with company-specific information sourced in this study. Thus, this calculator is judged to supply as accurate data as possible given the inherently variable nature of construction projects.

5 Conclusions and Recommendations

The carbon footprint of the NSC road network is estimated at 1,412 million tonnes CO_2e over a 50-year time period, with the road infrastructure carbon footprint estimated at 9.5 million tonnes CO_2e (i.e. for the construction, maintenance and rehabilitation of the roads).

South Africa contributes the most to this carbon footprint, at 54%, with Zambia the next most significant contributor at 17%.

The surface dressing pavement is the predominant pavement type on the NSC road network, and was found to have the lowest carbon footprint in its construction and non-routine maintenance. GHG emissions associated with the construction and rehabilitation of an asphalt pavement were found to be up to double those of the surface dressing pavement (both on granular base).

Operation of the road network, that is the GHG emissions from the road traffic using the road network, is by far the greatest contributor to the carbon footprint (contributing greater than 92% for all road links and greater than 99% for the road network as a whole, if a 50-year time period is considered).

The next most significant contributor to emissions is rehabilitation, where the GHG emissions of a partial reconstruction project is equivalent on average to half the emissions of the initial road construction. With each road link predicted to need between 2-4 partial reconstructions and 6-20 resurfacings, it stands to reason that this phase should be the most significant contributor to the infrastructure carbon footprint over a 50-year time period. This also means that the frequency of rehabilitation works is the most influential variable in determining the carbon footprint of the road infrastructure.

Given that the operation phase contributes by far the most to the carbon footprint, variables that are influential in determining the operational phase emissions contribute most to the uncertainty of carbon footprint as a whole. The growth rate assumed for road traffic is by far the most significant variable here. However, to a degree this is inherently uncertain, as growth models are by their very nature uncertain. Nonetheless, the greater the time period considered, the more uncertain the carbon footprint can be expected to be. Also contributing to the uncertainty of the operational phase are various key assumptions, including the fact that all vehicle classes grow at the same rate, and that the average annual daily traffic (AADT) can be considered representative for the entire length of the road link. Both these factors would tend to overestimate the road traffic and thus the carbon footprint.

The carbon footprint is considered to be as accurate and complete as current data sources allow. The emissions datasets used in the study are considered to be of good accuracy and completeness, and the best available, even though these were only partially representative of the Southern African context. Uncertainty in the results is thought to arise more from the activity data applied in the study. For example, assumptions had to be made for many of the road links as to their pavement type and thickness of the layers. Furthermore, many of the key activity data are inherently variable, such as the number of periodic maintenance works to take place over the next 20-50 years.

There are therefore a number of measures that could be taken to improve the estimate of the carbon footprint. These include for the infrastructure carbon footprint:

- Continuing to improve the database on the road links, especially where there are gaps on pavement types and thicknesses, as these are the key determinants for the construction carbon footprint.
- Including all aspects of the NSC road links in the database, including data on bridges (lengths and materials of construction), more detail on the types of drainage installed along the road links, information on the terrain through which the road links pass, and road area (including verges) etc. The former are needed so that all aspects of infrastructure and construction can be included, whilst the latter would

allow a more accurate picture of the carbon impact of land use change to be obtained.
- Relationships should be built with the national road agencies within the NSC corridor so that information can be obtained on the planned maintenance and rehabilitation schedules for the roads. Good contacts need to be made so that the information can be updated regularly. At the same time, time-series data should start to be kept on maintenance and rehabilitation works undertaken on the road links. This is important, because whilst schedules offer an ideal path for road maintenance, the reality appears to be that there are often delays and maintenance ends up being emergency rather than scheduled. Actual time-series data would therefore provide a good counter-point to the planned future works.
- On the basis of other studies, routine maintenance is unlikely to be material to the results, but this should be verified. If possible, contacts should be made with contractors working along the NSC. If, as on the South African road links, a single company is awarded a long-term contract to maintain sections of the road, then it should be possible to build relationships with these companies. To obtain good data on maintenance, average data over a long time period (5-10 years) and lengthy stretch of road is required.

For the operation phase carbon footprint:

- A better understanding of the AADT data in terms of how representative it is for traffic along the entire length of the road link for the whole year, and if not, what adaptations could be made to make it more so.
- Research on the growth of passenger vehicles on the NSC road links. Only studies that look at growth in freight traffic were found to inform this study, although passenger vehicles are seen be the predominant vehicle class on many of the NSC road links.
- Further customisation of fuel efficiency data for vehicles on the NSC road network. A large number of factors affect the fuel efficiency of good vehicles, including loading, age of vehicle, road conditions (pavement quality, elevation, traffic congestion etc.). Actual fuel efficiency from truckers and fleet operators would therefore offer the best data source, as these factors are too varied to accurately customise fuel consumption models. A more detailed breakdown in vehicle classes, and/or details on typical makes and models of vehicles would allow for a more accurate estimate of the fuel consumption of passenger vehicles.

It is clear from the results that use of the road infrastructure is far more important in terms of the carbon footprint than constructing and maintaining the road infrastructure. Thus, measures that reduce operational emissions are of high importance rather than reducing construction impacts (although the latter are still important). As such, important research avenues are those that look at reducing the fuel consumption of vehicles, including different road designs and pavement types, and reducing traffic congestion. Also important is looking more holistically at transport corridors, and at future transport options such as road to rail migration.

Measures to improve road durability also offer important improvement potential, as the high rate of rehabilitation required on the roads quickly amounts to more than the emissions of the original construction. Thus, building roads with a longer design period and with more frequent seals should be investigated. Such tools as life cycle costing (LCC) would provide a useful assessment measure in such cases.

There are also a number of research initiatives that look at “greener” road materials, especially the use of a higher content of recycled materials in road construction. These also offer interesting improvement opportunities, but it should be carefully assessed that the use of such materials do not cause the road to require more maintenance or negatively affect the fuel efficiency of the vehicles using the roads, which was found to be where the majority of the road impact lies (for carbon impact, as well as for a wider suite of life cycle environmental impacts).

Assessing such improvement measures should take a life cycle view, so that carbon impacts are not shifted between life cycle phases (e.g. from operation into infrastructure), especially if new pavement types require non-conventional road materials. Improvement measures should also preferably be assessed by life cycle assessment, to avoid carbon impacts being prioritised at the potential expense of other impacts, e.g. water footprint, impacts on ecosystems etc.

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Appendix

Table 22: Global warming potentials of greenhouse gases according to IPCC 2007[35] (100 year timeframe)

Emission to air	CAS number	GWP (kg CO_2e / kg)
1-Propanol, 3,3,3-trifluoro-2,2-bis(trifluoromethyl)-, HFE-7100	014117-17-0	297
Butane, 1,1,1,3,3-pentafluoro-, HFC-365mfc	000406-58-6	794
Butane, perfluoro-	000355-25-9	8860
Butane, perfluorocyclo-, PFC-318	000115-25-3	10300
Carbon dioxide	000124-38-9	1
Carbon dioxide, fossil	000124-38-9	1
Carbon dioxide, land transformation	000124-38-9	1
Chloroform	000067-66-3	31
Dimethyl ether	000115-10-6	1
Dinitrogen monoxide	010024-97-2	298
Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	000075-68-3	2310
Ethane, 1-chloro-2,2,2-trifluoro-(difluoromethoxy)-, HCFE-235da2	026675-46-7	350
Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	001717-00-6	725
Ethane, 1,1-difluoro-, HFC-152a	000075-37-6	124
Ethane, 1,1,1-trichloro-, HCFC-140	000071-55-6	146
Ethane, 1,1,1-trifluoro-, HFC-143a	000420-46-2	4470
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	000811-97-2	1430
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	000076-13-1	6130
Ethane, 1,1,2-trifluoro-, HFC-143	000430-66-0	353
Ethane, 1,1,2,2-tetrafluoro-, HFC-134	000359-35-3	1100
Ethane, 1,2-dibromotetrafluoro-, Halon 2402	000124-73-2	1640
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	000076-14-2	10000
Ethane, 1,2-difluoro-, HFC-152	000624-72-6	53
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	002837-89-0	609
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	000306-83-2	77
Ethane, chloropentafluoro-, CFC-115	000076-15-3	7370
Ethane, fluoro-, HFC-161	000353-36-6	12
Ethane, hexafluoro-, HFC-116	000076-16-4	12200
Ethane, pentafluoro-, HFC-125	000354-33-6	3500
Ether, 1,1,1-trifluoromethyl methyl-, HFE-143a	000421-14-7	756
Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347mcc3	000406-78-0	575
Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347mcf2	000406-78-0	374
Ether, 1,1,2,2-Tetrafluoroethyl methyl-, HFE-254cb2	000425-88-7	359
Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356mec3	000382-34-3	101
Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcc3	000382-34-3	110

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[35] *Climate Change 2007. IPCC Fourth Assessment Report. The Physical Science Basis. http://www.ipcc.ch/ipccreports/ar4-wg1.htm*

Emission to air	CAS number	GWP (kg CO_2e / kg)
Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcf2	000382-34-3	265
Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcf3	000382-34-3	502
Ether, 1,2,2-trifluoroethyl trifluoromethyl-, HFE-236ea2	084011-06-3	989
Ether, 1,2,2-trifluoroethyl trifluoromethyl-, HFE-236fa	084011-06-3	487
Ether, 2,2,3,3,3-Pentafluoropropyl methyl-, HFE-365mcf3	000378-16-5	11
Ether, di(difluoromethyl), HFE-134	001691-17-4	6320
Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245cb2	001885-48-9	708
Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245fa1	001885-48-9	286
Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245fa2	001885-48-9	659
Ether, ethyl 1,1,2,2-tetrafluoroethyl-, HFE-374pc2	000512-51-6	557
Ether, nonafluorobutane ethyl-, HFE569sf2 (HFE-7200)		59
Ether, pentafluoromethyl-, HFE-125	003822-68-2	14900
Hexane, perfluoro-	000355-42-0	9300
HFE-227EA		1540
HFE-236ca12 (HG-10)		2800
HFE-263fb2		11
HFE-329mcc2		919
HFE-338mcf2		552
HFE-338pcc13 (HG-01)		1500
HFE-347pcf2		580
HFE-43-10pccc124 (H-Galden1040x)		1870
Methane	000074-82-8	25
Methane, biogenic	000074-82-8	22
Methane, bromo-, Halon 1001	000074-83-9	5
Methane, bromochlorodifluoro-, Halon 1211	000353-59-3	1890
Methane, bromodifluoro-, Halon 1201	001511-62-2	404
Methane, bromotrifluoro-, Halon 1301	000075-63-8	7140
Methane, chlorodifluoro-, HCFC-22	000075-45-6	1810
Methane, chlorotrifluoro-, CFC-13	000075-72-9	14400
Methane, dibromo-	000074-95-3	1.54
Methane, dichloro-, HCC-30	000075-09-2	8.7
Methane, dichlorodifluoro-, CFC-12	000075-71-8	10900
Methane, dichlorofluoro-, HCFC-21	000075-43-4	151
Methane, difluoro-, HFC-32	000075-10-5	675
Methane, fluoro-, HFC-41	000593-53-3	92
Methane, fossil	000074-82-8	25
Methane, iodotrifluoro-	002314-97-8	0.4
Methane, monochloro-, R-40	000074-87-3	13
Methane, tetrachloro-, CFC-10	000056-23-5	1400
Methane, tetrafluoro-, CFC-14	000075-73-0	7390
Methane, trichlorofluoro-, CFC-11	000075-69-4	4750
Methane, trifluoro-, HFC-23	000075-46-7	14800
Nitrogen fluoride	007783-54-2	17200

Emission to air	CAS number	GWP (kg CO_2e / kg)
Pentane, 2,3-dihydroperfluoro-, HFC-4310mee	138495-42-8	1640
Pentane, perfluoro-	000678-26-2	9160
PFC-9-1-18		7500
PFPMIE		10300
Propane, 1,1,1,2,2,3-hexafluoro-, HFC-236cb	000677-56-5	1340
Propane, 1,1,1,2,3,3-hexafluoro-, HFC-236ea	000431-63-0	1370
Propane, 1,1,1,2,3,3,3-heptafluoro-, HFC-227ea	000431-89-0	3220
Propane, 1,1,1,3,3,3-hexafluoro-, HCFC-236fa	000690-39-1	9810
Propane, 1,1,2,2,3-pentafluoro-, HFC-245ca	000679-86-7	693
Propane, 1,1,3,3-tetrafluoro-, HFC-245fa	004556-24-5	1030
Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb	000507-55-1	595
Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca	000422-56-0	122
Propane, perfluoro-	000076-19-7	8830
Propane, perfluorocyclo-		17340
Sulfur hexafluoride	002551-62-4	22800
Trifluoromethylsulfur pentafluoride	000373-80-8	17700

Table 23: Classification of road sections along the north-south corridor road network

Country/ border	Section name	Pavement type[36]	Surface type[37]		Base type		Section length (km)
Red text indicates where surface and/or base types have been estimated based on those most commonly used within the NSC for the particular pavement type and country. **The acronyms in the table are according to the classification system in the Highway Development and Management Series Model (HDM-4) explained in Table 5.**							
DRC	Likasi - Kolwezi	n/a	-	Gravel	GB	Gravel	176
Malawi	BP Mchinji - Junction M1 Lilongwe	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	116
RSA	Pietersburg - Pretoria	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	261
RSA	Pretoria - Johannesburg	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	58
RSA	Messina - Pretoria	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	454
RSA	End BP Beit Bridge - Messina	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	19
RSA	Zeerust R57 - Pretoria	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	227
RSA	BP Gabarone - Zeerust R57	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	125
RSA	Johannesburg - Durban	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	578
Tanzania	Mbeya - Igawa	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	108
Tanzania	Turn off A2 - Dar-es-salaam	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	87
Tanzania	Dar-es-salaam - Port	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	42
Tanzania	BP Songwe - Junction Tanzam	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	101
Tanzania	Mafinga - Iringa (Start of DANIDA)	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	76
Tanzania	Iringa Start of DANIDA - Concrete Ikokoto	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	60
Tanzania	Concrete Kitonga Gorge - Iyovi (End DANIDA)	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	85
Tanzania	BP Tunduma - Mbeya	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	103
Zambia	End Asphalt Overlay - BP Mchinji	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	256
Zambia	TO Luanshya - Kitwe	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	39
Zambia	Start Asphalt Overlay -Luangwa Bridge	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	33
Zambia	End of Bridge - End Asphalt Overlay	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	97

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[36] *The pavement type classification extracted from updated HDM-4 efficiency study spread sheet "Review_of_North-South_Corridor_Data_V05 - 24 July 2013.xls" received 14 July.*

[37] *Surface type and base type extracted from TMSA document "Data base Carbon June 2013.xls" received 1 July 2013.*

Country/ border	Section name	Pavement type[36]	Surface type[37]		Base type		Section length (km)
Red text indicates where surface and/or base types have been estimated based on those most commonly used within the NSC for the particular pavement type and country. The acronyms in the table are according to the classification system in the Highway Development and Management Series Model (HDM-4) explained in Table 5.							
Zambia	Kitwe - Chingola	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	50
Zambia	Kapiri Moshi - Junction T3	AMGB	**HMA**	**Hot mix asphalt concrete**	**GB**	**Gravel**	77
Zambia	Chingola - Start BP Zambia	AMGB	HMA	Hot mix asphalt concrete	**GB**	**Gravel**	40
Zambia	Junction T3 - TO Luanshya	AMGB	HMA	Hot mix asphalt concrete	**GB**	**Gravel**	32
Zambia	Kapiri Mposhi - Serenje	AMGB	HMA	Hot mix asphalt concrete	**GB**	**Gravel**	192
Zambia	Turnoff T1 - Mazabuka	AMGB	PM	Penetration Macadam	**GB**	**Gravel**	66
Zambia	Kabwe -Kapiri Moshi	AMSB	HMA	Hot mix asphalt concrete	SB	Cement stabilised base	66
Zambia	Lusaka SE RAB - End 3 Lane T2	AMSB	HMA	Hot mix asphalt concrete	SB	Cement stabilised base	4
Zambia	T2 End 3 Lane - T2 End 2 Lane	AMSB	HMA	Hot mix asphalt concrete	SB	Cement stabilised base	11
Zambia	T2 End of 2 Lane - Turn Off T1	AMSB	HMA	Hot mix asphalt concrete	SB	Cement stabilised base	40
Zambia	Monze - Choma	AMSB	HMA	Hot mix asphalt concrete	SB	Cement stabilised base	98
Zambia	Choma - Zimba	AMSB	HMA	Hot mix asphalt concrete	SB	Cement stabilised base	115
Zambia	End of Dual Carriageway Lumumba - Kabwe	AMSB	**HMA**	**Hot mix asphalt concrete**	SB	Cement stabilised base	132
Zambia	Lusaka NE RAB - End of Dual Carriageway Lumumba	AMSB	**HMA**	**Hot mix asphalt concrete**	SB	Cement stabilised base	3
Zambia	Zimba - Weigh Bridge	AMSB	HMA	Hot mix asphalt concrete	SB	Cement stabilised base	74
Zambia	WeighBridge - Turn off M10	AMSB	**HMA**	**Hot mix asphalt concrete**	SB	Cement stabilised base	3
Botswana	Gaborone - Boatle	STGB	**SD**	**Single surface dressing**	**GB**	**Calcrete**	21
Botswana	Dibete - Artesia	STGB	SD	Single surface dressing	GB	Calcrete	30
Botswana	Boatle - Lobatse	STGB	**SD**	**Single surface dressing**	**GB**	**Calcrete**	51
Botswana	Lobatse - Ramatlabama	STGB	**SD**	**Single surface dressing**	**GB**	**Calcrete**	49
Botswana	Francis Town - Ramokgwebana/Plum Tree	STGB	**SD**	**Single surface dressing**	**GB**	**Calcrete**	77
Botswana	Artesia - Rasesa	STGB	**SD**	**Single surface dressing**	GB	Calcrete	40
Botswana	Rasesa - Gabarone	STGB	**SD**	**Single surface dressing**	GB	Calcrete	30
Botswana	BP Kazungula - Pandamatenga	STGB	**SD**	**Single surface dressing**	GB	Calcrete	109
Botswana	Pandamatenga - Start of Construction	STGB	**SD**	**Single surface dressing**	**GB**	**Calcrete**	10

Country/ border	Section name	Pavement type[36]	Surface type[37]		Base type		Section length (km)
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Botswana	Start of Construction - End of Construction	STGB	**SD**	**Single surface dressing**	GB	Calcrete	135
Botswana	End of Construction - Nata	STGB	**SD**	**Single surface dressing**	GB	Calcrete	54
Botswana	Nata - Sebina junction	STGB	**SD**	**Single surface dressing**	GB	Calcrete	140
Botswana	Sebina junction - Francis Town	STGB	**SD**	**Single surface dressing**	GB	Calcrete	47
Botswana	Francis Town - Tonota	STGB	**SD**	**Single surface dressing**	GB	Calcrete	40
Botswana	Tonota - Serule	STGB	**SD**	**Single surface dressing**	GB	Calcrete	60
Botswana	Serule - Palapye	STGB	**SD**	**Single surface dressing**	GB	Calcrete	76
Botswana	Palapye - Mahalpye	STGB	SD	Single surface dressing	GB	Calcrete	72
Botswana	Mahalpye - Dibete	STGB	SD	Single surface dressing	GB	Calcrete	100
Botswana	Palapye - Lerala T.Off (75BRD)	STGB	**SD**	**Single surface dressing**	GB	Calcrete	80
Botswana	Lerela T.Off - Martin's Drift (26BRD)	STGB	SD	Single surface dressing	**GB**	**Calcrete**	31
DRC	Lubumbashi - Likasi	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	123
DRC	Kasumbelesa - Lubumbashi	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	93
DRC	End DRC - Kasumbelesa	STGB	SD	Single surface dressing	**GB**	**Gravel**	8
Malawi	Junction KIA Airport - TOR Kasungu	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	100
Malawi	Roundabout Karonga - BP Songwe	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	45
Malawi	Junction M1 Lilongwe - Junction KIA Airport	STGB	SD	Single surface dressing	**GB**	**Gravel**	20
Malawi	Mzuzu - Bwengu	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	53
Malawi	Bwengu - Chiweta	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	60
Malawi	Chiweta - Bottom of Escarpment	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	48
Malawi	TOR Kasungu - Jenda	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	85
Malawi	Chingeni - Zalewa	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	61
Malawi	Nsipe - Chingeni	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	21
Malawi	Junction M1 Lilongwe - Bunda TO	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	13
Malawi	Bunda TO - Nsipe	STGB	SD	Single surface dressing	**GB**	**Gravel**	159

Country/ border	Section name	Pavement type[36]	Surface type[37]		Base type		Section length (km)
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Malawi	Bottom of Escarpment - Roundabout Karonga	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	56
Malawi	Jenda - TOL Mzimba	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	46
Malawi	TOL Mzimba - Mzuzu	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	95
Malawi	TO Mwanza - Border Post Mwanza	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	51
Malawi	TO Mwanza - Blantyre	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	46
RSA	BP - Pietersburg	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	179
Tanzania	Igawa -Makambako	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	60
Tanzania	Makambako - Mafinga	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	82
Tanzania	End of DANIDA - Start Mikuni Park	STGB	SD	Single surface dressing	**GB**	**Gravel**	39
Tanzania	Start of Mikuni Park - End of Mikuni Park	STGB	SD	Single surface dressing	**GB**	**Gravel**	43
Tanzania	End of Mikuni Park - TOL A2	STGB	SD	Single surface dressing	**GB**	**Gravel**	89
Zambia	Turn off M10 - BP Livingstone	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	9
Zambia	End of Dual Carriageway - Start of AO	STGB	SD	Single surface dressing	**GB**	**Gravel**	184
Zimbabwe	End BP Chirundu - Makuti	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	75
Zimbabwe	Makuti - Karoi	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	78
Zimbabwe	Karoi - Chinhoyi	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	94
Zimbabwe	Chinhoyi - Harare CB1	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	101
Zimbabwe	Harare CB2 - Chivhu	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	141
Zimbabwe	Chivhu - Masvingo	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	151
Zimbabwe	Masvingo - Turn Off	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	95
Zimbabwe	Turn Off - BP Beit Bridge	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	184
Zimbabwe	BP Livingstone - Hwange	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	110
Zimbabwe	Hwange - Bulawayo	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	331
Zimbabwe	Bulawayo - Gwanda	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	120
Zimbabwe	Gwanda - W.Nicholson	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	52

Country/ border	Section name	Pavement type[36]	Surface type[37]		Base type		Section length (km)
Red text indicates where surface and/or base types have been estimated based on those most commonly used within the NSC for the particular pavement type and country. **The acronyms in the table are according to the classification system in the Highway Development and Management Series Model (HDM-4) explained in Table 5.**							
Zimbabwe	W.Nicholson - BP Beit Bridge	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	148
Zimbabwe	Harare - Murewa	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	106
Zimbabwe	Murewa - Nyamapanda	STGB	**SD**	**Single surface dressing**	**GB**	**Gravel**	172
Zimbabwe	Ramokgwebana/Plum Tree - Bulawayo	STGB	SD	Single surface dressing	**GB**	**Gravel**	100
Zambia	Mazabuka - Monze	STSB	SD	Single surface dressing	SB	Bitumen stabilised base	64
Zambia	Mpika - Chinsali	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	164
Zambia	Chinsali - Isoka	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	99
Zambia	Chingola - Solwezi	**STSB**	SD	Single surface dressing	SB	Cement stabilised base	167
Zambia	Turn off T1 - Start of New Road	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	20
Zambia	Start of New Road - End of New Road	**STSB**	**SD**	**Single surface dressing**	SB	Cement stabilised base	34
Zambia	End of New Road - BP Chirundu	STSB	**SD**	**Single surface dressing**	**SB**	**Cement stabilised base**	25
Zambia	Turn off M10 - TOL BP	STSB	SD	Single surface dressing	SB	Cement stabilised base	65
Zambia	TOLBP - Pontoon	STSB	SD	Single surface dressing	SB	Cement stabilised base	3
Zambia	North End Roundabout - End of Dual Carriageway	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	13
Zambia	Serenje -Mpika	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	235
Zambia	Isoka - BP Nakonde	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	106
Mozambique	Mwanza - Zobue	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	6
Mozambique	Zobue - Tete Bridge	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	118
Mozambique	Tete Bridge - Border Post Nyamapanda	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	138
Mozambique	Zobue - Dedza	STSB	**SD**	**Single surface dressing**	SB	Cement stabilised base	150
Tanzania	Concrete Ikokoto - Concrete Kitonga Gorge	JRCP	CP	Concrete	**GB**	**Gravel**	7

Table 24: Carbon footprint over 20 year time period (thousand tonnes co$_2$e) of road links in Botswana

Road links: Botswana	All phases	Operation only	Infrastructure only	% contribution of infrastructure to total	Section length (km)
BP Kazungula - Pandamatenga	693	660	33.67	4.9%	109
Pandamatenga - Start of Construction	65	62	3.39	5.2%	10
Start of Construction - End of Construction	862	817	44.81	5.2%	135
End of Construction - Nata	343	326	17.86	5.2%	54
Nata - Sebina junction	894	847	46.47	5.2%	140
Sebina junction - Francis Town	379	364	15.60	4.1%	47
Francis Town - Tonota	1,220	1,207	12.32	1.0%	40
Tonota - Serule	1,830	1,811	18.48	1.0%	60
Serule - Palapye	1,011	988	23.40	2.3%	76
Palapye - Mahalpye	1,225	1,203	22.83	1.9%	72
Mahalpye - Dibete	2,087	2,055	31.71	1.5%	100
Dibete - Artesia	627	617	9.88	1.6%	30
Artesia - Rasesa	1,166	1,154	12.41	1.1%	40
Rasesa - Gabarone	1,132	1,112	19.74	1.7%	30
Gaborone - Boatle	966	953	13.23	1.4%	21
Boatle - Lobatse	1,276	1,259	16.80	1.3%	51
Lobatse - Ramatlabama	1,226	1,210	16.14	1.3%	49
Palapye - Lerala T.Off (75BRD)	731	705	26.54	3.6%	80
Lerela T.Off - Martin's Drift (26BRD)	283	273	9.64	3.4%	31
Francis Town - Ramokgwebana/Plum Tree	590	567	23.43	4.0%	77
Total	18,606	18,188	418	2.2%	1,252

Table 25: Carbon footprint over 20 year time period (thousand tonnes CO$_2$e) of road links in the Democratic Republic of Congo (DRC)

Road links: DRC	All phases	Operation only	Infrastructure only	% contribution of infrastructure to total	Section length (km)
Likasi - Kolwezi	1,638	1,549	89.02	5.4%	176
Lubumbashi - Likasi	1,140	1,106	34.30	3.0%	123
Kasumbelesa - Lubumbashi	1,104	1,086	17.95	1.6%	93
End DRC - Kasumbelesa	95	93	1.54	1.6%	8
Total	3,978	3,835	143	3.6%	400

Table 26: **Carbon footprint over 20 year time period (thousand tonnes CO_2e) of road links in Malawi**

Road links: Malawi	All phases	Operation only	Infrastructure only	% contribution of infrastructure to total	Section length (km)
BP Mchinji - Junction M1 Lilongwe	2,015	1,937	77.82	3.9%	116
Junction M1 Lilongwe - Junction KIA Airport	1,995	1,989	6.48	0.3%	20
Junction KIA Airport - TOR Kasungu	1,685	1,656	28.79	1.7%	100
TOR Kasungu - Jenda	791	760	30.71	3.9%	85
Jenda - TOL Mzimba	282	264	18.12	6.4%	46
TOL Mzimba - Mzuzu	1,500	1,470	29.46	2.0%	95
Mzuzu - Bwengu	867	852	14.65	1.7%	53
Bwengu - Chiweta	687	671	16.61	2.4%	60
Chiweta - Bottom of Escarpment	303	289	13.35	4.4%	48
Bottom of Escarpment - Roundabout Karonga	349	334	15.18	4.3%	56
Roundabout Karonga - BP Songwe	256	245	11.25	4.4%	45
Junction M1 Lilongwe - Bunda TO	1,368	1,364	3.93	0.3%	13
Bunda TO - Nsipe	3,555	3,507	47.93	1.3%	159
Nsipe - Chingeni	410	404	6.34	1.5%	21
Chingeni - Zalewa	882	864	18.42	2.1%	61
TO Mwanza - Border Post Mwanza	450	435	15.82	3.5%	51
TO Mwanza - Blantyre	1,859	1,845	14.36	0.8%	46
Total	19,255	18,885	369	1.9%	1,076

Table 27: **Carbon footprint over 20 year time period (thousand tonnes CO_2e) of road links in Mozambique**

Road links: Mozambique	All phases	Operation only	Infrastructure only	% contribution of infrastructure to total	Section length (km)
Mwanza - Zobue	190	188	1.99	1.0%	6
Zobue - Tete Bridge	5,003	4,964	39.07	0.8%	118
Tete Bridge - Border Post Nyamapanda	2,168	2,122	45.70	2.1%	138
Zobue - Dedza	371	321	49.67	13%	150
Total	7,732	7,596	136	1.8%	412

Table 28: **Carbon footprint over 20 year time period (thousand tonnes CO_2e) of road links in Tanzania**

Road links: Tanzania	All phases	Operation only	Infrastructure only	% contribution of infrastructure to total	Section length (km)
BP Tunduma - Mbeya	2,386	2,321	65.33	2.7%	103
Mbeya - Igawa	2,498	2,429	68.61	2.7%	108
Igawa -Makambako	1,371	1,355	16.39	1.2%	60
Makambako - Mafinga	2,220	2,197	22.41	1.0%	82
Mafinga - Iringa (Start of DANIDA)	2,069	2,034	34.92	1.7%	76
Iringa Start of DANIDA - Concrete Ikokoto	1,636	1,611	25.49	1.6%	60
Concrete Ikokoto - Concrete Kitonga Gorge	223	198	24.63	11.0%	7
Concrete Kitonga Gorge - Iyovi (End DANIDA)	2,311	2,275	36.00	1.6%	85
End of DANIDA - Start Mikuni Park	1,062	1,053	8.81	0.8%	39
Start of Mikuni Park - End of Mikuni Park	1,162	1,152	9.64	0.8%	43
End of Mikuni Park - TOL A2	2,402	2,382	19.94	0.8%	89
Turn off A2 - Dar-es-salaam	7,994	7,932	61.43	0.8%	87
Dar-es-salaam - Port	8,650	8,620	29.66	0.3%	42
BP Songwe - Junction Tanzam	1,562	1,482	79.81	5.1%	101
Total	37,546	37,043	503	1.3%	982

Table 29: **Carbon footprint over 20 year time period (thousand tonnes CO_2e) of road links in Zambia**

Road sections	All phases	Operation only	Infrastructure only	% contribution of infrastructure to total	Section length (km)
Chingola - Start BP Zambia	612	588	24.03	3.9%	40
Kitwe - Chingola	4,005	3,970	34.39	0.9%	50
TO Luanshya - Kitwe	2,817	2,788	29.12	1.0%	39
Junction T3 - TO Luanshya	1,565	1,541	23.71	1.5%	32
Kapiri Moshi - Junction T3	4,824	4,763	61.13	1.3%	77
Kabwe -Kapiri Moshi	3,903	3,838	65.76	1.7%	66
End of Dual Carriageway Lumumba - Kabwe	7,763	7,658	105.19	1.4%	132
Lusaka NE RAB - End of Dual Carriageway Lumumba	195	192	2.64	1.4%	3
Lusaka SE RAB - End 3 Lane T2	218	215	3.04	1.4%	4
T2 End 3 Lane - T2 End 2 Lane	561	552	8.55	1.5%	11
T2 End of 2 Lane - Turn Off T1	2,028	1,997	31.63	1.6%	40
Turn off T1 - Start of New Road	461	451	10.44	2.3%	20
Start of New Road - End of New Road	805	788	16.57	2.1%	34
End of New Road - BP Chirundu	414	400	13.39	3.2%	25
Chingola - Solwezi	2,325	2,240	85.63	3.7%	167
Turnoff T1 - Mazabuka	3,051	3,017	34.16	1.1%	66
Mazabuka - Monze	1,418	1,388	29.77	2.1%	64
Monze - Choma	2,522	2,447	75.67	3.0%	98
Choma - Zimba	2,186	2,097	88.80	4.1%	115
Zimba - Weigh Bridge	1,127	1,063	64.57	5.7%	74
WeighBridge - Turn off M10	50	48	2.86	5.7%	3
Turn off M10 - TOL BP	481	449	32.15	6.7%	65
TOLBP - Pontoon	25	24	1.58	6.2%	3
Turn off M10 - BP Livingstone	150	147	2.92	1.9%	9
Kapiri Mposhi - Serenje	2,768	2,636	131.85	4.8%	192
Serenje -Mpika	3,923	3,786	137.44	3.5%	235
Mpika - Chinsali	1,210	1,134	76.40	6.3%	164
Chinsali - Isoka	731	685	46.12	6.3%	99
Isoka - BP Nakonde	2,566	2,515	51.17	2.0%	106
North End Roundabout - End of Dual Carriageway	441	435	6.31	1.4%	13
End of Dual Carriageway - Start of AO	5,222	5,174	47.71	0.9%	184
Start Asphalt Overlay -Luangwa Bridge	949	929	19.14	2.0%	33
End of Bridge - End Asphalt Overlay	2,681	2,624	56.98	2.1%	97
End Asphalt Overlay - BP Mchinji	2,287	2,165	121.88	5.3%	256
Total	66,284	64,741	1,543	2.3%	2,616

Table 30: **Carbon footprint over 20 year time period (thousand tonnes CO_2e) of road links in Zimbabwe**

Road links: Zimbabwe	All phases	Operation only	Infrastructure only	% contribution of infrastructure to total	Section length (km)
End BP Chirundu - Makuti	955	932	23.22	2.4%	75
Makuti - Karoi	995	970	25.08	2.5%	78
Karoi - Chinhoyi	1,671	1,641	30.23	1.8%	94
Chinhoyi - Harare CB1	2,558	2,526	32.48	1.3%	101
Harare CB2 - Chivhu	5,295	5,250	45.34	0.9%	141
Chivhu - Masvingo	2,751	2,702	48.56	1.8%	151
Masvingo - Turn Off	1,721	1,692	28.58	1.7%	95
Turn Off - BP Beit Bridge	4,051	3,998	53.14	1.3%	184
Ramokgwebana/Plum Tree - Bulawayo	677	646	30.37	4.5%	100
BP Livingstone - Hwange	549	515	34.05	6.2%	110
Hwange - Bulawayo	2,689	2,582	106.45	4.0%	331
Bulawayo - Gwanda	945	908	36.10	3.8%	120
Gwanda - W.Nicholson	409	394	15.64	3.8%	52
W.Nicholson - BP Beit Bridge	1,165	1,120	44.52	3.8%	148
Harare - Murewa	2,290	2,259	31.54	1.4%	106
Murewa - Nyamapanda	3,716	3,665	51.18	1.4%	172
Total	32,438	31,801	636	2.0%	2,058

Table 31: **Carbon footprint over 20 year time period (thousand tonnes CO_2e) of road links in South Africa**

Road links: South Africa	All phases	Operation only	Infrastructure only	% contribution of infrastructure to total	Section length (km)
Pietersburg - Pretoria	16,594	16,372	222.42	1.3%	261
BP - Pietersburg	11,314	11,228	85.40	0.8%	179
Pretoria - Johannesburg	16,358	16,309	49.43	0.3%	58
Messina - Pretoria	28,586	28,218	367.34	1.3%	454
End BP Beit Bridge - Messina	1,019	1,005	13.22	1.3%	19
Johannesburg - Durban	130,320	129,767	553.04	0.4%	578
Zeerust R57 - Pretoria	15,079	14,885	193.45	1.3%	227
BP Gabarone - Zeerust R57	4,643	4,556	86.99	1.9%	125
Total	223,912	222,341	1,571	0.7%	1,901

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