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Effects of alignment on CO_2 emissions from the construction and use phases of highway infrastructure

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Declaration

This thesis is my own work and contains nothing which is the outcome of work done in collaboration with others, except where specifically indicated in the text. It has not been previously submitted, in part or whole, to any university or institution for any degree, diploma or other qualification. This thesis is less than 65,000 words in length including footnotes, tables, figures, appendices, and the bibliography, and contains less than 150 figures.

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Abstract

The environmental aspect of sustainability is currently high on many agendas due at least in part to the issue of climate change, manifesting in the monitoring of CO_2 emissions from all activities within all industrial sectors, with construction projects being no exception.

The concept of Whole Life Carbon (WLC) involves understanding the carbon impact of an infrastructure project from its beginning, through its serviceable life, to the end of its life. The WLC concept can be applied to future infrastructure projects to assist in decision making, to ensure the correct project is taken forward in terms of minimising carbon emissions across the life time of the infrastructure.

The life cycle of a highway project comprises the planning, design, construction, operation, use and decommissioning phases. For a new 23km motorway project in the UK, when considering the construction and use phases, the CO_2 emissions from vehicles using the road comprised 91% over a 40 year period. With the majority of CO_2 resulting from the use phase, any measures taken to minimise the impacts of this could potentially significantly reduce the CO_2 over the lifetime of a highway.

It is during the planning stage that decisions can be made to reduce the WLC; by forecasting the impact of different design options at the different future phases of the life cycle. This thesis considers the effect of highway alignment, which is a decision taken early in a project's life cycle.

The gradient of a highway can have a significant impact on the fuel consumption (and hence CO_2 emissions) of the vehicles operating on it. To design the alignment around an optimum earthworks phase in terms of time, cost and carbon may result in a construction phase with a lower impact, yet the long term effect of the subsequent gradients on vehicle fuel consumption may yield a significantly higher level of CO_2 emissions than the amount saved during the efficient construction operation. Conversely, an intensive earthworks operation may result in a CO_2 intensive construction phase yet result in long term benefits throughout the life cycle, as the fuel consumed by the vehicles operating on the highway is reduced.

To understand the effect of the vertical alignment through the life cycle, the CO_2 in both the construction and use phases has been calculated. A methodology to calculate the CO_2 from the earthworks operations has been developed. The instantaneous emission model, PHEM, has been used to calculate the CO_2 from the vehicles using a highway.

Different vehicle types have been assessed over hypothetical terrains, with the application of varying fleet mixes and vehicle speeds enabling an understanding of the effect of alignment on typical vehicle flows. These alignments have been modified, requiring more CO_2 intensive earthworks operations, to understand the potential benefits the new alignment can bring to the use phase, and the overall life cycle.

The methodology developed has been applied to an actual case study that had six very different horizontal and vertical alignments. A second real and current project was used to gain an understanding of the CO_2 impacts of choosing an embankment over a viaduct structure.

Contents

List of Appendices

List of figures

List of tables

List of photographs

Glossary

AADT	Average Annual Daily Traffic
ATC	Automatic Traffic Count
ADT	Articulated Dump Trucks
AIRE	Analysis of Instantaneous Road Emissions
ATC	Automatic Traffic Count
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
C	Carbon
CEEQUAL	Civil Engineering Environmental Quality Assessment and Award Scheme
CESMM	Civil Engineerning Standard Method of Measurement
CMEM	Comprehensive Modal Emissions Model
CO	Carbon monoxide
CO_2	Carbon dioxide
COBA	COst Benefit Analysis program
COST	European Cooperation in the field of Scientific and Technical Research
DECC	Department of Energy and Climate Change
DfT	Department for Transport
DMRB	Design Manual for Roads and Bridges
DTM	Digital Terrain Model
EA	Environment Agency
EC	Embodied CO_2
EE	Embodied Energy
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EPBD	European Energy Performance of Buildings
EPD	Environmental Product Declaration
EU	European Union
FL	Fully laden
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HA	Highways Agency
HC	Hydrocarbon
HGV	Heavy Goods Vehicle
HL	Half laden
HMRC	Her Majesty's Revenue and Customs
ICE	Institution of Civil Engineers
ICE	Inventory of Carbon and Energy
ICE	Internal Combustion Engine
ICES	Institution of Civil Engineering Surveyors
IEM	Instantaneous Emission Modelling
IERD	Integration of the Measurement of Energy Usage into Road Design
IGT	Innovation and Growth Team
IRF	International Roads Federation
ISO	International Standards Organisation
LCA	Life Cycle Assessment
LGV	Light Goods Vehicle
MMP	Major Motorway Project

MODEM	MODelling of EMissions and fuel consumption in urban areas
NAEI	National Atmospheric Emission Inventory
NCHRP	National Cooperative Highway Research Program
NO_x	Oxides of Nitrogen
NPV	Net Present Value
OFWAT	Water Services Regulation Authority
OICA	International Organisation of Motor Vehicle Manufacturers
PARAMICS	PARAllel MICroscopic Simulation
PCR	Product Category Rules
PHEM	Passenger Car and Heavy-duty Emissions Model
PM	Particulate Matter
RDT	Rigid Dump Trucks
SATURN	Simulation and Assignment of Traffic to Urban Road Networks
TRL	Transport Research Laboratory
TTW	Tank to Wheel
TUBA	Transport Users Benefit Appraisal
TUG	Graz University of Technology
UL	Unladen
VOC	Vehicle Operating Costs
WebTAG	Transport Analysis Guidance Website
WLC	Whole Life Carbon
WTT	Well to Tank

Chapter 1

Introduction

The overarching aim of this research was to contribute towards the present challenge of achieving low carbon[1] infrastructure, specifically highway infrastructure; with the theme being to understand the relationship between carbon expended in construction (capital carbon) and carbon expended during the lifetime (operational carbon) of a highway.

1.1 Sustainable infrastructure

Investment in UK roads, rail and electricity generating capacity has been demonstrated to have a stronger positive effect on the level of Gross Domestic Product (GDP) per capita and on short term growth than any other type of capital investment (Egert *et al*., 2009). The UK must invest to maintain and improve its current infrastructure, and must undertake the investment to complement the legally-binding targets set out in the Climate Change Act 2008. The National Infrastructure Plan, published in 2010, identifies that:

> *[I]nfrastructure is carbon intensive and a revolution is needed, particularly in transport and energy, to meet legally binding targets. [...] To ensure that these targets are met will require fundamental changes [...] to the way infrastructure in the UK is planned, coordinated and delivered.*

(HM Treasury, 2010)

Such investment and development in infrastructure is required for the UK to continue to grow economically, and needs to be delivered without detriment to the environmental and social agendas. Construction is a major industry in the UK, worth over £100bn per year and accounting for 8% of GDP (BERR, 2008). The Government has developed the Strategy for Sustainable Construction after identifying that:

> *The output of the construction industry, be it public buildings, commercial buildings, homes or infrastructure such as our roads, harbours and sea defences, has a major impact on our ability to maintain a sustainable economy overall and has a major impact on our environment.*

[1] The term carbon refers to carbon dioxide (or CO_2). Not equivalent CO_2 (CO_2e).

Moreover, it is clear that we cannot meet our declared environmental targets without dramatically reducing the environmental impact of buildings and infrastructure construction; we have to change the way we design and build.

(BERR, 2008)

1.2 Low carbon infrastructure

The environmental aspect of sustainability is currently high on many agendas due at least in part to the issue of climate change, manifesting in the monitoring of CO_2 emissions from all activities within all industrial sectors – with construction projects being no exception.

Construction can be divided broadly into buildings and infrastructure projects. The latter covers a vast range of projects: from pumping stations to motorways, and flood defences to power stations. Naturally, the narrower buildings arena, which is more easily separated into houses and non-domestic buildings, has been tackled first. Established regulations are in place to ensure that new houses are built to stringent standards; through Part L of the Building Regulations and the Code for Sustainable Homes. Similarly for non-domestic buildings, there is the European Energy Performance of Buildings Directive (EPBD) and the same Part L of the Building Regulations. These standards ensure buildings are designed to be energy efficient during the time in which they are most energy intensive, in their occupation; energy consumed during the occupied time of a building accounts for 80% of its lifetime energy consumption (Skanska, 2010).

At the forefront of sustainable building construction, the Building Research Establishment (BRE) has developed methodologies and tools to enable the impacts of buildings to be assessed in terms of sustainability. The BRE developed tool, BREEAM, is an environmental assessment tool that considers the environmental credentials of a building project, assigning scores based on their environmental merits.

A comparable tool owned jointly by a number of shareholders including the Institution of Civil Engineers (ICE) and developed specifically for civil engineering projects is CEEQUAL (the Civil Engineering Environmental Quality Assessment and Award Scheme). CEEQUAL encourages engineers to adopt an environmentally friendly approach to design solutions, yet lacks the quantitative and objective measures that would enhance the credibility of such tools. A small focus is placed on carbon and energy, with only 9.5% of the available marks obtainable through the energy and carbon section. The assessment has an 'energy consumption and carbon emissions in use' section, requiring the following questions to be answered:

Is there evidence that the design has considered options for reducing the energy consumption and carbon emissions of the project during operation, including the option of designing-out the need for energy-consuming equipment and the energy requirements in maintenance?

> *Is there evidence of appropriate measures having been incorporated to reduce energy consumption in use?*
>
> (CEEQUAL, 2010)

The questions are useful to promote low carbon design as they encourage the designer to consider the infrastructure beyond its initial construction. However, the small proportion of the overall points that can be achieved from tackling these questions can often result in them being neglected in favour of the more easily attainable points. More importantly the lack of regulation or standards in the infrastructure industry to encourage sustainable construction, and more specifically low carbon construction, means that assessments such as CEEQUAL are simply a way of publicising the work of designers; driven by client requirements rather than a desire for the best solution.

Recommendations in the Low Carbon Construction Innovation and Growth Team (IGT) Final Report focus around the need for clarity of targets and the cooperation between government and industry. They are directed at Government due to the scale of the challenge ahead and hence the requirement for high-level Government intervention to set the agenda. The current agenda within the construction industry is for:

> *[C]ompanies working in the sector (designers, contractors and suppliers) [to] typically develop competitive advantage via cost efficiency rather than investment in cutting edge innovation; and this applies equally to steps that might be taken towards the provision of low carbon solutions.*
>
> (IGT, 2010)

Identification of the problem is a good first step. Changing the game-play of an industry that is, like many others, inherently driven by cost, will be difficult. In theory, due to the relatively few number of client types within the infrastructure industry it should be made easier. In practice, with the sometimes conflicting duties of these clients, their lack of long-term strategy and poor communication, it will prove to be a difficult task. However, the overarching goal for the industry must be to design and deliver low carbon infrastructure at the right cost. Infrastructure costs are arrived at through the calculation of the Whole Life Cost expressed as a Net Present Value (NPV) through the application of UK Treasury discount rates. Great consideration has been given to the way that values are assigned to carbon emissions; in the UK, DECC (2009) produced a revised approach to the valuation of carbon in UK policy appraisal. The use of discount rates in carbon valuation indicates that carbon emitted into the atmosphere now has a different impact than carbon emitted into the atmosphere in the future. Any discount rates greater than zero, in environmental economic terms, assumes the welfare of future generations is less important than of present generations.

High discount rates have resulted in construction projects with lower capital costs and higher operating costs. Currently:

> *[T]he UK approach to the provision of infrastructure has been to focus on the initial construction and associated capital cost, with minimal attention to the requirement for lifelong maintenance or future upgrade.*
>
> (IGT, 2010)

Conversely, a bias towards capital expenditure has been exhibited by the water sector of the construction industry. Encouragement to invest in capital assets due to the manner in which they are remunerated in the capital value of the company have been discussed (OFWAT, 2011). As a result companies may opt for the option with the best financial return.

An integrated and holistic approach to both cost and carbon across the whole life of an infrastructure asset is necessary to achieve economically viable low carbon construction. Jowitt *et al.* (Publication pending) suggested an approach to considering carbon in infrastructure decisions; acknowledging that there will be no single solution that will minimise cost, carbon and socio-economic impacts; with something having to be traded off. Understanding the Pareto efficiency of these parameters will ensure:

> *This trade-off is determined consciously at the decision stage and not implicitly by transforming all but one of the decision parameters into the currency of the other (usually costs). [...] Doing otherwise places too much confidence on the market – the assumed costs of carbon, the basis of their derivation and their volatility – rather than strategic policy objectives.*
>
> (Jowitt *et al.,* Publication pending)

The ICE has launched its Low Carbon Trajectory report (ICE, 2011). The critical message is that of whole life carbon; ensuring that the carbon implications of a scheme, regardless of size, are considered at each stage of its life. It suggests that a high level methodology should be developed and applied at the concept stage, to establish whether the scheme is strategically the correct option. Once the most appropriate option is identified, a detailed methodology should then be applied to consider the carbon emissions at each stage of the infrastructure assets life to ensure the lowest carbon design is adopted. The key priorities have been identified as follows:

> *Government must ensure an effective and consistent carbon price is at the centre of a package of stable, long term incentives for developing low carbon infrastructure*
>
> *The infrastructure owner and the Civil Engineering Industry must systematically apply the concepts of Capital Carbon and Operational Carbon to Infrastructure*
>
> *ICE should lead an industry effort to establish a high level evaluation methodology aimed at the concept proof stage of infrastructure projects*
>
> (ICE, 2011)

1.3 Whole life carbon

The concept of Whole Life Carbon (WLC) involves understanding the carbon impact of an infrastructure project from its beginning, through its serviceable life, to the end of its life. The WLC concept can be applied to future infrastructure projects to assist in decision making, to ensure the correct project is taken forward in terms of minimising carbon emissions across the life time of the infrastructure. The life cycle of any infrastructure project can be divided into the phases shown in Figure 1.

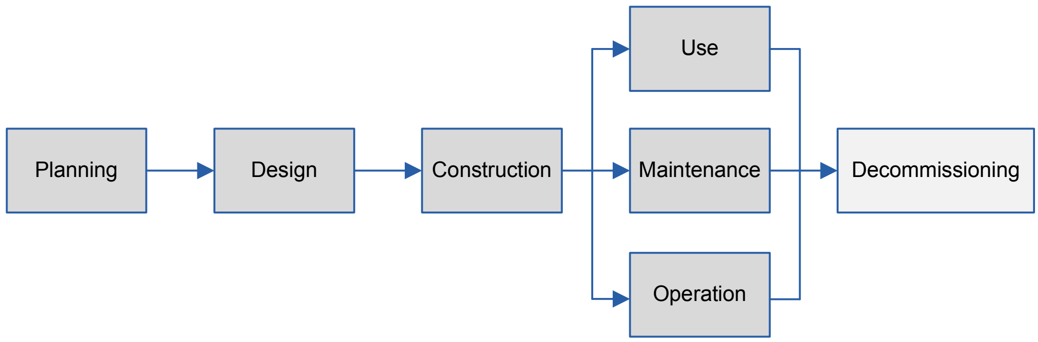


Figure 1 Life cycle phases of infrastructure projects

The individual phases are detailed below.

Construction	this phase is primarily concerned with the embodied carbon of the materials used in construction. Also included in this phase is the carbon produced by the machinery used on site, the transportation of materials and labour to site, and on-site energy consumption.
Operation	the carbon associated with the day-to-day operation of infrastructure.
Use	the carbon from the functional use. For example, for a highway, this would include the carbon emitted by vehicles using the highway.
Maintenance	the carbon associated with the periodic maintenance that is required for it to operate as intended.
Decommissioning	refers to when infrastructure has reached the end of it serviceable life. It is preferable for this phase not be reached with ongoing maintenance keeping it serviceable. If the end-of-life is reached, then the materials can be reused, recycled or disposed of.

Although planning and design are listed as part of the life cycle, due to the relatively low carbon associated with these phases they are often excluded from assessment or incorporated into the construction phase. They remain included in the life cycle as it is during these phases that crucial decisions can be made that affect the subsequent and often more carbon intensive phases.

The ideal time to act on carbon is at the early stages – during the planning and design phases – when decisions are taken that have effects which manifest throughout the life cycle. Using the whole life carbon approach can positively influence the planning and design of a project; to ensure decisions are made that aim to reduce carbon throughout a project's lifetime.

Although the emissions from the construction, operation, maintenance, use and decommissioning phases are addressed with efforts to quantify and minimise them, it is often done so individually in a disjointed approach. By considering all phases in terms of carbon in an integrated and holistic manner it can be said that a WLC approach has been taken. Singular assessments of individual phases can fail to identify important issues that would be highlighted in a life cycle approach.

For example, designing a road pavement constructed from Material A with low embodied carbon may result in a favourable score for construction. However, by neglecting to consider the maintenance phase, Material A with initially attractive properties may subsequently require higher material and energy input throughout its maintenance. Conversely, Material B with higher initial embodied carbon content may then require less material and energy input throughout its maintenance phase, and over the two phases prove to be the more favourable option.

Currently there is no standard approach to WLC assessment of infrastructure. The Carbon Management Framework for Major Infrastructure Projects (FFTF, 2009) does not set out in detail how to quantify WLC yet defines an approach that can be taken, which is comprehensive and sufficiently broad to make it applicable to any form of infrastructure project.

Most UK civil engineering companies have some form of carbon quantification approach or tool, with the majority using the same data sets as input. The Inventory of Carbon and Energy (ICE) database being the common data set for the calculation of the embodied carbon in materials. Many of these tools require a bill of quantities as input, which at the planning stage, when such detailed data is not always available, can ultimately prove less valuable as ideally carbon should be quantified during the planning stage to inform the option appraisal process.

Many calculation tools calculate the CO_2 from the construction phase alone; which although is very useful, the output should be used mindfully, with an awareness that only one part of the life cycle has been fully considered. Assessing carbon in only one phase of the life cycle can result in one design option being favourable over another. Yet the option that is apparently favourable could yield higher carbon emissions when it enters the subsequent phase.

1.4 Low carbon highway infrastructure

In the UK, for any new highway scheme, carbon is addressed under the Transport Analysis Guidance (TAG) Unit 3.3.5: The Greenhouse Gases Sub-Objective. The carbon impact is calculated through a comparison of the 'with scheme' and 'without scheme' scenario and subsequently incorporated into the cost benefit analysis. The only phase of the life cycle that is assessed is the use phase – covering the emissions from the vehicles operating on the highway. The remaining phases are discussed, but then dismissed:

> *[T]his assessment should consider all greenhouse gas emissions, including those resulting from the production of materials used in any infrastructure [...] as well as those resulting from changes to the use of transport fuels. However, there are proportionality issues and practical difficulties in reliably and consistently estimating non-carbon greenhouse gas emissions and embedded carbon emissions. Therefore, at this stage, no assessment of these emissions is required.*
>
> (DfT, 2011)

It is the intention to include the carbon impacts from the remaining phases in future assessments, until that time, they are expected to be reported qualitatively.

New highway infrastructure continues to be built; to enable continued economic growth, as a remedy to traffic congestion problems, and to extend infrastructure to new development sites. For the reasons stated above it is important that it is constructed using a whole life carbon approach.

1.5 Focus of research

The design of a highway alignment is a sophisticated process. As a general rule, linear infrastructure must respect the existing and developed environment through which it passes. As a result such infrastructure is not always flat and straight – they possess vertical and horizontal curves in their alignments to evade or to be compatible with the existing constraints. Design of this alignment is critical in the effort to balance the safety and comfort needs of the road user with the value of preserving the integrity of the environment. With the additional issue of climate change, there is also a growing requirement to reduce the impact of any scheme on the environment by minimising the associated carbon.

A highway engineer would seek to design a road alignment that is sympathetic to the natural surroundings and satisfies the required design conditions. Often however, the horizontal alignment is determined by physical features and the vertical alignment is determined by the earthworks.

The earthworks operation is both time consuming and costly, hence the designer will aim to minimise this aspect of the construction phase by minimising the cut and fill and the import and export of earthwork materials to and from the project site. An outcome of this cost-governed exercise is a highway that meets the needs of the users in terms of alignment, but also keeps the capital cost to the client at a minimum. In the context of the highway's life cycle, however, as previously discussed regarding pavement design, minimising the time, cost and carbon at the construction stage alone may be detrimental to the project's lifetime CO_2 emissions.

The reason for this is that the gradient of a highway can have an impact on the fuel consumption (and hence CO_2 emissions) of the vehicles operating on it. To design the alignment around an optimum earthworks phase in terms of time, cost and carbon may result in a construction phase with lower impact - yet the long term effect of the subsequent gradients on vehicle fuel consumption may yield a significantly higher level of CO_2 emissions than the amount saved during the efficient construction operation. Conversely, an intensive earthworks operation may result in a CO_2 intensive construction phase yet result in long term benefits throughout the life cycle, as the fuel consumed by the vehicles operating on the highway is reduced.

The Design Manual for Roads and Bridges (DMRB) suggests that the adoption of gradients steeper than the desirable maximum could make significant savings in construction or environmental costs but would also result in higher user costs:

> *Effects of Steep Gradients: In hilly terrain the adoption of gradients steeper than Desirable Maximum could make significant savings in construction or environmental costs, but would also result in higher user costs, i.e. by delays, fuel and accidents. Whilst on motorways the disbenefits associated with the consequently high traffic volumes indicate that 4% gradient should normally be regarded as the Absolute Maximum, on all purpose roads an economic assessment of the effects of adopting a steeper gradient should be carried out to determine the economic trade-off between construction/ environmental cost savings and disbenefits to traffic.*

(Highway Agency, 2002)

The DMRB recognises the initial construction phase as having an environmental impact which can be minimised by a steeper gradient. The long term impact of this steeper gradient is not classed as an environmental cost but as a cost for the user. This is of course correct, as the users' vehicle fuel consumption would increase. However, the long term environmental impacts of an increased gradient should also be considered.

The appraisal programs suggested by DMRB for new highway schemes are COBA and TUBA; which use estimated changes in fuel consumption to produce estimates of carbon emissions, for 'with scheme' and 'without scheme' scenarios, and the present value of their monetary value as an automatic output. The guidance referring to the application of these appraisal programs on road schemes is WebTAG Unit 3.3.5[2].

1.6 Aim of research

Understanding the balance between earthworks, road alignment and use emissions is key to making informed decisions with regard to the best design option. It is possible that the CO_2 minimised through the choice of alignment at the design stage could outweigh decisions on pavement design and materials used.

An empirical relationship to show the relationship between changes in vertical and horizontal would inform highway engineers early on in the design process and make them aware of the long term consequences of their alignment choices. It is important to extend the consideration further along the

[2] WebTAG Unit 3.3.5 available at http://www.dft.gov.uk/webtag/documents/expert/unit3.3.5.php

life cycle as it is evident that for infrastructure projects the use phase constitutes the largest proportion of lifetime emissions. Therefore, the effect of the alignment should be considered throughout the use phase.

The research aim is to determine whether it is advantageous to opt to produce more CO_2 emissions in the initial construction of a highway, to create a less energy consuming, and hence CO_2 emitting, infrastructure solution in the longer-term. The objectives are given in more detail in Chapter 3, but briefly comprise of:

- Quantifying CO_2 emissions from earthwork operations
- Developing a methodology to assess the CO_2 emissions from vehicles on varying alignments
- Assessing the effect of alignments on different vehicle types at different speeds
- Understanding the effect of fleet mix and vehicle technology on CO_2 emissions
- Quantifying the payback periods required for different alignments
- Understanding the factors that influence payback periods

1.7 Thesis structure

The remainder of this research thesis is structured as follows:

- **Chapter 2** Background study: New motorway project
  The carbon assessment of a proposed motorway scheme is detailed. It was this project that initiated the research presented within this thesis.

- **Chapter 3** Review of current methods and models
  The findings of the literature review are given; covering the previous research undertaken into the effects of alignment, the current approach to highway design and the various types of emission models.

- **Chapter 4** Approach to research
  The type of research that was undertaken is explained within this chapter, along with the approach taken.

- **Chapter 5** CO_2 from earthworks operations
  An approach to modelling CO_2 emissions from earthworks activities is detailed, with hypothetical models used to demonstrate the impacts of different earthworks strategies.

- **Chapter 6** Hypothetical alignments
  Two realistic hypothetical terrains have been used to understand the impact of different vertical alignment options on both CO_2 emissions from the construction phase and the use phase.

- **Chapter 7** Alignment case study

  The assessment methodology is applied to the six different alignment options of an actual highway project, with the alignment being amended through the earthworks to attempt to improve the alignment to result in benefits to the use phase.

- **Chapter 8** Earthworks based structures case study

  The use of an earthworks embankment instead of a viaduct on an actual project is detailed, with the potential CO_2 savings being placed in the context of the project's whole life carbon.

- **Chapter 9** Consideration of traffic interaction

  The effects of traffic interaction and its potential impact on the results previously presented are briefly addressed.

- **Chapter 10** Conclusions and recommendations for further work

  The conclusions resulting from the research project are discussed along with recommendations for the future approach to highway alignment design and potential future research topics.

Chapter 2

Background study: New motorway project

2.1 Introduction

This chapter details the project that instigated the research. The project cannot be directly referred to due to confidentiality reasons and is herein referred to as a Major Motorway Project (MMP)

2.1.1 Project history

At the time of the CO_2 assessment detailed within this chapter, the MMP under consideration comprised a section of new motorway acting as the relief road plus complementary measures on an existing motorway over a 26 km section. The existing motorway passes through the centre of a town, consisting mainly of 3-lane sections, decreasing to 2 lanes through a tunnelled section. It is in severe need of major maintenance. However, the lack of an alternative route for the high traffic flows that utilise the route has resulted in an ongoing postponement of the maintenance programme. The geometric layout of the existing motorway (which in certain locations does not conform to present motorway standards) in conjunction with the high traffic flows, result in regular incidents. The relief road, a 23 km section of dual 3-lane motorway, was presented as a solution to the sub-standard existing motorway, offering an alternative route to by-pass the constraints imposed by the town, and enabling the maintenance to be undertaken on a highway network that has the spare capacity to handle the disruption.

2.1.2 Scope of assessment

Objections to the MMP were anticipated; specifically on environmental grounds. The Environmental Impact Assessment (EIA) required for all projects of this type was to cover the main environmental issues. However, the issue of climate change and CO_2 emissions from road transport were becoming increasingly topical and therefore an estimate of the CO_2 implications of the new scheme was attempted.

It was commonly understood that vehicles that operate in congested conditions (resulting in varying levels of idling, acceleration and deceleration) use more fuel than vehicles that operate in free flow conditions (which allow drivers to maintain constant speeds). In view of this, the possibility of the MMP reducing overall CO_2 emissions from the motorway network in the area was highlighted, due to the relief road reducing the congestion on the existing motorway, enabling the vehicles using the network to operate in free flow conditions. Potentially lowering fuel consumption and hence CO_2 emissions, despite the increase in vehicle km anticipated due to the availability of the new road.

It was also understood that the majority of CO_2 emissions associated with the life time of a highway project would result from the vehicles operating on the highway. Initially, therefore, the focus of the project was on calculating the CO_2 from the use phase of the life cycle.

After completing the assessment of the CO_2 emissions expected from the use phase it was necessary to put the result into context. Therefore, the CO_2 from the construction phase was estimated. Three main components were considered separately – earthworks, structures and pavements. It was appreciated that the list was not exhaustive and that not all aspects within each area had been fully considered. The exercise was to gain a rough understanding of the magnitude of the CO_2 from the main construction elements in order to make a comparison with the CO_2 in use.

2.2 CO_2 assessment of the construction phase

The construction phase of the infrastructure life cycle was divided into three elements: earthworks, structures and road pavement. Each element is addressed in the following sections.

2.2.1 Earthworks

Estimating the CO_2 from an earthworks operation is difficult, as unlike estimating the embodied CO_2 from materials for which precise quantities are known, the quantities and processes for the earthworks cannot always be as easily determined. This can be due to many reasons, including the accuracy of the site investigation on which quantities are based, variations in a contractor's approach to the operation or variations in the machinery used.

The motorway project was approximately 23 km in length with two interchanges at each end of the highway resulting in two major cut locations. Table 2.1 provides general information on the linear site taken from the previously developed earthworks strategy, which provided the main information regarding cut and fill volumes. The earthworks strategy divided the site into 16 sub-sites, each with varying amounts of cut and fill required. The sections that connect the relief road to the existing motorway were the only two sites requiring excavation work. Based on the earthworks volumes presented in Table 2.1 (interpreted from the earthworks strategy drawing for the project), assumptions were made to develop an earthworks operation that could be assessed on a CO_2 basis.

The CO_2 from the earthworks operation was estimated through the use of a model that was developed as part of this research, and which is described in detail in Chapter 5. After making initial attempts to quantify the earthworks CO_2 for this project it was realised that research into typical earthworks operations was required in order to obtain a reasonable estimate. Hence the earthworks calculations described within in this chapter were completed after the research detailed in Chapter 5 was undertaken.

The imported materials were assumed to be sourced from a location 10km away by road, due to a number of quarries being located within this distance. The materials exported off-site for disposal were assumed to be taken to a location 20km away by road, as it was anticipated that they would be accommodated within this radius. The movement of materials within the chainage were assumed to have been undertaken with 35T excavators and 30T Articulated Dump Trucks (ADTs) – a mid-range combination in terms of fuel consumption (Fraser, 2010).

Table 2.1 Earthworks details (taken from Arup, 2001)

Site Number	Start chainage (m)	End chainage (m)	Cut (m3)	Fill (m3)
1	2,100	3,700	3,682,388	200,400
2	3,700	4,800	-	775,000
3	4,800	5,800	-	146,250
4	5,800	6,800	-	349,850
5	6,800	8,600	-	326,750
6	8,800	9,050	-	92,300
7	4,500	4,600	-	77,300
8	7,500	7,600	-	73,650
9	11,700	11,800	-	83,200
10	12,900	13,000	-	394,500
11	14,900	15,000	-	57,950
12	11,800	19,300	-	886,850
13	17,900	18,000	-	74,025
14	19,300	20,050	-	220,950
15	20,050	20,300	-	73,450
16	20,300	23,700	976,614	603,476
Import material			320,425	
Off-site disposal of suitable material				306,888
Off-site disposal of unsuitable material				236,638
		BALANCE	**4,979,427**	**4,979,427**

The CO_2 values presented reflect a simple mass haul operation. It is apparent that this site is unusual due to the large cut sites at each end of the motorway. It is likely that the earthworks strategy taken forward may have been different to what is presented within this thesis.

The linear site under consideration had two large cut sites at each end, with fill being required along the chainage. This situation resulted in long haul distances which increased the CO_2 resulting from the dump trucks used to haul the material from the excavation site to the deposition site. The CO_2 from the cut and fill operations equated to approximately 23,000 tonnes.

Figure 2.1 shows the total CO_2 pertaining to each aspect of the earthworks operation for the motorway project – the CO_2 associated with the excavation, haul and deposition and compaction is shown. Site 1 and Site 16 were the major cut sites and therefore are responsible for the excavation CO_2. Although the excavated materials were hauled to other locations along the linear site, the haul

CO_2 has been included in the site from which it was hauled from – in this case Site 1 and Site 16. The CO_2 associated with the remaining sites, Sites 2 to 15, is from the deposition and compaction elements of the earthworks cycle.

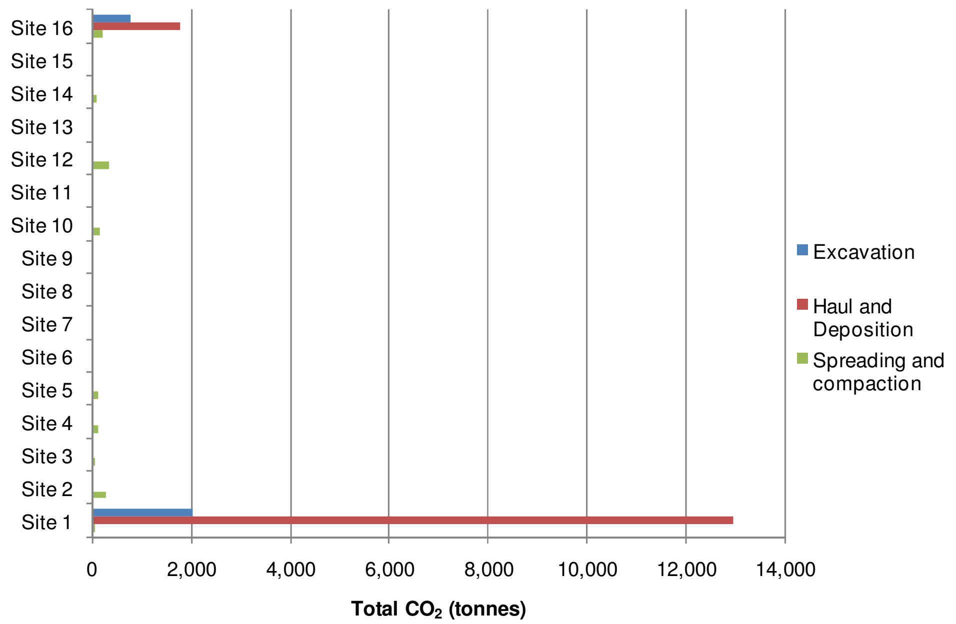


Figure 2.1 Total CO_2 pertaining to aspects of the earthworks operation for each site

Details of how the CO_2 is calculated for the earthworks operations is given in detail in Chapter 5; where each earthworks activity is given with the calculation process for calculating the fuel consumption for the plant used and hence the resultant CO_2 emissions.

Figure 2.2 shows the CO_2 pertaining to each aspect of the earthworks operation for the motorway project on a per m^3 basis for the 16 sites. The spreading and compaction value remains the same for all sites due to the activity not being dependent on any other activity and not varying with haul distances. The CO_2 per m^3 for excavation varies slightly between Site 1 and 16 due to variations in excavator efficiencies. The haul and deposition value alters significantly as this is heavily dependent on the haul distances, the distances that the haul plant were required to travel from Site 1 were higher than from Site 16 – hence the higher CO_2 value per m^3 of material hauled.

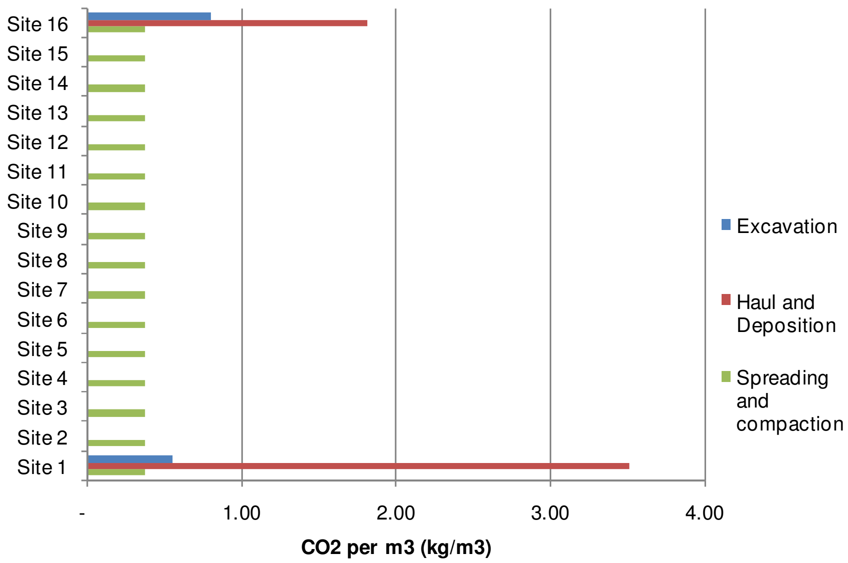


Figure 2.2 CO_2 per m^3 pertaining to aspects of the earthworks operation for each site

2.2.2 CO_2 from the structures

In total there were 26 proposed structures required along the alignment of the motorway. Seven structures were included in the CO_2 assessment: one footbridge, one under-bridge, a viaduct, two over-bridges, one subway and one culvert. In cost terms, these seven structures equated to 73% of the total cost for all structures on the project. For this reason the CO_2 resulting from the seven structures has been factored by 1.37 – assuming the CO_2 proportion broadly reflects the cost proportions.

The Arup CO_2ST® carbon calculator was used to calculate the CO_2 from the construction of the structures. The structures were considered in terms of the materials used, the transportation of these materials to site and the machinery used on-site. Quantities of materials were estimated from the detailed design drawings. The transportation was based around different transportation distances for specific materials. Steel, precast concrete and in-situ concrete were allocated the distances of 50, 70 and 10 km respectively – these are the default values within the CO_2ST® model and reflect the typical distances that these materials can be sourced within. The CO_2 from construction was based on the default plant and machinery data within the CO_2ST® model and reflect the typical plant requirements and subsequent energy consumption values.

The CO_2 resulting from the seven structures and foundations along the alignment was 226,000 tonnes. When factored to account for the remaining 19 structures the total CO_2 was 310,000 tonnes. Figure 2.3 shows the total CO_2 for the seven structures assessed; disaggregated by the CO_2 associated with materials, transportation and construction. The majority of the CO_2 results from the materials used within construction, the CO_2 associated with the plant and machinery is the next largest contributor, with the transportation contributing a relatively small amount of CO_2.

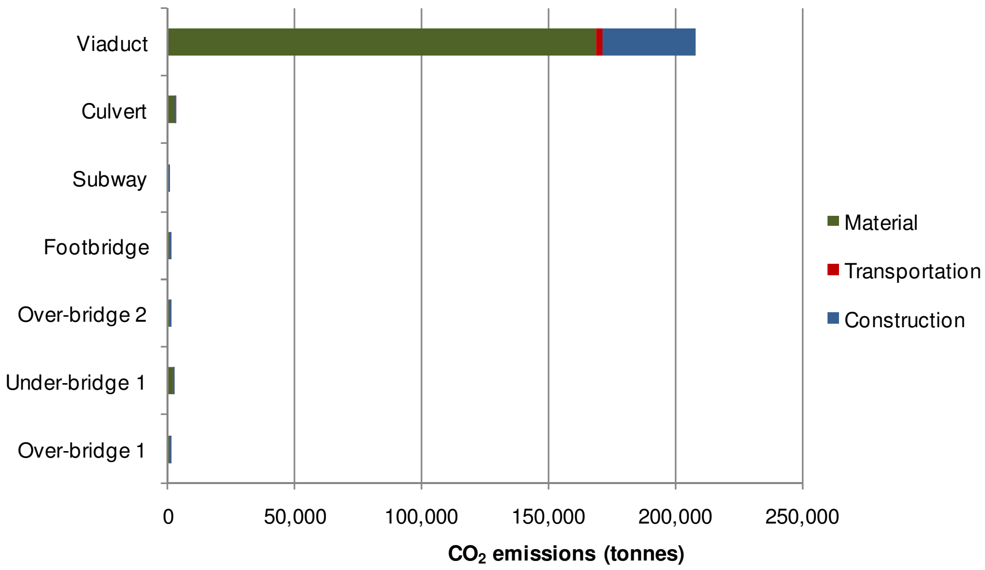


Figure 2.3 Total Embodied CO_2 for structures assessed in tonnes

Figure 2.4 shows the CO_2 per unit area for the seven structures assessed; disaggregated by the CO_2 associated with materials, transportation and construction on a tonnes per m^2 of bridge deck basis. From the study of Figure 2.3 it is apparent that the viaduct is the major contributor to the total CO_2 from the structures. This remains true, yet Figure 2.4 illustrates that the viaduct is in fact an efficient structure in terms of CO_2 per m^2 of bridge deck. This is due to the initial mobilisation activities being divided over a larger project; whereas, for a small project such as the footbridge, the mobilisation and initial site preparation is still required yet can only be divided over a small deck area.

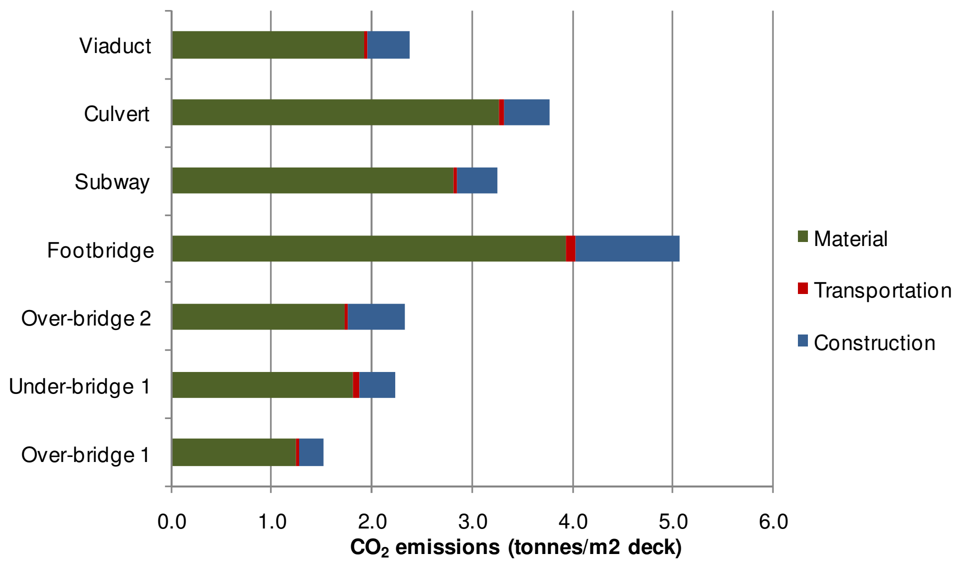


Figure 2.4 Embodied CO_2 for structures assessed in tonnes per m^2 bridge deck

2.2.3 CO_2 from the road pavement

The CO_2 from the pavement was again sub-divided into three elements; from the materials, the transportation of these materials to site and the use of plant and machinery on site. There were various sections of highway proposed, ranging from slip roads to 3-lane roads. Therefore, the pavement was split into 12 sections, enabling the CO_2 to be calculated separately by road section and then aggregated to give a final CO_2 value.

Figure 2.5 shows the CO_2 for the 12 sections of pavement; disaggregated by the CO_2 associated with materials, transportation and machinery. Similar to the structures, it is the materials that are responsible for the majority of the CO_2, with the construction plant and machinery responsible for the second largest amount, followed by transportation. The total CO_2 from the pavement was 200,000 tonnes of CO_2.

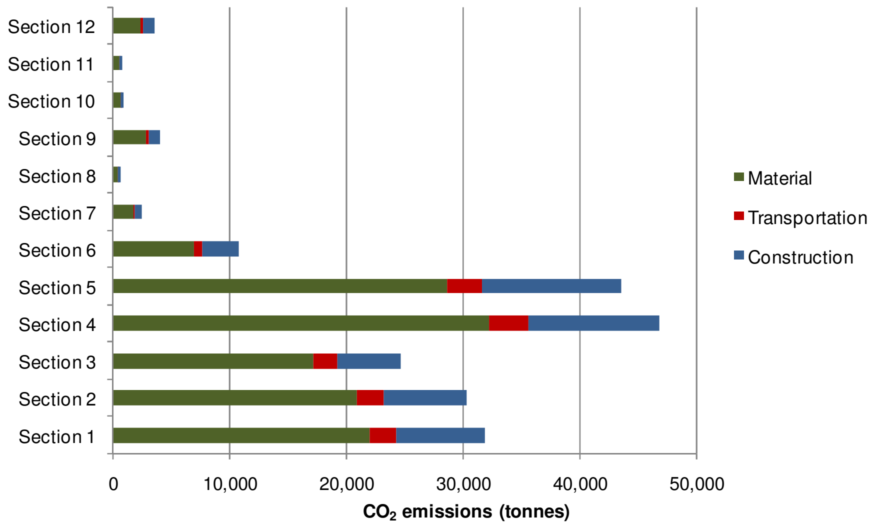


Figure 2.5 Total CO_2 for pavement in tonnes

Figure 2.6 shows the CO_2 for the 12 sections of pavement on a tonnes of CO_2 per m^2 of pavement basis. Section 7 has the highest CO_2 per m^2 as this section refers to the slip roads, which are short sections of single carriageway road typically constructed on an embankment. Hence, when the materials and plant are considered on a per m^2 basis they become less efficient.

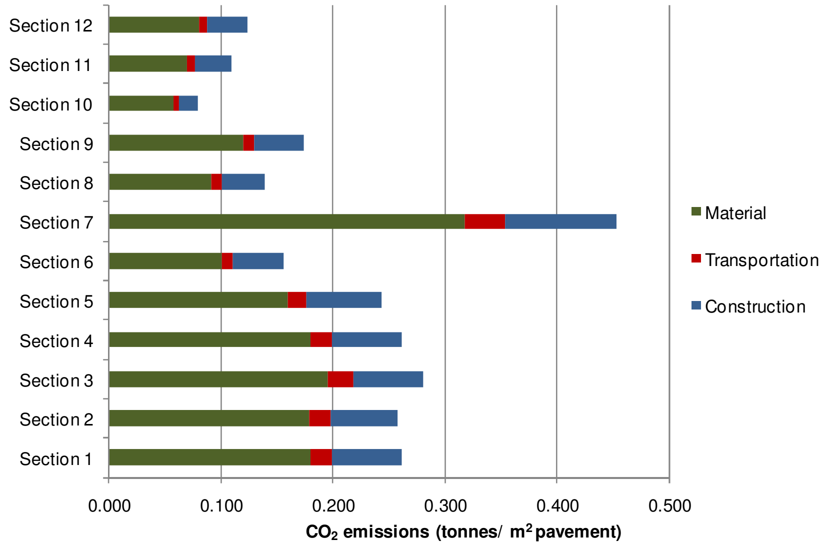


Figure 2.6 Embodied CO_2 for pavement in tonnes per m^2

2.2.4 Construction CO_2 summary

The total CO_2 from the structures, earthworks and pavement construction is 533,000 tonnes. The structures contributed 310,000 tonnes, 200,000 tonnes resulted from the pavement and 23,000 tonnes from the earthworks. Figure 2.7 shows the breakdown between the three main construction elements.

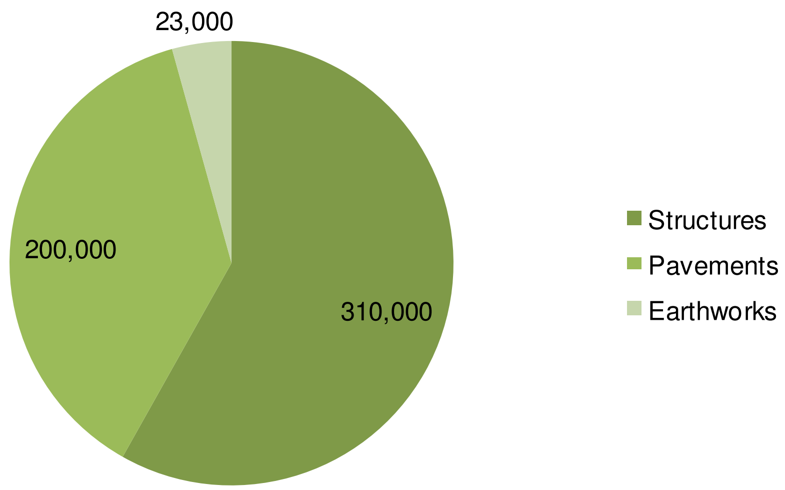


Figure 2.7 Total CO_2 contributions from structures, earthworks and pavement

The earthworks operation constituted only 4% of the overall construction phase when the structures and pavements were included in the assessment. This particular earthworks operation involved the movement of over 4 million m^3 of material, which is a substantial operation.

2.3 CO_2 assessment of the use phase

2.3.1 Average speed emission modelling

The methodology presented in the DMRB is to calculate vehicle emissions based upon an average speed modelling approach, dependent on two parameters: 1) type of vehicle and 2) average vehicle speed. Within DMRB, the following equation is provided to enable fuel consumption to be calculated as a function of average speed for seven vehicle types (Highways Agency, 2007).

$$L = (a + b.v + c.v^2 + d.v^3) / v$$

Where:

L = fuel consumption, expressed in litres per kilometre;

v = average speed in kilometres per hour; and

a, b, c, d are parameters defined for each vehicle category.

To calculate network wide CO_2 emissions using the above approach, data can be taken from a strategic transport model - the previously developed SATURN models (Arup, 2008) were used for this purpose. Each highway link in the model has an average speed and it is assumed that every vehicle moving along the link is travelling at that speed. Typical output from the SATURN model is presented in Appendix A. Through the use of this data and the functions given in the DMRB a CO_2 value was calculated for all vehicles on all links in the model. SATURN transport models were developed for the road network for the following scenarios:

- Do Minimum (without the relief motorway)
- Do Something (with the relief motorway)

The Do Something scenario was expected to enable more efficient driving due to the additional capacity being provided. This expectation, alongside the knowledge that the existing motorway is currently operating beyond its capacity, with vehicles driving in congested conditions, meant a significant difference was anticipated between the two scenarios in terms of efficiency. For the purpose of the exercise, efficiency was measured in terms of grams of CO_2 released per km across the entire road network.

Table 2.2 shows the modelled CO_2 emissions for the Do Minimum and Do Something scenarios. The greatest difference was between the AM peak hours. The Inter-peak has the highest emissions on a g per km basis; likely to be due to the higher average speeds that vehicles are able to travel at during this time period.

Table 2.2 CO_2 emissions for MMP scenarios based on average speed emission modelling for the 2016 opening year

Period	Do Minimum CO_2 (kg/hr)	CO_2 per vehicle km (g/km)	Do Something CO_2 (kg/hr)	CO_2 per vehicle km (g/km)
AM peak	138,000	252	143,000	246
Inter-peak	138,000	268	143,000	246
PM peak	128,000	268	132,000	246

The uncertainty of an estimate resulting from a traffic model is a combination of the statistical errors of measurement and sampling, the specification errors of the mathematical models used and the errors inherent in forecasting (Highways Agency, 1996). Assessing traffic model errors can be considered in the following three main areas: data errors; model specification errors; and forecasting errors.

It is apparent that numerous errors can be present in traffic models; hence it is important that the model can reproduce measured traffic flows and speeds in the year of calibration. For that reason the DMRB requires traffic models to undergo a rigorous validation exercise to ensure they are fit for purpose and that the model output is reliable. Firstly, the calibration of the model is checked; through choosing the correct parameters that will fit the model to the observed data. Secondly, the model is validated through assessing the model output against observed data. DMRB requires strict validation criteria are met for the model to be used with confidence.

The initial exercise described above showed higher total emissions in the Do Something scenario yet lower g per km values, indicating an improvement in efficiency. Greater differences than those reported were anticipated from the emission modelling and it was assumed that an average speed emission modelling approach would not adequately detect the differences in driving patterns that would influence the fuel consumption. An average speed approach is less appropriate for a project which is likely to alter driving patterns, i.e. a project likely to alleviate stop-start driving conditions, which the MMP was predicted to do. The DMRB highlights the limitations of average speed emission modelling:

> *The most widely used approximations for estimating road traffic emissions are based on two parameters only: the type of vehicle and its average speed. In many cases, this is the only practical approach as data for a more complex evaluation are not available. However, in determining the methodology to use for a particular application, some attention should be given to the exact nature of the project and its likely consequences on vehicle emissions. In some cases, such as projects which result in variations in driving patterns but do not greatly affect average speed, a more detailed emission model may be required. It may be necessary to use an 'instantaneous' emission model, in which emissions are related to vehicle operation (usually via a vehicle speed-time profile) on a second-by-second basis. Examples of such models include MODEM and PHEM. These instantaneous emissions models usually require vehicle operating information from a micro-simulation traffic model such as VISSIM or PARAMICS.*
>
> Highways Agency (2007)

2.3.2 Instantaneous emission modelling

After undertaking the average speed modelling and reviewing the expected project outcomes with regards to the above DMRB recommendation it was deemed necessary to use an instantaneous emission model. In order to calculate emissions using this method for all vehicles on a network a micro-simulation traffic model was required to provide the second-by-second vehicle data. The VISSIM micro-simulation modelling package was used to model the road network and traffic flows and hence used to provide this second-by-second data (Vissim, 2011). An emission model known as EnvPro is incorporated into the VISSIM software package; the model is based on the instantaneous emission model, MODEM. This means that the data output from the VISSIM model can be input into EnvPro and the total CO_2 emissions for the entire vehicle fleet operating on the network can be calculated. The term 'fleet' refers to the traffic flow, comprised of different vehicle types that use a highway and is used throughout this thesis. More detail is given on the set-up of instantaneous emission models in the Literature Review presented in Chapter 4.

Again, two transport models were developed for the road network for the following scenarios:

- Do Minimum – comprising 26km of existing motorway with nine junctions; and
- Do Something – the 'Do Minimum' model with an additional 23km of new motorway with tie-in interchanges and two intermediate junctions.

The anticipated opening year of the highway, 2016, and the future year of 2031 were modelled for each scenario. Figure 2.8a shows the existing motorway in the Do Minimum model, and Figure 2.8b shows the existing motorway and proposed relief road in the Do Something model.

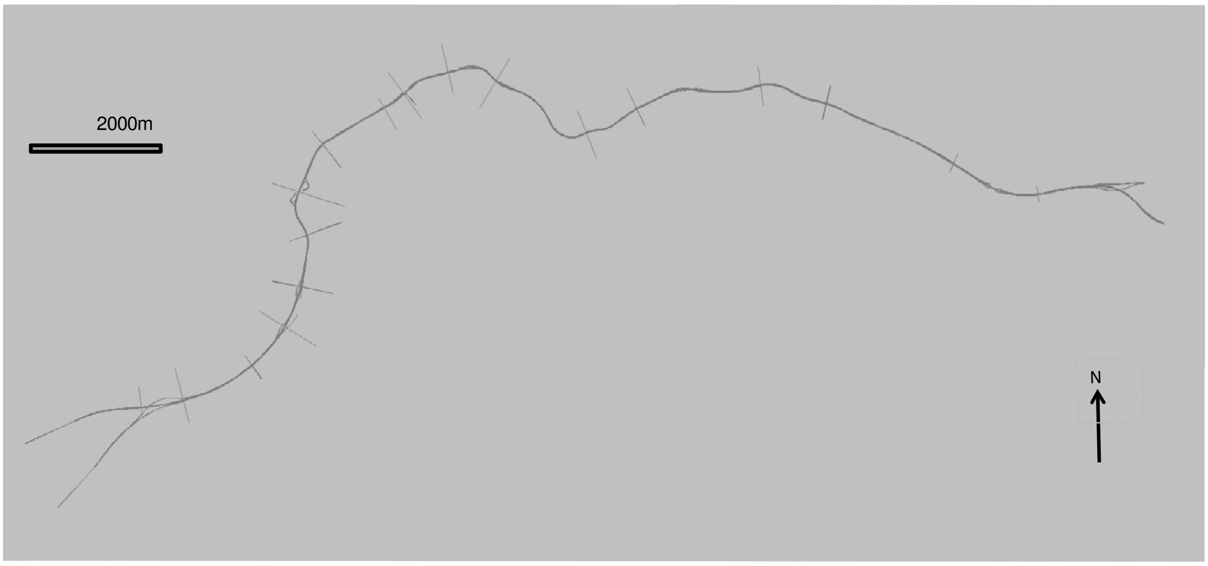


Figure 2.8a Extent of VISSIM model in Do Minimum Scenario

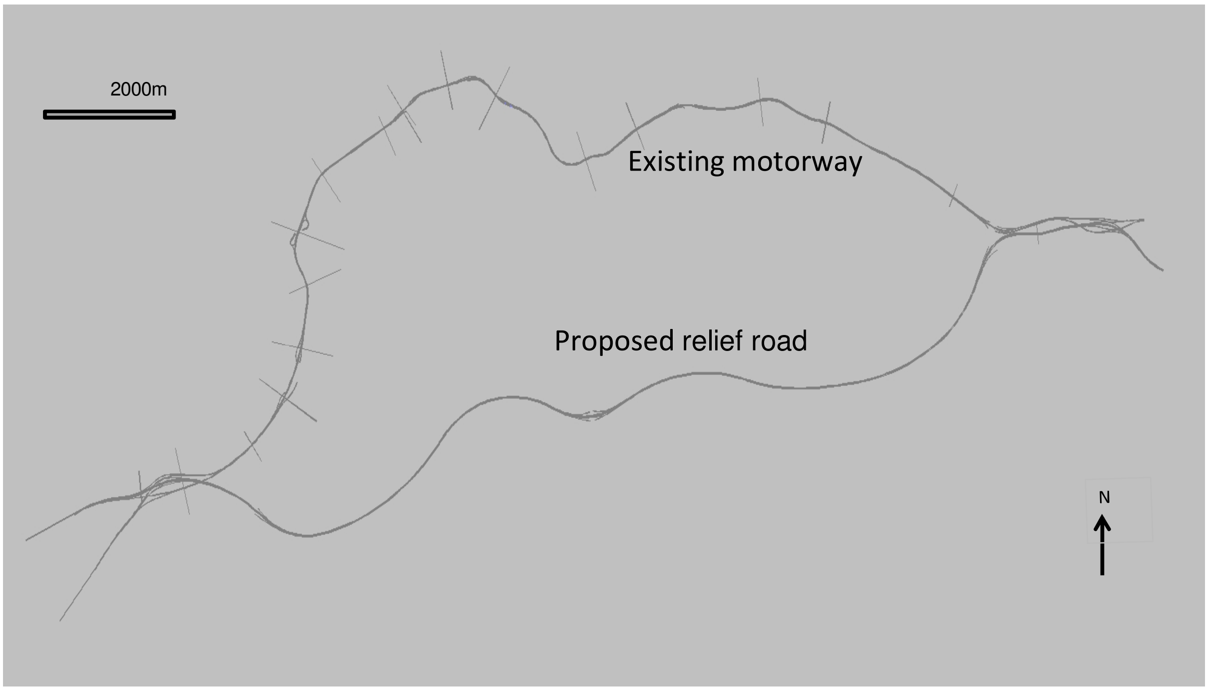


Figure 2.8b Extent of VISSIM model in Do Something Scenario

The models cover a 12 hour time period, the results from which were factored to give daily and yearly traffic flows (Arup, 2008). The factor used to convert 12 hour flows to 24 hour flows was derived from the Automatic Traffic Count (ATC) data collected in the scheme traffic surveys – by calculating the proportion of daily traffic flow that occurs within the 12 hour period. The 24 hour flow to annual flow conversion was undertaken using weekly ATC data – by calculating the proportion of weekly traffic flow that occurs within a typical day and factoring this further using local traffic data to obtain an annual traffic flow value. The CO_2 emissions output by the VISSIM-MODEM models are presented in Table 2.3 for the years of 2016 and 2031. In 2016, there is a 9% reduction in emissions and a 17% reduction in 2031.

Table 2.3 Results from VISSIM-MODEM models

Year	Do Minimum (tonnes/day)	Do Minimum (tonnes/year)	Do Something (tonnes/day)	Do Something (tonnes/year)
2016	360	137,000	330	125,000
2031	420	160,000	350	133,000

2.4 Discussion of results

The construction phase contributes a significant amount of CO_2, which equates to the CO_2 emissions released by vehicles using the highway over approximately a four year period. Figure 2.9 shows the construction CO_2 in the context of the use CO_2 over a 40 year period – it equates to around 10%. A highway life cycle assessment (LCA) undertaken by Stripple (2001) calculated the embodied energy (EE) from the construction phase of a 1km section of asphalt highway to be 23 TJ. To put this figure into context Stripple assumed the traffic flow to be 5000 cars per 24 hours. Therefore, the EE from the construction phase equated to 10% of the EE from the operational phase over a 40 year period.

Stripple did not include structures in his assessment and used a lower vehicle flow rate and, therefore, direct comparisons cannot be made between the two assessments. A broad comparison can be made by excluding the structures from the motorway assessment, which results in the construction accounting for 4% over the 40 year period. This figure is comparable to that of Stripple, and is lower due to the smaller traffic volumes that Stripple assumed resulting in the construction phase appearing to contribute more EE.

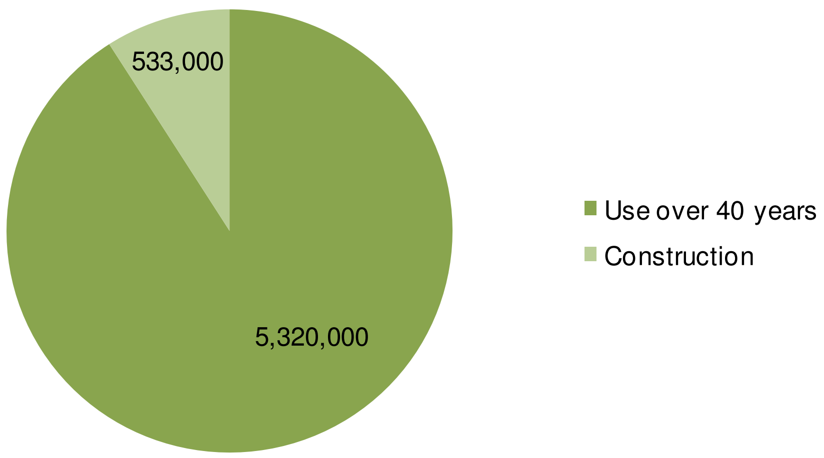


Figure 2.9 Construction CO_2 in the context of the use CO_2 over a 40 year period

Figure 2.10 shows the annual cumulative CO_2 emissions from the use of the highway in the Do Minimum scenario (red line) and in the Do Something scenario (black line). The Do Minimum scenario starts at zero as there are no initial CO_2 emissions occurring, and the Do Something scenario starts at 533,000 tonnes to reflect the CO_2 from the construction of the new motorway. The efficient operating conditions provided by the additional road in the Do Something scenario give a year-on-year CO_2 reduction, and after approximately 24 years the Do Something scenario results in fewer overall emissions.

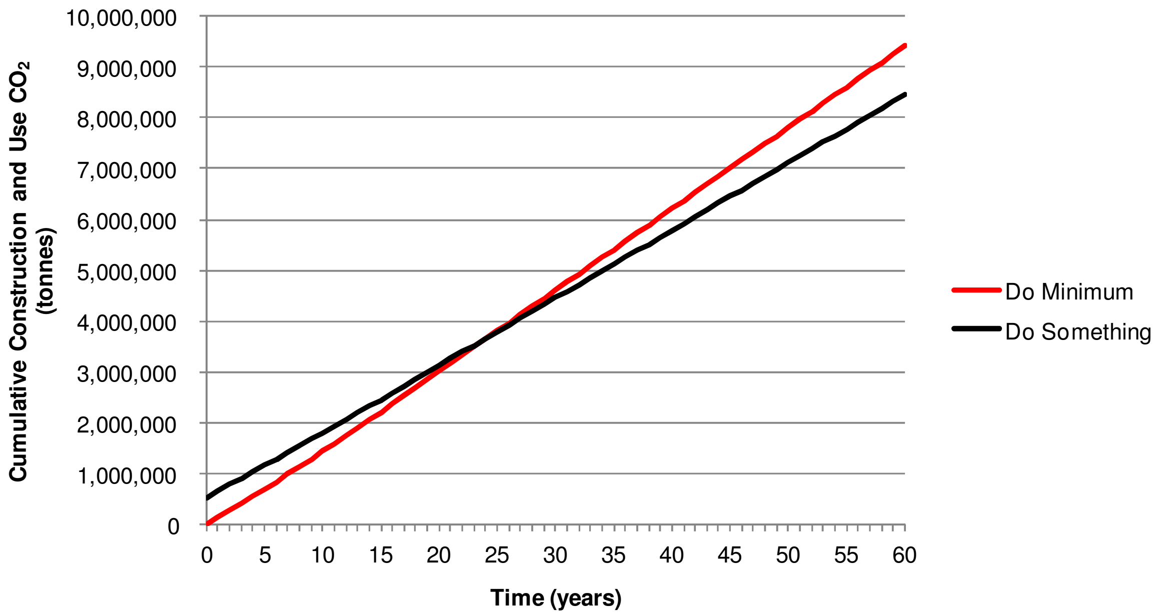


Figure 2.10 Payback period

2.5 Conclusions

The study presented within this chapter highlights the importance of undertaking a whole life carbon assessment in order to make informed decisions. A whole life carbon assessment should be undertaken, looking at all phases of a highway's life, in order to gain a complete representation of the effect of new highway infrastructure on CO_2.

When assessing the CO_2 resulting from the use phase it has been suggested that the construction of a relief road would lead to an overall decrease in CO_2 emissions due to more efficient driving being enabled (Carr, 2010). For this particular project this is indeed the case and the reductions are sufficiently substantial to offset the CO_2 resulting from its construction.

The annual reductions in CO_2 brought about by the free flowing driving conditions facilitated by the new relief road are, when considered independently, substantial CO_2 amounts. However, when compared to the construction CO_2 are relatively small. Leading to an approximate payback period of around 24 years – a simplistic estimate that neglected to consider the CO_2 associated with the maintenance and operation; inclusion of which would lengthen the payback period.

The construction of new highway infrastructure is not opposed. Instead the use of a whole life carbon approach at the planning stage of a highway project is promoted. To ensure informed decisions are made early on that provide benefits throughout the life time of the infrastructure. The importance of the information resulting from this whole life carbon assessment should also be considered carefully; a conclusion should be drawn with regards to whether the carbon impact is of sufficient significance to solely base decisions on, with courses of action being taken accordingly. Currently the outputs of any carbon assessments are monetised and input to an overarching economic assessment, and therefore the carbon impacts of a scheme are given the same weighting as the many other issues that have to be considered, such as accidents and time savings.

Once the highway is constructed, the use is beyond the control of the designer. However, decisions can be made by designers that will yield benefits during the use phase, such as road surfaces that minimise rolling resistance and alignments that complement the technologies of the vehicles using the highway.

Chapter 3

Approach to research

3.1 Research motivation

Previous work undertaken whilst at Arup, presented in Chapter 2, highlighted the magnitude of the emissions in use when compared to the emissions associated with construction, over the lifetime of a highway. The motivation for the work undertaken and subsequently presented within this thesis was to understand how a highway designer can make decisions in the design phase that can positively influence the use phase of the life cycle of a highway. In Chapter 2, Figure 2.11 showed the required payback period, for the annual benefits brought about by the new highway scheme to offset the initial CO_2 expended in construction, to be 24 years. Figure 3.1 shows the same graph, with the addition of two further scenarios: Do Something with a 50% reduction in construction CO_2, and Do Something with 10% lower use CO_2, with new payback periods of 15 and 17 years, respectively.

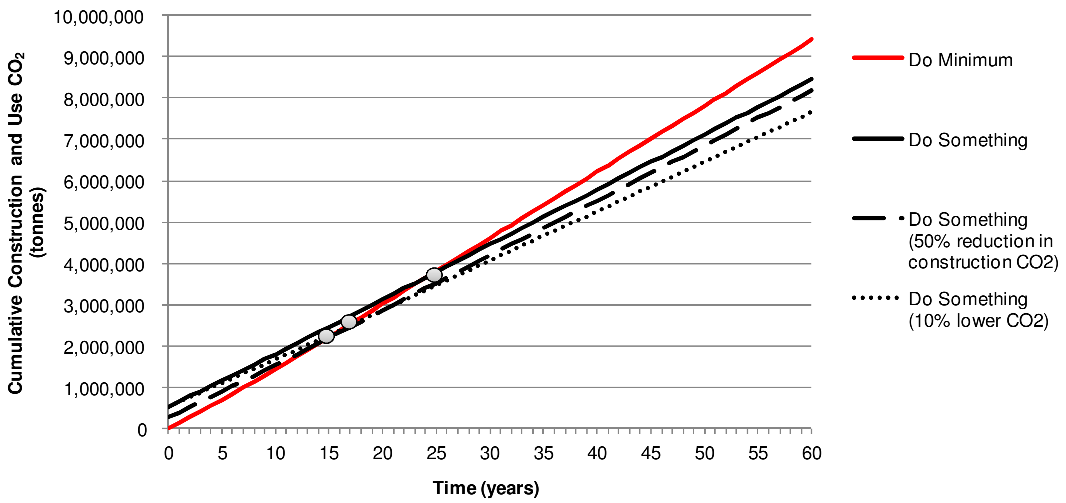


Figure 3.1 Payback periods for different Do Something scenarios

The Do Something scenario with lower initial CO_2 expenditure requires less time to payback, yet over a 60 year period the Do Something scenario with the use phase that results in 10% less CO_2 emissions saves more CO_2 over the project horizon.

The LCA of highways is now a well researched and understood area, with attempts made to develop streamlined LCA tools for considering the impact of road construction (Treloar *et al.*, 1999). Many full LCAs have been undertaken, considering different construction materials and maintenance programmes and it is felt unnecessary to explore the area further. The issue of highway alignment in the life cycle context is lesser understood, emphasised by the standards offered by the DMRB (Highways Agency, 2002). Therefore, the effect of alignment on life cycle CO_2 emissions will be the focus of this research.

3.2 Research aim

The aim is to understand whether a more CO_2 intensive construction operation will result in an alignment that would result in less fuel consumption and hence less CO_2 emissions in the use phase. This is illustrated hypothetically in Figure 3.2 for a valley; a shallow alignment would require an embankment resulting in more CO_2 being expended in the construction phase, however, the CO_2 associated with the use phase could be expected to decrease. Overall, the total CO_2 could be anticipated to decrease due to the expectation that changes to the construction phase which only contributes a small proportion of whole life carbon, would result in changes to the use phase, which contributes a large proportion to the whole life carbon.

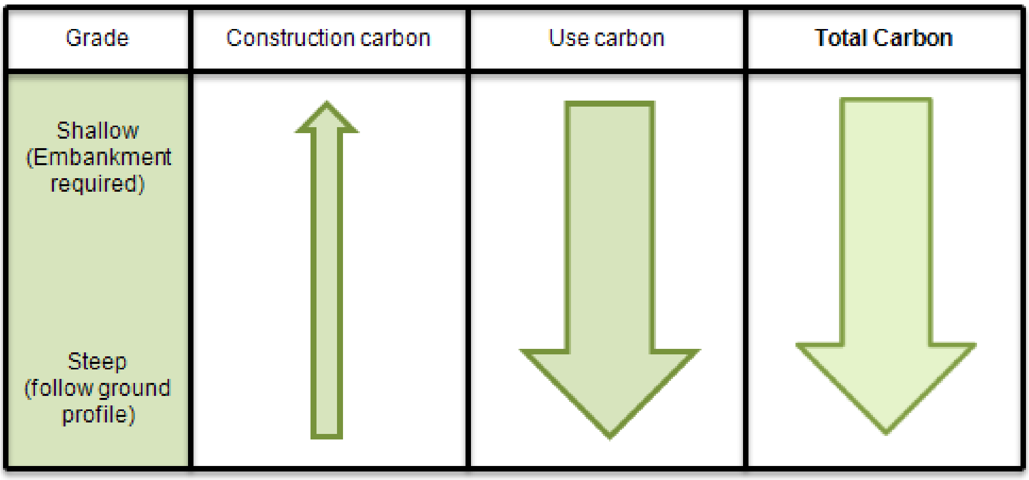


Figure 3.2 Illustration of research aims

3.3 Research

3.3.1 The research process

Fellows and Liu (2008) described research as a:

> *[A] dynamic process, [..] implying, although not requiring, that a contingency approach will be helpful. Early in the study, links between problems (which may either be topics or issues), theories, previous findings and methods will be*

postulated. The links should form a coherent chain, and so may need to be adapted as the work develops and findings emerge. The goal must be to maintain coherence and complementarity; only by such an approach will the results and conclusions be robust.

The research process is set out in Figure 3.3 (Bryman & Cramer, 1994).

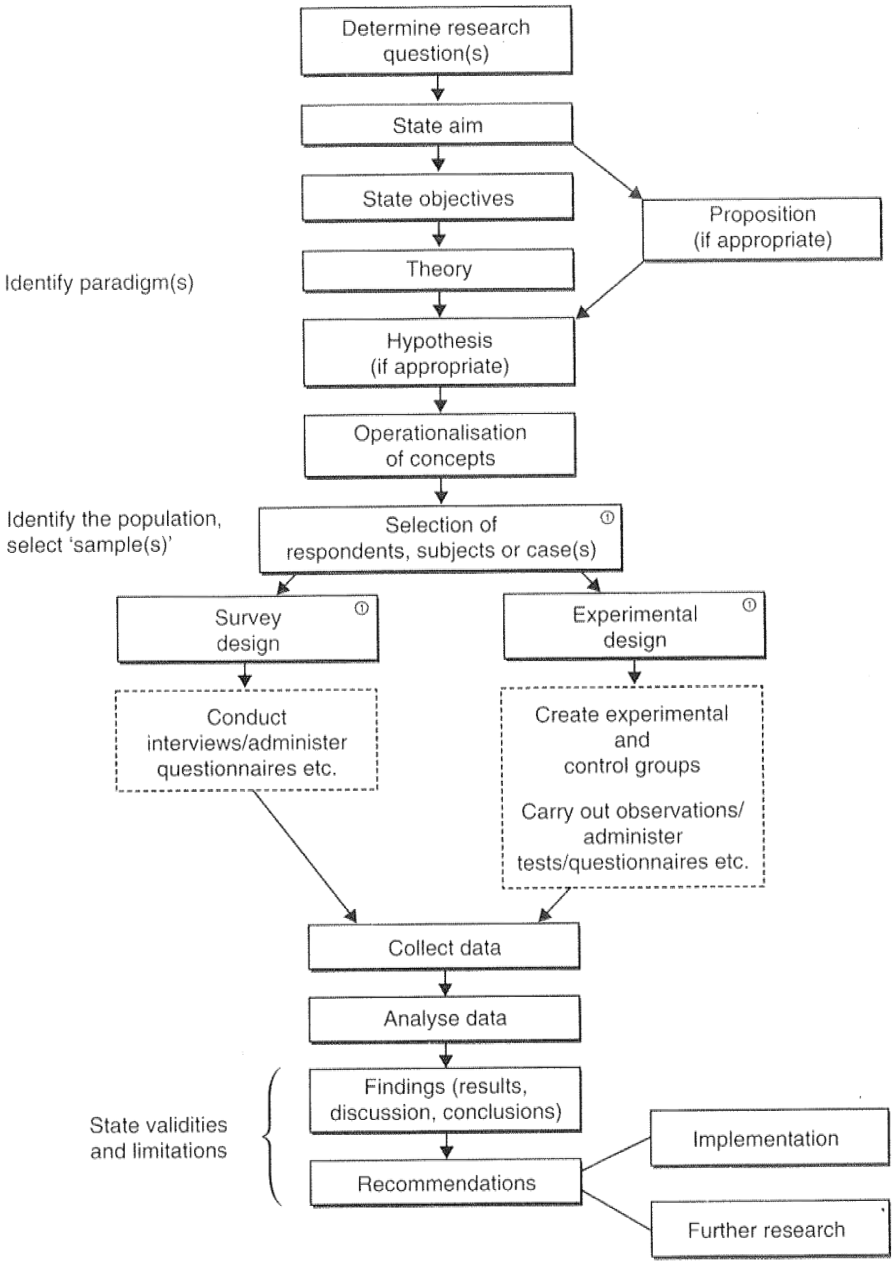


Figure 3.3 Research process

3.3.2 Research paradigms

The paradigm is the adopted set of beliefs that will guide the research. The two main research paradigms are positivist and constructivist; these are detailed in Table 3.1.

Table 3.1 Positivist and constructivist paradigms

	Paradigm	
	Positivist	Constructivist
Ontology (nature of reality)	Tangible Exists outside me Objective Can be apprehended Can be measured	Is constructed Relative to me Subjective Construction are not more or less true, only more or less informed
Epistemology (nature of knowledge)	Knower and the known are independent The influence of the researcher on the researched can be controlled Replicable findings are "true"	Knower and the known are interactively linked Findings are "created" as research proceeds
Axiology (role of values)	Inquiry is objective and thus value-free Values and biases can be eliminated through the use of rigorous procedures	Inquiry is value-bound Values are inherent in the context of the study The researcher's values affect the study

Quantitative research is typically associated with the positivist approach and usually involves experiments that examine cause-effect relationships and yield numerical data; whereas qualitative researchers are more likely to be constructivists who employ strategies that involve exploring themes within non-numeric data (Creswell, 2002).

There are two different approaches to research, deductive and inductive. Deductive reasoning takes a ‘top-down approach’ and takes knowledge from the general type to the more specific. The deductive approach takes a theory, develops a hypothesis, tests the hypothesis through observation and a conclusion follows on logically from the available facts. Inductive reasoning takes a ‘bottom-up approach’ and takes knowledge from the specific type to the more general; based on observations patterns are identified and generalisations and theories emerge. The approaches are illustrated in Figure 3.4.

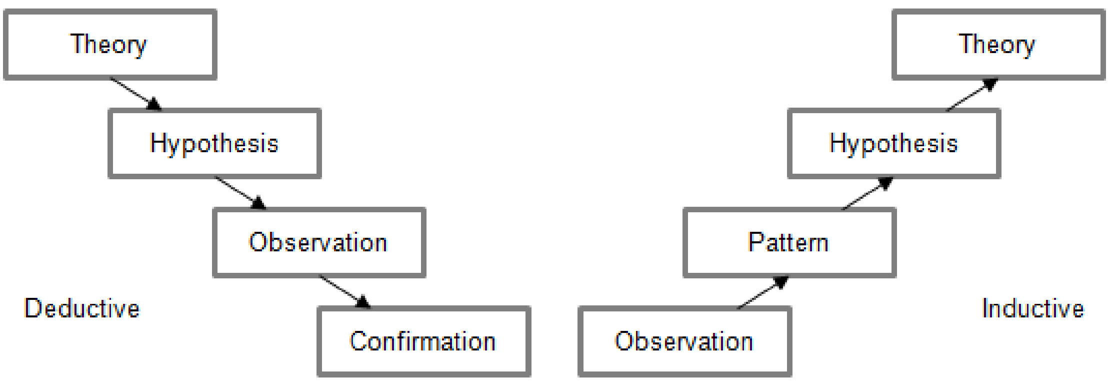


Figure 3.4 Deductive and inductive research

3.4 Research methodology

3.4.1 Positioning the research

The research can be positioned as inductive, positivist, and quantitative. Project work undertaken prior to the research resulted in observations that provoked further investigations. Quantitative research was necessary to identify patterns and to enable hypotheses and theories to be developed, and hence the research can be described as inductive. The methodology for this research is illustrated in Figure 3.5.

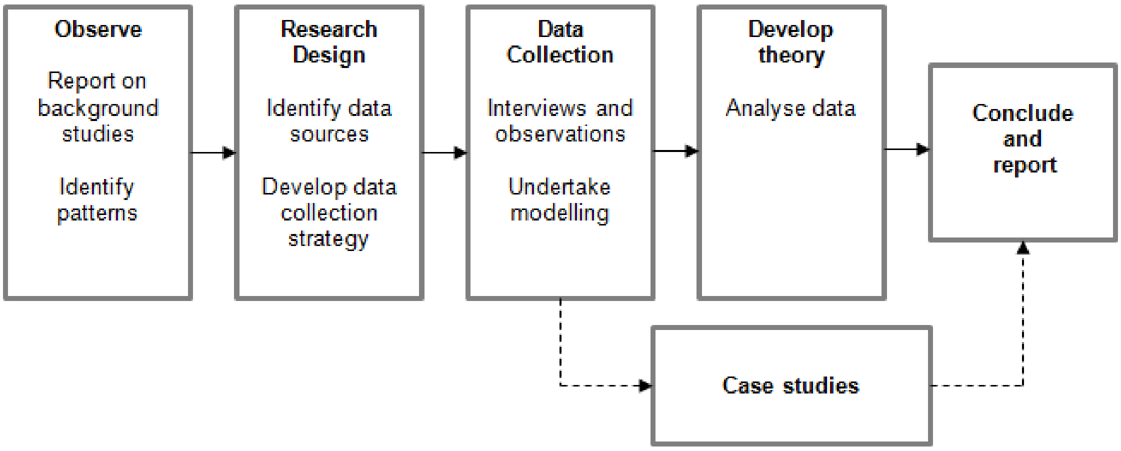


Figure 3.5 The research methodology

3.4.2 Focussing the research

Outcomes of the research undertaken and presented in Chapter 2 resulted in observations that defined the central research question, which is:

> **How can the vertical alignment of a highway be amended to result in an alignment that is more favourable in terms of fuel consumption, and hence lower CO_2 emissions across its life?**

To address this central question, the following sub-questions were considered:

- How does the earthworks operation that is required to achieve the alignment impact on construction CO_2?
- How does the highway gradient impact on different vehicle types?
- To what extent does vehicle technology affect the outcome?
- To what extent does the fleet composition affect the outcome?
- Over what time period the highway project should be considered?

3.4.3 Data sources and analysis

There were two streams of information that were required to answer the research question. The first stream involved the CO_2 emissions from the vehicles using the highways. A review of emission models, presented in Chapter 4, showed the PHEM emission model to be most appropriate. Detailed highway alignment data was required for input to the PHEM model; the reports that can be output from the highway alignment software Microstation InRoads provided this data on the modelled highways.

The second stream was the CO_2 associated with the earthworks operations. Although the undertaking of bulk earthworks operations is fairly consistent in terms of machinery use, the strategy adopted can vary between projects. To understand the strategy a major earthworks contractor, C A Blackwell (Contracts) Ltd, was consulted and interviewed with a range of data extracted.

Data on the case studies was provided from Arup who were acting as design consultants for both projects.

3.4.4 Use of case studies

The methodology developed to address the research question was applied to the selected highway case study (presented in Chapter 7) as it was both a real and current project that had numerous alignments which varied significantly. The author also had access to the data and information required to undertake the assessment, and therefore it was a timely opportunity to apply the methodology to an actual project.

Yin (2003) states that the use of a single case study is justifiable when it is: revelatory, extreme / unique, representative or a critical test of well-formulated theory. The case study in Chapter 7 cannot fully satisfy this description. However, it was not the intention for the case study to inform the hypothesis and so it was included for demonstrative purposes only.

Likewise, the case study used in Chapter 8, was also a current and real example that could demonstrate a methodological approach to the application of the whole life carbon concept on a project. Unlike the highway case study detailed in Chapter 7 the outcome of this case study was presented to the client and used to inform decision-making.

3.5 Experimental design

> *An experiment is an activity or process, a combination of activities, which produces events, possible outcomes. [...] [E]xperiments are devised and conducted as tests to investigate any relationship(s) between the activities carried out and the resultant outcomes.*
>
> Fellows & Liu (2008)

Hicks (1982) described an experiment as a study in which certain independent variables can be manipulated and their effect on one or more dependent variables is determined. The focus of this research is the gradient of a highway and therefore this variable will be isolated through the design of the experiment and the subsequent consequences for the other variables will be monitored. The research experiment, and its main variables, is shown schematically in Figure 3.6.

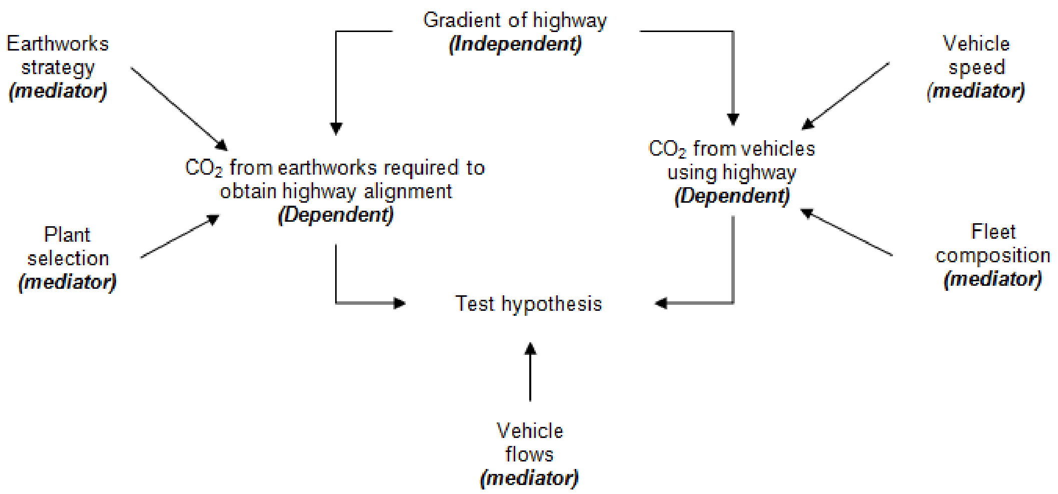


Figure 3.6 Variables of research experiment

3.5.1 Earthworks

The processes undertaken within an earthworks operation required research and a model to be developed that could be used to both assess the earthworks associated with the hypothetical alignments and the actual case studies considered. The involvement of the specialist earthworks contractor to provide site-based data was imperative to the development of a realistic model.

3.5.2 Hypothetical terrains and alignments

Numerical simulations of vehicles in the use phase were performed on simple road geometries to examine whether it is preferable to invest more CO_2 in the construction phase (through additional earthworks) to achieve an alignment that would result in CO_2 benefits, through reduced fuel consumption, in the use phase.

Hypothetical terrains (a hill and valley) were used to enable this to be investigated. It was assumed that following the terrains was feasible in highway alignment terms; meaning that no additional earthworks would be required. However, to test the effect of amending the vertical alignment, different alignments were designed which would require additional earthworks operations. The different alignments would affect CO_2 in two ways: (1) the CO_2 resulting from the additional earthworks required to construct the alignment, and (2) the CO_2 emission change from the vehicles using the highway in the use phase.

To compare the impact of the varying alignments on the vehicles using the highway in the use phase, the effect on the entire vehicle fleet needs to be known. However, in order to understand the impact on the fleet, the impact on the individual vehicles that comprises the fleet has to be firstly assessed.

The process that has been undertaken is illustrated schematically in Figure 3.7. The starting point was to develop a hypothetical terrain; for a given terrain there are obviously many different possible highway alignments that can be taken through it. But a specific hypothetical vertical alignment was developed, which for the purpose of this explanation can be referred to as Alignment A. The emissions from the individual vehicles operating on Alignment A were then analysed using the PHEM instantaneous emission model; enabling the emissions to be calculated as the vehicles travel along the alignment by taking into account the immediate gradient. Each vehicle type was assessed at a range of speeds. Through analysis of the individual vehicles a typical fleet and speed mix was applied to give a fleet emission. The terrains, together with the alignments, were then used to calculate the earthworks volumes required to construct the alignment. Using the earthworks CO_2 model that was developed, the volumes were then translated into a CO_2 value. The effect on the fleet in the use phase and the CO_2 from the construction phase could then be compiled to allow the relationship between the alignment and CO_2 to be understood.

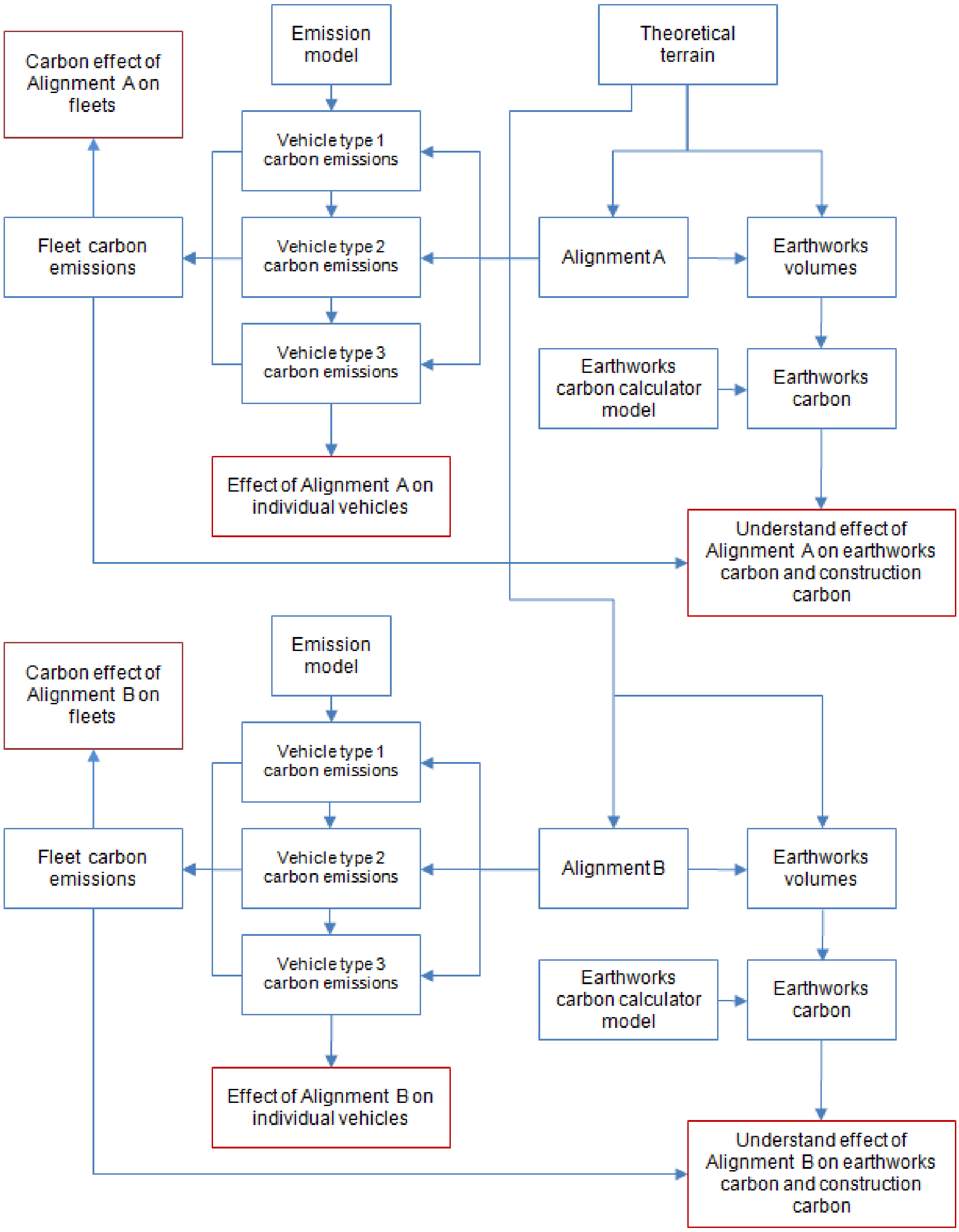


Figure 3.7 Assessment process

3.5.3 Study boundaries

The study boundaries taken for this research are shown in Figure 3.8; the items included in the assessment lie within the blue box, with the items outside of this box being excluded. The items shown on the diagram that have been excluded are not exhaustive.

For the earthworks element the focus is on the CO_2 associated with the fuel consumed by the earthmoving plant, the use of man-made materials and the transportation of these materials to site. For the use phase the sole focus is on the fuel consumed by the vehicles using the highway.

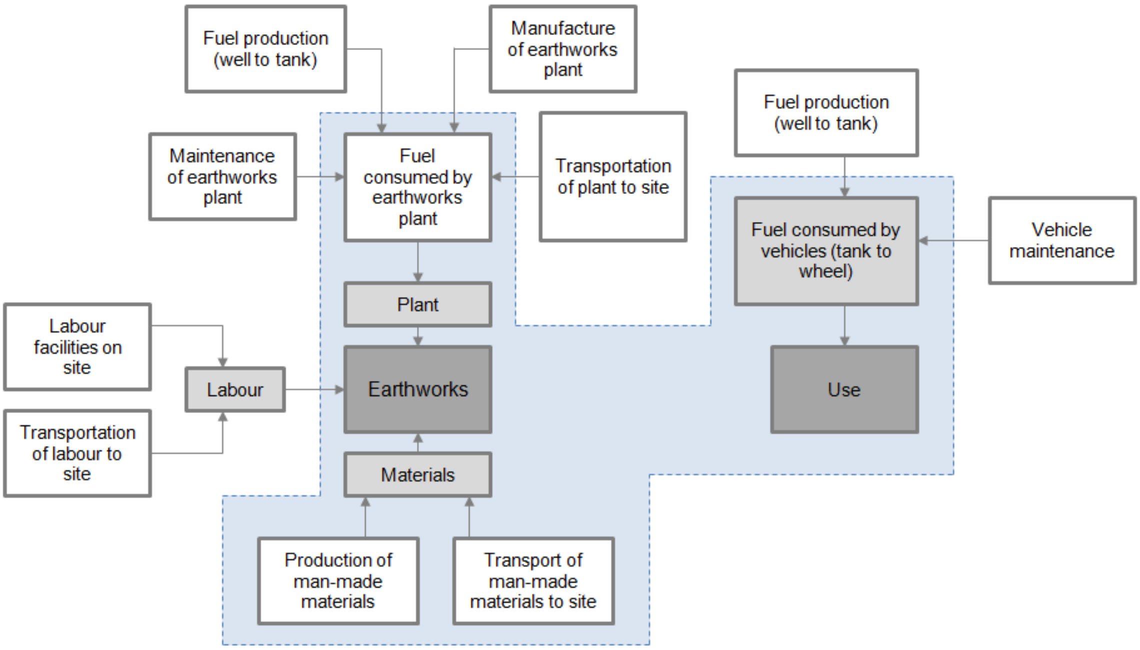


Figure 3.8 Study boundaries

3.5.4 Greenhouse gas emissions considered

The focus of this research is on CO_2 emissions and not CO_2-equivalent emissions. The model that was found to be most appropriate for the use emission modelling outputs total carbon emissions only. The resultant focus on CO_2 emissions alone was deemed acceptable due to these being responsible for the majority of the Global Warming Potential in road transportation, as shown in Table 3.2.

Table 3.2 Proportion CO_2 has of overall GWP (adapted from Baron *et al.*, 2011)

Road vehicle	Proportion of CO_2 of overall GWP
Car, operated with petrol / diesel	96.1%
Car, operated with natural gas	92.9%
Lorry, operated with diesel	96.1%

Chapter 4

Review of current models and approaches

4.1 Introduction

There were two work streams required for this research. The first is the study of earthworks used to create the vertical alignment of a highway, and the second is the study of the emissions resulting from vehicles using a highway. The assumption was made that no structures were to be needed as a result of the different gradients.

Within this chapter **Section 4.2: Sustainability terminology** considers the general concepts surrounding the sustainability of construction works, and more specifically the sustainability of highway construction in **Section 4.3: Sustainability of highway projects**. Previous research in this field is covered in **Section 4.4 Previous highway gradient research.** A review of emission modelling techniques is presented in **Section 4.5 Review of emission modelling,** and finally a review of the current approach to highway design is given in **Section 4.6 Current approach to UK highway alignment**.

4.2 Sustainability terminology

4.2.1 Life cycle assessment

Life cycle thinking has been in use by the manufacturing industry for some time and its history is well documented in Hunt and Franklin (1996) and Boustead (1996). During recent years life cycle thinking has come to the attention of the construction industry, as it realises that in order to meet sustainable construction goals it needs to address construction activities at all stages of the life cycle rather than just at the construction stage. The following section details the various terms relevant to this approach in the context of the construction industry.

Life cycle assessment (LCA) is the investigation and valuation of the environmental impacts attributed to a given product or service over its life or a defined assessment period. LCA takes a systems approach and is multi-criteria in its assessment, which are both key to sustainable decision-making. In construction terms, the system can refer to a single construction product, a construction element (e.g. a retaining wall) or an entire civil engineering project over its lifetime (e.g. a highway scheme).

The actual process of undertaking an LCA assessment is up to the discretion of the LCA practitioner. Although ISO standards provide guidance on how they should be undertaken, the standards can be interpreted in various ways meaning they can be manipulated and hence different LCAs are not always comparable. At the outset of an LCA, the methodology to be used, also known as the Product Category Rules (PCR) should be defined, which detail the aim and scope of the assessment, the system boundaries and the three essential steps – characterisation, normalisation and weighting.

4.2.2 Embodied energy (EE)

Pantelidou (2008) listed numerous definitions of Embodied Energy:

- *According to CSIRO 2007, Embodied Energy is the energy consumed by all of the processes associated with the production of a building, from the acquisition of natural resources to product delivery, including mining, manufacturing of materials and equipment, transport and administrative cost. (CSIRO, 2007).*
- *From the University of Bath Inventory of Carbon & Energy (ICE): Embodied energy is the total primary energy consumed during the life time of a product. Ideally the boundaries would be set from the extraction of raw materials (inc fuels) to the end of the products lifetime (including energy from; manufacturing, transport, energy to manufacture capital equipment, heating & lighting of factory...etc), this boundary condition is known as Cradle to Grave. It has become common practice to specify the embodied energy as Cradle to Gate, which includes all energy (in primary form) until the product leaves the factory gate. The final boundary condition is Cradle to Site, which includes all energy consumed until the product has reached the point of use (i.e. building site) (Hammond & Jones, 2008).*
- *The Wikipedia definition: Embodied energy is the energy required to manufacture, and supply to the point of use, a product, material or service. The boundaries of the embodied energy definition quite often vary: cradle to grave includes all the energy produced throughout the life of the product; cradle to site includes the energy produced to the point of delivery on site etc.*

The generally accepted definition for embodied energy as provided by Treloar (1994) is:

> *The quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipment and in other supporting functions i.e. direct energy plus indirect energy.*

It is clear that many definitions of EE exist, and all are perfectly acceptable if the boundaries of the study are clearly defined to avoid double-counting or omissions.

EE is often given in MJ per kg of product. Although there is a strong correlation between EE and CO_2, the conversion can vary depending on the type and source of the energy used in the manufacturing process to create the product. If a product is manufactured using energy from a low carbon intensive electricity grid, then the resulting Embodied CO_2 would be less than if the product was produced using energy sourced from a highly carbon intensive grid. However, research has been undertaken to give an average figure for the conversion of EE into Embodied CO_2 (EC). The global average figure is that for every GJ of EE, 0.098 tonnes of CO_2 is produced (CSIRO, 2009).

In infrastructure terms, EE can be divided into two categories – initial and recurring. Initial EE constitutes the energy resulting from construction, including the extraction of raw materials, their processing, manufacturing, and transportation to site. The recurring EE is the energy used to complete the maintenance processes.

The focus of the research is to understand the relationship between the initial CO_2 from the construction of a designed highway alignment and the influence of the resultant road gradient on the recurring use vehicle CO_2 emissions. The use emissions will be calculated from the conversion of the amount of fuel consumed into CO_2 emissions, and as a result, the energy used in the construction will also be reported in units of CO_2.

Currently a set of European standards are being developed by the Technical Committee CEN/TC 350 (Sustainability of construction works) to support the sustainability assessment of construction products and the built environment (CEN, 2009). A key area in development by this committee is the standardised Environmental Product Declaration (EPD), which is at the CEN enquiry stage. This outlines the requirement for all manufacturers of construction products or materials to declare relevant environmental information pertaining to the product in a standardised manner. Manufacturers will have to report on the impacts of their products on the following as a mandatory requirement. These indicators are assigned to impact categories of a Life Cycle Impact Assessment (LCIA):

- Global warming potential
- Ozone depletion potential
- Acidification potential for air and water
- Eutrophication potential
- Photochemical ozone creation potential
- Ionising radiation (optional)

In addition, manufacturers will be required to report on the following indicators which are based on the Life Cycle Inventory (LCI) but are not assigned to an impact category in a LCIA:

- Use of renewable material resources other than primary energy
- Use of renewable material resources, primary energy
- Use of non-renewable energy resources

Finally, manufacturers will be required to report on the waste to disposal resulting from their product (embodied waste), this data will be derived from the Life Cycle Assessment (LCA) but not assigned to impact categories of the LCIA and will cover:

- hazardous waste;
- non hazardous waste; and

- radioactive waste.

As a minimum, the EPD will have to cover the production stage (cradle to factory gate) of the life cycle. Certain manufacturers will endeavour to demonstrate their product's capability throughout the service life and will present information covering all life cycle stages (cradle to grave):

- product stage (mandatory)
- construction stage
- use stage – operation and maintenance
- end of life

Key to a meaningful life cycle analysis is a high quality of data, and specific data quality requirements are set out in the EPD methodology. Data will have to be specific to the product under assessment in terms of geographical and technological coverage and be recent.

Establishing the EPD procedure for individual construction products and enforcing it as a mandatory requirement is a necessary step in developing a framework for the assessment of the environmental performance of buildings. It is the eventual intention of the CEN/TC 350 to produce a standardized system for the assessment of the sustainability of buildings using a life cycle approach, a system that will heavily utilise EPD data.

A shift to a life cycle approach to assess the sustainability of buildings is occurring and, within the near future, will be an area that designers will have to consider in detail to demonstrate the sustainability of their designs and decisions. Buildings have been the focus of life cycle analysis applications as they are a significant source of CO_2 emissions. The majority of these emissions throughout a buildings life can be attributed to the use phase, when the building and its occupants are consuming energy.

The focus will widen to incorporate civil engineering works and it will, at some point, also be mandatory to consider and quantify infrastructure projects in terms of the entire life cycle from cradle to grave. Consideration will need to be given to the use phase; for which the definition of use can vary considerably across a range of civil engineering projects.

Boundaries specific to transport projects include Well to Tank (WTT) and Tank to Wheel (TTW). The WTT evaluation accounts for the energy used and the associated GHG emitted in the processes required to deliver the finished fuel to the tank of a vehicle. The TTW evaluation accounts for the energy and the associated GHG emitted by the fuel production and the combustion of the fuel within the vehicles engine (CONCAWE, 2007).

4.3 Sustainability of highway projects

Although not necessarily in an integrated or fairly weighted manner, the three aspects of sustainability (social, environment and economy) have been incorporated into the decision-making surrounding highway projects in the UK for many years. The driver behind the construction of major highways has been to meet regional and local needs; both social and economic. The recognition of the environmental impacts came later, but now is also an important consideration.

Highway infrastructure, the associated traffic flows and the environmental impacts of these have been an area of investigation for decades. Methodologies are continually being introduced by engineering consultancies to enable the sustainability of designs and projects to be measured and assessed. Overarching bodies such as the Highways Agency (HA) are also developing similar tools for general use.

The HA recognises that the CO_2 emissions associated with vehicles once the highway network is in use account for the majority of all CO_2 emissions associated with the highway network. The HA believe these to be considered in the planning and designing of highway schemes using the methodologies given in WebTAG Unit 3.5. A scoping study was commissioned by the HA to understand the efforts required to ensure CO_2 emissions associated with the construction of highway schemes are also considered (Fry *et al.,* 2004). The preference to avoid or reduce adverse environmental impacts at source was stressed. Potential mitigation measures included a considered route, modifications to the detailed design, and the appropriate selection of materials and working methods.

4.3.1 LCA of highway construction

To date, Stripple (2001) provides the most comprehensive methodology and data for the life cycle assessment of highways – providing detailed inventory data covering highway construction, maintenance and operation. Stripple's intent was to demonstrate the importance of aspects of the highway life cycle for phases and activities other than the use phase.

The main structure of a life cycle of a highway, as consider by Stripple (2001), is shown in Figure 4.1. With the initial stage being the construction phase, involving the excavations, foundation reinforcement and pavement construction. The next stage is the operation and maintenance, involving the maintenance of peripheral equipment, verges and winter maintenance. These phases reccur throughout the life time depending upon the requirements determined by traffic usage and design standards. The 'final disposal' stage is not the end of the highways life; Stripple (2001) states that through continous maintenance the highway is successively replaced.

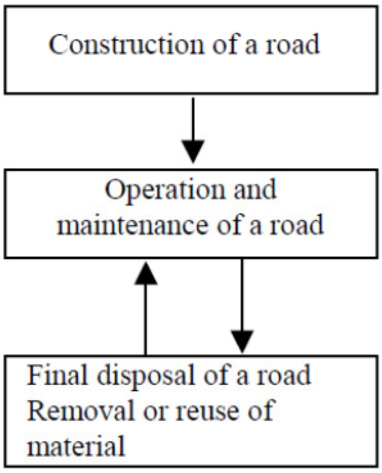


Figure 4.1 Main structure of life cycle for a road (from Stripple, 2001)

Stripple (2001) identified the difficulties of applying standardised data to linear infrastructure, such as highways, due to the significant variations that can exist between the individual sites that comprise single projects, the main variation being the excavation work required and how this can alter the internal haulage efforts required. Figure 4.2 shows a schematic of the relationship between the terrain, balanced route of the highway and the transportation direction of the excavated material. Stripple (2001) highlighted the possible benefits to the traffic of designing a flatter highway in relation to the inputs to the highway construction process, yet this was not considered in detail in his model.

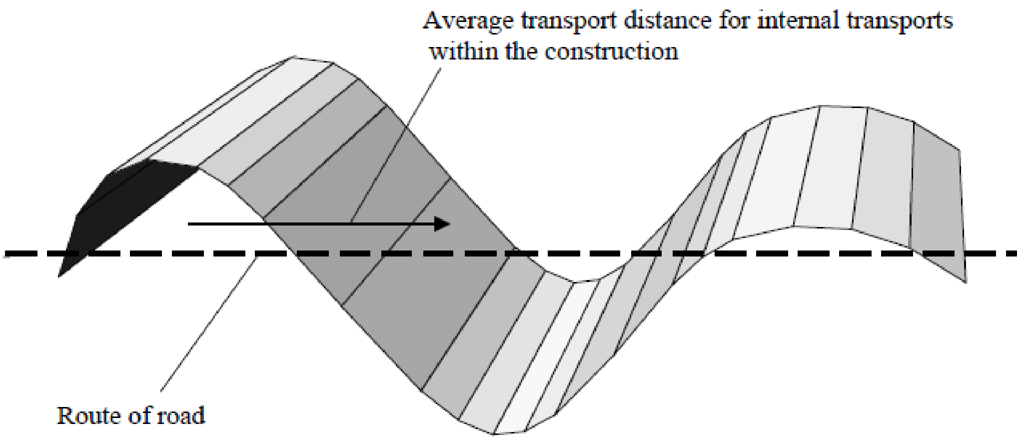


Figure 4.2 Schematic diagram of relationship between the terrain, the balanced route and direction of transportation of excavated material (from Stripple, 2001)

Stripple undertook an LCA for three types of road over a 1km length over a 40 year period of use – an asphalt (hot method), asphalt (cold method) and a concrete road. The LCA included all aspects of road construction, operation and maintenance with the exclusion of the impacts of the vehicles using the highway. The total energy consumption was calculated at around 23 TJ and 27 TJ for the asphalt and concrete roads respectively. The difference in energy consumption between the hot and cold methods used for the asphalt surface were reported as very small (Stripple, 2001).

To put the results in to the context of the energy used by vehicles operating on the 1km section of road; Stripple (2001) assumed the highway would have a vehicle flow of 5000 cars in each 24 hour period. The fuel consumed by the vehicles over the 40 year period amounted to 229.2 TJ. Table 4.1

shows how the energy consumed from the construction, operation and maintenance compares to the energy in the use phase. For the concrete road, when the energy intensive road lighting and traffic control aspects are included in the comparison, the proportion of energy from the construction, operation and maintenance is 11.8%, demonstrating that the use phase is responsible for the majority of the energy over the highway lifetime.

Table 4.1 Percentage of energy from construction, operation and maintenance of road over 40 year period (adapted from Stripple, 2001)

Road type	Percentage of energy from construction, operation and maintenance of road over 40 year period **including** road lights and traffic control (%)	Percentage of energy from construction, operation and maintenance of road over 40 year period **excluding** road lights and traffic control (%)
Asphalt (hot method)	10.1	4.9
Asphalt (cold method)	9.9	4.7
Concrete road	11.8	6.6

Treloar *et al.* (1999) developed a streamlined LCA method for considering the environmental impact of road construction. Unlike Stripple (2001), the methodology included the road use, as shown by the conceptual model in Figure 4.3. An Australian road was selected for the assessment that had previously been assessed on a life cycle cost basis by Porter and Tinni (1993). The road had a concrete pavement, a design life of 40 years, a sample length of 5 km (comprising a 33m length of cut and 667m length of fill) and a traffic flow of 10,000 vehicles per day (comprising 90% cars and 10% trucks).

The assessment attributed a value of 130,000 GJ to the initial construction of the road over the 5km length. This equates to 26 TJ/km which is comparable to 27 TJ suggested by Stripple (2001). The energy consumed by the vehicles operating over the 5km section was 4,090,000 GJ. For this example the initial energy consumed during construction equates to around 3% of the energy consumed by the vehicles that operate on the road during the 40 year period.

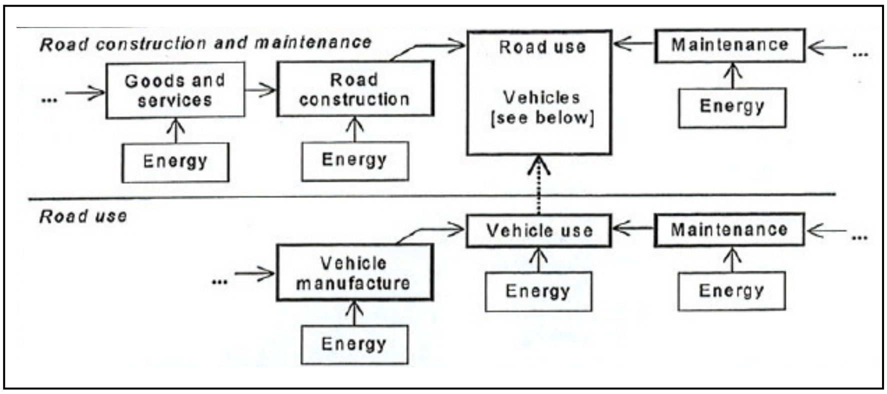


Figure 4.3 Conceptual diagram of streamlined LCA (adapted from Treloar *et al.*, 1999)

Another LCA model, developed by the Technical University of Denmark, is ROAD-RES (Birgisdóttir, 2005). This assesses the environmental impacts of using recycled materials over virgin materials in the construction of a road. The model enables the user to assess the environmental impacts and resource consumption at different stages of the road construction and compare several solutions for design and maintenance (Christensen *et al.*, 2006). The model considers five main stages: design, construction, operation and maintenance, and demolition. The earthworks operation is considered as a sub-stage in the construction stage and the difficulties of standardising the earthworks is highlighted due to the huge variations that can occur between projects.

An evaluation of the Florence highway widening scheme was undertaken by Corti *et al*. (2003); to quantify the benefits of an additional third lane along a 24.5km section of highway using an LCA approach. The current highway endured heavy traffic flows resulting in congestion and a reduction in the environmental quality of the surrounding areas. The assessment covered the construction of the road, resurfacing every 5 years and the emissions based on the actual recorded traffic flows using CORINAIR emission factors. The results of the LCA indicated that the operation phase accounts for 99% of the CO_2 emissions and 98% of the energy consumed. These high figures may reflect the inclusion of the fuel production processes. In comparing the CO_2 emissions for the present scenario with the scenario that included an additional lane, the latter reported a 31% decrease over 20 years of use emissions due to relief of traffic congestion.

4.3.2 Geotechnical aspects of highway construction

Previous research has identified the benefits of using low carbon intensive natural materials as construction materials. One focus has been on rammed earth, which is:

> *[O]ne such construction technology that has seen renewed interest in recent years. The energy required to manufacture materials (i.e. embodied energy) is a significant component of the life cycle energy associated with buildings. [...]. Rammed earth was found to have significantly less embodied energy than cavity brick construction [...] but was approximately equivalent to brick veneer construction.*

(Treloar, 2001)

More recently, Lax (2010) compared rammed soil to soil that has been stabilised with cement to give a higher compressive strength, and concluded that

> *Overall the results have been successful in demonstrating the sustainability of using rammed earth as a construction material, as it is scoring at the top end of the Green Guide above many other construction methods currently listed. It also has a third of the embodied carbon impact of many of the other construction methods in the A+ category. Therefore if carbon was the governing factor in determining construction methods in the future then rammed earth could enter into mainstream construction more easily.*

The Green Guide is part of BREEAM and rates building materials using an A+ to E ranking system, with A+ representing the best environmental performance (BRE, 2011). The rankings are based on LCAs using BRE's Environmental Profiles Methodology 2008 and take into account many environmental impacts. Therefore, although rammed soil scores well in the climate change and fossil fuel depletion categories, this does not necessary result in an A+ rating.

To understand the issues of sustainability that surround geotechnics the HA commissioned Hillier *et al.* (2005) to produce a report on the subject. Five themes were addressed: 1) Land take, 2) Geotechnical construction, 3) Geotechnical maintenance, 4) Highway Usage and 5) Decommissioning. Highway usage has been included as one of

> *[t]he principal considerations for which geotechnics can contribute to improved sustainability in highway usage [,] via the provision of appropriate road gradients by means of cuttings and embankments (and tunnels/bridges).*
>
> (Hillier *et al.,* 2005)

Hillier *et al.* (2005) set out the scope for the study of highway geotechnics to include:

- Earthworks at grade, including ground improvements
- Cuttings, including soft to intermediate support (batters to nailing)
- Embankments

4.4 Previous gradient research

Extensive research has been undertaken to investigate the effects of road gradients on vehicle emissions. Hassel and Weber (1997) researched into the influence of gradient and demonstrated that it cannot be assumed that the extra emission when travelling uphill is compensated by the corresponding reduction in emissions when travelling downhill. Emission tests were undertaken on a range of vehicle types for gradients ranging from -6% to +6%. Coefficients were derived for the calculation of gradient factors for different vehicle categories and gradient classes for use with a standard equation based on vehicle speed.

The graph in Figure 4.4 shows the calculated fuel consumption correction factors for the different gradients at a range of speeds using the coefficients for passenger and light duty vehicles. Figure 4.5 shows the same information but for a 32 - 40 tonne heavy duty vehicle. In both figures the correction factors are given for the positive and negative gradients separately, and also for the average of the two. For the light duty vehicle, in Figure 4.4, the combined uphill and downhill correction factors are greater than 1 for all gradients at all speeds with the exception of the +4 / -4 combination between 20 and 30kph. For the heavy duty vehicle, in Figure 4.5, the combined correction factors are always greater than 1, and for the +6% / -6% case are always greater than 1.5. These two extracts show the potential significance of road gradient on heavy vehicles.

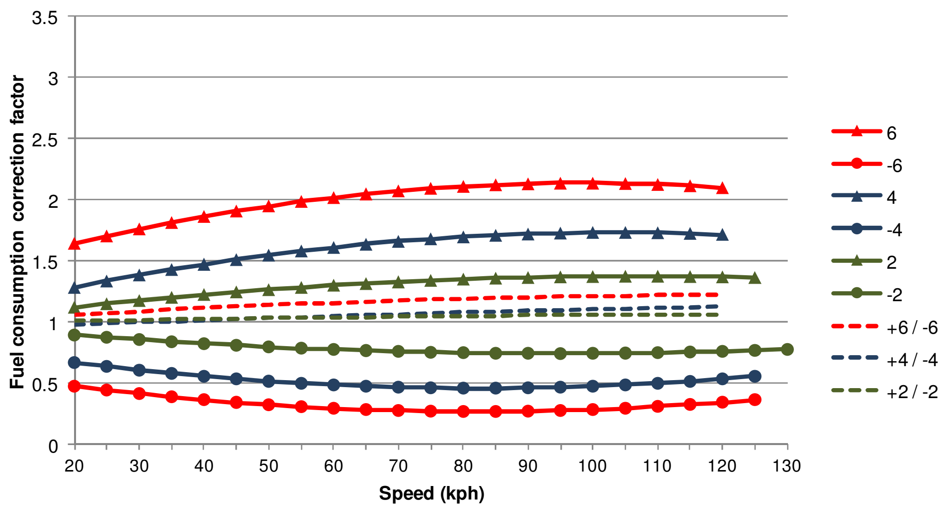


Figure 4.4 Fuel consumption correction factors for passenger and light duty vehicles (using data from Hassel and Weber (1997))

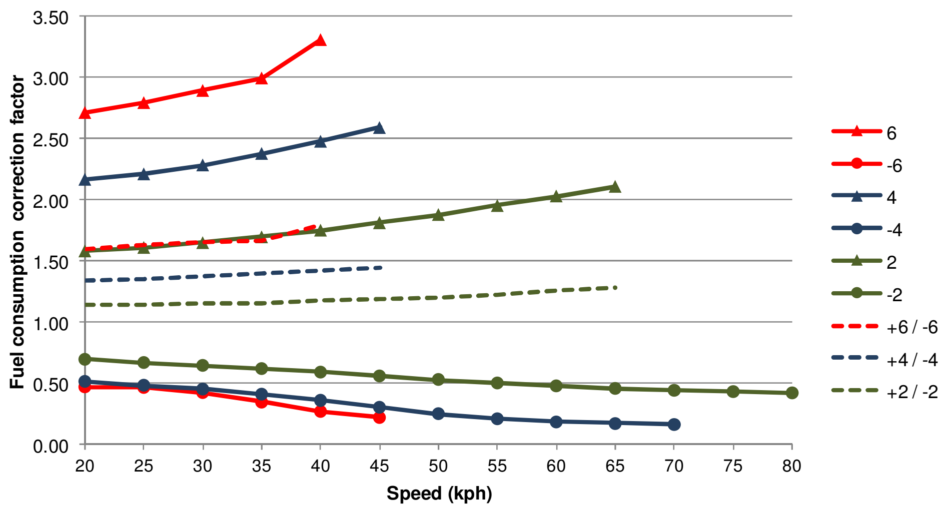


Figure 4.5 Fuel consumption correction factors for 32 – 40 tonne heavy duty vehicles (using data from Hassel and Weber (1997))

4.4.1 Parry and Potter (1995)

Studies by Parry and Potter (1995) demonstrated the potential significance of gradients on vehicle fuel consumption. The study identified energy calculation processes and data for construction, maintenance and road use (albeit some of the source data had been derived from studies in the 1970s and 1980s).

A simple model compared fuel usage for three hypothetical alignments:

1. A direct line with a cutting through a hill to provide a level horizontal alignment;
2. A route over the hill with equal positive and negative grades either side; and,
3. A flat gradient going round the hill, thereby increasing the overall route length.

Table 4.2 shows the construction and maintenance and the annual energy consumed by vehicles using the three alternate highways. For the vehicle flows assumed in their study, the energy consumed in one year of use is comparable to the energy consumed during both construction and maintenance. This table also shows the total energy consumed over a notional 40 year period; using this figure along with the energy from construction and maintenance allowed a total energy value over the 40 year period to be calculated. From this study it was concluded that it is beneficial to expend more energy in construction to obtain a level alignment through the hill, rather than taking the alignment over or around the hill. The annual reduction in energy consumption when considering the 'cutting through the hill' option over the 'over the hill option' is 9.5%, which over the 40 year time period results in a total energy saving of 6.8%.

Table 4.2 Energy associated with different alignments (adapted from Parry and Potter (1995))

Alignment	Construction and maintenance (TJ)	Annual energy consumption (TJ)	Over 40 years (TJ)	TOTAL (TJ)
1. Cutting through hill	2,092	1,358	54,320	56,412
2. Over the hill	519	1,500	60,000	60,519
3. Around the hill	616	1,544	61,760	62,376

The calculation procedure assumes consistent fuel consumption, fuel energy content, and traffic profile (comprising cars, vans, rigid trucks and articulated trucks to 38t)). This study showed the potential to reduce energy consumption over the lifetime of a highway through the provision of alignments that are more favourable in terms of fuel consumption.

4.4.2 Hillier *et al.* (2005)

Hillier *et al.* (2005) proposed a system for scoring the sustainability of a proposed highway when it was in the use phase; by calculating the energy consumed over its effective length rather than its actual length, with the effective length taking into account the gradients.

Figure 4.6 shows the gradient factors that should be applied to highways with graded vertical alignments; there are two graphs, one showing the gradient factor for fuel consumption alone, and one showing the gradient factor for all environmental factors (including fuel consumption and local pollutants). This graph shows that if a vehicle were travelling along an uphill section of equal length to the downhill section, of +1% and -1% respectively, that this would equate to travelling on a level section in terms of fuel consumption. For steeper gradient combinations this is not the case, and it is shown to always be detrimental to travel on these. The gradient factors given within Hillier *et al.* (2005) have been taken from the extensive study undertaken by Hassel *et al.* (1997).

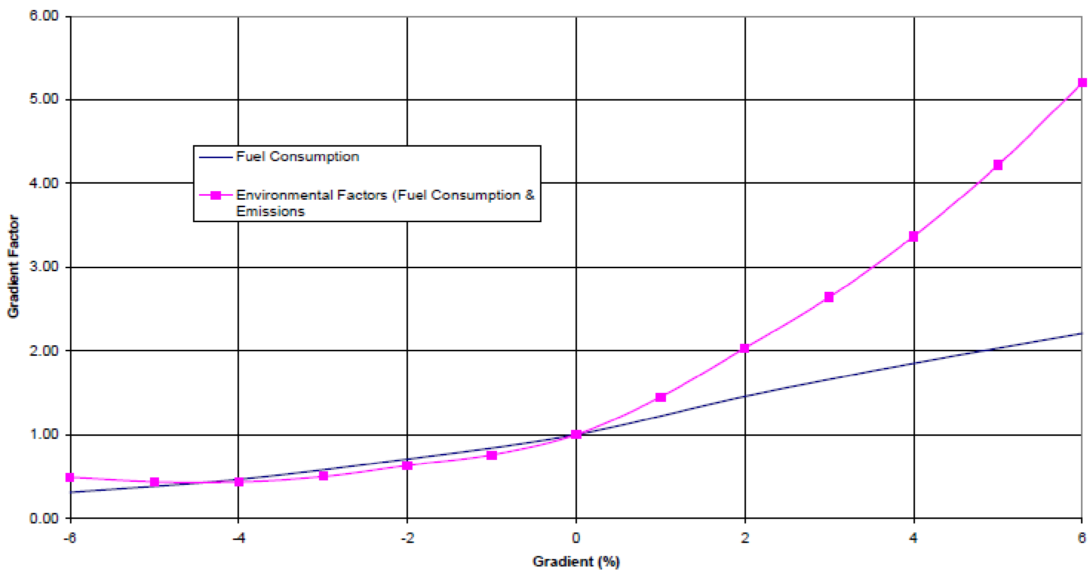


Figure 4.6 Gradient factors (taken from Hillier *et al.* (2005))

To ensure the Hassel *et al.,* (1997) derived gradient factors were aligned with the Parry and Potter (1995) results a study was undertaken with the newly calculated energy values in use being substituted into the Parry and Potter study. The results showed the fuel consumption predictions between the present model and Parry and Potter models to be comfortably consistent (i.e. within 10% of each other) (Hillier *et al.* (2005).

4.4.3 Butler (2006)

The Integration of the Measurement of Energy Usage into Road Design (IERD) project was designed to reduce the energy used in the construction of roads and the energy consumed by the vehicles using the roads (Butler, 2006). The platform used to convey the reductions and the main outcome of the project was the software Joulesave. This was designed in conjunction with the engineering software company Bentley and was designed specifically to be used with MX Road (Bentley road design software). Joulesave calculates the amount of energy used during the construction of the road and the energy used by vehicles operating on the road over a 20 year period.

The intention is for a designer to use the software whilst a highway scheme is in its early stages; in order for the energy implications of the different alignment options to be understood, and to inform the route selection process.

Four highway schemes with differing alignments were assessed as part of the research project in:

- Czech republic, a dual carriageway, with two alignments
- Portugal, a dual carriageway, with two alignments
- France, a single carriageway, with four alignments
- Ireland, a single carriageway, with five alignments

The energy breakdown between the construction of the highway and the use of the highway over a 20 year period is shown in Figure 4.7 for the dual carriageways and Figure 4.8 for the single carriageways. For all highways there is a small variation between the energy associated with the construction of the alternative alignments, yet the energy associated with the use varies considerably.

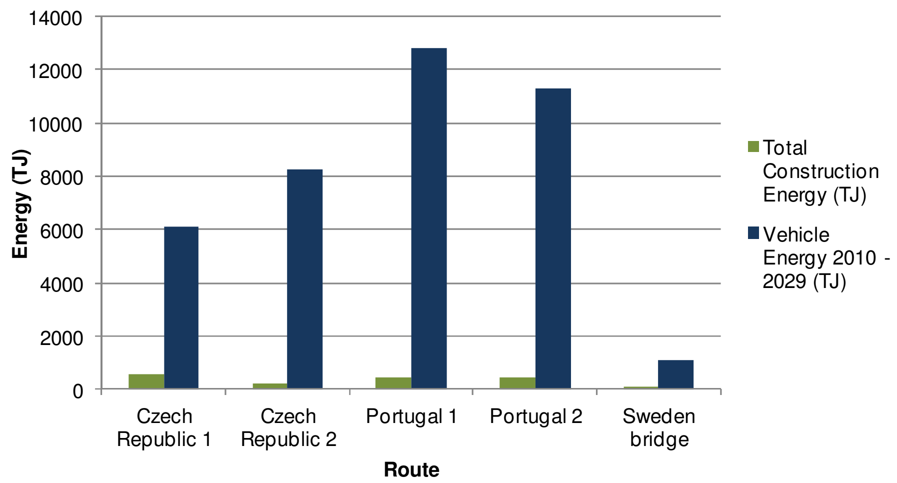


Figure 4.7 Energy breakdown by construction and use for dual carriageway routes (based on data from Butler (2006))

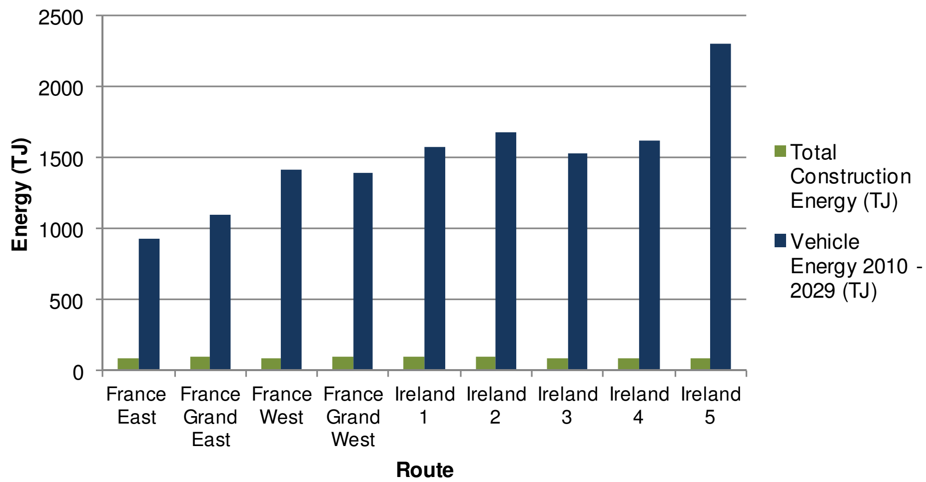


Figure 4.8 Energy breakdown by construction and use for single carriageway routes (based on data from Butler (2006))

When considering the total energy (including construction and use) over the 20 year period the construction accounted for between 4% and 10% for single carriageways, and 3% and 12% for dual carriageways.

4.4.3.1 Construction energy

The construction energy included the energy from the machinery and the energy embodied in the materials used in construction. These are detailed below.

Machinery energy

Within the JOULESAVE software is a list of typical road construction activity sectors with corresponding energy consumption values on a unit basis. Activity sectors include drainage, services, earthworks, pavements, structures and road markings. Each sector was again sub-divided into items, and a detailed list of machinery used for each item compiled. Empirical data was then collected on each road scheme under consideration to enable a fuel consumption value and typical output rates for each activity sector, and a subsequent 'placement energy' for road construction to be derived.

A unit type approach was also taken for the earthworks. Due to the wide variety of soil and rock types found along different routes a single soil type was not assumed. Instead a classification system was created for the different geomaterials: Type A is a material that can be excavated with an excavator, Type B requires ripping before excavation, and Type C requires blasting before excavation. Again the data used pertaining to the earthworks was collected on site.

Materials energy

The materials energy centres on the energy required in the production of aggregates and bitumen. The production of these materials was observed and data pertaining to their production was sourced from production plants. For the extraction, processing and stockpiling of aggregates the fuel consumed gave a value of 28.38 MJ / tonne of aggregates (Butler, 2006). The energy associated with the production of bitumen equated to 4883 MJ / tonne (Butler, 2006). The quantities of bitumen and aggregates required per kilometre of constructed road then enabled a unit value of energy to be obtained – MJ of energy per kilometre of road.

The aggregate value (0.02838 MJ/kg) is comparable to the ICE embodied energy values which range from 0.01 MJ/kg to 0.50 MJ/kg.

The ICE database reports an embodied energy value for bitumen in the range of between 4.40 MJ/kg and 50 MJ/kg (Hammond and Jones, 2011). The IERD value of 4.883 MJ per kg, is therefore, comparable to the lower ICE value and to the value given by Stripple (2001) of 3.798 MJ/kg. A further bitumen embodied energy value from the European Bitumen Association of 0.51 MJ/kg (Eurobitume, 2011) is available but less comparable to other values obtained.

4.4.3.2 Use energy

To enable the energy in use to be calculated an emission model was required. It was decided early in the project that VETO, developed by the Swedish National Road and Transport Research Institute, would be the model used (Butler, 2006). Other emission models were considered and subsequently revealed to be inappropriate. CMEM was one such model. Although it was found to be a comprehensive emissions model there were three main drawbacks identified:

- CMEM requires significant data input; the type of data that is output by micro-simulation traffic modelling software.
- The CMEM vehicle database is based on the Californian vehicle fleet in 1997.

For the above reasons, the CMEM model was deemed to be unsuitable for the intended purpose.

4.4.3.3 Approach to modelling

Developing, calibrating and validating a micro-simulation transport model for an area of road network can be a lengthy process. However, the output of such a model is necessary input to instantaneous emission models such as CMEM and PHEM – more detail on these model types is provided in Section 4.5.

The following work detailed within this section has been undertaken by Butler (2006) and has been included to demonstrate the approach to modelling used within that research and to highlight the pertinent findings.

VETO is based on instantaneous emission modelling approaches (Butler, 2006). Although VETO does not model the interactions between traffic on sections of the highway, it does make attempts to model the change in vehicle speeds, and hence acceleration and deceleration, required as vehicles move between road sections with different speeds. VETO also estimates the vehicle speeds along horizontal curves; as a function of the speed before the curve and the radius. The speed is assumed to be constant along the length of the curve.

VETO simulates engine power by taking to account all the driving resistances that would occur in real world driving conditions, and is calculated according to:

$$P_{engine\ power} = P_{air\ drag} + P_{acceleration} + P_{gradient} + P_{auxillaries} + P_{transmission\ losses}$$

The power demands for each component, as calculated by the PHEM model, are detailed further in Section 4.5.5. When PHEM is used to calculate emissions it is done so based on actual vehicle data or on simulated data output from micro-simulation traffic models. Although VETO uses a similar approach to calculating engine power, the data that this is based on is input by the user, who is required to provide vehicle data, road data, driving behaviour data, and weather conditions.

The user defines the **road data** by sections, providing the following information:

- Start chainage;
- Road width;
- Speed limit;
- Macro texture
- Gradient;

- Horizontal radius ; and
- Super elevation.

The user is also required to provide the following **vehicle data** for the vehicles using the road sections:

- Frontal area of vehicle;
- Air drag coefficient;
- Vehicle mass; and
- Goal speed – specific desired speeds can be defined for certain speed limits and road widths.

Additionally, the following **driver behaviour data** is required:

- Percentage use of maximum torque
- Gear change decisions – the maximum engine speed that can be reached, the minimum engine speed before a lower gear is required, and the time taken to change gear.
- Deceleration – the deceleration rate at different speed intervals.

The following **weather conditions** are required:

- Wind speed
- Air pressure
- Air temperature

The program calculates energy by calculating the fuel consumed on individual road sections and then aggregating the values to give an overall energy. The data input by the user enables VETO to produce a speed and acceleration profile that in turn can be input into an engine map to give a fuel consumption value.

Only petrol cars, trucks and trucks with trailers were considered in this project, as shown in Table 4.3. A wider range of vehicle types would need to be assessed to understand the effect of different alignments on these.

Table 4.3 IERD vehicles used

Vehicle	Model year	Power (kw)	Gross vehicle weight (kg)	Empty vehicle weight (kg)	Maximum load (kg)	Frontal area (m^2)	Air drag coefficient	Load factor
Petrol car	2005	61	1468	1042	426	4.01	0.33	33%
Truck	2005	193	17900	9000	8900	6.00	0.57	42%
Truck plus trailer	2005	273	32400	13100	19300	8.30	0.50	53%

The IERD project has not considered the effect of the interaction of traffic on the different alignments, with the justification being that if the traffic flow is to be below the road capacity then the interaction should not alter the results significantly.

VETO does consider the effect of horizontal curves on speed; the model recalculates the speed dependent on the speed before the curve and the radius of the curve. However independent studies have shown that vehicle speeds vary along the curve and that speed reduction does not necessarily occur before the curve is entered (Lindqvist, 1991).

4.4.3.4 Results and analysis

The VETO model was run for each alignment for a car, a truck and a truck plus a trailer. Details of the alignments are provided in Table 4.4.

Table 4.4 Details of highways assessed

Route	Road Type	Length (km)
Czech Republic 1	Dual carriageway	16.73
Czech Republic 2	Dual carriageway	16.00
France East	Single carriageway	13.45
France Grand East	Single carriageway	16.60
France West	Single carriageway	12.53
France Grand West	Single carriageway	12.79
Ireland 1	Single carriageway	12.57
Ireland 2	Single carriageway	12.37
Ireland 3	Single carriageway	11.43
Ireland 4	Single carriageway	11.45
Ireland 5	Single carriageway	13.13
Portugal Sol 1	Dual carriageway	15.60
Portugal Sol 1	Dual carriageway	15.90
Sweden	Dual carriageway	5.70

The energy used (MJ/km) for each vehicle is shown graphically in Figure 4.9. The energy used by cars is consistent across all routes. However, much greater variations are apparent with the truck and truck plus trailer vehicles.

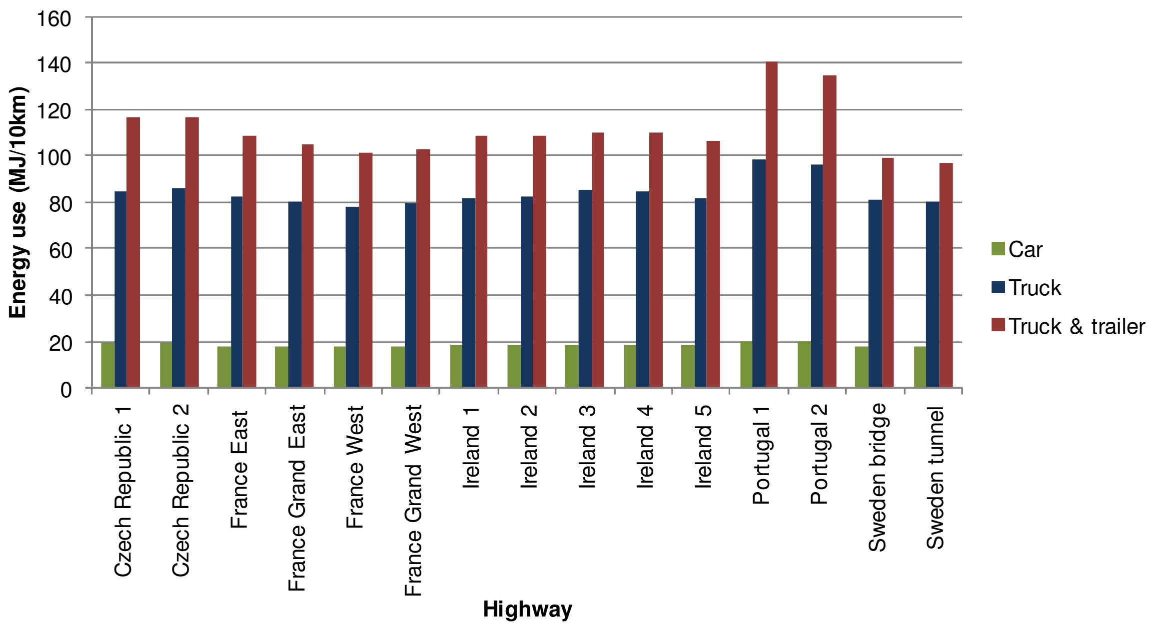


Figure 4.9 Energy use by vehicle type on all highways (based on data from Butler (2006))

4.4.3.5 Effect of geometry

To understand the impact the horizontal alignment has on the energy use, the relationship between the Average Degree of Curvature (ADC) and the energy consumed was analysed. Figure 4.10 shows the impact of varying ADC on the energy consumption of the car – demonstrating a minor impact on energy with increasing ADC values.

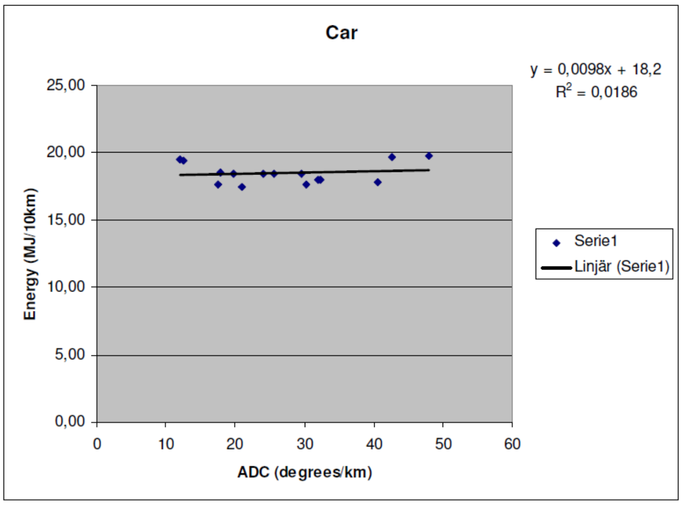


Figure 4.10 Impact of ADC on energy consumption of car (taken from Butler (2006))

For the truck and trailer vehicle, shown in Figure 4.11, again there is no real correlation between the ADC and energy consumption; and the study concluded that for both the car and truck the ADC is of minor importance.

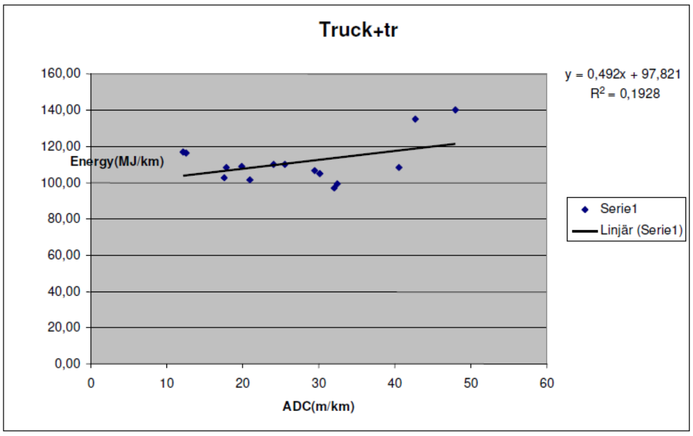


Figure 4.11 Impact of ADC on energy consumption of truck and trailer (taken from Butler (2006))

To further understand the impact of geometry, specifically the vertical alignment, the Rise and Fall (RF) was considered against the energy consumed – as shown in Figure 4.12 for a car and Figure 4.13 for a truck with trailer. Both figures show a good correlation between RF and energy. For the car in Figure 4.12 the increase in energy from an RF of 10m/km to 40m/km is around 24%, whereas for the truck and trailer this increase is around 38%. The RF, and hence vertical alignment, was concluded to be of major importance, more specifically for the heavier vehicles.

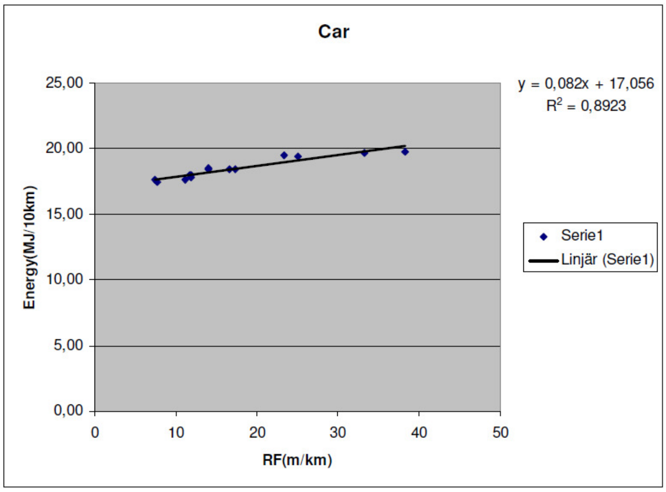


Figure 4.12 Impact of RF on energy consumption of car (taken from Butler (2006))

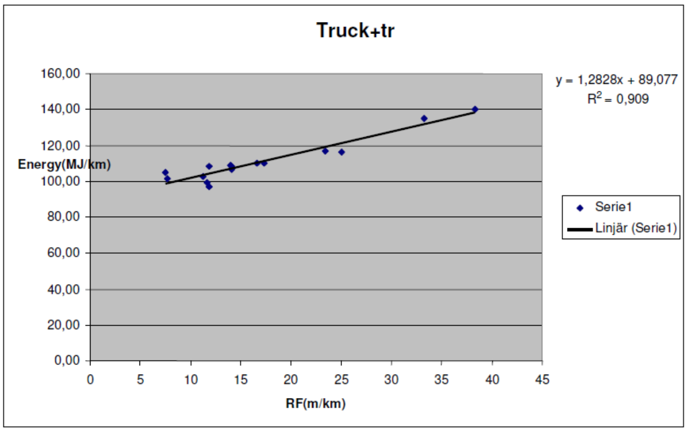


Figure 4.13 Impact of RF on energy consumption of truck and trailer (taken from Butler (2006))

Butler (2006) selected five routes to undertake an extreme analysis on; in which the horizontal curves were removed to achieve a straighter alignment. The modified horizontal alignments were normalised to the original horizontal alignments, as shown in Figure 4.14. The effect is more noticeable on the truck and truck with trailer vehicles, with the car being less affected. However, the effect is small; with the maximum reduction in energy consumed being 4.2%.

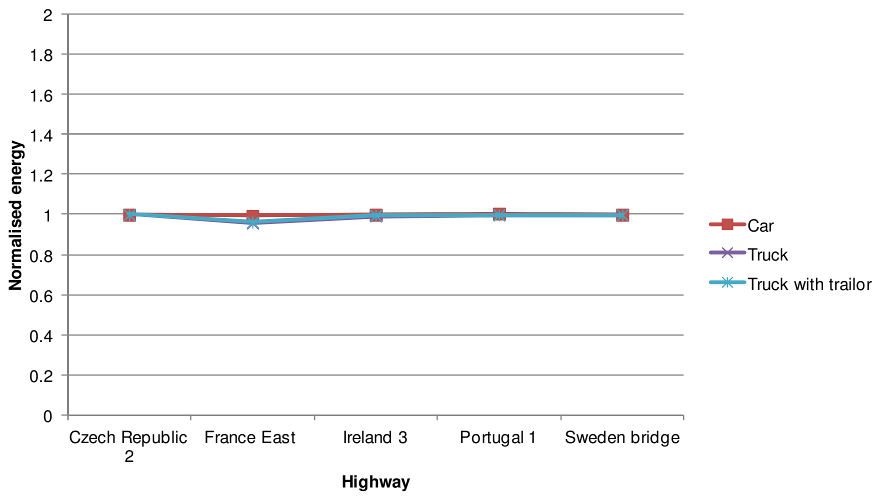


Figure 4.14 Energy for straight alignments normalised to original horizontal alignments (based on data from Butler (2006))

A further analysis was undertaken; eliminating all the vertical curves to effectively achieve a level highway. The modified vertical alignments were normalised to the original vertical alignments, as shown in Figure 4.15. The effect is more noticeable on the truck and truck plus trailer vehicles, with the car being less affected. However, all of the modified alignments (level alignments) resulted in a decrease in energy consumed.

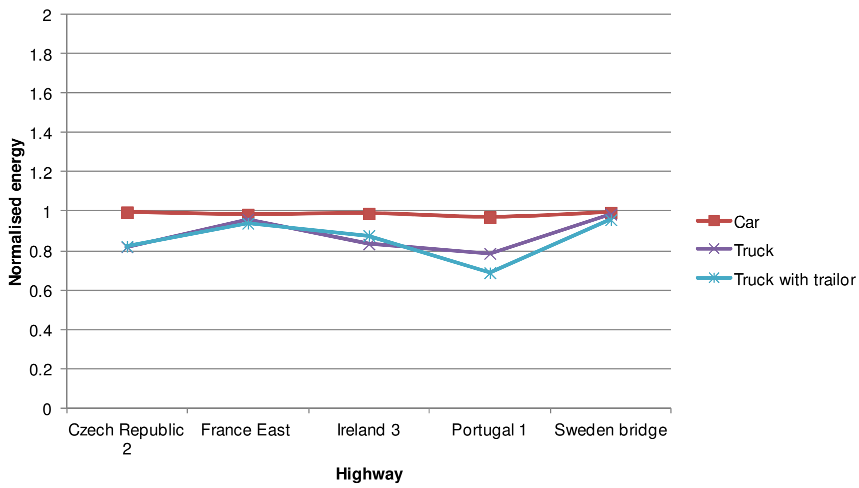


Figure 4.15 Energy for level alignments normalised to original vertical alignments (based on data from Butler (2006))

4.4.3.6 Route selection and optimisation

Within the final project report (Butler, 2006) the ability of the JOULESAVE program to demonstrate the potential energy savings between different route options for a particular highway scheme is shown through scheme examples. One particular example is the N25 Bypass scheme in Ireland; showing the nine potential routes and the 11% savings in energy attainable if the lowest energy consuming route is selected (Butler, 2006).

Within the study an attempt was also made to optimise the vertical alignment of the N25 Dungarvan Bypass; which has a steep gradient at one section. The vertical alignment at the section was amended from the original 6% alignment to 5%, 4% and 3% gradients. It was understood that such shallower alignments would require larger earthworks operations, and the aim of this exercise was to understand whether the additional energy expended in construction would lead to significant savings over the lifetime of the road. The results of this exercise are shown in Figure 4.16, which shows the construction energy, the use energy from the vehicles using the highway between the years of 2010 and 2029, and the vehicle efficiencies per km.

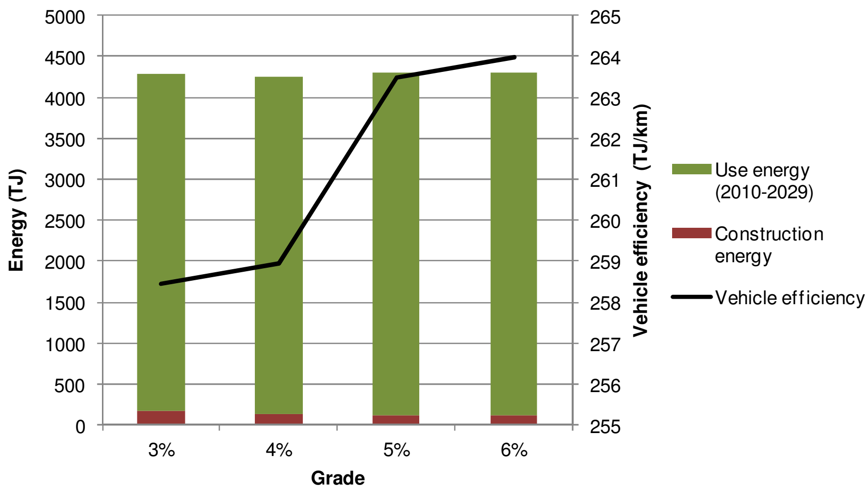


Figure 4.16 The construction energy, the use energy from the vehicles using the highway between the years of 2010 and 2029, and the vehicle efficiencies per km (based on data from Butler (2006))

When the use energy is considered alone there is a 0.2%, 1.9% and 4.1% saving from the 5%, 4% and 3% gradients respectively. Therefore, for the more level highway there are greater energy savings resulting in the use phase. This is reflected by the decrease in vehicle efficiencies as the gradient increases, with more energy required to overcome a steeper gradient. No explanation is offered as to why the efficiencies at 3% and 4% are similar, and also at 5% and 6%.

When the total energy is considered, i.e. when the construction is incorporated, the savings in energy are 0.3%, 1.3% and 0.6% from the 5%, 4% and 3% gradients respectively. The savings do not increase with decreasing gradient due to the construction energy for the 6% gradient being higher than for the 4% gradient; however, no explanation is given for this result.

The final report concludes that:

> *[E]nergy savings could be made in the operation of a road and, to a lesser extent, in the construction of a road. Evaluation of the energy implications of a scheme during the design stages could lead to significant savings over the life of a road.*
>
> (Butler, 2006)

JOULESAVE is recommended to understand both the construction and use energy for different route options and also to optimise the selected route in terms of its vertical alignment. The construction energy results from empirical data collected during the project duration. However, the use energy results from the use of the VETO emission modelling program which is not transparent.

4.5 Review of emission modelling

4.5.1 Types of emission model

Vehicle emission levels are dependent on numerous factors, including: vehicle type, engine size and technology, fuel type, weight, operation and the gradient at which the vehicle is operating on.

Numerous models that attempt to replicate vehicle emissions are available; these vary with the scale of application, the approach to the emission calculation and the input data required. The main model types, which are described in more detail below, include:

- Emission factor
- Average speed
- Modal
- Traffic situation
- Instantaneous

4.5.1.1 Emission factor

A simple approach to emission modelling that uses general emission factors for particular vehicles and driving types, usually presented in terms of an emission per unit distance e.g. grams per kilometre. The emission factors are derived from measurements from various vehicles that are monitored over specific drive cycles to give representative factors. In the absence of detailed data, or for use at a large geographical scale, emission factors are appropriate. Such an approach neglects detailed vehicle operation, or even detailed road link information, yet can be used to provide indicative values.

4.5.1.2 Average speed

Average speed models assume that emissions vary with the average speed of a specific trip for a certain vehicle type. The average speed methodology can be used to attain an emission value on an individual trip basis (using data on the trip length and average speed) or road link basis (using data on the speeds of all the vehicles on the link, to calculate an average link speed, and the link length). Figure 4.17 shows a typical emission curve using an average speed approach.

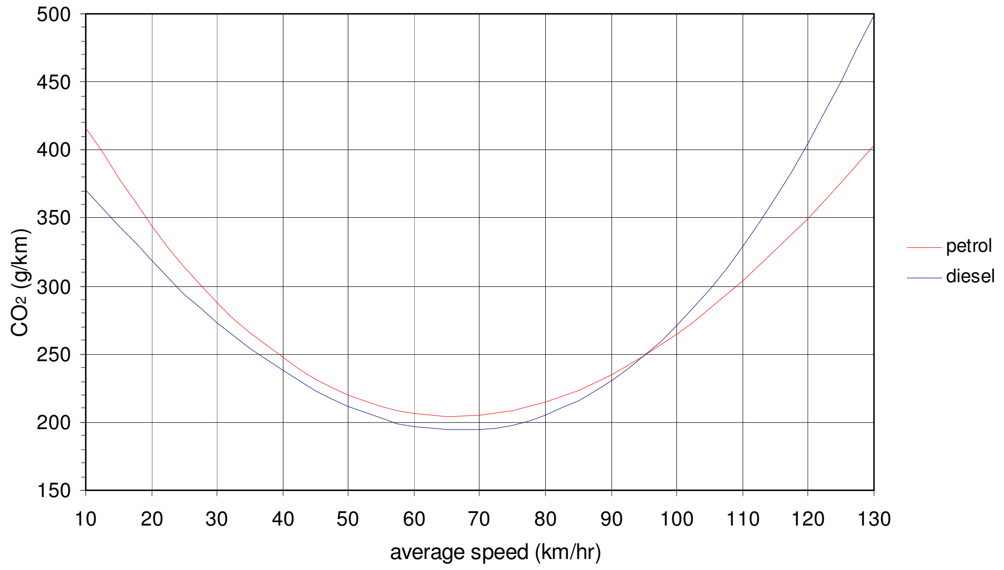


Figure 4.17 CO_2 emissions for LGV using the DMRB average speed approach

From studying the curve the limitations of the approach are apparent, due to awareness that:

- No two drive cycles will be the same – with varying periods of operational states resulting in varying emission levels. Therefore, to assume that a certain speed will have a set emission value is flawed.
- It is misrepresentative to assume an average speed on a road link that will be used by many vehicles at many different speeds with differing driving behaviours.

Average speed modelling is widely used due to the wide availability of the necessary inputs and its ease of use in terms of time and cost resources. They are deemed suitable for large-scale applications such as regional and national emission inventories, yet they have been used not always appropriately in a much wider range of applications (McCrae *et al.*, 2006). Particularly in situations which have resulted in significant changes in driving behaviour; with the coarse average speed modelling approach unable to detect the resultant variation in emissions.

To understand the impact of local pollutant emissions from vehicles resulting from a highway scheme, air quality assessments are undertaken in accordance with the guidance in the DMRB, which also adopts an average speed approach to emission modelling.

4.5.1.3 Modal

Modal models attempt to consider the different modes of vehicle operation in their calculation – these are steady state, acceleration, deceleration and idling. Similar to an average speed approach, an emission is calculated dependent on the average speed and also according to the specific mode that it is operating in.

Modal models are an improvement on average speed modelling at a local-scale, as they take into account different operating conditions on road links, albeit at a macro-scale, and therefore provide more refined emission estimations.

4.5.1.4 Traffic situation

This model type uses both changes in speed and operating condition to estimate emissions for different traffic situations. The traffic situations relate to traffic scenarios with emission issues that are known by the user. The use of such models is heavily dependent on the user and how they define a traffic situation, which in turn is a function of traffic speed, volume and the operation. A widely used European traffic situation model is the Handbook of Emission Factors (HBEFA, 2009) - containing emission factors for a representative sample of vehicles with correction factors to adjust for: cold-starts, gradient, altitude, driving conditions and vehicle age. Traffic situation models offer further refinement to average speed and modal models yet are reliable on the subjectivity of the user in defining traffic situations, for which universal definitions are not available.

4.5.1.5 Instantaneous

Instantaneous models provide a more precise description of a vehicles operation and the associated emissions. In essence, the emissions and fuel consumption are calculated for individual vehicles with unique drive cycles by relating emission rates to instantaneous speed and acceleration on a second-by-second basis. Recent advances in instantaneous models have also enabled the effect of gradient to be taken into account in the calculation of emissions. Engine maps are used within the model, derived from real-world tests, to relate the instantaneous speed and acceleration to emission values. Figure 4.18 presents an example of an engine map derived by Barlow (1999) using data collected from a ‘modern petrol car’ when in operation on the M25 motorway. An engine map allows an emission to be derived using the vehicle speed and acceleration as input data. The instantaneous speed (measured in m/s) and instantaneous engine load factor (the product of the speed and acceleration measured in m^2/s^3) can be used to obtain the instantaneous fuel consumption of the vehicle travelling in these conditions at any given second.

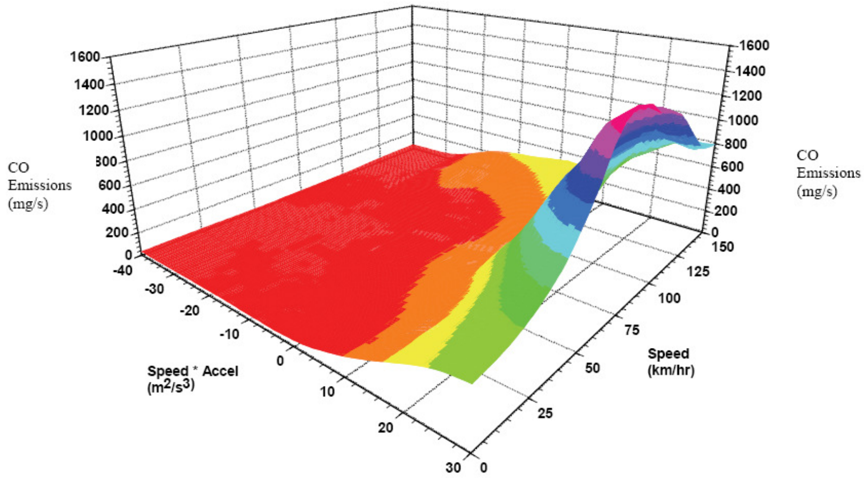


Figure 4.18 Engine map showing CO Emissions for a 'modern petrol car' (Barlow, 1999)

In theory such models can accurately model vehicle emissions as they have the ability to consider individual drive cycles and assign an emission dependent on a vehicles operation at every second. It is however, with its limitations, due to the difficulty in measuring emissions on a continuous basis with a high degree of precision whilst allocating them to the correct operating conditions that created them (McCrae *et al*., 2006). The reason for this is due to (1) the time that is taken to transport the exhaust gases to the analysing equipment resulting in a time lag, and (2) the mixing of gases in the exhaust system resulting in a dampening of the emission peaks.

The main drawback of instantaneous models is the detail of the input data required; with temporal operational vehicle information being the necessary input - which is time consuming, costly and difficult to collect. A solution to this is the use of micro-simulation traffic models that can replicate and output the detailed vehicle movements required by instantaneous emission models.

4.5.2 Recommended model type

The purpose of this research was to understand the influence of vertical and horizontal alignment on the life cycle CO_2 emissions of highway infrastructure. Therefore, to model the use emissions an emission model is required that is considered to be the most accurate in its approach and data. Fundamentally however, the model must consider the influence of gradient on the emissions of a vehicle. This review of all the emission models currently available has indicated that an instantaneous emission model is suitable for the research.

In the previous section, the difficulties of allocating the correct emission value to the operational condition that produced it in laboratory measurements were briefly discussed, with the emission being damped and delayed. In certain instantaneous models the time delay is addressed by shifting the data back by a fixed time value to realign the emissions with the correct operating condition; however Weilenmann *et al*. (2002) demonstrated that this delay is not constant and can vary depending on the gas flow rate in the exhaust. Therefore, simply shifting the emission signal by a fixed value can result in model inaccuracies, yet such an approach does at least attempt to address the issue. Such models were termed 'adjusted' by Boulter *et al*. (2006) to reflect the adjustments made to the emissions in response to these issues.

This section provides an overview of the instantaneous emission models that are available for use and that relate vehicle emissions to highway gradient. The models discussed are CMEM (Comprehensive Modal Emissions Model) and PHEM (Passenger car and Heavy-duty vehicle Emissions Model).

CMEM

CMEM was developed in the 1990s for the National Cooperative Highway Research Program (NCHRP) and the United States Environmental Protection Agency (EPA). Being an instantaneous emission model it calculates emissions and fuel consumption based on different operational conditions across a range of US specific vehicle types. For this reason it is not appropriate for use in countries that are regulated by European Union (EU) emission standards. The car categories are 'no catalyst', 'two-way catalyst' and 'three-way catalyst'. Therefore, in order to use this model in the EU an exercise would have to be undertaken to relate the CMEM vehicle categories to the corresponding EU categories. Were this successfully undertaken, for other reasons including different design standards, emission controls and a preliminary assessment of the model that identified unrealistically high emission factors, Barlow *et al*. (2007a) concluded that the use of CMEM in Europe cannot be recommended.

PHEM

PHEM is the product of late nineties European funding (COST [3] and ARTEMIS) for research conducted by TUG, Graz, Austria to expand the database of European HGV instantaneous emission characteristics, and to improve the methodology for estimating emissions and fuel consumption. The engine power is simulated on a second-by-second basis based on the driving resistances and transmission losses. The engine speed is calculated from the transmission ratios, wheel diameter and gear shift rules from the measured test cycle. The results are engine maps that relate instantaneous engine speed and load (speed *x* acceleration), with correction functions for transient operations (such as gear changing). Figure 4.19 shows a schematic diagram of the PHEM model.

3 European Cooperation in the field of Scientific and Technical Research (COST) 346 project

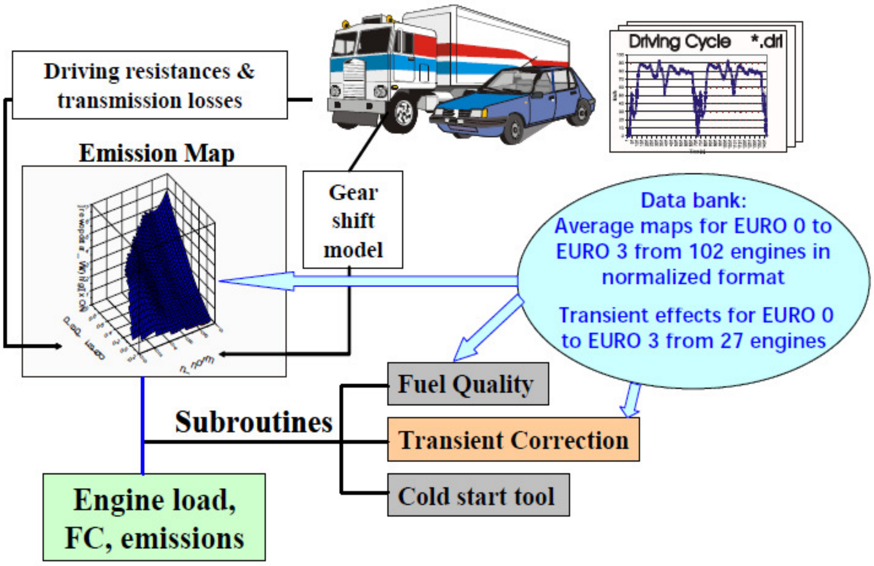


Figure 4.19 Schematic picture of PHEM model (from COST (2006))

HGVs were the original focus of this research, using the common methodology of measuring HGV engine emissions on engine test beds. PHEM was subsequently extended to include passenger cars following the development of a method to derive engine maps from engines and emission measurements, using the common methodology of measuring car engines on a chassis dynamometer.

4.5.3 Model selection

According to Barlow *et al.* (2007b), PHEM is a state-of-the-art emission factor model that is flexible; the user can define vehicle characteristics in detail, with the vehicles complying with European emission legislation. Boulter *et al.* (2007) conducted a comprehensive review of the instantaneous emission models available for the estimation of emissions (in practice these were CMEM, MODEM[4] and PHEM), and concluded that the model that is most relevant to modern European vehicles is PHEM.

4.5.3.1 Accuracy of PHEM

An evaluation of the pertinent instantaneous emission models was undertaken on behalf of the Highways Agency (HA) by the Transport Research Laboratory (TRL) to determine their suitability for wide-scale use (Barlow *et al*., 2007b). The two models under scrutiny were PHEM and MODEM, with an additional provisional evaluation of CMEM.

To determine the accuracy of these models, four comparisons were undertaken using the following:

- Laboratory measurements

[4] A comprehensive instantaneous emission model excluded from this review due to it not accounting for gradients in its emission calculation

- On-board measurements
- Results from the inversion of an air pollution model
- Air quality measurements in the Hatfield tunnel

The assessments are described in more detail below.

Laboratory measurements

The speeds used for previous laboratory tests were input into PHEM, with the modelled outputs compared to the laboratory measurements. The results showed that the majority of values were underestimated by PHEM, yet PHEM gave close estimates of CO_2[5] and fuel consumption – with CO_2 being within 20% of the measured values in most cases, which is considered to be very accurate (Barlow *et al.*, 2007b).

Comparisons with on-board measurements

The driving cycle measured from on-board a Euro III petrol car was input into PHEM, with the modelled results compared to the on-board measurements. Similar to the laboratory measurements there was a very good agreement with the on-board fuel consumption data and PHEM (Barlow *et al.*, 2007b).

Inversion of air pollution model and measurements from Hatfield tunnel

An approach to determine the emission factors for vehicles is to invert an air pollution prediction model. A non-inverted model would use data on vehicle flows, types, speeds and emission factors in combination with meteorological conditions and air dispersion techniques to predict the concentration of a pollutant at a receptor point. The inversion of such a model uses known pollutant concentrations, meteorological conditions, vehicle flows, types and speeds to arrive at an emission factor. Errors are associated with the inverse modelling approach and further refinements are required to ensure the results are reliable and comparable. The Hatfield tunnel was used in this assessment (Barlow *et al.*, 2007b), where measurements were much lower than the values predicted by PHEM and any advantages of using an instantaneous emission model for such a detailed air quality exercise were not identified.

4.5.4 Final recommendation

Extensive studies have been undertaken that demonstrate the capability of the PHEM model in replicating measured CO_2 emissions from real-world tests and therefore its ability to predict emissions from theoretical input data. Assessments have concluded that MODEM is as equally good as PHEM at predicting emissions from light-duty vehicles in a European setting, despite its maturity and the assumptions used for modern vehicles. Table 4.5 summarises the capabilities of the three models discussed in this chapter.

[5] PHEM does not calculate CO_2 directly – it is calculated using the carbon balance equation detailed in Directive 93/116/EC

PHEM is, however, the preferred model choice for this research, as unlike MODEM it calculates emissions using the imperative factors of gradient and vehicle load. Additionally, PHEM is an 'adjusted' model that attempts to account for the affect of time lag and damping.

Finally, an important consideration, that has not previously been discussed, is the production of input data that is appropriate for the PHEM model. The drawback of instantaneous models has been highlighted; due to requirement of detailed input data on which the emission calculations are based. A solution to this problem is to use micro-simulation traffic models to replicate vehicle movements and utilise the output data from such models as the input data to PHEM.

Table 4.5 Comparison of capabilities of instantaneous emission models

Model	***MODEM***	***CMEM***	***PHEM***
Location	Europe	US	Europe
Vehicle types	Petrol cars Diesel cars	Normal-emitting cars (12 classes) High-emitting cars (5 classes) HGVs (9 classes)	Petrol cars Diesel cars Rigid HGVs (8 classes) HGV (6 classes) Coaches (2 classes) Buses (3 classes)
Euro emission standards (cars)	pre-Euro I to Euro I	*US classifications*	pre-Euro I to Euro IV
Euro emission standards (HGVs)	-	-	pre-Euro I to Euro V
Pollutants			
Carbon monoxide (CO)	✓	✓	✓
Hydrocarbons (HC)	✓	✓	✓
Oxides of Nitrogen (NOx)	✓	✓	✓
Carbon dioxide (CO2)	✓	✓	
Fuel consumption	✓	✓	✓
Inputs			
v(t)*	✓	✓	✓
gradient		✓	✓
full-load curve			✓

** v(t) = driving pattern (vehicle speed as a function of time)*

Boulter *et al*. (2007) investigated the instantaneous emission models that are linked to micro-simulation transport models. At the time of publishing the paired models that were available, and ready to use with no further integration of the models necessary, were VISSIM[6]-MODEM and Paramics-MODEM. VISSIM was twinned with PHEM for a project led by RPS consultancy (and commissioned by the HA) – only for a trial assessment, with the combined models not becoming commercially available afterwards.

In October 2008, a version of S-Paramics was released by SIAS that included a PHEM post-processor, enabling vehicle movements to be modelled within the software with the subsequent outputs being suitable for input to a PHEM based post-processor. The post-processor is described in the following section.

[6] VISSIM is a commercial micro-simulation traffic model developed by PTV, Germany

4.5.5 PHEM post-processor

The developers of S-Paramics, SIAS, have incorporated PHEM into their software and have tailored the incorporation to UK fleet statistics (Defra, 2002). The S-Paramics post-processor tool generates individual vehicle trip emissions using S-Paramics outputs and Instantaneous Emissions Modelling (IEM) data tables from TRL. This is combined with UK vehicle fleet composition projections from the National Atmospheric Emissions Inventory (NAEI) and HGV vehicle proportions from the D*f*T (SIAS, 2009). The user can therefore use the default fleet values to extract emissions from a large traffic model. Alternatively, the S-Paramics post-processor provides the user with the option of amending the vehicle fleet to their specification.

SIAS also developed the emission software referred to as AIRE (Analysis of Instantaneous Road Emissions) which was released in June 2011. The software is the same as the previously referred to post-processor, requiring the same input data and producing the same output.

The set-up of the PHEM post-processor is shown schematically in Figure 4.20. The input to the post-processor (the output from Paramics) is speed, acceleration, vehicle ID and gradient – all allocated to a specific time stamp. This information is processed through the PHEM engine maps, to provide an emission output for the various emissions.

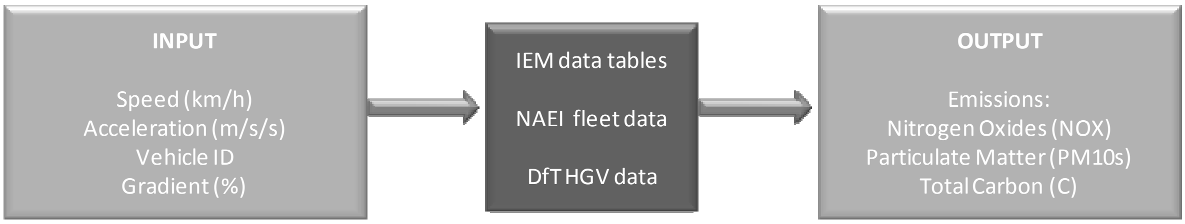


Figure 4.20 Schematic of S-Paramics post-processor

The main vehicle types (car, LGV and HGV) and the sub-categories that are considered in the PHEM IEM tables are shown in Table 4.6 to Table 4.8. For each vehicle type the available engine sizes, load categories and Euro emission standards are shown.

Table 4.6 Types of car included in PHEM

Fuel type	Engine size	Load	Euro standard
Petrol	< 1.4 l	unladen half-laden fully-laden	Pre Euro I Euro I Euro II Euro III Euro IV
	1.4 - 2.0 l		
	> 2.0 l		
Diesel	< 2.0 l		
	> 2.0 l		

Table 4.7 Types of LGV included in PHEM

Fuel type	Engine size	Load	Euro standard
Petrol	one size	unladen half-laden fully-laden	Pre Euro I Euro I Euro II Euro III Euro IV
Diesel			

Table 4.8 Types of HGV included in PHEM

Fuel type	HGV type	Weight	Load	Condition	Euro standard
diesel	rigid	3.5-7.5t	unladen half-laden fully-laden	urban rural motorway	Euro II Euro III Euro IV
		7.5-12t			
		12-14t			
		14-20t			
		20-26t			
		26-28t			
		28-32t			
		over 32t			
	artic	14-20t			Euro IV Euro V Euro VI
		20-28t			
		28-34t			
		34-40t			
		34-40t			
		34-40t			
		40-50t			

4.5.5.1 PHEM emission calculation

Fuel consumption and emissions are interpolated from engine maps for each second of a vehicle's journey. In order to undertake this interpolation the engine speed and actual engine power demand must first be known. The engine speed is calculated using the transmission ratios and a gear shift model. The power required is the total of the power to overcome rolling resistance and air drag, to accelerate, to overcome changes in gradient, to power auxiliaries and the power lost in transmission:

$$P_{required} = P_{rolling\ resistance} + P_{air\ drag} + P_{acceleration} + P_{gradient} + P_{auxillaries}$$

The rolling resistance is the power loss at the wheels, and is considered according to:

$$P_{rolling\ resistance} = m \cdot g \cdot (f_{r0} + f_{r1} \cdot v + f_{r2} \cdot v^2 + f_{r3} \cdot v^3 + f_{r4} \cdot v^4) \cdot v$$

Where m = curb-mass of the vehicle

g = gravitation coefficient

f_{ro}...f_{r4} = rolling resistance polynomial coefficients

v = vehicle speed

The rolling resistance polynomial coefficients are usually very small and hence the rolling resistance is proportionate to velocity, with the resistance increasing with increasing speed. Evidently the rolling resistance would also increase with a higher vehicle mass.

The power to overcome the air drag on a vehicle is calculated as:

$$\boldsymbol{P_{air\ drag} = c_d \cdot A_f \cdot \frac{\rho}{2} \cdot v^2 \cdot v}$$

Where

c_d = air drag coefficient

A_f = frontal area of vehicle

ρ = air density

$f_{ro}...f_{r4}$ = rolling resistance polynomial coefficients

v = vehicle speed

From the above equation it is apparent that the power required to overcome the air drag is proportionate to v^3. Therefore at lower speeds the power required is small, with the power required increasing significantly at higher speeds.

The acceleration is the power required when the vehicle's speed changes, or when the rotational speed of the power train's rotating components change. The power required to do this is calculated according to:

$$P_{acceleration} = m \cdot \frac{dv}{dt} \cdot v + \sum_i \Theta_i \cdot \frac{d\omega_i}{dt} \cdot \omega_i$$

Where:

m = curb-mass of the vehicle

v = vehicle speed

Θ_i = moment of inertia of component *i*

ω_i = angular speed of component *i*

On a graded road, the power required to change altitude is calculated according to:

$$P_{gradient} = m \cdot g \cdot \underbrace{\frac{dh}{dt}}_{=s \cdot v}$$

Where:

m = curb-mass of the vehicle

v = vehicle speed

g = gravitation coefficient

h= altitude

s = road gradient

The power requirement varies at different speeds for different road gradients. The steeper the gradient is, a greater amount of power is required - with the power requirements also increasing as speed increases.

The power for auxiliaries is for the additional equipment on a vehicle that requires power e.g. electrical, pneumatic and hydraulic devices, and air conditioning. Auxiliaries can require a varying amount of power; however, it is common to assume a constant power value. For example, for a 34-40tonne HGV, the auxiliary power parameter set in PHEM is taken to be 3.8% of rated engine power.

4.5.5.2 Applicability of PHEM

The PHEM instantaneous emission model can output a range of emissions based on a range of gradients (from -6% to 6%) and based on speeds of up to 200 kph. The validity of these emission values at such high speeds is questionable, especially for large heavy vehicles traversing steep gradients. Hassel and Weber (1997) derived fuel consumption correction factors for different vehicle types operating on gradients between -6% and 6%, with the correction factors only being applicable across specific speed ranges, these are shown in Figures 4.4 and 4.5. For light duty vehicles, the factors were valid up to 125 kph for the +2% gradient, and up to 120 kph for the +4% and +6% gradients. For the heavy duty vehicles the factors were valid for speeds up to 65 kph, 45 kph and 40 kph for the +2%, +4% and +6% gradients respectively (Hassel and Weber, 1997).

To understand the validity of PHEM across the speed range its output has been compared to the emission values output using the methodology given in WebTAG, shown in Figure 4.21a. The WebTAG emissions do not take into account the gradient and hence have been compared to PHEM emissions that have been calculated using a 0% gradient. The PHEM diesel car emissions seem reasonably consistent with the WebTAG diesel car emissions, yet at the higher speeds the WebTAG approach reports increasingly higher emissions. The PHEM petrol car emissions are again consistent with the WebTAG petrol car emissions; however, at approximately 130 kph the WebTAG emissions decrease with increasing speed.

For the Articulated HGV, shown in Figure 4.21b, the WebTAG emissions are higher than the PHEM emissions across all load cases. The WebTAG emissions begin to decrease at 100 kph; a similar pattern occurs with the PHEM emissions between 110 and 120 kph depending on the load case. The

Rigid HGV, in Figure 4.21c, shows a similar decrease for both the WebTAG and PHEM emissions after certain speeds, with the WebTAG emission values being higher than the emissions reported by PHEM.

It is apparent from Figure 4.21 that the PHEM post-processor will accept any speed as input and provide an emission as output. At higher speeds these emissions are likely to be inaccurate and therefore cannot be used. There is confidence that the PHEM model can output a valid emission value up to the maximum speeds shown in Table 4.9, and therefore subsequent assessments have not used speeds higher than those presented. These speeds were determined through examination of the speed-emission profiles of the different vehicle types operating on the varying gradients – when the emissions began to demonstrate abnormal patterns (i.e. decreasing with increasing speeds) the maximum valid speed was taken to be the final speed before this pattern started to occur.

In the following tables and figures UL refers to unladen, HL refer to half-laden and FL refers to fully-laden.

Table 4.9 Maximum speeds for use with PHEM for different vehicles types on varying gradients

Vehicle	Maximum valid speed (kph)		
	+2%	+4%	+6%
Petrol car	160	155	145
Diesel car	140	130	120
LGV	135	125	110
Rigid HGV UL	100	90	80
Rigid HGV HL	90	80	70
Rigid HGV FL	85	75	65
Artic HGV UL	100	100	90
Artic HGV HL	95	75	55
Artic HGV FL	80	55	50

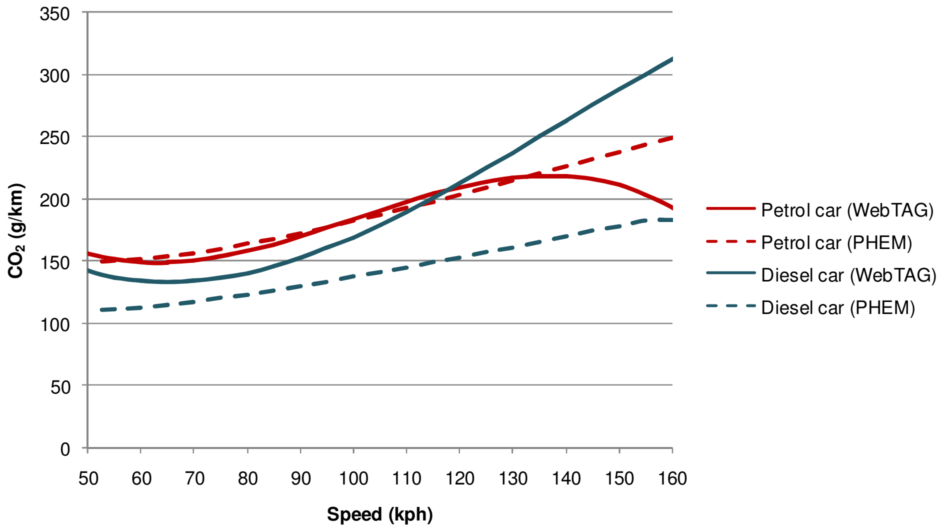


Figure 4.21a Comparison of PHEM and WebTAG emission values for petrol and diesel car

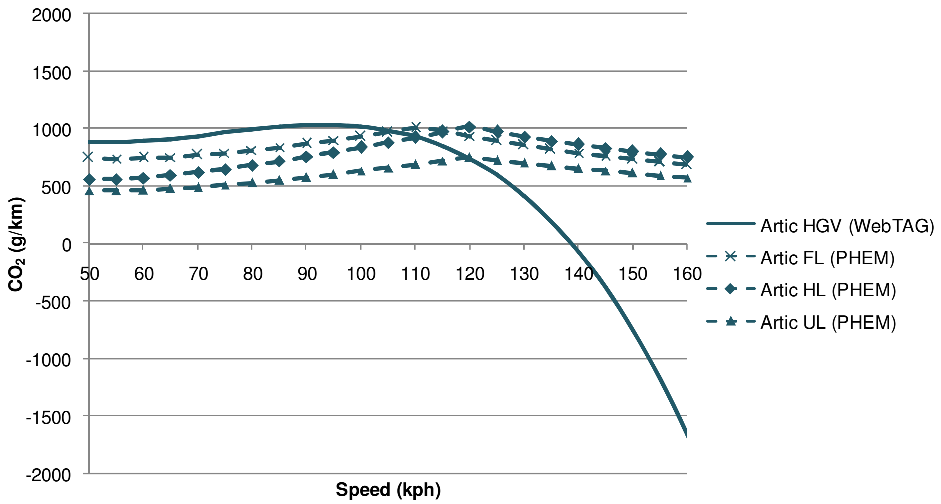


Figure 4.21b Comparison of PHEM and WebTAG emission values for Articulated HGV

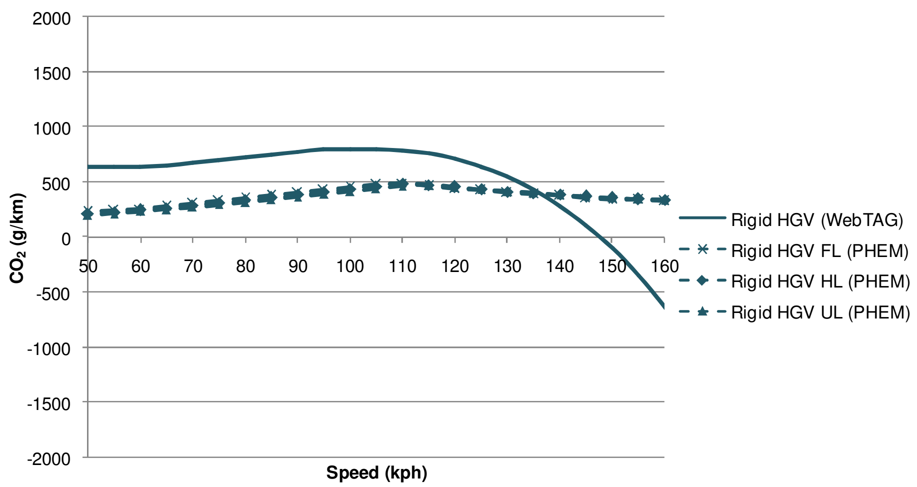


Figure 4.21c Comparison of PHEM and WebTAG emission values for Rigid HGV

4.6 Current approach to UK highway alignment

The WebTAG Unit 3.3.5 (DfT, 2011) states that carbon emissions should be considered in terms of the change in the equivalent tonnes of carbon released as a result of implementing a highway scheme. Carbon emissions are estimated from fuel consumption in the 'without scheme' and 'with scheme' scenarios. Changes in carbon emissions for the opening year and over the whole appraisal period, as well as the monetary value for carbon emissions over the whole appraisal period are calculated.

The economic assessment suggested by DMRB for new highway schemes, is COBA (DfT, 2011); this attempts to enable the effect of adopting a steeper gradient to be understood in terms of the economic trade-off between construction and environmental cost savings, and the disbenefits to traffic.

The COBA (COst Benefit Analysis) program, developed by the Transport Research Laboratory (TRL) on behalf of the Department for Transport (DfT), is used in the appraisal of trunk road and highway schemes in the UK (with the exception of Scotland). COBA compares the cost of road schemes with the benefits gained by the road user in terms of time, vehicle operating costs (VOC) and accidents, with the results being expressed in monetary terms.

Transport projects are usually proposed to bring improvements to the areas of environment, economy, safety, accessibility and integration. The measured outputs from COBA relate to these areas: economic objectives are measured in terms of changes to journey-time and VOC; safety objectives are measured in terms of changes in accident costs and casualties; and environmental changes are measured in terms of the changes in the amount of fuel used (and hence CO_2 emissions). Figure 4.22 demonstrates the basic principles behind COBA for highway schemes.

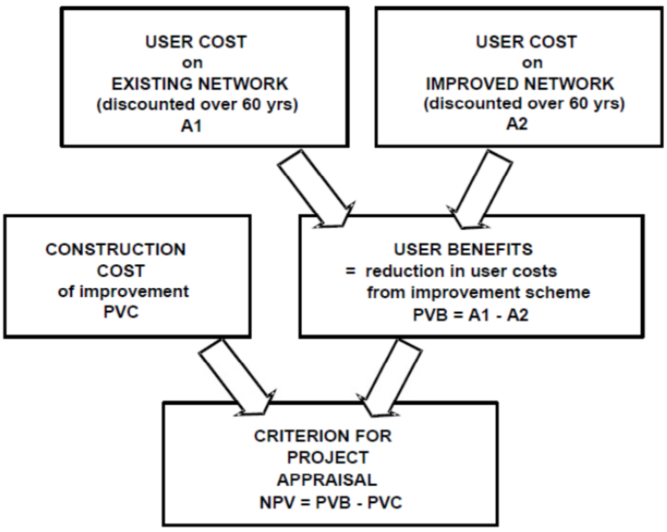


Figure 4.22 Basic principles of COBA (from Highways Agency, 2002)

In summary, the COBA assessment is focused upon the economic benefits and disbenefits associated with new highway schemes. To provide a common denominator for comparison, and to ensure carbon emissions associated with new schemes are incorporated into the assessment, these are also translated into monetary values. The carbon emission components recommended for consideration in COBA are the emissions from the use phase, with the carbon related to the construction yet to be considered.

As the alignment of a highway changes the characteristics of the vehicles using it will vary. COBA takes this into consideration when calculating the benefits of highway schemes, by requiring a detailed geometric description of the study network – the road links and junctions.

The emission calculation that is undertaken in the COBA program is based on an average link speed, which is a function of a number of parameters including Bendiness and Hilliness. A detailed description of the calculation can be found in Appendix B.

COBA uses the guidelines set out in DMRB to calculate the fuel consumed based on an average link speed, which is subsequently converted into CO_2 emissions, the formulae for which is shown in Section 2.3.1. Figure 4.23 shows the DMRB emissions curve for carbon (converted to represent CO_2) for petrol and diesel cars (using data from DMRB, 2007). At each speed (v), the fuel consumption can be calculated using the appropriate parameters for the vehicle type under consideration.

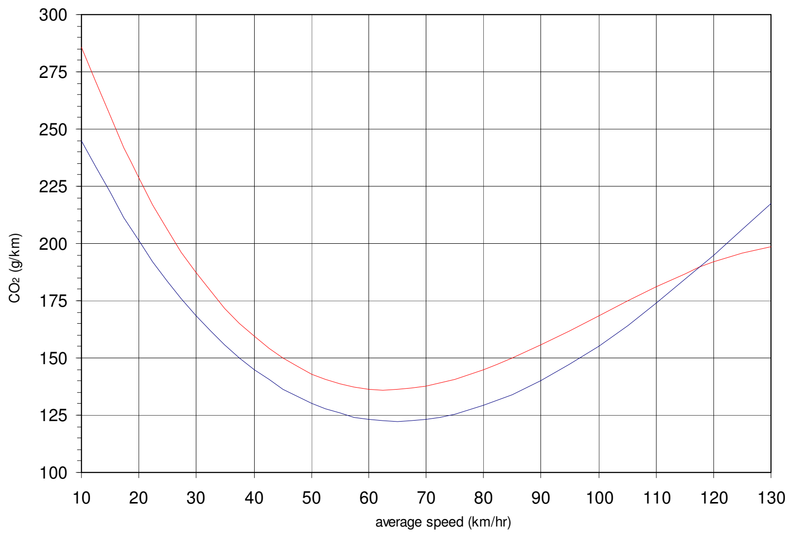


Figure 4.23 Petrol (red) and diesel (blue) car CO_2 emissions using the DMRB procedure

Using an average speed approach to emission modelling is practical as it requires only basic information about the traffic on a road link – speed, vehicle type and flow. However, as the speed is averaged it can offer no differentiation between different drive cycles and can often underestimate or overestimate emissions. Average speed modelling is recognised as an unsuitable approach in certain circumstances yet it is recommended as it complements the data that is often available (TRL, 2006).

For any given average speed there is likely to be a significant variation in the total fuel consumption due to the different combinations of instantaneous speed and engine load represented by each drive cycle. A variety of driving patterns could equate to a single average speed, with each drive cycle having a unique emission value associated with it. Research has been undertaken into the possible variations associated with average speeds, with various emissions resulting from a two mile trip at an average speed of 25mph. The best fuel consumption achieved was 81.8 miles per gallon, compared to the worst at 24.3 miles per gallon (McGordon, 2009).

The equations prescribed by COBA (in Appendix B) for the calculation of speed on links take into account the hilliness and bendiness of a road. Put simply, the presence of hills and bends result in a reduction of the link speed. It is known, from previous research, that a change in the vertical alignment of a road will impose a greater load on a vehicle engine on the inclined section and a smaller load on the declined section. If a vehicle's speed was 90kph on a flat road and this was subsequently corrected to account for the hilliness and reduced to 70kph, it is apparent from considering the above emission curve that this would report a decrease in emissions - ignoring the additional load the engine is subjected to due to the vehicle having to travel uphill - and consequently misreporting the emissions.

4.7 Conclusion

The aim of the research that has been undertaken by the author, and is subsequently presented within this thesis, was to produce information that will assist in the decision-making process required of highway designers when choosing the most suitable alignment. The three previous research efforts detailed within Section 4.4 have indicated that expending more CO_2 or energy in the construction phase can result in overall lifetime savings, yet are not sufficiently transparent or detailed enough to inform decision making.

The recommended approach to assessing the benefits of new highway schemes and indeed the variations in alignments of the different route options of such schemes has been reviewed and the simplicity of the data requirements highlighted. The recommended methodology was concluded to be unrefined and not sufficiently sophisticated to enable any variations between scheme or route options to be detected.

The research undertaken by Butler (2006) was comprehensive, yet was undertaken with the overarching aim being to produce software that could be used during the highway design process. Therefore the main outcome was a commercial product that is not transparent, with the user being presented with a final answer rather than an understanding of the problems and possible solutions.

An instantaneous emission model should be used to calculate the use emissions, with the most suitable model determined to be PHEM. The validity of the PHEM model has been considered and it was concluded that the model should be used carefully, with maximum speeds having been identified; over which the emission results output by the model should not be used.

Chapter 5

CO_2 from earthworks operations

5.1 Introduction

For most construction activities, materials are required and this contributes to the overall CO_2. Bulk earthworks are different; the CO_2 from this construction element is predominantly associated with the use of machinery to move materials that are already on site.

A previous version of the Arup Carbon Calculator (CO_2ST®) was used on the major motorway project (detailed in Chapter 2), and it was recognised that the treatment of earthworks within this tool was not sufficiently refined to deal with a construction operation that is sensitive to machine selection and use.

The earthworks methodology adopted within CO_2ST® used an aggregated approach to the calculation of Embodied CO_2 (EC) associated with an earthworks operation. However, it has been recognised that a more detailed approach is required.

A model was required that used earthworks methodologies and typical plant selection to provide a more accurate estimation of EC. It was envisaged the model would be composed of two parts. For projects for which detailed cut and fill data is available, the model would be able to utilise this input data along with user defined information pertaining to deposition sites and transportation methods, with machine types being principally selected according to haul distance and ground conditions. The development of this detailed calculation methodology is a pre-requisite to the second part, which will provide high-level indicative values for use when detailed earthworks strategy data is not available.

The work within this chapter was undertaken with assistance from Alan Phear and Niall Fraser, who provided detailed knowledge on the processes undertaken by earthworks contractors.

5.1.1 Embodied CO_2 in earthworks

The CO_2 emitted from construction activities consists of three components: CO_2 emitted from the manufacture of construction materials; CO_2 emitted from the transportation of materials, labour and plant to and from site; and CO_2 emitted by the machinery used during construction. In most cases, the materials CO_2 is by far the dominant component of the construction emissions. In contrast, with earthwork activities, there is no CO_2 associated with manufacturing of materials; the soil or rock excavated and backfilled is usually already on site and the associated CO_2 is primarily from the fuel used by machinery and transportation.

Accurately predicting the machinery use and haul of materials within the site is, therefore, imperative to attaining a realistic CO_2 value associated with the earthworks. The extent of the earthworks varies from project to project, and therefore a standardised CO_2 value should not be assumed.

5.1.2 Background to earthworks

Earthworks are the most common product of civil engineering operations. Nothing can be built without some excavation and some transfer of soil (or rock) from one part of a site to another. Traditionally, and up until the late twentieth century, earthworks were a construction activity which mostly used natural materials and which had a very low carbon footprint. This remains the same today – at least relative to other construction activities. Earthworks still predominantly uses excavated natural materials (whereas most construction materials are manufactured and contain significant amounts of embodied energy).

5.1.2.1 History

The thousands of miles of railway earthworks constructed in the mid nineteenth century had a very low carbon footprint. They were predominantly excavated by pick and shovel using large amounts of manual labour. Horse-drawn wagons transported the material to fill areas, which were as close as practicable to the cut location. The embankments were constructed by side- or end-tipping with little or no compaction of the fill material.

The materials used were predominantly natural and locally won and varied considerably, matching the variation in geology. The alignments were designed with the aim of achieving a balance of the cut and fill quantities and, because of the effort involved, haulage distances were minimized. Therefore, if there was insufficient material for an embankment, a borrow pit was opened up close by. Likewise surplus spoil excavated from cuttings or tunnels was often placed close by, to minimize the haulage required.

Some of these techniques are still considered good practice today. However, there is a current trend to lower road and rail alignments to reduce visual and noise impacts. This makes it more difficult to balance the cut and fill volumes, so increasingly landscaping bunds are designed to redress this balance (Kwan *et al.*, 1997).

It was not until the late nineteenth century that earthworks sites started to be increasingly mechanized, primarily as a result of labour shortages. For example, many steam excavators were used for construction of the Manchester Ship Canal in the 1880s (Trenter, 2001). The rate of mechanization of earthmoving equipment increased, particularly in the United States, in the 1920s and 1930s. This equipment was introduced to the UK during the Second World War for the rapid construction of hundreds of military airfields (Perry *et al.,* 2003). Around this time the importance of good compaction of fill material was also recognised. Modern earthmoving methods using diesel-powered plant to dig, haul, place and compact the fill material subsequently developed rapidly in the UK, and particularly during the construction of the British motorway network in the 1960s, 1970s and 1980s.

5.1.2.2 Measuring the environmental impact of earthworks

The environmental impact of construction processes is regulated throughout Europe, although the emphasis on mitigation methods varies from country to country. However, the logic of and benefit from certain activities in terms of energy efficiency and carbon footprint has often not been considered by those carrying out environmental impact assessments. Most of the current environmental legislation for infrastructure projects does not require a detailed examination of benefit or 'payback period' in terms of carbon footprint and energy efficiency in construction, maintenance and end-of-life replacement (O'Riordan & Phear, 2009), although this situation may soon change.

In the UK, several large infrastructure clients have now introduced carbon calculators for their construction activities. These documents and tools provide a basic framework by which the carbon footprint can be estimated for significant movements of earthwork and other materials. Such calculation systems enable broad decisions to be made but are not sufficient to allow different methodologies to be compared.

5.1.2.3 Potential uses of carbon calculations in the procurement of earthworks projects

As experience in the use of carbon calculators grows, so such calculations can be incorporated into design, optioneering and value engineering activities. Infrastructure clients, designers, and contractors are all finding carbon accounting to be a useful tool, but in different ways.

Designers are increasingly using carbon calculations in combination with traditional cost comparisons to decide between different schemes and when optimizing earthworks designs. The capture of information to feed into whole life evaluation activities is challenging, and often there is no single, correct answer. Cost alone will increasingly be considered too crude a variable on which to base a course of action.

Contractors are increasingly applying carbon accounting to their construction management systems. This is because it has been realised that carbon reduction is a useful way to combine environmental management and 'lean construction' methods, and there is great legal and ethical pressure on contractors to manage and minimise the environmental impact of their work (Kwan *et al.,* 1997). There is also always great pressure to increase operational efficiency, reduce costs and make best use of resources. Both topics are concerned with controlling waste. Environmental impact from construction plant is closely linked to the efficient use, or otherwise, of that plant and carbon accounting is a good way to show this.

Good construction practice will also reduce both waste and environmental impact. Examples of this are coordinated planning of the different workstreams, e.g. by workspace booking, and by making good quality workmanship a key objective: Poor workmanship increases waste, costs and the carbon footprint.

5.1.2.4 Potential use of carbon calculations to assess the environmental impact of earthworks

As a result of extensive environmental protests in the early 1990s against new transport infrastructure projects, there is increasing pressure in the UK to minimize the environmental impact of such projects. Many such impacts are currently only assessed on a qualitative basis or by using qualitative scoring systems, such as the CEEQUAL system (CEEQUAL, 2010). This makes it more difficult to correctly assess the relative importance of, for example, ecological impacts compared to impacts measured quantitatively such as costs, traffic flow consequences, waste reduction and carbon footprint. Despite this, there is a need to balance the ecological impacts of earthworks with these less newsworthy impacts. For example, it is debatable whether the substantial cost, carbon footprint and effort of carrying out motorway widening works within the existing landtake justifies the ecological value of the retention of the vegetation. Arguably, if greater space were made available, more efficient construction methods could be adopted and these would most probably reduce the carbon emissions during the works.

5.1.2.5 Effects on earthworks practice of recent environmental legislation

A new regulatory framework (i.e. the Landfill Tax and the Aggregates Tax) was introduced in the late 1990s to ensure that good environmental practice was adopted so as to minimise the use of scarce primary aggregates and to minimise waste. This legislation is increasingly driving good commercial practice. Thus minimization of waste through beneficial re-use and / or recycling of site-won materials is increasingly important, particularly with regard to earthworks. As a result of the Landfill Tax and the increasing cost of disposing material off site, it is increasingly economic to add lime to marginal site won materials to dry them out and render them acceptable for re-use. Likewise, the flexible design of landscaping so as to retain the maximum amount of excavated materials on site is increasingly common. This will particularly be the case on major projects of regional or national importance where a planned approach can be made between the promoter, regulator, stakeholders and the designers and constructors (e.g. Warren *et al.*, 2003).

5.1.2.6 History of plant selection

In selecting the type of plant in order to undertake an earthmoving scheme in the optimum manner, the specialist contractor will consider not just scheme-specific factors but also corporate factors. Scheme specific factors include: ground conditions, weather conditions, project calendar, the layout and size of the site and the position of its cut and fill areas. As for the corporate factors, continuity of workload for the selected equipment for its anticipated period of ownership is at the forefront of the specialist's mind (Fraser, 2010).

Plant selection is a dynamic entity. In the last thirty years there has been a sea-change in plant selection trends in the UK civil engineering earthmoving sector.

In the 1960s and 1970s peak of motorway construction the motorised scraper was the earthmover of choice. In heavier going and on uphill hauls, twin-engine scrapers were deployed. Otherwise single-engine variants were called upon. The poorest ground conditions and the longest hauls, typically over 1500 metres, would have seen 25-30T capacity rigid dump trucks (RDT) or retired road-going tippers pressed into service, as would rock schemes; loaded by early variants of the hydraulic excavator in the 20-40T class (Fraser,1992).

Nowadays, large-scale earthmoving schemes are fewer and further between and the industry has moved towards a more versatile earthmoving combination in the shape of the hydraulic excavator and articulated dump truck (ADT) team. These are better suited to smaller and more congested sites, capable of working in almost any ground conditions and have the ability to operate in weather conditions that would have rained-off a scraper fleet. The excavator and ADT combination is the versatile solution to many earthmoving schemes today.

Extensive research and design by the plant manufacturers in the last thirty years has seen the capacity of the ADT and digger increase, to the extent that its principle criticism has now been answered – that of lack of payload and therefore productivity in good ground and weather conditions.

This research and development has also led to a far more fuel efficient earthmoving solution than the motorised scraper ever presented. As gas oil prices have steadily increased, the fuel demands of the scraper fleets, particularly the twin-engine variants, has rendered them little short of uneconomic on all but the shortest haul applications.

Towed scrapers continue to find, as they always have done, a niche on very short haul (less than 300m) cut to fill activities on larger sites and are still favoured by many specialists for topsoil stripping duties. Otherwise, the backacter / ADT team is responsible for, almost without exception, all of the earthmoving undertaken in UK civil engineering today. Isolated examples of rock schemes calling for the deployment of larger capacity (50T) and tougher rigid dumptrucks (still loaded by the flexible hydraulic backacter) periodically emerge as do, but even less frequently, examples of ageing scraper fleets transferring from the mining / quarrying sector to undertake limited campaigns on large construction sites in the height of the summer (Fraser, 1992).

5.1.2.7 Use of Inventory of Carbon and Energy database for calculation of CO_2 from earthworks

The Inventory of Carbon and Energy (ICE), produced by the University of Bath has become an important resource for embodied CO_2 and embodied energy coefficients for many building materials. The inventory contains data collected from secondary sources in the public domain (Hammond & Jones, 2011).

The coefficients within the database have been adopted and used within widely recognised industry carbon calculator tools in order to assess CO_2 for infrastructure projects. For example, the ICE data has formed the basis of the embodied CO_2 values presented in the CESMM3 Carbon and Price Book 2011. Within this book the import of 1000m^3 of sub-soil results in 33.8 tonnes of CO_2 (ICE *et al.*, 2011); this has been derived from the ICE figure of 0.023 t CO_2 / t soil when using a bulk density of 1.5t / m^3.

The correct use of the ICE database is imperative in order to arrive at an accurate embodied CO_2 estimate. Misuse of the data can potentially result in elements of construction, such as the earthworks, being credited with large proportions of the overall project CO_2. Consequentially, these incorrectly identified carbon intensive areas become the focus of carbon reduction practices, with the actual CO_2 intensive areas receiving less attention.

Table 5.1 shows the embodied CO_2 coefficients from the ICE database that are used in many carbon calculator tools. Soil, clay, sand and aggregate are common earthworks materials. General steel and general concrete have been included for comparative purposes.

Table 5.1 Embodied CO_2 in materials

Material	Embodied Carbon (kg CO_2 / kg)
Soil *(rammed)**	0.023
Clay *(baked products)**	0.220
Sand	0.005
Aggregate	0.005
General steel	1.770
General concrete	0.130

* Until recently the soil and clay categories were not as refined and did not refer to the soil being rammed or the clay being baked. Therefore, the ICE values in the table were, and still are, included in many widely utilised carbon calculators; noteworthy examples are the HA and Environment Agency (EA) models.

5.2 Model development

The aim was to develop a spreadsheet-based model that would facilitate the calculation of CO_2 from earthworks operations. The model that has been developed primarily considers bulk earthworks. In addition, it is capable of estimating the CO_2 associated with the use of modification additives (lime) to improve the physical properties of marginal soils.

The tool developed for this project has been designed under the guidance of an earthworks contractor. It is divided into two main sections: (1) the movement of materials already located on the site and (2) importing materials to site. The movement of materials already located on site has been sub-divided into (1a) materials retained on site and (1b) materials taken off site.

In Table 5.2, under (1a), the CO_2 and cost relating to the machinery use and modification of fill materials are described. The costs relating to the applicable charges and levies are also detailed.

Under (1b) the CO_2 and cost relating to the machinery use and transportation are described, with the costs associated with the applicable charges and levies. For (2) the CO_2 from materials and transportation are detailed along with the applicable charges.

Table 5.2 Components of earthworks operations

Activity	CO_2	Cost
1. Movement of materials already located on the site		
(a) Kept on-site		
Machinery	CO_2 released from fuel used by machinery to excavate, haul, deposit and compact materials within the site.	Cost of operatives and machinery used to excavate, haul, deposit and compact materials within the site.
Modification of fill material	CO_2 released from fuel used by mixing plant. (CO_2 from materials and their transportation is included in 2.)	Cost of use of mixing plant.
Charges and levies	*Not applicable*	Royalties paid to landowners for either importing materials from their land or disposing of materials to their land. The land being adjacent to the site. Aggregate levies and landfill taxes apply to materials imported and disposed of respectively.
(b) Taken off-site		
Machinery	CO_2 released from fuel used by machinery to excavate materials. CO_2 released from fuel used by excavators used to load road-based transportation.	Cost of machinery used to excavate materials. Cost of machinery used to load external transportation.
Transportation	CO_2 released from fuel used by road-based transportation of material from the construction site to the final off-site disposal site.	Cost of transportation used to take materials to disposal site.
Charges	*Not applicable*	Tipping charges and landfill tax apply to materials disposed of at landfill sites.
2. Importing materials to site		
Materials	Embodied CO_2 in materials used.	Cost of materials used. This cost is assumed to include the cost of transportation to site.
Transportation	CO_2 released from fuel used to transport material from source to site.	*Cost of transportation is assumed to be covered in the cost of materials.*
Charges		Aggregate levies paid on imported aggregates.

5.2.1 Machine selection

From the input data the haul distance is calculated. The model then gives guidance on the machine selection for excavation and haul dependent on the haul distance. Figure 5.1 illustrates the machine types suitable for different haul distances.

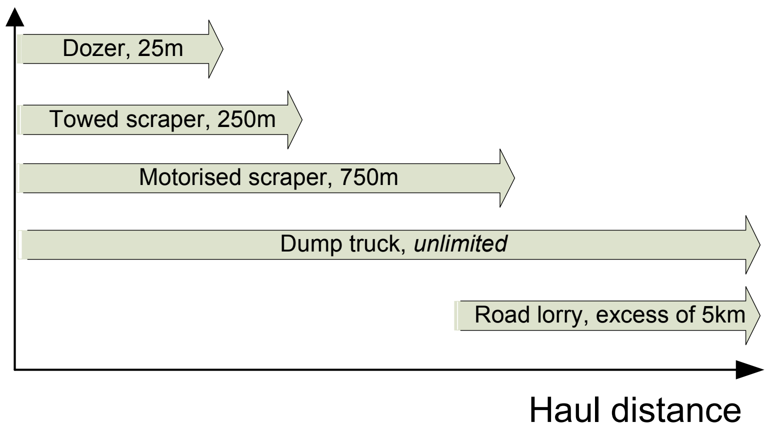


Figure 5.1 Typical haul distances of different plant

A primary machine and a secondary machine are normally required to move materials on site. A primary machine is the 'master machine', with the 'secondary machine' being a serving machine. For example, an excavator would be classed as a primary machine with dump trucks serving as secondary machines. Or, a dozer (sometimes referred to as a 'pusher') would be classed as a primary machine with scrapers serving as secondary machines.

Typical primary and secondary machinery pairings are given in Table 5.3; based on experience to ensure that two machines complement one another in terms of output capabilities.

Table 5.3 Typical machinery pairing (Fraser, 2010)

Primary machine				Secondary machines
Machine type	Kw	Size* (Tonnes)	Example	
Scraper - single engine	250	30	Cat 621	Crawler Dozers 50T (Cat D9)
Scraper - single engine	350	45	Cat 631	Crawler Dozers 65T (Cat D10)
Scraper - twin engine	425	35	Cat 627	Crawler Dozers 50T (Cat D9)
Scraper - twin engine	550	50	Cat 637	Crawler Dozers 65T (Cat D10)
Scraper - twin engine	725	70	Cat 657	2 x Crawler Dozers 65T (Cat D10)
Towed scraper	300	60	Cat D9 & box	Cat D9
Excavator	100	25	Cat 320	ADT 25T (Bell 25)
Excavator	150	30	Cat 325	ADT 25T (Bell 25)
Excavator	200	35	Cat 330	ADT 30T (Bell 30)
Excavator	250	45	Cat 345	ADT 30T (Bell 30)
Excavator	300	70	Cat 365	ADT 40T (Bell 40)
Excavator	400	85	Cat 385	ADT 50T (Bell 50)

* *Operating weight empty*

Photograph 5.1 illustrates the excavator acting as the primary machine with an ADT serving as a secondary machine.

Photograph 5.1 Excavator and ADT pairing

Photograph 5.2 illustrates the pusher (dozer) acting as the primary machine and the motorised scraper serving as the secondary machine.

Photograph 5.2 Pusher (dozer) and motorised twin-engine scraper pairing

5.2.2 Fuel consumption

5.2.2.1 Excavation and haul

The fuel consumption is calculated for each machine type dependent on the hours each machine is used for. This is a function of many factors that can vary from machine to machine. The methodology used to calculate the fuel consumed, and hence CO_2 emissions, from the primary and secondary machine combinations are set out below.

The secondary machine has a fixed capacity in terms of the weight of material it can carry and, therefore, the volume of material it can haul is dependent on the density of material:

$$Haulage\ capacity\ based\ on\ density\ (m^3) = \frac{Haulage\ unit\ capacity\ (t)}{Density\ of\ material\ (t/m^3)}$$

The time taken for the primary machine to load the secondary machine is given by:

$$Load\ time\ (mins) = \frac{Haulage\ unit\ capacity\ based\ on\ density\ (m^3)}{Excavator\ bucket\ size\ (m^3)} \times Cycle\ time\ (mins)$$

The cycle time is the total of the time taken for the primary machine to load the secondary machine, the time taken for the outbound haul of the secondary machine to the site of deposition, the time taken for the return haul to the site of excavation, plus the spot time and tip time of the secondary machine:

$$Cycle\ time\ (mins) = Load\ time\ (mins) + Outbound\ haul\ (mins) + Return\ haul\ (mins) + Spot\ time\ (mins) + Tip\ time(mins)$$

The output of the primary machine can be calculated using:

$$Calculated\ output\ (m^3) = \frac{Minutes\ worked\ per\ hour\ (mins)}{Spot\ time\ of\ secondary\ machine\ (mins) + Load\ time\ of\ secondary\ machine\ (mins)} \times Haulage\ unit\ capacity\ based\ on\ density\ (m^3)$$

The number of hours that the primary machine is used for can be calculated from the volume required to be excavated and the calculated output of the machinery pairing:

$$Primary\ machine\ hours = \frac{Volume\ (m3)}{Calculated\ output(m^3/hour)}$$

The number of cycles that can be completed per hour can be calculated using the effective number of minutes in an hour and the cycle duration:

$$No.of\ cycles\ per\ hour = \frac{Minutes\ worked\ per\ hour\ (mins)}{Cycle\ time\ (mins)}$$

The number of secondary machines required to complement the output of the primary machine can be calculated based on the output, the cycles per hour and the haulage unit capacity:

$$No.of\ secondary\ machines = \frac{Calculated\ output\ (m^3)}{No.of\ cycles\ \times Haulage\ unit\ capacity\ based\ on\ density\ (m^3)}$$

The number of hours worked by the secondary machines can be calculated based on the number of machines and the hours worked by the primary machine:

$$Secondary\ machine\ hours\ (hours) = No.of\ secondary\ machines\ \times Primary\ machine\ hours\ (hours)$$

The methodology used to calculate the CO_2 from the use of primary and secondary machines has been summarised and is shown schematically in Figure 5.2.

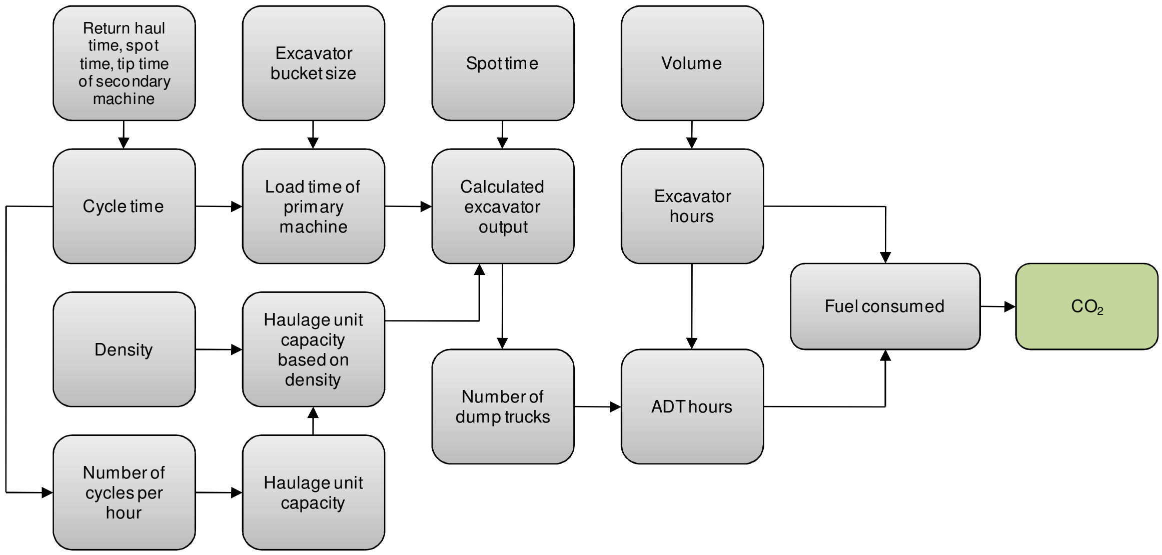


Figure 5.2 CO_2 calculation methodology for primary and secondary machinery pairings

5.2.2.2 Placing fill

The time taken to for a dozer to place the tipped fill can be calculated based on the volume to be placed and the time the dozer requires to place 10m^3 of fill:

$$Dozer\ hours\ (hours) = \frac{Volume\ (m^3)}{10} \times Time\ taken\ to\ spread\ 10m^3$$

The method to calculate the CO_2 emitted by the dozer to place the fill is shown schematically in Figure 5.3.

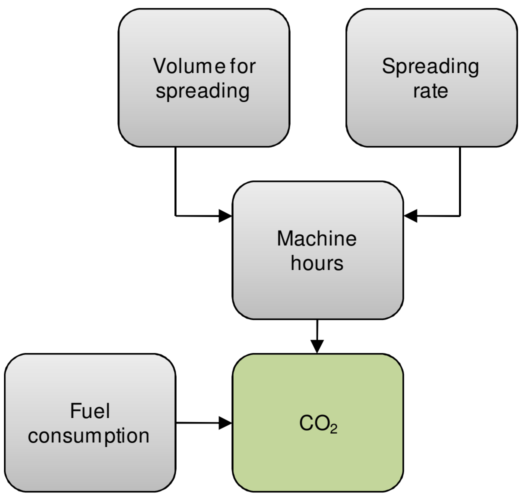


Figure 5.3 CO_2 calculation methodology for dozer

5.2.2.3 Compaction

The time taken to compact placed fill is dependent on the roller output capabilities and can be calculated by:

$$Roller\ output = \frac{Roller\ width(m)\ \times 0.9\ \times Speed\ \ (m/hr) \times 0.85\ \times Depth\ of\ layers\ (m)}{No.of\ passes}$$

The factor of 0.9 is used to account for down-time within the working hour, and the factor of 0.85 is used to give the effective width of the roller.

Once the roller output is known the number of hours for which it is required can be calculated:

$$Compactor\ hours\ (hours) = \frac{Volume\ (m^3)}{Roller\ output\ (m^3/hour}$$

The method to calculate the CO_2 emitted by the compactor is shown schematically in Figure 5.4.

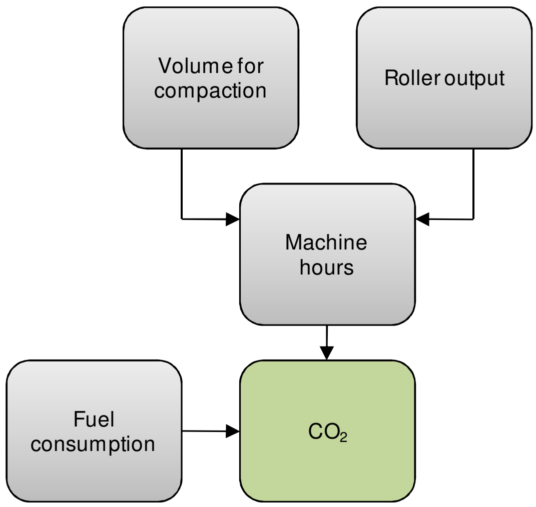


Figure 5.4 Fuel consumption calculation methodology for compactor

When the hours of operation are known, the fuel consumed is estimated using the data from The Reference Manual for Construction Plant (ICES, 2003), extracts of which can be found in Appendix C. Fuel consumption figures are provided for each machine type, and for different engine sizes under normal operating conditions. For light duties / conditions it is recommended that fuel consumption figures are decreased by 25%. For heavy duties it is recommended that fuel consumption figures are increased by 50% (ICES, 2003). Heavy duties / conditions can be defined as operations on soft ground with uphill movements. Light duties / conditions can be defined as operations on hard and level ground (ICES, 2003).

The emission factor used to convert the fuel consumed into a CO_2 value is taken from the "2009 Guidelines to Defra / DECC's GHG Conversion Factors for Company reporting" – giving the figure of 2.6391 kg/CO_2 /litre (DECC, 2009).

5.2.3 Cost calculation

Cost of machinery and labour

The machine costs are based on the machine hours which were also required to calculate the fuel consumption and hence CO_2 emissions (refer to previous section).

The machine costs, shown in Table 5.4 were extracted from the Civil Engineering Contractor's Association schedule of dayworks carried out incidental to contract work (CECA, 2007). The equipment costs are inclusive of gas oil and maintenance. The labour rates are estimates of typical costs of employment (Fraser, 2010).

Table 5.4 CECA plant rates and labour rates

Plant	Costs (£/hr)	
	CECA rate	Labour rate
Scraper	164.500	22.5
Dozer (as pusher)	195.960	22.5
Excavator	117.096	22.5
Grader	171.588	22.5
Compactor	160.056	22.5
ADT	107.556	22.5
Stabilisation mixing plant	600.00	22.5
Dozer (for placing)	73.992	22.5

Cost of disposal

For soil that is disposed to landfill there is the option of the Lower Rate or Standard Rate of Landfill Tax - these are £2.50/tonne and £48 /tonne respectively (HMRC, 2010). A tipping charge would also be incurred; this has been taken as £5/m^3 (Fraser, 2010).

For soil that is disposed of on adjacent land, the landfill tax still applies. There would also be a royalty charge paid to the landowner; this has been typically taken to be £5/m^3 (Fraser, 2010).

Cost of importing

For soil that is imported the Aggregate Levy is applicable - currently at £1.95/tonne (HMRC, 2010). There would also be the purchase cost of the material.

For soil that is imported from adjacent land, the aggregate levy still applies. There would also be a royalty charge paid to the landowner; this is entirely up to the discretion of the landowner but can be assumed to be £5/m^3 (Fraser, 2010), which would include any reinstatement costs necessary.

Cost of lime

The purchase cost of lime has been taken to be £80/tonne (Fraser, 2010); the transportation of the lime to site is included within this cost.

5.2.4 Lime modification

The addition of lime can be used to render unacceptable or landscape (Class 4) materials to a state of being acceptable Class 1, Class 2 or Class 3 materials. There is no prescriptive approach for the use of lime for general fill improvement; it is undertaken by the earthworks contractor using the most appropriate methods.

The lime modification process of spreading the additive on the recently placed fill and mixing it into the soil has been aggregated to a fuel consumption value of 100 litres of fuel used per 150-175m^3 of earth treated. As a worst-case scenario the figure of 100 litres per 150m^3 treated has been adopted. Photograph 5.3 shows the process of lime modification.

The amount of lime required is difficult to specify due to the expedient nature of the process but normally only 1% to 2% (by dry weight) of lime is required for all general fill materials requiring rendering (Highways Agency, 2007). As a worst-case scenario the 2% figure has been adopted.

Photograph 5.3 Process of lime modification

5.2.5 Model validation

A validation exercise was undertaken to ensure the model could produce fuel consumption values that were consistent with those observed on actual earthworks projects. Excavate and haul, place, compaction and lime modification data was provided by Fraser (2012) for a range of machinery for the following large earthworks projects:

- M60 Motorway (1999-2002)
- HS1 (2000-2002)
- Eastern Quarry (2006)
- Heathrow T5 (2002-2005)
- Landfill Stansted (2009)

The projects were divided into sub-operations that dealt with different areas of the site and therefore required different strategies and machinery combinations to reflect the ground conditions and haul distances. This is the reason there are numerous comparisons between the modelled and actual fuel consumption for the same project; for example, for the excavator and ADT operations shown in Figure 5.5, five sub-operations for the M60 were used in the validation with volumes excavated ranging from 50,000 to 500,000 m^3, and with haul distances ranging from 250 to 1,250 m.

Figure 5.5 shows the modelled excavate and haul fuel consumption compared to the actual fuel consumption data collected during the on-site operations. Three excavator and ADT combinations were validated, with the modelled fuel consumption within +/- 10% of the observed fuel consumption. The main variations occurred on the M60 Motorway project using the 45T Excavator and 35T ADT combination; however there was no consistent under- or over-estimation using the model.

Two typical dozers were used to validate the spreading or placing operations that take place on earthworks projects – the Cat D7 and the Cat D9. Figure 5.5b shows the comparison of the actual fuel consumption with the modelled fuel consumption. The modelled fuel consumption is within +/- 10% of the actual fuel consumption in all cases with the exception of a sub-operation on the M60 motorway project in which the modelled fuel consumption was 14% lower than the actual fuel consumption. On investigation into this particular project it was understood that fuel consumption levels were higher than normal due to poor weather resulting in difficult ground conditions (Fraser, 2012).

The modelled and actual fuel consumption values are shown in Figure 5.5c for seven compaction sub-operations. Most modelled values are comfortably within +/- 10% of the actual fuel consumption. The M60 Motorway example again shows the model to underestimate the fuel consumed, likely to be due to the difficult ground conditions. For the Heathrow T5 project, the model overestimated the fuel by 12%, however, on the other Heathrow T5 sub-operation the model underestimated fuel by 2%.

A final validation of the model in terms of lime modification was undertaken for four projects in which this method was used to improve the workability of the fill material. The modelling of this technique showed the greatest variation, with the model overestimating the fuel consumption by 20% on the M60 project. Yet for the remaining three projects the modelled and actual fuel consumption values were reasonably consistent. The M60 Motorway project was again shown to be difficult to model; however, lime modification is a process that can vary considerably between projects.

Overall the model developed to estimate the fuel consumed during typical earthworks operations has been shown to produce values that are consistent with actual recorded values on major projects. The model can therefore be used with confidence to inform the remainder of this research.

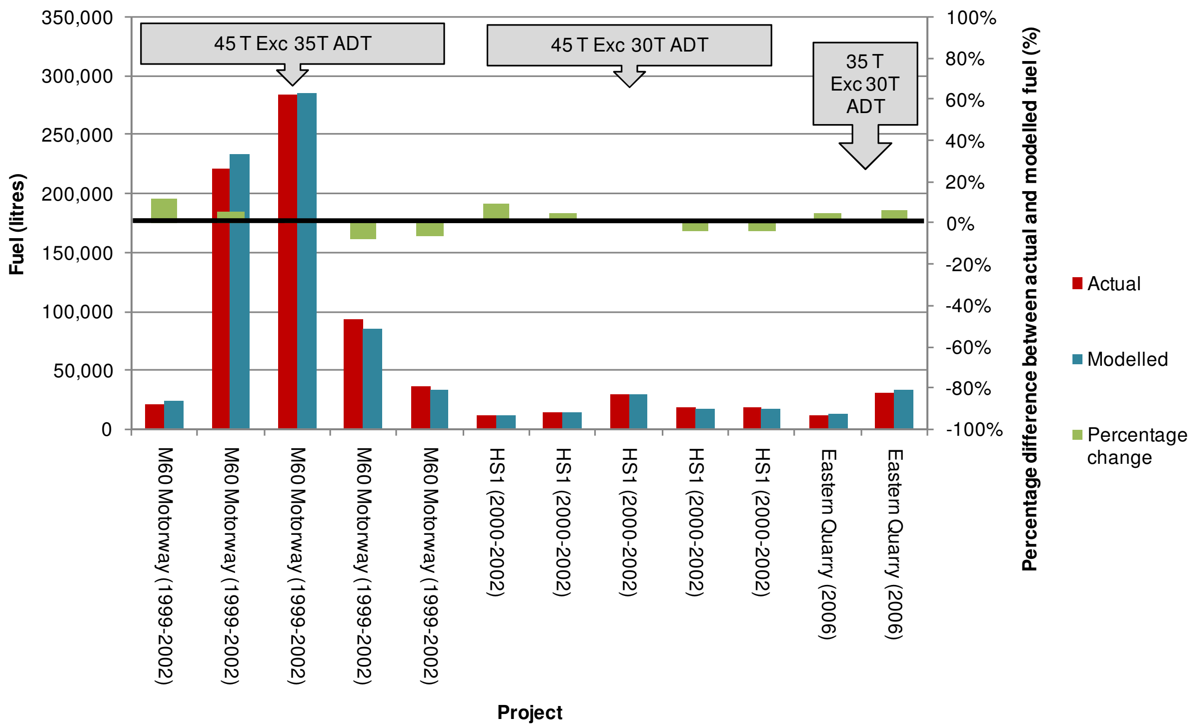


Figure 5.5a Actual and modelled fuel consumption for excavate and haul operations

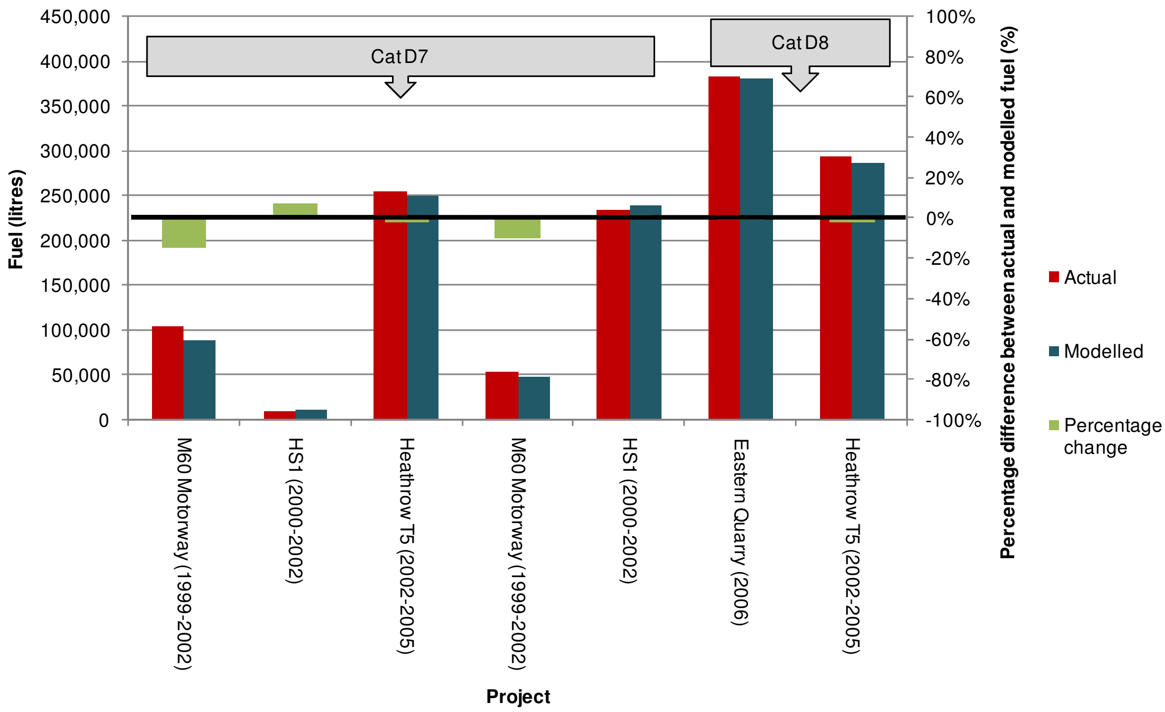


Figure 5.5b Actual and modelled fuel consumption for dozer operations

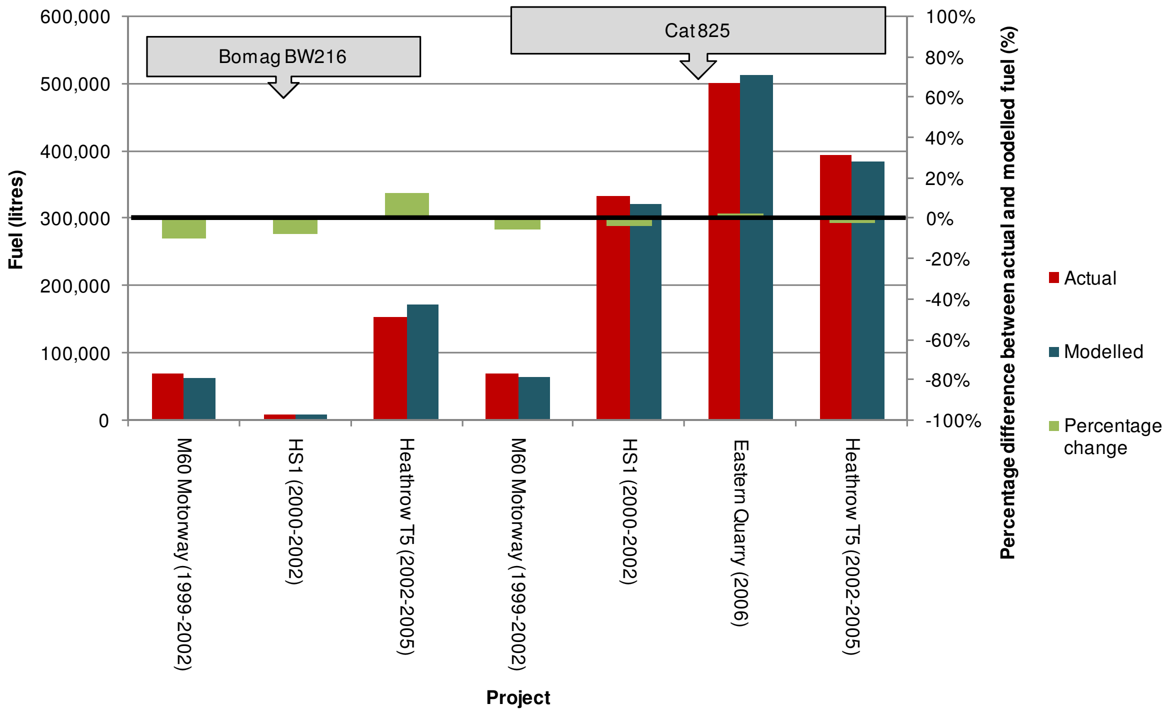


Figure 5.5c Actual and modelled fuel consumption for compaction operations

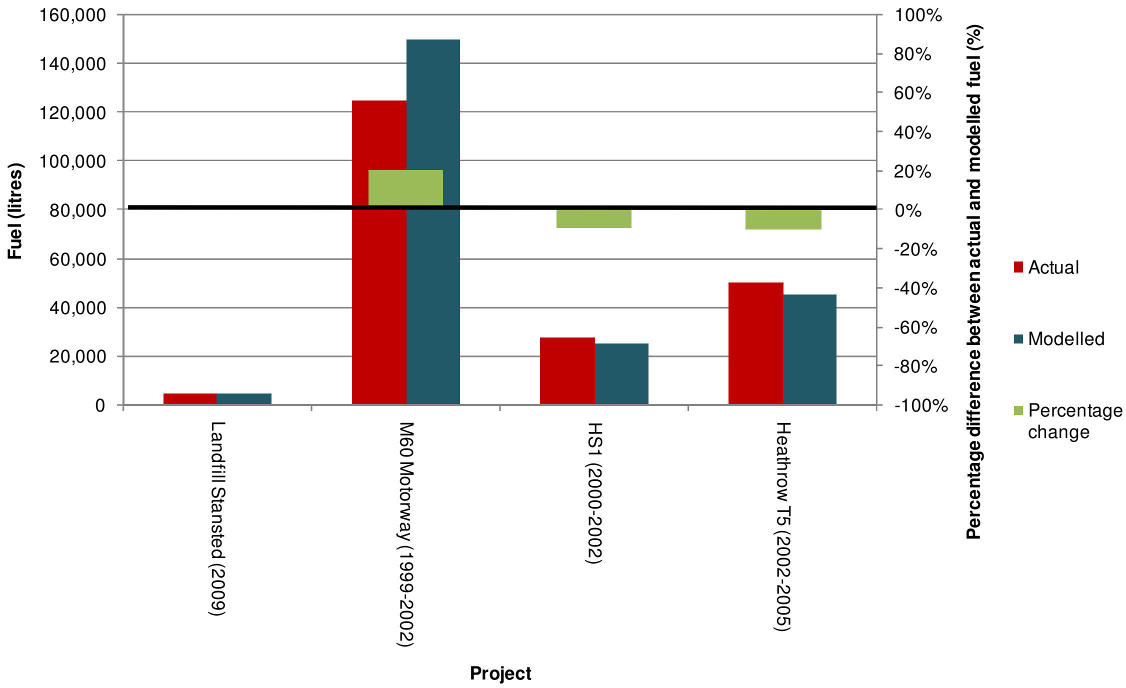


Figure 5.5d Actual and modelled fuel consumption for lime modification operations

5.3 Hypothetical comparisons

5.3.1 Scenarios

Actual site data pertaining to earthworks operations can be complex; due to issues such as commercial considerations, programme constraints and environmental concerns. Therefore, to enable the available options to be simply understood, a hypothetical terrain has been developed so as to not obscure the main issues with site specific complexities. The hypothetical scenarios were developed to reflect typical earthwork situations; the model is a good representation of a real-life site as it incorporates a near balance of cut and fill. Table 5.5 summarises the cut and fill requirements of this hypothetical site. The volumes are representative of a typical highway scheme; for example, the embankment (Site 3) is around 9m high when assuming a highway corridor width of 33m. The hypothetical site incorporates good quality fill material, and also fill material of a lower quality that requires modification to improve its workability; enabling the impact of lime modification to be understood. A borrow pit has also been incorporated to allow for the impact of financial levies and charges to be realised in the context of the cost of the typical bulk earthworks operations.

Table 5.5 Earthworks requirements

Material	Cut (m^3)	Fill (m^3)	Balance(m^3)
Class 1 - Acceptable	500,000	700,000	-200,000
Class 4 - Landscape	200,000	100,000	+100,000
TOTAL	700,000	800,000	-100,000

The site has an overall deficit of acceptable material of 200,000m^3. The site has an overall surplus of Class 4 material of 100,000m^3.

The basic site is illustrated in Figure 5.5 – showing the locations of the cut and fill sites; the existing ground level (solid line) and the proposed finished level (dashed line).

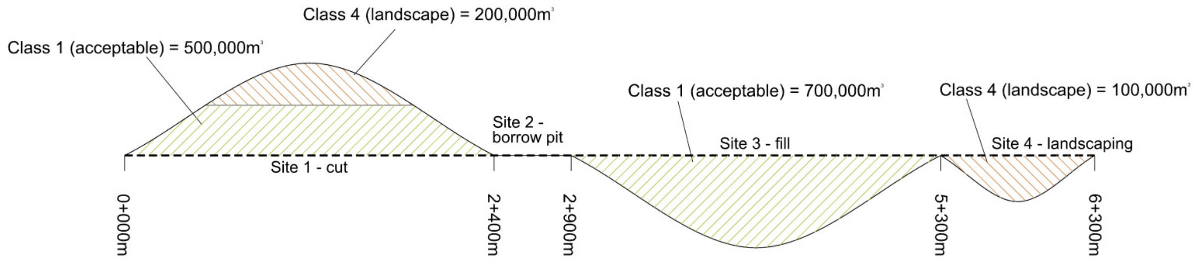


Figure 5.5 Illustration of hypothetical terrain

To meet the proposed finished level three scenarios have been assessed. The scenarios have been developed to enable the impact of the three main earthworks options available for a scheme that has a supply of fill material (which is partly unsuitable) and an overall deficit of material. The options would be: dispose of all the unsuitable material and bring in new and suitable supplies, adjust the proposed finished level to negate the need for new supplies, or to use lime to modify the unsuitable material to negate the need for new supplies.

Based on these available options the three scenarios that have been developed are:

1. Disposing of unacceptable material and importing a greater quantity of acceptable from an adjacent borrow pit
2. Rebalance by redesign of the finished road level, disposing of unacceptable material and importing a lesser quantity of acceptable from an adjacent borrow pit
3. Modify existing unacceptable material with lime to render it acceptable for use and importing a lesser quantity of acceptable from an adjacent borrow pit

Scenario 1: Disposing of unacceptable material and importing a greater quantity of acceptable material from an adjacent borrow pit

Figure 5.6 illustrates Scenario 1. The earthworks operation can be summarised as:

- 500,000m^3 excavated and moved from Site 1 to Site 3.
- 100,000m^3 of Class 4 material excavated from Site 1 and used for landscaping at Site 4.
- 100,000m^3 excavated from Site 1 and transported by road to a final disposal site 10km away.
- 200,000m^3 imported from an on-site borrow pit (Site 2) and placed at Site 3.

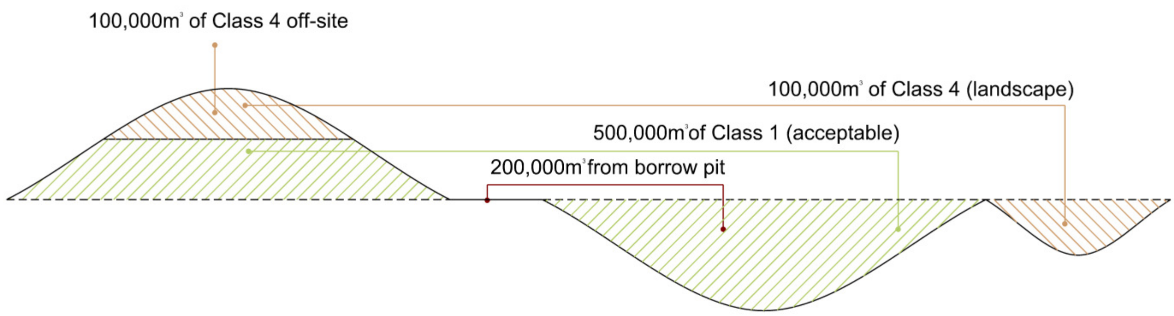


Figure 5.6 Schematic of Scenario 1

Scenario 2: Rebalance by redesign of the finished road level, disposing of unacceptable material and importing a lesser quantity of acceptable from an adjacent borrow pit

Figure 5.7 illustrates Scenario 2. The earthworks operation can be summarised as:

- 550,000m^3 excavated and moved from Site 1 to Site 3.
- 100,000m^3 of Class 4 material excavated from Site 1 and used for landscaping at Site 4.
- 100,000m^3 excavated from Site 1 and transported by road to a final disposal site 10km away.
- 100,000m^3 imported from an on-site borrow pit (Site 2) and placed at Site 3.

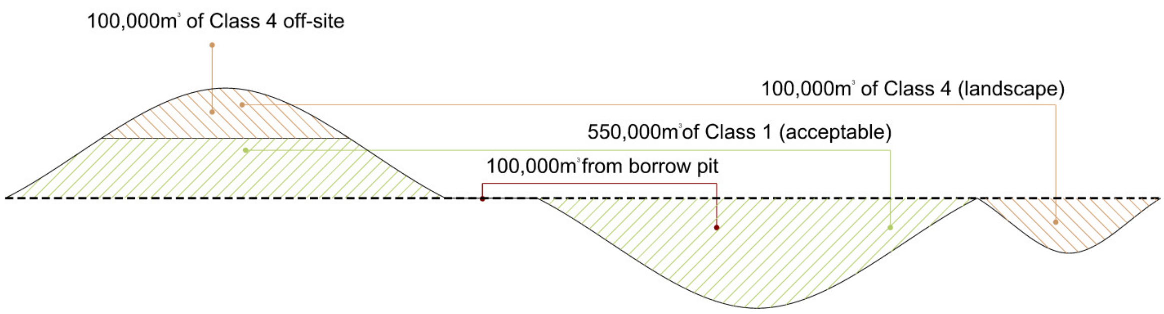


Figure 5.7 Schematic of Scenario 2

Scenario 3: Modify existing Class 4 material with lime to render it acceptable for use and importing a lesser quantity of acceptable from an adjacent borrow pit

Figure 5.8 illustrates Scenario 3. The earthworks operation can be summarised as:

- 500,000m^3 excavated and moved from Site 1 to Site 3.
- 100,000m^3 of Class 4 material excavated from Site 1 and used for landscaping at Site 4.
- 100,000m^3 excavated from Site 1 and placed and modified with lime at Site 3.
- 100,000m^3 imported from an on-site borrow pit (Site 2) and placed at Site 3.

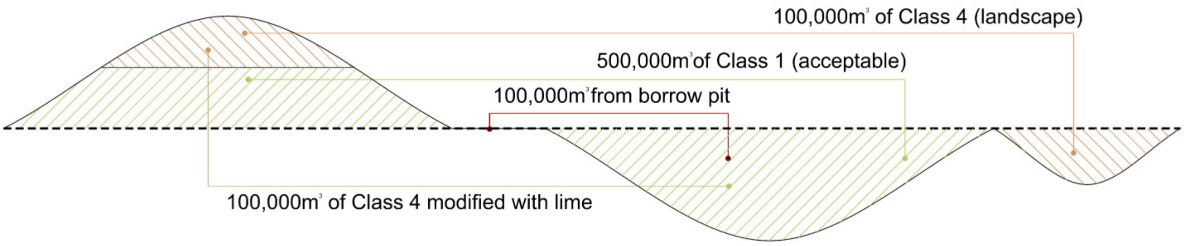


Figure 5.8 Schematic of Scenario 3

5.3.2 Summary of scenarios

The three scenarios detailed above are summarised in Table 5.6. The cut / fill material volume has been separated into the Acceptable and Class 4 categories. The imported and exported volumes of materials are given, along with the volume to be modified.

Table 5.6 Summary of scenarios under consideration

Scenario	Cut material (m^3)		Fill material (m^3)		Imported material (m^3)	Exported material (m^3)	Modified material (m^3)
	Acceptable	Class 4	Acceptable	Class 4			
1	500,000	200,000	700,000	100,000	200,000	100,000	-
2	550,000	200,000	650,000	100,000	100,000	100,000	-
3	500,000	200,000	700,000	100,000	100,000	-	100,000

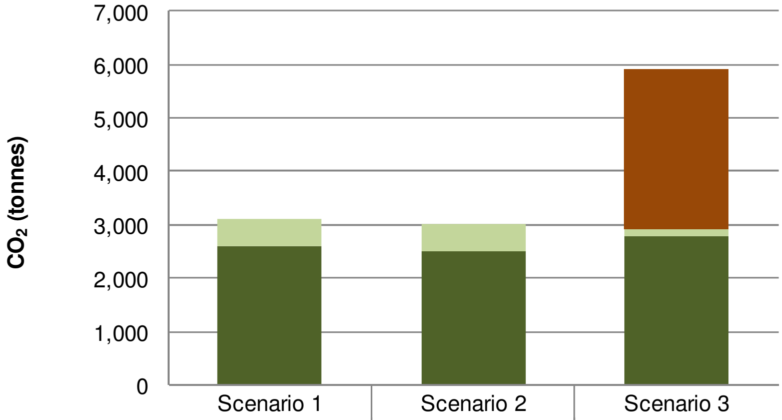
The following assumptions have been made pertaining to the transportation, haul distances, and the plant selection:

- The distance for the transportation of lime from its source to the site is 80km, as this is typically the distance within which lime can be sourced (Fraser, 2010).
- The imported material will be won from a borrow pit located close to the fill site. The excavation and haulage from the borrow pit are included in the calculations as an excavation and haul activity, as it is assumed that the movement of materials can be undertaken with site-based plant rather than road-based plant.
- Waste is transported by lorry to a landfill site located 10km away by road, as this is typically the distance within which waste can be disposed of (Fraser, 2010).
- A 35T excavator has been used with a 30T ADT for the excavation and haul of materials.
- A 20T crawler dozer has been used for spreading.
- An all-purpose compactor (e.g. Bomag BW216) has been used for compaction – requiring 5 passes on each 300mm layer.
- The haul distances are taken to be from the centre of the cut site to the centre of the fill site
- Modification of Class 4 material is done with addition of 2% by dry weight of lime.
- The fill imported from the borrow pit is subject to a royalty charge of £5/m^3. It is also subject to the Aggregate Levy of £2/tonne.
- Class 4 material disposed of off-site is subject to a tipping charge of £5/m^3 and landfill tax of £2.5/tonne.

5.3.3 Results

5.3.3.1 CO_2 and cost breakdown

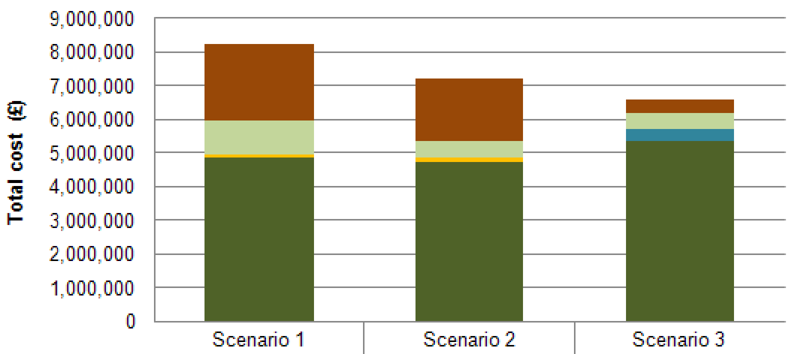
Figure 5.9 shows the CO_2 breakdown by the contribution from the machinery used, the transportation of materials and the embodied CO_2 in the materials used. A similar amount of excavation, haul, deposition and compaction is required for each scenario; hence the CO_2 from machinery is fairly consistent across all scenarios. In Scenario 1 and 2, 100,000m^3 of unacceptable material is taken off-site; hence the CO_2 from transportation is the same for both. In Scenario 3, the transportation is lower due to no material being taken off-site; the CO_2 from transportation shown is from the transport of the lime to site. The lime is also responsible for the significant amount of CO_2 in materials in Scenario 3.



	Scenario 1	Scenario 2	Scenario 3
Embodied CO2 in materials	0	0	3,000
CO2 from transportation	500	500	100
CO2 from machinery	2,600	2,500	2,800

Figure 5.9 Headline CO_2 results for each scenario

Figure 5.10 shows the cost breakdown by the cost of machinery, cost of transportation, cost of imported materials and the typical charges applied to earthworks operations. Similar to the CO_2, a similar amount of excavation, haul, deposition and compaction is required for each scenario; hence the cost from machinery is fairly consistent across all scenarios. It is slightly higher in Scenario 3 due to the use of additional machinery required to undertake the lime modification. The cost of transportation is the same in Scenario 1 and 2 due to the same volume being taken off site. Twice the volume of material is sourced from adjacent land in Scenario 1 over Scenario 2, resulting in twice the landowner royalty charges. The financial levies include the Landfill Tax, the aggregate levy and commercial tipping charges – Scenario 1 and 2 have the same contribution from Landfill Tax and tipping charges due to the same volume being sent to landfill. Scenario 2 takes a smaller volume from the borrow pit and hence incurs less Aggregate Levy.

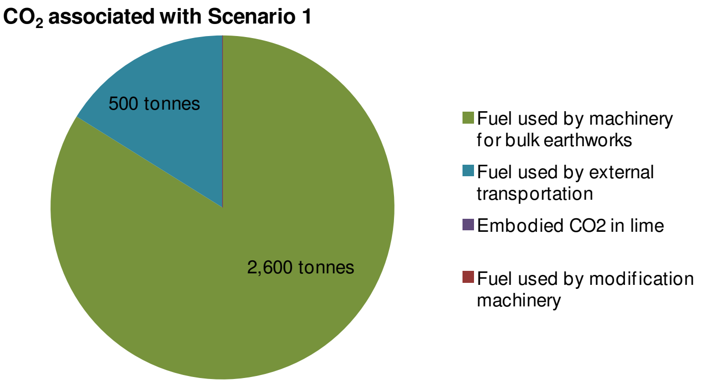


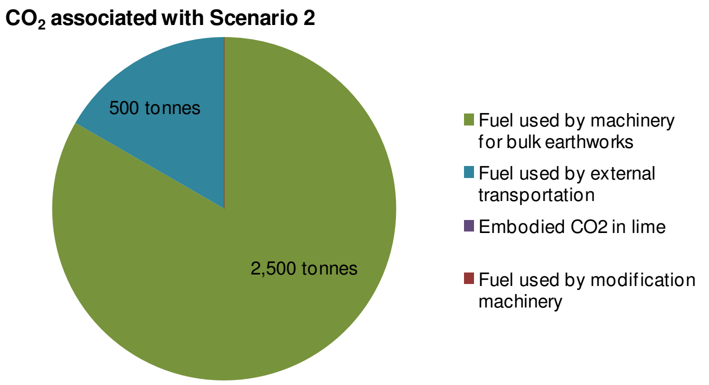
	Scenario 1	Scenario 2	Scenario 3
Financial levies	2,280,000	1,890,000	390,000
Landowner royalty charges	1,000,000	500,000	500,000
Cost of materials	0	0	320,000
Cost of transportation	100,000	100,000	0
Cost of machinery	4,871,100	4,742,100	5,371,000

Figure 5.10 Headline cost results for each scenario

5.3.3.2 Detailed cost and CO_2 breakdown for each scenario

The CO_2 and cost associated with each scenario is presented in detail in Appendix D. The CO_2 information is also represented in the graphs in Figure 5.11, which demonstrate the significance in CO_2 terms of the use of lime. The embodied CO_2 in the lime in Scenario 3 equates to approximately the amount of CO_2 resulting from the machinery and the transportation. However, a conservative estimate was made in terms of the lime used; the higher value of 2% by dry weight of the fill material was assumed.





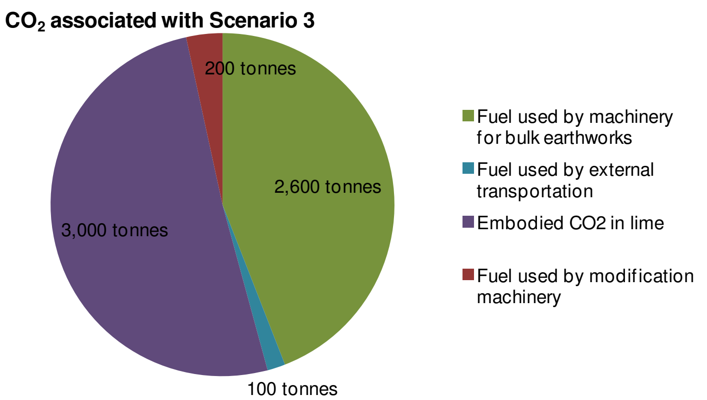


Figure 5.11 CO_2 associated with each scenario

5.4 Indicative CO_2 values

For guidance at the planning stage of a project, before detailed data is available, indicative CO_2 and cost values for typical earthwork activities would be useful to assist in high level decision-making. Indicative values have been calculated by using the model developed and detailed within this chapter, and hence the calculated values presented within this section in the following figures have been derived from the model.

Figure 5.12 illustrates how the separate earthworks activities are addressed in this section; they are categorised as 'to site', 'on site' and 'from site' activities.

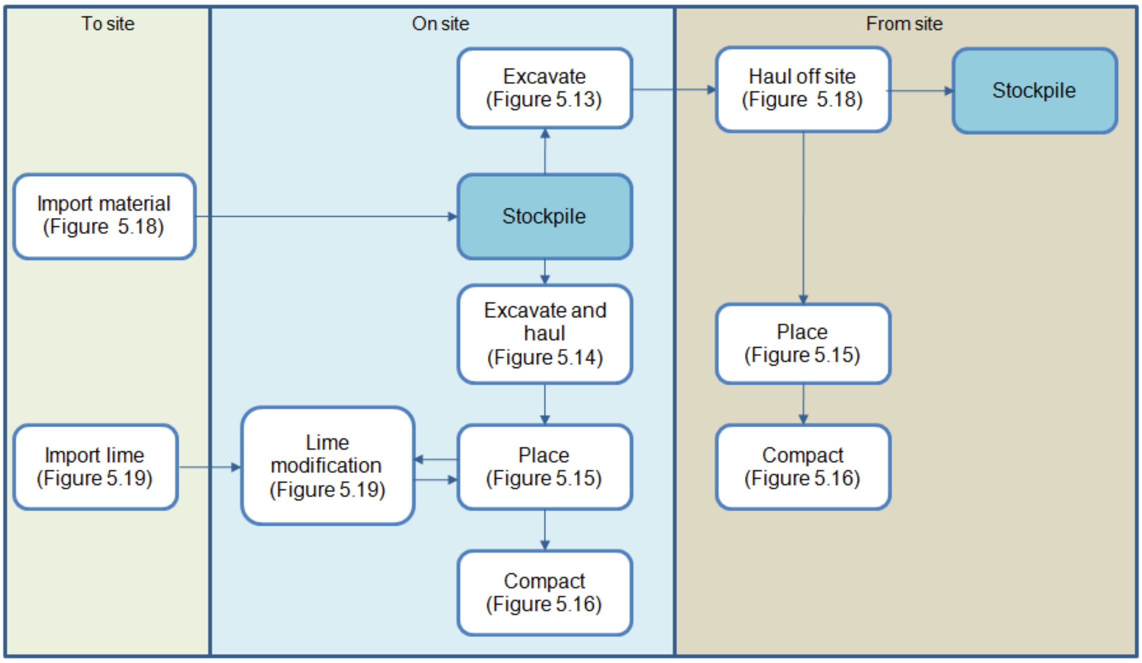


Figure 5.12 Illustration of how earthworks activities are addressed in this section

5.4.1 Excavation

5.4.1.1 Excavator

This activity covers excavation alone. It should be used when excavation is being undertaken with a haul that does not use an ADT. For example, when material is being taken from a stockpile site and taken off-site by road lorry.

Figure 5.13 shows the CO_2 per 1,000m^3 excavated for different sized excavators. The higher CO_2 value shown for the 35 tonne excavator is due to the bucket size that is allowable on the plant. The bucket size used on the 35 tonne excavator is slightly larger than the bucket size allowable for the 30 tonne excavator. Yet the fuel consumption difference between the two excavators is large because of the difference in engine power requirements. With the additional fuel consumption not being matched with a greater bucket capacity, the CO_2 per 1,000m^3 is higher.

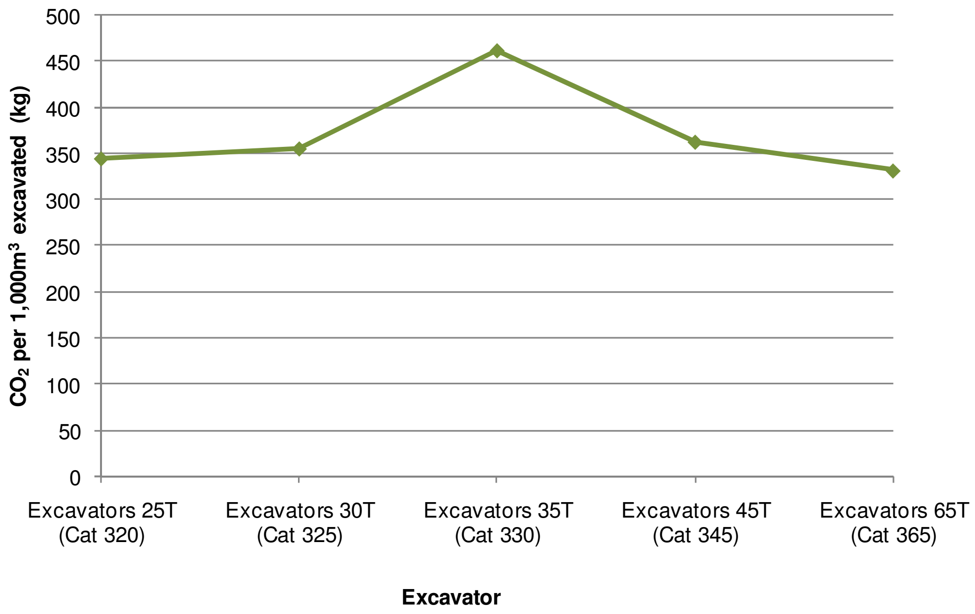


Figure 5.13 CO_2 per 1,000m^3 of material excavated

5.4.1.2 Excavator and ADT

ADTs are the most commonly used dump truck for hauling materials due to their 'go anywhere' capabilities. Figure 5.14 shows the CO_2 per 1,000m^3 excavated and hauled over varying distances, for typical excavator and ADT combinations. As anticipated the CO_2 increases as haul distances increase. The increase in CO_2 will predominantly result from the haul aspect and hence will from the ADT.

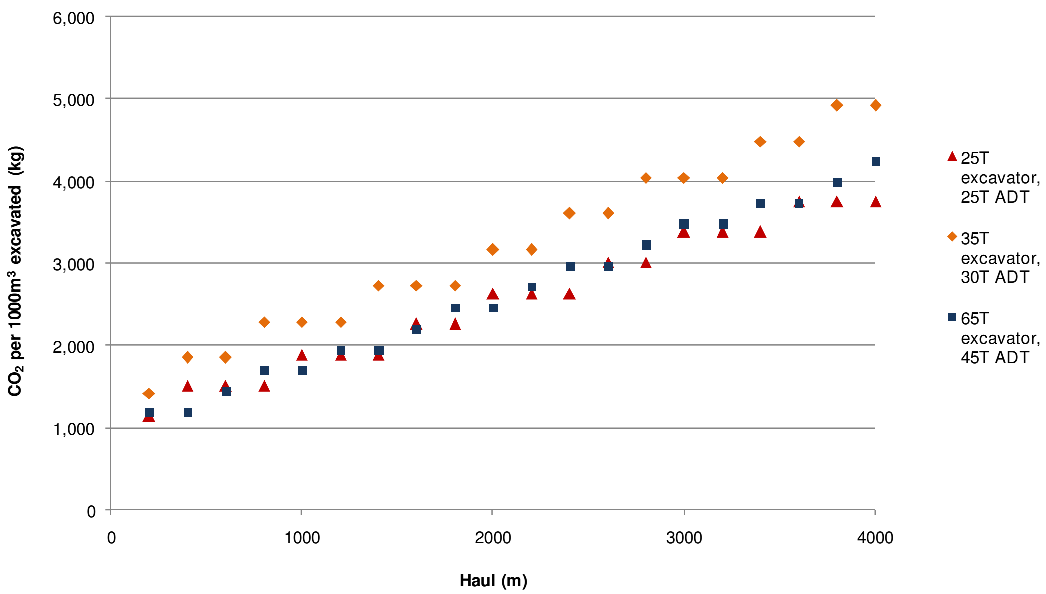


Figure 5.14 CO_2 per 1,000m^3 of material excavated against varying haul distances for excavator and ADT combinations

5.4.2 Deposition

Figure 5.15 shows the amount of CO_2 associated with the placing of fill material using various sizes of crawler dozers. Although the larger dozers have a higher output and can place material more quickly, the power requirements are much larger and they are in fact less efficient in terms of the CO_2 emitted per 1000m^3 placed when compared to the smaller dozer plant.

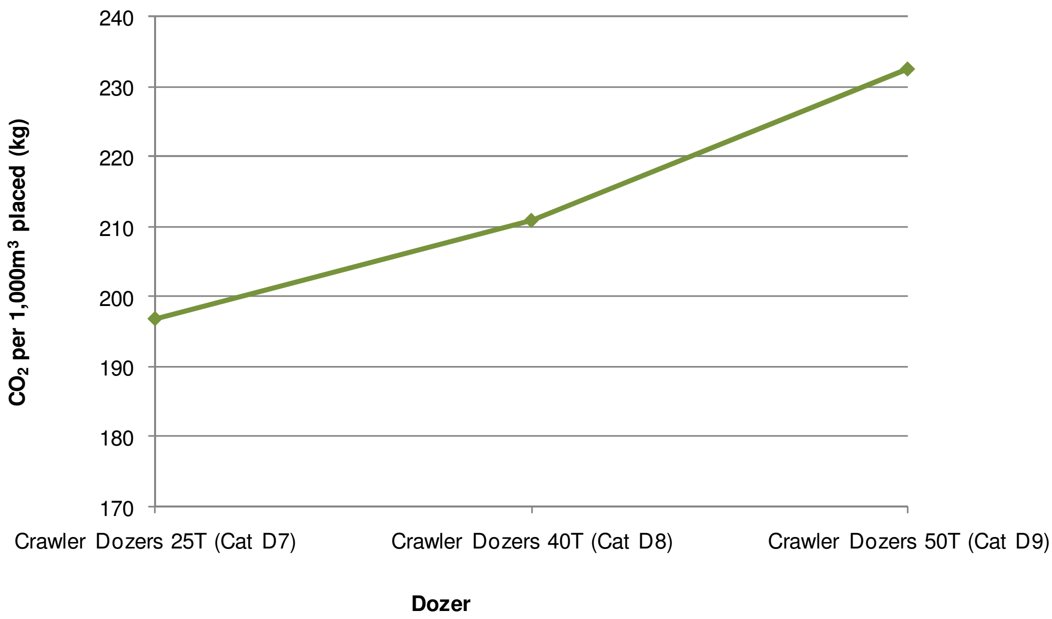


Figure 5.15 CO_2 per 1,000m^3 of material placed for different dozer sizes

5.4.3 Compaction

Indicative values of CO_2 for the compaction process are shown in Figure 5.16. The CO_2 is for 1,000m^3 of fill compacted using a machine typically used for compaction; a BOMAG BW 216 (Fraser, 2010). Embankments are constructed in layers, with the depths of layers specified. The number of passes of the compactor over each layer is also specified by the designer. Figure 5.16 shows the effect of varying the depths of layers and number of passes on the CO_2 from the compaction. The CO_2 per 1000m^3 of fill compacted increases with the number of passes required due to the compactor having to be used for a longer period of time. It also makes sense that the CO_2 decreases as the depths of layers increase, with the compactor being able to treat more material in the required number of passes and therefore requiring less time to complete the operation.

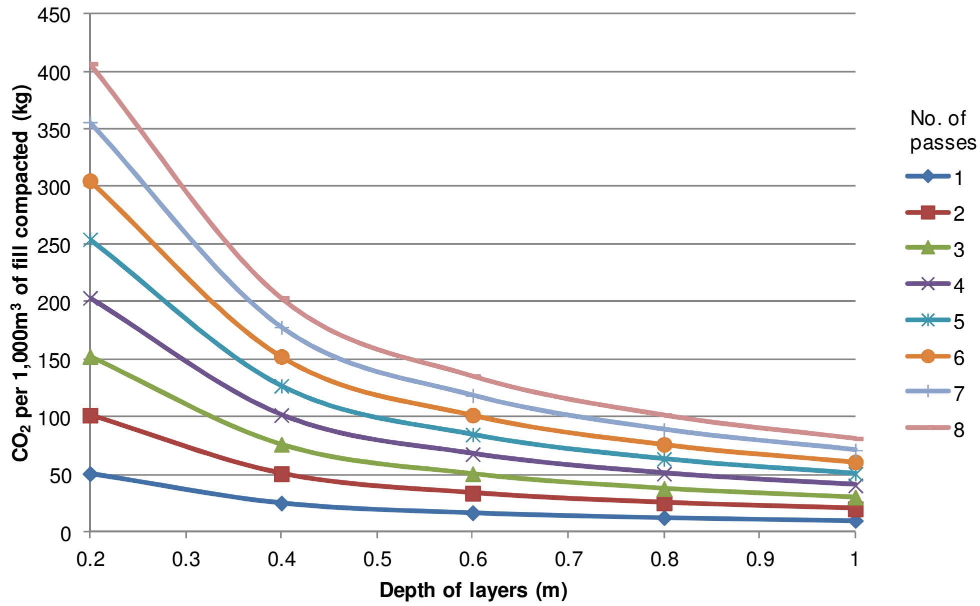


Figure 5.16 CO_2 per 1,000m^3 of material compacted dependent on depth of layer and number of passes

5.4.4 Lime modification

Indicative values of CO_2 for the lime modification process are shown in Figure 5.17. The CO_2 is for 1,000m^3 of CO_2 modified using the GeoFirma plant shown in Photograph 5.3. The proportion of the fill that requires treatment and the percentage of lime added based on the dry weight of the fill impact on the CO_2 from the process, as shown in Figure 5.17. The resultant CO_2 increases as expected as the % of lime by dry weight increases and as the percentage of fill requiring treatment increases.

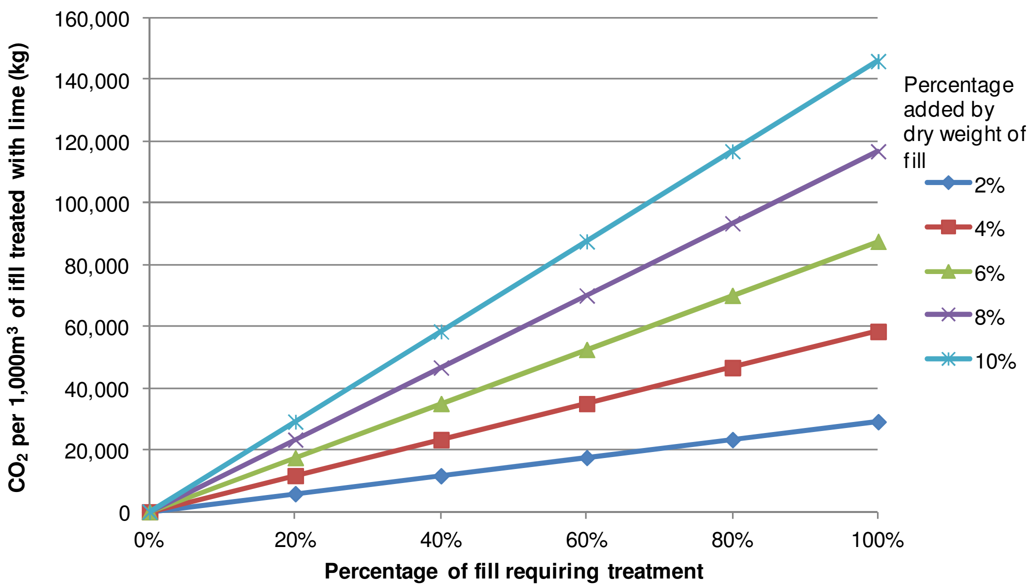


Figure 5.17 CO_2 per 1,000m^3 of material modified with lime dependent on the percentage requiring treatment and the percentage of lime added

The CO_2 from the transportation of the lime to site should also be included. The import of materials to site and the export of materials from site are covered in Section 5.4.5.

5.4.5 Transportation of materials to site and from site

Figure 5.18 shows the CO_2 associated with the transportation by road of 1,000m^3 of material; the CO_2 values shown are for the transportation over a 1 km distance. The amount that can be carried by a road lorry depends on the load capacity and the bulk density of material being transported – the higher the bulk density, the smaller the volume that can transported, resulting in a greater number of trips required and hence higher CO_2 values.

The entire round-trip has been considered. In one direction the road lorry is assumed empty and therefore the emission factor used was for an un-laden vehicle. For the trip in the other direction, the road lorry is assumed to be full and therefore the emission factor used was for a fully-laden vehicle. The emission factors used are given in Table 5.7 (Defra, 2010).

Table 5.7 Emission factors for road lorries (Defra, 2010)

Load capacity of road lorry (tonnes)	CO_2 emission per km (g/km)	
	Un-laden	Fully laden
20	527.6	619.4
25	671.3	863
30	798.1	1148.5

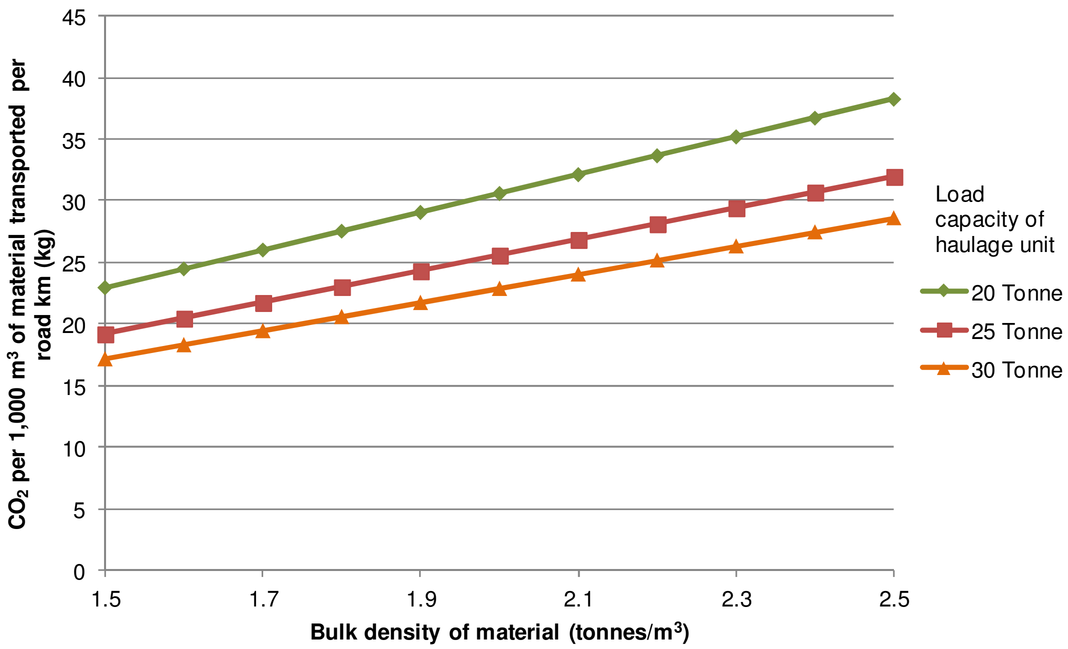


Figure 5.18 CO_2 associated with the transportation of 1,000m^3 of material

When considering the CO_2 from the process of lime modification, the transportation of the lime should also be considered. Figure 5.19 shows the CO_2 from the transportation by road per 1,000m^3 of material modified with lime. Similarly, as for the transportation of materials to site, the entire round-trip has been considered. For the trip to the site the road lorry is assumed to be full and therefore the emission factor used was for a fully-laden vehicle. For the trip away from the site the road lorry is assumed to be empty and therefore the emission factor used was for an un-laden vehicle.

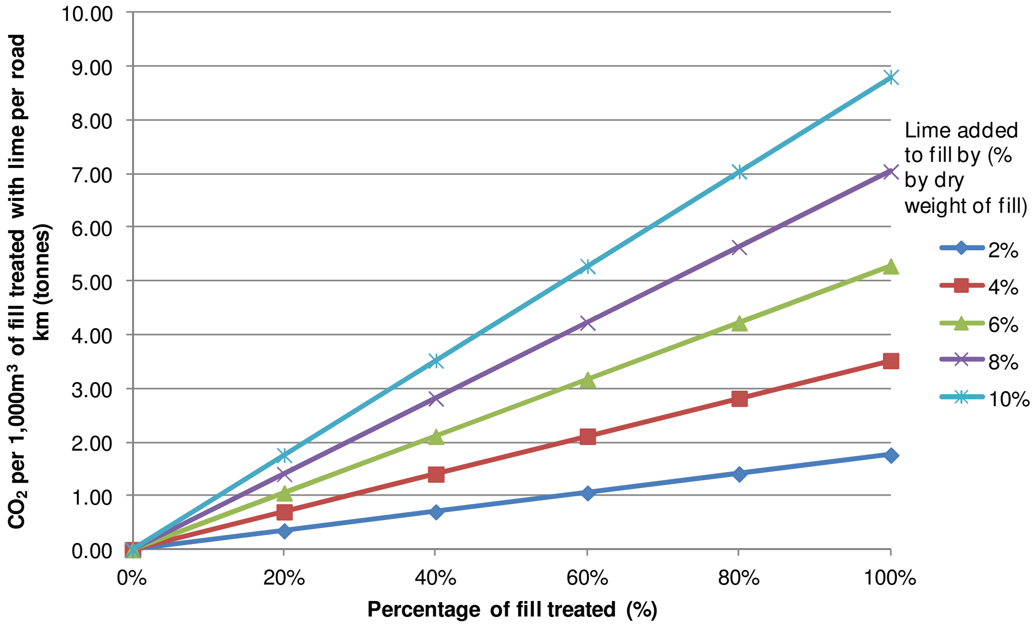


Figure 5.19 CO_2 associated with the transportation of lime material per 1,000m^3 of fill treated

From studying the above graphs that give indicative results for typical earthworks activities the carbon intensity of the use of lime to modify marginal soils is apparent. All CO_2 values are given per 1000m^3 of earthworks, and for the use of lime shown in Figure 5.17, the CO_2 is significantly greater than any other activity, even when only small volumes of lime are added and when small volumes of the fill material are treated. Much further down the scale in carbon intensity terms, is the excavation and haul operation which can produce large amounts of CO_2 when long haul distances are used. The remaining activities, such as deposition and compaction, are again less carbon intensive due to the plant operating over shorter distances.

5.5 Discussion

5.5.1 Use of lime to improve physical properties of soil

It is apparent from the background motorway study, in Chapter 2, that the earthworks can have a low impact on the carbon emissions of the overall project if site-won materials are utilised. However, this is not the case when manufactured materials such as lime are imported to site to modify low grade soil.

Earthworks contractors tend towards on-site lime modification of low grade excavated soil as an alternative to disposing of low grade materials off-site and importing fill to site.

The reason is that legislation has resulted in lime being the more economical option. The Waste Strategy for England (Defra, 2007) identified construction waste as a priority action and subsequent fiscal and legislative tools have been introduced to improve resource efficiency and decrease waste production.

With the Landfill Tax and Aggregate Levy making disposing of materials off-site and importing materials to site more costly, retaining materials within the site is imperative to reducing the earthworks costs, and hence is the reason contractors opt for the use of lime as an alternative. Likewise, the flexible design of landscaping so as to retain the maximum amount of excavated materials on site is increasingly common.

CO_2 is the only environmental indicator detailed within this thesis. Although the scenarios that involved off-site disposal and imported new materials have the lower associated CO_2 emissions, a decision cannot be based on this alone. The Landfill tax and the Aggregate Levy were introduced to regulate waste disposal to landfill and to reduce resource consumption, both are important environmental impact indicators that should be taken into account.

5.5.2 Use of ICE database for earthworks CO_2 calculations

The Inventory of Carbon and Energy (ICE), produced by the University of Bath has become an important resource for embodied CO_2 and embodied energy coefficients for many building materials. The inventory contains data collected from secondary sources in the public domain (Hammond and Jones, 2008). The coefficients within the database have been adopted and used within widely recognised industry carbon calculator tools in order to assess CO_2 for infrastructure projects. However it is important to understand the applicability of these coefficients when using them.

This research project raised some issues with regards to the use of the ICE data for soil, clay and sand when calculating the EC of earthworks operations. The ICE values for these materials are incorporated within the Highways Agency Carbon Accounting Tool, and as a result highways projects are reporting high EC figures associated with earthworks.

To highlight the issue, the A421 Highway Improvement scheme reported a carbon footprint of 131,642 tonnes for a quarterly period in 2010 (Highways Agency, 2010). 122,351 tonnes of this carbon was attributed to materials used; 68% of which (82,660 tonnes) was attributed to 197,751m^3 of excavated clay. (NB. The ICE figure of 0.22kg CO_2/ kg was used with a density of 1.9 tonnes /m^3)

Using the earthworks tool resulting from this research project to give a comparison – excavating 197,751m^3 of clay is estimated to result in 99 tonnes of CO_2. This figure is approximately 0.1% of the value attained when using the ICE figure of 0.22kg CO_2/ kg.

The spreadsheet-based tool that has been developed has been done so from first principles – by understanding the on-site activities of an earthworks contractor – to enable an accurate estimate of fuel consumption to be obtained.

The issue is not with the ICE database value, but with the use of it. The value of 0.22kg CO_2/ kg was originally given for ‘General clay’ and was later clarified to be ‘General simple baked clay products’ and thus is not appropriate for excavated clay. Similarly, the value for soil of 0.023 kg CO_2 /kg, refers to 'General (Rammed) soil' and hence includes the necessary processing required to produce rammed soil.

The correct use of the ICE database is imperative in order to arrive at an accurate embodied CO_2 estimate. Misuse of the data can result in elements of construction, such as the earthworks, being credited with large proportions of the overall projects CO_2. Consequentially, these incorrectly identified carbon intensive areas become the focus of carbon reduction practices, with the actual carbon intensive areas receiving less attention.

This earthworks carbon calculator tool has enabled the CO_2 produced by earthworks activities to be more accurately estimated. The hypothetical site model shows that the approach used by the tool (i.e. to consider the individual earthwork movements to arrive at an overall fuel consumption and CO_2 value) is easy and pragmatic to use and fits well with normal earthworks planning methods.

5.6 Conclusions

As a result of the research project, a useful tool has been developed that enables the CO_2 produced by earthworks activities to be more accurately estimated. The tool takes a disaggregated approach to ensure the individual earthwork movements are considered to arrive at an overall fuel consumption value. The bottom-up approach produces more reliable CO_2 values over top-down approaches that use standardised CO_2 values per unit of earthworks activity.

Most construction materials have reasonably standardised production processes and so CO_2 coefficients can be more confidently applied to calculate embodied CO_2. The use of published embodied CO_2 coefficients is usually not appropriate when calculating the CO_2 associated with earthworks operations. Cut and fill sites, volumes and haulage distances are unique for each project and hence the machinery used is also unique. For this reason, CO_2 should be calculated using a bottom-up approach; by estimating the machinery requirements for the necessary movements, the fuel used by the machinery and the subsequent CO_2 emitted from the combustion of the fuel.

The use of lime modification in earthworks has been investigated and shown to increase embodied CO_2 compared to earthworks carried out without lime addition. In the hypothetical scenarios presented, the use of lime increased the total CO_2 by around 90%. However, environmental legislation has distorted the relative costs of the various earthworks activities resulting in lime modification becoming more economically favourable.

Understanding the CO_2 resulting from infrastructure projects is increasingly important due to the issues of climate change. It is vital that the CO_2 associated with the infrastructure project is correctly estimated to ensure the elements responsible for the CO_2 are identified and acted on. Accurate modelling of the embodied CO_2 of earthworks operations will ensure the correct amount of CO_2 is attributed to the earthworks part of projects - enabling the truly CO_2 intensive elements of construction to be highlighted and addressed.

An outcome of the research detailed within this chapter was the spreadsheet-based model for estimating the CO_2 resulting from earthworks operations for linear infrastructure projects. This model was used throughout the remainder of the research; for the hypothetical alignments in Chapter 6 and the case studies presented in Chapters 7 and 8.

Chapter 6

Hypothetical alignments

6.1 Introduction

The work presented within this chapter has been designed to enable the effect of alignments on the resultant CO_2 emissions of different vehicle types and on fleets to be understood. The approach to this process has been described in Chapter 3 by Figure 3.7.

In **Section 6.1 Hypothetical Terrains** the terrains for which different alignments have been designed for testing are described. The individual vehicle types are assessed over these alignments in **Section 6.2 Effect of alignments on CO_2 emissions of individual vehicles**. Fleets comprised of these individual vehicle types are considered in **Section 6.3 Effect of alignments on fleets**. The CO_2 associated with the construction of the alignments is detailed in **Section 6.4 Effect of alignments on earthworks CO_2**. Finally, the earthworks CO_2 and the CO_2 emissions from vehicle use are brought together in **Section 6.5 Impact of alignment on construction and use**.

The approach to quantifying CO_2 from bulk earthwork operations has been described in detail in Chapter 5. The methodology used to quantify the CO_2 from the vehicles using the highways is detailed in Appendix E.

6.1.1 Hypothetical terrains

Two hypothetical terrains were used – a hill and a valley. In the case of the hill, the vertical alignment could follow the profile of the existing terrain; or, alternatively, the highway could be cut into the hill to result in a shallower vertical alignment. In the case of the valley, the vertical alignment could follow the profile of the existing terrain; or, alternatively, the highway could be constructed on an embankment resulting in a shallower vertical alignment.

An alternative to a cutting is a tunnel and the alternative to an embankment is a viaduct; however, the focus of the research is on bulk earthworks operations.

6.1.2 Vehicle types

Four vehicle types were assessed: a car, a Lights Goods Vehicle (LGV), a Rigid Heavy Goods Vehicle (HGV), and an Articulated HGV. For the Rigid and Articulated HGV the load that it carries can vary significantly, hence three load cases have been considered; unladen, half-laden, and fully-laden. Therefore, in total there are nine vehicle categories that have been assessed individually over the hypothetical alignments; these are detailed in Table 6.1.

Table 6.1 Details of the vehicle categories used

Vehicle	Fuel	Engine Size (litres)	Gross vehicle weight (tonnes)	Euro emission standard	Load
Car	Petrol	1.4 to 2.0	Under 2.5	Euro 4	-
Car	Diesel	1.4 to 2.0	Under 2.5	Euro 4	-
LGV	Diesel	-	-	Euro 5	-
Rigid HGV	Diesel	-	3.5 to 7.5	Euro 5	Unladen (UL)
Rigid HGV	Diesel	-	3.5 to 7.5	Euro 5	Half-laden (HL)
Rigid HGV	Diesel	-	3.5 to 7.5	Euro 5	Fully-laden (FL)
Articulated HGV	Diesel	-	34 to 40	Euro 5	Unladen (UL)
Articulated HGV	Diesel	-	34 to 40	Euro 5	Half-laden (HL)
Articulated HGV	Diesel	-	34 to 40	Euro 5	Fully-laden (FL)

Only conventional vehicles powered by the internal combustion engine have been considered in this assessment. A scenario has been considered, further into the study, which assumes the widespread use of the electric light vehicle. However, only so far as to omit the light vehicle from the study and assume that it is powered by an alternative source with zero CO_2 emissions. Therefore, the effect of different alignments has not been considered on the electric vehicle.

6.1.3 Terrains and alignments

6.1.3.1 Hill

To understand the effect of differing gradients on the fuel consumed by vehicles, a simple hypothetical hill has been used in this study. The dimensions of the hill are shown in Figure 6.1. The level alignment will act as the control for comparison with the three alignments of varying gradients:

- The steepest alignment has an uphill section (C) of 6% and a downhill section (E) of -6%. This alignment will herein be referred to as +6 -6.
- The steepest alignment has an uphill section (C) of 4% and a downhill section (E) of -4%. This alignment will herein be referred to as +4 -4.
- The steepest alignment has an uphill section (C) of 2% and a downhill section (E) of -2%. This alignment will herein be referred to as +2 -2.

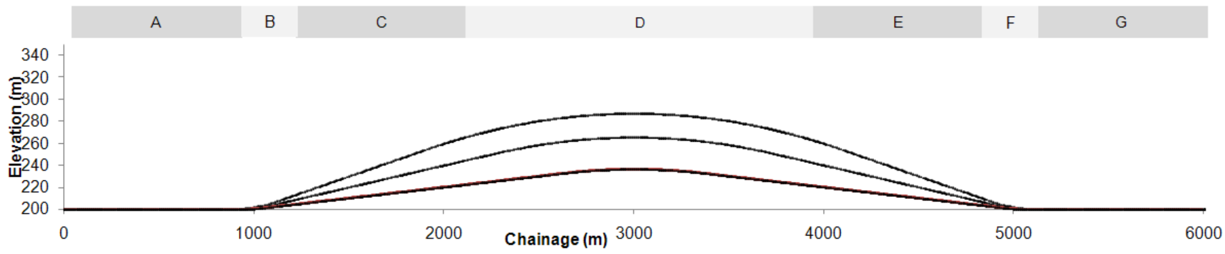


Figure 6.1 Dimensions of hypothetical hill

The length of the sag curves at B and F, and the length of the crest curve at D are given in Table 6.2 for a highway with a design speed of 120 kph. All outputs presented within this section refer to highways with a design speed of 120 kph; due to the majority of new highway projects that have significantly different alignment options being high speed rural roads with design speeds of 120kph.

Table 6.2 Dimensions of hill alignments

Section C (%)	Section E (%)	Length of curve (m)		
		Sag curve at Section B	Crest curve at Section D	Sag curve at Section F
6	-6	222	2184	222
4	-4	148	1456	148
2	-2	74	728	74

The hill could be considered to be of large proportions with uphill (C) and downhill (E) section lengths of 2000m in length. Such proportions were assessed to ensure adequate distances of the uphill and downhill gradients could be traversed by the vehicles – due to the lengths of the crest curves required to transition between the steeper grades.

6.1.3.2 Valley

In addition to the symmetrical hill terrain, which can have a varying alignment dependent on the size of the cutting, a valley has also been considered, which can have a varying alignment dependent on the size of the embankment.

The dimensions of the symmetrical valley terrain are shown in Figure 6.2. The level alignment will act as the control for comparison with the three alignments of varying gradients:

- The steepest alignment has a downhill section (C) of -6% and an uphill section (E) of +6%. This alignment will herein be referred to as -6 +6.
- The steepest alignment has a downhill section (C) of -4% and an uphill section (E) of +4%. This alignment will herein be referred to as -4 +4.
- The steepest alignment has a downhill section (C) of -2% and an uphill section (E) of +2%. This alignment will herein be referred to as -2 +2.

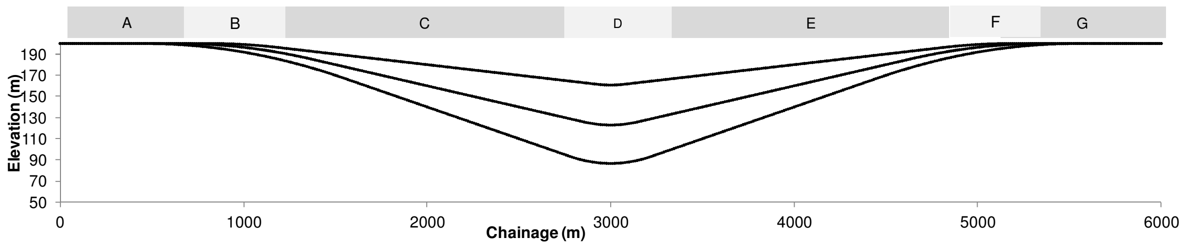


Figure 6.2 Dimensions of hypothetical valley

The length of the crest curves at B and F, and the length of the sag curve at D are given in Table 6.3 for a highway with a design speed of 120 kph.

Table 6.3 Dimensions of symmetrical valley alignments

Section C (%)	Section E (%)	Length of curve (m)		
		Crest curve at Section B	Sag curve at Section D	Crest curve at Section F
-6	6	1092	444	1092
-4	4	728	296	728
-2	2	364	148	364

From the dimensions of the hill and valley terrain given, it is apparent that both terrains have inclines and declines of equal lengths and gradients. Due to the vehicles being assessed at constant speeds it is not relevant whether the incline or decline is traversed first. Therefore, the assessment of both a valley and hill terrain could be questioned. Although the inclines and declines are the same, the hill would result in two sag curves and one crest curve, with the valley resulting in one sag curve and two crest curves. The required design length of the transition curve depends on whether it is a crest or sag curve, and hence the lengths of the curves will impact on the lengths of the inclined and declined sections. Therefore, both a hill and terrain have been considered to understand whether there is a noticeable difference resulting from the transition curve lengths.

6.2 Effect of alignments on CO_2 emissions of individual vehicles

Although all vehicle types have been analysed in detail, not all of the output is presented. The following has been presented within this section:

- A detailed analysis of the petrol car
- A detailed analysis of the half-laden articulated HGV
- An overview of the diesel car and the LGV
- An overview of the unladen and fully-laden load cases for the articulated HGV
- An overview of the unladen, half-laden and fully-laden load cases for the rigid HGV

6.2.1 Petrol cars

Figure 6.3 shows the effect of the symmetrical hill alignments on the petrol car. Firstly, Figure 6.3a shows the CO_2 emissions across a range of speeds, for which the PHEM emission model was deemed valid, for all four vertical alignments; +6 -6, +4 -4, +2 -2 and level. For the level alignment, the emissions increase with increasing speed, and this same general effect of increasing emissions with increasing speeds occurs across all alignments. Figure 6.3a shows that for the graded alignments at certain speeds it is beneficial, in terms of lower CO_2 emissions, for the petrol car to travel on a graded alignment rather than on a level alignment.

To demonstrate this more clearly the emissions have been normalised as shown in Figure 6.3b. The emissions have been normalised to the emissions resulting from the petrol car travelling on the level alignment at that particular speed. For example, a petrol car travelling at 120 kph on a level alignment produces 1219 g of CO_2, whereas, on the +6 -6 alignment it produces 1200 g of CO_2. Therefore the normalised value for that alignment is taken to be 0.997. The occurrence of the petrol car producing less CO_2 emissions when travelling on the graded vertical alignments than on the level alignment is apparent over the speed range from 100kph to 135 kph for both the +6 -6 and +4 -4 alignments. It is also the case for the +2 -2 alignment but over a narrower speed range of 110 kph to 125 kph.

Although it appears that it would be beneficial to be travelling in these higher speed ranges to take advantage of the graded alignments, which result in lower emissions – it is apparent from Figure 6.3a that at these higher speeds the petrol car produces higher emissions that at the lower speeds. Figure 6.3a shows the absolute CO_2 emissions, and that the level alignment results in the lowest emissions up to a certain speed, when the graded alignments become favourable. Therefore, to take advantage of the beneficial effect of the graded alignment the car needs to be travelling at a higher speed, at which point the overall emissions are higher.

The lower emissions over the graded alignments can be explained by Figures 6.3c, 6.3d and 6.3e for the +6 -6, +4 -4 and +2 -2 alignments, respectively. These figures show the total carbon emission rate released (in mg per second) as the petrol car travels over the alignment – the alignment is demonstrated by the black line. In Figure 6.3c, for the +6 -6 alignment, using the petrol car travelling at a speed of 120 kph as an example, the emission rate on the uphill section is 2727 mg/s and on the downhill section 800 mg/s. The average of the uphill and downhill sections is 1764 mg/s, which is lower than the emission rate on a level section at 1847 mg/s.

The same effect is seen in Figure 6.3d, for the +4 -4 alignment case for all speeds except at 90kph. For all speeds below 90 kph the effect is not observed. At 90 kph the uphill 4% section produces 1758 mg/s and the downhill -4% sections produces 608 mg/s. This results in an average of 1183 mg/s which is higher than on the level alignment at 1176 mg/s.

Again, the same effect is apparent in Figure 6.3e in the +2 -2 alignment case, but to a lesser extent. The difference between the uphill and downhill emission rates at the shallower grades is smaller, and so the effect only occurs at the higher speeds.

Figure 6.3f shows the proportion of the total carbon emissions that result from the sections (shown in Figure 6.2) of the alignment for the 100 kph case. The sections shown on the graph refer to the following:

- Section 1 – Section A
- Section 2 – Section B
- Section 3 – Section C
- Section 4 – Section D
- Section 5 – Section E
- Section 6 – Section F
- Section 7 – Section G

Results in the figure emphasise how the steeper downhill graded sections can reduce emissions; Section 5 which refers to the decline in the +6 -6 alignment only contributes a small proportion, whereas in the +2 -2 alignment it contributes more significantly. Figure 6.3f also demonstrates the large contributions from the sag curves (Section 2 and 6) and crest curve (Section 4) on the steeper grades; the steeper gradients require longer transition curve lengths and therefore the offsetting effect of the downhill gradient on the uphill gradient is reduced.

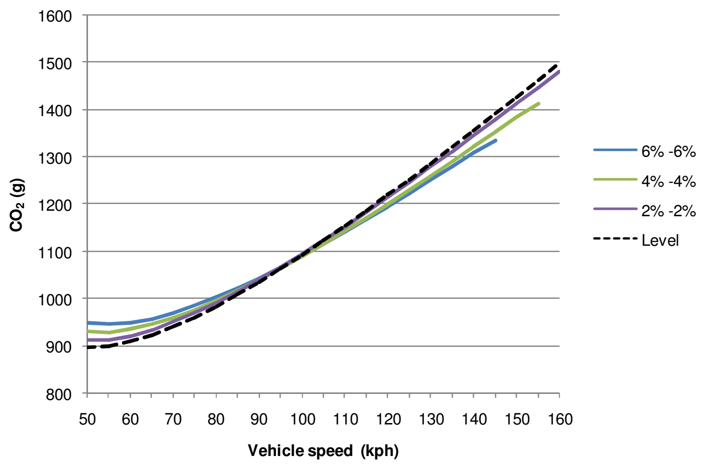


Figure 6.3a CO_2 for a petrol car on the symmetrical hill alignments

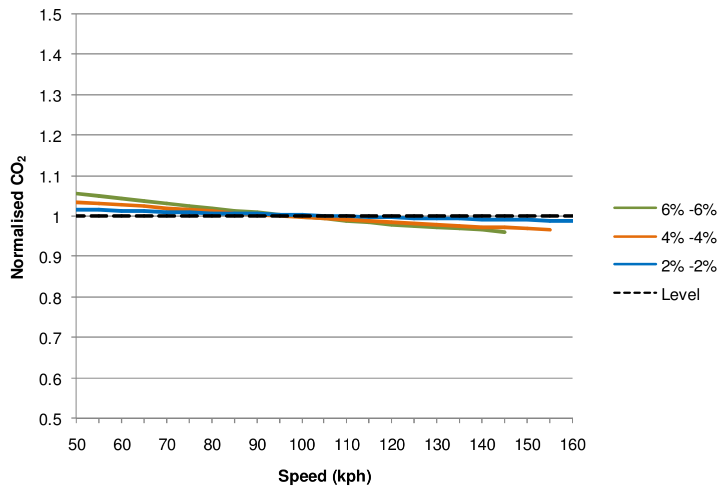


Figure 6.3b Normalised CO_2 for a petrol car on the symmetrical hill alignments

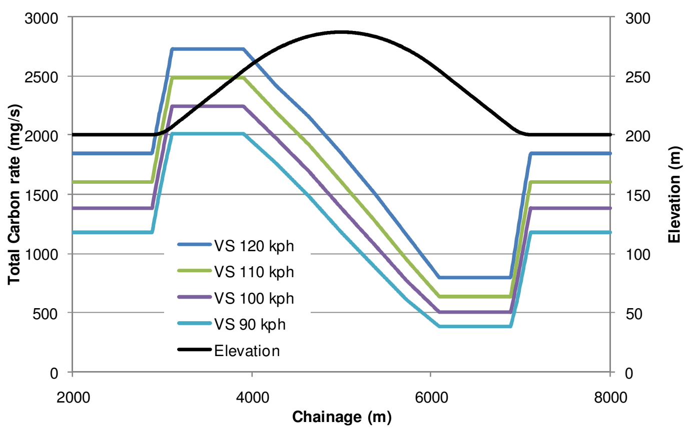


Figure 6.3c Total carbon for a petrol car on the +6 -6 alignment

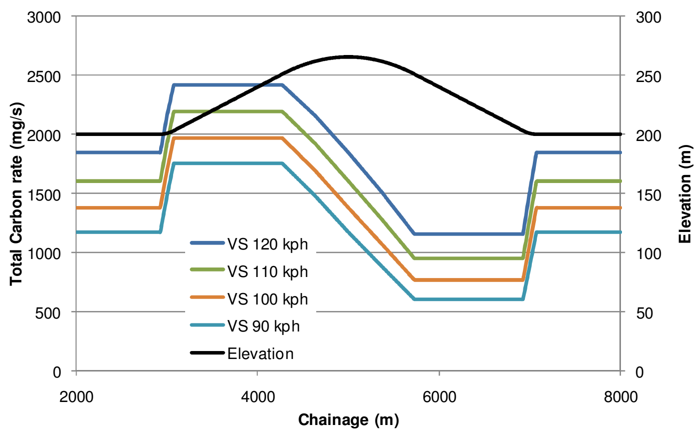


Figure 6.3d Total carbon for a petrol car on the +4 -4 alignment

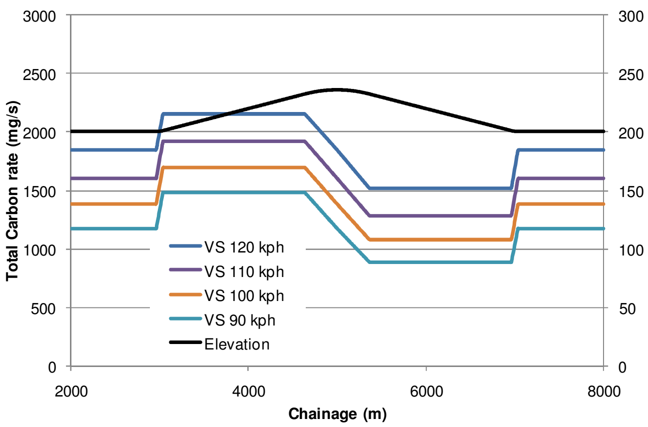


Figure 6.3e Total carbon for a petrol car on the +2 -2 alignment

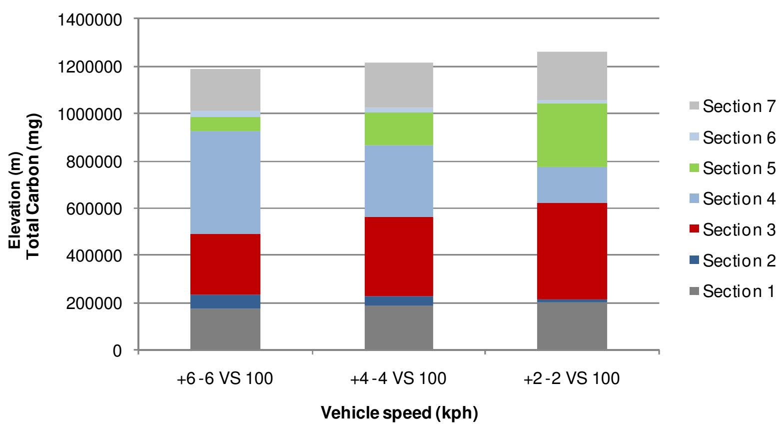


Figure 6.3f Total Carbon emissions for a petrol car by section on hill alignments at vehicle speed of 100 kph

Figure 6.4 shows the effect of the valley alignments on the petrol car. Similarly for the hill, Figure 6.4a shows the CO_2 emissions across a range of speeds for all four vertical alignments; -6 +6, -4 +4, -2 +2 and level. A similar pattern is shown as for the petrol car over the hill alignments; with the graded alignments resulting in lower emissions than the level alignment for certain speeds.

To highlight this effect the emissions have been normalised to the emissions resulting from the petrol car travelling on the level alignment at that particular speed, as shown in Figure 6.4b.

The petrol car emissions when operating on the varying alignments of the valley terrain are very similar to the emissions on the hill gradients. This was to be expected due to both sets of alignments having the same gradients and being of the same dimensions. The differences result from the shorter length of the transition curves between the downhill and uphill sections.

Figures 6.5c, 6.5d and 6.5e show the total carbon emission rate as the petrol car travels over the different alignments. The shorter sag curve means there is more opportunity for the offsetting effect to occur.

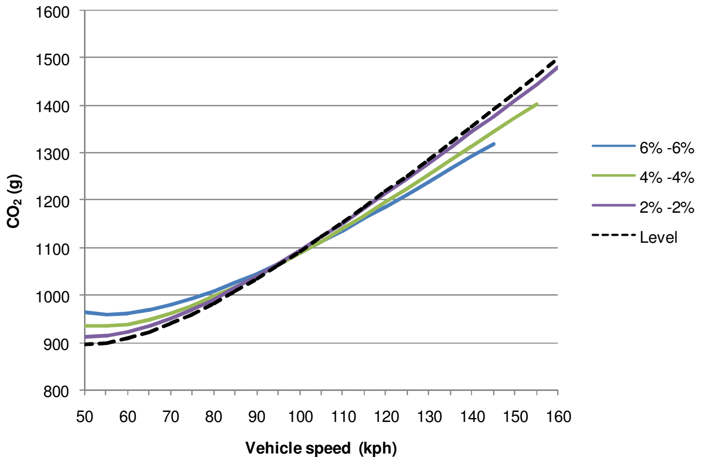


Figure 6.4a CO_2 for a petrol car on the valley alignments

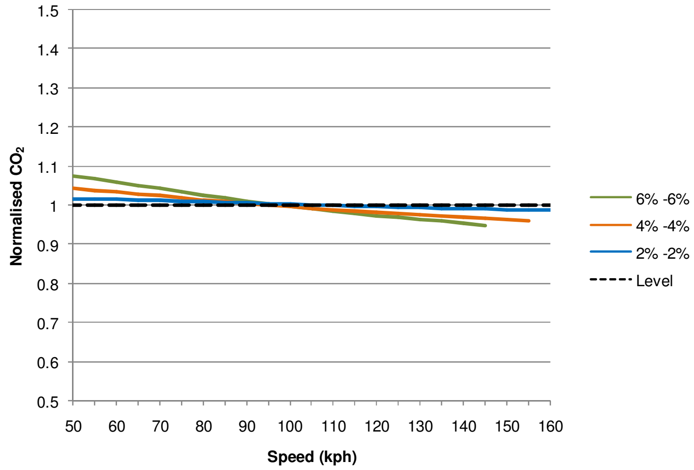


Figure 6.4b Normalised CO_2 emissions for a petrol car on the valley alignments

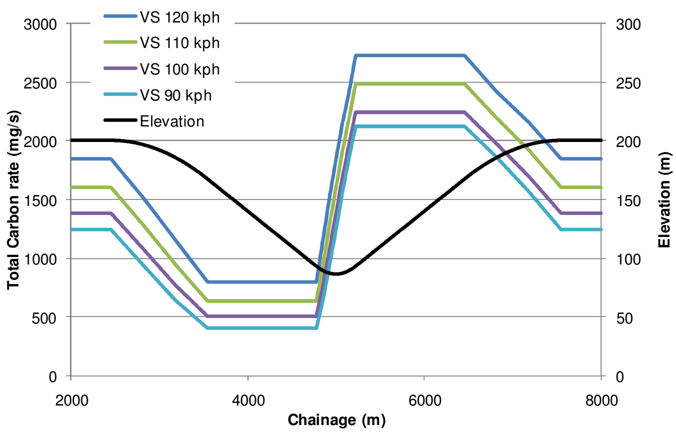


Figure 6.4c Total carbon rate for a petrol car on the -6 +6 valley alignment

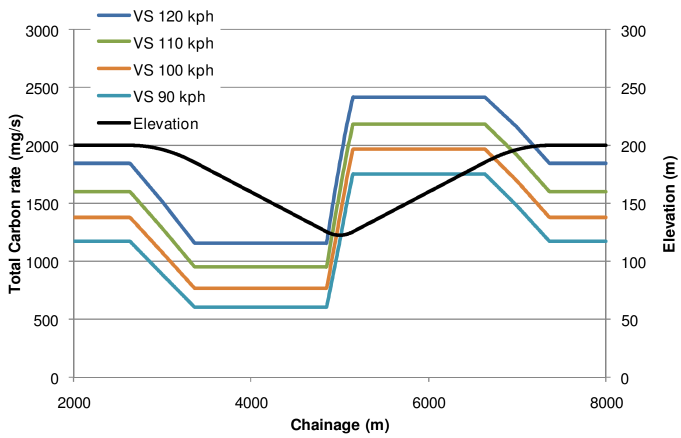


Figure 6.4d Total carbon rate for a petrol car on the -4 +4 valley alignment

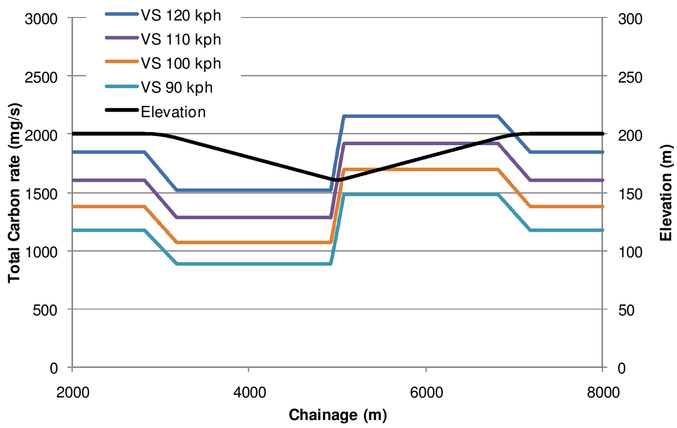


Figure 6.4e Total carbon rate for a petrol car on the -2 +2 valley alignment

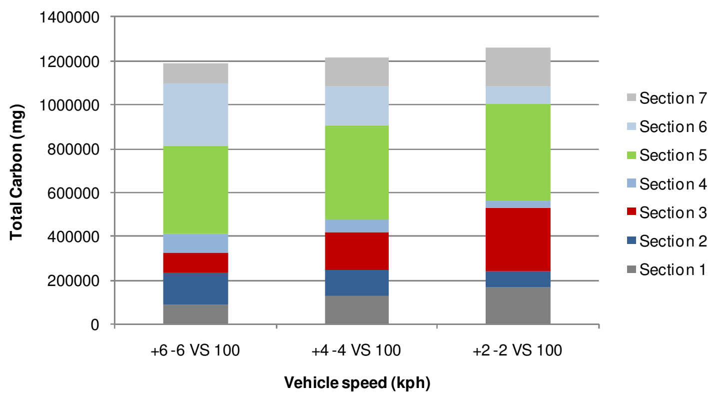


Figure 6.4f Total carbon emissions for a petrol car by section on the valley alignments at a vehicle speed of 100kph

6.2.2 The internal combustion engine (ICE)

The ICE has low efficiency at low engine loads, and it is important to remember that the engine load is not the engine speed. To demonstrate this Figure 6.5 shows the maximum torque curve and the road load torque curve; the difference between the two curves is the available torque. This available torque is present to allow a vehicle to change its operating conditions. For example, for a vehicle operating with an engine speed of 3000 rpm, there is torque available should the vehicle need more power to accelerate or travel uphill.

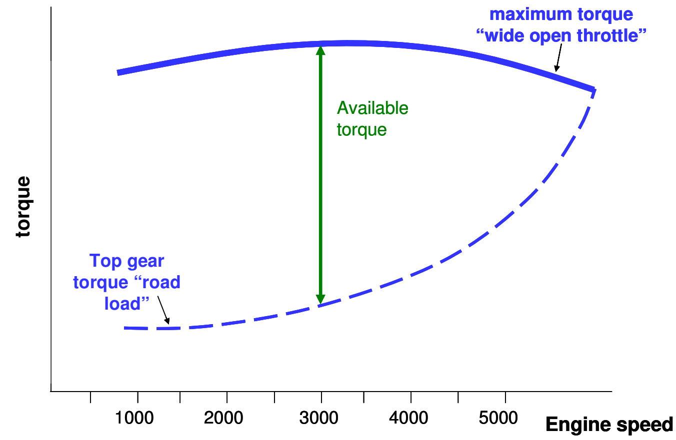


Figure 6.5 Depiction of available torque (Collings, 2009)

Figure 6.6 shows the same illustrative engine map with the fuel consumption curves included. It is apparent that as the torque increases and becomes closer to the maximum torque curve, the fuel consumption is less - with the most efficient operating point indicated on the diagram. Therefore, the closer the engine gets to the maximum torque, the more efficient it becomes. The reason for this is that the power that is available is being usefully utilised.

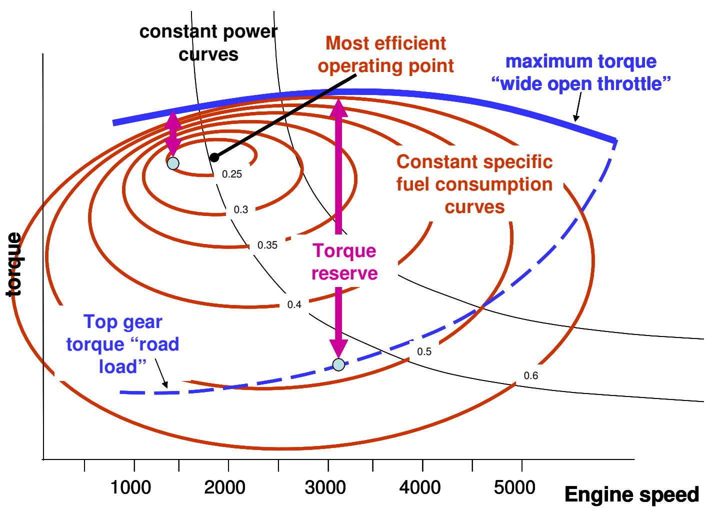


Figure 6.6 Depiction of engine efficiency (Collings, 2009)

The ICE varies hugely in efficiency dependent on the operating requirements, and for this reason it is possible for fuel consumption figures to be counter-intuitive. For example, a vehicle traversing a hill with an equal incline and decline can require less fuel than a vehicle on a level road of equal length. The conservation of energy principle can be used to argue against the feasibility of this; with a vehicle traversing a hill consuming less fuel and hence appearing to create energy. If the type of engine in question were to have a high level of efficiency then the conservation of energy argument would stand true; with the power output being expected to approximately match the input.

Figure 6.7 shows how the torque would increase if a vehicle were travelling uphill; more of the available torque would be utilised, meaning the engine would work more efficiently.

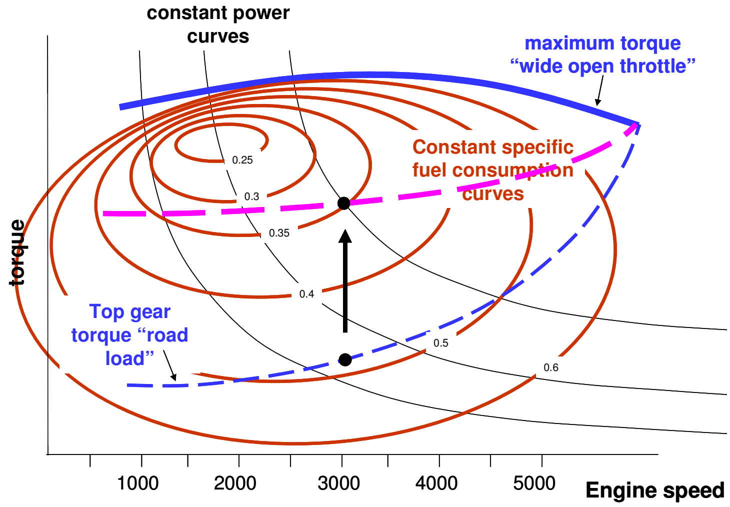


Figure 6.7 Depiction of engine efficiency with increased torque (Collings, 2009)

The reduction in CO_2 at the higher speeds can be attributed to the increase in fuel required to get the vehicle up the hill being offset by the reduction in fuel required to get the vehicle down the hill; resulting in a decrease when compared to a vehicle travelling on a level road. At the lower speeds the decrease in fuel consumption on the decline does not offset the increase in fuel consumption on the incline and hence results in higher emissions than on a level highway. For all gradients, there is a certain speed when the downhill section no longer offsets the uphill section, and the non-level highways begin to increase emissions.

6.2.3 Articulated HGVs

The CO_2 emissions from the half-laden articulated HGV have been shown in detail in Figure 6.8, in the same way that they were presented for the petrol car, in order to enable direct comparison.

Figure 6.8a shows the normalised CO_2 emissions across a range of speeds for all four vertical alignments; +6 -6, +4 -4, +2 -2 and level. The range of speeds varies due to the PHEM model only producing realistic emission results over a certain speed range.

For the level alignment, shown in Figure 6.8a, the pattern of the emissions increasing with increasing speed that is seen for the petrol car is also apparent here. However, for the half-laden articulated HGV, there is no speed at which it is beneficial to travel on a graded alignment. Figure 6.8b demonstrates that this can be as much as 90% higher for the +6 -6 alignment at 50 kph, where the emissions have been normalised to the emissions resulting from the HGV when travelling on the level alignment at that particular speed.

Across all alignments it is beneficial for the HGVs to operate on a level highway, unlike for the lighter vehicles, which can benefit from graded alignments. Also, for the lighter vehicles the difference between the graded alignment and level alignment is in the region of +/-10%. Whereas, for the HGV, the difference is as much as +90% at the lowest speeds considered.

Figure 6.8f shows the proportion of the total carbon emissions that result from the sections of the alignment for the 50 kph case – with the sections having been defined in Section 6.2.1. The figure shows the large proportion of emissions that emanate from the incline (Section 3). This emphasises how the steeper downhill graded sections can reduce emissions; Section 5 in the +6 -6 alignment only contributes a small proportion, whereas in the +2 -2 alignment it contributes more significantly. Figure 6.8f also demonstrates the large contributions from the sag and crest curve sections on the steeper grades; this is due to the transition curves also being graded, and from these results it is apparent that any gradient increases HGV emissions.

Figure 6.9 shows the articulated HGV emissions for all load cases on the hill alignments. The normalised CO_2 results for an articulated HGV are presented for an un-laden vehicle in Figure 6.9a, a half-laden vehicle in Figure 6.9c, and a fully-laden vehicle in Figure 6.9e. The actual CO_2 emissions for an un-laden articulated HGV are shown in Figure 6.9b, a half-laden articulated HGV in Figure 6.9d, and a fully-laden articulated HGV in Figure 6.9f.

There is no benefit in operating an articulated HGV on a graded alignment – this stands true for all load cases. When considering the level alignment emissions alone across the three load cases there is significant increases in emissions as a result of the additional load without the influence of gradients.

The results for the articulated HGV are shown in Figure 6.10 for all load cases for the valley; both the total CO_2 emissions and normalised CO_2 emissions are shown for each load case. The negative effects of the articulated HGVs traversing graded alignments are much more apparent on the valley alignments than on the hill alignments. This is due to the shorter crest and sag curves increasing the lengths of the graded sections – any gradient increases overall emissions and so any increase in the length of the graded sections will further increase the detrimental effect.

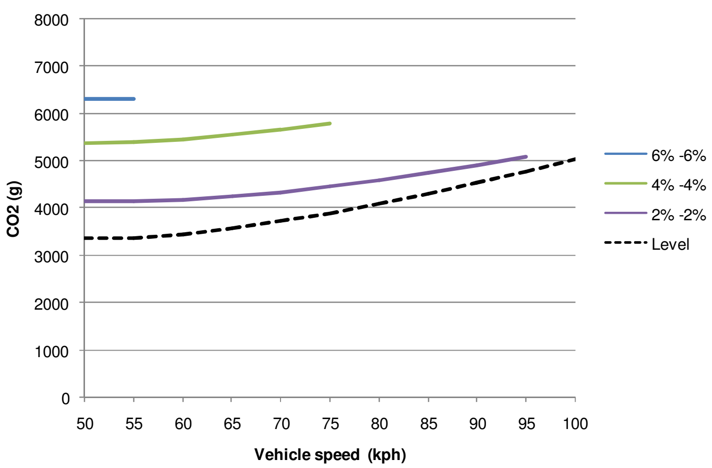


Figure 6.8a CO_2 for a half-laden articulated HGV on the hill alignment

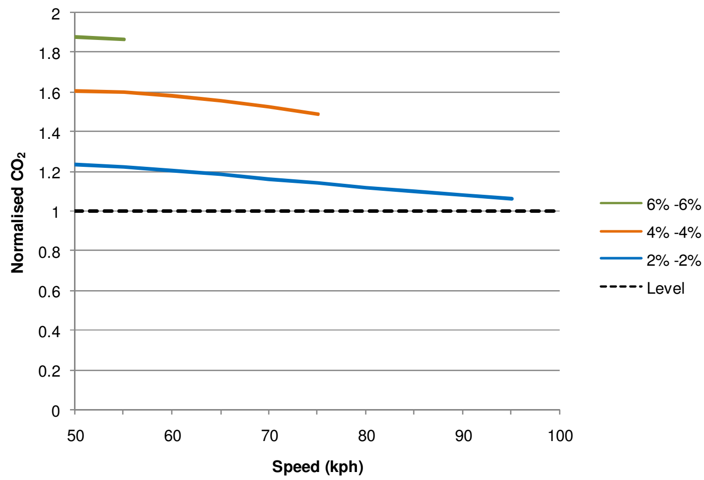
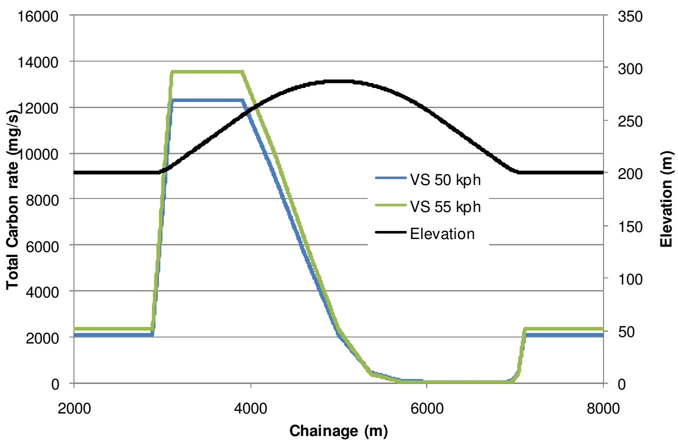


Figure 6.8b Normalised CO_2 for a half-laden articulated HGV on the hill alignment



zFigure 6.8c Total carbon rate for a half-laden articulated HGV on the +6% -6% alignment

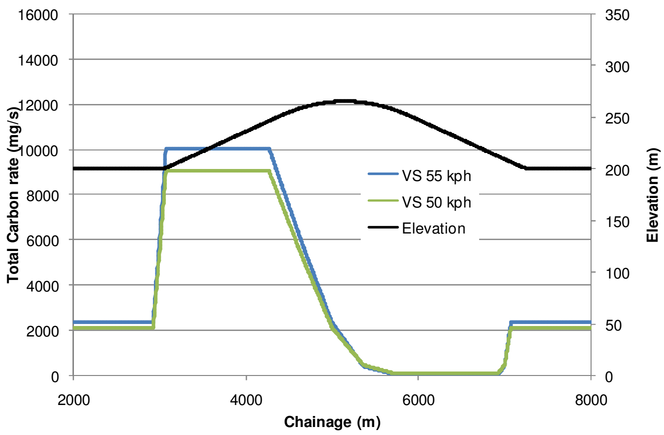


Figure 6.8d Total carbon rate for a half-laden articulated HGV on the +4% -4% alignment

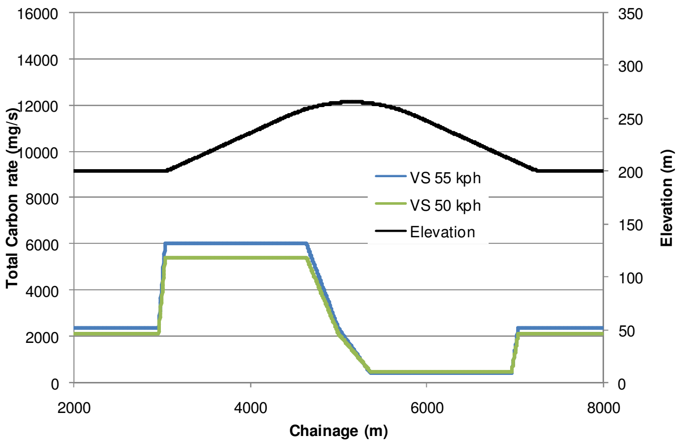


Figure 6.8e Total carbon rate for a half-laden articulated HGV on the +2% -2% alignment

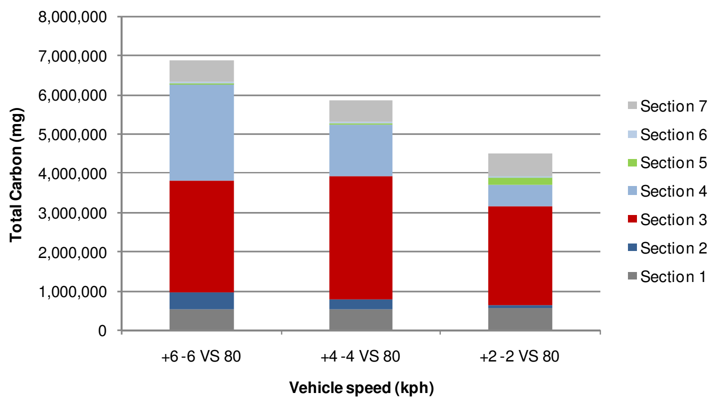


Figure 6.8f Total carbon emissions for a half-laden articulated HGV by section on the hill alignments at vehicle speed of 100 kph

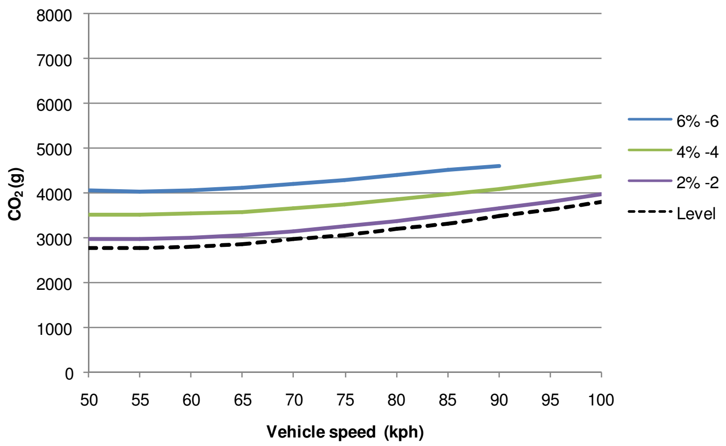


Figure 6.9a CO_2 for an un-laden articulated HGV on the hill alignments

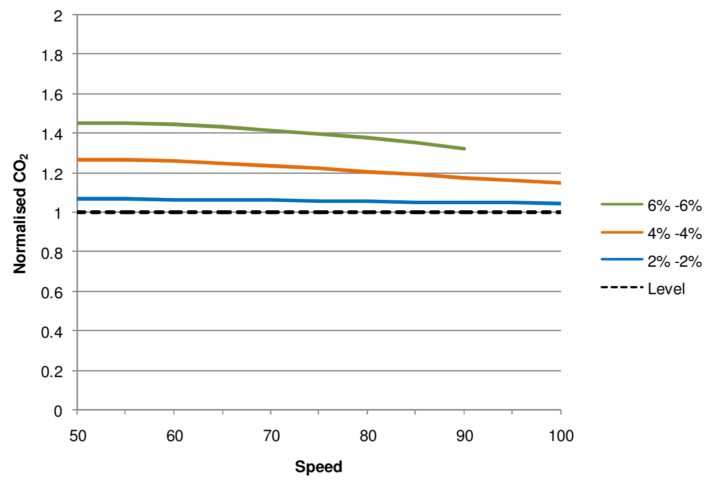


Figure 6.9b Normalised CO_2 emissions for an un-laden articulated HGV on the hill alignments

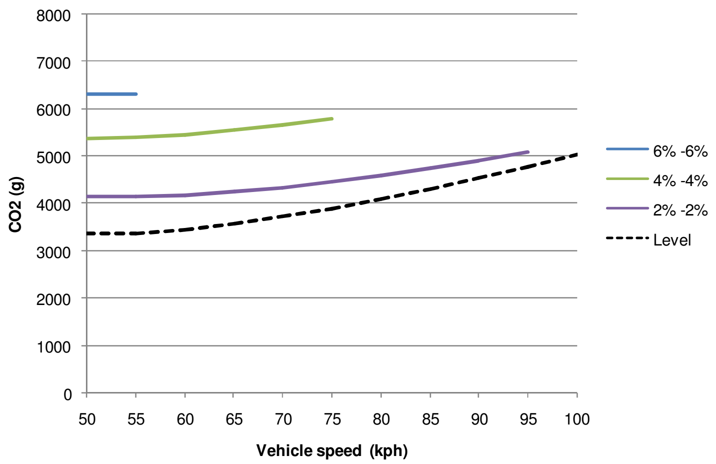


Figure 6.9c CO_2 for a half-laden articulated HGV on the hill alignments

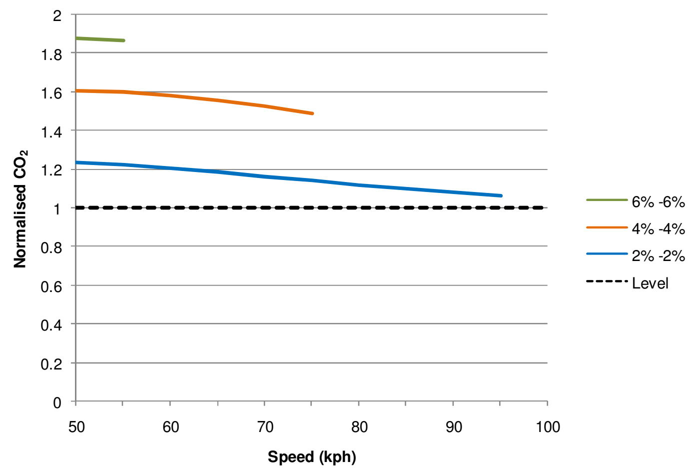


Figure 6.9d Normalised CO_2 emissions for a half-laden articulated HGV on the hill alignments

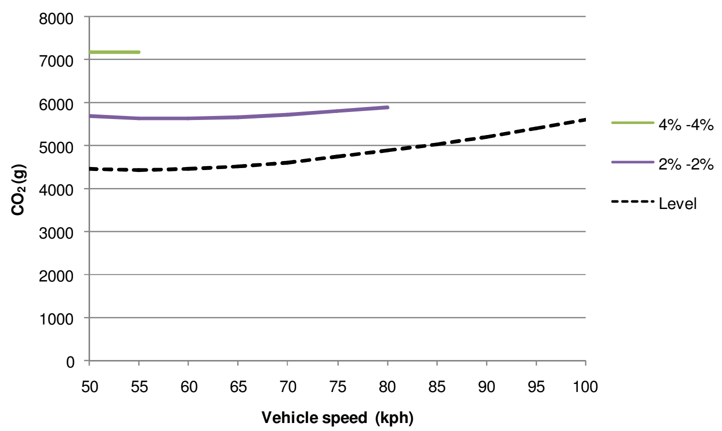


Figure 6.9e CO_2 for a fully-laden articulated HGV on the hill alignments

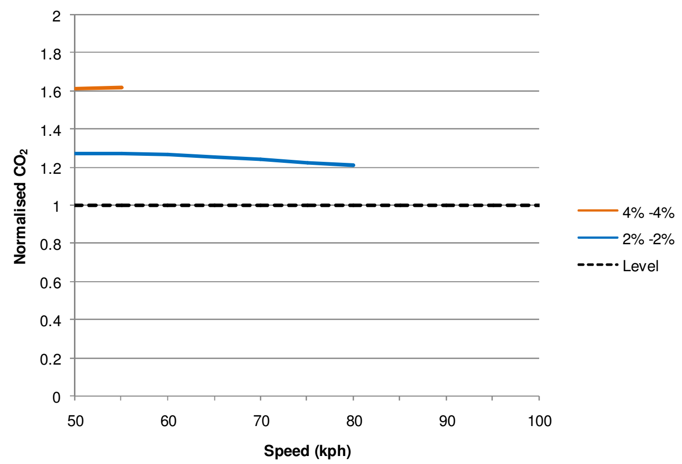


Figure 6.9f Normalised CO_2 emissions for a fully-laden articulated HGV on the hill alignments

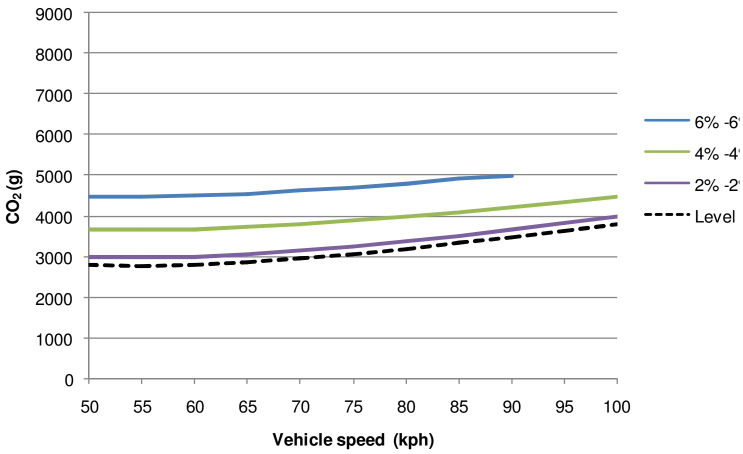


Figure 6.10a CO_2 for an un-laden artic HGV on the valley alignments

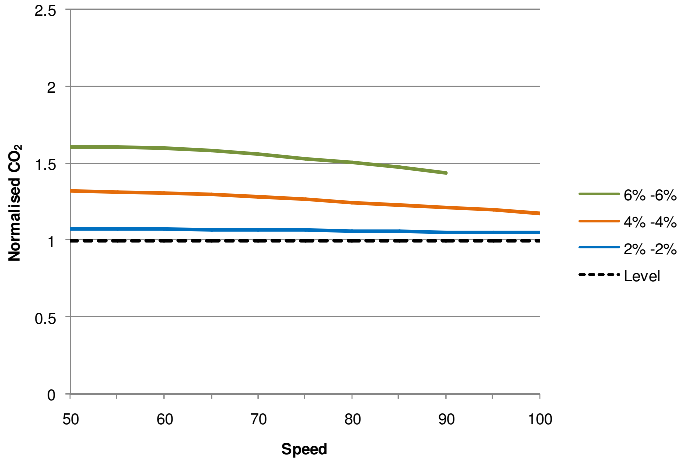


Figure 6.10b Normalised CO_2 for an un-laden artic HGV on the valley alignments

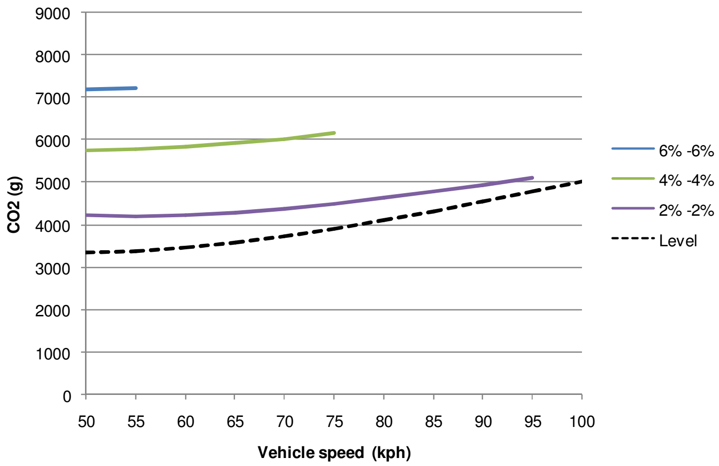


Figure 6.10c CO_2 for a half-laden artic HGV on the valley alignments

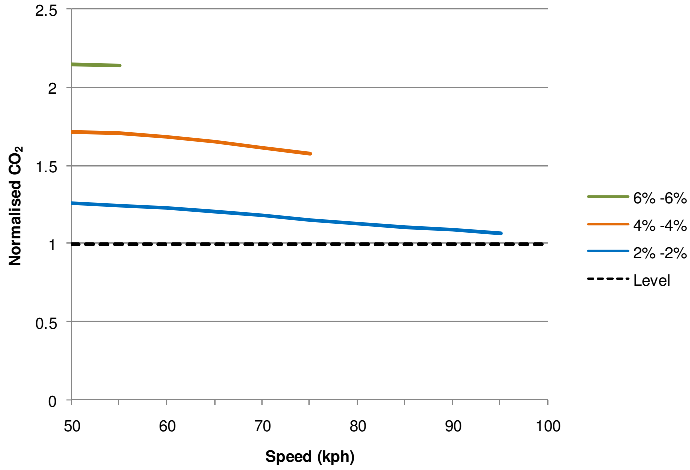


Figure 6.10d Normalised CO_2 for an half-laden artic HGV on the valley alignments

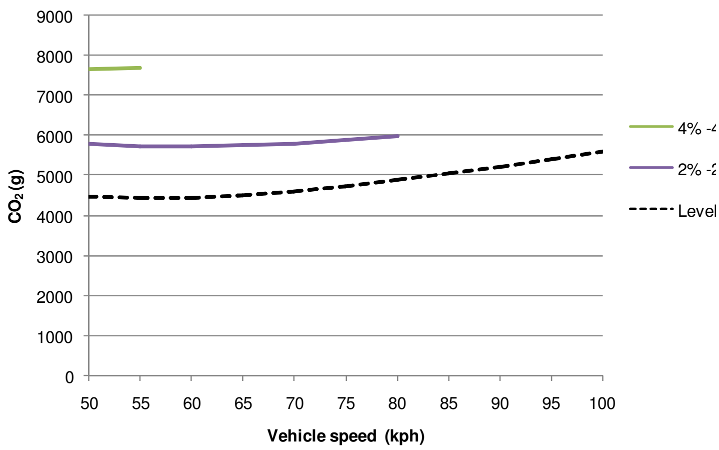


Figure 6.10e CO_2 for a fully-laden artic HGV on the valley alignments

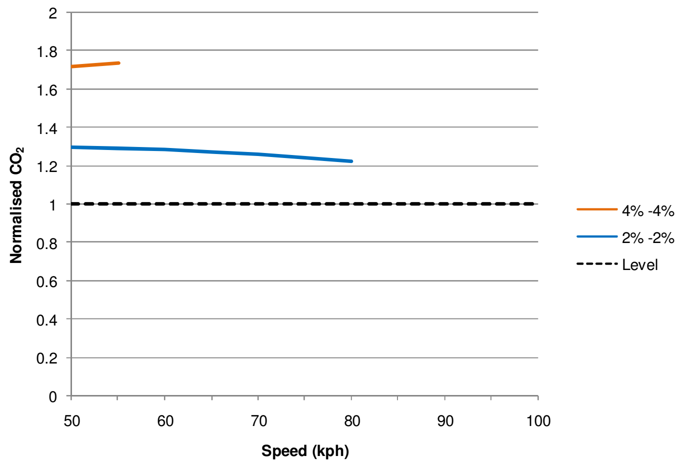


Figure 6.1 f Normalised CO_2 for an fully-laden artic HGV on the valley alignments

6.2.4 Diesel car and LGV

Results shown previously for the petrol car are also reflected by the diesel car and LGV – with the downhill section offsetting the uphill section, and in some cases resulting in fewer emissions than would be produced on a level alignment.

Despite it appearing beneficial to have a graded alignment when vehicles are travelling at higher speeds, the absolute emissions indicate that at the higher speeds more CO_2 is produced, as shown in Figure 6.11a. The rate of increase in CO_2 emissions as the speed increases for the diesel engine car is much lower than for the petrol engine car; with the curve in Figure 6.11a being much flatter; due to the additional available torque, meaning that when the vehicle speed increases and increases the drag, although the engine has to work harder, the utilisation of the already available torque means that it is working more efficiently.

For the LGV, shown in Figure 6.11c, the offsetting effect is apparent on the alignments; the speed range at which the offsetting effect occurs for the LGV for all alignments is similar to the diesel car. Despite it appearing beneficial to have a graded alignment when vehicles are travelling at higher speeds, the absolute emissions indicate that at the higher speeds more CO_2 is produced.

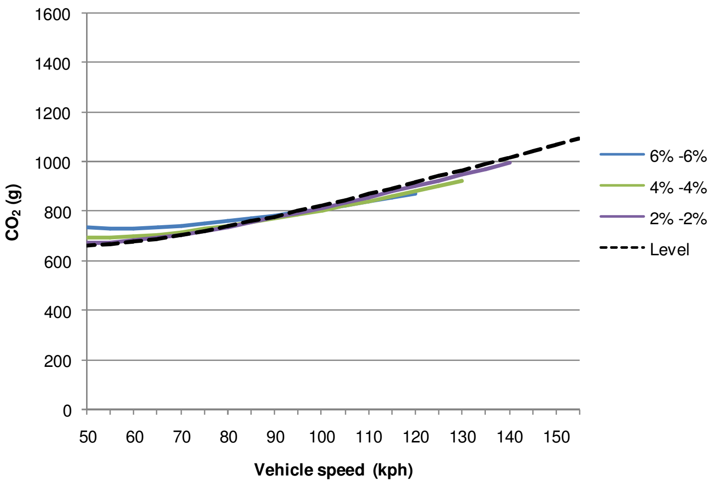


Figure 6.11a CO_2 for a diesel car on the hill alignments

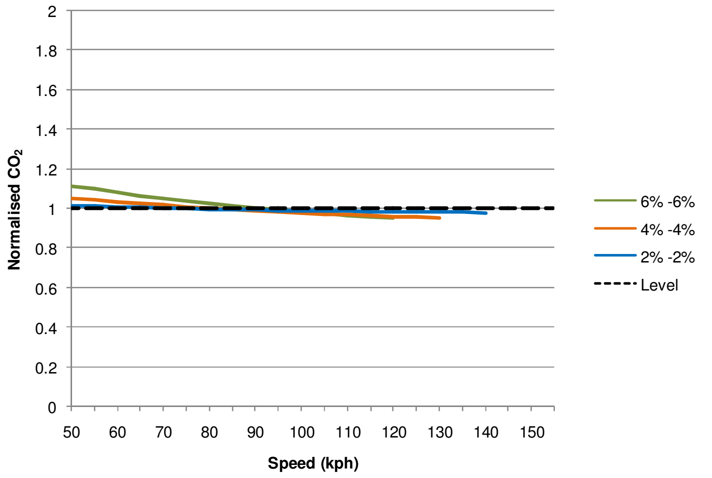


Figure 6.11b Normalised CO_2 emissions for a diesel car on the hill alignments

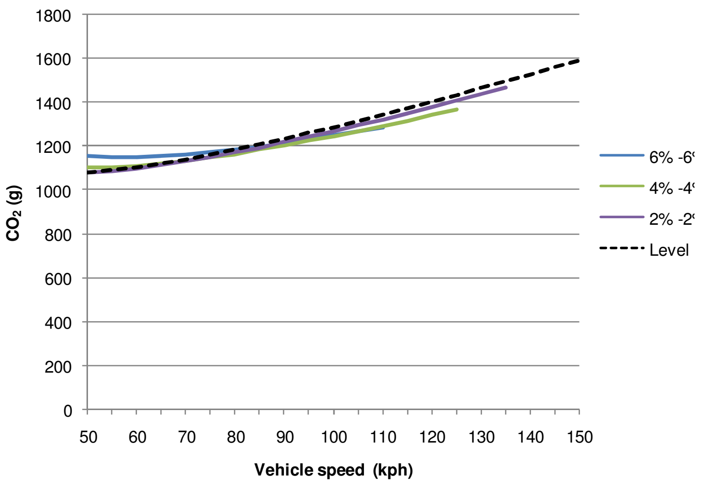


Figure 6.11c CO_2 for a LGV on the hill alignments

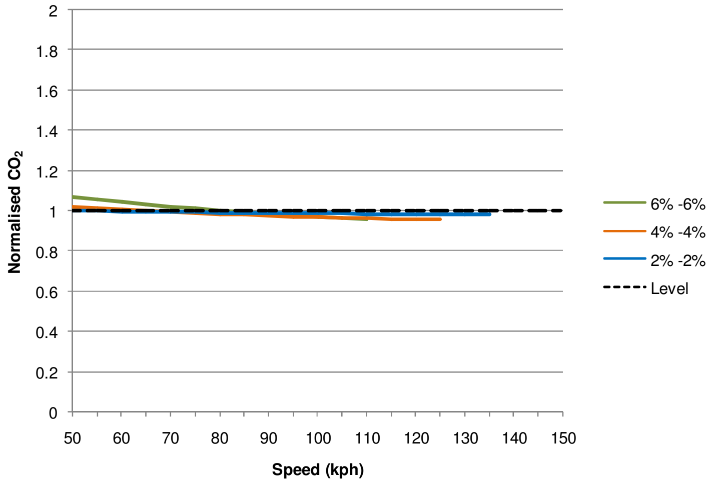


Figure 6.11d Normalised CO_2 emissions for a LGV on the hill alignments

In Figure 6.12a the normalised emissions for the diesel car on the different alignments for the symmetrical valley are shown. When compared to the diesel car emissions on the symmetrical hill alignments, the emissions are lower. This is the same for the diesel LGV as shown in Figure 6.12c and 6.12d; the additional opportunity to travel up and down a steep gradient through the use of shorter sag curve also benefits this vehicle type. It appears that the diesel engine vehicles, when positively affected by gradients, receive a greater positive effect than for the petrol engine cars.

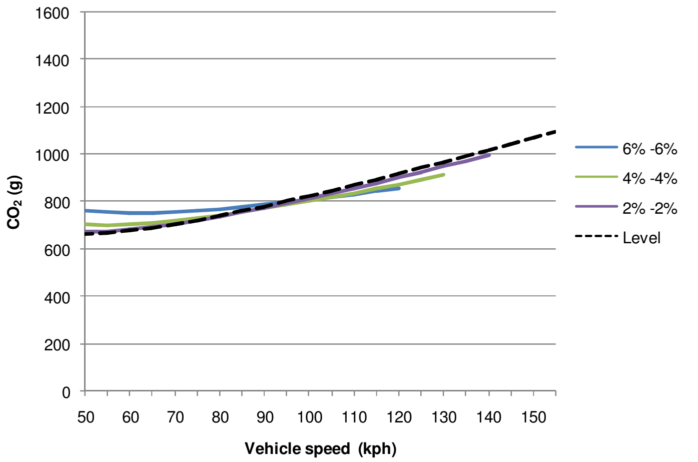


Figure 6.12a CO_2 for a diesel car on the valley alignments

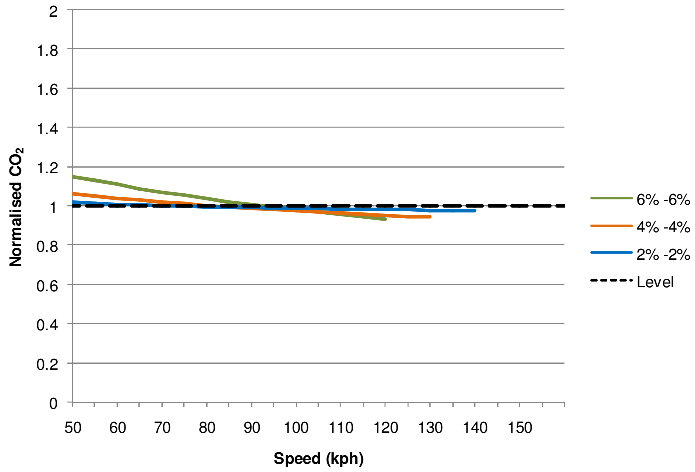


Figure 6.12b Normalised CO_2 emissions for a diesel car on the valley alignments

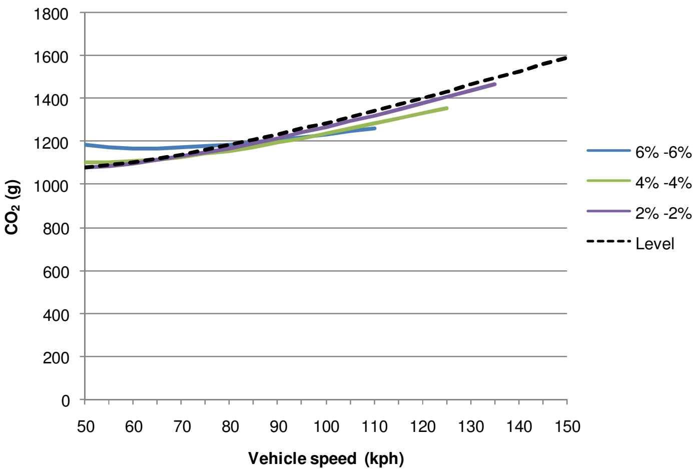


Figure 6. 12c CO_2 for an LGV on the valley alignments

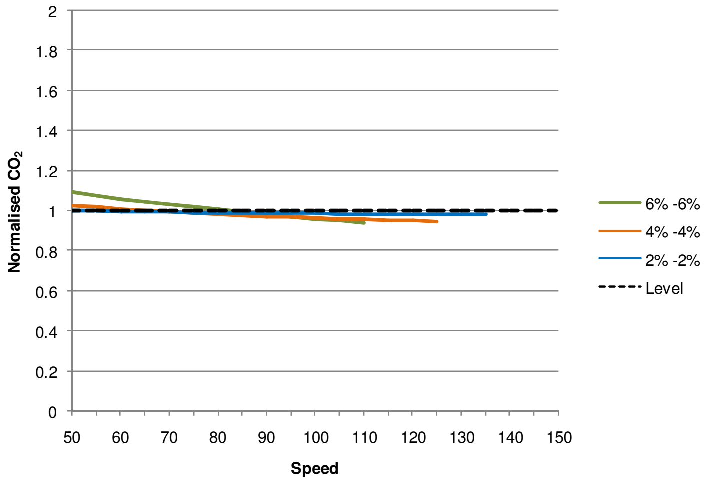


Figure 6.12d Normalised CO_2 for an LGV on the valley alignments

6.2.5 Rigid HGVs

In the following section, the normalised and absolute emissions are presented for the Rigid HGV for the unladen, half-laden and fully-laden load cases. These are shown for the hill in Figure 6.13, and in Figure 6.14 for the valley.

The actual CO_2 emissions for an un-laden Rigid HGV are shown in Figure 6.13a, a half-laden rigid HGV in Figure 6.13c, and a fully-laden Rigid HGV in Figure 6.13e. The normalised CO_2 results for a Rigid HGV are presented in Figure 6.13b for an un-laden vehicle, in Figure 6.13d for a half-laden vehicle, and in Figure 6.13f for a fully-laden vehicle.

A similar reaction to the alignments across all load cases is apparent in Figure 6.13. The graded alignments have a detrimental effect on the emissions and it would be preferable for the vehicles to operate on the level alignment. As shown in Figure 6.13b, the +6 -6 alignment at the lowest speed results in an increase in emissions of 20%. For the half-laden case, in Figure 6.13c, the increase is around 30%. For the fully-laden case, in Figure 6.13e, the increase is around 40%.

The results for the rigid HGV are shown in Figure 6.14 for all load cases for the valley alignments; both the total CO_2 emissions and normalised CO_2 emissions and are shown for each load case. Only on the +2 -2 alignment does the level alignment produce higher emissions than the graded alignment, which occurs at the higher end of the speed range.

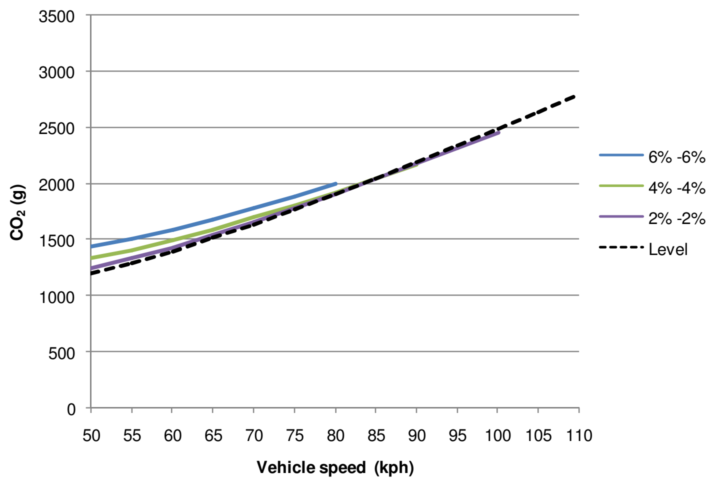


Figure 6.13a CO_2 for an un-laden rigid HGV on the hill alignments

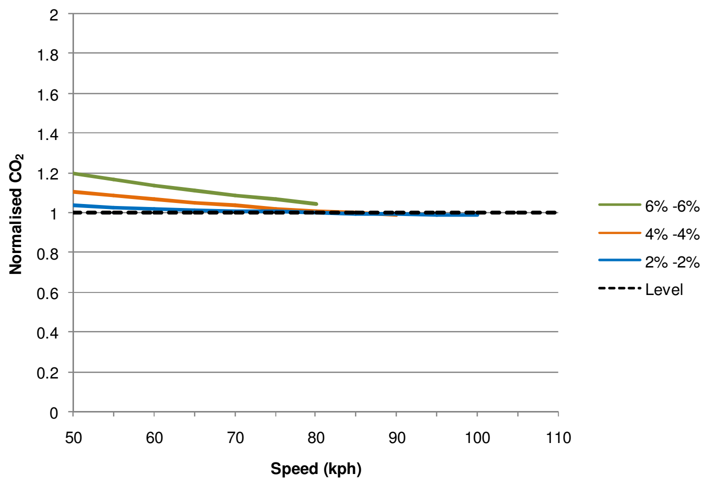


Figure 6.13b Normalised CO_2 emissions for an un-laden rigid HGV on the hill alignments

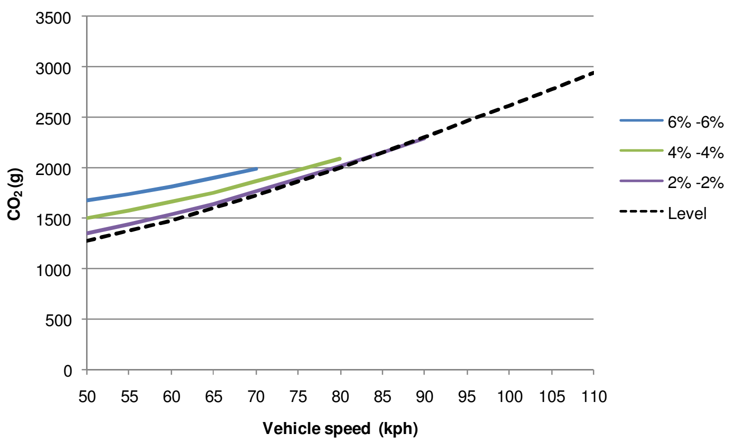


Figure 6.13c CO_2 for a half-laden rigid HGV on the hill alignments

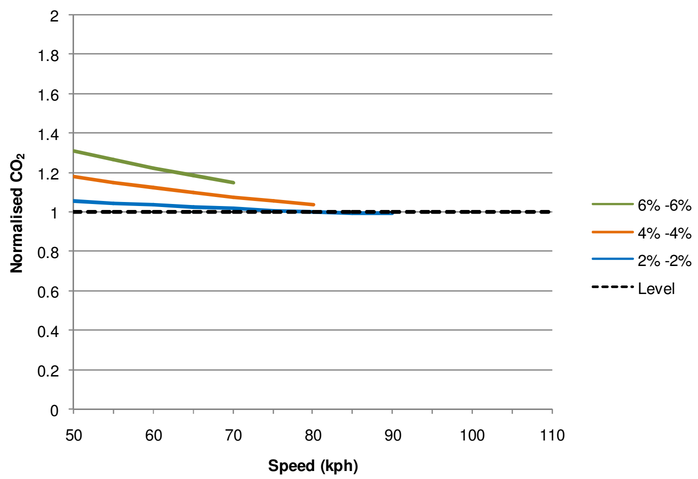


Figure 6.13d Normalised CO_2 emissions for a half-laden rigid HGV on the hill alignments

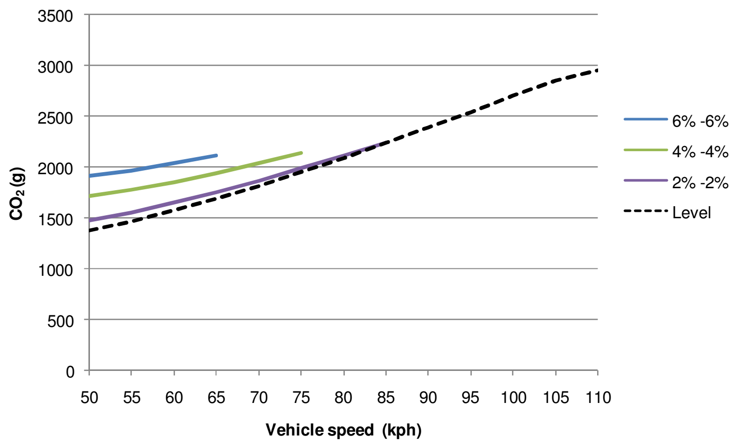


Figure 6.13e CO_2 for a fully-laden rigid HGV on the hill alignments

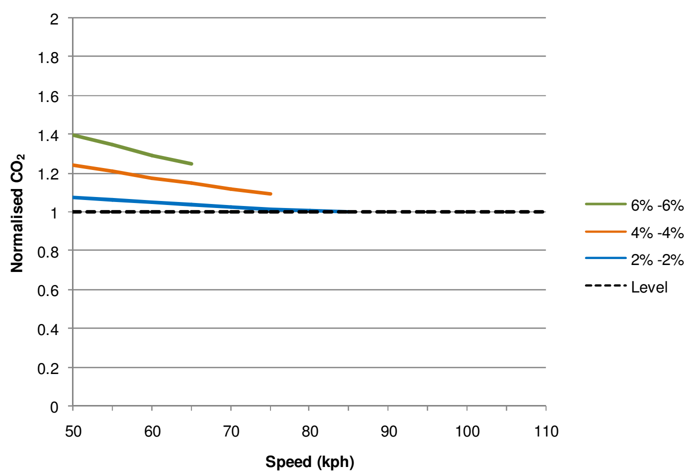


Figure 6.13f Normalised CO_2 emissions for a fully-laden rigid HGV on the hill alignments

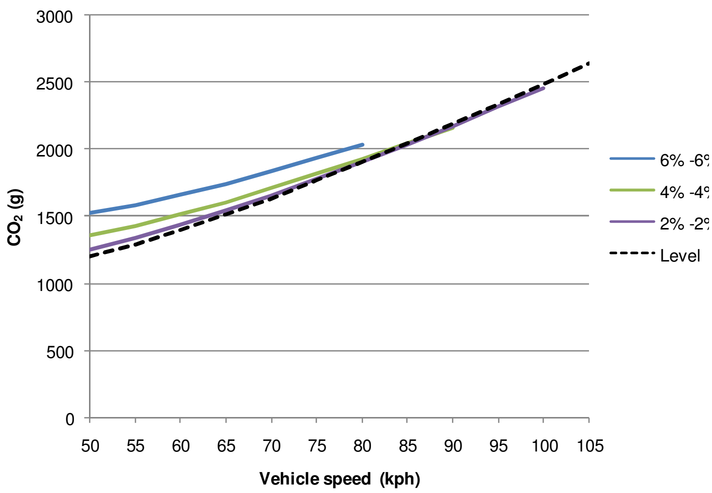


Figure 6.14a CO_2 for an un-laden rigid HGV on the valley alignments

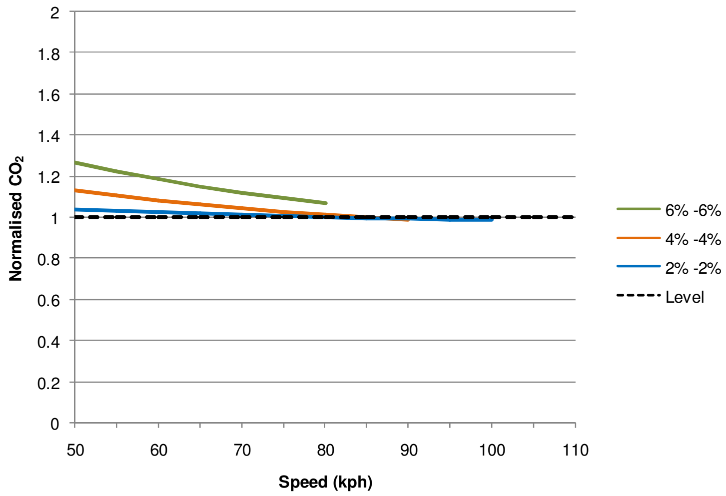


Figure 6.14b Normalised CO_2 for an un-laden rigid HGV on the valley alignments

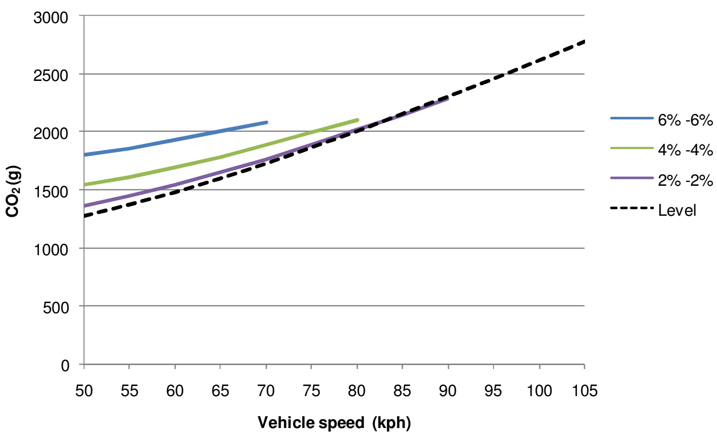


Figure 6.14c CO_2 for a half-laden rigid HGV on the valley alignments

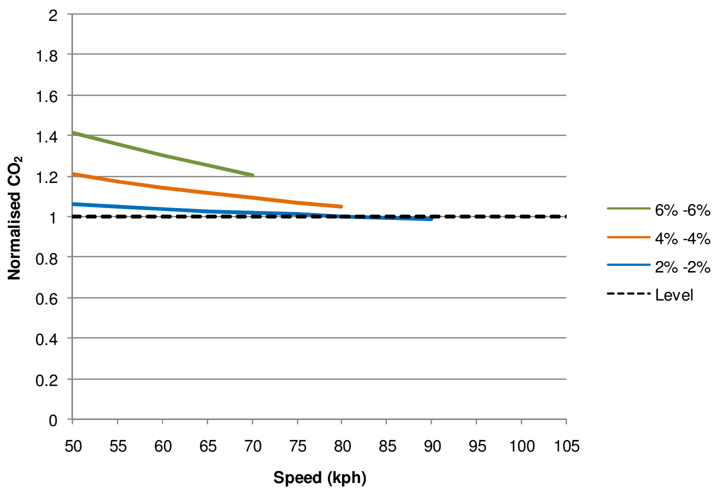


Figure 6.14d Normalised CO_2 for a half-laden rigid HGV on the valley alignments

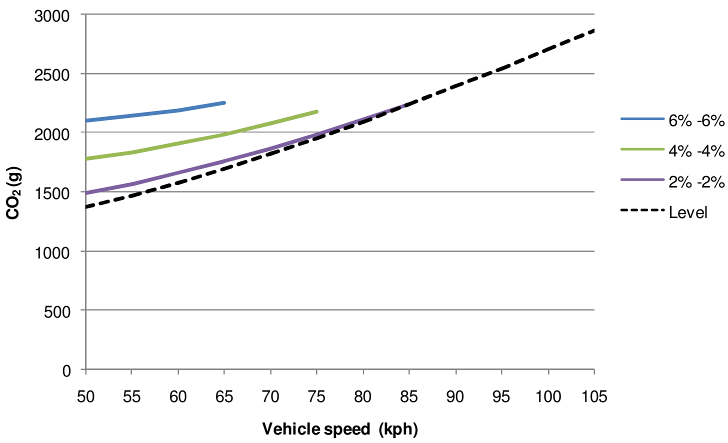


Figure 6.14e CO_2 for a fully-laden rigid HGV on the valley alignments

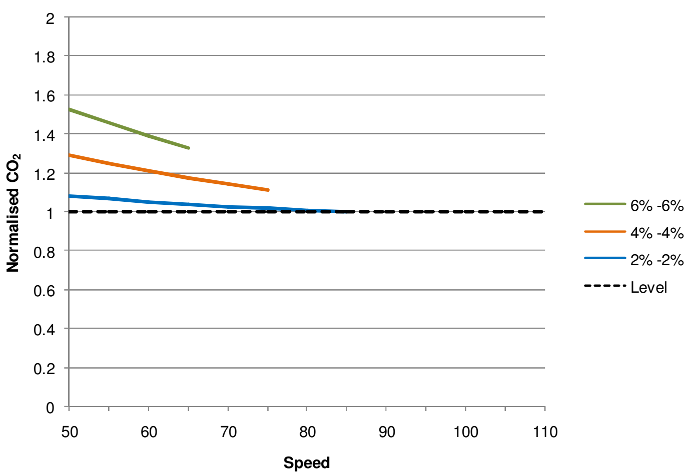


Figure 6.14f Normalised CO_2 for a fully-laden rigid HGV on the valley alignments

6.2.6 Summary

Nine different vehicles have been assessed over the level and graded alignments that were designed for a simple hypothetical hill and valley terrain. To summarise the overall effects of the graded alignments on vehicle emissions, Figure 6.15 shows the CO_2 emission by vehicle type on the level alignment (black data point), and the range of emissions (black range bars) resulting from the vehicles operating on the graded alignments. Figure 6.15a, 6.15b and 6.15c refer to the 90 kph, 70 kph and 50 kph speeds respectively.

In Figure 6.15a for the speed of 90 kph, there is little effect on the lighter vehicles – petrol car, diesel car and LGV – with a very small difference between the level and graded emissions. Conversely, the articulated HGV is largely affected by the gradients, with the graded emissions being significantly higher than the level emissions. The rigid HGVs, although classed as HGVs, show the characteristics of the lighter vehicles, by benefitting from the graded alignments. This can be explained by the size of the Rigid HGV assessed, which is at the smaller end of the Rigid HGV scale.

These presentation methods allow the benefits of the graded alignments on the lighter vehicles to be placed into the context. Although it appears advantageous to operate light vehicles on such alignments the resulting consequence on the heavier articulated HGVs outweighs any benefits.

In summary, Figure 6.15 demonstrates how lighter vehicles are slightly affected by gradients and how heavier vehicles are majorly negatively affected. The apparent benefit, shown earlier in this chapter, of operating light vehicles on a graded alignment is placed into perspective against the large negative impacts of these gradients on heavier vehicle emissions.

To summarise the overall effects of the graded valley alignments on vehicle emissions, Figure 6.16 shows the CO_2 emission by vehicle type. There is little effect on the lighter vehicles – petrol car, diesel car and LGV – with a very small difference between the level and graded emissions. Conversely, the articulated HGVs are hugely affected by the gradients, with the graded emissions being significantly higher than the level emissions.

As seen in the previous results, the lighter vehicles can be more positively affected by the longer graded sections and shorter transition curves associated with the valley alignments. However, from comparing Figure 6.15 and 6.16 these additional positive benefits are small. Previous results also demonstrated how the valley attributes negatively impacted the heavier vehicles; the scale of the negative impacts is greater than the positive impacts on the lighter vehicles.

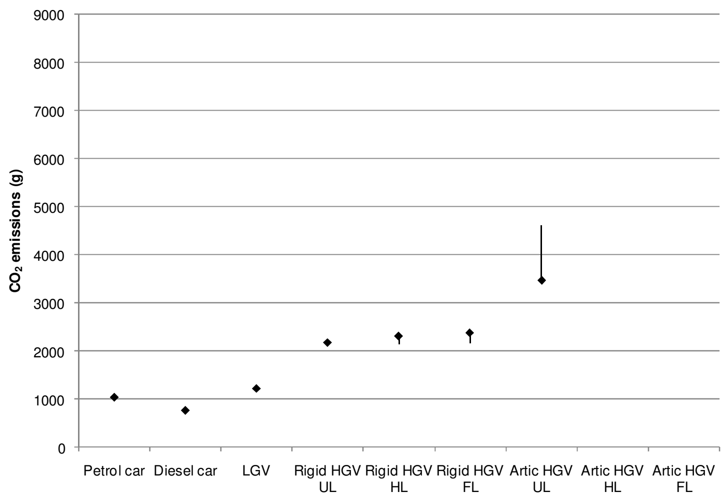


Figure 6.15a Variation in CO_2 emissions for all vehicle types over all hill alignments at 90 kph

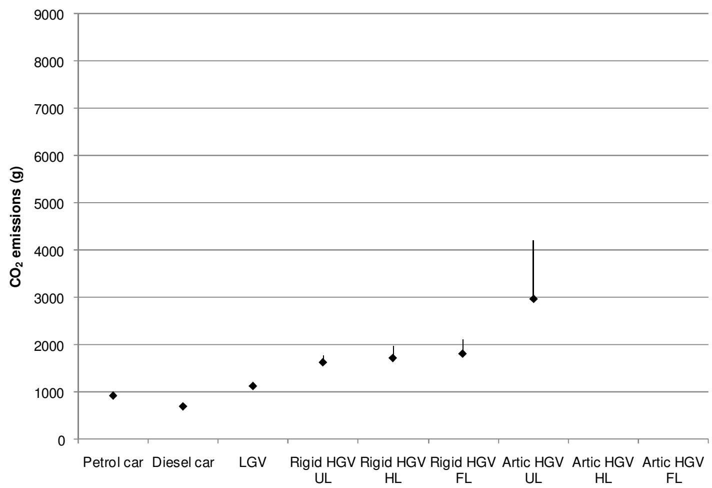


Figure 6.15b Variation in CO_2 emissions for all vehicle types over all hill alignments at 70 kph

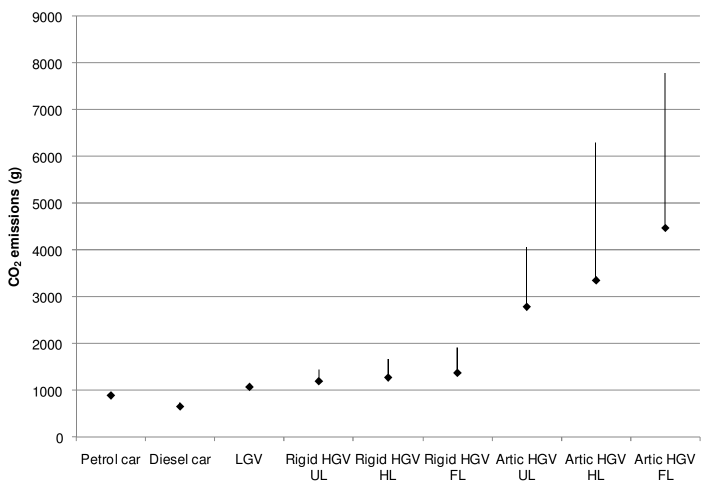


Figure 6.15c Variation in CO_2 emissions for all vehicle types over all hill alignments at 50 kph

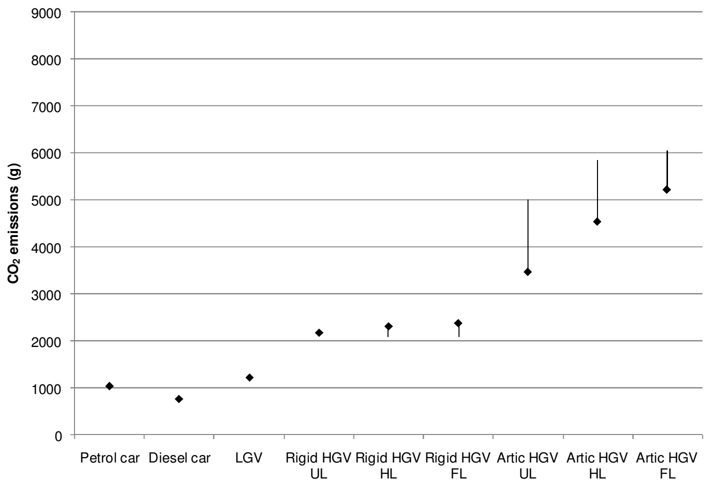


Figure 6.16a Variation in CO_2 emissions for all vehicle types over all valley alignments at 90 kph

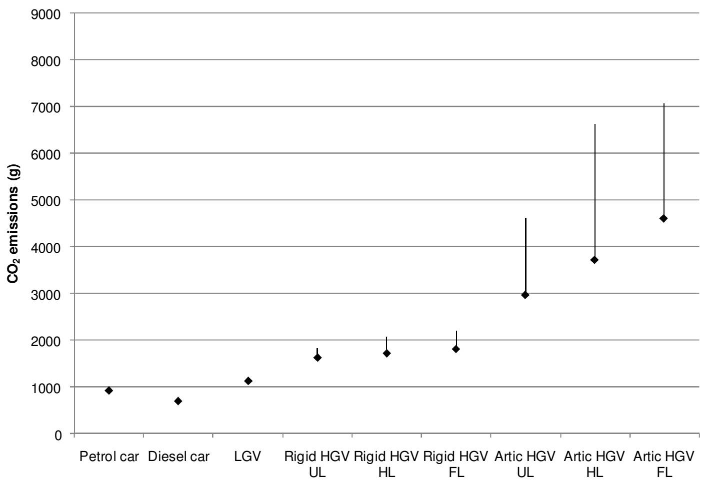


Figure 6.16b Variation in CO_2 emissions for all vehicle types over all valley alignments at 70kph

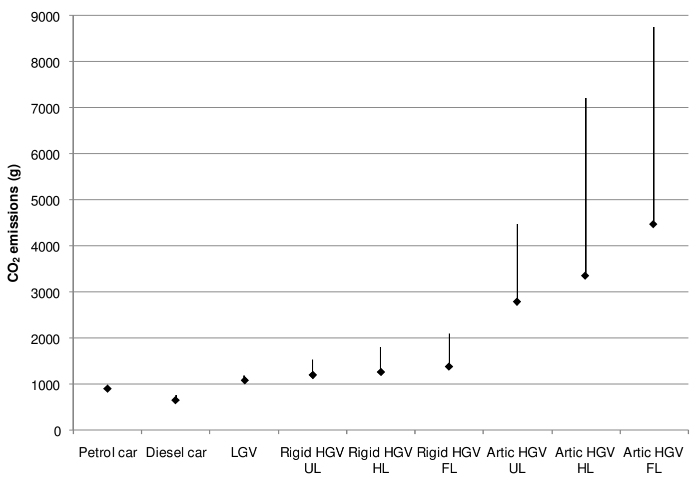


Figure 6.16c Variation in CO_2 emissions for all vehicle types over all valley alignments at 50 kph

6.3 Effect of alignments on fleets

In the previous section, the effect of different alignments on CO_2 emissions has been presented for individual vehicles operating on the symmetrical hill and the symmetrical valley. It is apparent that different alignments have varying effects on different vehicles. For this reason it was important to consider the effect of alignment on a fleet comprised of different vehicle types travelling at different speeds. In this section typical fleets are developed and subsequently applied to the hill in Section 6.3.3 and the valley in Section 6.3.4.

6.3.1 Scenarios

Three scenarios were developed for assessment, these are described below.

- **Scenario 1 – Business as Usual.** This uses the NAEI fleet mix for the year of 2025 which consists of a fleet composition as shown in Table 6.4 (Defra, 2010). The petrol LGV and bus have not been assessed over the alignments, and due to them comprising only a small proportion of the fleet, have been omitted from the assessment. The remaining fleet has been adjusted to compensate for the omission; which is shown as a corrected percentage in Table 6.4.

Table 6.4 Business as Usual fleet mix

Vehicle	Percentage	Corrected percentage
Petrol car	66.8	67.8
Diesel car	17.1	17.4
Petrol LGV	1.2	0
Diesel LGV	10.7	12.1
Rigid HGV	2.0	2.0
Articulated HGV	0.7	0.7
Buses	1.5	0
Total	100	100

- **Scenario 2 – Low Carbon Future**. The UK Low Carbon Transition Plan (H M Government, 2009) predicts private passenger transport will be based on the electric vehicle (powered by a renewable energy sourced electric grid) and freight transport will remain using conventional engines but fuelled by responsibly sourced biodiesel. Passenger cars have been excluded in Table 6.5, with the only vehicles assessed being HGVs.

Table 6.5 Low Carbon Future fleet mix

Vehicle	Percentage	Corrected percentage
Petrol car	66.8	0
Diesel car	17.1	0
Petrol LGV	1.2	0
Diesel LGV	10.7	0
Rigid HGV	2.0	74.1
Articulated HGV	0.7	25.9
Buses	1.5	0
Total	100	100

Scenario 3 – Lower speeds. The knowledge that lower speed limits result in lower CO_2 emissions is widespread; in the USA, even as long ago as 1973, in response to the oil crisis a lower national speed limit was introduced. For all the hypothetical cases previously considered in this chapter, it was only the case for the graded alignment to reduce emissions at the higher speeds. For example, a petrol car only produces fewer emissions on graded alignments than on a level alignment over the speed of 100 kph. The lowering of the speeds within this scenario was therefore predicted to produce some interesting results, with the lower speeds potentially negating the benefits of graded alignments on light vehicles. For Scenario 1 and Scenario 2 the speed profiles have been taken as those shown in Figure 6.17: The data is from DfT Automatic Traffic Counters which has taken average speeds at 27 motorway site locations (DfT, 2010). The observed speeds are divided into eight speeds ranges: under 50 mph, 50-59 mph, 60-64 mph, 65-69 mph, 70-74 mph, 75-79 mph, 80-89 mph and over 90 mph. The individual vehicle assessments considered speeds between different speed ranges for different vehicle types at increments of 5 kph – these had to be translated to reflect a fleet with the observed speeds. The number of vehicles with speeds that occurred in the speed ranges listed above is divided across the speed range – giving the number of vehicles travelling at speeds in 1 kph increments. These speeds were then re-categorised into speeds at 5kph increments, reflecting the previous individual vehicle assessments. When the observed speeds exceeded the speeds at which PHEM ceased to provide reliable results, the vehicles travelling at these higher observed speeds were assigned to the maximum reliable speed.

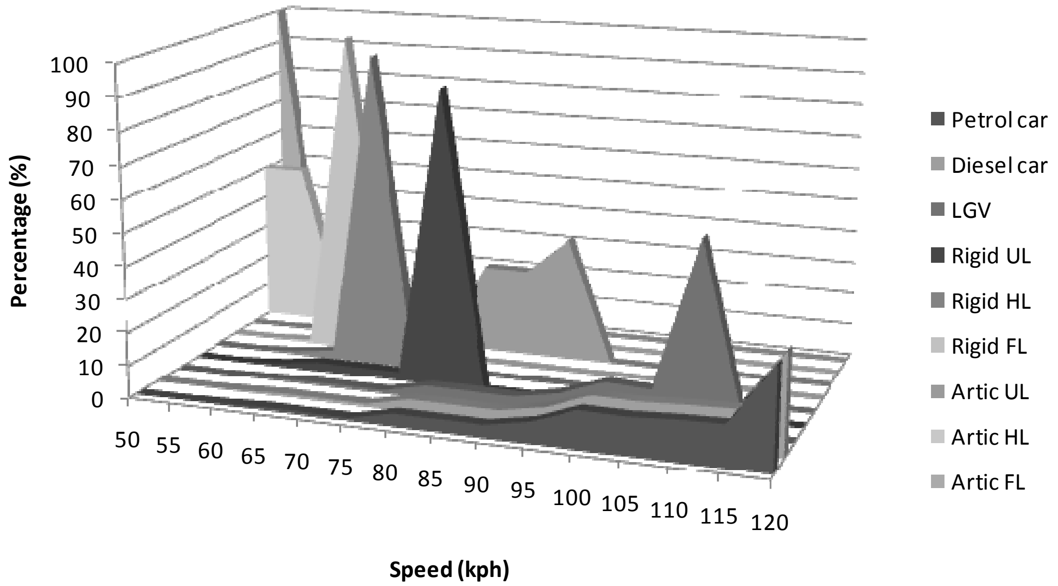


Figure 6.17 Speed profiles for Scenarios 1 and 2

Scenario 3 considers the effects of lower speed limits; the speed profile for this scenario is a shifted version of the profile shown in Figure 6.17. All speeds have been decreased by 10 kph, with the new profile shown in Figure 6.18.

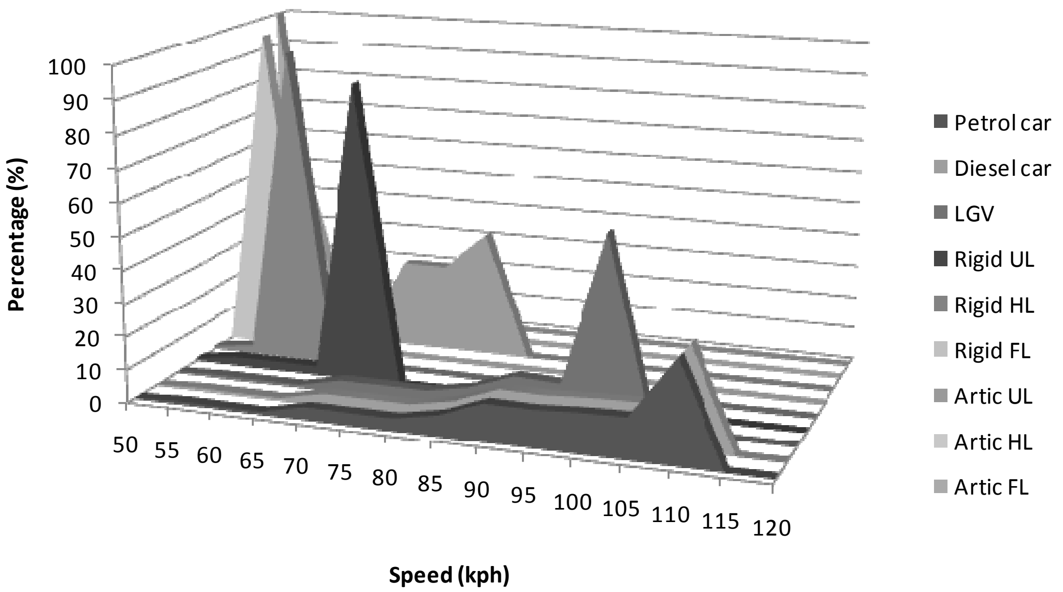


Figure 6.18 Speed profiles for Scenario 3

6.3.2 Methodology

To convert the individual vehicle emissions specific to a particular alignment into a total fleet emission specific to that alignment, firstly, an arbitrary flow of 1,000 vehicles was assumed. The fleet distribution was then applied to get the flows of each vehicle type. For both the rigid HGV and the articulated HGV there were three possible load cases – un-laden, half-laden and fully-laden. The percentages of the rigid HGV and articulated HGV flows that are divided into these loads are shown in Table 6.6.

Table 6.6 Percentage split of loading cases

Load case	% of vehicle type
Un-laden	40%
Half-laden	20%
Fully-laden	40%

Once the 1,000 vehicle flow has been sub-divided into the nine vehicle categories, the flow by vehicle type was then divided into vehicle speeds, as shown in Figure 6.17 for Scenario 1 and 2, and Figure 6.18 for Scenario 3.

6.3.3 Hill fleet emissions

The absolute emissions are shown in Figure 6.19a for the three scenarios and three alignments. As Scenario 2 assumes that the lighter contingent of the fleet is powered by an alternative source, it is only the heavier vehicles that are accounted for in this assessment, hence the significantly lower total CO_2.

The normalised CO_2 for the three fleet scenarios over the three alignments of the hill are shown in Figure 6.19b. The fleet emissions have been normalised to the emissions produced by the same fleet operating on the level alignment. For example, for Scenario 1 on the +6 -6 alignment the total CO_2 emissions from the 1,000 vehicle flow was 1,500 kg, whereas, on the level alignment this was 1,450 kg CO_2, giving a normalised CO_2 value of 1.03.

The light vehicles are not heavily influenced by the graded highway, and in some cases benefit from the gradients. It could, therefore, be expected that this effect in conjunction with the large proportion of the fleet that they comprise, could offset the negative effects on the heavier vehicles, which only comprise a small proportion of the fleet. However, this is not the case; the negative effect on the HGVs outweighs the negligible or beneficial effects on the light vehicles. Therefore, overall, the fleet traversing the hill terrain would prefer to operate on a level alignment.

It is the fleet in Scenario 2 that is most affected by the gradients; due to the fleet only comprising of heavy vehicles, which have previously been shown to be most susceptible to gradients.

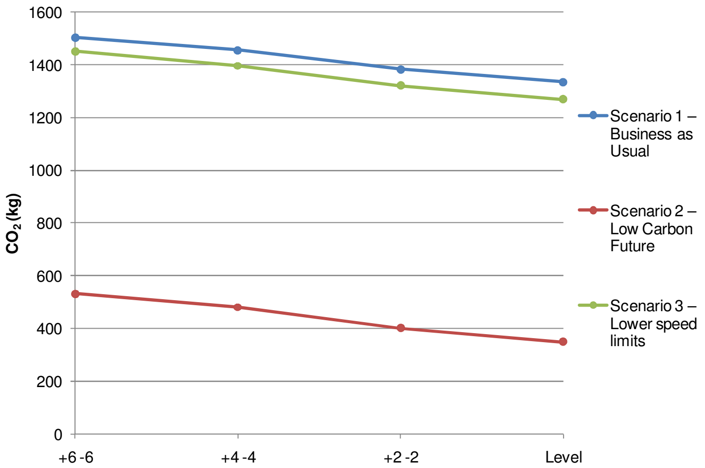


Figure 6.19a Total fleet CO_2 emissions for all alignments over the hill

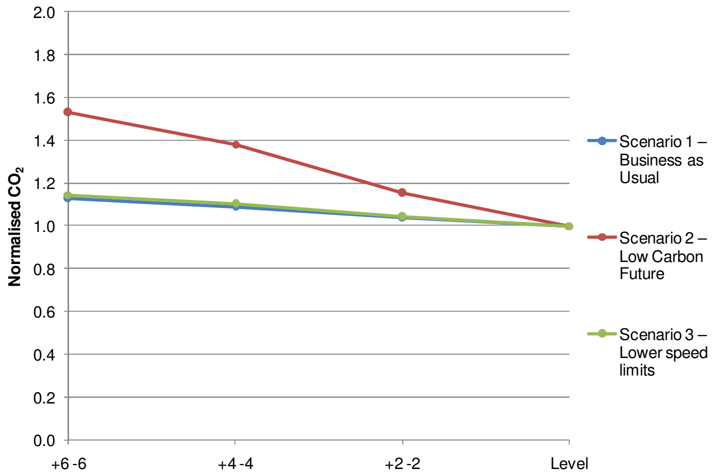


Figure 6.19b Normalised fleet CO_2 emissions for all alignments over the hill

6.3.4 Valley fleet emission

The same scenarios have been applied to the valley, using the same speed and fleet proportions. From the output of the study of the effects of the alignments on individual vehicles it was expected that the fleet emissions for the valley alignments would be similar to the fleet emissions for the hill alignments. Figure 6.20a and 6.20b demonstrate that this is the case in both Scenario 1 and 3, where the normalised emissions are similar to the hill across all alignments. The normalised emissions are higher in Scenario 2 than for the hill due to it comprising only heavy vehicles; which suffered more as a result of the shorter transition curves on the symmetrical valley alignments.

As was the case for the hill, the fleet traversing the valley terrain would prefer to operate on a level alignment.

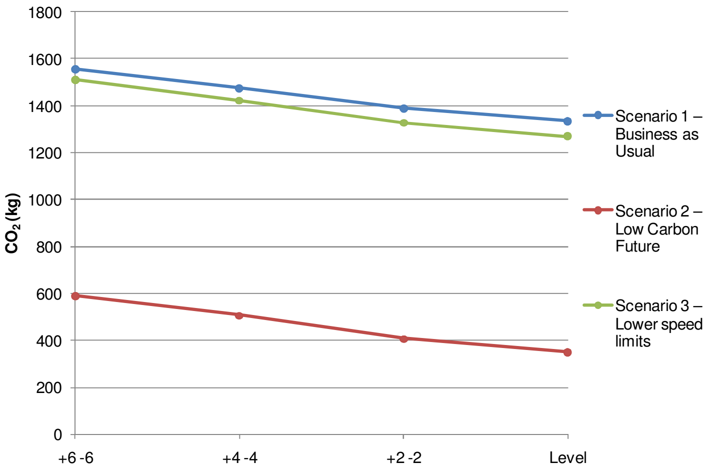


Figure 6.20a Total fleet CO_2 emissions for all alignments over valley

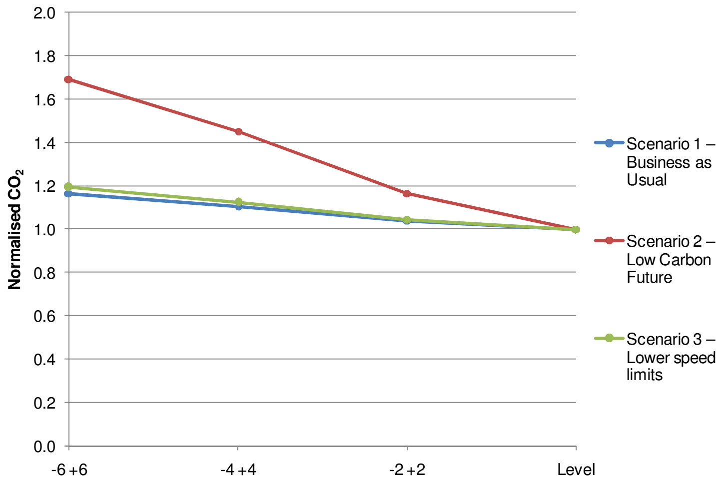


Figure 6.20b Normalised fleet CO_2 emissions for all alignments over valley

6.4 Effect of alignments on CO_2 from earthworks

The hypothetical alignments have been designed to enable the effect of alignment on whole life carbon of highways to be understood. In order to construct the vertical alignments considered an earthworks operation would be necessary to achieve the required alignment.

This section details the anticipated CO_2 from the earthworks operations required to construct the +6 -6, +4 -4, +2 -2 and level alignments for the hill terrain. Also, the anticipated CO_2 from the earthworks operations required to construct the -6 +6, -4 +4, -2 +2 and level alignments for the valley terrain.

A hypothetical hill terrain and a hypothetical valley were developed. The starting profile of the hill terrain closely followed the steepest hill highway alignment of +6 -6, and likewise the starting profile of the valley terrain closely followed the steepest valley alignment of -6 +6. Therefore, it was feasible for a vertical alignment to follow the profile of the hill terrain with only a very small earthworks operation required. Or, alternatively, it was possible to cut through the hill to obtain an alignment with a shallower gradient. Likewise for the valley, it was feasible for the vertical alignment to follow the profile of the valley with only a very small earthworks operation required. Or, alternatively, it was possible to construct an embankment in the valley to obtain an alignment with a shallower gradient.

6.4.1 Earthworks assumptions

The spreadsheet model described in Chapter 5 has been used to calculate the CO_2 associated with the earthworks. Typically there is a wide range of plant that can be used to undertake an earthworks operation; to address the range of plant options a number of plant combinations have been considered. The machinery pairing of the excavator and articulated dump truck (ADT) have been used in the following combinations:

- 25 tonne excavator and 30 tonne ADT
- 35 tonne excavator and 30 tonne ADT
- 45 tonne excavator and 35 tonne ADT

The earthworks volumes have been taken from the intersection of an alignment model (.alg) with a digital terrain model (.dtm) in Microstation Inroads. This is done by running a template along the vertical alignment, with the template representing the cross section of the highway. The template used to obtain the earthworks volumes given in this section is shown in Figure 6.21 - it represents a typical 3-lane motorway with lane widths totalling 11 m, a central reservation width of 3.5 m, a verge width of 1.5 m, and 1:2 cutting slopes.

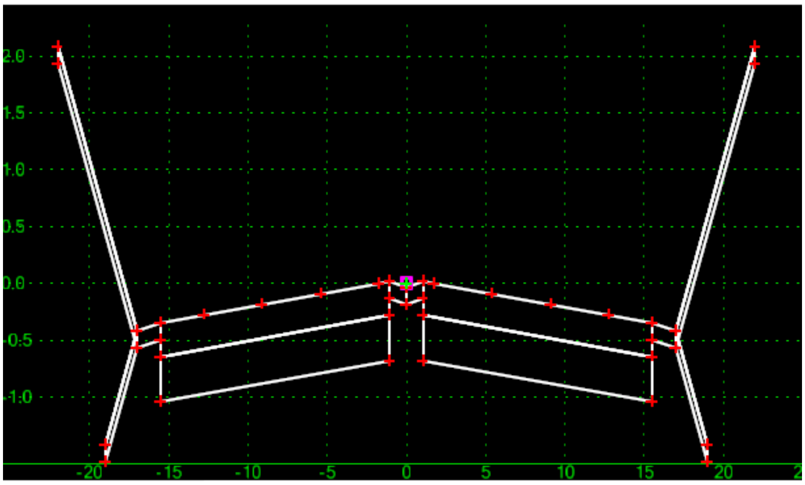


Figure 6.21 Earthworks template

The earthworks CO_2 values are based on the machinery operating in materials that would require normal levels of fuel consumption i.e. not in material that would first require ripping or blasting.

6.4.1.1 Internal site haul

To minimise efforts engineers attempt to haul the material over the shortest distance possible. For the hypothetical hill scenario either all the spoil material would be (A) hauled from the excavation site to one side of the cutting, or (B) the spoil would be excavated and deposited either side of the cutting. For such an earthworks operation the excess spoil from the cutting could be retained on site or exported from the site to another location. The surplus material for the level alignment is large, and there may not be the potential for accommodating this on-site; however, nearby land could possibly accommodate it. For this reason, two sub-scenarios have been considered: (i) assumes the materials are retained on site and (ii) assumes the materials are exported from site to another location.

For the hypothetical valley scenario either all the fill would be (A) hauled from one side of the embankment, or (B) from either side of the embankment. For such an earthworks operation the required embankment fill could be sourced on site or imported to site from another location. The required embankment fill to achieve the level alignment is large, and there may not be the potential to source this on-site; however, nearby land could act as a borrow pit. For this reason, two sub-scenarios have been considered: (i) assumes the materials are sourced on site and (ii) assumes the materials are imported to site from another location.

6.4.1.2 External transportation

In the scenarios for which external transportation is required - when material is imported to site from an external location, or when material is removed from site and deposited at an external destination, a distance of 5km by road lorry has been assumed.

Double-handling has also been assumed to occur. For example, for the cutting, when material is excavated and hauled by an ADT to a stockpile location, if this material is to be subsequently taken off site by road lorry, it is assumed that an excavator has to be used to load the road lorry. Therefore, the material is effectively excavated twice. Similarly for an embankment, when the fill material is imported from an external site, the excavation at the external source site is included – the material is then hauled by road lorry and deposited at a stockpile site and is subsequently excavated again and hauled to its final destination.

Table 6.7 Summary of scenarios for symmetrical hill

Scenario	Internal transportation	External transportation
A(i)	To or from one side	On site retention or sourcing
A(ii)	To or from one side	Off site retention or sourcing
B(i)	To or from both sides	On site retention or sourcing
B(ii)	To or from both sides	Off site retention or sourcing

6.4.2 Hill earthworks

For the hypothetical hill considered, in an ideal situation, the profile of the terrain would be closely followed to minimise the earthworks operation to keep costs and construction time to a minimum. This section explores the CO_2 associated with the earthworks required to achieve the shallower alignments. Table 6.8 shows the cut and fill volumes, taken directly from Microstation Inroads, associated with the alignments intersecting the hypothetical hill terrain.

Table 6.8 Earthworks associated with alignments

Alignment	Cut (m^3)	Fill (m^3)	Balance (m^3)
Level	37,106,390	40	37,106,360
+2 -2	16,449,250	40	16,449,210
+4 -4	4,665,590	40	4,665,550
+6 -6	36,480	110	36,370

The CO_2 associated with the different alignments for Scenario A (excavated material hauled to one side of cutting) for the different machinery pairings are shown in Figure 6.22. The solid lines represent option (i), which assumes the materials are accommodated on site. The dotted lines represent option (ii), which assumes the material is removed from the site to another location. Option (ii) firstly requires excavation and haul to the stockpile site, and then further excavation from the stockpile site and removal off site using road transport – explaining why option (ii) has higher CO_2 emissions across all machinery pairings.

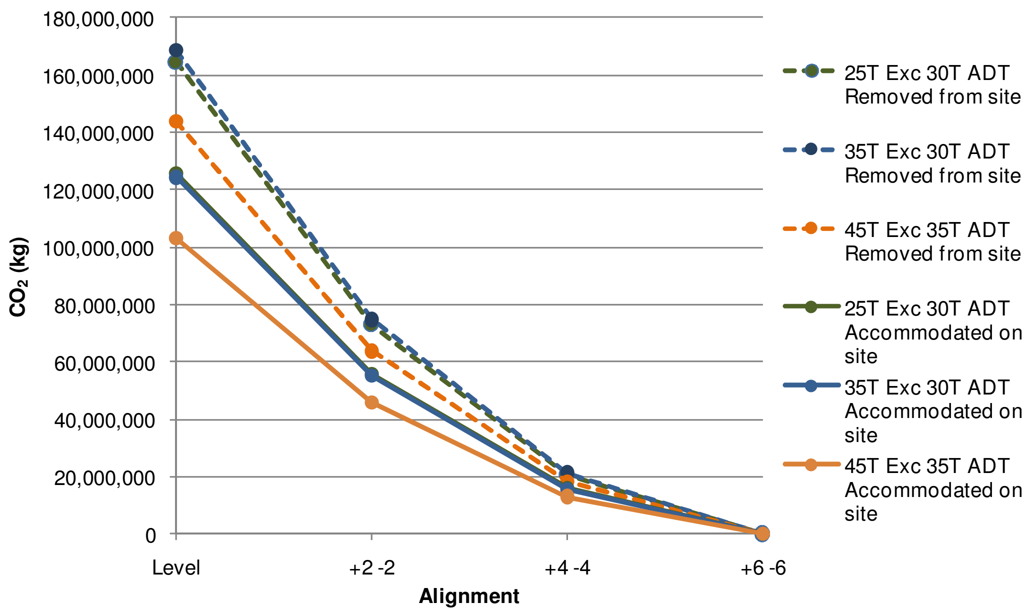


Figure 6.22 CO_2 from earthworks required for hill for Scenario A

The CO_2 associated with the different alignments for Scenario B (excavated material hauled to either side of cutting) are shown in Figure 6.23.

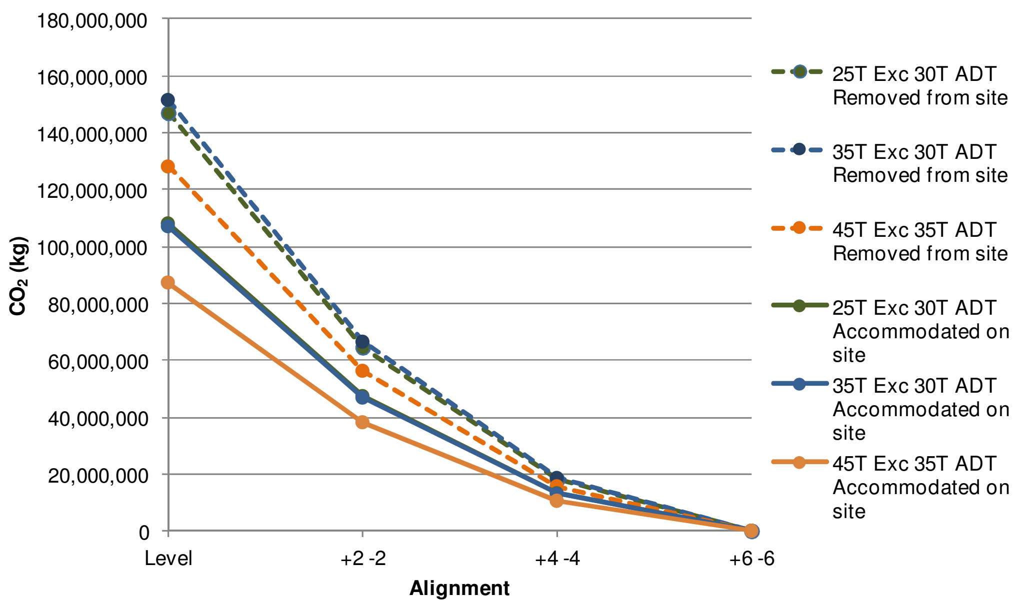


Figure 6.23 CO_2 from earthworks required for hill for Scenario B

Scenario A assumes all the excavated material is hauled to one side of the cutting and results in the highest amount of CO_2, with Scenario B resulting in lower CO_2 emissions. This was to be expected due to the long haul distances required for the materials excavated from the side of the hill that is the opposite side of the stockpile site. For both sub-scenario (i) and (ii) the use of a 45 tonne excavator in combination with a 35T ADT results in the lowest CO_2. The earthworks to achieve the level alignment demonstrate the impact of earthwork strategy and material choice, with the most CO_2 intensive scenario resulting in over 60% more CO_2 than the least.

Table 6.9 shows the CO_2 dependent on the final destination of the excavated material, giving the lowest and highest CO_2 value calculated for each alignment.

Table 6.9 CO_2 from earthworks for both scenarios across all hill alignments

Destination of excavated material	CO_2 (tonnes)							
	Level		2% -2%		4% -4%		6% -6%	
	Low	High	Low	High	Low	High	Low	High
Off site	128,000	169,000	56,000	75,000	16,000	21,000	< 1,000	< 1,000
On site	87,000	126,000	38,000	56,000	11,000	16,000	< 1,000	< 1,000

The results of the hill assessment are shown graphically in Figure 6.24. The significant differences between the low and high values result from different machinery and varying earthworks strategies.

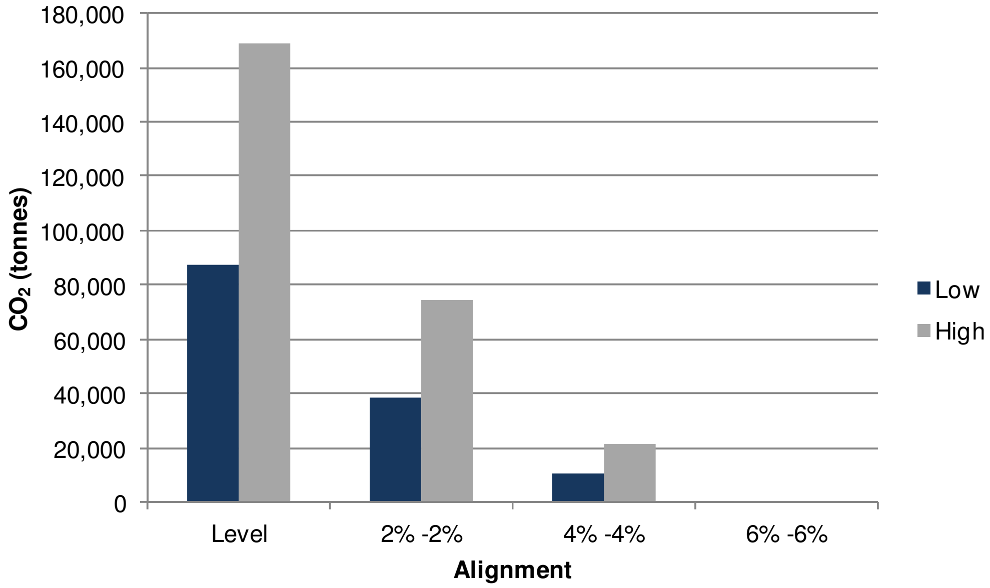


Figure 6.24 Range of CO_2 values from earthworks to construct alignments on hill terrain

6.4.3 Valley earthworks

Similarly for the hypothetical hill alignments, in terms of minimising the earthworks operation required, the terrain would preferably be followed. Table 6.10 shows the cut and fill volumes, taken directly from Microstation Inroads, associated with the alignments intersecting the hypothetical valley terrain.

Table 6.10 Earthworks associated with valley alignments

Alignment	Cut (m^3)	Fill (m^3)	Balance (m^3)
Level	6,280	45,908,800	- 45,902,520
+2 -2	6,280	22,128,980	- 22,122,700
+4 -4	6,320	6,849,670	- 6,843,350
+6 -6	36,480	120	36,360

The CO_2 associated with the different alignments for Scenario A (excavated material hauled from one side of cutting) for the different machinery pairings are shown in Figure 6.25. The solid lines represent option (i), which assumes the materials are sourced on site. The dotted line lines represent option (ii), which involves importing the material from another location.

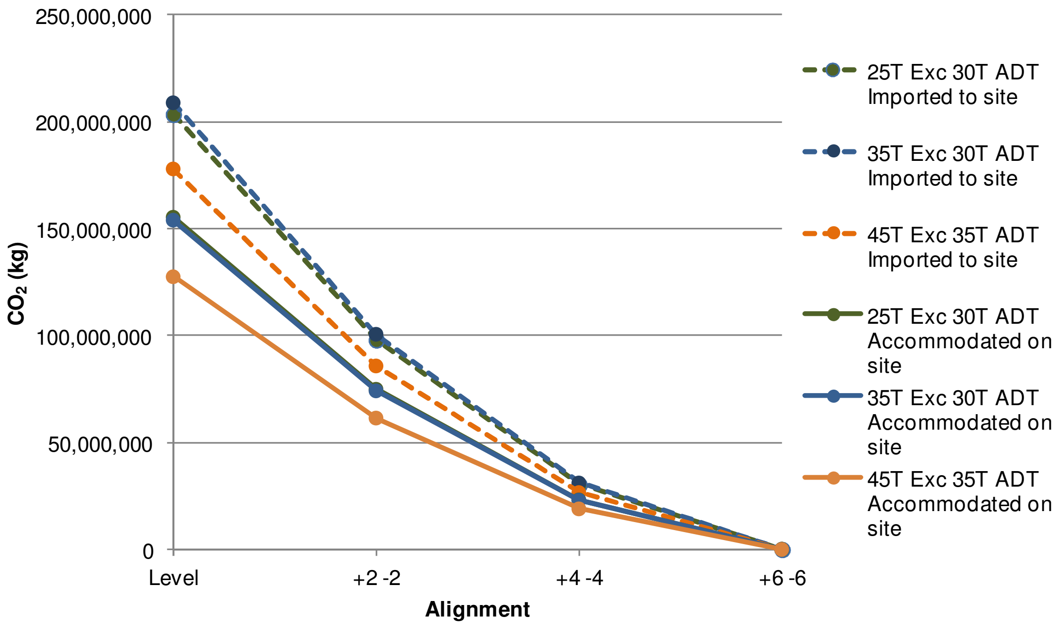


Figure 6.25 CO_2 from earthworks required for valley for Scenario A

The CO_2 associated with the different alignments for Scenario B (excavated material hauled from either side of cutting) are shown in Figure 6.26.

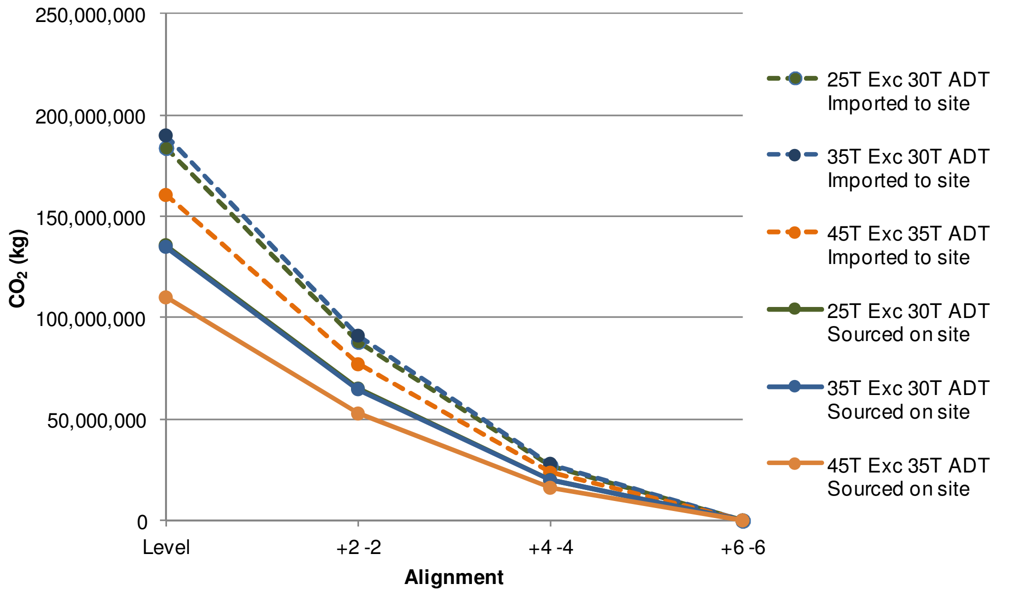


Figure 6.26 CO_2 from earthworks required for valley for Scenario B

The CO_2 for both scenarios is shown in Table 6.11 – giving the lowest and highest CO_2 value calculated for each alignment on the valley terrain.

Table 6.11 CO_2 from earthworks for both scenarios across all valley alignments

Source of fill material	CO_2 (tonnes)							
	Level		2% -2%		4% -4%		6% -6%	
	Low	High	Low	High	Low	High	Low	High
Off site	161,000	209,000	77,000	101,000	24,000	31,000	< 1,000	< 1,000
On site	110,000	155,000	53,000	75,000	16,000	23,000	< 1,000	< 1,000

The results of the valley assessment are shown graphically in Figure 6.27, with the lowest and highest values shown for each alignment. Again, the significant differences between the low and high values result from different machinery, varying earthworks strategies, and whether the material can be sourced on site.

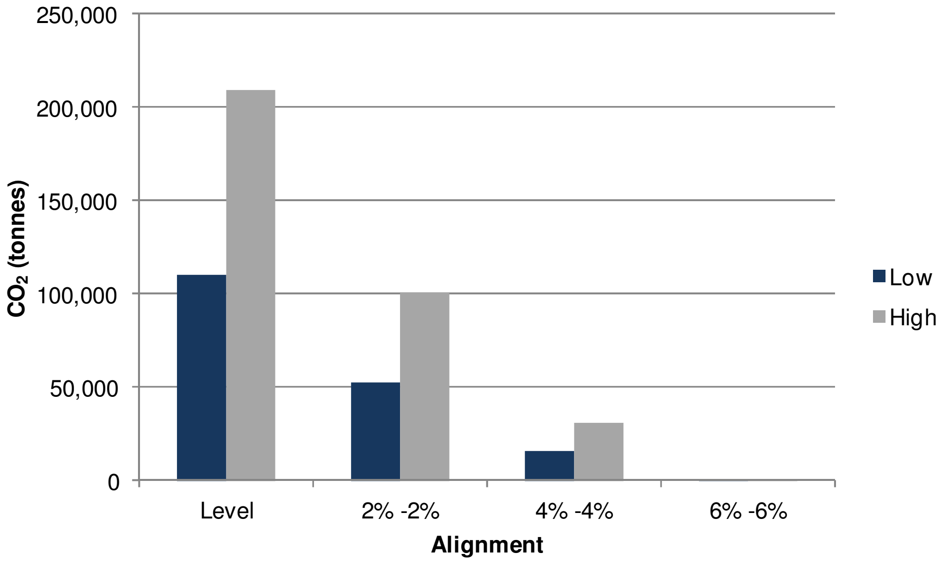


Figure 6.27 Range of CO_2 values for earthworks to construct alignments on valley terrain

6.4.4 Use of lime in earthworks operations

The CO_2 impact of the use of lime in earthworks to improve the workability has been explored in Chapter 5. The embodied CO_2 in the lime material and the plant used to incorporate the lime into the fill results in significant additional CO_2 over bulk earthworks activities that do not use lime.

To address the impact of the use of lime, the valley alignments have been considered. It has been assumed that an arbitrary 20% of the fill material would require treatment. 2% of lime (by dry weight) was also assumed to be added, due to typical amounts being between 1% and 2% (Highways Agency, 2007). Table 6.12 shows the CO_2 associated with the modification of the earthworks with lime for the different alignments of the valley terrain.

Table 6.12 CO_2 associated with the use of lime in valley alignments

Alignment	CO_2 (tonnes)			
	Embodied in lime	Transportation of lime	Modification plant	APPROX TOTAL
Level	268,000	2,000	< 1,000	271,000
-2 +2	129,000	1,000	< 1,000	131,000
-4 +4	40,000	< 1,000	< 1,000	42,000
-6 +6	< 1,000	< 1,000	< 1,000	3,000

From Table 6.11, the lower value for the earthworks operation for the level alignment was given as 110,000 tonnes of CO_2. When 20% of the fill is treated with 2% lime the 271,000 tonnes of CO_2 from this is also included to bring the total to 381,000 tonnes, as shown in Table 6.12, resulting in over 3 times more CO_2. This order of increase in CO_2 applies across all alignments when lime is used.

6.5 Impact of alignment on construction and use

Terrains have been used to assess hypothetical alignments both in the use phase and in the construction phase. As previously discussed, following the profile of the terrain was a possibility and the individual and fleet assessments presented within this chapter have indeed done this. Within this section the aim is to understand the impacts of amending the alignment, from the terrain to a less graded alignment, on both the construction and use CO_2. New terms have been introduced to describe this; for example, ‘terrain to +2 -2’ refers to the process of taking the alignment that follows the profile of the hill terrain down to the +2 -2 alignment. The data for the ‘terrain’ alignment has been taken from the +6 -6 alignment for the hill and the -6 +6 alignment for the valley.

6.5.1 Hill

The CO_2 emission values for each scenario for the hill are presented in Table 6.13, based on the vehicle speeds and fleet compositions detailed in Section 6.3, but using a typical average UK motorway fleet of 84,852 vehicles per day (Dft, 2010). Also presented is the maximum percentage saving that can be achieved and the maximum potential annual savings. For each scenario the CO_2 emissions reduce as the alignment becomes less graded. The maximum percentage saving is the potential reduction between the alignment producing the highest emissions and the alignment producing the lowest emissions. The maximum annual savings is the potential reduction between alignments over a 365-day period.

Table 6.13 CO_2 emissions for each scenario for the hill alignment

Scenario	Daily CO_2 emissions (kg)				Maximum saving (%)	Maximum annual saving (tonnes)
	+6 -6	+4 -4	+2 -2	Level		
Scenario 1 – Business as Usual	130,000	120,000	120,000	110,000	3%	1,000
Scenario 2 – Low Carbon Future	50,000	40,000	30,000	30,000	10%	1,400
Scenario 3 – Lower speed limits	120,000	120,000	110,000	110,000	4%	5,700

When the CO_2 required for the earthworks operation is known along with the annual saving resulting from the alignment, the time required to pay back the CO_2 expended in the earthworks can be calculated.

Considering Scenario 1, with the vehicle flow of 84,852 per day, CO_2 emissions can be reduced by 1,500 tonnes per year through the adoption of a +4 -4 over the terrain alignment as shown in Table 6.14. The lower CO_2 value associated with the earthworks required to construct this alignment is 11,000 tonnes which would require a payback period of less than 10 years. The higher value of 21,000 tonnes would require a payback period of less than 20 years.

Table 6.14 Terrain to +4 -4 alignment

Scenario	Earthworks CO_2 (tonnes)		Annual use CO_2 emissions saving (tonnes)	% savings over terrain alignment	Payback (years)	
	Low	High			Low	High
1			1,500	3%	< 10	< 20
2	11,000	21,000	1,600	10%	< 10	< 20
3			1,700	4%	< 10	< 20

The payback periods required to go from the terrain alignment to the +2 -2 alignment are shown in Table 6.15.

Table 6.15 Terrain to +2 -2 alignment

Scenario	Earthworks CO_2 (tonnes)		Annual use CO_2 emissions saving (tonnes)	% savings over terrain alignment	Payback (years)	
	Low	High			Low	High
1			3,700	8%	< 10	< 20
2	38,000	75,000	4,000	24%	< 10	< 20
3			4,100	9%	< 10	< 20

Table 6.16 shows the terrain alignment to level alignment payback periods. Considering Scenario 1, with the vehicle flow of 84,852 per day, CO_2 emissions can be reduced by 5,200 tonnes per year through the adoption of a level highway over the terrain alignment. The best-case CO_2 associated with the earthworks required to construct this alignment is 87,000 tonnes. The annual reduction in CO_2 therefore allows the additional CO_2 expended at the construction stage to be recovered over a period of less than 20 years.

Table 6.16 Terrain to level alignment

Scenario	Earthworks CO_2 (tonnes)		Annual use CO_2 emissions saving (tonnes)	% savings over terrain alignment	Payback (years)	
	Low	High			Low	High
1			5,200	11%	< 20	< 40
2	87,000	169,000	5,700	35%	< 20	< 30
3			5,700	13%	< 20	< 30

Scenario 1 has the highest pay back duration across all alignments; due to it consistently having the lowest savings over the terrain alignments. In Scenario 1, when the terrain alignment is taken to the +4 -4 alignment only 3% savings are made, when taken to the +2 -2 there are 8% savings and when taken to the level alignment there are 11% savings. These small savings result in the long payback periods.

For Scenario 3, the savings are 4%, 9% and 13% for the 'terrain to +4 -4', 'terrain to +2 -2' and 'terrain to level' cases respectively. For Scenario 2, the savings are 10%, 24% and 35% for the 'terrain to +4 -4', 'terrain to +2 -2' and 'terrain to level' cases respectively.

Despite the savings applying to a smaller total fleet emission, Scenario 2 has shorter payback periods than Scenario 1; emphasising how the sometimes beneficial impacts of gradients on the lighter vehicles at certain speeds can help offset the detrimental impacts on the heavier vehicles. When the speeds lower in Scenario 3, the graded alignments no longer benefit the lighter vehicles and so the shallower alignments in Scenario 3 save more CO_2 than in Scenario1 and hence Scenario 3 has the shorter payback periods.

The required outcome of this assessment was to understand whether it is worthwhile to expend more CO_2 in the earthworks operation as part of the construction phase, to obtain alignments that are more favourable in the use phase. Table 6.17 demonstrates whether it is worthwhile by showing the:

- CO_2 from the earthworks operation required to construct the alignment;
- Total CO_2 produced by the fleet using the alignment over a 60 year period;
- CO_2 reductions brought about by using the shallower alignments over the terrain alignment;
- Net CO_2 reduced, which has been taken as the CO_2 reductions less the CO_2 required for the earthworks operation; and
- Percentage CO_2 saved from the use of the shallower alignments over a 60 year period, taken as the net CO_2 reduced as a percentage of the total CO_2 produced by the fleet.

For Scenario 1 the percentage of CO_2 saved is small over the 60 year time frame. This is due to the benefits to the light vehicles, when operating at the higher speeds, offsetting the detrimental effects on the heavier vehicles. In Scenario 2, which considers the HGVs only, the percentage saved is highest across all alignments. The benefits to Scenario 3 fall between Scenario 1 and 2.

Table 6.17 Savings over 60 year period for hill terrain for lower earthworks value

Alignment	Scenario	Earthworks CO_2 (tonnes)	Total CO_2 over 60 years (tonnes)	CO_2 reduced over 60 years over terrain alignment (tonnes)	Net CO_2 reduced (CO_2 reduced minus earthworks CO_2)	% saved over 60 years
	1		2,701,000	92,000	82,000	3%
+4 -4	2	11,000	896,000	95,000	84,000	9%
	3		2,597,000	102,000	92,000	4%
	1		2,573,000	221,000	182,000	7%
+2 -2	2	38,000	748,000	243,000	205,000	27%
	3		2,455,000	244,000	205,000	8%
	1		2,480,000	313,000	226,000	9%
Level	2	87,000	648,000	342,000	255,000	39%
	3		2,356,000	343,000	256,000	11%

The percentage savings are shown graphically for the lower earthworks value in Figure 6.28.

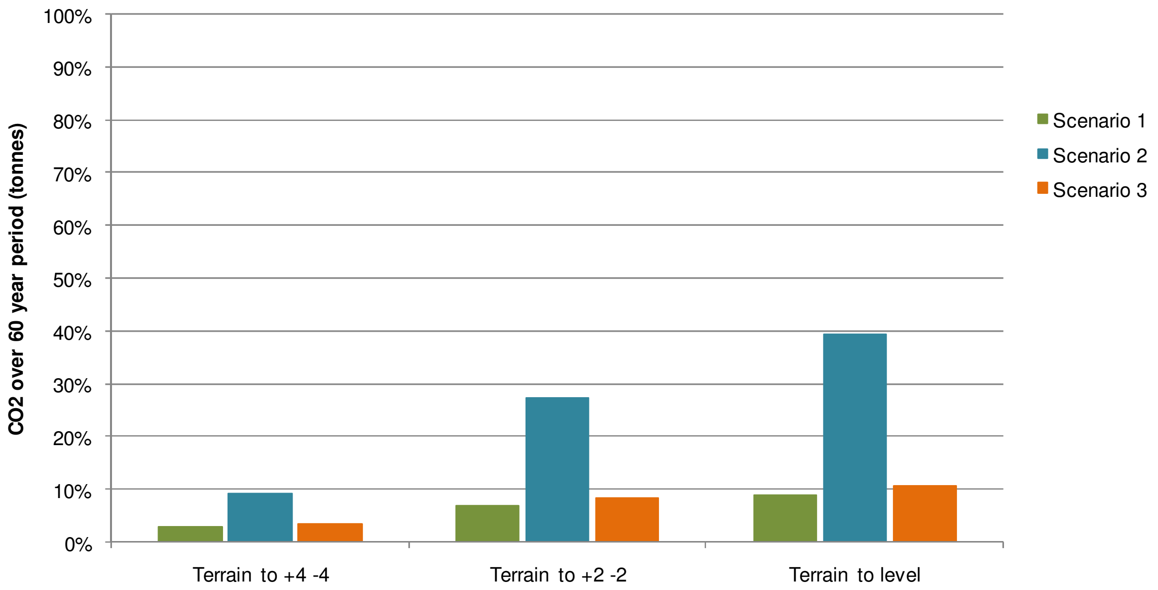


Figure 6.28 Percentage savings over 60 year period for hill terrain for lower earthworks value

The same data is presented in Table 6.18 for the higher earthworks value. The percentage of CO_2 saved over the 60 year time frame is smaller – this is clearly demonstrated in Figure 6.29. As is the case for the lower earthworks values previously presented, Scenario 2 shows the highest savings, followed by Scenario 3; this was expected as the year on year emission savings from the use phase are constant regardless of the earthworks CO_2. The higher earthworks scenarios demonstrates that if such large quantities of CO_2 are expended in the earthworks in the construction phase, that there would not be a large return on the investment within the typical highway appraisal period.

Table 6.18 Savings over 60 year period for hill terrain for higher earthworks value

Alignment	Scenario	Earthworks CO_2 (tonnes)	Total CO_2 over 60 years (tonnes)	CO_2 reduced over 60 years over terrain alignment (tonnes)	Net CO_2 reduced (total CO_2 minus earthworks CO_2)	% saved over 60 years
	1		3,339,000	92,000	71,000	2%
+4 -4	2	21,000	896,000	95,000	74,000	8%
	3		2,597,000	102,000	81,000	3%
	1		2,573,000	221,000	146,000	6%
+2 -2	2	75,000	748,000	243,000	168,000	22%
	3		2,455,000	244,000	169,000	7%
	1		2,480,000	313,000	145,000	6%
Level	2	169,000	648,000	342,000	174,000	27%
	3		2,356,000	343,000	175,000	7%

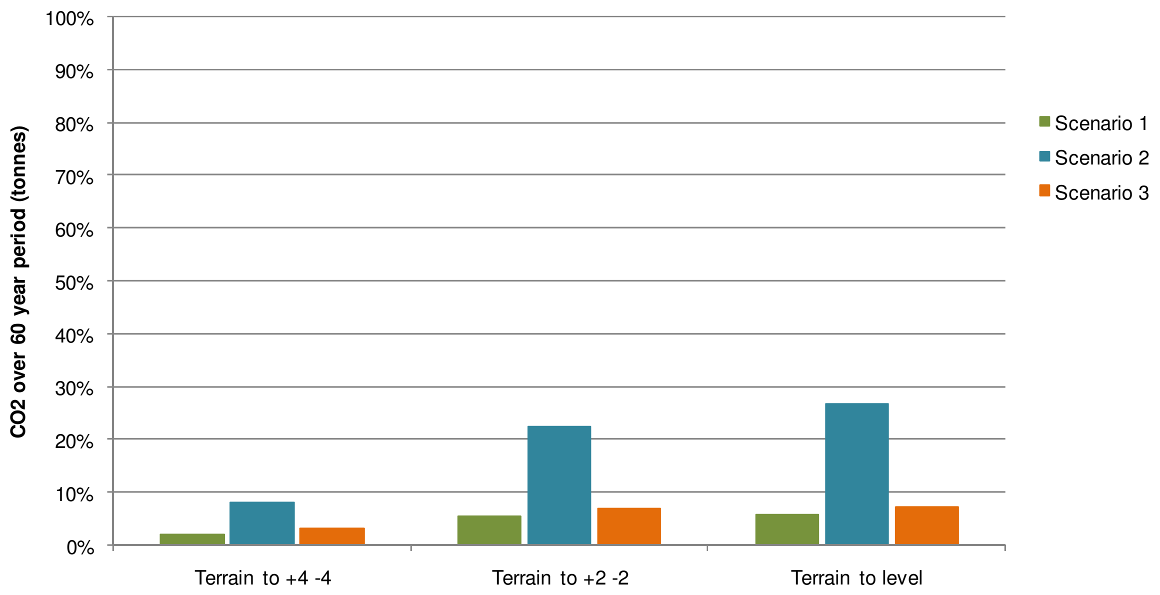


Figure 6.29 Percentage savings over 60 year period for hill terrain for higher earthworks value

6.5.2 Valley

As previously shown for the hill scenario, the CO_2 emissions values for each scenario for the valley are presented in Table 6.19.

Table 6.19 CO_2 emissions for each scenario for valley alignments

Scenario	Daily CO_2 emissions (kg)				Maximum daily saving (%)	Maximum annual saving (tonnes)
	-6 +6	-4 +4	-2 +2	Level		
Scenario 1 – Business as Usual	132,000	125,000	118,000	113,000	14%	6,900
Scenario 2 – Low Carbon Future	50,000	43,000	35,000	30,000	40%	7,300
Scenario 3 – Lower speed limits	128,000	121,000	112,000	108,000	16%	7,300

For Scenario 1 Business as Usual, when considering the use of lower earthworks value to take the alignment from the profile of the valley to a level alignment, the time taken to payback the additional CO_2 expended in the earthworks is less than 10 years, as shown in Table 6.19. To take the alignment from the profile of the valley to a -4% +4% and a -2% +2% alignment, it would require less than 10 and less than 20 years respectively to pay back the additional CO_2 expended in the earthworks operations, as shown in Table 6.21 and Table 6.22.

Table 6.20 Valley terrain to -4 +4 alignment

Scenario	Earthworks CO_2 (tonnes)		Annual use CO_2 emissions saving (tonnes)	% savings over terrain alignment	Payback (years)	
	Low	High			Low	High
1	16,000	31,000	2,500	5%	< 10	< 20
2			2,600	14%	< 10	< 20
3			2,700	6%	< 10	< 20

Table 6.21 Valley terrain to -2 +2 alignment

Scenario	Earthworks CO_2 (tonnes)		Annual use CO_2 emissions saving (tonnes)	% savings over terrain alignment	Payback (years)	
	Low	High			Low	High
1	53,000	101,000	5,200	11%	< 10	< 30
2			5,700	31%	< 10	< 30
3			5,700	12%	< 10	< 30

Table 6.22 Valley terrain to level alignment

Scenario	Earthworks CO_2 (tonnes)		Annual use CO_2 emissions saving (tonnes)	% savings over terrain alignment	Payback (years)	
	Low	High			Low	High
1			6,900	14%	< 20	< 30
2	110,000	209,000	7,500	41%	< 20	< 30
3			7,500	16%	< 20	< 30

Overall, the payback periods for the shallower alignments are shorter for the valley terrain due to the greater annual savings. An explanation for this has been given in Section 6.2; the shorter transition curves and hence longer graded sections amplify the offsetting effect on the lighter vehicles, but not sufficiently to counteract the greater negative effect on the heavier vehicles. The shallower alignments, therefore, produce a greater overall benefit and hence reduce the payback period for the earthworks.

The data shown in Table 6.18 for the hill terrain is also shown below in Table 6.23 for the valley terrain, for the lower earthworks values. Again for Scenario 1 the percentage of CO_2 saved is small over the 60 year time frame. This is due to the benefits to the light vehicles, when operating at the higher speeds, offsetting the detrimental effects on the heavier vehicles. In Scenario 3, which considers the HGVs only, the percentage saved is highest across all alignments. The benefits to Scenario 3 fall between Scenario 1 and 2.

Table 6.23 Savings over 60 year period for valley terrain for lower earthworks value

Alignment	Scenario	Earthworks CO_2 (tonnes)	Total CO_2 over 60 years (tonnes)	CO_2 reduced over 60 years over terrain alignment (tonnes)	Net CO_2 reduced (total CO_2 minus earthworks CO_2)	% saved over 60 years
	1		3,711,000	150,000	134,000	4%
-4 +4	2	16,000	941,000	156,000	140,000	15%
	3		2,641,000	166,000	150,000	6%
	1		2,580,000	312,000	259,000	10%
-2 +2	2	53,000	756,000	341,000	289,000	38%
	3		2,463,000	344,000	291,000	12%
	1		2,480,000	411,000	301,000	12%
Level	2	110,000	648,000	449,000	339,000	52%
	3		2,356,000	451,000	341,000	14%

The percentage savings are shown graphically in Figure 6.30 for the lower earthworks CO_2 values. There is clearly a greater benefit to reducing the gradients of the valley, shown by the higher percentage CO_2 savings over the 60 year time frame.

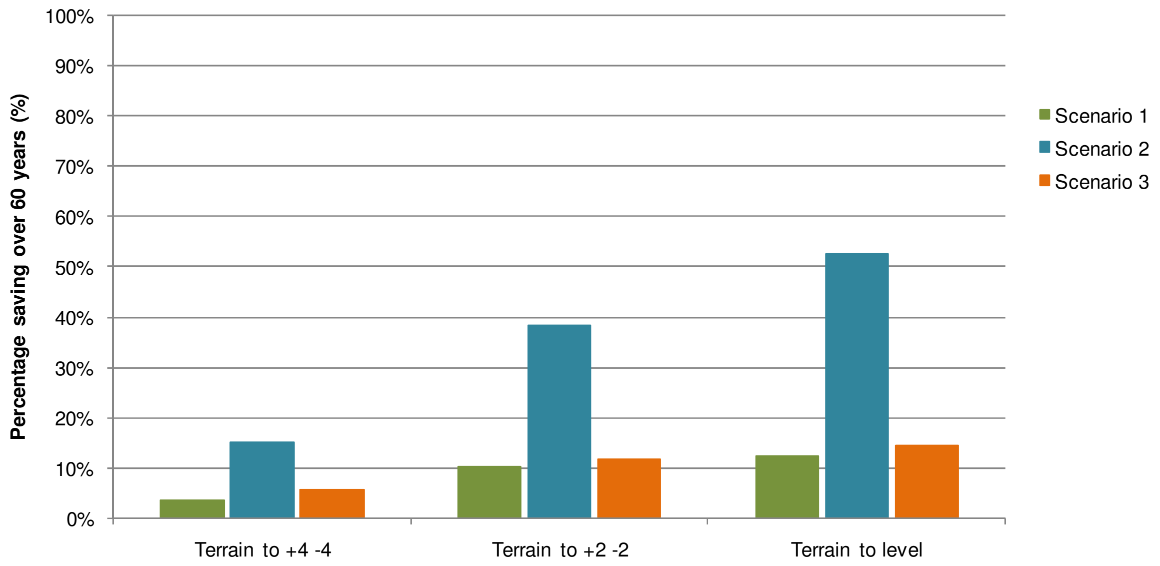


Figure 6.30 Percentage savings over 60 year period for valley terrain for lower earthworks value

Table 6.24 shows the net CO_2 reduced over a 60 year time frame for the valley terrain with the higher earthworks value. A significant saving is consistently seen across Scenario 2 for all alignments.

Table 6.24 Savings over 60 year period for valley terrain for higher earthworks value

Alignment	Scenario	Earthworks CO_2 (tonnes)	Total CO_2 over 60 years (tonnes)	CO_2 reduced over 60 years over terrain alignment (tonnes)	Net CO_2 reduced (CO_2 reduced minus earthworks CO_2)	% saved over 60 years
	1		3,711,000	150,000	119,000	3%
-4 +4	2	31,000	941,000	156,000	125,000	13%
	3		2,641,000	166,000	135,000	5%
	1		2,580,000	312,000	211,000	8%
-2 +2	2	101,000	756,000	341,000	241,000	32%
	3		2,463,000	344,000	243,000	10%
	1		2,480,000	411,000	203,000	8%
Level	2	209,000	648,000	449,000	240,000	37%
	3		2,356,000	451,000	242,000	10%

This is shown graphically in Figure 6.31 for the valley terrain with the higher of the earthworks CO_2 values.

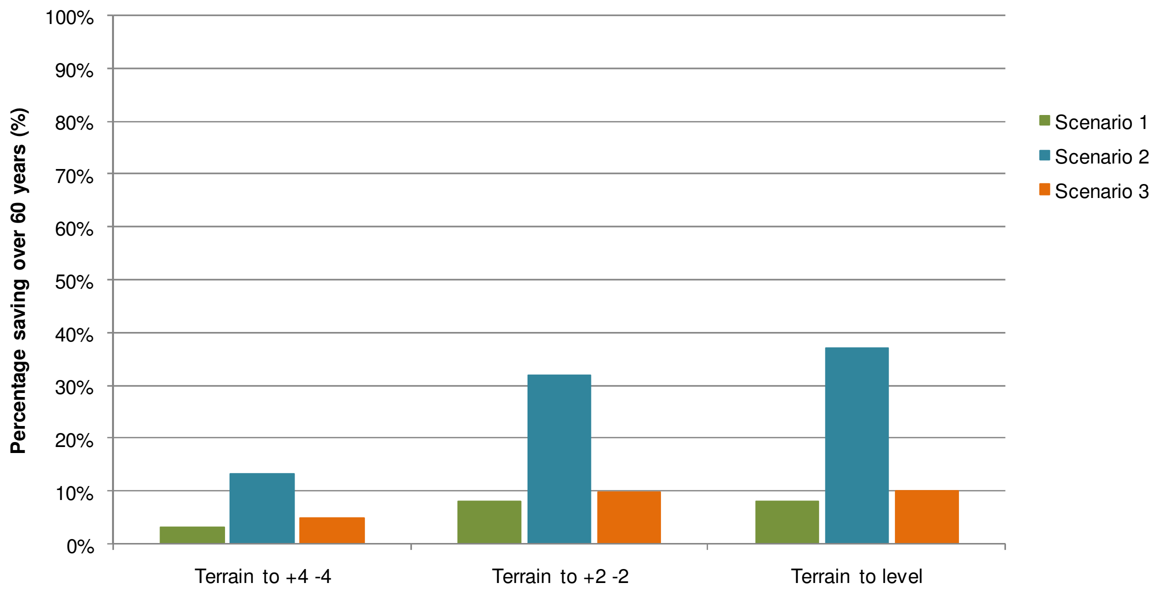


Figure 6.31 Percentage savings over 60 year period for valley terrain for higher earthworks value

6.6 Discussion

The assessment undertaken within this chapter has been based on the average flow of 84,851 vehicles per day and the typical fleet mix of an average UK motorway (Dft, 2010). The amount of CO_2 reduced from the shallower alignments would vary with vehicle flows, and hence the payback periods for the additional CO_2 expended in the earthworks would also vary.

Scenario 1, Business as Usual, has the longest payback durations. This is due to the lighter vehicles benefiting from the graded alignments which enable the resultant higher emissions from the heavier vehicles to be partly offset. Scenario 2, which considers the heavier vehicles only, benefits greatly from the shallower alignments; despite the vehicle flows being low the lifetime CO_2 emissions can be substantially reduced. Scenario 3, with the 10 kph lower vehicles speeds, has the shortest payback periods of all the scenarios considered. This is due to the lower speeds meaning that the lighter vehicles are less positively affected by the graded alignments; in conjunction with the consistent negative impacts to the heavier vehicles, the entire fleet benefits from the shallower alignments. Therefore, the benefits of the shallower alignments along with the large vehicle flows mean the scenario has the shortest paybacks.

Figure 6.32 demonstrates how the payback durations would vary with vehicle flows for the three scenarios considered. Figure 6.32a shows the payback periods against the vehicle flows for Scenario 1. For highways with low vehicle flows the payback time is very long. For example, to payback the additional CO_2 expended to take the alignment from the terrain alignment to the +4 -4 alignment at a flow of 10,000 vehicles per day it would take approximately 150 years. At the higher flows, for example the average motorway flow of 84,851 vehicles per day it would take around 30 years.

Figure 6.32b shows the pay back durations for Scenario 2, and Figure 6.32c shows them for Scenario 3. Again, for both scenarios at the low vehicle flows the payback durations are very long, and it is questionable whether extra efforts should be put into obtaining level alignments on highways that do not receive high traffic volumes.

All traffic flows do, at some point in the future, payback the additional CO_2 expended in the earthworks operation. However, the time required for the payback to occur and for CO_2 to begin to be saved is significant. The average flow on 'A' roads in Great Britain in rural areas is 10,900 vehicles per day (DfT, 2010); such a low flow would have an extremely long payback period, and it would certainly not be recouped within the 60 year period that highways are typically appraised over.

It was anticipated that the low CO_2 intensity of earthworks operations could have been used advantageously to achieve highway alignments that would result in sufficient CO_2 savings in the use phase to payback the additional CO_2 expended, and furthermore to save CO_2 over the project's lifetime.

The question is: Is it the CO_2 value expended in the earthworks at construction that is particularly large, or is it that the annual savings brought about by shallower alignments are particularly small? Referring back to the motorway case study that initiated this research (detailed in Chapter 2), the construction of the 23km length of 3-lane dual carriageway equated to 200,000 tonnes of CO_2. Comparatively, the earthworks operation required to take the valley terrain to a level alignment through the construction of an embankment comprised of 46 million m^3 of fill and resulted in 101,000 and 209,000 tonnes of CO_2, for the lower and higher values respectively. When comparing the embankment to the long stretch of motorway in such a manner, the earthworks CO_2 does appear high. Although the activity is a low intensive one in CO_2 terms, it is the scale of the earthworks operation that creates the large CO_2 value associated with it. Using the motorway project again as an example, the entire earthworks operation for that had a cut and fill balance of approximately 5 million m^3.

The annual savings for the valley terrain when taken to the level alignment are 14%, 40% and 16% for Scenarios 1, 2 and 3 respectively. These can be considered as notable savings. Therefore, in answer to the proposed question, it is the earthworks CO_2 that is substantial and causing the long payback periods.

Akin to the automobile industry, which is investing heavily in technology to reduce fuel consumption and hence CO_2 emissions, the earthmoving industry is also investing heavily to reduce the fuel consumed by its plant and machinery. JCB has invested £80 million to develop the JCB Ecomax diesel engine; one of the key benefits is improved fuel consumption, with reports of between a 5% and 10% reduction (JCB, 2010). Technology such as this could further lower the CO_2 intensity of earthworks and decrease earthworks related CO_2. Variation in the earthworks CO_2 would result in changes to the payback durations; with lower earthworks CO_2 values equating to shorter payback durations.

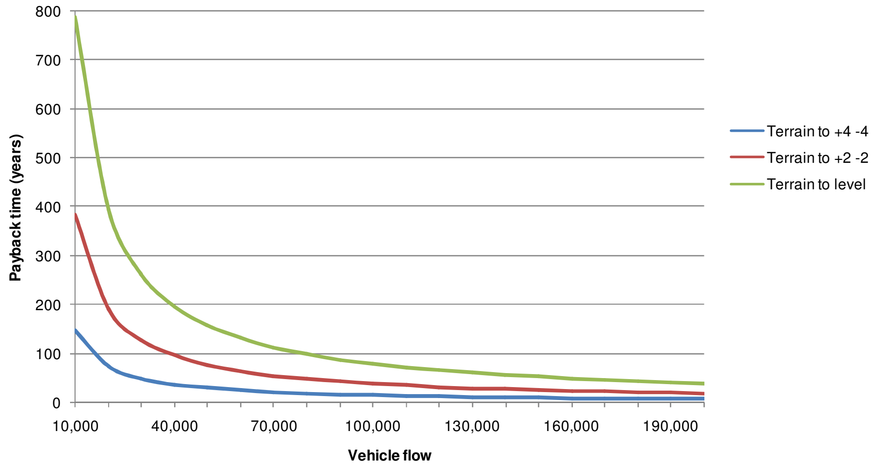


Figure 6.32a Scenario 1 payback periods versus vehicle flows

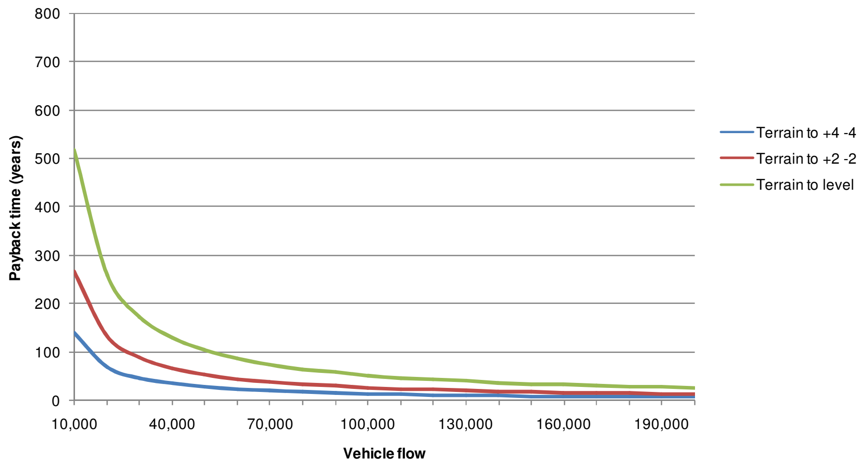


Figure 6.32b Scenario 2 payback periods versus vehicle flows

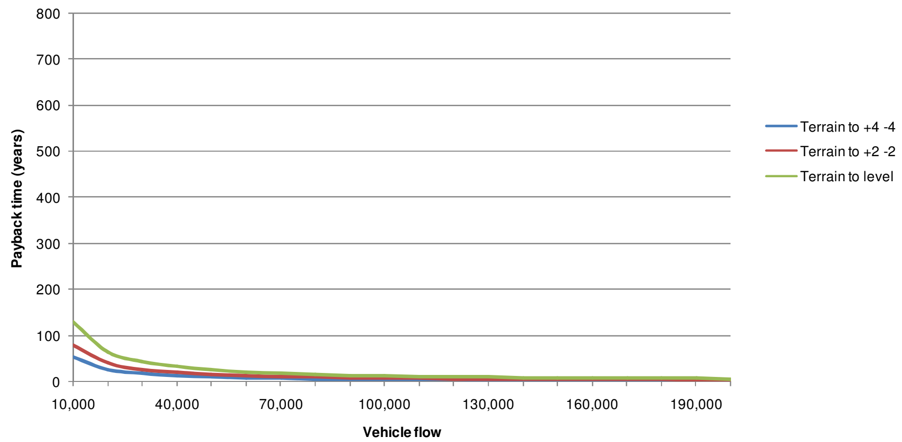


Figure 6.32c Scenario 3 payback periods versus vehicle flows

6.7 Conclusion

Within this chapter, the effect of alignments on individual vehicle types has been firstly assessed. This process of isolating and understanding the individual effects enabled the consequences on vehicle fleets to be identified.

In conclusion, the lighter vehicles are not greatly affected by gradients whereas the heavier vehicles are severely affected. In fact, in certain cases, light vehicles can actually benefit from traversing a steep uphill gradient followed by a steep downhill gradient – resulting in less CO_2 emissions than if the vehicle was to travel on a level road over the same distance. Although this seems counter-intuitive, it occurs due to the uphill section requiring the ICE to operate more efficiently, with the downhill section requiring very little fuel supply. Therefore, the slight increase in CO_2 emissions on the uphill section is offset by the very small CO_2 emissions produced on the downhill section.

This ‘offsetting effect’ does not occur for lighter vehicles at lower speeds, nor does it occur for heavier vehicles. Indeed, there is both a negative and much greater effect on the heavier vehicles. Although, similarly for lighter vehicles, the downhill section requires less fuel supply to the engine, the uphill section requires significantly more fuel which cannot be offset by the downhill reduction.

The fleets are made up of predominantly lighter vehicles, with heavier vehicles usually comprising less than 10% of the total. The assessment presented within this chapter demonstrates that the positive impact of graded alignments on lighter vehicles is always outweighed by the negative effect on heavier vehicles, despite the small proportion of the fleet that these constitute.

Therefore, level alignments would be preferred over graded alignments. This is particularly true under Scenario 2, which assumed the lighter vehicles are alternatively fuelled and concentrates on heavier vehicles only. Scenario 3, Lower Speeds, is next to benefit from the level alignment, with the lower speeds lessening the benefits to the lighter vehicles. Scenario 1, Business as Usual, which although still benefits overall from the level alignment, benefits the least, with the higher speeds increasing the positive effects on the lighter vehicles and partially counteracting the higher emissions resulting from the negative impact on the heavier vehicles.

The CO_2 expended in the construction of the shallower earthworks is significant due to the large volumes of material required to be excavated or placed. Earthworks remain a low carbon intensive activity, yet it is the scale of the operations required in the hypothetical alignments assessed that mean significant amounts of CO_2 are associated with them.

Chapter 7

Alignment case study

7.1 Introduction

Hypothetical hill and valley terrains were considered in Chapter 6, with different vertical alignments analysed to understand the impact on tailpipe CO_2 emissions from the vehicles operating on them, and the impact on the CO_2 resulting from the earthworks operations required to facilitate the alignments. Within this chapter the same methodology has been applied to an actual highway scheme to understand whether it is better to intervene at the construction phase, and expend more CO_2, to reduce CO_2 emissions in the use phase.

7.2 Highway scheme case study

7.2.1 Background to scheme

The confidential highway scheme, herein referred to as the A1, used within this case study is currently a single carriageway road 14km in length.

The Stage 1 scheme assessment that is designed to identify preferred route corridors was completed in 2008. Twelve corridors were initially assessed, four of which were discounted at an early stage based upon broad assessment criteria. At the final stage of the Stage 1 assessment, two of the remaining eight corridors were taken forward to the Stage 2 assessment.

For the purposes of the Stage 2 assessment the scheme was divided into three sections – A, B and C, as shown in Figure 7.1. Section A covers the south of the scheme and incorporates a small village, with the options of on-line improvements or a by-pass being considered. Section B covers the centre section of the scheme and incorporates a town, with two possible corridor options from Stage 1, a by-pass to the east or a by-pass to the west. Section C covers the north of the scheme for which on-line improvements are being considered.

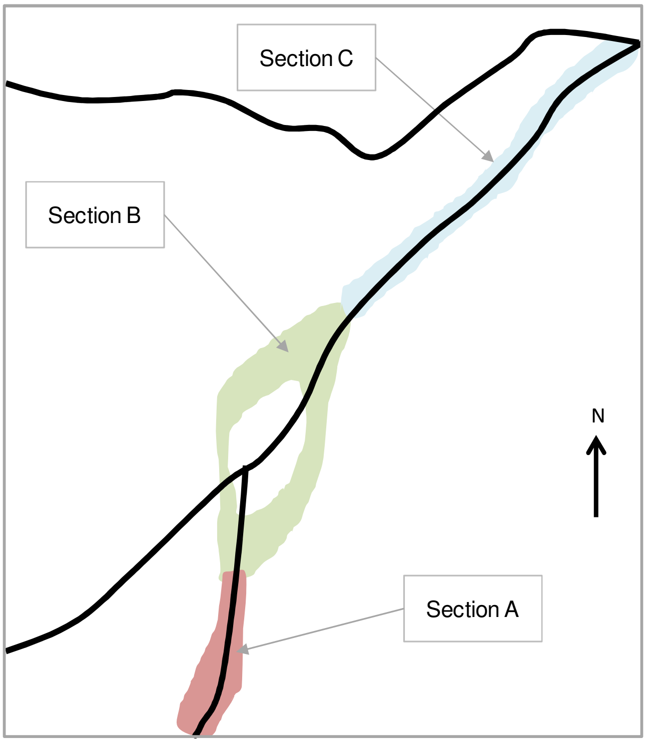


Figure 7.1 Sections of road scheme

7.2.2 Approach to case study

This thesis is attempting to understand the impact of alignment on CO_2 emissions across the life cycle. For this reason, Section B (from Figure 7.1) will be considered in the case study due the variations in both vertical and horizontal alignments between the alternative routes. In the Stage 2 assessment the Section B area was split into four sub-corridors; A, B, C and D, as shown in Figure 7.2.

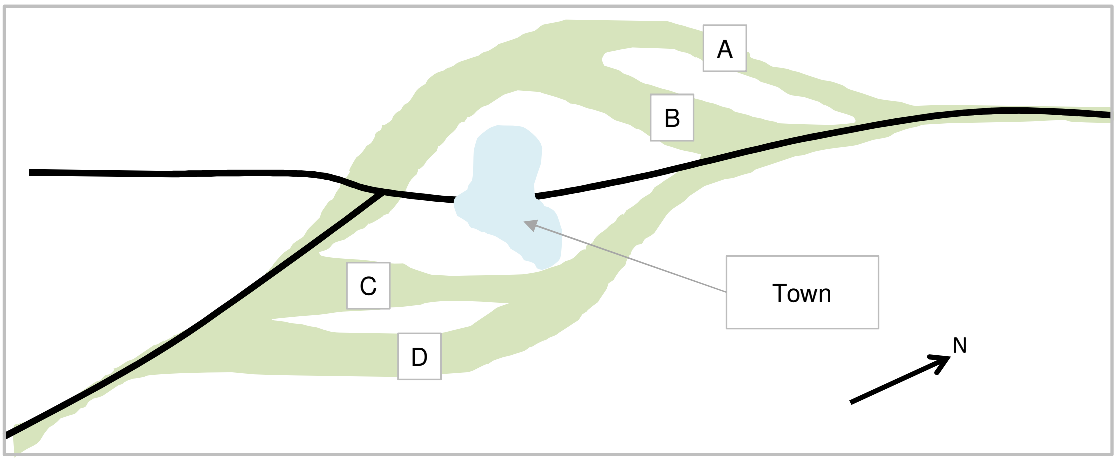


Figure 7.2 Four sub-corridors of Section B

There were six alignment options for Section B of the scheme. Routes B1, B2, B3 and B6 pass the town to the West, and Routes B4 and B5 pass it to the East.

The main considerations for route selection in Section B were the proximity of the route and impact on existing residential properties, watercourses, and the impact on agricultural land. However, the only consideration in this chapter is the impact of the alignments on CO_2 emissions; in the construction and use phases of the highway.

Figure 7.3a shows the western route options in profile running from south to north. The routes to the west of the town traverse a valley with gradients reaching +/- 4% for B3 and B6, +/- 2.5% for B2, and +/- 3.3% for B1 at the northern graded section. On the southern graded section the gradients are more similar; ranging from +/- 2.5 % to +/- 3%. Figure 7.3b shows the profiles of the graded sections for the western routes – the northern graded section is significant in both length and grade and would be likely to be detrimental to vehicles that have to ascend it.

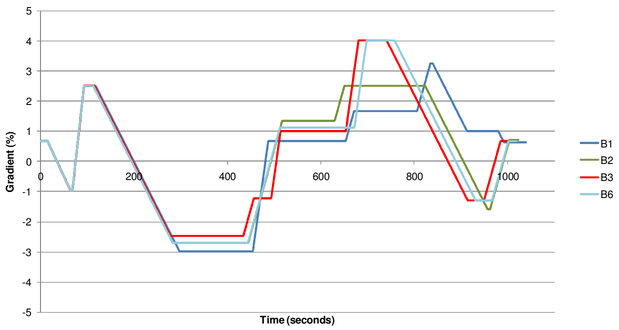


Figure 7.3a Gradients of western route options

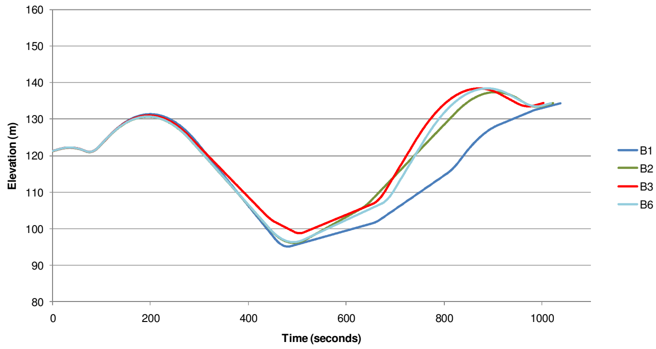


Figure 7.3b Profiles of western route options

The routes to the east undulate more. Route B5 has a similar southern graded section to the western routes, as shown in Figure 7.4a. On the southern section the routes reach gradients of between +/-3% and +/-4%. Unlike the western routes, the eastern routes do not have a constant decline or incline in the northern section; there is a secondary valley section, as shown in Figure 7.4b.

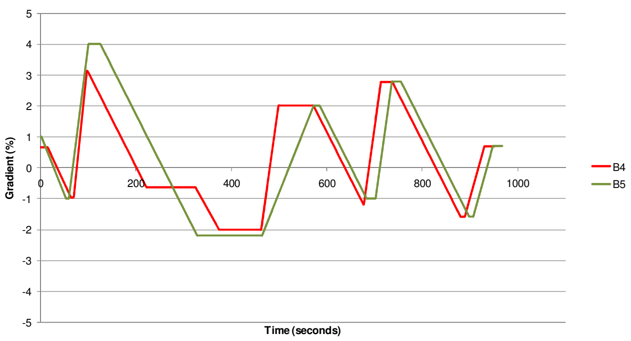


Figure 7.4a Gradients of eastern route options

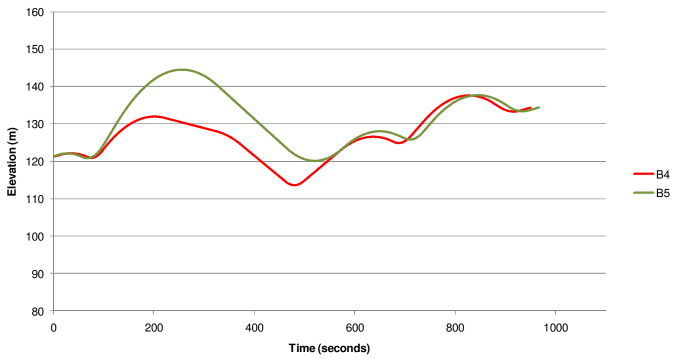


Figure 7.4b Profiles of eastern route options

All routes have varying horizontal alignments which contribute to the variation in the lengths of the routes. It is apparent that the eastern routes are shorter than the western options; detailed route lengths are given in Table 7.1. Were all routes to be level with the only variation being the horizontal alignment then the length of the route would be singularly important, however, it is the case that all routes have both varying vertical and horizontal alignments, and it is the absolute CO_2 produced by the route that is critical. Nonetheless, the total CO_2 will be normalised to route length to understand the efficiency of both the vertical and horizontal alignments.

Table 7.1 Route lengths

Route	Length (m)
B1	5770
B2	5680
B3	5570
B4	5280
B5	5370
B6	5660

7.2.3 Use CO_2

Within Chapter 6 the results of individual vehicles operating on differing hypothetical alignments have been presented. Petrol cars, diesel cars, LGVs, Rigid HGVs and Articulated HGVs were modelled individually over a hypothetical valley and hill to understand how alignments and hence gradients impacted on a range of vehicle types.

The main outcome from Chapter 6 was that graded alignments have smaller impacts on light vehicles such as cars and LGVs, with certain graded alignments yielding lower emissions than the equivalent level alignment at certain speeds. Conversely, graded alignments have a significant detrimental impact on heavier vehicles, which yield lower emissions on level alignments. To replicate the alignment effect on real-world highways, vehicle fleets were considered that reflect the typical vehicle mixes seen on UK roads. A similar approach has been taken to this case study; the effect of the alignments on each vehicle type have been assessed and subsequently used to assess a typical fleet on those alignments.

7.2.3.1 Individual vehicles

The same nine vehicle types have been used as in Chapter 6; Table 6.1 provides a detailed breakdown of the vehicle types. The results of the analysis on the petrol car and the half-laden articulated HGV are shown within this section to give an indication of how the alignments effect the emissions. The remaining seven vehicle types have been analysed in a similar manner, and although they are not presented in this chapter they are, however, included within the fleet analysis section.

The CO_2 emissions for a petrol car are subsequently shown. Firstly, in Figure 7.5a, the total CO_2 emissions are shown for each alignment in the northbound direction; as expected the emissions increase with increasing vehicle speed. Figure 7.5b shows the CO_2 emission for each northbound route normalised to the CO_2 emissions that would be produced if the route were level at that particular speed.

The total CO_2 emissions for the petrol car travelling in the southbound direction are shown in Figure 7.5c. The emissions are higher in the northbound direction when compared to the southbound; due to the longer decline when travelling southbound. For example, for Route B1, at 75 kph the northbound results in 7 % more emissions than the southbound.

The southbound petrol car benefits from the graded alignment, yet it is detrimental in the northbound direction at speeds less then around 130kph. At 110kph, the petrol car on route B4 yields 990g CO_2 in the northbound direction, yet only 937g CO_2 in the southbound direction. Figure 7.5d demonstrates the benefits of the long declined section in the southbound direction on the petrol car – at all speeds the graded alignment results in lower emissions than on the level alignment due to the lower emissions on the decline offsetting the increase in emissions on the incline.

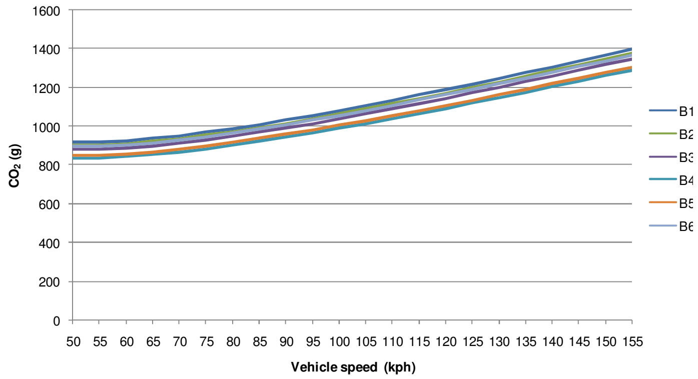


Figure 7.5a CO_2 emissions for northbound petrol car

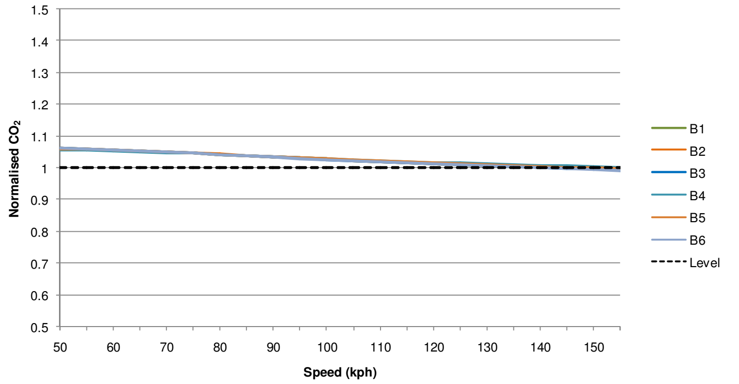


Figure 7.5b Normalised CO_2 emissions for northbound petrol car

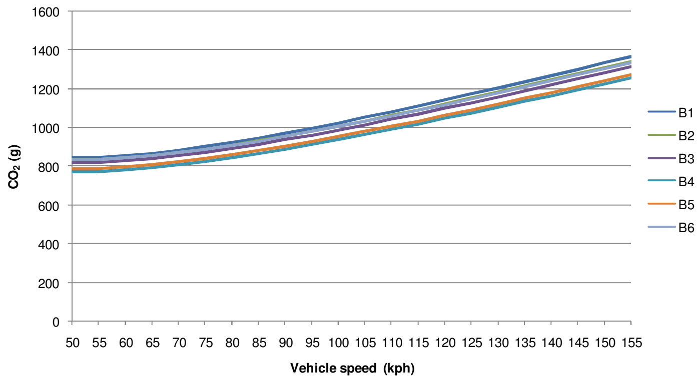


Figure 7.5c CO_2 emissions for southbound petrol car

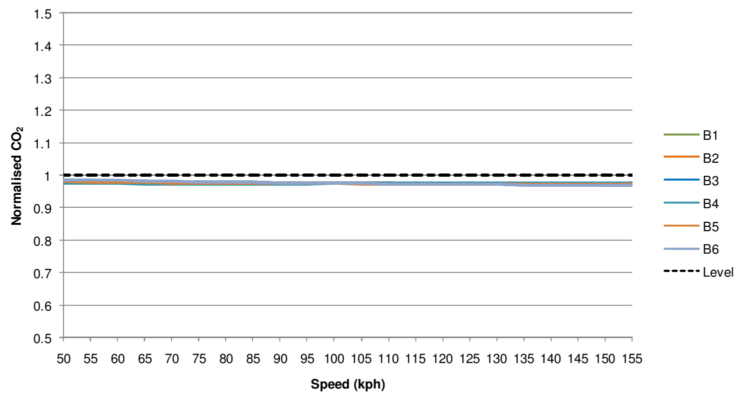


Figure 7.5d Normalised CO_2 emissions for southbound petrol car

The effect of the routes on the heavier vehicles is more dramatic than on the light vehicles. The total emissions for the northbound and southbound directions are shown in Figure 7.6a and 7.6c respectively. Similarly to the petrol car the emissions are higher in the northbound direction, at 75 kph for Route B1 the emissions are 28% higher for the HGV compared to 7 % for the petrol car.

The longer incline at the northern end of the western routes results in up to around 50% higher emissions at the lower speeds, as shown in Figure 7.6b. This figure also shows that over the entire speed range it is the level alignment that remains preferable in both the southbound and northbound cases.

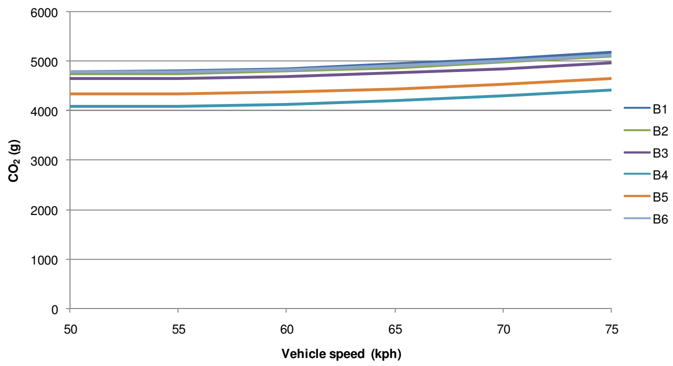


Figure 7.6a CO_2 emissions for northbound half-laden articulated HGV

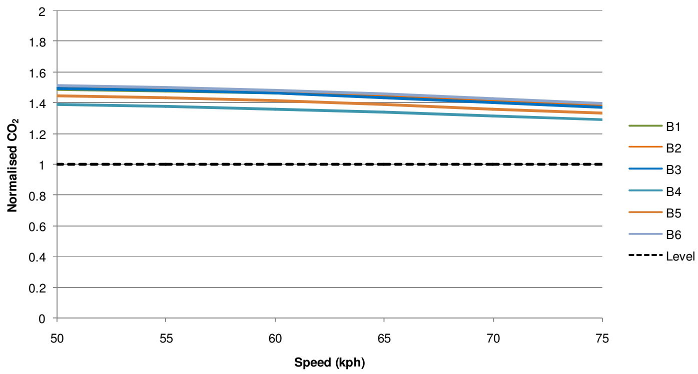


Figure 7.6b Normalised CO_2 emissions for northbound half-laden articulated HGV

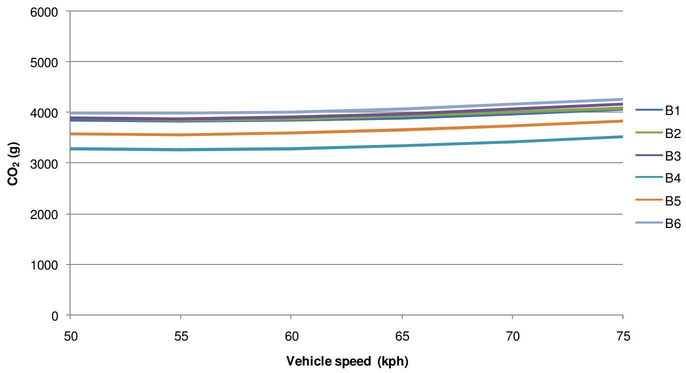


Figure 7.6c CO_2 emissions for southbound half-laden articulated HGV

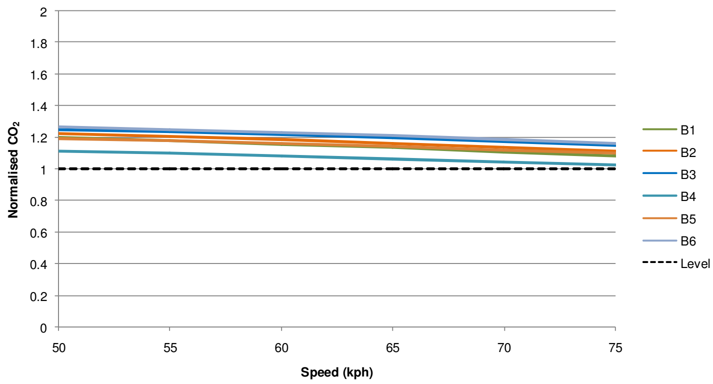


Figure 7.6d Normalised CO_2 emissions for southbound half-laden articulated HGV

7.2.3.2 Fleets

In Section 7.2.3.1 the effect of the different route alignments on a petrol car and a half-laden articulated HGV were assessed. A similar assessment was undertaken for a diesel car, LGV, rigid HGV (unladen, half-laden and fully-laden) and an articulated HGV (unladen and fully-laden). Once all vehicle types had been assessed it was possible to understand how the alignments could impact on the CO_2 emissions of a typical vehicle fleet.

The outcome of the modelling undertaken in the traffic assessment indicated that different routes would be expected to carry different vehicle flows; it was possible for vehicles to make a choice between whether to travel on the existing route or on the new route. Table 7.2 shows for each of the six routes: the 2-way AADT on the new A1 bypass, the 2-way AADT on the existing A1 through the town, and the 2-way HGV flow on the existing A1 through the town. For the western routes (B1, B2, B3 and B6), the same flows are expected on the new bypass and the existing bypass; with the majority of the traffic, including HGVs, being removed from the existing A1 road. However, the eastern routes are expected to remove less vehicles from the existing A1, with more traffic, including HGVs, preferring to travel through the town than on the new bypass.

Table 7.2 Traffic assessment summary (adapted from Arup (2009))

Route	B1	B2	B3	B4	B5	B6
New A1 bypass (Total 2-way AADT)	22,010	22,010	22,010	20,525	20,420	22,010
Existing A1 (Total 2-way AADT)	2,422	2,422	2,422	3,123	3,136	2,421

The vehicle flows shown in Table 7.2 have been used in the subsequent fleet assessment. The flows have been split equally between the northbound and southbound directions. The fleet mix used reflects the projected 2025 fleet mix for rural roads from Defra (2002). Due to only diesel LGVs being considered in the individual vehicle assessments, the petrol LGVs have been included in the diesel LGV category. Similarly, due to buses not being considered these have been excluded from the fleet and the remaining fleet subsequently corrected to allow for these omissions.

Table 7.3 Fleet composition

Vehicle	Percentage	Corrected percentage
Petrol car	64.3%	64.7%
Diesel car	16.4%	16.6%
Petrol LGV	1.3%	0.0%
Diesel LGV	11.3%	12.6%
Rigid HGV	2.9%	2.9%
Articulated HGV	3.2%	3.2%
Buses	0.7%	0.0%
Total	100%	100%

Individual vehicles on the northbound and southbound routes have been previously presented. The southbound route, with its long decline, is shown to be beneficial over the level route for the petrol car. The northbound, however, is not beneficial, showing an increase over the level route across all speeds except those over around 130kph. Neither the north nor southbound route is beneficial to the half-laden articulated HGV.

Figure 7.7 shows the fleet emissions for the northbound and the southbound directions, across all three scenarios. The bar graphs show the total emissions from the new route (blue bar) and the existing route (green bar). Also shown are the grams of CO_2 per vehicle km travelled; these are the same for the existing route across all the alignment options but have been included for comparative purposes.

Figure 7.7a and 7.7b show the results for Scenario 1 for the northbound and southbound directions respectively. There is very little variation between the route efficiencies of the northbound directions across all alignments, as shown in Figure 7.7a. The same is seen for the southbound direction, in Figure 7.7b. However, there is a notable difference between the total emissions across the six alignments. In both directions it is Route B1 that yields the highest emissions and Route B4 that yields the lowest; attributed to Route B1 being the longest and B4 the shortest.

For Scenario 2, there is a greater variation in the route efficiencies for the northbound and southbound direction, as shown in Figure 7.7c and 7.7d respectively. The visible variations are because this scenario only considers the HGVs, which have demonstrated previously to be particularly susceptible to varying vertical alignments. Routes B4 and B5 are the most efficient in the northbound direction, and Routes B1 and B4 in the southbound direction. Despite these variations in efficiency, there appears to be less variation between the total emissions in Scenario 2 than there was for Scenario 1, which showed little variation in route efficiencies. There are in fact greater variations between the routes in Scenario 2; there is a 22% difference between the highest and lowest emitting northbound routes (B1 and B4); whereas, for Scenario 1 there was only a 15% difference (between B1 and B4).

Again, as seen in Scenario 1, there is a very small variation in route efficiencies in the northbound and southbound direction across all routes for Scenario 3, as shown in Figure 7.7e and 7.7f respectively. Overall, however, the total emissions are lower than for Scenario 1 due to the lower vehicle speeds.

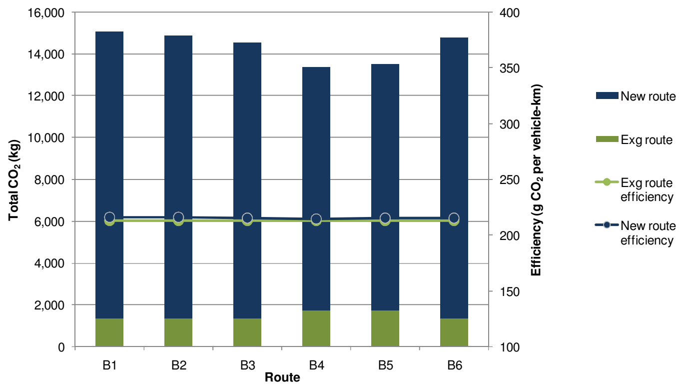


Figure 7.7a Northbound fleet emissions for actual flows for Scenario 1

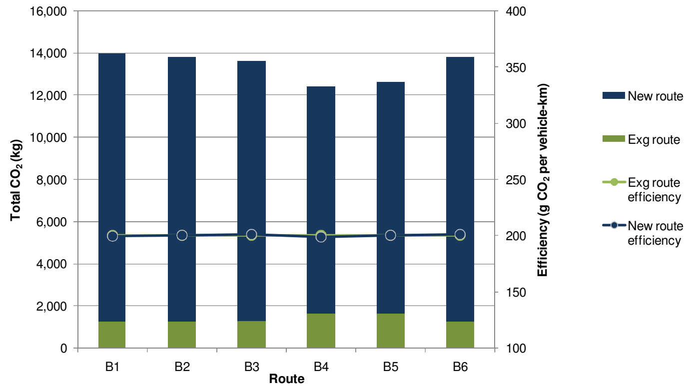


Figure 7.7b Southbound fleet emissions for actual flows for Scenario 1

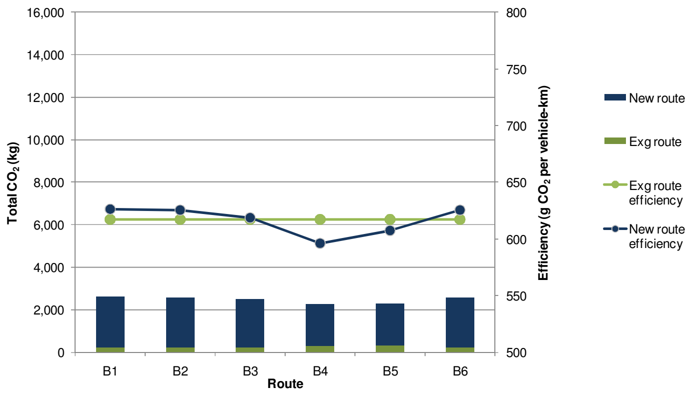


Figure 7.7c Northbound fleet emissions for actual flows for Scenario 2

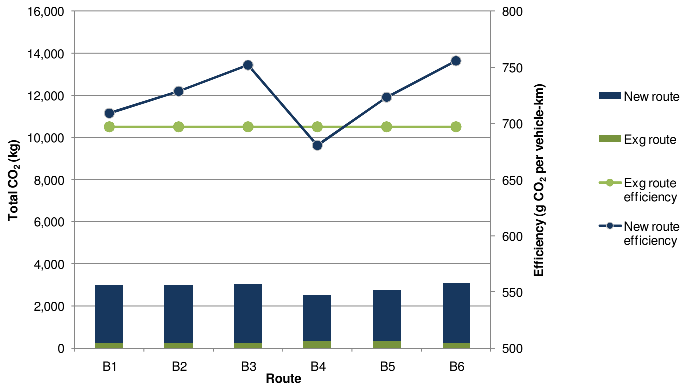


Figure 7.7d Southbound fleet emissions for actual flows for Scenario 2

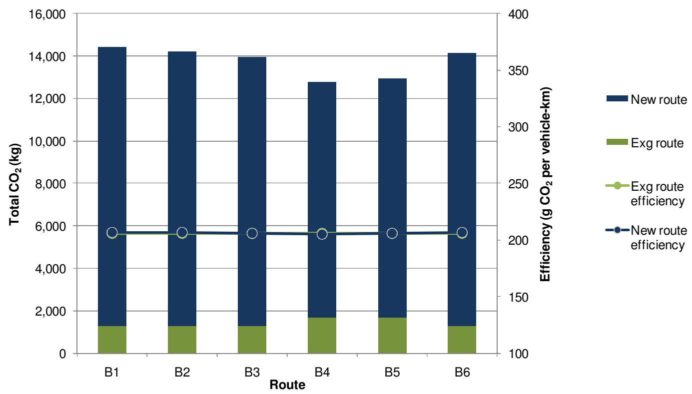


Figure 7.7e Northbound fleet emissions for actual flows for Scenario 3

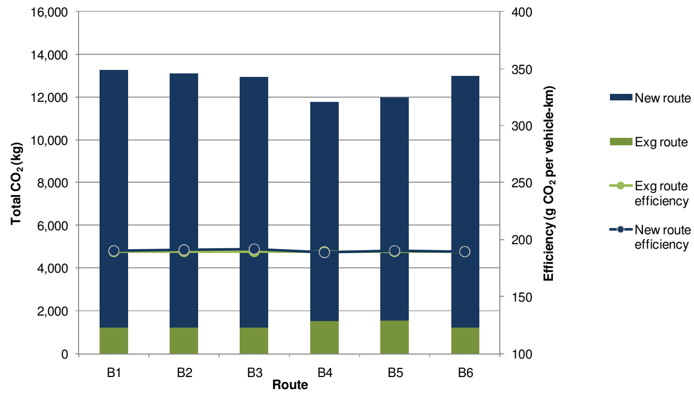


Figure 7.7f Southbound fleet emissions for actual flows for Scenario 3

The normalised CO_2 emissions for the northbound, southbound and both directions are shown in Figure 7.8a, 7.8b and 7.8c respectively. The emissions have been normalised to the emissions that would be released if the routes were level. For all scenarios in the northbound direction the emissions are higher on the graded alignments, and it would be preferable to operate on a level alignment. This is particularly true for Scenario 2 which only considers HGVs; on all routes the proposed alignments result in at least a 22% increase in emissions. Scenario 1, although negatively affected by the gradients, is not as affected as Scenario 3; the reason being is that the lighter vehicles benefit from operating on the proposed alignments at the higher speeds in Scenario 1 and this benefit partly offsets the detrimental effect on the heavier contingent of the fleet. Whereas, in Scenario 3 the lighter vehicles are travelling at slightly lower speeds which results in less of a benefit and so cannot offset the heavier vehicles as much.

The southbound direction, shown in Figure 7.8b, appears to benefit Scenario 1 and 3 across all alignments. From previous analyses, it was anticipated that the HGVs in Scenario 2 would not benefit from the graded alignments.

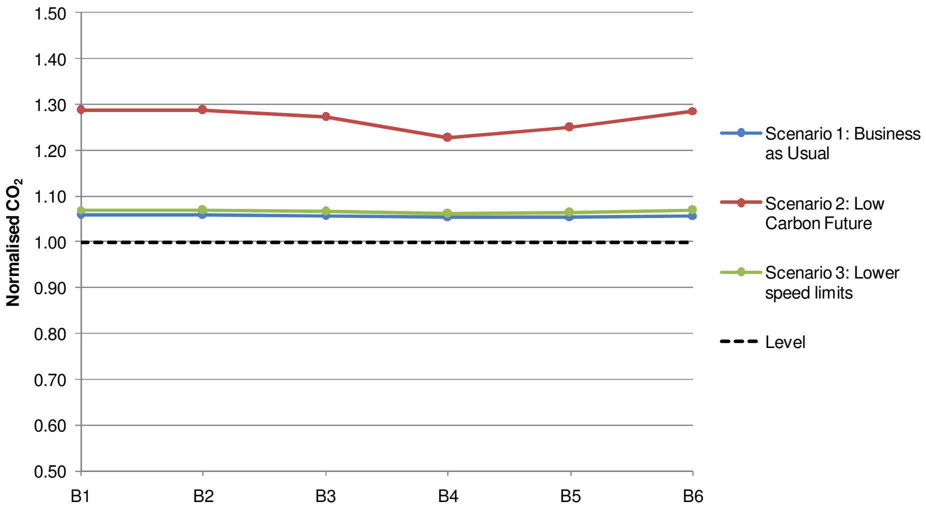


Figure 7.8a Normalised northbound emissions

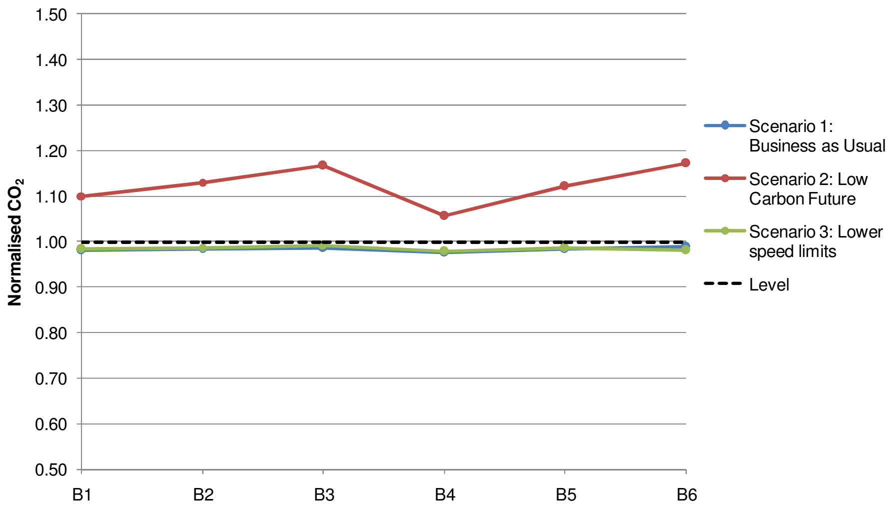


Figure 7.8b Normalised southbound emissions

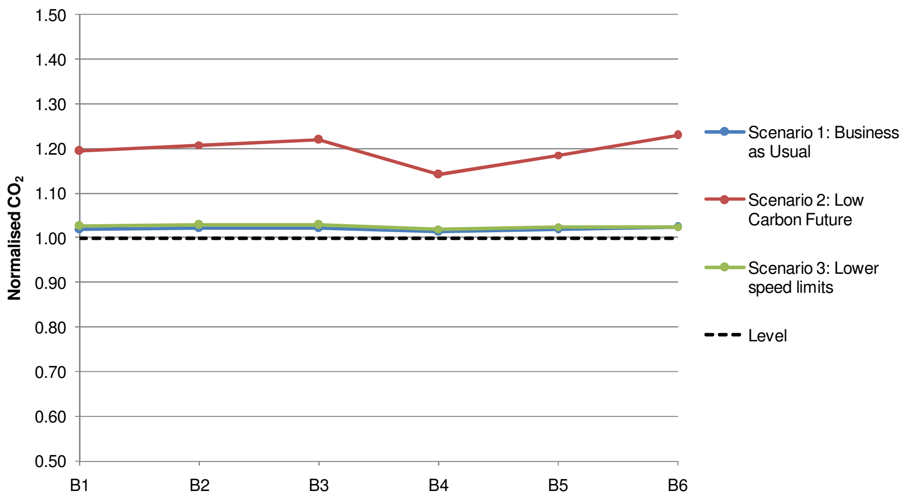


Figure 7.8c Normalised emissions for both directions

The total emissions for each route across the scenarios are presented in Table 7.4 – the total emissions is the sum of the emissions from the existing route and the emissions from the new route. For all scenarios it is Route B4 that produces the lowest emission values and Route B1 that produces the highest; which corresponds to the shortest and longest routes respectively. The exception is in Scenario 2 where the highest emitting route is B6.

Table 7.4 Absolute emissions for proposed routes

Scenario		B1	B2	B3	B4	B5	B6
Scenario 1 –	New route	26,500	26,000	25,600	22,400	22,800	26,000
Business as	Existing route	2,600	2,600	2,600	3,400	3,400	2,600
usual	TOTAL	25,200	24,800	24,500	21,300	21,700	24,600
Scenario 2 –	New route	5,100	5,100	5,100	4,100	4,400	5,200
Low carbon	Existing route	500	500	500	600	600	500
future	TOTAL	5,600	5,600	5,600	4,700	5,000	5,700
Scenario 3 –	New route	25,200	24,800	24,500	21,300	21,700	24,600
Lower speed	Existing route	2,500	2,500	2,500	3,200	3,200	2,500
limits	TOTAL	27,700	27,300	27,000	24,500	24,900	27,100

Figure 7.9 shows the total emissions for the proposed alignments (green) and the total emissions that would result if the routes were level (blue). For Scenario 1, shown in Figure 7.9a, the emission savings from a levelled alignment are small and range from 2% to 3%. The reductions for Scenario 2 are more noteworthy, with reductions ranging from 1% to 6%. Greater reductions were expected for Scenario 2, due to only HGVs being considered, which benefit greatly from a level alignment. The reductions for Scenario 3 range from 1% to 2%.

When considering Scenario 1, the Business as Usual situation, the reduction between the lowest emitting proposed route (B4) and highest emitting proposed route (B1) is 15%. Over a 60 year period this would amount to a saving of around 87,000 tonnes of CO_2. With focus on the lowest emitting alignment, B4, the level version of this alignment could result in a saving of approximately 9,000 tonnes of CO_2 over the proposed alignment over a 60 year period. Therefore, the savings from chosing the lowest emittting proposed alignment are greater than the savings that can be brought about through efforts to obtain a level alignment. Under Scenario 2 the savings from a level alignment for B4 are lower – saving less than 1,000 tonnes over the 60 year period when compared to the proposed B4 alignment.

The levelling of the routes does not make a major difference and whether it would be worthwhile to expend more CO_2 in the construction phase to achieve a level alignment is questionable. The difference between the proposed alignment and level alignment of B4 for the routes over 60 years is 9,000 tonnes in Scenario 1; from outcome of previous work in this thesis it would be anticipated that the additional efforts required to obtain a level alignment would exceed this value in CO_2 terms.

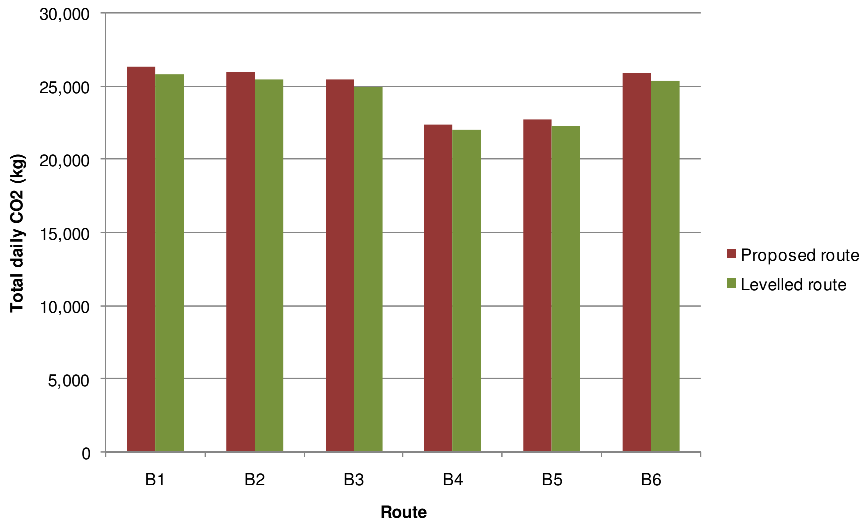


Figure 7.9a Total emissions for Scenario 1 for proposed and levelled alignments

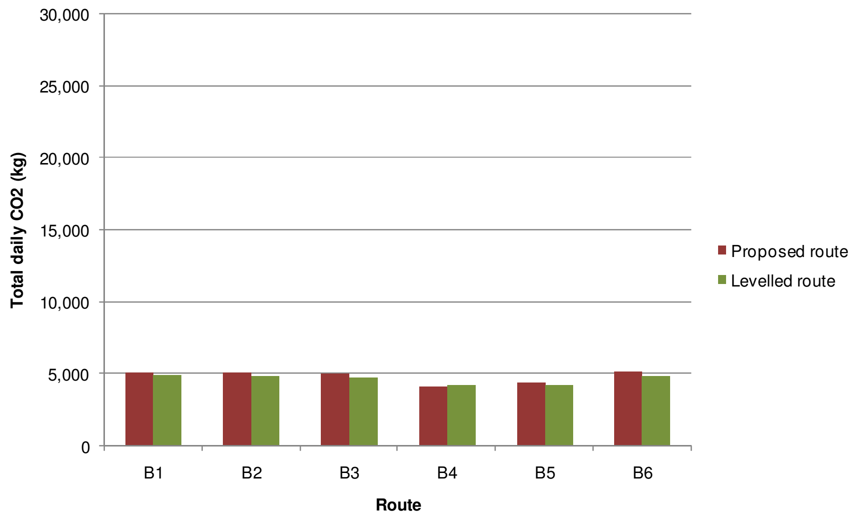


Figure 7.9b Total emissions for Scenario 2 for proposed and levelled alignments

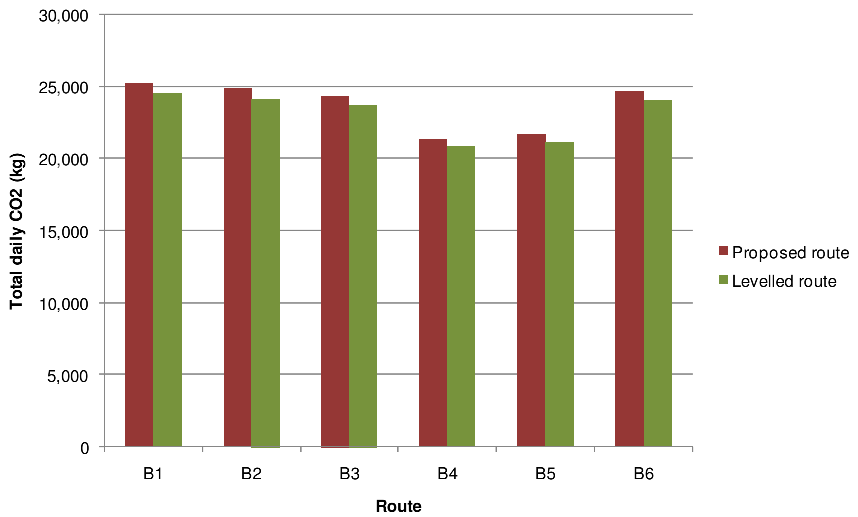


Figure 7.9c Total emissions for Scenario 3 for proposed and levelled alignments

7.2.4 Earthworks

For many actual projects, levelling the alignment through the construction of an embankment may be difficult, if not altogether impossible due to restraints and considerations such as time, costs and site boundary constraints. Route 4 has been identified as the most efficient route; with both the lowest emission rate per kilometre, and lowest total emission. B4 has therefore been focused upon and the vertical alignment amended, as shown in Figure 7.10. The amendments have been made to attempt to achieve further efficiency in the use phase, by removing the valley and providing a level section. Due to the terrain at the location of the scheme, and the changes in ground level, it is not possible to create an entirely level route, and hence only one section has been hypothetically made level.

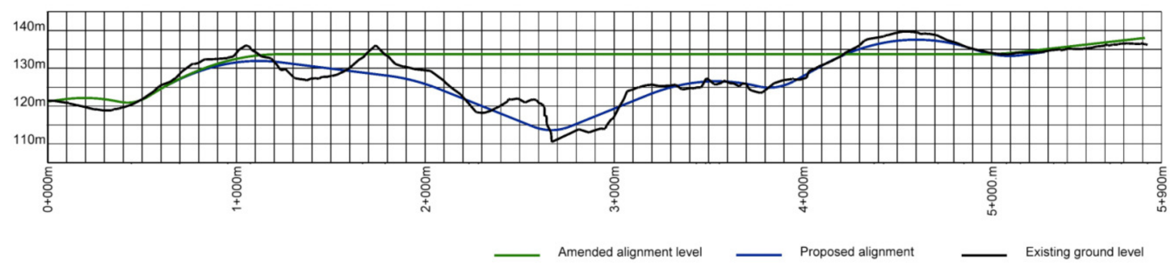


Figure 7.10 Long section of proposed and amended B4 vertical alignment

Arguably, in addition to the possible difficulty in levelling an alignment it may also be unfeasible to construct this level alignment through an embankment structure. The focus of this research is, however, on the use of earthworks to achieve beneficial highway alignments and therefore the levelled alignment has been assumed to be facilitated by an earthworks embankment. The question of whether an embankment is a preferred option over a viaduct alternative is addressed in Chapter 8.

All routes were amended and levelled; this was done to understand whether the earthworks operation required to obtain a level version of B4 was representative of the other alignments. The earthworks associated with the proposed and levelled alignments are shown in Table 7.5 for all routes; the cut and fill volumes are shown with their respective percentage changes. The levelled version of Route B4, the focus of this assessment, requires 16% more cut and 2147% more fill. The earthworks volumes required to level Route B4 are actually the smallest of the alignments; with Route B2 requiring 4713% more fill and Route B6 requiring 302% more cut.

Table 7.5 Earthworks volumes for proposed and amended alignments

Route	Volumes (m^3)					
	Cut			Fill		
	Proposed alignment	Amended alignment	Percentage change (%)	Proposed alignment	Amended alignment	Percentage change (%)
B1	40,000	139,000	-248%	300,000	8,513,000	-2738%
B2	137,000	156,000	-14%	129,000	6,209,000	-4713%
B3	122,000	101,000	17%	101,000	1,886,000	-1767%
B4	133,000	154,000	-16%	64,000	1,438,000	-2147%
B5	126,000	282,000	-124%	73,000	2,763,000	-3685%
B6	107,000	430,000	-302%	155,000	5,678,000	-3563%

7.2.4.1 Methodology and assumptions

The route of B4 has been divided into zones which are 200m in length. For example Zone 1 extends from 0m to 200m along the chainage, and Zone 2 from 200m to 400m along the chainage. This continues along the length of the route which ends at 5825m; resulting in a final zone of 25m in length. All movements have been assumed to occur from or to the central point of the zone.

The template used to obtain the earthworks volumes given in this section is shown in Figure 7.11 - it represents a typical 2-lane dual carriageway with lane widths totalling 7.3 m, a central reservation width of 2.5 m, a verge width of 1.5 m, and 1:2 slopes.

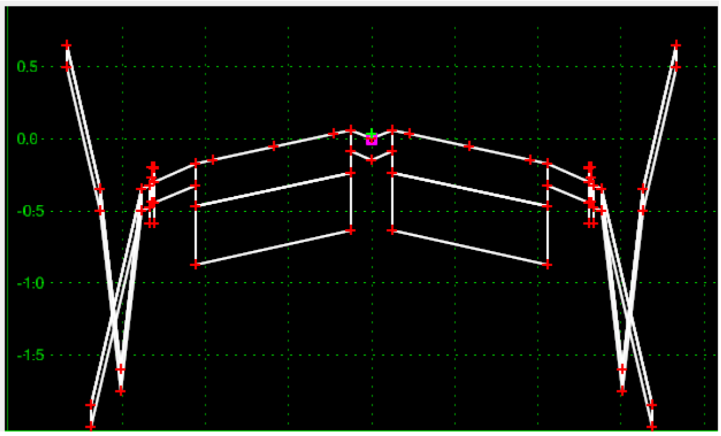


Figure 7.11 Template for 2-lane dual carriageway

It has been assumed that the fill material would not be sourced within the site but from a location 5000m away and would require hauling by road.

Two stockpile locations have been assumed – one at 2200m along the chainage and the second at 3200m along the chainage. There are also two potential source locations for these materials – both taken to be 5000m from the stockpile sites.

Three machinery pairings have been considered, the details of each pairing are presented in Appendix F. The pairings are a:

- 25 tonne excavator with a 30 tonne ADT
- 35 tonne excavator with a 30 tonne ADT
- 45 tonne excavator with a 35 tonne ADT

With regards to double handling: All material sourced off-site was assumed to be excavated at the external location and loaded onto a road lorry, then hauled to site and tipped at one of the stockpile locations. The subsequent use of this material would then require a further excavation operation and site haul to its final location. In terms of the placing and compaction, it is assumed that all material excavated and hauled internally to another location has to be both placed and compacted. A 25 tonne crawler dozer (a Cat D7) has been taken for the spreader, and a 20T roller (a Bomag BW 216) for the compactor.

7.2.4.2 Earthworks CO_2

The CO_2 associated with each earthworks movement for the three machinery pairings assessed is presented in Appendix G. The sum of each movement for each machinery pairing is shown in Figure 7.12; disaggregated into CO_2 from excavation, site haul, place, compaction and the road haul of the externally sourced materials to site.

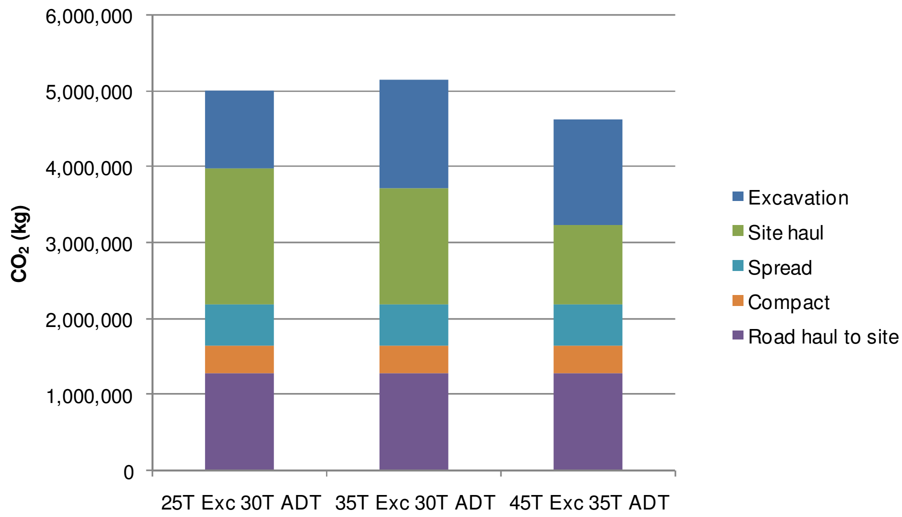


Figure 7.12 CO_2 for earthworks operation for different machinery pairings

The 45 tonne excavator and the 35 tonne ADT is the most efficient pairing for this earthworks operation, with the 35 tonne excavator and the 30 tonnes ADT being the least efficient and resulting in 12% more CO_2.

Figure 7.12 shows the CO_2 associated with the earthworks with no use of lime to improve the workability of the fill material. Previous work, in Chapter 5, has demonstrated the impact of the use of lime on total CO_2. Therefore, to understand the potential use of lime for this specific earthworks operation, two further cases have been considered:

- The use of lime (at 2% by dry weight of the fill) to treat 20% of the fill material; and
- The use of lime (at 2% by dry weight of the fill) to treat 40% of the fill material.

The results for all three cases of lime use are shown in Figure 7.13 for the three machinery pairings. The results shown in Figure 7.12 are represented by the green line in Figure 7.13. The use of lime has a significant detrimental impact on the CO_2 emissions; potentially increasing CO_2 by 395% when considering the ‘no lime’ against the ‘40% of fill treated’ cases.

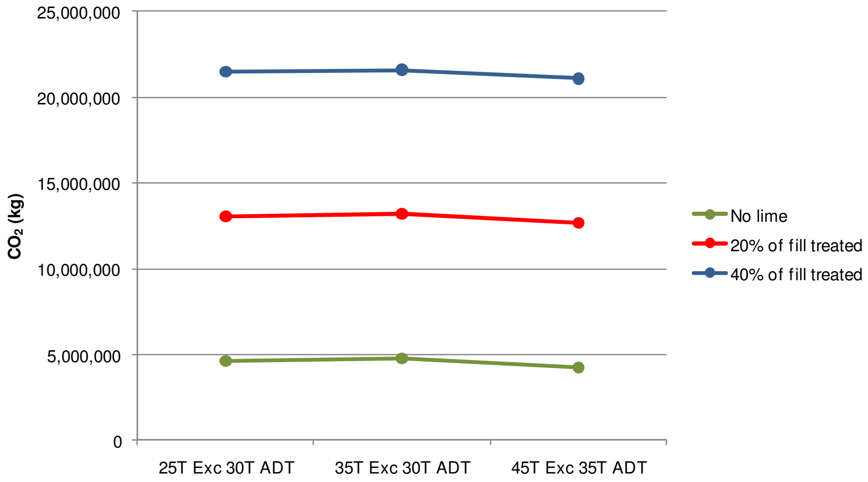


Figure 7.13 CO_2 for earthworks operation for different machinery pairings with varying amounts of lime

7.2.5 Discussion

The difference between the proposed alignment and level alignment over 60 years is 9,000 tonnes of CO_2 under Scenario 1 for the vehicle flows, fleet mix and vehicle speeds considered. The outcome of the earthworks assessment indicated that the additional CO_2 expended in the construction of the level alignment could range between 4,000 and 22,000 tonnes (when lime is used). Therefore, based on these assumptions and calculations, the payback could range from 25 to 150 years, and the CO_2 expended in construction of the level alignment could be recovered within the typical 60 year appraisal period of a highway scheme. For Scenario 2 and 3 the CO_2 expended in construction would certainly not be recovered within the 60 year period.

The flows on this particular highway are higher than the typical flows on UK dual carriageways; approximately 22,000 vehicles per day compared to 10,900 vehicles per day on a rural A-road in the UK (Defra, 2002). It would therefore be expected that the high flows would return the CO_2 expended in construction over a shorter time period. However, the high flows are only high relative to the average dual carriageway flows, and are not high enough to result in large annual reductions in CO_2 in the use phase.

When considering the lower CO_2 value for the earthworks operation required to take the alignment from its proposed form to its amended form, which equates to 4,000 tonnes, this is not a significant amount when compared to the CO_2 that could be anticipated from the highway pavement. A typical rural all-purpose dual carriageway would result in 1,480 kg CO_2 per m length (Dudek, 2009); for the 5280 m long Route 4 this would equate to approximately 7,800 tonnes of CO_2.

7.2.6 Conclusion

The case study detailed in this chapter emphasises the relevance of vehicle flows. This particular dual carriageway has high traffic flows relative to the average flows on rural dual carriageways in the UK. Despite the flows being considered high in terms of dual carriageway flows, they are in fact quite low and over a 60 year period under Scenario 1 only 9,000 tonnes of CO_2 is reduced. The resultant CO_2 from the earthworks required to create the alignment would be repaid within a 60 year period.

The highest emitting route was B1, and it was possible to reduce CO_2 emissions by 15% alone through the selection of Route B4 instead. The reduction that could be made by selecting Route B4 and making it completely level would further reduce emissions to 17%. This highlights the importance of selecting the route which results in the least CO_2 emissions, with a 15% reduction possible through the selection of one proposed route over another.

When the methodology recommended within the WebTAG Environment sub-objective was followed, the eastern routes (B4 and B5) were identified as resulting in the highest emissions with all the western routes (B1, B2, B3 and B6) resulting in the same emission levels. This highlights the lack of refinement in this recommended and widely adopted approach, with the results from this chapter demonstrating the potential benefits of adopting a more sophisticated approach to assessing the alignments of different route options.

Chapter 8

Earthworks based structures case study

8.1 Introduction

The CO_2 from earthworks operations can be low compared to other construction activities when the materials used within the earthworks operation are sourced on site. For this reason, the use of a structure comprised of earthworks fill would seem preferable in CO_2 terms over a structure made of new CO_2 intensive materials such as concrete and steel. This chapter considers the use of earthworks structures over alternative structures from man-made materials.

This project, which cannot be identified for confidentiality reasons, involves the conversion of a single 3-lane carriageway into a dual 2-lane carriageway. The improvements to this particular section are off-line and therefore involve the construction of an entirely new section of highway.

The main objective of the CO_2 assessment was to demonstrate the potential CO_2 benefits of an embankment over a viaduct, through a detailed assessment of the construction of both. Any benefits would be more meaningful when considered in the context of the entire construction phase CO_2 to enable the magnitude of any potential savings to be understood. Again the potential benefits of the selection of an embankment would also be more meaningful in the context of the rest of the life cycle; construction, use, operation and maintenance. Therefore, the scheme has also been considered over a 60 year period.

A detailed assessment of the construction phase has been undertaken to fully understand the CO_2 implications of an embankment compared to a viaduct. The assessments of the remaining phases (use, maintenance and operation) were undertaken in a more approximate manner to enable the CO_2 benefits to be understood in the context of the CO_2 from the whole life of the scheme.

8.2 CO_2 impact of structure choice

This section considers the CO_2 implications of the choice of structure; whether it is preferable in CO_2 terms to use an embankment or a viaduct. An earthworks operation is necessary regardless of structure choice, although it will, of course, alter with the option. The earthworks operation is considered in Section 8.2.1.

The embankment operation would also require some supplementary structures; these are covered in Section 8.2.2. The viaduct is considered in Section 8.2.3. A comparison of the CO_2 related to each option is undertaken in Section 8.2.4.

8.2.1 Earthworks

The earthworks assessment is based on the mass haul schedule provided by the contractor, Carillion (2011). This schedule provided was based on the scheme that included an embankment, rather than the initially proposed viaduct. The CO_2 assessment for the embankment is, therefore, based on the mass haul schedule that has been developed for the actual scheme. The CO_2 assessment for the viaduct option is also based on the mass haul schedule for the actual scheme; with the excavated material that is intended for the embankment instead being transported to a stockpile location.

The earthworks operation had been assessed in detail; the earthworks activities have been considered individually, with a fuel consumption and hence CO_2 emission being assigned to each movement. The activities are:

- Excavation and haul (on-site). These operations are based on the pairing of a 30T excavator with a 35T ADT. Two machine pairings have been assigned to the internal movement of material: the first to excavate and haul dry cohesive material, and the second pairing to excavate and haul hardrock material. The haul distance is dependent on the location of the excavation and deposition, and hence is variable.
- Excavation and haul (off-site). These operations are based on the pairing of a 30T excavator with a road lorry. The haul distance to the stockpile location varies between 0.8km and 4.3km.
- Spreading. This operation is based on the use of a 20T crawler dozer.
- Compaction. Based on the use of a typical compactor (a Bomag BW 216). The depth of layers for compaction has been taken at 300mm, with each layer requiring 4 passes of the roller.
- Processing. This operation, to convert the excavated rock into useable materials of consistent size, has been given a fixed output for all excavated materials that require processing. The materials have been assumed to be processed twice.

The individual movements associated with the earthworks operations are given in Appendix H. However, for presentation purposes, and in order for the outcome of the earthworks CO_2 assessment to be understood easily, the earthworks have been presented graphically in Figure 8.1. The earthworks have been aggregated to:

- Material excavated and taken off-site to stockpile by road (red)
- Material excavated and hauled to a destination on site (dark blue)
- Material excavated, processed, and hauled to a destination on site (light blue)

From Figure 8.1, it is apparent that for the viaduct case a significant volume would be taken off site (red bars).

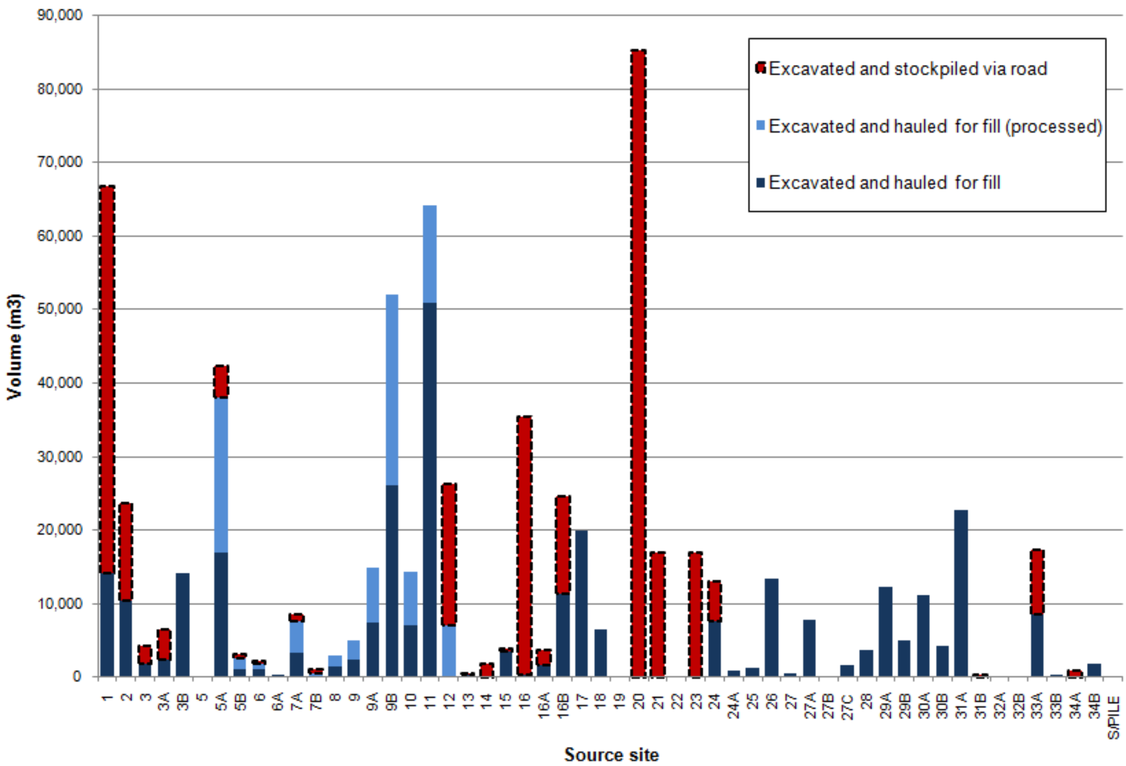


Figure 8.1 Earthworks volumes for viaduct option

For the embankment option, the earthworks volumes have been presented graphically in Figure 8.2. The earthworks have been disaggregated, and in addition to the categories shown in Figure 8.1, there is also the following:

- Material excavated and hauled to the embankment site (yellow)
- Processed material to embankment site (orange)

It is apparent that the significant volume that was to be transported off-site for the viaduct option, shown by the red bars in Figure 8.1, is now being retained on site and used at the embankment site – shown by the yellow bars in Figure 8.2.

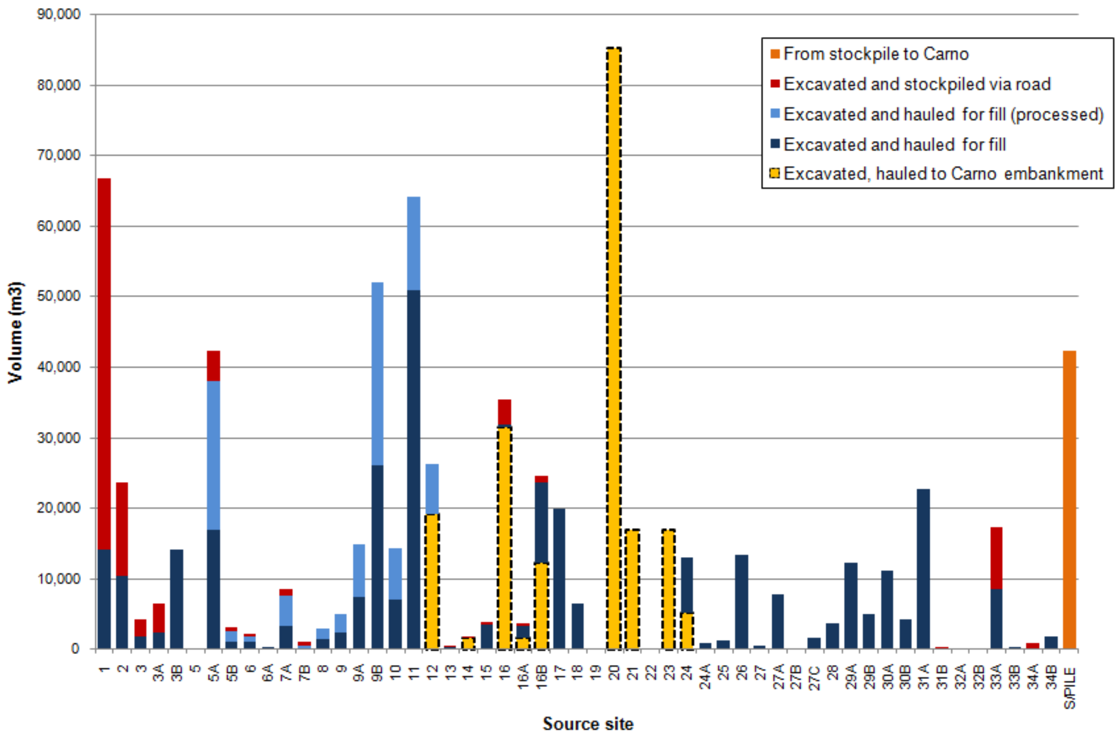


Figure 8.2 Earthworks volumes for embankment option

To enable the CO_2 to be calculated, the earthworks operation was separated into activities undertaken by different plant. The fuel consumed by each plant type was calculated and then translated into a CO_2 emission. Table 8.1 shows the CO_2 per plant activity for the embankment operation and the viaduct operation. Overall, the addition of the embankment has increased CO_2 emissions by 17% (this is also presented graphically in Figure 8.3).

Table 8.1 CO_2 breakdown for options

Activity	CO_2 (tonnes)		Percentage change
	Viaduct	Embankment	
Excavator	410	430	5%
ADT	360	590	64%
Road haul	110	60	-45%
Spread	50	80	60%
Compaction	50	90	80%
Processing	710	710	0%
TOTAL	1690	1970	16%

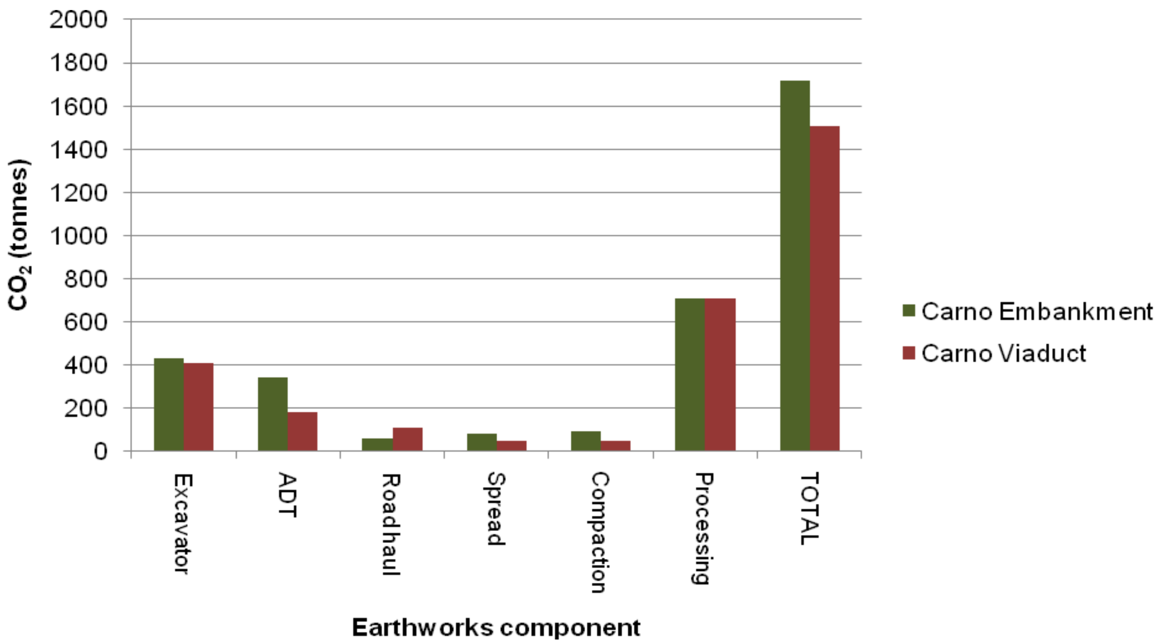


Figure 8.3 CO_2 breakdown by earthworks activity for both options

A reason for the increase in the embankment option CO_2 is that more material is being excavated, spread and compacted, and this is reflected in a CO_2 increase for these activities. Another reason is that more material is being transported on-site to the embankment location using articulated dump trucks (ADTs). Whereas, in the viaduct option, more material is transported by road using standard rigid HGVs. Road haulage using HGVs is a more efficient transportation method, with 5.6 litres of fuel used per hour[7] (Defra, 2010) for the rigid HGV used in this study, compared to 20 litres per hour for the ADT used in this study (ICES, 2001).

8.2.2 Supplementary embankment structures

The embankment option required supplementary structures to both facitlitate the design and also to ensure movements within the valley were not restricted. The structures associated with the embankments are:

- An arch;
- abutment foundations;
- a concrete lined channel;
- an adit;
- reinforced earth walls; and,
- a reinforced concrete retaining wall.

[7] Based on the Defra emission factor of 798.1 g/km for an unladen rigid HGV over 17 tonnes, 1148.5 g/km for a fully-laden rigid HGV over 17 tonnes, and assuming a speed of 16 kph.

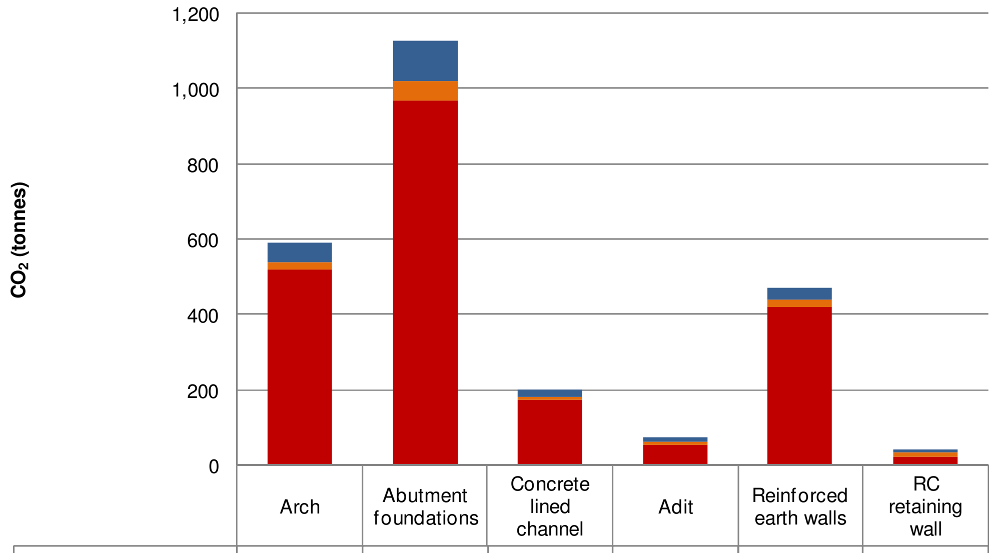
The CO_2 for all structures has been calculated based upon the three constituent materials – concrete, steel and formwork. The CO_2 per unit of these three constituent materials; from the materials, the plant used and the transportation are presented in Appendix I. Table 8.2 shows the quantities of these materials for the six structures.

Table 8.2 Quantities of principal materials

Structure	Concrete (m^3)	Steel (tonnes)	Formwork* (m^2)
Arch	648	175	1,944
Abutment foundations	1,643	246	4,928
Concrete lined channel	200	24	600
Adit	74	15	222
Precast panels	672	121	-
RC retaining wall	29	5	121

* *The formwork has been estimated at three times the volume of concrete*

The total CO_2 from the embankment structures is 2,391 tonnes. The contribution from the structure types is shown in Figure 8.4. The abutment foundations are responsible for a large proportion of the CO_2, followed by the arch structure that runs through the embankment, and the reinforced earth walls – these are reflective of the quantities of materials that have been used in their construction.



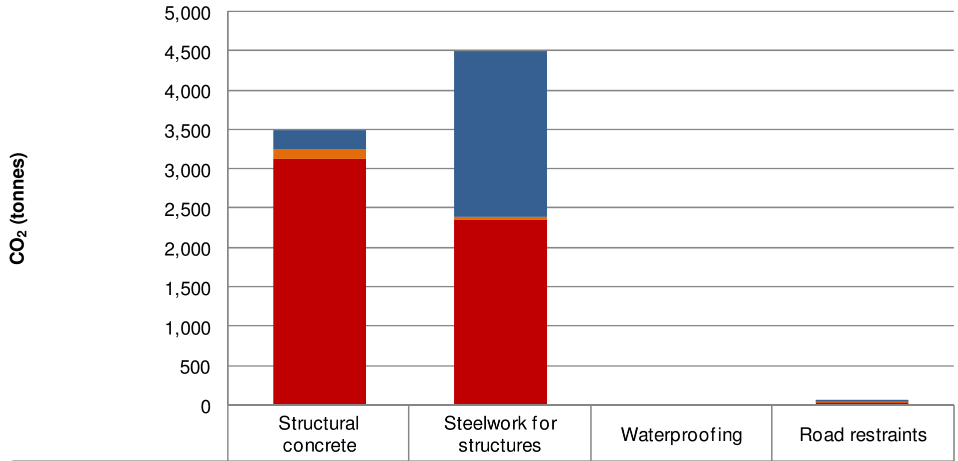
	Arch	Abutment foundations	Concrete lined channel	Adit	Reinforced earth walls	RC retaining wall
Labour and Plant	50	110	20	10	30	10
Transport	20	50	10	10	20	10
Embodied in materials	520	970	170	50	420	20

Figure 8.4 CO_2 breakdown by embankment structure

8.2.3 Viaduct

The viaduct has been calculated using the CO_2ST® appraisal tool. The viaduct dimensions and information were input, and these are presented in Appendix J. Normally the outputs of the tool would include structural concrete, steelwork for structures, water proofing, road restraints, earthworks and drainage. Due to the viaduct being directly compared to the embankment, for which only the earthworks and associated structures were assessed, the earthworks and drainage have been excluded from the outputs of the CO_2ST® appraisal tool.

The CO_2 associated with the different elements of construction of the viaduct is shown in Figure 8.5.



	Structural concrete	Steelwork for structures	Waterproofing	Road restraints
Labour and Plant	240	2,110	0	10
Transport	130	40	10	0
Embodied in materials	3,130	2,360	10	60

Figure 8.5 CO_2 breakdown for viaduct

The CO_2 associated with the elements of the viaduct structure that have been assessed is 8,000 tonnes. A large proportion of the steelwork CO_2 is from labour and plant due to the use of a large crawler crane for the erection of the steelwork.

8.2.4 Embankment and viaduct comparison

The total CO_2 for the embankment and the viaduct option are shown in Table 8.3. The CO_2 difference in earthworks is relatively small; with the embankment increasing CO_2 by 17%. The structures are also shown in the table; with the entire structures CO_2 for the viaduct option resulting from the viaduct itself. Whereas for the embankment, it is the numerous supplementary structures that are associated with it that comprise the structures CO_2.

Table 8.3 Total CO_2 for both options

Component	CO_2 (tonnes)	
	Embankment	Viaduct
Earthworks	2,000	1,700
Structures	2,500	8,000
TOTAL	4,500	9,700

The embankment and its associated structures have an overall CO_2 value of approximately 4,500 tonnes, which is 5,200 tonnes less than the viaduct option which results in 9,700 tonnes. The additional CO_2 from the earthworks required to construct the embankment is small; it is the embankment structures that significantly increase the CO_2 for this option.

8.3 CO_2 from construction

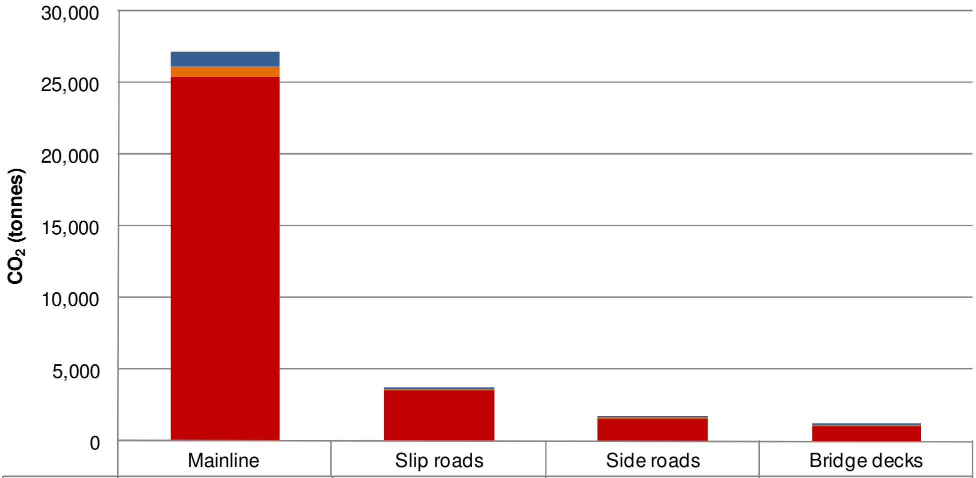
The main elements of the construction of the scheme are the earthworks, the road pavement and the structures. These are addressed separately below, and summed at the end of this section to give a total value for construction CO_2.

8.3.1 Earthworks

The CO_2 resulting from the anticipated earthworks operation was calculated in Section 8.2.3.1. An embankment is to be taken forward for construction and therefore the total CO_2 from the earthworks is estimated at 2,000 tonnes of CO_2.

8.3.2 Pavement

The pavement schedule (Carillion, 2011) was used to calculate the pavement CO_2. In this case, the pavement involves the base, binder course and wearing course. The capping and sub-base have been included in the earthworks section. The mainline, slip roads, side roads and bridge deck pavements were all considered for embodied CO_2 in materials, CO_2 from transportation, and from labour and plant. The majority of the CO_2 can be attributed to the materials used, as shown in Figure 8.6. The total CO_2 from the pavement is 34,000 tonnes.



	Mainline	Slip roads	Side roads	Bridge decks
L&P	1,010	120	70	50
Transport	730	100	50	30
Embodied	25,450	3,550	1,640	1,120

Figure 8.6 CO_2 breakdown for pavements

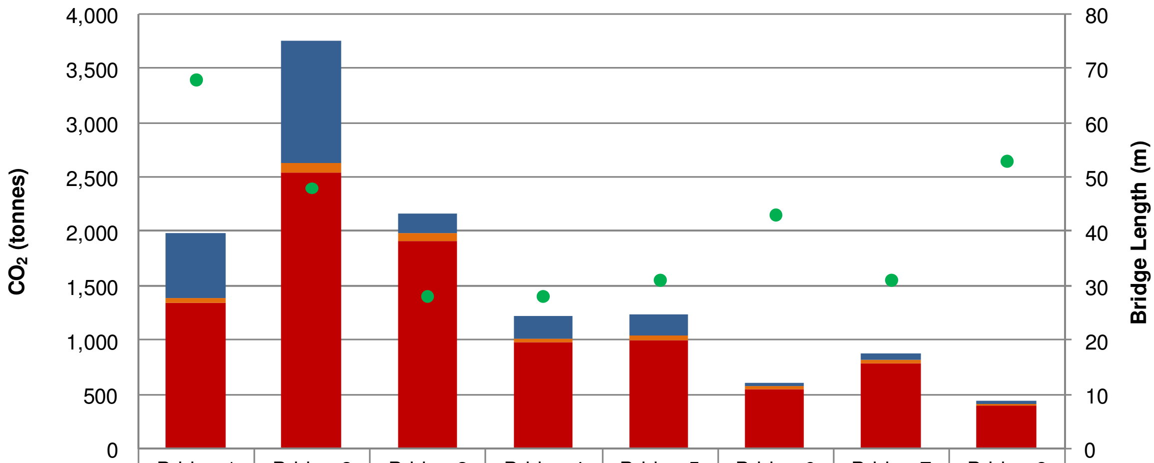
8.3.3 Structures

The structures have been separated into bridges and civil structures.

8.3.3.1 Bridges

All the bridges detailed within this chapter are the type of bridge that would facilitate a 2-lane dual carriageway. Due to currently limited data on all the bridges for the scheme, CO_2 for one of each of the different bridge types was calculated in full using the CO_2ST® tool. Four steel composite bridges were assessed; Bridges 2, 3, 4 and 5, for which Bridge 2 was taken as the typical structure. For this typical structure the CO_2 was calculated in detail for the materials, plant and transportation, which was normalised to the area of the bridge deck. These CO_2 rates per unit area of deck were then applied to the known areas of the bridge decks for the remaining bridges. Three precast bridges were assessed; Bridges 6, 7 and 8, for which the Bridge 6 was taken as the typical structure. Bridge 1 was calculated in full using the CO_2ST® tool.

Bridges 3 and 5 required bored pile foundations; the CO_2 from these are included within the values presented below. The CO_2 associated with each bridge is shown in Figure 8.7, with the total estimated CO_2 associated with the bridge structures being taken to be approximately 12,000 tonnes.



	Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5	Bridge 6	Bridge 7	Bridge 8
L&P	600	1,130	180	210	190	40	60	30
Transport	40	80	70	30	40	20	30	20
Embodied	1,350	2,550	1,920	990	1,010	560	790	400
Length	68	48	28	28	31	43	31	53

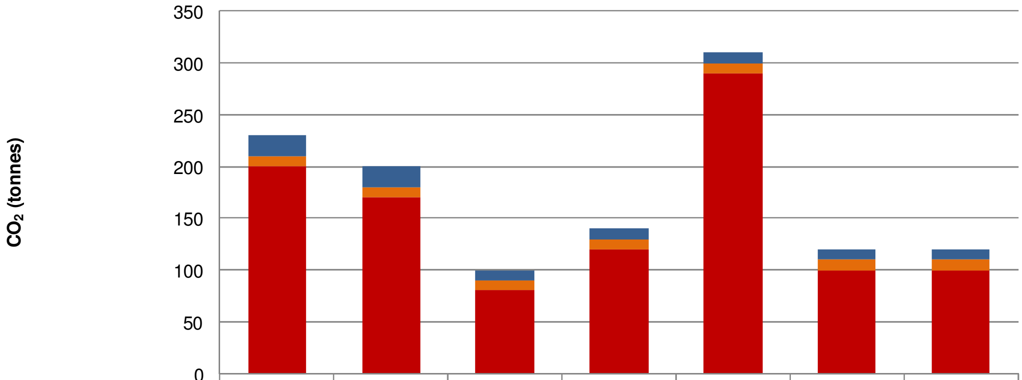
Figure 8.7 CO_2 and length breakdown by bridge

8.3.3.2 Civil structures

The CO_2 associated with the civil structures, with the exception of the RC retaining walls and culverts, has been calculated based upon the quantities of the main constituent materials. The CO_2 associated with the RC retaining walls and culverts is output from the CO_2ST® tool; based on input data pertaining to the dimensions and steel content of the structures. The civil structures considered are:

- 7No. RC retaining wall
- 2No. RC culverts
- 3 No. Reinforced earth wall
- 1 No. Corrugated steel culvert
- 2 No. Mass concrete walls
- Rock anchors
- Structure requiring additional concrete

The total CO_2 for all civil structures is 1,200 tonnes, and the CO_2 for each structure type is shown in Figure 8.8.



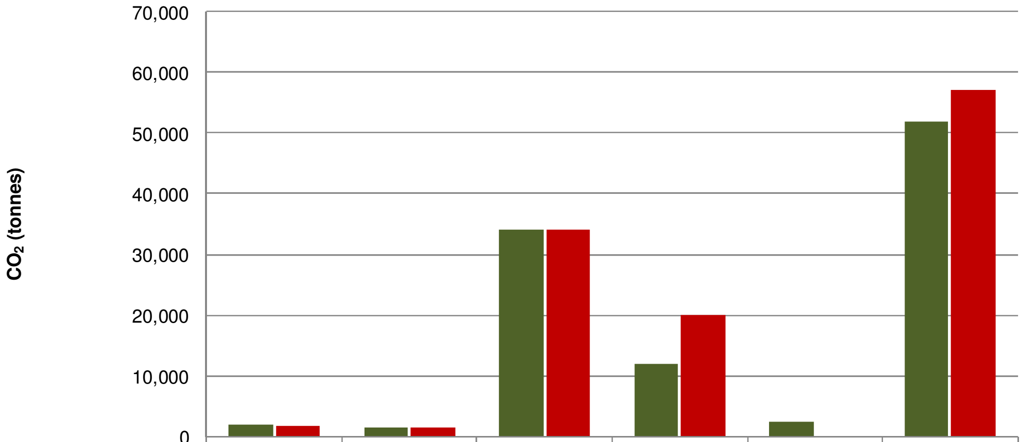
	Culverts	RC walls	Mass concrete walls	Reinforced earth walls	Rock anchors	Corrugated Steel Culvert	Additional concrete
Labour and Plant	20	20	10	10	10	10	10
Transportation	10	10	10	10	10	10	10
Embodied in materials	200	170	80	120	290	100	100

Figure 8.8 CO_2 breakdown by civil structure

8.3.4 Total construction CO_2

The total CO_2 from the construction phase assessed is 52,000 tonnes. It is important to note that the scope of the CO_2 associated with the individual components takes into account only certain elements of construction. For example, although the pavements have been assessed, the related highway elements have not been included – e.g. the lighting columns and road restraints. When all the other supporting construction components are also considered, the pavement materials comprise approximately 82% of the overall CO_2 – the supporting calculations for this can be viewed in Appendix K.

Despite the viaduct option not being taken forward to construction, for comparative purposes, the total CO_2 for the option has been calculated at approximately 57,000 tonnes. Both the embankment and the viaduct options are shown in Figure 8.9. Based on the construction components, for which CO_2 has been calculated, the viaduct structure over the embankment results in an increase of around 5,000 tonnes of CO_2 - a 10 % increase in overall construction CO_2.



	Earthworks	Civil Structures	Pavements	Bridges	Embankment Structures	TOTAL
Embankment option	2,000	1,500	34,000	12,000	2,500	52,000
Viaduct option	1,700	1,500	34,000	20,000	0	57,200

Figure 8.9 CO_2 breakdown by construction element

Through application of the 'correction factor' (calculated in Appendix K) the CO_2 can be factored to give a more representative value that would make allowances for the supporting construction components that were not included in this assessment. There is sufficient confidence in the accuracy of the earthworks CO_2 value, and so only the civil structures, bridges and supplementary embankment structures have been factored. The resulting factored value is 63,000 tonnes of CO_2 for the embankment and 70,000 tonnes for the viaduct.

8.4 Use phase

The WebTAG guidance, Unit 3.3.5 The Greenhouse Gases Sub-Objective, states that all greenhouse gas emissions, including those from the construction phase should be considered under the assessment set out in the sub-objective (DfT, 2011). However, it recognises the significant data requirements for estimating the emissions from the construction. For this reason, it is recommended that the carbon impacts should be qualitatively noted where possible. The Greenhouse Gases Sub-Objective does, however, require the carbon emission changes from the use phase to be quantified.

The use phase emissions are presented in the following section. Section 8.4.2 details the CO_2 emissions from the use phase using the WebTAG recommended approach, and Section 8.4.3 using an approach recommended by DMRB for schemes aimed at relieving congestion. Both approaches are based on different types of emission modelling; these are explained in Chapter 4.

8.4.1 Results from WebTAG emission modelling

Input to the WebTAG emission modelling has been the output from the strategic transport model, SATURN (detail on the use of SATURN output in emission calculations has been provided in Section 2.3.1). Output from SATURN is in the form of vehicle flows and average vehicle speeds along individual roads, which lends itself to average speed emission modelling. When an average road speed is known, the function given in WebTAG Unit 3.5.6 can be used to calculate the fuel consumed by the different vehicle types when travelling at that speed.

The SATURN model has a base year of 2009, and two forecast years, 2015 and 2030. In the forecast years two scenarios have been modelled, a Do Minimum scenario (without the relief road) and a Do Something scenario (with the relief road).

For each model there is an AM, an inter-peak and a PM time period. Using the SATURN output from each time period the CO_2 has been calculated, and then converted to a 12-hour CO_2 emission using the previously derived peak hour to peak period factors. The 12-hour emission was then converted to an annual emission using the annual traffic factors. The annual emissions are shown in Table 8.4.

Table 8.4 Annual CO_2 for scenarios

Year	Annual CO_2 (tonnes)		Percentage change
	Do Minimum	Do Something	
2015	393,000	395,000	+ 0.5%
2030	483,000	486,000	+ 0.6%

The annual vehicle-kilometres travelled are shown in Table 8.5.

Table 8.5 Annual vehicle-km travelled for scenarios

	Annual vehicle km travelled (km)		Percentage change
Year	Do Minimum	Do Something	
2015	1,717,000,000	1,724,000,000	+ 0.4%
2030	2,188,000,000	2,200,000,000	+ 0.5%

The efficiency of the network can be considered in terms of the emissions per km travelled. These are shown in Table 8.6.

Table 8.6 Emission rate for scenarios

Year	Emission rate (g/km)		Percentage change
	Do Minimum	Do Something	
2015	229	229	0%
2030	221	221	0%

In brief, there is an increase in emissions in the Do Something scenario for both years – this increase in emissions is similar to the increase in vehicle-km travelled on the entire network.

Average speed emission modelling cannot always convey the improvements to a transport network brought about by a new relief road; due to average speeds not reflecting stop-start congestion. Although this type of emission modelling is recommended in WebTAG (and DMRB), it is recognised that it is not an approach that is appropriate to every scheme.

Table 8.7 shows the average speeds for each period, for both future years, in the Do Minimum and Do Something scenario - the average speeds across the network increases slightly in all situations.

Table 8.7 Network average speeds for scenarios from model output

Year	Period	Average network speed (kph)		Percentage change
		Do Minimum	Do Something	
2015	AM	78.6	79.5	+ 1.1%
	IP	82.8	83.5	+ 0.9%
	PM	78.2	79.1	+ 1.1%
2030	AM	76.4	77.5	+ 1.4%
	IP	81.5	82.3	+ 1.0%
	PM	76.0	76.6	+ 0.8%

Figure 8.10 shows CO_2 emissions against speed (derived from the WebTAG function); it is apparent that at lower speeds the emissions increase dramatically, at higher speeds emissions also increase, and in the mid-speed range emissions are at their lowest. According to the curve, for example, a petrol car is at its most efficient at an average speed of 67 kph; speeds lower than this and speeds higher than this would result in higher emissions.

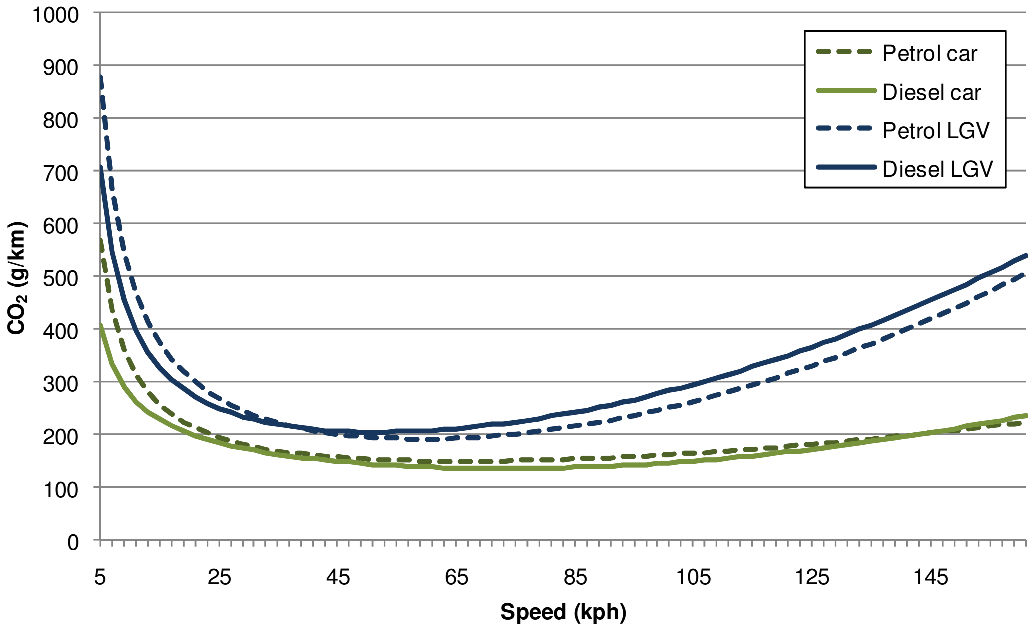


Figure 8.10 Average speed emission curves

The higher average speeds in the Do Something scenario has taken the point along the curve from an average speed that produces lower emissions to an average speed that produces higher emissions; as a free flow network will inevitably decrease journey times and hence increase vehicle speeds, as demonstrated in Table 8.7.

It is likely that the vehicles in the Do Something scenario are benefiting from the relief road which will provide a free-flowing state, with less congestion. Using the recommended WebTAG approach, which can only communicate the scheme effects through vehicle speeds, for a project such as this, can result in the benefits from the removal of congestion being disregarded (this issue has been addressed previously in Section 2.3.1).

The average speed WebTAG emission modelling can be ambiguous and the outputs should be used prudently and, ideally, a more sophisticated approach using instantaneous emission modelling should be taken.

8.4.2 Instantaneous emission modelling

As recommended in DMRB, for projects which result in variations in driving patterns but do not greatly affect average speed, a more detailed emission model may be required (Highways Agency, 2007). For this reason, a micro-simulation traffic model was developed that could provide input to an instantaneous emission model. A micro-simulation transport model was developed using the VISSIM software, as documented in Arup (2011), this has an integrated emission calculation module, EnvPro, which is based on the MODEM instantaneous emission model.

Models were developed for the same future years as the strategic SATURN model, for the AM, Inter-peak, and PM peak periods. The resulting CO_2 emissions from the modelling are shown in Table 8.8 for the AM peak, in Table 8.9 for the Inter-peak, and Table 8.10 for the PM peak.

Table 8.8 CO_2 emissions from AM VISSIM model (Arup, 2011)

Year	AM CO_2 emissions (kg)		Percentage change
	Do Minimum	Do Something	
2009	5,500	-	-
2015	7,000	6,200	-11%
2030	7,500	7,700	3%

Table 8.9 CO_2 emissions from Inter-peak VISSIM model (Arup, 2011)

Year	Inter-peak CO_2 emissions (kg)		Percentage change
	Do Minimum	Do Something	
2009	4,300	-	-
2015	4,800	4,200	-13%
2030	6,500	6,600	2%

Table 8.10 CO_2 emissions from PM VISSIM model (Arup, 2011)

Year	PM CO_2 emissions (kg)		Percentage change
	Do Minimum	Do Something	
2009	6,100	-	-
2015	6,900	6,900	0%
2030	8,500	8,300	-2%

The AM and inter-peak peak hours benefit from the new highway scheme in 2015 with an 11% and 13% reduction in emissions respectively. This effect is replicated in the 2030 future year in the PM peak when emissions are reduced by 2%, yet not in the AM and inter-peak hour, when emissions become marginally higher in the Do Something scenario over the Do Minimum scenario.

This slight increase in emissions in the Do Something scenario in the AM and inter-peak hours of 2030 is a result of traffic growth. The emission reductions brought about by the free-flow traffic conditions in these peak hours is outweighed by the increase in emissions from the higher volumes of vehicles.

When these emissions are factored they result in the annual CO_2 emissions shown in Table 8.11. The year of 2015 demonstrates a worthwhile improvement as a result of the highway scheme, with a 12% decrease in carbon emissions in the Do Something. In the future year of 2030 there is less of an improvement, with the Do Something scenario resulting in 3% higher emissions.

Table 8.11 Annual CO_2 emissions from VISSIM model

Year	Annual CO_2 (tonnes)		Percentage change
	Do Minimum	Do Something	
2009	21,000	-	-
2015	25,000	22,000	-12%
2030	31,000	32,000	3%

8.4.3 CO_2 from the use phase

The WebTAG average speed modelling has not identified any benefits resulting from the relief road – the percentage changes between the Do Minimum and Do Something scenario are insignificant and no conclusion can be drawn from the results.

The results from the instantaneous emission modelling show a greater variation, and hence differences between the two scenarios have been detected using this more sophisticated approach. The Do Something scenario resulted in less CO_2 emissions than in the Do Minimum scenario in 2015, with a slight increase over the Do Minimum scenario in 2030.

Although there are limitations with average speed modelling, it is a useful approach to enable the magnitude of the emissions associated with a road network to be understood. The emission levels resulting from the VISSIM-EnvPro instantaneous emission modelling were lower than expected in terms of grams of emission released per kilometre travelled. These lower emission results were output from EnvPro, and due to this being a closed program in which the calculations are not visible to the user, only the relative differences between the scenarios have been used. The WebTAG approach can, therefore, provide a reliable absolute answer; whereas the instantaneous modelling can provide a relative answer by detecting the differences between scenarios.

The emissions associated with the links that comprise the mainline relief road have been extracted from the WebTAG emission results and are shown in Table 8.12 for the eastbound and westbound directions.

Table 8.12 CO_2 emissions for A465 mainline using WebTAG approach

Direction	CO_2 (tonnes)	
	2015	2030
Eastbound	5,700	5,800
Westbound	6,600	6,800
Both directions	14,300	14,600

The annual carbon from the use phase has been taken to be the value from the 2030 future year; approximately 15,000 tonnes of carbon. This value is to be input into the whole life carbon assessment which covers a 60 years appraisal period. The carbon from the use has been capped at the 2030 level as there are many variables that cannot be predicted beyond these years – such as engine efficiencies and technologies.

8.5 Indicative CO_2 from maintenance and operation

The main activities that fall within this phase of the life cycle are those that involve the maintenance of the:

- Wearing course;
- Road markings;
- Railings and fences;
- Road signs; and
- Lighting.

There is also the maintenance that can be considered reactive; for example, the replacement of a crash barrier after an incident.

The main activities that fall within the operation phase of the life cycle are:

- Operation of traffic lights and lighting
- Gritting
- Grass cutting
- Clearance of verges

In the absence of any data pertaining to the maintenance and operation over the appraisal period for this particular scheme, output from detailed research has been used to estimate the CO_2 associated these phases. The Inventory of CO_2 and Energy (ICE) database (Hammond, 20011), through research undertaken by Stripple (2001) has quantified the CO_2 contributions from the construction, maintenance and operation phases as shown in Table 8.13.

Table 8.13 Contribution from construction, maintenance and operation phases

Phase	Percentage
Construction	25%
Maintenance	14%
Operation	61%

The data is based on the construction, maintenance and operation of a highway and, therefore, the maintenance and operation of the structures along the highway are not covered.

The total from construction, using the factored value, is 70,000 tonnes of CO_2. Based on this value and the breakdowns in Table 8.13, the estimated CO_2 values for maintenance and operation are presented in Table 8.14.

Table 8.14 Estimated CO_2 from maintenance and operation over 60 year period

Phase	CO_2 (tonnes)
Maintenance	34,000
Operation	170,000

Figure 8.11 shows the estimated whole life CO_2 value of the highway scheme over a 60 year period. The use phase contributes the most to the overall CO_2; contributing 76% of the total 1.16 million tonnes. The purpose of reaching an estimated value for the whole life of the scheme was to understand the impact of the choice of structure in the context of the CO_2 associated with the scheme over a 60 year period. The 5,000 tonnes reduced through the use of the embankment equates to around a 0.5% reduction over the 60 year time period. Would the embankment have not required the supporting structures, and it had simply been a comparison between an earthworks exercise and a bridge structure then an 0.8% reduction would have resulted.

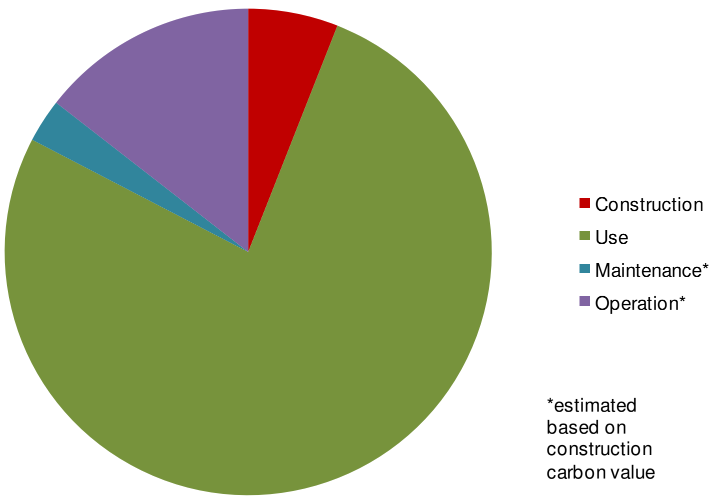


Figure 8.11 Whole life CO_2 over 60 years

8.6 Conclusion

CO_2 values have been presented for the construction, use, maintenance and operation phases of the life cycle of the highway scheme. Only the pavement, structures and earthworks have been considered in the construction phase. It has therefore been assumed that not all of the construction phase CO_2 has been included in this assessment and as a result a factor has been applied to the value calculated to try to account for this additional CO_2. The maintenance and operation values are based solely on the factored construction phase CO_2 value.

Chapter 9

Consideration of the effect of traffic interaction

9.1 Introduction

From the onset of this research project it was decided that, in order to isolate, and hence understand, the effect of highway alignment on the CO_2 emissions resulting from vehicles using a highway, that the vehicle speeds would be kept constant. The approach taken, which is detailed in Chapter 3 Approach to Research, defines the speed as a mediator that affects the dependent variable of CO_2 from vehicles, which is in turn influenced by the independent variable of highway gradient.

The research undertaken by Parry and Potter (1995), and detailed in Chapter 4, used a constant vehicle speed to assess the impact of gradient, and likewise the work of Hillier (2005) also used constant speeds based upon the emission factors derived from Hassel and Weber (1997). Whereas, the research undertaken by Butler (2006) used the VETO traffic model; this is based on instantaneous emission modelling approaches. Although VETO does not model the interactions between traffic on sections of the highway, it does make attempts to model the change in vehicle speeds, and hence acceleration and deceleration, required as vehicles move between road sections with different speed limits.

The work of Butler (2006) is the most advanced in terms of using an instantaneous emission model that takes into account the gradient at each time step when calculating the emissions, in addition to the speed and acceleration. The attempts to replicate the required acceleration and deceleration between different road sections are also worthwhile. However, the lack of attention given to the effect of traffic interaction should not be neglected. The outcomes of Butler (2006) demonstrated the potential benefits of expending more CO_2 in the construction phase to bring about benefits in the use phase. Yet these results were not shown transparently due to them being calculated by the computer program, JOULESAVE, which was the final product of the research project. The emission model VETO is run within the JOULESAVE program meaning that the effect of alignment cannot be viewed or understood in detail.

The purpose of the research presented within this thesis has been to understand in a detailed manner the effect of road alignments on vehicle CO_2 emissions. To be able to do this the speed had to be kept constant. It is appreciated that this would not be a true representation of an actual highway as traffic interaction and driver behaviour would mean that speeds would not remain constant and hence deceleration and acceleration would occur. However, the focus of this research was on the construction of new highway infrastructure, which should have sufficient capacity to result in fewer traffic interactions.

This chapter considers the potential effect of traffic interaction on the results of the work presented within this thesis. It is not the intention for this chapter to attempt to identify a relationship between the results presented thus far and the results that could be expected should traffic interaction and driver behaviour be taken into account. The purpose of this chapter is purely to highlight that these factors could alter the results.

9.2 Indicative assessment

To demonstrate how the traffic interaction can impact on the modelled CO_2 emissions resulting from vehicles using highways with different vertical alignments, a simple highway has been modelled within S-Paramics. The highway model is a 2-lane dual carriageway with the dimensions shown in Figure 9.1. Overtaking is permitted to occur within this model, and to ensure there are variations between the different runs an individual random seed has been specified for each.

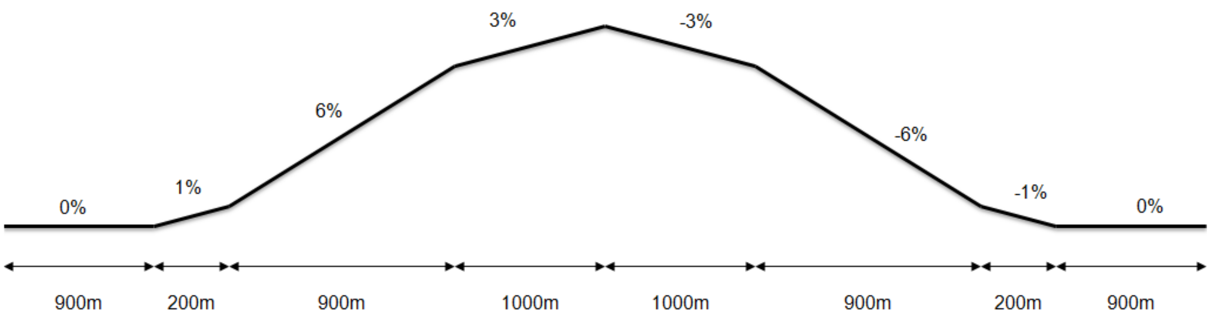


Figure 9.1 Dimensions of highway model

The consequence of traffic interaction is vehicles with periods of constant speeds, periods of acceleration and periods of deceleration. The assessments undertaken in Chapter 6 assume a constant speed and hence have no periods of acceleration or deceleration. To briefly understand how these compare, the S-Paramics model of the highway shown in Figure 9.1 has been run so that the traffic contained within the model interacts and results in varying speeds and hence acceleration and deceleration.

When a simulation is run in S-Paramics two useful files that are output are the trips-all.csv file and the carpositions.csv file. The program assigns a tag number to each vehicle within the model, and traces it along its journey at 0.5 second intervals. It is the carpositions.csv file that collates this data, along with data on the speed, gradient and acceleration at every 0.5 second interval. The trips-all.csv file, instead of collating data on a time step basis, collates data by vehicle tag number and summarises the entire trip of the vehicle being tagged. Both the trips-all.csv and carpositions.csv files are used when the PHEM emission post-processor is run – which assigns emissions to the individual time-steps and also emissions to overall vehicle trips.

The aim of this indicative assessment was to compare (1) vehicles that travel at constant speeds with (2) vehicles that accelerate and decelerate and hence travel at varying speeds but that have the same average speed as (1). The process undertaken to arrive at the two data sets for comparison is shown schematically in Figure 9.2. Firstly the highway alignment shown in Figure 9.1 was modelled within the S-Paramics software and assigned a traffic flow. A simulation of the model was run; the carposition.csv files produced by S-Paramics were then taken, manipulated and processed using the PHEM post-processor to give two data sets for comparison:

1. Total carbon emissions for the total fleet using actual vehicle path data, i.e. using the instantaneous vehicle speeds and accelerations output by S-Paramics.

2. Total carbon emissions for the total fleet using average speed data, i.e. using the vehicle path data but using the average speeds of each vehicle and setting the acceleration to zero.

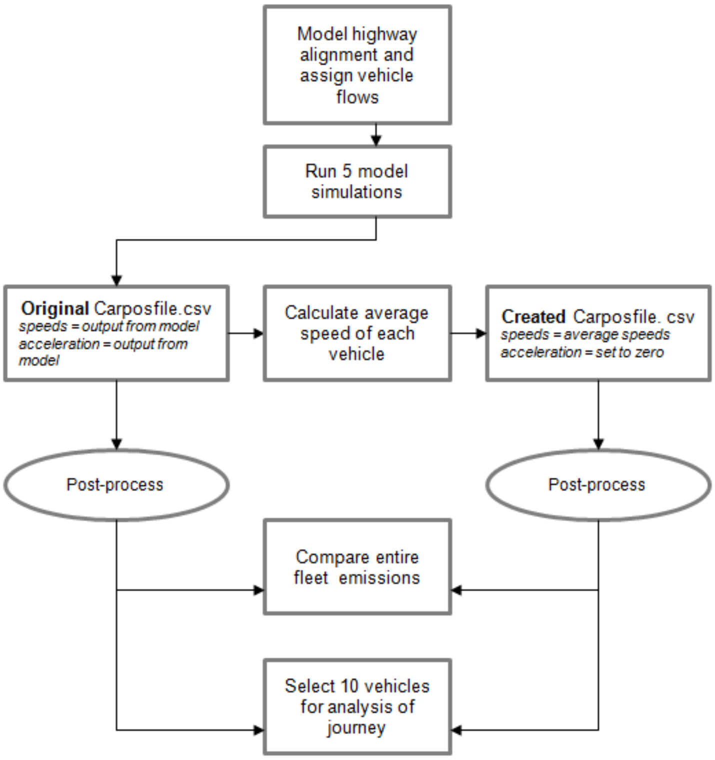


Figure 9.2 Process to create data sets for comparison

9.3 Results of indicative assessment

9.3.1 Fleet comparison

The simulation period has been taken as one hour from 10am, and two vehicle flows have been considered: 1000 and 2000 vehicles split into cars (80%), rigid HGVs (10%) and articulated HGVs (10%). The vehicles are released onto the model at a constant rate over the one hour period. Five runs of each simulation were undertaken; the total fleet CO_2 emissions for these are shown in Figure 9.3.

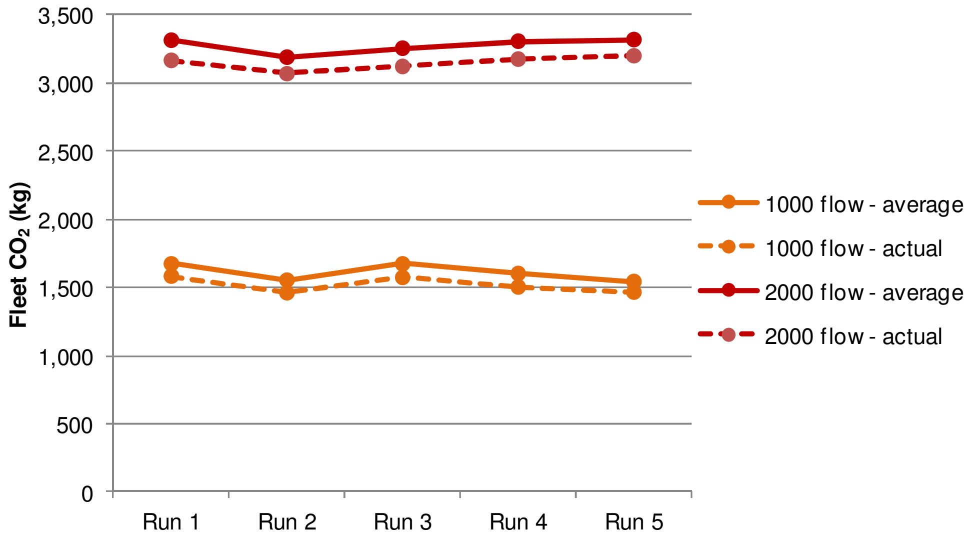


Figure 9.3 Fleet emissions for the five model runs

Overall the emissions for the runs based on the actual speed data are lower than the emissions based on the average speed data. For the 1000 flow scenario the emissions are between 5.3% and 6.5% higher for the average speed data used over the actual speed data. In the case of the 2000 vehicle flow scenario the emissions are between 3.7% and 4.6% higher. More interactions would be expected with higher vehicle flows and these results would suggest that, for this particular the model, the interactions appear to reduce emissions. A more detailed study of individual vehicles is required to understand this.

9.3.2 Comparison of isolated vehicles

For further comparison ten vehicles were selected from Run 1 and Run 3 from the 2000 vehicle flow scenario for isolation and analysis.

9.3.2.1 Run 001

Ten vehicles were selected from each run; those selected from Run 001 are detailed in Table 9.1.

Table 9.1 Vehicles selected from Run 001

Tag No.	Vehicle Type	Average speed (mph)	CO_2 based on actual speed data(g)	CO_2 based on average speed data(g)
196	Artic HGV	49	4,842	5,019
279	Petrol car	55	957	924
619	Rigid HGV	54	4,312	4,395
1162	Petrol car	72	1,056	1,024
1618	Petrol car	61	1,103	1,025
706	Rigid HGV	54	4,032	4,184
939	Artic HGV	55	4,865	5,002
1340	Petrol car	56	922	929
1481	Petrol car	59	944	903
1078	Petrol car	59	944	903

The assessments undertaken throughout this thesis have been based on vehicles travelling at constant speeds over different alignments. Therefore, the average speed emissions have been normalised to the actual speed emissions, and are shown in Figure 9.4. In all cases, the average speed emissions are within the range of -7% and +4% of the actual speed emissions.

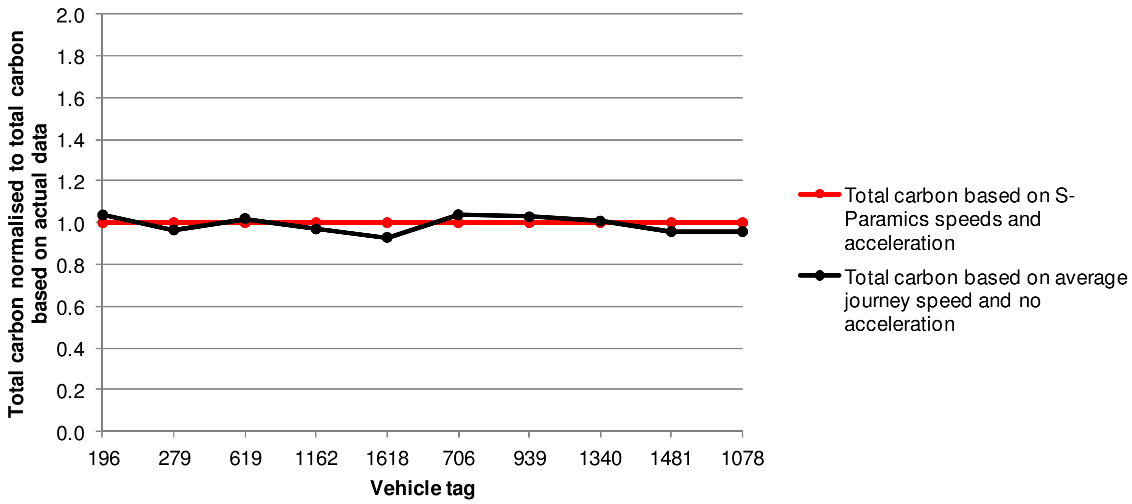


Figure 9.4 Total carbon emissions of average speed data normalised to total carbon emissions of actual speed data for Run 001

Vehicle 1340, a petrol car, has average speed emissions that are only 0.8% higher than the emissions that are calculated from the actual speed data. Figure 9.5 shows the total carbon emission rates that were assigned to each time step when the carpositions.csv files were post-processed – the rates for the actual speed data from S-Paramics (red) and the average speed emissions (black) are shown. It would be expected that in order to obtain two very similar total emission results the emission-time profile would be similar in both cases; Figure 9.5 shows that, despite the similar emission results, this is not the case, and in fact speed changes and accelerations occur frequently in the actual speed data.

It should also be noted that it is apparent that the final level section is excluded from the emission calculations, and hence from Figure 9.5, due to the way that the micro-simulation traffic software traces vehicles on the final link that leads to the zone that acts as a traffic-sink. This is, however, not an issue as it is excluded from all assessments and will not therefore alter the comparisons; there are still two models that can be directly compared.

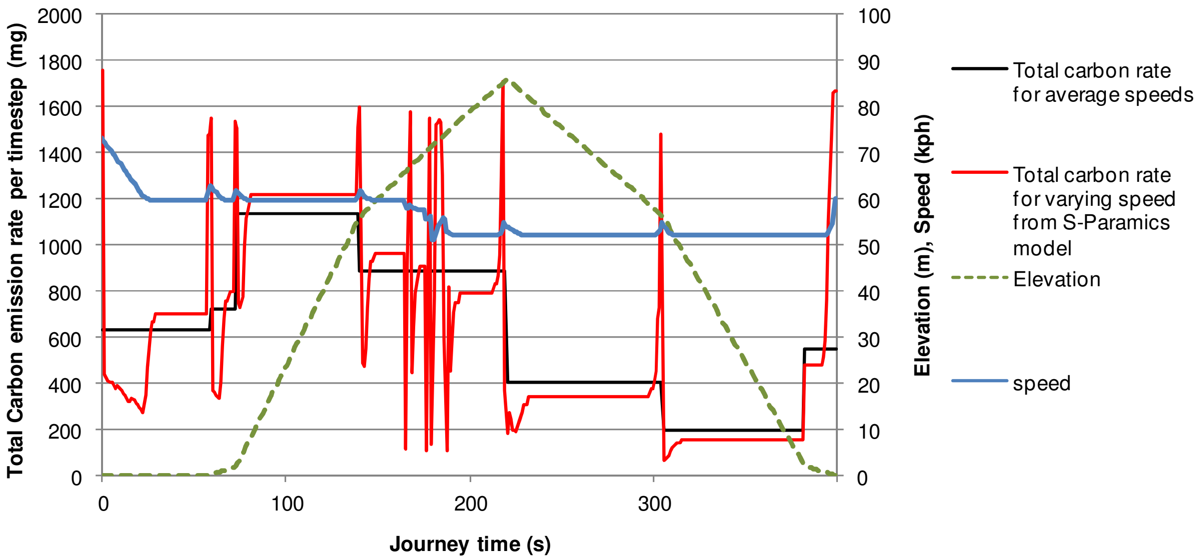


Figure 9.5 Emission rates along journey of vehicle 1340

Likewise, it would be anticipated that two very similar emission-time profiles would produce very similar overall emissions. However, for vehicle 196, an articulated HGV, which has an almost identical emission-time profile for both the average speed data and the actual speed data as shown in Figure 9.6, the emissions based on the average speed data are 3.6% higher.

The difference comes from the initial section of the journey, as shown in Figure 9.6, where the vehicle is very gradually decelerating and hence the actual speed emission rate is lower than the average speed emission rate which assumed no acceleration. When the actual speed vehicle maintains near to the average speed over the remainder of the journey, and is not accelerating, it has the same emission rate as the average speed based vehicle.

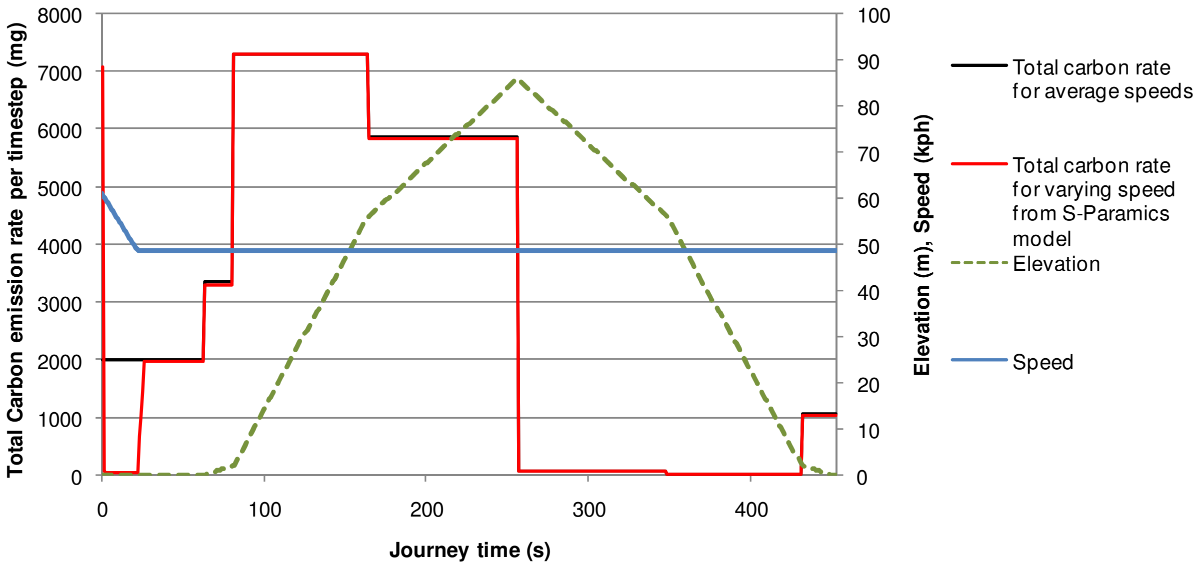


Figure 9.6 Emission rates along journey of vehicle 196

The emissions based on the average speed data for Vehicle 1618, a petrol car, are 7.1% lower than the emissions based on the actual speed data. The emission-time profile, shown in Figure 9.7, shows the varying emissions resulting from the changes in speeds and hence acceleration and deceleration.

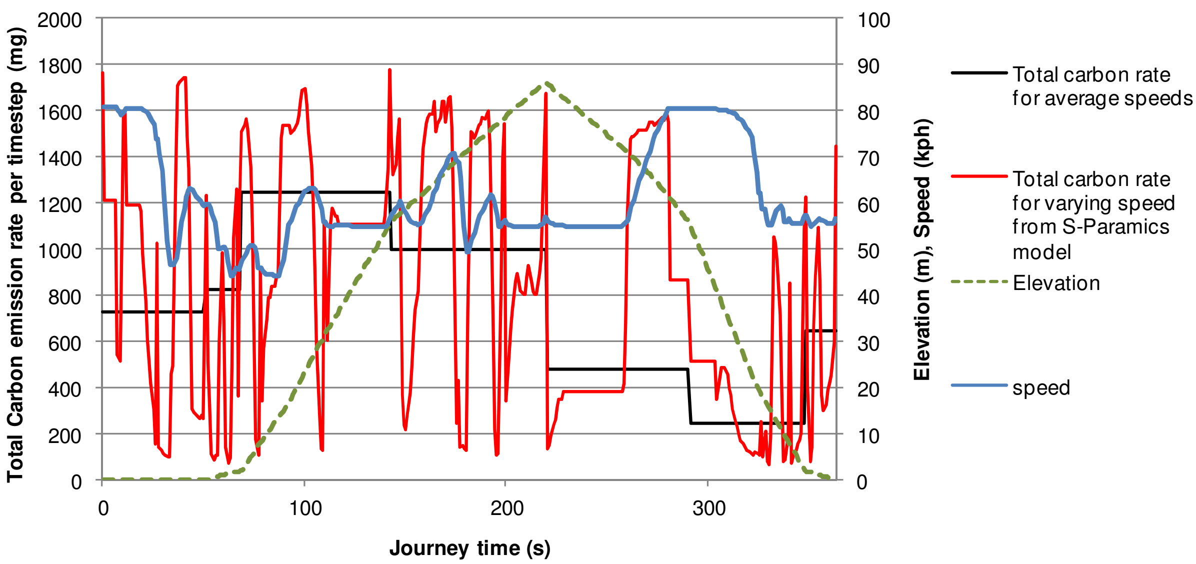


Figure 9.7 Emission rates along journey of vehicle 1618

9.3.2.2 Run 003

Ten vehicles were selected from Run 003 are detailed in Table 9.2.

Table 9.2 Vehicles selected from Run 003

Tag No.	Vehicle Type	Average speed (mph)	CO_2 based on actual speed data(g)	CO_2 based on average speed data(g)
17	Petrol car	68	1,145	1,010
321	Artic HGV	49	4,682	5,000
413	Artic HGV	46	4,726	5,243
656	Petrol car	63	1,068	958
741	Petrol car	73	1,118	1,078
954	Petrol car	57	898	939
1144	Artic HGV	57	4,286	4,748
1375	Rigid HGV	54	4,511	4,011
1606	Artic HGV	56	4,297	4,714
1792	Petrol car	61	1,094	947

Again, the emissions from the average speed model runs have been normalised to the actual speed emissions, shown in Figure 9.8. In this case, the average speed emissions range from 13% lower to 11% higher than the actual speed emissions.

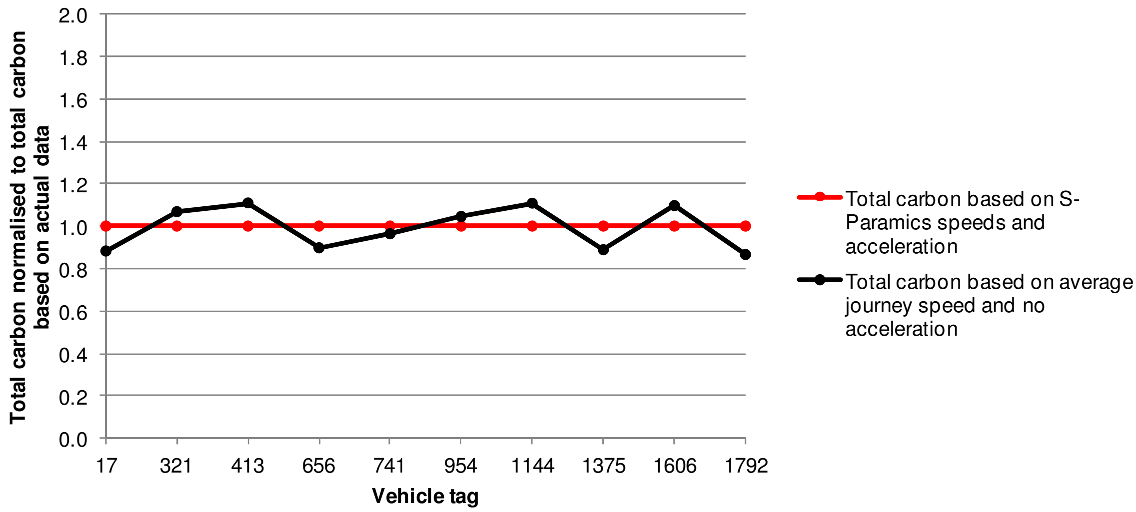


Figure 9.8 Total carbon emissions of average speed based data normalised to total carbon emissions from actual data for Run 003

Vehicle 1792, a petrol car, has 13% lower emissions when using average speed based data due to the many variations in the emission-time profile as shown in Figure 9.9.

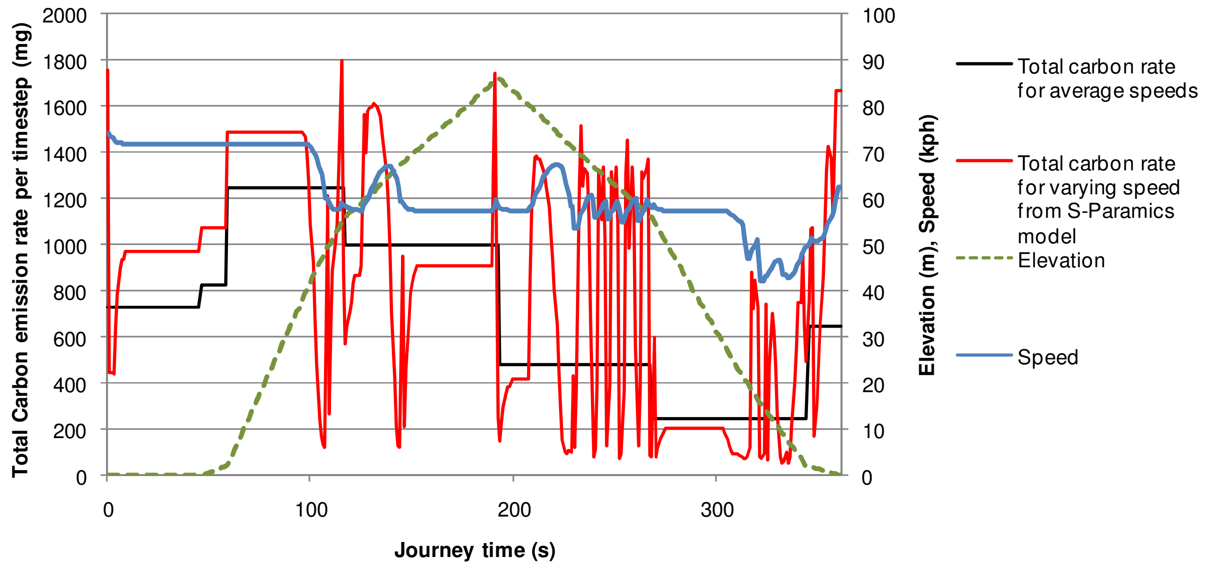


Figure 9.9 Emission rates along journey of vehicle 1792

The emission-profile for Vehicle 1144, an articulated HGV, shown in Figure 9.10, is similar for both the actual speeds and the average speeds; yet there is still an 11% difference between the two total emissions. A similar observation was made of Vehicle 196 in Run 1 (Figure 9.6).

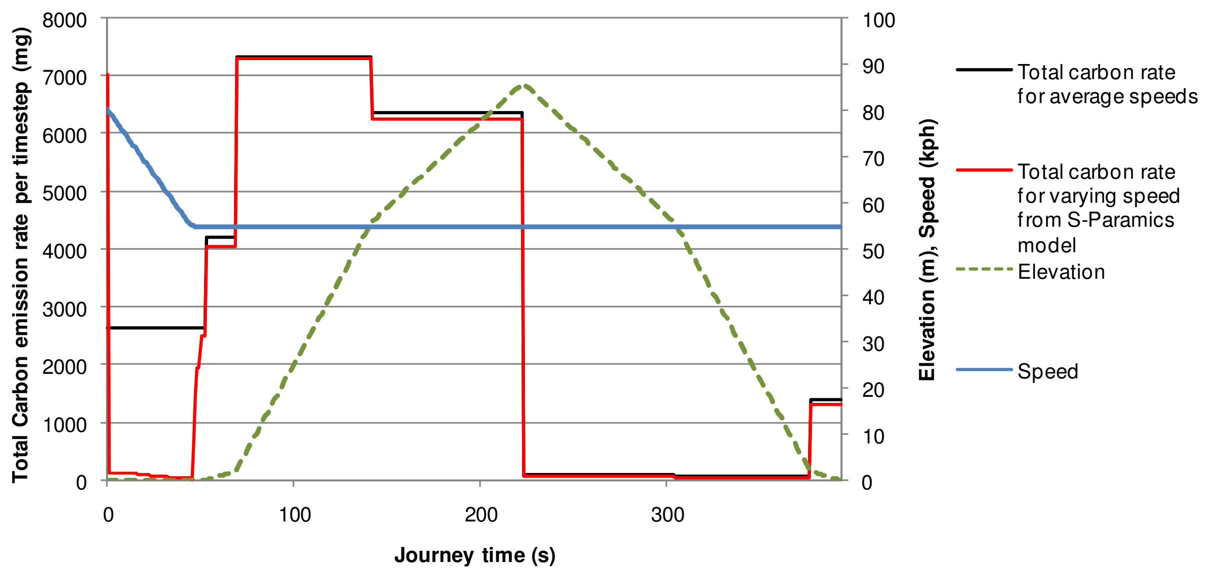


Figure 9.10 Emission rates along journey of vehicle 1144

9.4 Conclusion

The purpose of this chapter was to highlight the potential effect of traffic interaction on emissions. The purpose was not to identify a relationship between emissions resulting from vehicles with constant speeds and vehicles operating within a true-to-life environment and hence being subject to acceleration and deceleration. This chapter has demonstrated that when vehicles are within traffic or are subject to speed changes due to driver behaviour that the emissions can either increase or decrease when compared to the emissions that would result from a vehicle travelling at a constant speed. The variations shown in Figure 9.4 are quite different to those shown in Figure 9.8, which suggests that a larger sample size is required.

The assessment undertaken and presented within this chapter has indicated that the emissions from vehicles with varying speeds and from vehicles with constant speeds can vary by up to 13%. This is only true for the small sample of vehicles assessed and for the particular highway that has been modelled and subsequently tested within S-Paramics. A detailed and thorough investigation would be required to gain a firm understanding of the magnitude of this impact on the conclusions that emerged from previous chapters.

In Chapter 6 vehicles were modelled over different vertical alignments at constant speeds; such an approach was adopted to ensure that the resultant effect on CO_2 emissions could be isolated and understood. The approach taken is deemed to be valid, due to the traffic flow on new highways being below the road capacity; therefore, the interactions that do occur do not alter the results significantly.

Chapter 10

Conclusions and recommendations for further work

This research stemmed from the carbon footprinting assessment of the proposed motorway project that was undertaken by the author for Arup. The project brought the author's attention to the small contribution to the overall construction carbon from the earthworks operations, the large magnitude of the emissions in use relative to the emissions from construction, and the importance of using the appropriate emission modelling to inform decision making regarding the strategic effects of new road schemes on carbon emissions.

When a new road is opened in the UK, the processes, procedures and assessments that will have been adhered to and undertaken are extensive and can span a long time. Numerous documents will have been produced by different specialist groups to inform the final decision regarding the need for, the positioning of, and the design of the new highway. This approach can be described as an iterative multi-disciplinary design process, where an environmental design is developed along with the engineering design to produce a final scheme design. The assessment and reporting procedures can be quite rigid, with individual disciplines working largely independently of one another to complete their own assignments. A multi-disciplinary approach is necessary so as not to place excessive emphasis on one facet and only a modest emphasis on another. However, the objectives are not weighted and the final decision is therefore based on a considered appreciation of all the effects.

Regardless of how the required tasks are completed, the outcome is normally alternative routes and their subsequent effect on a range of objectives and sub-objectives. Theoretically the route option with the perceived least detrimental effects, which meets the performance criteria and does not entail excessive cost, will be taken forward.

This research is focussed upon the Environment objective, and specifically the greenhouse gases sub-objective. The standard approach prescribed in this sub-objective is to take each route option and to assess it in terms of the greenhouse gases that would result from the vehicles using it over a 60-year timeframe. Although this particular approach does consider the use phase, it can fail to consider in detail the potential effects that the different vertical alignments of the different route options have. The research undertaken and presented within this thesis is based around a whole-life carbon approach, meaning that consideration is given to the resultant effect of the decisions made in the early stages of a project on the later project stages. In particular, how an alignment can be designed in such a way so as to minimise the carbon emissions during the use phase; by constructing a more favourable alignment through the use of low carbon intensive earthworks. The investigation has centred on whether more CO_2 should be expended in the construction phase (specifically the earthworks) to result in an alignment that would potentially reduce emissions in the use phase.

Earthworks can constitute a small proportion of lifetime carbon emissions of highway infrastructure when in comparison to the contribution from the use phase. However, estimating the CO_2 resulting from an earthworks operation can be complex.

1 m^3 of concrete is likely to have a similar embodied CO_2 value whether it is used in a building project or a rail project. The reason is that, similar to other construction materials, it will have reasonably standardised production processes and will be produced under controlled conditions. However, 1m^3 of embankment material can have an embodied CO_2 content that can vary considerably between a building and a rail project, due to the earthworks strategies being unique for each. It was therefore concluded that CO_2 should be calculated using a bottom-up approach; by estimating the machinery requirements for the necessary movements, the fuel used by the machinery and the subsequent CO_2 emitted from the combustion of the fuel. Despite this, indicative CO_2 values were derived to enable estimates of CO_2 from earthworks; these are provided in Chapter 5.

The CO_2 emitted from construction activities consists of three components: CO_2 emitted from the manufacture of construction materials; CO_2 emitted from the transportation of materials, labour and plant to and from site; and CO_2 emitted by the machinery used during construction. In most cases, the materials CO_2 is by far the dominant component of the construction emissions. In contrast, with earthwork activities, there is no CO_2 associated with manufacturing of materials; the soil or rock excavated and backfilled is usually already on site and the associated CO_2 is primarily from the fuel used by machinery and transportation. In general earthworks can be described as being low carbon.

However, when the process of lime modification is used in earthworks there is an increase in embodied CO_2 compared to earthworks carried out without the addition of lime. In the hypothetical scenarios presented in Chapter 5, the use of lime increased the total CO_2 by around 90%. The Waste Strategy for England (Defra, 2007) identified construction waste as a priority action and subsequent fiscal and legislative tools have been introduced to improve resource efficiency and decrease waste production. With the Landfill Tax and Aggregate Levy making disposing of materials off-site and importing materials to site more costly, retaining materials within the site is imperative to reducing the earthworks costs, and hence is the reason contractors opt for the use of lime as an alternative. Therefore, legislation has resulted in lime being the more economical option. It is important to note that CO_2 is the only environmental indicator addressed within this thesis. The Landfill tax and the Aggregates Levy were introduced to regulate waste disposal to landfill and reduce resource consumption, which are also important environmental impact indicators, and so it is not being suggested that CO_2 emissions are of greater priority and hence lime should no longer be used. Instead, the use of lime and its high embodied CO_2 content should be publicised along with its viable alternatives.

Once a methodology had been established to quantify the CO_2 associated with the construction of differing vertical alignments, the next step was to quantify the CO_2 emitted by vehicles using these alignments. Hypothetical alignments were developed, a hill and a terrain, with the theory being that they were of suitable gradients for the highway to follow the profile of the terrain whilst requiring only a very small earthworks operation. To obtain a shallower alignment a larger earthworks operation would be necessary – either a larger embankment in the valley case or a larger cutting in the hill case. This resulted in a range of alignments to be tested, ranging from a level alignment to alignments with the steepest allowable gradient on UK motorways, which is 6%.

Detailed results of the assessments have been presented in Chapter 6. An interesting outcome was that contrary to expectations, lighter vehicles (cars and LGVs) can, dependent on the speed at which they are travelling at, require less fuel on a highway in a hill or valley than on a level highway. The reduction can be attributed to the increase in fuel required to get the vehicle up the hill being offset by the reduction in fuel required to get the vehicle down the hill. The effect is unique to this specific form of traction and may not be the case for alternatively powered vehicles.

The occurrence of lighter vehicles favouring graded highways tends to be the case at higher vehicle speeds. This positive effect on the lighter vehicles is exaggerated on the valley alignment with the same gradients due to the shorter transition curve lengths extending the graded sections and therefore maximising this apparent offsetting effect.

These positive benefits on the lighter vehicles become quite insignificant when compared to the negative effects on the heavier vehicles (HGVs). Again using the +6 -6 hill alignment as an example, the petrol car on the graded alignment can result in between 2% lower and 7% higher CO_2 emissions than what would be emitted on the level alignment, whereas for the half-laden articulated HGV there can be an increase in emissions of between 8% and 88%.

In answer to the question of '*how does alignment effect the emissions of different vehicles?*', the overarching conclusion is that variations in the vertical alignment of a highway have a small either positive or negative effect on lighter vehicles and a greater negative effect on heavier vehicles.

But of course it is not just single vehicle types that use highways, and the important question of '*how does alignment effect fleet emissions?*' has been addressed. Although the benefits to the light vehicles were small in comparison to the detrimental effects on the heavy vehicles, there was a possibility that the large proportion of light vehicles relative to the proportion of heavier vehicles would result in an overall benefit. This was tested through the modelling of typical vehicle fleets. Three fleet scenarios were considered, all of which were based on the NAEI projected fleet mixes for the year of 2025 with the speeds based on the recorded DfT data from 2010. Despite the actual recorded speeds being for 2010, they can be assumed to complement the 2025 fleet data as it is anticipated that there will be no change to highway speed limits. The scenarios were:

1. Business as Usual, assuming all vehicles are powered by the conventional ICE
2. Low Carbon Future, assuming that only heavy vehicles are powered by the conventional ICE with the light vehicles being powered by an alternative zero carbon source.
3. Lower speeds, assuming all vehicles are powered by the conventional ICE, as in Scenario 1, but with all vehicle speeds being 10 kph lower.

As previously discussed the light vehicles were not heavily influenced by the graded highway, and in some cases benefited from the gradients. It could, therefore, be expected that this effect in conjunction with the large proportion of the fleet that they comprise, could offset the negative effects on the heavier vehicles, which only comprise a small proportion of the fleet. However, this is not the case; the negative effect on the HGVs outweighs the negligible negative or beneficial effects on the light vehicles. Therefore, overall for the case of the hill and valley assessed, the fleet under Scenario 1 traversing the graded terrains would prefer to operate on a level alignment. In the case of Scenario 2, due to the fleet consisting of only heavy vehicles, the level alignment is further preferable over the graded alignments.

It is possible to conclude from the hypothetical terrains, that despite the potentially beneficial consequences manifesting in the lighter vehicles when travelling over graded alignments, the heavier vehicle contingent of the fleet overshadows any benefits and overall a level alignment is always preferred. It is important to note that this conclusion assumes a graded alignment with uphill and downhill sections of equal length, with the same fleet mixes and fleet speeds in each direction.

Another aim was to understand '*how the vehicle speeds affect the emissions?',* and it can be said that level alignments are even more preferable at lower speeds. This is not to be confused with the fact that lower speeds result in lower emissions, which is of course true due to the lesser effect of air resistance at lower speeds. In the context of the emissions from an entire fleet, these are lower at lower fleet speeds due to the offsetting effect apparent for the lighter vehicles tending to occur at higher speeds. Therefore, when the fleet speeds are lower, the offsetting effect occurs less which in turn does not counteract the higher emissions from the heavier vehicles. It is for this reason that the fleet in Scenario 3 again preferred the level alignment, and more so than the fleet in Scenario 1.

All types of vehicles assessed were powered by the ICE and thus a direct answer cannot be provided to the question of *'How does engine technology alter the effect of alignment?'.* Scenario 2 is for a possible future situation in which heavy vehicles use the ICE and are fuelled by diesel and in which light vehicles are alternatively powered; it can therefore give a reasonable indication of a different engine technology being used. The heavy vehicles are seriously affected by graded alignments, with no benefits to the lighter contingent of the fleet to counteract the negative effects and so it follows that there appears to be an even greater benefit of designing a level alignment.

The aim of the research was to understand whether or not it is worthwhile to expend more CO_2 in the construction phase through a more intensive earthworks operation to construct a more favourable alignment. The conclusion to this point has been that a level alignment proves beneficial for the use phase when typical vehicle fleets are considered. Which leads onto the crucial question of '*whether the CO_2 reductions in the use phase sufficiently offset the CO_2 increases in the construction phase?'*. If there is a reduction in CO_2 emissions in the use phase brought about by a more favourable alignment then it makes sense that eventually the CO_2 expended in the construction phase will be paid back. The time taken to pay back the CO_2 is important; especially in an industry where quick-wins are sought, where a life cycle perspective is not necessarily taken and when the technology is likely to evolve and change. The appraisal time frame for highway schemes in the UK is 60 years and therefore a net positive benefit over this time frame would be viewed satisfactorily.

In order to answer this question, the CO_2 associated with the earthworks required to construct the preferable shallower alignments was approximated using the 'bottom-up' approach developed in conjunction with the earthworks contractor. It has been previously discussed that the CO_2 can vary considerably with machinery choice and the strategy adopted; for this reason a low and high CO_2 value has been given based on what was deemed to be the most effective and least effective combination respectively. For this hill scenario, the high CO_2 value was as much as 60% higher than the low value.

Taking the hypothetical valley terrain to a terrain that would facilitate a level alignment, with a large earthworks operation in excess of 45 million m^3, was shown to result in around a minimum of 110,000 tonnes of CO_2. For the motorway project assessed, the earthworks to the road pavement CO_2 ratio was approximately 1:9. In the case of the levelled hypothetical alignment this ratio can be approximated at 8:1. The earthworks aspect of the construction phase would, therefore, become the dominating contributor to CO_2 despite no new materials being used; the CO_2 would result purely from the large quantities of fuel consumed by the earthmoving plant. The scale of the earthworks required would result in the earthworks becoming a major carbon source, despite earthworks being a relatively low carbon intensive activity.

This huge CO_2 emission resulting from the vast earthworks operation to create the level alignment in the case of the hypothetical valley could be viewed as an initial carbon penalty, which could potentially pay dividends throughout the lifetime of the highway as the vehicles using it use less fuel. However, the year on year savings brought about by the level alignment, based on the average UK motorway flows, fleets and speeds, are not sufficiently large enough to make this increase in CO_2 from the construction phase seem overly appealing. Extra efforts, in earthworks terms, to take the valley terrain to a level alignment can result in overall savings of 12%, 52% and 14% for Scenarios 1, 2 and 3 respectively over a 60 year period. When the higher earthworks value is assumed this is reduced to 8%, 37% and 10%. If the vehicle flows were higher, more CO_2 would be reduced due to more vehicles benefiting from the alignment and thus the percentage savings over the 60 year timeframe would be higher. Similarly, if the vehicle flows were lower the percentage savings would also be lower. Therefore in response to the question of *'how important are vehicle flows?'* the answer would have to be that they are very important. In fact, before beginning to consider whether to attempt to optimise an alignment, the expected vehicle throughput of the road should be of primary importance.

The A1 case study detailed in Chapter 7 emphasises the relevance of vehicle flows. This particular dual carriageway has high traffic flows relative to the average flows on rural dual carriageways in the UK. The earthworks operation required to obtain an improved alignment for the route was also relatively low and has been estimated to be between around 4,000 and 22,000 tonnes of CO_2. For comparison, when using the lower earthworks value, this makes the earthworks to pavement CO_2 ratio approximately 1:2. It would be expected that the relatively high traffic flows for a dual carriageway type road and the relatively low earthworks value would result in a situation in which the additional CO_2 expended in construction would quickly reap rewards. This is not the case. Despite the flows being considered high in terms of dual carriageway flows, they are in fact quite low and over a 60 year period under Scenario 1 only 4,000 tonnes of CO_2 is reduced.

Although earthworks are low carbon intensive, it is the scale of the earthworks operation that creates the large CO_2 value associated with it. The annual savings in the use phase for the valley terrain when taken to the level alignment were 14%, 41% and 16% for Scenarios 1, 2 and 3 respectively. Therefore, it is the earthworks CO_2 that is substantial and causing the long payback periods. The earthmoving industry is investing heavily to reduce the fuel consumed by its plant and machinery. With technological improvements that result in lower fuel consumption, the CO_2 intensity of earthworks could be further lowered and potentially significantly decrease earthworks related CO_2. Variation in the earthworks CO_2 would result in changes to the payback durations; with lower earthworks CO_2 values equating to shorter payback durations.

With reference to higher flows resulting in a quicker payback period, in theory this is true. However, the well-researched relationship between traffic speed and flow could indicate otherwise (Mannering *et al.*, 2008). At the low flows being considered within this thesis, a doubling of the flows would not cause traffic to breakdown and would not seriously alter the conclusion. Although it is important to emphasise that simply stating that higher flows would payback CO_2 expended in earthworks more quickly is debatable, as at certain point the flows will reach a level that will impede free flow traffic movements and in turn create congestion which would subsequently increase fuel consumption.

In addition to the issue of high flows causing congestion, there is also the potential for traffic interaction on non-level highways to alter fuel consumption due to heavy vehicles slowing down and affecting the lighter vehicles. The subsequent effect on the lighter vehicles would be periods of deceleration from the desired speed followed by periods of acceleration to attain their desired speed again. To understand the resultant effect on fuel consumption a brief investigation was undertaken and has been presented in Chapter 9; with the aim being to establish whether the adopted approach used within this research of using an average vehicle speed would produce very different values to a speed that varied from second to second as a result of traffic interaction. The outcome was that the average speed approach reported slightly higher CO_2 emissions than the instantaneous speed approach when the entire fleet was considered. When individual vehicles were studied in more detail the two approaches varied in terms of which one resulted in a higher CO_2 emission; the average speed results varied from 13% lower to 11% higher than the actual speed emissions. This is an area that would need further investigation.

Returning to the A1 case study, the main outcome was that the resultant CO_2 from modifying the alignment of Route B4 would not be paid back within the typical 60-year appraisal period due to the low vehicle flows providing a small annual reduction in emissions. The highest emitting route was B1, and it was possible to reduce CO_2 emissions by 11% alone through the selection of Route B4 instead. The reduction that could be made by selecting Route B4 and making it completely level would further reduce emissions to 13%. This highlights the importance of selecting the route which results in the least CO_2 emissions, with an 11% reduction possible through the selection of one proposed route over another. When the methodology recommended within the WebTAG Environment sub-objective was followed, the eastern routes (B4 and B5) were identified as resulting in the highest emissions with all the western routes (B1, B2, B3 and B6) resulting in the same emission levels which were lower than the eastern routes. The scheme assessment report concluded there were no significant differences between the route options within Section B, and therefore this particular sub-objective had no influence in the determination of the route option preference.

The varying vertical and horizontal alignments of the six route options of the A1 case study are reflective of a typical highway project. The hypothetical alignments considered in Chapter 6 were straight roads with only varying vertical alignments which would be unlikely to occur in the real-world. In the case of the A1 the emissions were normalised to the length of the route to enable a comparison to be made between the different route options. The varying horizontal and vertical alignments, which resulted in varying route lengths, would have a direct effect on the volume of materials used in the road pavement. Within this research the CO_2 resulting from the pavement construction has not been considered and therefore it should be acknowledged that there may be an option whereby a level alignment is not straight but follows a contour and so is more sinuous. In this event, the alignment might be longer and in this case the CO_2 associated with paving the additional length could be relevant, as could any congestion associated with the shorter visibility distances.

The prescribed WebTAG assessment methodology was also followed for the highway scheme used as a case study in Chapter 8. However, a supplementary assessment was undertaken as part of this research work by the author to understand the carbon implication of structure choice (a viaduct or embankment option) at a section of the scheme. Although the low carbon intensity of earthworks had been promoted through this research, the CO_2 associated with both a viaduct and an embankment was quantified to inform decision making. Both the embankment option and the viaduct option would result in the same final alignments. The issue being addressed was which option had the lowest carbon impact at construction. The outcome of this assessment highlighted the savings that can be made through the use of an earthworks embankment, when fill material is sourced within the site, over the use of a viaduct that is comprised of man-made processed materials. The estimated CO_2 from the earthworks required to construct the embankment was 300 tonnes, and the CO_2 from the construction of the viaduct was estimated at 8,000 tonnes; when compared in this manner the viaduct results in 27 times more CO_2. However, supplementary structures were also required to be used in conjunction with the earthworks to obtain an embankment that would not restrict movements within the valley and to ensure it remained within land take boundaries. With these additional structures the CO_2 associated with the embankment option increased to 4,500 tonnes, which meant the embankment option still proved favourable due to it resulting in around half the CO_2 associated with the viaduct. This study highlighted how natural materials within earthworks can be used as an alternative to reduce CO_2 from the construction phase.

To understand the calculated CO_2 saving from the embankment in the context of the CO_2 from the entire scheme across its lifetime a broad approximation of the whole life carbon was made. Using this whole life carbon estimate it was concluded that by taking forward the embankment option the total scheme CO_2 would reduce by 0.5% over a 60 year period. Should the structures have not been required to supplement the embankment this figure would have been higher at 0.8%. Although these figures are not astoundingly high, they are at the very least, noteworthy. Efforts should be made to reduce CO_2 where possible. When a vehicle technology is widely used, which results in zero emissions from the use phase, attention will naturally move to the construction phase, which currently receives little consideration due to it being overshadowed by the huge CO_2 emissions resulting from a highway's use.

The case study described above is a good example of how carbon assessments can be approached on highway schemes. The scheme developer had already satisfied the necessary criteria set out in the WebTAG guidance, yet took further steps to ensure they understood the carbon implications of their decisions. Currently no assessment of CO_2 emissions from construction is required which is, according to WebTAG, due to proportionality issues and practical difficulties in reliably and consistently estimating non-carbon greenhouse gases (DfT, 2011). Until this is changed carbon assessments will only be undertaken by the more environmentally conscious.

Likewise, both the background motorway study and the A1 highway scheme case study highlighted the limitations and inaccuracies surrounding the present WebTAG approach to assessing CO_2 emissions in the use phase. The DMRB recognises that this approach is widely used due to data limitations making it the only practical approach, which means that a more detailed approach would be more timely and costly. The DMRB does, however, recommend that thought should be given to whether the scheme is likely to result in variations in driving patterns, for example whether it is likely to relieve congestion. If it is likely to result in variations, the DMRB then recommends an approach that utilises the modelled second-by-second data of every vehicle on the highway network. Many people are unaware of the more detailed approach and would be unlikely to embark on such an expensive time consuming exercise if it were not a necessary requirement. Hence, the few highway schemes that have used the more sophisticated approach have done so with an ulterior motive; to demonstrate the benefits of the scheme, to either obtain funding more easily or to expel opposition.

Despite the methodology detailed within WebTAG, and recommended for use by the DMRB, being suitable to enable the magnitude of emissions associated with highway schemes to be quantified in a sufficiently accurate manner, it is advised that the literature be revised to ensure that users are aware of the limitations and drawbacks of the approach. It is recommended that the more sophisticated approach, in which a microsimulation transport model is developed to be used in conjunction with an instantaneous emission model to quantify the emission differences between 'with scheme' and 'without scheme' scenarios, is adopted for significant highway schemes. This is especially important in the UK where new highway schemes tend to be constructed to relieve congestion. The more accurate data obtained will ensure decision-making is well informed with regards to the effects on CO_2 emissions from vehicles using the road network.

The new motorway case study detailed in Chapter 2 showed how the effect of traffic interaction can become detrimental and how the construction of a new highway can be justified through relieving or minimising this interaction. The case study showed that despite there being an increase in vehicle-kilometres travelled there was an overall reduction in carbon emissions due to the vehicles being able to operate in a more efficient manner, and hence produce less grams of CO_2 per kilometre travelled. These results were obtained through the use of the more sophisticated approach.

WebTAG, and hence the DMRB, should also recommend an approach to assessing CO_2 associated with the construction phase of a highway scheme. Schemes are under consideration now that will be constructed in the next decade. To neglect to address the important aspect of CO_2 from construction now could potentially result in future highway schemes for which insufficient attention is given to its initial CO_2 impact at construction, and subsequent recurring CO_2 throughout its maintenance.

The conclusion that has emerged from this research is that a whole life carbon approach should be adopted for all new highway schemes, yet that consideration should not necessarily be given to the vertical alignment. Vertical alignments are currently governed by the aim of achieving an earthworks balance. Minimising highway gradients is currently desirable to minimise user costs and accident costs, and is done within the limits of the site's cut and fill balance. Design of the vertical alignment is done from the perspective of the construction phase alone; it is not done to benefit any other phase and is certainly not done to minimise fuel consumption and hence CO_2 emissions in the use phase.

Movement towards a whole life carbon approach is highly recommended to ensure that the consequences of design choices are traced through the life cycle. This research concludes that the consequential effect of the highway alignment on CO_2 emissions in the use phase is not a highly important design consideration, especially for highways with low anticipated traffic flows. The methodology currently used to assess different route alignment options is too primitive to detect the changes in vehicle emissions resulting from highways with gradients, and hence, should vehicle flows be high enough to make consideration of this aspect of design worthwhile, a more detailed approach should be taken such as the one used throughout this research.

It was the intention to ascertain '*whether it is beneficial to expend more CO_2 in the earthworks element of the construction phase to reduce CO_2 in the use phase?'*. From the hypothetical terrains considered the conclusion would be that it is in some cases it would indeed be beneficial to do so. In the Business as Usual scenario these savings over the 60 year period of consideration would be quite small. Under the different future scenarios, the long-term benefits would be more palpable, especially under the Low Carbon Future scenario which assumes only heavy vehicles would be powered by the ICE.

It is important to note that the above results were based on assumed vehicle flows that reflected UK average vehicle flows. Vehicle speeds and the fleet mix are important factors when deciding whether it is worthwhile investing CO_2 in a more beneficial alignment, but what is of huge importance is the flow of vehicles that would be anticipated to use the highway. As the results have indicated, level alignments do tend to benefit typical vehicle fleets, but if the flow is low then the resultant CO_2 reduction will take an extremely long time to enable the additional CO_2 expended in construction to be recouped.

Vehicles flows, of course, vary between projects, but it is not only flows that vary; no two highway projects are the same and so it is impossible to state that the desired vertical alignment should be a level one for all projects. Therefore, it is suggested that a detailed assessment of all route options for new highway schemes is undertaken in addition to the required assessment set out in WebTAG and the DMRB. The assessment procedure taken for the A1 case study provided worthwhile results and utilised data that was a by-product of the highway design process, and therefore it was not necessary to collect further data.

An inductive approach to this research was taken which was designed to take knowledge on the subject from the more specific to the general, with the premise that a theory would emerge. The results of the background study involving the assessment of the motorway project indicated for this specific project that the earthworks were minimal in terms of CO_2 emissions. Based upon this individual study and observation, hypothetical scenarios were developed and tested to attempt to gain an understanding of whether this low carbon construction activity could be used advantageously to obtain an alignment that would yield long-term benefits whilst the highway was in use. Application of the methodology developed on an actual case study, together with the hypothetical results, showed that small but worthwhile savings can be created through efforts to improve the vertical alignment. In theory, under the right conditions, and where possible, CO_2 emissions can be reduced through the adoption of a more favourable level alignment.

There are elements of this thesis which could be further researched. Areas that the author would be interested in exploring are:

- **Alternative earthworks techniques that result in lower CO_2 emissions**
  It was shown that despite earthworks being low intensive in carbon terms that the scale of the earthworks operations required, due to the large volumes needed to be removed from cuttings or imported to embankments, resulted in large CO_2 values. The embankment and cuttings used within this research used typical 1:2 slope gradients. Other geotechnical techniques can be used to enable the slopes to be steeper such as soil nailing, reinforced

earth, retaining walls, and the use of gabions. A comparison of these alternatives with the more straightforward bulk earthworks assumed, and the subsequent effect on the conclusion would be of interest.

Additionally, the use of additives to improve the properties of soil could be investigated; specifically materials that have a low embodied CO_2 content or that are a by-product of industrial processes.

- **Study of the effects of alignment on alternative vehicle technologies**
  The ICE was the focus of this research and it demonstrated some unexpected behaviour in terms of efficiency. It would be interesting to understand how varying alignments can impact on different technologies such as hybrid systems or electric-powered vehicles.

- **Further case studies**
  Case studies were used within this research to demonstrate how the methodology applied to the hypothetical alignments can be applied to real-world case studies. They were not used in the usual manner to inform the hypothesis and were included for demonstrative purposes only. With most highway schemes being unique with different fleet mixes, speed and flows, the use of more case studies would further indicate whether it is worthwhile to expend more CO_2 in construction to result in a beneficial use phase.

- **Widen study boundaries**
  The boundaries of this research were defined in Chapter 3. A similar study with a widening of the study boundaries would provide and understanding of how these can the effect the conclusion. A specific area for investigation would be the CO_2 associated with the production of fuel, as both the construction (earthworks) and use phases excluded this portion.

Chapter 11

References

Agency, H. (2002). *Volume 13 Economic assessment of road schemes.* Bedford: Highways Agency.

Arup. (2009). *A8 Belfast to Larne Dual Carriageway Stage 2 Scheme Assessment Report.* Belfast: Arup.

Arup. (2001). *M4 Relief Road Magor to Castleton. Construction strategy report.* Cardiff: Arup.

Arup. (2011). *Microsimulation Traffic Model Report (11/7994).* Cardiff: Arup.

Arup. (2008). SATURN model output data. Cardiff: Arup.

Baker, B. (2009, October 14). Inetrview on Arup carbon calculator tool. *Personal communication* . Birmingham, UK.

Barlow, T. J. (1999). *M25 Variable speed limit scheme. The effect on vehicle exhaust emissions. Highways Agency project report summary note.* Berkshire: TRL.

Barlow, T. J., Boulter, P. G., & & McCrae, I. S. (2007). *Scoping study on the potential for instantaneous emission modelling summary report.* Berkshire: TRL.

Barlow, T., Boulter, P. G., & McCrae, I. S. (2007). *An evaluation of instantaneous emission models.* Berkshire: TRL.

Baron, T., Martinetti, G., & Pepion, D. (2011). *Carbon footprint of high speed rail.* Paris: International Union of Railways (UIC).

BERR. (2008). *Strategy for Sustainable Construction.* London: H M Government.

Birgisdottir, H. (2005, July). Life cycle assessment model for road construction and use of residues from waste incineration. *PhD Thesis* . Lyngby, Denmark: Technical University of Denmark.

Boulter, P. G., & McCrae, I. S. (2007). *The links between micro-scale traffic, emission and air pollution models.* Berkshire: TRL.

Boulter, P., McCrae, I., & Barlow, T. (2006). *A review of instantaneous emission models for road vehicles.* Berkshire: TRL.

Boustead, I. (1996). LCA - how it came about - the beginning in the UK. *International Journal of LCA* , 147-150.

BRE. (2011). *The Green Guide to Specification*. Retrieved November 11, 2011, from BRE web site: http://www.bre.co.uk/greenguide

Bryman, A., & Cramer, D. (1994). *Quantitative data analysis for social scientists.* London: Routledge.

Butler, R. (2006). *Integration of the Measurement of Energy Usage into Road Design.* Waterford: Commision of the European Communities Directorate-General for Energy and Transport.

Butler, R., & Kennedy, E. (2006). *Integration of the measurement of energy usage into road design.* Waterford: Commission of the European Directorate General for Energy and Transport.

Carillion. (2011, May). Mass haul schedule. Warrington, UK: Carillion plc.

Carillion. (2011, May). Pavement schedule. Warrington, UK: Carillion plc.

Carr, P. (2010). Building a Relief Road: Relieving Congestion – Reducing CO2? Cardiff.

CECA. (2007). *Schedules of Dayworks Carried Out Incidental to Contract Work (July 2007).* London: CECA.

CEEQUAL. (2010). *CEEQUAL Scheme description and assessment process handbook.* London: CEEQUAL Ltd.

CEN. (2009). *Sustainability of construction works*. Retrieved November 10, 2011, from CEN: http://www.cen.eu/cen/Sectors/Sectors/Construction/SustainableConstruction/Pages/CEN_TC350.aspx

Chester, M. V., & Howarth, A. (2009). Environmental assessment of passenger transportation shoudl include infrastrcuture and supply chains. *Environmental Research Letters 4: 024008 (8pp), doi: 10.1088/1748-9326/4/2/024008* .

Christensen, T. H., Birgisdottir, H., & Bhander, G. S. (2006). Life cycle assessment of residue use in road construction. *Sixth International Conference on the Environmental and Techincal Implications of Construction with alternative materials*, (pp. 617-627). Utrecht.

Collings, N. (2009). Internal Combustion Engine Presentation. Cambridge: University of Cambridge.

Concawe; Eucar; JRC. (2007). *Well-to-wheels analysis of future automotive fuels and powertrains in the european context.* Brussels: CONCAWE.

Corti, A., & Lombardi, L. (2003). Evaluation of the Florence highway widening plan by means of LCA. *Urban Transport and the Environment in the 21st Century*, (pp. 625-634). Crete.

COST. (2006). *Final report: Energy and fuel consumption in heavy duty vehicles.* Graz: COST (European Cooperation in the field of scientific and technical research).

Creswell, J. W. (2002). Research design: qualitative, quantitative, and mixed method approaches. Thousand Oaks, California: Sage Publications.

CSIRO. (2007). *Material science and engineering*. Retrieved October 15, 2007, from CSIRO: http://www.csiro.au/org/CMSE.html

DECC. (2009). *2009 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting.* AEA Technology.

DECC. (2011). *2011 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors.* London: Defra.

DECC. (2009). *Carbon valuation in UK policy appraisal: A revised approach.* London: Department of Energy and Climate Change.

DEFRA. (2010). *2010 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors.* London: DEFRA.

DEFRA. (2002). *UK Fleet Projections from 1996.* Retrieved 02 02, 2010, from NAEI: naei.defra.gov.uk/other/uk_fleet_composition_projections_v2.xls

Defra. (2007). *Waste Strategy for England 2007.* London: Defra.

DfT. (2010, October 26). *Road traffic and statistics TRA0301.* Retrieved October 26, 2010, from Department for Transport: http://www2.dft.gov.uk/pgr/statistics/datatablespublications/roads/traffic/

DfT. (2010, October 26). *Road traffic statistics.* Retrieved October 26, 2010, from Department for Transport TRA0303: http://www2.dft.gov.uk/pgr/statistics/datatablespublications/roads/traffic/

DfT. (2010, October 26). *Road traffic statistics.* Retrieved October 26, 2010, from Department for Transport TRA0404: http://www2.dft.gov.uk/pgr/statistics/datatablespublications/roads/traffic/

DfT. (2011). *The Greenhouse Gases Sub-Objective TAG Unit 3.3.5.* London: Department for Transport.

Dudek, E. (2009, April). CO2 contribution of pavement composition spreadsheets. Liverpool, UK.

Egert, B., Kozluk, T., & Sutherland, D. (2009). Infrastructure and Growth: Empirical Evidence. *OECD Economics Department Working Papers, No. 685* . OECD Publishing.

Eurobitume. (2011). *Life Cycle Inventory: Bitumen.* Brussels: European Bitumen Association.

Fellows, R., & Liu, A. (2008). *Research methods for construction.* Chichester: Blackwell Publishing Ltd.

Fraser, N. (1992). *A study of machine selection trends in British earthmoving.* Reading: Univeristy of Reading.

Fraser, N. (2010, January 29). Account of CA Blackwell earthworks methodologies and procedures. (L. Hughes, Interviewer)

Fraser, N. (2012, May). Fuel consumption project data. C A Blackwell.

Fry, C., Eliis, S., McColl-Grubb, V., & Griffiths, P. (2004). *Calculating carbon emissions from Highways Agency construction and maintenance activities - scoping paper.* Berkshire: TRL.

Fry, C., Ellis, S., McColl-Grubb, V., & Griffiths, P. (2004). *Calculating carbon emissions from HIghways Agency construction and maintenance activities - scoping paper.* Berkshire: TRL.

FTTF. (2009). *Carbon Management Framework for Major Infrastructure Projects.* London: Forum for the Future.

H M Government. (2009). *The UK Low Carbon Transition Plan: National strategy for climate and energy.* London: The Stationary Office.

Hammond, G., & Jones, C. (2011). *Embodied Carbon: The Inventory of Carbon and Energy (ICE).* BSRIA.

HBEFA. (2009). *HBEFA Introduction*. Retrieved July 23, 2009, from HBEFA: http://www.hbefa.net

Highways Agency. (2010). *A421Improvements M1 Junction 14 to Bedford. Progress report Number 47.* Bedford: Highways Agency.

Highways Agency. (2007). *DMRB Treatment of fill and capping materials using either lime or cement or both, Advice Note HA 74/07.* Bedford: Highways Agency.

Highways Agency. (2007). DMRB Volume 11 Environmental assessment, Section 3 Environmental assessment techniques, Part 1 Air Quality. Bedford, UK: Highways Agency.

Highways Agency. (2007). *DMRB Volume 11 Environmental assessment, Section 3 Environmental assessment techniques, Part 1 Air Quality.* Bedford: Highways Agency.

Highways Agency. (1996, May). DMRB Volume 12 Traffic Appraisal of Road Schemes Section 1 Traffic Appraisal Manual. Bedford, UK: Highways Agency.

Highways Agency. (1996). *DMRB Volume 12 Traffic Appraisal of Road Schemes Section 1 Traffic Appraisal Manual.* Highways Agency.

Highways Agency. (2002). *Volume 13 Economic assessment of road schemes.* Bedford: Highways Agency.

Highways Agency. (2002). *Volume 6 Road Geometry Section 1 Links Part 1 Highway Link Design.* Bedford: Highways Agency.

Highways Agency; WSP; PB. (2008). *HA Carbon Accouting Tool - Explanatory Report V1 Working Draft.* Bedford: Highways Agency.

HM Revenue and Customs. (2010, June 10). *A general guide to landfill tax*. Retrieved June 10, 2010, from HMRC web site: http://customs.hmrc.gov.uk

HM Revenue and Customs. (2010, July 5). *FAQ: Aggregates Levy*. Retrieved July 5, 2010, from HMRC: http://customs.hmrc.gov.uk

Hunt, R. G., & Franklin, W. E. (1996). LCA - how it came about - personal reflections on the origin and development of LCA in the USA. *International Journal of LCA* , 1-4.

ICE; Franklin and Andrews. (2010). *CESSM3 Carbon and Price Book 2011.* London: Thomas Telford.

ICES. (2003). *The Reference Manual for Construction Plant.* Cheshire: Institution of Civil Engineering Surveyors .

IGT. (2010). *Low Carbon Construction Innovation and Growth Team.* London: H M Government.

Insitution of Civil Enginners (ICE). (2011). *CESMM3 Carbon and Price Book 2011.* London: Thomas Telford.

JCB. (2010, March 22). *Press Release*. Retrieved September 5, 2011, from JCB website: http://www.jcb.com/presscentre/NewsItem.aspx?ID=788

Jones, C. (2010, April 16). *Inventory of Carbon and Energy: Home Page*. Retrieved April 16, 2010, from University of Bath Wiki: https://wiki.bath.ac.uk/display/ICE/Home+Page

Jowitt, P., Johnson, A., Moir, S., & Grenfell, R. (Publication pending). A Protocol for Carbon Accounting in Infrastructure Decisions. *Civil Engineering Proceedings* .

Kwan, J., Sceal, J., Bryson, F. E., Stabury, J., Bickerdike, J., & Jardine, F. (1997). *Ground Engineering spoil: Good management practice.* CIRIA Report 179.

Lax, C. (2010). Life cycle assessment of rammed earth. *MEng Dissertation* . Univeristy of Bath.

Mannering, F. L., Washburn, S. S., & Kilareski, W. P. (2008). *Principles of Highway Engineering and Traffic Analysis.* London: Wiley.

McCrae, I. S., Barlow, T. J., & & Latham, S. L. (2006). *Instantaneous vehicle emission monitoring.* Berkshire: TRL.

McGordon, A. (2009, February 01). Understanding the SAVE average speed drive cycle study. (L. Hughes, Interviewer)

OFWAT. (2011). *Capex bias in the water and sewerage sectors in England and Wales - substance, perception or myth?* Birmingham: OFWAT.

O'Riordan, N., & Phear, A. (2009). Measuring and mitigating the environmental impact of earthworks and other geotechnical processes. *Earthworks in Europe 2nd International Seminar*, (p. Keynote paper).

Pantelidou, H. (2008). *Sustainability of geotechnical and structural assets. Review of embodied energy in construction of geotechnical highway structures.* London: Arup.

Parry, A., & Potter, J. (1995). *Energy consumption in road construction and use. Unpublished project Report PR/CE/48/95 E106A/HE,.* Crowthorne: TRL.

Perry, J., Pedley, M., & Reid, M. (2003). *Infrastructure embankments - condition appraisal and remedial treatment.* CIRIA Report C592.

Porter, K. F., & Tinni, A. (1993). *Life cylcle costing; Whole-of-life cost analysis for heavy duty pavements.* Australian Asphalt Pavement Association.

SIAS. (2009). *S Paramics emissions post processor. A guide to and instructions for using the S-Paramics emissions post-processor tool.* Edinburgh: SIAS.

Skanska. (2010, November). Carbon Footprinting in Construction. London: Skanska.

Smith, R. A., Kersey, J. R., & Griffiths, P. J. (2002). *The construction industry mass balance: Resource use, wastes and emissions.* Viridis.

Stripple, H. (2001). *Life cycle assessment of roads: A pilot study for inventory analysis.* Gothenberg.

Treloar, G., Love, P., & Smith, J. (1999). Streamlines life cycle assessment: A method for considering the impact of environmental factors of road construction. *ARCOM 15th Annual Conference, 11th-13th September.* Liverpool.

Treloar, G., Owen, C., & Fay, C. (2001). Environmental assessment of rammed earth construction systems. *Structural Survey, Vol. 19 Iss: 2* , pp. 99-106.

Trenter, N. A. (2001). *Earthworks - a guide.* London: Thomas Telford.

UK, I. (2010). *National Infrastructure Plan.* London: H M Treasury.

Vissim. (2011). *VISSIM - Multi-Modal Traffic Flow Modeling*. Retrieved December 11, 2011, from PTV Vissim wed site: http://www.vissim.de

Warren, C., Phear, A., Schulteis, T., & Gregg, I. (2003). Treatment of chalk spoil from CTRL Thames tunnel. *Proceedings of the Underground Construction Conference.* London.

Weilenmann, M., Soltic, P., & Ajtay, D. Describing and compensating gas transport dynamics and accurate instantaneous emission modelling. *11th International Symposium: Transport and Air Pollution.* Graz.

Yin, R. K. (2003). Case Study Research: Design and Methods. Thousand Oaks, California: Sage Publications.

Appendix A: Example SATURN output

A node	B node	flow	% HGV	car	lgv	hgv	bus	Ax	Ay	Bx	By	av_speed
1123	1000	1415.075	0.016688	1313.86	77.6	23.615		330522	191983	330153	191912	58.07
1257	1000	878.775	0.028261	795.89	58.05	24.835		330130	191725	330153	191912	28.38
1011	1000	804.445	0.024694	739.21	45.37	19.865		330036	192076	330153	191912	34.21
1012	1000	125.255	0.052333	111.75	6.95	6.555		330219	192102	330153	191912	22.55
1122	1001	1577.415	0.038338	1431.43	85.51	60.475		330619	191982	330575	191998	10.47
1123	1001	574.25	0.012904	527.8	39.04	7.41		330522	191983	330575	191998	5.89
1121	1001	344.6	0	327.93	16.67	0		330580	192049	330575	191998	12.7
1005	1002	1482.725	0.017222	1358.1	99.09	25.535		331237	189951	331262	190070	80
1122	1002	2038.855	0.034228	1821.89	147.18	69.785		330619	191982	331262	190070	112
1003	1002	1165.57	0.05013	1060.05	47.09	58.43		331255	190003	331262	190070	48
1005	1003	671.83	0.031139	560.56	90.35	20.92		331237	189951	331255	190003	10.76
1002	1003	701.39	0.034218	620.64	56.75	24		331262	190070	331255	190003	11.67
1004	1003	1165.605	0.050133	1060.08	47.09	58.435		331315	189981	331255	190003	11.4
1120	1004	2440.315	0.027203	2225.41	148.52	66.385		331940	189812	331315	189981	64
1003	1004	671.86	0.031137	560.59	90.35	20.92		331255	190003	331315	189981	48
1002	1004	1337.465	0.034233	1201.25	90.43	45.785		331262	190070	331315	189981	80
5800	1005	2154.545	0.021561	1918.65	189.44	46.455		331154	189758	331237	189951	80
1003	1005	701.39	0.034218	620.64	56.75	24		331255	190003	331237	189951	48
1004	1005	1274.65	0.006237	1165.27	101.43	7.95		331315	189981	331237	189951	80
5800	1006	1641.085	0.018436	1469.53	141.3	30.255		331154	189758	330941	189228	74.13
1010	1007	1678.925	0.014554	1511.69	142.8	24.435		331019	188595	330922	189252	77.17
1117	1007	557.805	0.033067	476.4	62.96	18.445		330968	188954	330922	189252	45.63
1113	1008	2393.68	0.028563	2146.64	178.67	68.37		331016	188976	331080	188945	3.44
1412	1008	746.105	0.034506	641.81	78.55	25.745		331219	188951	331080	188945	3.48
1006	1009	477.895	0.04161	403.29	54.72	19.885		330941	189228	331047	188600	78.39
1114	1009	260.375	0.015036	249.55	6.91	3.915		331062	188861	331047	188600	41.55
1416	1010	2023.435	0.016272	1822.06	168.45	32.925		331085	188434	331019	188595	74.3
1000	1011	1202.935	0.037047	1092.62	65.75	44.565		330153	191912	330036	192076	96
1000	1012	10.125	0.013333	9.86	0.13	0.135		330153	191912	330219	192102	48
1121	1013	1883.91	0.032247	1703.64	119.52	60.75		330580	192049	330589	192196	112
1115	1111	1796.635	0.017113	1608.09	157.8	30.745		331042	188857	330999	188851	27.18
1010	1111	344.51	0.024644	310.38	25.64	8.49		331019	188595	330999	188851	2.42
1118	1112	1082.595	0.040629	969.54	69.07	43.985		330900	189152	330999	189027	19.12
1006	1112	1163.19	0.008915	1066.24	86.58	10.37		330941	189228	330999	189027	24.72
1117	1113	148.685	0.090426	113.06	22.18	13.445		330968	188954	331016	188976	5.94
1112	1113	2245.68	0.024153	2035.75	155.69	54.24		330999	189027	331016	188976	20.78
1008	1114	2772.51	0.020581	2493.94	221.51	57.06		331080	188945	331062	188861	29.14
1114	1115	1405.46	0.018898	1248.92	129.98	26.56		331062	188861	331042	188857	26.68
1269	1115	460.545	0.011845	420.95	34.14	5.455		331138	188387	331042	188857	4
1111	1116	2087.685	0.01831	1870.55	178.91	38.225		330999	188851	330943	188910	6.91
1516	1116	1072.395	0.030637	929.42	110.12	32.855		330893	188893	330943	188910	1.39
1116	1117	2233.955	0.022809	1966.81	216.19	50.955		330943	188910	330968	188954	22.49
1117	1118	1527.46	0.012485	1377.34	131.05	19.07		330968	188954	330900	189152	39.88
1839	1118	1082.595	0.040629	969.54	69.07	43.985		330846	189270	330900	189152	40.3
1004	1119	2009.43	0.033159	1760.35	182.45	66.63		331315	189981	331819	190019	57.06
1402	1120	1004.05	0.010667	931.65	61.69	10.71		332266	189786	331940	189812	57.36
1223	1120	1436.65	0.038478	1294.5	86.87	55.28		331994	189877	331940	189812	46.2
1013	1121	1808.83	0.03468	1621.24	124.86	62.73		330589	192196	330580	192049	112
1001	1121	1577.415	0.038338	1431.43	85.51	60.475		330575	191998	330580	192049	80
1123	1121	306.89	0	272.42	34.47	0		330522	191983	330580	192049	80
1002	1122	2648.2	0.031629	2418.1	146.34	83.76		331262	190070	330619	191982	112
1001	1122	574.25	0.012904	527.8	39.04	7.41		330575	191998	330619	191982	80
1121	1122	1464.23	0.042842	1293.31	108.19	62.73		330580	192049	330619	191982	80
1000	1123	881.14	0.00841	800.22	73.51	7.41		330153	191912	330522	191983	112
1001	1123	344.6	0	327.93	16.67	0		330575	191998	330522	191983	80
1122	1123	1070.81	0.02175	986.7	60.82	23.29		330619	191982	330522	191983	80
8016	1200	5164.08	0.059405	4533.6	323.71	306.77		327960.8	185308.6	325760	184083	96.17
8012	1201	5565.335	0.073062	4743.18	415.54	406.615		326234.6	184419.1	328001	185400	89.81
1201	1202	4191.17	0.06313	3636.56	290.02	264.59		328001	185400	328394	186185	96.65
1649	1202	1547.72	0.036176	1385.04	106.69	55.99		328372	185930	328394	186185	61.54
1200	1203	2893.045	0.079928	2471.45	190.36	231.235		325760	184083	325288	184039	83.06
8003	1204	5741.245	0.05536	5026.57	396.84	317.835		328394	186235	328318	187689	78.81
1204	1205	4830.3	0.064667	4196.9	321.04	312.36		328318	187689	328410	187979	67.84
1400	1205	452.57	0.090351	350.98	60.7	40.89		328398	187832	328410	187979	47.36
8005	1207	5282.775	0.066862	4547.9	381.66	353.215		328546	188098.2	329999	189375	67.56
1207	1208	3266.52	0.081126	2786.24	215.28	265		329999	189375	330674	189828	70.65
1262	1208	137.735	0.007805	135.83	0.83	1.075		330480	189738	330674	189828	30.29
8004	1210	3404.3	0.07821	2921.8	216.25	266.25		330745.9	189845.5	330989	189906	62.9
1210	1212	3404.3	0.07821	2921.8	216.25	266.25		330989	189906	332043	189955	68.26
1119	1212	828.145	0.078917	659.79	103	65.355		331819	190019	332043	189955	55.63
1212	1213	4232.355	0.078348	3581.79	318.97	331.595		332043	189955	332463	189694	88.07
1402	1213	277.335	0.018191	262.16	10.13	5.045		332266	189786	332463	189694	37.81
1216	1214	2034.175	0.048484	1756.16	179.39	98.625		335492	189656	335772	189718	71.23
8006	1216	4509.885	0.074602	3844.47	328.97	336.445		332618.6	189694.7	335492	189656	97.45
1377	1217	344.135	0.091403	285.29	27.39	31.455		336160	189718	336504	189672	73.08
1216	1217	2475.705	0.096064	2088.3	149.58	237.825		335492	189656	336504	189672	96.21
3081	1219	4775.31	0.048156	4365.42	179.93	229.96		340075	188789	336486	189501	86.88
1219	1220	3897.56	0.050498	3541.53	159.21	196.82		336486	189501	335571	189456	41.38

Appendix B: COBA assessment

DMRB Volume 13 Section 1 Part 5: *Speed on links* provides a methodology to predict the speed for different vehicle types. On rural roads, where there is minimal interaction between road links and junctions, relationships are used to predict the link speed depending on the link geometry and traffic flow. On urban roads the road network is considered as an interacting system; with COBA using speed-flow relationships based on observed average journey speeds.

Figure B.1 shows how changes in the horizontal alignment of rural roads are considered. The 'bendiness' (parameter name = BEND) is measured as the total change in direction in degrees per kilometre.

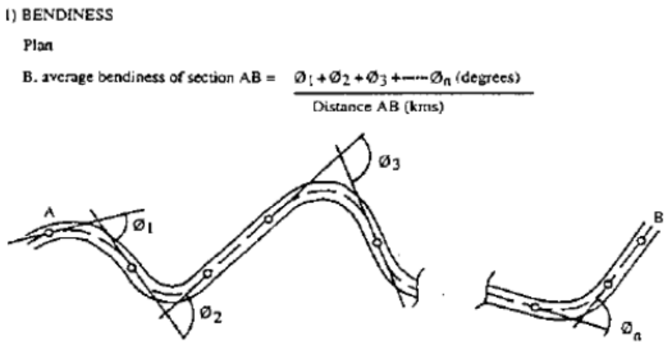


Figure B.1 Calculation of BEND - change in horizontal alignment (adapted from DMRB, 2002b)

Figure B.2 shows how the change in the vertical alignment of rural roads is considered. The 'hilliness' (parameter name = HILLS) is measured by the total rise and fall in metres per kilometre.

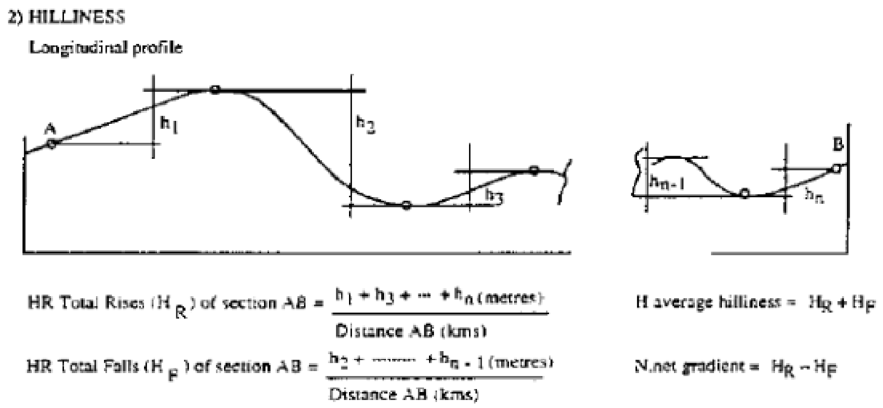


Figure B.2 Calculation of HILLS - change in vertical alignment (adapted from DMRB, 2002b)

Various other parameters are used to within COBA to calculate the average speed; these are shown in Figure B.3.

SYMBOL	VARIABLE DESCRIPTION	TYPICAL VALUES Min		Max
DES	Is road designed to TD9 (DMRB 6.1.1.) Standards?	Yes	or	No
BEND	Bendiness; total change of direction (deg/km)	0		150
HILLS	Hilliness; total rise and fall (m/km)	0		45
NG	Net gradient one-way links only (m/km)	-45		45
JUNC	Side roads intersecting, both directions (no/km)	0		5
CWID	Average carriageway width between white line edge markings, excluding any painted out portion (m)	6		11
SWID	Average width of hard strip on both sides, including width of white line (m)	0		1.0
VWID	Average verge width, both sides (m)	0		7
VISI	Average sight distance (m)	100		550
PHV	Percentage of heavy vehicles (OGV1 + OGV2 + PSV)	2		30
V_L, V_H	Speed of light and heavy vehicles (kph)	45		90
S_L, S_H	Speed/flow slope of light and heavy vehicles (kph reduction per 1000 increase in Q)	5		50
Q	Flow all vehicles (vehs/hour/dir)			
Q_B	Breakpoint: the value of Q at which the speed/flow slope of light vehicles changes (vehs/hour/dir)		0.8 Q_C	
Q_C	Capacity flag: defined as the maximum realistic value of Q (vehs/hour/dir)	900		1600

Figure B.3 Parameters used in speed prediction formulae *(adapted from DMRB, 2002a)*

To predict the speed (in kph) for light vehicles less than the breakpoint (Q_B) on an all-purpose dual carriageway or motorway (extracted from DMRB, 2002b):

$V_L = K_L$ - 0.1 x BEND

- 0.14 x HILL (two-way links only)

- 0.28 x H_R (one-way links only)

- $S_L Q$,

where K_L is
108 for dual 2-lane all-purpose (COBA Class 2)
115 for dual 3-lane all-purpose (COBA Class 3)
111 for dual 2-lane motorways (COBA Class 4)
118 for dual 3-lane motorways (COBA Class 5)
118 for dual 4-lane motorways (COBA Class 6),

S_L the speed/flow slope for light vehicles,
is 6 kph per 1000 vehicles.

To predict the speed (in kph) for light vehicles greater than the breakpoint Q_B (extracted from DMRB, 2002b):

$$V_L = V_B - 33(Q - Q_B)/1000.$$

To predict the speed (in kph) for heavy vehicles, for all flow levels (extracted from DMRB, 2002b):

$$V_H = K_H \quad - 0.1 \times BEND$$
$$- 0.25 \times HILLS \text{ (two-way links only)}$$
$$- 0.5 \times H_R \text{ (one-way links only),}$$

where K_H is	86 for all-purpose	(COBA Classes 2 and 3)
	93 for motorways	(COBA Classes 4, 5 and 6),

subject to the constraint that if the calculated value of V_H is greater than V_L then V_H is set equal to V_L.

The COBA manual states that once an average speed has been calculated for the vehicle types required, determined by the road geometry, visibilities and flow rates, then the speed should be used to arrive at an emission estimate using the procedure set-out in DMRB (taken from WebTAG Unit 3.5.6).

Appendix C: ICES equipment fuel consumption rates

Small dumpers	
engine	litres / hour
5kW	1.3
7.5kW	2.0
10kW	3.0
15 kW	4.0
20 kW	4.9
30 kW	7.0
50 kW	12.0

(a)

Scrapers	
engine	litres / hour
150 kW	34.0
200 kW	45.0
250 kW	56.0
300 kW	67.5
400 kW	85.0

(b)

Rollers	
engine	litres / hour
10 kW	2.0
15 kW	3.0
25 kW	5.0
50 kW	9.0
75 kW	14.0
100 kW	18.0

(c)

Excavators (Hydraulic backhoe)	
engine	litres / hour
10 kW	2.5
20 kW	4.5
40 kW	9.0
60 kW	13.0
80 kW	17.0
100 kW	21.0
125 kW	27.0
150 kW	32.0
175 kW	38.0
200 kW	41.0
250 kW	50.0

(d)

Rear dump trucks	
engine	litres / hour
200 kW	16.0
250 kW	20.0
300 kW	25.0
400 kW	32.0
500 kW	40.0
600 kW	47.0
750 kW	58.0
1000 kW	75.0

(e)

Graders	
engine	litres / hour
75 kW	14.0
100 kW	18.0
150 kW	26.0
200 kW	33.0

(f)

Power ratings and associated fuel consumption for typical earthworks machinery **(**ICES, 2001)

Appendix D: Details of earthworks scenarios

	CO_2 (tonnes)			Cost (£)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
1. Movement of materials already located on the site						
(a) Kept on-site						
Machinery						
Excavation	595	539	574	943,000	879,000	937,000
Haul and deposition	1653	1649	1758	3,144,000	3,122,000	3,328,000
Spreading and compaction	301	282	301	691,000	648,000	691,000
Modification						
Modification processes	0	0	184	0	0	415,000
Charges						
Royalty charge	-	-	-	1,000,000	500,000	500,000
Aggregate levy	-	-	-	780,000	390,000	390,000
Landfill tax	-	-	-	-	-	-
(b) Taken off-site						
Machinery						
Excavation	55	55	0	93,100	93,100	0
Transportation						
Transportation	528	528	0	100,000	100,000	0
Charges						
Disposal costs (Landfill tax and tipping charge)	-	-	-	1,500,000	1,500,000	0
2. Importing materials to site						
Materials						
Imported materials	0	0	2960	-	-	320,000
Transportation						
Transportation of materials	0	0	42	-	-	-
Charges						
Aggregate tax	-	-	-	-	-	-
Royalty charge	-	-	-	-	-	-
TOTAL	***3,132***	***3,054***	***5,820***	***8,251,100***	***7,232,100***	***6,581,000***

The PHEM post-processor can calculate Total Carbon, NO_x and PM_{10} emissions on a time-step by time-step basis. It calculates the emissions at each time-step using the following data:

- time-step (seconds)
- x, y and z coordinates
- gradient (%)
- speed (mph)
- acceleration (m/s^2)

The use of an instantaneous emission model is very data intensive and it is common to use the output from a micro-simulation transport model which can provide the above listed data for each vehicle on the transport network at each time-step. Micro-simulation models are good at modelling transport interactions; however, the representation of the road alignments in the model can be crude due to the user having to draw the network model using links, or lines. Therefore, curved sections of the vertical and horizontal alignment tend to be simplified. The focus of this research was to understand the detailed effect of road alignment on vehicle emissions and therefore an alternative way of obtaining the required data for input into the PHEM post-processor was developed.

Microstation Inroads is software used by engineers to design highways. The software can also produce detailed geometry reports pertaining to the highways modelled; these reports can provide the key data elements required to run the PHEM post-processor.

The reporting tool used in Inroads was a ‘geometry report by station’ - giving details of the geometry of the alignment (x, y, z coordinates and the gradient) at each station. The distance between stations is equal to one time-step; hence the distances between stations vary with vehicle speed. To ensure an accurate emission is calculated in PHEM, one time-step was taken to be 0.25 seconds; therefore, for example, one time step at 160 kph equates to 11.111 m. An example of the geometry report for the +6% -6% alignment at a vehicle speed of 160 kph is shown in Table E.1.

The stations are measured along the horizontal alignment, and not along the vertical alignment. This means that the distance travelled along a curved section of the vertical alignment will be longer than the distance between two stations. To account for this the geometry report is amended – the distances travelled along the vertical alignment between stations is translated to a time dependent on the speed under consideration. On a level section of highway the time between two stations would equate to a single time-step. However, on a curved section the time between two stations would be greater than one time-step. The recalculated time-steps for the geometry report shown in Table E.1 have been appended to the table and are presented in the final grey shaded column. The recalculated time-steps are also shown in Figure E.1. On the level section of the highway at the beginning of the route (between station 0 m and 888.89 m) 1.000 of a time-step occurs. However, when the route begins to incline after this point there are more time-steps between each station. The number of time-steps along the sag curve increase along the curve. Then, when the route reaches the +6% incline the number of time-steps between the stations is constant and around 1.0020.

The number of time-steps that occur between the stations on the sections with a constant gradient would be expected to be the same. However, from Figure E.1 it is apparent that certain stations have a greater number of time-steps between them – this occurs consistently along the alignment. The reason for this is that the geometry report only outputs data to the nearest millimetre; hence, at every twelfth station the distance between that station and the subsequent station increases by 1mm due to rounding.

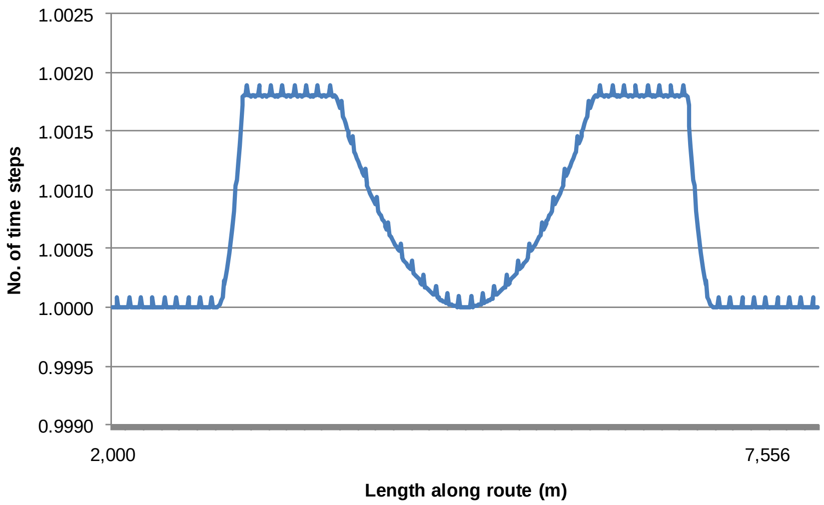


Figure E.1 Number of time steps along alignment

The hypothetical alignments use a constant speed (dependent on the vehicle speed under consideration), and therefore the acceleration was taken to be 0 m/s^2. The speed and acceleration data, in conjunction with the data from Inroads results in all of the data required to create the input file that is processed by the PHEM post-processor. An example of the input file for the +6% -6% alignment using a vehicle speed of 160 kph is given in Table E.2 and shown by the grey shaded area.

When the PHEM model runs it reads each line of data in the input files and looks up the speed and acceleration at each time-step on an engine map specific to the vehicle type and gradient case – the engine map then reports an emission rate (in mg) on the input file. The post-processed columns are appended to Table E.2 and are shown by the green shaded area.

The PHEM post-processor has been developed to read the first two lines of data to calculate the length of the time-step, and to assume that the remaining run of data uses the same time-step. This created an issue as the number of time-steps that occur between stations varies, as illustrated in Figure E.1. To address this issue the emissions have been amended by multiplying the emission by the number of time-steps that occur between the stations. The amended emissions have been appended to Table E.2 and are shown by the blue shaded area.

Type	Station	Northing	Easting	Elevation	Grade	No. of time-steps
S+O	0+00.00	9000	2000	200	0.00%	0
S+O	0+11.11	9000	2011.111	200	0.00%	1.000
S+O	0+22.22	9000	2022.222	200	0.00%	1.000
S+O	0+33.33	9000	2033.333	200	0.00%	1.000
S+O	0+44.44	9000	2044.444	200	0.00%	1.000
S+O	0+55.56	9000	2055.556	200	0.00%	1.000
S+O	0+66.67	9000	2066.667	200	0.00%	1.000
S+O	0+77.78	9000	2077.778	200	0.00%	1.000
S+O	0+88.89	9000	2088.889	200	0.00%	1.000
S+O	1+00.00	9000	2100	200	0.00%	1.000
S+O	1+11.11	9000	2111.111	200	0.00%	1.000
S+O	1+22.22	9000	2122.222	200	0.00%	1.000
S+O	1+33.33	9000	2133.333	200	0.00%	1.000
S+O	1+44.44	9000	2144.444	200	0.00%	1.000
S+O	1+55.56	9000	2155.556	200	0.00%	1.000
S+O	1+66.67	9000	2166.667	200	0.00%	1.000
S+O	1+77.78	9000	2177.778	200	0.00%	1.000
S+O	1+88.89	9000	2188.889	200	0.00%	1.000
S+O	2+00.00	9000	2200	200	0.00%	1.000
S+O	2+11.11	9000	2211.111	200	0.00%	1.000
S+O	2+22.22	9000	2222.222	200	0.00%	1.000
S+O	2+33.33	9000	2233.333	200	0.00%	1.000
S+O	2+44.44	9000	2244.444	200	0.00%	1.000
S+O	2+55.56	9000	2255.556	200	0.00%	1.000
S+O	2+66.67	9000	2266.667	200	0.00%	1.000
S+O	2+77.78	9000	2277.778	200	0.00%	1.000
S+O	2+88.89	9000	2288.889	200	0.00%	1.000
S+O	3+00.00	9000	2300	200	0.00%	1.000
S+O	3+11.11	9000	2311.111	200	0.00%	1.000
S+O	3+22.22	9000	2322.222	200	0.00%	1.000
S+O	3+33.33	9000	2333.333	200	0.00%	1.000
S+O	3+44.44	9000	2344.444	200	0.00%	1.000
S+O	3+55.56	9000	2355.556	200	0.00%	1.000
S+O	3+66.67	9000	2366.667	200	0.00%	1.000
S+O	3+77.78	9000	2377.778	200	0.00%	1.000
S+O	3+88.89	9000	2388.889	200	0.00%	1.000
S+O	4+00.00	9000	2400	200	0.00%	1.000
S+O	4+11.11	9000	2411.111	200	0.00%	1.000
S+O	4+22.22	9000	2422.222	200	0.00%	1.000
S+O	4+33.33	9000	2433.333	200	0.00%	1.000
S+O	4+44.44	9000	2444.444	200	0.00%	1.000
S+O	4+55.56	9000	2455.556	200	0.00%	1.000
S+O	4+66.67	9000	2466.667	200	0.00%	1.000
S+O	4+77.78	9000	2477.778	200	0.00%	1.000
S+O	4+88.89	9000	2488.889	200	0.00%	1.000
S+O	5+00.00	9000	2500	200	0.00%	1.000
S+O	5+11.11	9000	2511.111	200	0.00%	1.000
S+O	5+22.22	9000	2522.222	200	0.00%	1.000
S+O	5+33.33	9000	2533.333	200	0.00%	1.000
S+O	5+44.44	9000	2544.444	200	0.00%	1.000
S+O	5+55.56	9000	2555.556	200	0.00%	1.000
S+O	5+66.67	9000	2566.667	200	0.00%	1.000
S+O	5+77.78	9000	2577.778	200	0.00%	1.000
S+O	5+88.89	9000	2588.889	200	0.00%	1.000
S+O	6+00.00	9000	2600	200	0.00%	1.000
S+O	6+11.11	9000	2611.111	200	0.00%	1.000
S+O	6+22.22	9000	2622.222	200	0.00%	1.000
S+O	6+33.33	9000	2633.333	200	0.00%	1.000
S+O	6+44.44	9000	2644.444	200	0.00%	1.000
S+O	6+55.56	9000	2655.556	200	0.00%	1.000
S+O	6+66.67	9000	2666.667	200	0.00%	1.000
S+O	6+77.78	9000	2677.778	200	0.00%	1.000
S+O	6+88.89	9000	2688.889	200	0.00%	1.000
S+O	7+00.00	9000	2700	200	0.00%	1.000
S+O	7+11.11	9000	2711.111	200	0.00%	1.000
S+O	7+22.22	9000	2722.222	200	0.00%	1.000
S+O	7+33.33	9000	2733.333	200	0.00%	1.000
S+O	7+44.44	9000	2744.444	200	0.00%	1.000
S+O	7+55.56	9000	2755.556	200	0.00%	1.000
S+O	7+66.67	9000	2766.667	200	0.00%	1.000
S+O	7+77.78	9000	2777.778	200	0.00%	1.000
S+O	7+88.89	9000	2788.889	200	0.00%	1.000
S+O	8+00.00	9000	2800	200	0.00%	1.000
S+O	8+11.11	9000	2811.111	200	0.00%	1.000
S+O	8+22.22	9000	2822.222	200	0.00%	1.000
S+O	8+33.33	9000	2833.333	200	0.00%	1.000

Type	Station	Northing	Easting	Elevation	Grade	No. of time-steps
S+O	8+44.44	9000	2844.444	200	0.00%	1.000
S+O	8+55.56	9000	2855.556	200	0.00%	1.000
S+O	8+66.67	9000	2866.667	200	0.00%	1.000
S+O	8+77.78	9000	2877.778	200	0.00%	1.000
S+O	8+88.89	9000	2888.889	200	0.00%	1.000
S+O	9+00.00	9000	2900	200.016	0.30%	1.000
S+O	9+11.11	9000	2911.111	200.066	0.60%	1.000
S+O	9+22.22	9000	2922.222	200.149	0.90%	1.000
S+O	9+33.33	9000	2933.333	200.266	1.20%	1.000
S+O	9+44.44	9000	2944.444	200.415	1.50%	1.000
S+O	9+55.56	9000	2955.556	200.599	1.80%	1.000
S+O	9+66.67	9000	2966.667	200.815	2.10%	1.000
S+O	9+77.78	9000	2977.778	201.065	2.40%	1.000
S+O	9+88.89	9000	2988.889	201.348	2.70%	1.000
S+O	10+00.00	9000	3000	201.665	3.00%	1.000
S+O	10+11.11	9000	3011.111	202.015	3.30%	1.000
S+O	10+22.22	9000	3022.222	202.398	3.60%	1.001
S+O	10+33.33	9000	3033.333	202.815	3.90%	1.001
S+O	10+44.44	9000	3044.444	203.265	4.20%	1.001
S+O	10+55.56	9000	3055.556	203.749	4.50%	1.001
S+O	10+66.67	9000	3066.667	204.266	4.80%	1.001
S+O	10+77.78	9000	3077.778	204.816	5.10%	1.001
S+O	10+88.89	9000	3088.889	205.399	5.40%	1.001
S+O	11+00.00	9000	3100	206.016	5.70%	1.002
S+O	11+11.11	9000	3111.111	206.667	6.00%	1.002
S+O	11+22.22	9000	3122.222	207.333	6.00%	1.002
S+O	11+33.33	9000	3133.333	208	6.00%	1.002
S+O	11+44.44	9000	3144.444	208.667	6.00%	1.002
S+O	11+55.56	9000	3155.556	209.333	6.00%	1.002
S+O	11+66.67	9000	3166.667	210	6.00%	1.002
S+O	11+77.78	9000	3177.778	210.667	6.00%	1.002
S+O	11+88.89	9000	3188.889	211.333	6.00%	1.002
S+O	12+00.00	9000	3200	212	6.00%	1.002
S+O	12+11.11	9000	3211.111	212.667	6.00%	1.002
S+O	12+22.22	9000	3222.222	213.333	6.00%	1.002
S+O	12+33.33	9000	3233.333	214	6.00%	1.002
S+O	12+44.44	9000	3244.444	214.667	6.00%	1.002
S+O	12+55.56	9000	3255.556	215.333	6.00%	1.002
S+O	12+66.67	9000	3266.667	216	6.00%	1.002
S+O	12+77.78	9000	3277.778	216.667	6.00%	1.002
S+O	12+88.89	9000	3288.889	217.333	6.00%	1.002
S+O	13+00.00	9000	3300	218	6.00%	1.002
S+O	13+11.11	9000	3311.111	218.667	6.00%	1.002
S+O	13+22.22	9000	3322.222	219.333	6.00%	1.002
S+O	13+33.33	9000	3333.333	220	6.00%	1.002
S+O	13+44.44	9000	3344.444	220.667	6.00%	1.002
S+O	13+55.56	9000	3355.556	221.333	6.00%	1.002
S+O	13+66.67	9000	3366.667	222	6.00%	1.002
S+O	13+77.78	9000	3377.778	222.667	6.00%	1.002
S+O	13+88.89	9000	3388.889	223.333	6.00%	1.002
S+O	14+00.00	9000	3400	224	6.00%	1.002
S+O	14+11.11	9000	3411.111	224.667	6.00%	1.002
S+O	14+22.22	9000	3422.222	225.333	6.00%	1.002
S+O	14+33.33	9000	3433.333	226	6.00%	1.002
S+O	14+44.44	9000	3444.444	226.667	6.00%	1.002
S+O	14+55.56	9000	3455.556	227.333	6.00%	1.002
S+O	14+66.67	9000	3466.667	228	6.00%	1.002
S+O	14+77.78	9000	3477.778	228.667	6.00%	1.002
S+O	14+88.89	9000	3488.889	229.333	6.00%	1.002
S+O	15+00.00	9000	3500	230	6.00%	1.002
S+O	15+11.11	9000	3511.111	230.667	6.00%	1.002
S+O	15+22.22	9000	3522.222	231.333	6.00%	1.002
S+O	15+33.33	9000	3533.333	232	6.00%	1.002
S+O	15+44.44	9000	3544.444	232.667	6.00%	1.002
S+O	15+55.56	9000	3555.556	233.333	6.00%	1.002
S+O	15+66.67	9000	3566.667	234	6.00%	1.002
S+O	15+77.78	9000	3577.778	234.667	6.00%	1.002
S+O	15+88.89	9000	3588.889	235.333	6.00%	1.002
S+O	16+00.00	9000	3600	236	6.00%	1.002
S+O	16+11.11	9000	3611.111	236.667	6.00%	1.002
S+O	16+22.22	9000	3622.222	237.333	6.00%	1.002
S+O	16+33.33	9000	3633.333	238	6.00%	1.002
S+O	16+44.44	9000	3644.444	238.667	6.00%	1.002
S+O	16+55.56	9000	3655.556	239.333	6.00%	1.002
S+O	16+66.67	9000	3666.667	240	6.00%	1.002
S+O	16+77.78	9000	3677.778	240.667	6.00%	1.002

Type	Station	Northing	Easting	Elevation	Grade	No. of time-steps
S+O	16+88.89	9000	3688.889	241.333	6.00%	1.002
S+O	17+00.00	9000	3700	242	6.00%	1.002
S+O	17+11.11	9000	3711.111	242.667	6.00%	1.002
S+O	17+22.22	9000	3722.222	243.333	6.00%	1.002
S+O	17+33.33	9000	3733.333	244	6.00%	1.002
S+O	17+44.44	9000	3744.444	244.667	6.00%	1.002
S+O	17+55.56	9000	3755.556	245.333	6.00%	1.002
S+O	17+66.67	9000	3766.667	246	6.00%	1.002
S+O	17+77.78	9000	3777.778	246.667	6.00%	1.002
S+O	17+88.89	9000	3788.889	247.333	6.00%	1.002
S+O	18+00.00	9000	3800	248	6.00%	1.002
S+O	18+11.11	9000	3811.111	248.667	6.00%	1.002
S+O	18+22.22	9000	3822.222	249.333	6.00%	1.002
S+O	18+33.33	9000	3833.333	250	6.00%	1.002
S+O	18+44.44	9000	3844.444	250.667	6.00%	1.002
S+O	18+55.56	9000	3855.556	251.333	6.00%	1.002
S+O	18+66.67	9000	3866.667	252	6.00%	1.002
S+O	18+77.78	9000	3877.778	252.667	6.00%	1.002
S+O	18+88.89	9000	3888.889	253.333	6.00%	1.002
S+O	19+00.00	9000	3900	254	6.00%	1.002
S+O	19+11.11	9000	3911.111	254.666	5.98%	1.002
S+O	19+22.22	9000	3922.222	255.328	5.92%	1.002
S+O	19+33.33	9000	3933.333	255.982	5.86%	1.002
S+O	19+44.44	9000	3944.444	256.63	5.80%	1.002
S+O	19+55.56	9000	3955.556	257.271	5.74%	1.002
S+O	19+66.67	9000	3966.667	257.905	5.68%	1.002
S+O	19+77.78	9000	3977.778	258.533	5.62%	1.002
S+O	19+88.89	9000	3988.889	259.154	5.56%	1.002
S+O	20+00.00	9000	4000	259.767	5.50%	1.002
S+O	20+11.11	9000	4011.111	260.375	5.43%	1.001
S+O	20+22.22	9000	4022.222	260.975	5.37%	1.001
S+O	20+33.33	9000	4033.333	261.568	5.31%	1.001
S+O	20+44.44	9000	4044.444	262.155	5.25%	1.001
S+O	20+55.56	9000	4055.556	262.735	5.19%	1.001
S+O	20+66.67	9000	4066.667	263.308	5.13%	1.001
S+O	20+77.78	9000	4077.778	263.875	5.07%	1.001
S+O	20+88.89	9000	4088.889	264.434	5.01%	1.001
S+O	21+00.00	9000	4100	264.987	4.95%	1.001
S+O	21+11.11	9000	4111.111	265.533	4.88%	1.001
S+O	21+22.22	9000	4122.222	266.073	4.82%	1.001
S+O	21+33.33	9000	4133.333	266.605	4.76%	1.001
S+O	21+44.44	9000	4144.444	267.131	4.70%	1.001
S+O	21+55.56	9000	4155.556	267.65	4.64%	1.001
S+O	21+66.67	9000	4166.667	268.162	4.58%	1.001
S+O	21+77.78	9000	4177.778	268.667	4.52%	1.001
S+O	21+88.89	9000	4188.889	269.166	4.46%	1.001
S+O	22+00.00	9000	4200	269.658	4.40%	1.001
S+O	22+11.11	9000	4211.111	270.143	4.34%	1.001
S+O	22+22.22	9000	4222.222	270.621	4.27%	1.001
S+O	22+33.33	9000	4233.333	271.092	4.21%	1.001
S+O	22+44.44	9000	4244.444	271.557	4.15%	1.001
S+O	22+55.56	9000	4255.556	272.015	4.09%	1.001
S+O	22+66.67	9000	4266.667	272.466	4.03%	1.001
S+O	22+77.78	9000	4277.778	272.91	3.97%	1.001
S+O	22+88.89	9000	4288.889	273.348	3.91%	1.001
S+O	23+00.00	9000	4300	273.778	3.85%	1.001
S+O	23+11.11	9000	4311.111	274.202	3.79%	1.001
S+O	23+22.22	9000	4322.222	274.62	3.72%	1.001
S+O	23+33.33	9000	4333.333	275.03	3.66%	1.001
S+O	23+44.44	9000	4344.444	275.434	3.60%	1.001
S+O	23+55.56	9000	4355.556	275.83	3.54%	1.001
S+O	23+66.67	9000	4366.667	276.22	3.48%	1.001
S+O	23+77.78	9000	4377.778	276.604	3.42%	1.001
S+O	23+88.89	9000	4388.889	276.98	3.36%	1.001
S+O	24+00.00	9000	4400	277.35	3.30%	1.001
S+O	24+11.11	9000	4411.111	277.713	3.24%	1.001
S+O	24+22.22	9000	4422.222	278.069	3.18%	1.001
S+O	24+33.33	9000	4433.333	278.418	3.11%	1.000
S+O	24+44.44	9000	4444.444	278.761	3.05%	1.000
S+O	24+55.56	9000	4455.556	279.097	2.99%	1.001
S+O	24+66.67	9000	4466.667	279.426	2.93%	1.000
S+O	24+77.78	9000	4477.778	279.748	2.87%	1.000
S+O	24+88.89	9000	4488.889	280.063	2.81%	1.000
S+O	25+00.00	9000	4500	280.372	2.75%	1.000
S+O	25+11.11	9000	4511.111	280.674	2.69%	1.000
S+O	25+22.22	9000	4522.222	280.969	2.63%	1.000

Type	Station	Northing	Easting	Elevation	Grade	No. of time-steps
S+O	25+33.33	9000	4533.333	281.257	2.56%	1.000
S+O	25+44.44	9000	4544.444	281.539	2.50%	1.000
S+O	25+55.56	9000	4555.556	281.813	2.44%	1.000
S+O	25+66.67	9000	4566.667	282.081	2.38%	1.000
S+O	25+77.78	9000	4577.778	282.342	2.32%	1.000
S+O	25+88.89	9000	4588.889	282.597	2.26%	1.000
S+O	26+00.00	9000	4600	282.844	2.20%	1.000
S+O	26+11.11	9000	4611.111	283.085	2.14%	1.000
S+O	26+22.22	9000	4622.222	283.319	2.08%	1.000
S+O	26+33.33	9000	4633.333	283.546	2.02%	1.000
S+O	26+44.44	9000	4644.444	283.767	1.95%	1.000
S+O	26+55.56	9000	4655.556	283.981	1.89%	1.000
S+O	26+66.67	9000	4666.667	284.187	1.83%	1.000
S+O	26+77.78	9000	4677.778	284.388	1.77%	1.000
S+O	26+88.89	9000	4688.889	284.581	1.71%	1.000
S+O	27+00.00	9000	4700	284.767	1.65%	1.000
S+O	27+11.11	9000	4711.111	284.947	1.59%	1.000
S+O	27+22.22	9000	4722.222	285.12	1.53%	1.000
S+O	27+33.33	9000	4733.333	285.286	1.47%	1.000
S+O	27+44.44	9000	4744.444	285.446	1.40%	1.000
S+O	27+55.56	9000	4755.556	285.598	1.34%	1.000
S+O	27+66.67	9000	4766.667	285.744	1.28%	1.000
S+O	27+77.78	9000	4777.778	285.883	1.22%	1.000
S+O	27+88.89	9000	4788.889	286.016	1.16%	1.000
S+O	28+00.00	9000	4800	286.141	1.10%	1.000
S+O	28+11.11	9000	4811.111	286.26	1.04%	1.000
S+O	28+22.22	9000	4822.222	286.372	0.98%	1.000
S+O	28+33.33	9000	4833.333	286.477	0.92%	1.000
S+O	28+44.44	9000	4844.444	286.575	0.86%	1.000
S+O	28+55.56	9000	4855.556	286.667	0.79%	1.000
S+O	28+66.67	9000	4866.667	286.752	0.73%	1.000
S+O	28+77.78	9000	4877.778	286.83	0.67%	1.000
S+O	28+88.89	9000	4888.889	286.901	0.61%	1.000
S+O	29+00.00	9000	4900	286.965	0.55%	1.000
S+O	29+11.11	9000	4911.111	287.023	0.49%	1.000
S+O	29+22.22	9000	4922.222	287.074	0.43%	1.000
S+O	29+33.33	9000	4933.333	287.118	0.37%	1.000
S+O	29+44.44	9000	4944.444	287.155	0.31%	1.000
S+O	29+55.56	9000	4955.556	287.186	0.24%	1.000
S+O	29+66.67	9000	4966.667	287.209	0.18%	1.000
S+O	29+77.78	9000	4977.778	287.226	0.12%	1.000
S+O	29+88.89	9000	4988.889	287.237	0.06%	1.000
S+O	30+00.00	9000	5000	287.24	0.00%	1.000
S+O	30+11.11	9000	5011.111	287.237	-0.06%	1.000
S+O	30+22.22	9000	5022.222	287.226	-0.12%	1.000
S+O	30+33.33	9000	5033.333	287.209	-0.18%	1.000
S+O	30+44.44	9000	5044.444	287.186	-0.24%	1.000
S+O	30+55.56	9000	5055.556	287.155	-0.31%	1.000
S+O	30+66.67	9000	5066.667	287.118	-0.37%	1.000
S+O	30+77.78	9000	5077.778	287.074	-0.43%	1.000
S+O	30+88.89	9000	5088.889	287.023	-0.49%	1.000
S+O	31+00.00	9000	5100	286.965	-0.55%	1.000
S+O	31+11.11	9000	5111.111	286.901	-0.61%	1.000
S+O	31+22.22	9000	5122.222	286.83	-0.67%	1.000
S+O	31+33.33	9000	5133.333	286.752	-0.73%	1.000
S+O	31+44.44	9000	5144.444	286.667	-0.79%	1.000
S+O	31+55.56	9000	5155.556	286.575	-0.86%	1.000
S+O	31+66.67	9000	5166.667	286.477	-0.92%	1.000
S+O	31+77.78	9000	5177.778	286.372	-0.98%	1.000
S+O	31+88.89	9000	5188.889	286.26	-1.04%	1.000
S+O	32+00.00	9000	5200	286.141	-1.10%	1.000
S+O	32+11.11	9000	5211.111	286.016	-1.16%	1.000
S+O	32+22.22	9000	5222.222	285.883	-1.22%	1.000
S+O	32+33.33	9000	5233.333	285.744	-1.28%	1.000
S+O	32+44.44	9000	5244.444	285.598	-1.34%	1.000
S+O	32+55.56	9000	5255.556	285.446	-1.40%	1.000
S+O	32+66.67	9000	5266.667	285.286	-1.47%	1.000
S+O	32+77.78	9000	5277.778	285.12	-1.53%	1.000
S+O	32+88.89	9000	5288.889	284.947	-1.59%	1.000
S+O	33+00.00	9000	5300	284.767	-1.65%	1.000
S+O	33+11.11	9000	5311.111	284.581	-1.71%	1.000
S+O	33+22.22	9000	5322.222	284.388	-1.77%	1.000
S+O	33+33.33	9000	5333.333	284.187	-1.83%	1.000
S+O	33+44.44	9000	5344.444	283.981	-1.89%	1.000
S+O	33+55.56	9000	5355.556	283.767	-1.95%	1.000
S+O	33+66.67	9000	5366.667	283.546	-2.02%	1.000

Type	Station	Northing	Easting	Elevation	Grade	No. of time-steps
S+O	33+77.78	9000	5377.778	283.319	-2.08%	1.000
S+O	33+88.89	9000	5388.889	283.085	-2.14%	1.000
S+O	34+00.00	9000	5400	282.844	-2.20%	1.000
S+O	34+11.11	9000	5411.111	282.597	-2.26%	1.000
S+O	34+22.22	9000	5422.222	282.342	-2.32%	1.000
S+O	34+33.33	9000	5433.333	282.081	-2.38%	1.000
S+O	34+44.44	9000	5444.444	281.813	-2.44%	1.000
S+O	34+55.56	9000	5455.556	281.539	-2.50%	1.000
S+O	34+66.67	9000	5466.667	281.257	-2.56%	1.000
S+O	34+77.78	9000	5477.778	280.969	-2.63%	1.000
S+O	34+88.89	9000	5488.889	280.674	-2.69%	1.000
S+O	35+00.00	9000	5500	280.372	-2.75%	1.000
S+O	35+11.11	9000	5511.111	280.063	-2.81%	1.000
S+O	35+22.22	9000	5522.222	279.748	-2.87%	1.000
S+O	35+33.33	9000	5533.333	279.426	-2.93%	1.000
S+O	35+44.44	9000	5544.444	279.097	-2.99%	1.000
S+O	35+55.56	9000	5555.556	278.761	-3.05%	1.001
S+O	35+66.67	9000	5566.667	278.418	-3.11%	1.000
S+O	35+77.78	9000	5577.778	278.069	-3.18%	1.000
S+O	35+88.89	9000	5588.889	277.713	-3.24%	1.001
S+O	36+00.00	9000	5600	277.35	-3.30%	1.001
S+O	36+11.11	9000	5611.111	276.98	-3.36%	1.001
S+O	36+22.22	9000	5622.222	276.604	-3.42%	1.001
S+O	36+33.33	9000	5633.333	276.22	-3.48%	1.001
S+O	36+44.44	9000	5644.444	275.83	-3.54%	1.001
S+O	36+55.56	9000	5655.556	275.434	-3.60%	1.001
S+O	36+66.67	9000	5666.667	275.03	-3.66%	1.001
S+O	36+77.78	9000	5677.778	274.62	-3.72%	1.001
S+O	36+88.89	9000	5688.889	274.202	-3.79%	1.001
S+O	37+00.00	9000	5700	273.778	-3.85%	1.001
S+O	37+11.11	9000	5711.111	273.348	-3.91%	1.001
S+O	37+22.22	9000	5722.222	272.91	-3.97%	1.001
S+O	37+33.33	9000	5733.333	272.466	-4.03%	1.001
S+O	37+44.44	9000	5744.444	272.015	-4.09%	1.001
S+O	37+55.56	9000	5755.556	271.557	-4.15%	1.001
S+O	37+66.67	9000	5766.667	271.092	-4.21%	1.001
S+O	37+77.78	9000	5777.778	270.621	-4.27%	1.001
S+O	37+88.89	9000	5788.889	270.143	-4.34%	1.001
S+O	38+00.00	9000	5800	269.658	-4.40%	1.001
S+O	38+11.11	9000	5811.111	269.166	-4.46%	1.001
S+O	38+22.22	9000	5822.222	268.667	-4.52%	1.001
S+O	38+33.33	9000	5833.333	268.162	-4.58%	1.001
S+O	38+44.44	9000	5844.444	267.65	-4.64%	1.001
S+O	38+55.56	9000	5855.556	267.131	-4.70%	1.001
S+O	38+66.67	9000	5866.667	266.605	-4.76%	1.001
S+O	38+77.78	9000	5877.778	266.073	-4.82%	1.001
S+O	38+88.89	9000	5888.889	265.533	-4.88%	1.001
S+O	39+00.00	9000	5900	264.987	-4.95%	1.001
S+O	39+11.11	9000	5911.111	264.434	-5.01%	1.001
S+O	39+22.22	9000	5922.222	263.875	-5.07%	1.001
S+O	39+33.33	9000	5933.333	263.308	-5.13%	1.001
S+O	39+44.44	9000	5944.444	262.735	-5.19%	1.001
S+O	39+55.56	9000	5955.556	262.155	-5.25%	1.001
S+O	39+66.67	9000	5966.667	261.568	-5.31%	1.001
S+O	39+77.78	9000	5977.778	260.975	-5.37%	1.001
S+O	39+88.89	9000	5988.889	260.375	-5.43%	1.001
S+O	40+00.00	9000	6000	259.767	-5.50%	1.001
S+O	40+11.11	9000	6011.111	259.154	-5.56%	1.002
S+O	40+22.22	9000	6022.222	258.533	-5.62%	1.002
S+O	40+33.33	9000	6033.333	257.905	-5.68%	1.002
S+O	40+44.44	9000	6044.444	257.271	-5.74%	1.002
S+O	40+55.56	9000	6055.556	256.63	-5.80%	1.002
S+O	40+66.67	9000	6066.667	255.982	-5.86%	1.002
S+O	40+77.78	9000	6077.778	255.328	-5.92%	1.002
S+O	40+88.89	9000	6088.889	254.666	-5.98%	1.002
S+O	41+00.00	9000	6100	254	-6.00%	1.002
S+O	41+11.11	9000	6111.111	253.333	-6.00%	1.002
S+O	41+22.22	9000	6122.222	252.667	-6.00%	1.002
S+O	41+33.33	9000	6133.333	252	-6.00%	1.002
S+O	41+44.44	9000	6144.444	251.333	-6.00%	1.002
S+O	41+55.56	9000	6155.556	250.667	-6.00%	1.002
S+O	41+66.67	9000	6166.667	250	-6.00%	1.002
S+O	41+77.78	9000	6177.778	249.333	-6.00%	1.002
S+O	41+88.89	9000	6188.889	248.667	-6.00%	1.002
S+O	42+00.00	9000	6200	248	-6.00%	1.002
S+O	42+11.11	9000	6211.111	247.333	-6.00%	1.002

Type	Station	Northing	Easting	Elevation	Grade	No. of time-steps
S+O	42+22.22	9000	6222.222	246.667	-6.00%	1.002
S+O	42+33.33	9000	6233.333	246	-6.00%	1.002
S+O	42+44.44	9000	6244.444	245.333	-6.00%	1.002
S+O	42+55.56	9000	6255.556	244.667	-6.00%	1.002
S+O	42+66.67	9000	6266.667	244	-6.00%	1.002
S+O	42+77.78	9000	6277.778	243.333	-6.00%	1.002
S+O	42+88.89	9000	6288.889	242.667	-6.00%	1.002
S+O	43+00.00	9000	6300	242	-6.00%	1.002
S+O	43+11.11	9000	6311.111	241.333	-6.00%	1.002
S+O	43+22.22	9000	6322.222	240.667	-6.00%	1.002
S+O	43+33.33	9000	6333.333	240	-6.00%	1.002
S+O	43+44.44	9000	6344.444	239.333	-6.00%	1.002
S+O	43+55.56	9000	6355.556	238.667	-6.00%	1.002
S+O	43+66.67	9000	6366.667	238	-6.00%	1.002
S+O	43+77.78	9000	6377.778	237.333	-6.00%	1.002
S+O	43+88.89	9000	6388.889	236.667	-6.00%	1.002
S+O	44+00.00	9000	6400	236	-6.00%	1.002
S+O	44+11.11	9000	6411.111	235.333	-6.00%	1.002
S+O	44+22.22	9000	6422.222	234.667	-6.00%	1.002
S+O	44+33.33	9000	6433.333	234	-6.00%	1.002
S+O	44+44.44	9000	6444.444	233.333	-6.00%	1.002
S+O	44+55.56	9000	6455.556	232.667	-6.00%	1.002
S+O	44+66.67	9000	6466.667	232	-6.00%	1.002
S+O	44+77.78	9000	6477.778	231.333	-6.00%	1.002
S+O	44+88.89	9000	6488.889	230.667	-6.00%	1.002
S+O	45+00.00	9000	6500	230	-6.00%	1.002
S+O	45+11.11	9000	6511.111	229.333	-6.00%	1.002
S+O	45+22.22	9000	6522.222	228.667	-6.00%	1.002
S+O	45+33.33	9000	6533.333	228	-6.00%	1.002
S+O	45+44.44	9000	6544.444	227.333	-6.00%	1.002
S+O	45+55.56	9000	6555.556	226.667	-6.00%	1.002
S+O	45+66.67	9000	6566.667	226	-6.00%	1.002
S+O	45+77.78	9000	6577.778	225.333	-6.00%	1.002
S+O	45+88.89	9000	6588.889	224.667	-6.00%	1.002
S+O	46+00.00	9000	6600	224	-6.00%	1.002
S+O	46+11.11	9000	6611.111	223.333	-6.00%	1.002
S+O	46+22.22	9000	6622.222	222.667	-6.00%	1.002
S+O	46+33.33	9000	6633.333	222	-6.00%	1.002
S+O	46+44.44	9000	6644.444	221.333	-6.00%	1.002
S+O	46+55.56	9000	6655.556	220.667	-6.00%	1.002
S+O	46+66.67	9000	6666.667	220	-6.00%	1.002
S+O	46+77.78	9000	6677.778	219.333	-6.00%	1.002
S+O	46+88.89	9000	6688.889	218.667	-6.00%	1.002
S+O	47+00.00	9000	6700	218	-6.00%	1.002
S+O	47+11.11	9000	6711.111	217.333	-6.00%	1.002
S+O	47+22.22	9000	6722.222	216.667	-6.00%	1.002
S+O	47+33.33	9000	6733.333	216	-6.00%	1.002
S+O	47+44.44	9000	6744.444	215.333	-6.00%	1.002
S+O	47+55.56	9000	6755.556	214.667	-6.00%	1.002
S+O	47+66.67	9000	6766.667	214	-6.00%	1.002
S+O	47+77.78	9000	6777.778	213.333	-6.00%	1.002
S+O	47+88.89	9000	6788.889	212.667	-6.00%	1.002
S+O	48+00.00	9000	6800	212	-6.00%	1.002
S+O	48+11.11	9000	6811.111	211.333	-6.00%	1.002
S+O	48+22.22	9000	6822.222	210.667	-6.00%	1.002
S+O	48+33.33	9000	6833.333	210	-6.00%	1.002
S+O	48+44.44	9000	6844.444	209.333	-6.00%	1.002
S+O	48+55.56	9000	6855.556	208.667	-6.00%	1.002
S+O	48+66.67	9000	6866.667	208	-6.00%	1.002
S+O	48+77.78	9000	6877.778	207.333	-6.00%	1.002
S+O	48+88.89	9000	6888.889	206.667	-6.00%	1.002
S+O	49+00.00	9000	6900	206.016	-5.70%	1.002
S+O	49+11.11	9000	6911.111	205.399	-5.40%	1.002
S+O	49+22.22	9000	6922.222	204.816	-5.10%	1.001
S+O	49+33.33	9000	6933.333	204.266	-4.80%	1.001
S+O	49+44.44	9000	6944.444	203.749	-4.50%	1.001
S+O	49+55.56	9000	6955.556	203.265	-4.20%	1.001
S+O	49+66.67	9000	6966.667	202.815	-3.90%	1.001
S+O	49+77.78	9000	6977.778	202.398	-3.60%	1.001
S+O	49+88.89	9000	6988.889	202.015	-3.30%	1.001
S+O	50+00.00	9000	7000	201.665	-3.00%	1.000
S+O	50+11.11	9000	7011.111	201.348	-2.70%	1.000
S+O	50+22.22	9000	7022.222	201.065	-2.40%	1.000
S+O	50+33.33	9000	7033.333	200.815	-2.10%	1.000
S+O	50+44.44	9000	7044.444	200.599	-1.80%	1.000
S+O	50+55.56	9000	7055.556	200.415	-1.50%	1.000

Type	Station	Northing	Easting	Elevation	Grade	No. of time-steps
S+O	50+66.67	9000	7066.667	200.266	-1.20%	1.000
S+O	50+77.78	9000	7077.778	200.149	-0.90%	1.000
S+O	50+88.89	9000	7088.889	200.066	-0.60%	1.000
S+O	51+00.00	9000	7100	200.016	-0.30%	1.000
S+O	51+11.11	9000	7111.111	200	0.00%	1.000
S+O	51+22.22	9000	7122.222	200	0.00%	1.000
S+O	51+33.33	9000	7133.333	200	0.00%	1.000
S+O	51+44.44	9000	7144.444	200	0.00%	1.000
S+O	51+55.56	9000	7155.556	200	0.00%	1.000
S+O	51+66.67	9000	7166.667	200	0.00%	1.000
S+O	51+77.78	9000	7177.778	200	0.00%	1.000
S+O	51+88.89	9000	7188.889	200	0.00%	1.000
S+O	52+00.00	9000	7200	200	0.00%	1.000
S+O	52+11.11	9000	7211.111	200	0.00%	1.000
S+O	52+22.22	9000	7222.222	200	0.00%	1.000
S+O	52+33.33	9000	7233.333	200	0.00%	1.000
S+O	52+44.44	9000	7244.444	200	0.00%	1.000
S+O	52+55.56	9000	7255.556	200	0.00%	1.000
S+O	52+66.67	9000	7266.667	200	0.00%	1.000
S+O	52+77.78	9000	7277.778	200	0.00%	1.000
S+O	52+88.89	9000	7288.889	200	0.00%	1.000
S+O	53+00.00	9000	7300	200	0.00%	1.000
S+O	53+11.11	9000	7311.111	200	0.00%	1.000
S+O	53+22.22	9000	7322.222	200	0.00%	1.000
S+O	53+33.33	9000	7333.333	200	0.00%	1.000
S+O	53+44.44	9000	7344.444	200	0.00%	1.000
S+O	53+55.56	9000	7355.556	200	0.00%	1.000
S+O	53+66.67	9000	7366.667	200	0.00%	1.000
S+O	53+77.78	9000	7377.778	200	0.00%	1.000
S+O	53+88.89	9000	7388.889	200	0.00%	1.000
S+O	54+00.00	9000	7400	200	0.00%	1.000
S+O	54+11.11	9000	7411.111	200	0.00%	1.000
S+O	54+22.22	9000	7422.222	200	0.00%	1.000
S+O	54+33.33	9000	7433.333	200	0.00%	1.000
S+O	54+44.44	9000	7444.444	200	0.00%	1.000
S+O	54+55.56	9000	7455.556	200	0.00%	1.000
S+O	54+66.67	9000	7466.667	200	0.00%	1.000
S+O	54+77.78	9000	7477.778	200	0.00%	1.000
S+O	54+88.89	9000	7488.889	200	0.00%	1.000
S+O	55+00.00	9000	7500	200	0.00%	1.000
S+O	55+11.11	9000	7511.111	200	0.00%	1.000
S+O	55+22.22	9000	7522.222	200	0.00%	1.000
S+O	55+33.33	9000	7533.333	200	0.00%	1.000
S+O	55+44.44	9000	7544.444	200	0.00%	1.000
S+O	55+55.56	9000	7555.556	200	0.00%	1.000
S+O	55+66.67	9000	7566.667	200	0.00%	1.000
S+O	55+77.78	9000	7577.778	200	0.00%	1.000
S+O	55+88.89	9000	7588.889	200	0.00%	1.000
S+O	56+00.00	9000	7600	200	0.00%	1.000
S+O	56+11.11	9000	7611.111	200	0.00%	1.000
S+O	56+22.22	9000	7622.222	200	0.00%	1.000
S+O	56+33.33	9000	7633.333	200	0.00%	1.000
S+O	56+44.44	9000	7644.444	200	0.00%	1.000
S+O	56+55.56	9000	7655.556	200	0.00%	1.000
S+O	56+66.67	9000	7666.667	200	0.00%	1.000
S+O	56+77.78	9000	7677.778	200	0.00%	1.000
S+O	56+88.89	9000	7688.889	200	0.00%	1.000
S+O	57+00.00	9000	7700	200	0.00%	1.000
S+O	57+11.11	9000	7711.111	200	0.00%	1.000
S+O	57+22.22	9000	7722.222	200	0.00%	1.000
S+O	57+33.33	9000	7733.333	200	0.00%	1.000
S+O	57+44.44	9000	7744.444	200	0.00%	1.000
S+O	57+55.56	9000	7755.556	200	0.00%	1.000
S+O	57+66.67	9000	7766.667	200	0.00%	1.000
S+O	57+77.78	9000	7777.778	200	0.00%	1.000
S+O	57+88.89	9000	7788.889	200	0.00%	1.000
S+O	58+00.00	9000	7800	200	0.00%	1.000
S+O	58+11.11	9000	7811.111	200	0.00%	1.000
S+O	58+22.22	9000	7822.222	200	0.00%	1.000
S+O	58+33.33	9000	7833.333	200	0.00%	1.000
S+O	58+44.44	9000	7844.444	200	0.00%	1.000
S+O	58+55.56	9000	7855.556	200	0.00%	1.000
S+O	58+66.67	9000	7866.667	200	0.00%	1.000
S+O	58+77.78	9000	7877.778	200	0.00%	1.000
S+O	58+88.89	9000	7888.889	200	0.00%	1.000
S+O	59+00.00	9000	7900	200	0.00%	1.000

Type	Station	Northing	Easting	Elevation	Grade	No. of time-steps
S+O	59+11.11	9000	7911.111	200	0.00%	1.000
S+O	59+22.22	9000	7922.222	200	0.00%	1.000
S+O	59+33.33	9000	7933.333	200	0.00%	1.000
S+O	59+44.44	9000	7944.444	200	0.00%	1.000
S+O	59+55.56	9000	7955.556	200	0.00%	1.000
S+O	59+66.67	9000	7966.667	200	0.00%	1.000
S+O	59+77.78	9000	7977.778	200	0.00%	1.000
S+O	59+88.89	9000	7988.889	200	0.00%	1.000
S+O	60+00.00	9000	8000	200	0.00%	1.000

Table E.1 Example of Inroads geometry report for +6% -6% alignment and vehicle speed of 160 kph

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
0	1	0	1	1	1	9000	2000	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61				
1	1	0	1	1	1	9000	2011.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
2	1	0	1	1	1	9000	2022.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
3	1	0	1	1	1	9000	2033.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
4	1	0	1	1	1	9000	2044.444	200	90	0	0	0	99.41939	0	0	0	**0**	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
5.00009	1	0	1	1	1	9000	2055.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
6.00009	1	0	1	1	1	9000	2066.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
7.00009	1	0	1	1	1	9000	2077.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
8.00009	1	0	1	1	1	9000	2088.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
9.00009	1	0	1	1	1	9000	2100	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
10.00009	1	0	1	1	1	9000	2111.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
11.00009	1	0	1	1	1	9000	2122.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
12.00009	1	0	1	1	1	9000	2133.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
13.00009	1	0	1	1	1	9000	2144.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
14.00018	1	0	1	1	1	9000	2155.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
15.00018	1	0	1	1	1	9000	2166.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
16.00018	1	0	1	1	1	9000	2177.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
17.00018	1	0	1	1	1	9000	2188.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
18.00018	1	0	1	1	1	9000	2200	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
19.00018	1	0	1	1	1	9000	2211.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
20.00018	1	0	1	1	1	9000	2222.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
21.00018	1	0	1	1	1	9000	2233.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
22.00018	1	0	1	1	1	9000	2244.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
23.00027	1	0	1	1	1	9000	2255.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
24.00027	1	0	1	1	1	9000	2266.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
25.00027	1	0	1	1	1	9000	2277.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
26.00027	1	0	1	1	1	9000	2288.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
27.00027	1	0	1	1	1	9000	2300	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
28.00027	1	0	1	1	1	9000	2311.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
29.00027	1	0	1	1	1	9000	2322.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
30.00027	1	0	1	1	1	9000	2333.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
31.00027	1	0	1	1	1	9000	2344.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
32.00036	1	0	1	1	1	9000	2355.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
33.00036	1	0	1	1	1	9000	2366.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
34.00036	1	0	1	1	1	9000	2377.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
35.00036	1	0	1	1	1	9000	2388.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
36.00036	1	0	1	1	1	9000	2400	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
37.00036	1	0	1	1	1	9000	2411.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
38.00036	1	0	1	1	1	9000	2422.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
39.00036	1	0	1	1	1	9000	2433.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
40.00036	1	0	1	1	1	9000	2444.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
41.00045	1	0	1	1	1	9000	2455.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
42.00045	1	0	1	1	1	9000	2466.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
43.00045	1	0	1	1	1	9000	2477.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
44.00045	1	0	1	1	1	9000	2488.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
45.00045	1	0	1	1	1	9000	2500	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
46.00045	1	0	1	1	1	9000	2511.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
47.00045	1	0	1	1	1	9000	2522.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
48.00045	1	0	1	1	1	9000	2533.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
49.00045	1	0	1	1	1	9000	2544.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
50.00054	1	0	1	1	1	9000	2555.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
51.00054	1	0	1	1	1	9000	2566.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
52.00054	1	0	1	1	1	9000	2577.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
53.00054	1	0	1	1	1	9000	2588.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
54.00054	1	0	1	1	1	9000	2600	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
55.00054	1	0	1	1	1	9000	2611.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
56.00054	1	0	1	1	1	9000	2622.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
57.00054	1	0	1	1	1	9000	2633.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
58.00054	1	0	1	1	1	9000	2644.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
59.00063	1	0	1	1	1	9000	2655.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
60.00063	1	0	1	1	1	9000	2666.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
61.00063	1	0	1	1	1	9000	2677.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
62.00063	1	0	1	1	1	9000	2688.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
63.00063	1	0	1	1	1	9000	2700	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
64.00063	1	0	1	1	1	9000	2711.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
65.00063	1	0	1	1	1	9000	2722.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
66.00063	1	0	1	1	1	9000	2733.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
67.00063	1	0	1	1	1	9000	2744.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
68.00072	1	0	1	1	1	9000	2755.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
69.00072	1	0	1	1	1	9000	2766.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
70.00072	1	0	1	1	1	9000	2777.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
71.00072	1	0	1	1	1	9000	2788.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
72.00072	1	0	1	1	1	9000	2800	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
73.00072	1	0	1	1	1	9000	2811.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
74.00072	1	0	1	1	1	9000	2822.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
75.00072	1	0	1	1	1	9000	2833.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
76.00072	1	0	1	1	1	9000	2844.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
77.00081	1	0	1	1	1	9000	2855.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
78.00081	1	0	1	1	1	9000	2866.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
79.00081	1	0	1	1	1	9000	2877.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
80.00081	1	0	1	1	1	9000	2888.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
81.00081	1	0	1	1	1	9000	2900	200.016	90	0.082507	0.297	0	99.41939	0	0	0	0	0	0.1074	0.1582	3059.67		0.1180	0.1593	3026.61
82.00082	1	0	1	1	1	9000	2911.111	200.066	90	0.257832	0.598	0	99.41939	0	0	0	0	0	0.0966	0.1570	3093.18		0.1074	0.1582	3059.70
83.00085	1	0	1	1	1	9000	2922.222	200.149	90	0.427996	0.898	0	99.41939	0	0	0	0	0	0.0858	0.1559	3126.58		0.0966	0.1570	3093.27
84.0009	1	0	1	1	1	9000	2933.333	200.266	90	0.603308	1.198	0	99.41939	0	0	0	0	0	0.0750	0.1547	3159.97		0.0858	0.1559	3126.75
85.00099	1	0	1	1	1	9000	2944.444	200.415	90	0.768298	1.499	0	99.41939	0	0	0	0	0	0.0642	0.1536	3193.48		0.0750	0.1547	3160.25
86.00122	1	0	1	1	1	9000	2955.556	200.599	90	0.948656	1.799	0	99.41939	0	0	0	0	0	0.0535	0.1524	3226.88		0.0642	0.1536	3194.21
87.00141	1	0	1	1	1	9000	2966.667	200.815	90	1.113701	2.099	0	99.41939	0	0	0	0	0	0.0462	0.1521	3248.71		0.0535	0.1524	3227.49
88.00166	1	0	1	1	1	9000	2977.778	201.065	90	1.28895	2.399	0	99.41939	0	0	0	0	0	0.0462	0.1534	3247.07		0.0463	0.1521	3249.53
89.00199	1	0	1	1	1	9000	2988.889	201.348	90	1.459023	2.7	0	99.41939	0	0	0	0	0	0.0463	0.1547	3245.42		0.0463	0.1535	3248.12
90.00239	1	0	1	1	1	9000	3000	201.665	90	1.634222	3	0	99.41939	0	0	0	0	0	0.0463	0.1561	3243.78		0.0463	0.1548	3246.74
91.00289	1	0	1	1	1	9000	3011.111	202.015	90	1.804238	3.3	0	99.41939	0	0	0	0	0	0.0463	0.1574	3242.14		0.0463	0.1562	3245.39
92.00348	1	0	1	1	1	9000	3022.222	202.398	90	1.974224	3.601	0	99.41939	0	0	0	0	0	0.0463	0.1588	3240.5		0.0463	0.1575	3244.07
93.00419	1	0	1	1	1	9000	3033.333	202.815	90	2.149323	3.901	0	99.41939	0	0	0	0	0	0.0463	0.1601	3238.86		0.0463	0.1589	3242.78
94.00501	1	0	1	1	1	9000	3044.444	203.265	90	2.319235	4.201	0	99.41939	0	0	0	0	0	0.0473	0.1612	3248.28		0.0463	0.1602	3241.52
95.00605	1	0	1	1	1	9000	3055.556	203.749	90	2.494028	4.502	0	99.41939	0	0	0	0	0	0.0490	0.1621	3263.2		0.0474	0.1614	3251.65
96.00713	1	0	1	1	1	9000	3066.667	204.266	90	2.664078	4.802	0	99.41939	0	0	0	0	0	0.0506	0.1631	3278.07		0.0490	0.1623	3266.73
97.00835	1	0	1	1	1	9000	3077.778	204.816	90	2.833856	5.102	0	99.41939	0	0	0	0	0	0.0522	0.1640	3292.94		0.0506	0.1633	3282.08
98.00973	1	0	1	1	1	9000	3088.889	205.399	90	3.003585	5.402	0	99.41939	0	0	0	0	0	0.0538	0.1650	3307.81		0.0523	0.1643	3297.47
99.01127	1	0	1	1	1	9000	3100	206.016	90	3.178402	5.703	0	99.41939	0	0	0	0	0	0.0554	0.1659	3322.73		0.0539	0.1652	3312.91
100.013	1	0	1	1	1	9000	3111.111	206.667	90	3.35316	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0555	0.1662	3328.43
101.0148	1	0	1	1	1	9000	3122.222	207.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44
102.0166	1	0	1	1	1	9000	3133.333	208	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
103.0184	1	0	1	1	1	9000	3144.444	208.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)	Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
104.0203	1	0	1	1	1	9000	3155.556	209.333	90	3.429931	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0572	0.1672	3343.74
105.0221	1	0	1	1	1	9000	3166.667	210	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
106.0239	1	0	1	1	1	9000	3177.778	210.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
107.0257	1	0	1	1	1	9000	3188.889	211.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.44
108.0275	1	0	1	1	1	9000	3200	212	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
109.0293	1	0	1	1	1	9000	3211.111	212.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
110.0311	1	0	1	1	1	9000	3222.222	213.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.44
111.0329	1	0	1	1	1	9000	3233.333	214	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
112.0347	1	0	1	1	1	9000	3244.444	214.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
113.0365	1	0	1	1	1	9000	3255.556	215.333	90	3.429931	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0572	0.1672	3343.74
114.0383	1	0	1	1	1	9000	3266.667	216	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
115.0401	1	0	1	1	1	9000	3277.778	216.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
116.0419	1	0	1	1	1	9000	3288.889	217.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.44
117.0437	1	0	1	1	1	9000	3300	218	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
118.0455	1	0	1	1	1	9000	3311.111	218.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
119.0473	1	0	1	1	1	9000	3322.222	219.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.44
120.0491	1	0	1	1	1	9000	3333.333	220	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
121.0509	1	0	1	1	1	9000	3344.444	220.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
122.0528	1	0	1	1	1	9000	3355.556	221.333	90	3.429931	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0572	0.1672	3343.74
123.0546	1	0	1	1	1	9000	3366.667	222	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
124.0564	1	0	1	1	1	9000	3377.778	222.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
125.0582	1	0	1	1	1	9000	3388.889	223.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.44
126.06	1	0	1	1	1	9000	3400	224	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
127.0618	1	0	1	1	1	9000	3411.111	224.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46
128.0636	1	0	1	1	1	9000	3422.222	225.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.44
129.0654	1	0	1	1	1	9000	3433.333	226	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45	0.0571	0.1672	3343.46

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
130.0672	1	0	1	1	1	9000	3444.444	226.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
131.0691	1	0	1	1	1	9000	3455.556	227.333	90	3.429931	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0572	0.1672	3343.74
132.0709	1	0	1	1	1	9000	3466.667	228	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
133.0727	1	0	1	1	1	9000	3477.778	228.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
134.0745	1	0	1	1	1	9000	3488.889	229.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44
135.0763	1	0	1	1	1	9000	3500	230	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
136.0781	1	0	1	1	1	9000	3511.111	230.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
137.0799	1	0	1	1	1	9000	3522.222	231.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44
138.0817	1	0	1	1	1	9000	3533.333	232	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
139.0835	1	0	1	1	1	9000	3544.444	232.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
140.0854	1	0	1	1	1	9000	3555.556	233.333	90	3.429931	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0572	0.1672	3343.74
141.0872	1	0	1	1	1	9000	3566.667	234	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
142.089	1	0	1	1	1	9000	3577.778	234.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
143.0908	1	0	1	1	1	9000	3588.889	235.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44
144.0926	1	0	1	1	1	9000	3600	236	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
145.0944	1	0	1	1	1	9000	3611.111	236.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
146.0962	1	0	1	1	1	9000	3622.222	237.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44
147.098	1	0	1	1	1	9000	3633.333	238	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
148.0998	1	0	1	1	1	9000	3644.444	238.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
149.1016	1	0	1	1	1	9000	3655.556	239.333	90	3.429931	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0572	0.1672	3343.74
150.1034	1	0	1	1	1	9000	3666.667	240	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
151.1052	1	0	1	1	1	9000	3677.778	240.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
152.107	1	0	1	1	1	9000	3688.889	241.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44
153.1088	1	0	1	1	1	9000	3700	242	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
154.1106	1	0	1	1	1	9000	3711.111	242.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
155.1124	1	0	1	1	1	9000	3722.222	243.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
156.1142	1	0	1	1	1	9000	3733.333	244	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
157.116	1	0	1	1	1	9000	3744.444	244.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
158.1179	1	0	1	1	1	9000	3755.556	245.333	90	3.429931	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0572	0.1672	3343.74
159.1197	1	0	1	1	1	9000	3766.667	246	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
160.1215	1	0	1	1	1	9000	3777.778	246.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
161.1233	1	0	1	1	1	9000	3788.889	247.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44
162.1251	1	0	1	1	1	9000	3800	248	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
163.1269	1	0	1	1	1	9000	3811.111	248.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
164.1287	1	0	1	1	1	9000	3822.222	249.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44
165.1305	1	0	1	1	1	9000	3833.333	250	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
166.1323	1	0	1	1	1	9000	3844.444	250.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
167.1342	1	0	1	1	1	9000	3855.556	251.333	90	3.429931	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0572	0.1672	3343.74
168.136	1	0	1	1	1	9000	3866.667	252	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
169.1378	1	0	1	1	1	9000	3877.778	252.667	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
170.1396	1	0	1	1	1	9000	3888.889	253.333	90	3.430239	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.44
171.1414	1	0	1	1	1	9000	3900	254	90	3.435377	6	0	99.41939	0	0	0	0	0	0.0570	0.1669	3337.45		0.0571	0.1672	3343.46
172.1432	1	0	1	1	1	9000	3911.111	254.666	90	3.430239	5.983	0	99.41939	0	0	0	0	0	0.0570	0.1668	3336.61		0.0571	0.1672	3343.44
173.145	1	0	1	1	1	9000	3922.222	255.328	90	3.409686	5.922	0	99.41939	0	0	0	0	0	0.0566	0.1666	3333.58		0.0571	0.1671	3342.53
174.1467	1	0	1	1	1	9000	3933.333	255.982	90	3.368577	5.861	0	99.41939	0	0	0	0	0	0.0563	0.1665	3330.56		0.0567	0.1669	3339.35
175.1484	1	0	1	1	1	9000	3944.444	256.63	90	3.337742	5.8	0	99.41939	0	0	0	0	0	0.0560	0.1663	3327.54		0.0564	0.1667	3336.22
176.1501	1	0	1	1	1	9000	3955.556	257.271	90	3.30147	5.739	0	99.41939	0	0	0	0	0	0.0556	0.1661	3324.51		0.0561	0.1665	3333.37
177.1518	1	0	1	1	1	9000	3966.667	257.905	90	3.265789	5.678	0	99.41939	0	0	0	0	0	0.0553	0.1659	3321.49		0.0557	0.1663	3329.92
178.1534	1	0	1	1	1	9000	3977.778	258.533	90	3.234948	5.617	0	99.41939	0	0	0	0	0	0.0550	0.1657	3318.47		0.0554	0.1661	3326.79
179.1549	1	0	1	1	1	9000	3988.889	259.154	90	3.198965	5.556	0	99.41939	0	0	0	0	0	0.0547	0.1655	3315.44		0.0551	0.1659	3323.65
180.1564	1	0	1	1	1	9000	4000	259.767	90	3.157838	5.495	0	99.41939	0	0	0	0	0	0.0543	0.1653	3312.42		0.0547	0.1657	3320.48
181.1579	1	0	1	1	1	9000	4011.111	260.375	90	3.132133	5.434	0	99.41939	0	0	0	0	0	0.0540	0.1651	3309.4		0.0544	0.1655	3317.38

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
182.1594	1	0	1	1	1	9000	4022.222	260.975	90	3.091001	5.372	0	99.41939	0	0	0	0	0	0.0537	0.1649	3306.32		0.0541	0.1653	3314.22
183.1608	1	0	1	1	1	9000	4033.333	261.568	90	3.055008	5.311	0	99.41939	0	0	0	0	0	0.0533	0.1647	3303.3		0.0537	0.1651	3311.03
184.1622	1	0	1	1	1	9000	4044.444	262.155	90	3.024155	5.25	0	99.41939	0	0	0	0	0	0.0530	0.1645	3300.27		0.0534	0.1649	3307.91
185.1637	1	0	1	1	1	9000	4055.556	262.735	90	2.987889	5.189	0	99.41939	0	0	0	0	0	0.0527	0.1643	3297.25		0.0531	0.1648	3305.06
186.165	1	0	1	1	1	9000	4066.667	263.308	90	2.952158	5.128	0	99.41939	0	0	0	0	0	0.0523	0.1641	3294.23		0.0527	0.1645	3301.63
187.1663	1	0	1	1	1	9000	4077.778	263.875	90	2.921299	5.067	0	99.41939	0	0	0	0	0	0.0520	0.1639	3291.2		0.0524	0.1643	3298.52
188.1676	1	0	1	1	1	9000	4088.889	264.434	90	2.880151	5.006	0	99.41939	0	0	0	0	0	0.0517	0.1637	3288.18		0.0521	0.1641	3295.36
189.1688	1	0	1	1	1	9000	4100	264.987	90	2.849288	4.945	0	99.41939	0	0	0	0	0	0.0514	0.1635	3285.16		0.0517	0.1639	3292.25
190.17	1	0	1	1	1	9000	4111.111	265.533	90	2.81328	4.884	0	99.41939	0	0	0	0	0	0.0510	0.1634	3282.13		0.0514	0.1637	3289.12
191.1712	1	0	1	1	1	9000	4122.222	266.073	90	2.782413	4.823	0	99.41939	0	0	0	0	0	0.0507	0.1632	3279.11		0.0511	0.1635	3286.00
192.1723	1	0	1	1	1	9000	4133.333	266.605	90	2.741256	4.762	0	99.41939	0	0	0	0	0	0.0504	0.1630	3276.09		0.0508	0.1633	3282.87
193.1735	1	0	1	1	1	9000	4144.444	267.131	90	2.710386	4.701	0	99.41939	0	0	0	0	0	0.0500	0.1628	3273.06		0.0504	0.1631	3279.76
194.1746	1	0	1	1	1	9000	4155.556	267.65	90	2.674128	4.64	0	99.41939	0	0	0	0	0	0.0497	0.1626	3270.04		0.0501	0.1630	3276.92
195.1757	1	0	1	1	1	9000	4166.667	268.162	90	2.63835	4.579	0	99.41939	0	0	0	0	0	0.0494	0.1624	3267.01		0.0498	0.1628	3273.51
196.1767	1	0	1	1	1	9000	4177.778	268.667	90	2.602328	4.518	0	99.41939	0	0	0	0	0	0.0491	0.1622	3263.99		0.0494	0.1626	3270.38
197.1777	1	0	1	1	1	9000	4188.889	269.166	90	2.571451	4.457	0	99.41939	0	0	0	0	0	0.0487	0.1620	3260.97		0.0491	0.1624	3267.28
198.1787	1	0	1	1	1	9000	4200	269.658	90	2.535426	4.396	0	99.41939	0	0	0	0	0	0.0484	0.1618	3257.94		0.0488	0.1622	3264.17
199.1797	1	0	1	1	1	9000	4211.111	270.143	90	2.499399	4.335	0	99.41939	0	0	0	0	0	0.0481	0.1616	3254.92		0.0484	0.1620	3261.04
200.1806	1	0	1	1	1	9000	4222.222	270.621	90	2.46337	4.274	0	99.41939	0	0	0	0	0	0.0477	0.1614	3251.9		0.0481	0.1618	3257.93
201.1815	1	0	1	1	1	9000	4233.333	271.092	90	2.427339	4.213	0	99.41939	0	0	0	0	0	0.0474	0.1612	3248.87		0.0478	0.1616	3254.82
202.1824	1	0	1	1	1	9000	4244.444	271.557	90	2.396454	4.151	0	99.41939	0	0	0	0	0	0.0471	0.1610	3245.8		0.0474	0.1614	3251.71
203.1833	1	0	1	1	1	9000	4255.556	272.015	90	2.360207	4.09	0	99.41939	0	0	0	0	0	0.0467	0.1608	3242.78		0.0471	0.1612	3248.85
204.1841	1	0	1	1	1	9000	4266.667	272.466	90	2.324383	4.029	0	99.41939	0	0	0	0	0	0.0464	0.1606	3239.75		0.0468	0.1610	3245.45
205.1849	1	0	1	1	1	9000	4277.778	272.91	90	2.288345	3.968	0	99.41939	0	0	0	0	0	0.0463	0.1604	3238.49		0.0465	0.1608	3242.34
206.1857	1	0	1	1	1	9000	4288.889	273.348	90	2.257453	3.907	0	99.41939	0	0	0	0	0	0.0463	0.1601	3238.82		0.0463	0.1605	3241.01
207.1864	1	0	1	1	1	9000	4300	273.778	90	2.216263	3.846	0	99.41939	0	0	0	0	0	0.0463	0.1599	3239.16		0.0463	0.1603	3241.24

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
208.1872	1	0	1	1	1	9000	4311.111	274.202	90	2.185368	3.785	0	99.41939	0	0	0	0	0	0.0463	0.1596	3239.49		0.0463	0.1600	3241.52
209.1879	1	0	1	1	1	9000	4322.222	274.62	90	2.154473	3.724	0	99.41939	0	0	0	0	0	0.0463	0.1593	3239.82		0.0463	0.1597	3241.78
210.1886	1	0	1	1	1	9000	4333.333	275.03	90	2.113277	3.663	0	99.41939	0	0	0	0	0	0.0463	0.1590	3240.16		0.0463	0.1594	3242.03
211.1892	1	0	1	1	1	9000	4344.444	275.434	90	2.082378	3.602	0	99.41939	0	0	0	0	0	0.0463	0.1588	3240.49		0.0463	0.1592	3242.30
212.19	1	0	1	1	1	9000	4355.556	275.83	90	2.040995	3.541	0	99.41939	0	0	0	0	0	0.0463	0.1585	3240.82		0.0463	0.1589	3242.84
213.1906	1	0	1	1	1	9000	4366.667	276.22	90	2.010277	3.48	0	99.41939	0	0	0	0	0	0.0463	0.1582	3241.16		0.0463	0.1586	3242.82
214.1912	1	0	1	1	1	9000	4377.778	276.604	90	1.979374	3.419	0	99.41939	0	0	0	0	0	0.0463	0.1580	3241.49		0.0463	0.1583	3243.10
215.1917	1	0	1	1	1	9000	4388.889	276.98	90	1.938169	3.358	0	99.41939	0	0	0	0	0	0.0463	0.1577	3241.82		0.0463	0.1580	3243.35
216.1923	1	0	1	1	1	9000	4400	277.35	90	1.907264	3.297	0	99.41939	0	0	0	0	0	0.0463	0.1574	3242.16		0.0463	0.1578	3243.62
217.1928	1	0	1	1	1	9000	4411.111	277.713	90	1.871206	3.236	0	99.41939	0	0	0	0	0	0.0463	0.1571	3242.49		0.0463	0.1575	3243.89
218.1933	1	0	1	1	1	9000	4422.222	278.069	90	1.835147	3.175	0	99.41939	0	0	0	0	0	0.0463	0.1569	3242.83		0.0463	0.1572	3244.15
219.1938	1	0	1	1	1	9000	4433.333	278.418	90	1.799087	3.114	0	99.41939	0	0	0	0	0	0.0463	0.1566	3243.16		0.0463	0.1569	3244.43
220.1943	1	0	1	1	1	9000	4444.444	278.761	90	1.768177	3.053	0	99.41939	0	0	0	0	0	0.0463	0.1563	3243.49		0.0463	0.1567	3244.70
221.1949	1	0	1	1	1	9000	4455.556	279.097	90	1.731958	2.992	0	99.41939	0	0	0	0	0	0.0463	0.1561	3243.83		0.0463	0.1564	3245.26
222.1953	1	0	1	1	1	9000	4466.667	279.426	90	1.696049	2.93	0	99.41939	0	0	0	0	0	0.0463	0.1558	3244.17		0.0463	0.1561	3245.25
223.1957	1	0	1	1	1	9000	4477.778	279.748	90	1.659984	2.869	0	99.41939	0	0	0	0	0	0.0463	0.1555	3244.5		0.0463	0.1558	3245.53
224.1961	1	0	1	1	1	9000	4488.889	280.063	90	1.623917	2.808	0	99.41939	0	0	0	0	0	0.0463	0.1552	3244.83		0.0463	0.1556	3245.80
225.1965	1	0	1	1	1	9000	4500	280.372	90	1.593001	2.747	0	99.41939	0	0	0	0	0	0.0463	0.1550	3245.17		0.0463	0.1553	3246.08
226.1969	1	0	1	1	1	9000	4511.111	280.674	90	1.556932	2.686	0	99.41939	0	0	0	0	0	0.0463	0.1547	3245.5		0.0463	0.1550	3246.37
227.1972	1	0	1	1	1	9000	4522.222	280.969	90	1.520861	2.625	0	99.41939	0	0	0	0	0	0.0463	0.1544	3245.83		0.0463	0.1547	3246.64
228.1976	1	0	1	1	1	9000	4533.333	281.257	90	1.484789	2.564	0	99.41939	0	0	0	0	0	0.0463	0.1541	3246.17		0.0463	0.1545	3246.92
229.1979	1	0	1	1	1	9000	4544.444	281.539	90	1.453869	2.503	0	99.41939	0	0	0	0	0	0.0463	0.1539	3246.5		0.0463	0.1542	3247.22
230.1983	1	0	1	1	1	9000	4555.556	281.813	90	1.412515	2.442	0	99.41939	0	0	0	0	0	0.0463	0.1536	3246.83		0.0463	0.1539	3247.78
231.1986	1	0	1	1	1	9000	4566.667	282.081	90	1.38172	2.381	0	99.41939	0	0	0	0	0	0.0462	0.1533	3247.17		0.0463	0.1536	3247.77
232.1988	1	0	1	1	1	9000	4577.778	282.342	90	1.345644	2.32	0	99.41939	0	0	0	0	0	0.0462	0.1531	3247.5		0.0463	0.1534	3248.07
233.1991	1	0	1	1	1	9000	4588.889	282.597	90	1.31472	2.259	0	99.41939	0	0	0	0	0	0.0462	0.1528	3247.83		0.0463	0.1531	3248.36

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)	Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
234.1994	1	0	1	1	1	9000	4600	282.844	90	1.273488	2.198	0	99.41939	0	0	0	0	0	0.0462	0.1525	3248.17	0.0463	0.1528	3248.63
235.1996	1	0	1	1	1	9000	4611.111	283.085	90	1.242563	2.137	0	99.41939	0	0	0	0	0	0.0462	0.1522	3248.5	0.0463	0.1525	3248.93
236.1998	1	0	1	1	1	9000	4622.222	283.319	90	1.206483	2.076	0	99.41939	0	0	0	0	0	0.0462	0.1520	3248.84	0.0463	0.1523	3249.22
237.2	1	0	1	1	1	9000	4633.333	283.546	90	1.170402	2.015	0	99.41939	0	0	0	0	0	0.0462	0.1517	3249.17	0.0463	0.1520	3249.52
238.2002	1	0	1	1	1	9000	4644.444	283.767	90	1.139474	1.954	0	99.41939	0	0	0	0	0	0.0479	0.1518	3244.13	0.0463	0.1517	3249.81
239.2005	1	0	1	1	1	9000	4655.556	283.981	90	1.103292	1.893	0	99.41939	0	0	0	0	0	0.0501	0.1520	3237.34	0.0479	0.1518	3245.02
240.2007	1	0	1	1	1	9000	4666.667	284.187	90	1.062153	1.832	0	99.41939	0	0	0	0	0	0.0523	0.1523	3230.55	0.0501	0.1521	3237.90
241.2008	1	0	1	1	1	9000	4677.778	284.388	90	1.036378	1.77	0	99.41939	0	0	0	0	0	0.0545	0.1525	3223.65	0.0523	0.1523	3231.08
242.201	1	0	1	1	1	9000	4688.889	284.581	90	0.995138	1.709	0	99.41939	0	0	0	0	0	0.0567	0.1527	3216.86	0.0545	0.1525	3224.14
243.2011	1	0	1	1	1	9000	4700	284.767	90	0.959051	1.648	0	99.41939	0	0	0	0	0	0.0589	0.1530	3210.07	0.0567	0.1528	3217.31
244.2012	1	0	1	1	1	9000	4711.111	284.947	90	0.92812	1.587	0	99.41939	0	0	0	0	0	0.0611	0.1532	3203.28	0.0589	0.1530	3210.49
245.2014	1	0	1	1	1	9000	4722.222	285.12	90	0.892032	1.526	0	99.41939	0	0	0	0	0	0.0633	0.1535	3196.49	0.0611	0.1532	3203.67
246.2015	1	0	1	1	1	9000	4733.333	285.286	90	0.855944	1.465	0	99.41939	0	0	0	0	0	0.0654	0.1537	3189.69	0.0633	0.1535	3196.85
247.2016	1	0	1	1	1	9000	4744.444	285.446	90	0.82501	1.404	0	99.41939	0	0	0	0	0	0.0676	0.1539	3182.9	0.0655	0.1537	3190.02
248.2018	1	0	1	1	1	9000	4755.556	285.598	90	0.783695	1.343	0	99.41939	0	0	0	0	0	0.0698	0.1542	3176.11	0.0676	0.1540	3183.48
249.2019	1	0	1	1	1	9000	4766.667	285.744	90	0.752831	1.282	0	99.41939	0	0	0	0	0	0.0720	0.1544	3169.32	0.0698	0.1542	3176.38
250.2019	1	0	1	1	1	9000	4777.778	285.883	90	0.71674	1.221	0	99.41939	0	0	0	0	0	0.0742	0.1546	3162.53	0.0720	0.1544	3169.57
251.202	1	0	1	1	1	9000	4788.889	286.016	90	0.685805	1.16	0	99.41939	0	0	0	0	0	0.0764	0.1549	3155.74	0.0742	0.1546	3162.76
252.2021	1	0	1	1	1	9000	4800	286.141	90	0.644557	1.099	0	99.41939	0	0	0	0	0	0.0786	0.1551	3148.95	0.0764	0.1549	3155.94
253.2021	1	0	1	1	1	9000	4811.111	286.26	90	0.61362	1.038	0	99.41939	0	0	0	0	0	0.0808	0.1553	3142.16	0.0786	0.1551	3149.13
254.2022	1	0	1	1	1	9000	4822.222	286.372	90	0.577528	0.977	0	99.41939	0	0	0	0	0	0.0830	0.1556	3135.37	0.0808	0.1553	3142.32
255.2022	1	0	1	1	1	9000	4833.333	286.477	90	0.541434	0.916	0	99.41939	0	0	0	0	0	0.0851	0.1558	3128.58	0.0830	0.1556	3135.51
256.2023	1	0	1	1	1	9000	4844.444	286.575	90	0.505341	0.855	0	99.41939	0	0	0	0	0	0.0873	0.1560	3121.79	0.0852	0.1558	3128.70
257.2024	1	0	1	1	1	9000	4855.556	286.667	90	0.47436	0.794	0	99.41939	0	0	0	0	0	0.0895	0.1563	3115	0.0873	0.1561	3122.18
258.2024	1	0	1	1	1	9000	4866.667	286.752	90	0.438309	0.733	0	99.41939	0	0	0	0	0	0.0917	0.1565	3108.21	0.0895	0.1563	3115.09
259.2024	1	0	1	1	1	9000	4877.778	286.83	90	0.402214	0.672	0	99.41939	0	0	0	0	0	0.0939	0.1567	3101.42	0.0917	0.1565	3108.29

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
260.2025	1	0	1	1	1	9000	4888.889	286.901	90	0.366119	0.611	0	99.41939	0	0	0	0	0	0.0961	0.1570	3094.63		0.0939	0.1567	3101.48
261.2025	1	0	1	1	1	9000	4900	286.965	90	0.330023	0.55	0	99.41939	0	0	0	0	0	0.0983	0.1572	3087.84		0.0961	0.1570	3094.68
262.2025	1	0	1	1	1	9000	4911.111	287.023	90	0.299084	0.488	0	99.41939	0	0	0	0	0	0.1005	0.1575	3080.94		0.0983	0.1572	3087.88
263.2025	1	0	1	1	1	9000	4922.222	287.074	90	0.262988	0.427	0	99.41939	0	0	0	0	0	0.1027	0.1577	3074.15		0.1005	0.1575	3080.97
264.2025	1	0	1	1	1	9000	4933.333	287.118	90	0.226892	0.366	0	99.41939	0	0	0	0	0	0.1049	0.1579	3067.35		0.1027	0.1577	3074.17
265.2025	1	0	1	1	1	9000	4944.444	287.155	90	0.190796	0.305	0	99.41939	0	0	0	0	0	0.1071	0.1582	3060.56		0.1049	0.1579	3067.37
266.2026	1	0	1	1	1	9000	4955.556	287.186	90	0.159842	0.244	0	99.41939	0	0	0	0	0	0.1093	0.1584	3053.77		0.1071	0.1582	3060.85
267.2026	1	0	1	1	1	9000	4966.667	287.209	90	0.118603	0.183	0	99.41939	0	0	0	0	0	0.1115	0.1586	3046.98		0.1093	0.1584	3053.78
268.2026	1	0	1	1	1	9000	4977.778	287.226	90	0.087663	0.122	0	99.41939	0	0	0	0	0	0.1136	0.1589	3040.19		0.1115	0.1586	3046.98
269.2026	1	0	1	1	1	9000	4988.889	287.237	90	0.056723	0.061	0	99.41939	0	0	0	0	0	0.1158	0.1591	3033.4		0.1136	0.1589	3040.19
270.2026	1	0	1	1	1	9000	5000	287.24	90	0.01547	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1158	0.1591	3033.40
271.2026	1	0	1	1	1	9000	5011.111	287.237	90	-0.01547	-0.061	0	99.41939	0	0	0	0	0	0.1213	0.1591	3016.26		0.1180	0.1593	3026.61
272.2026	1	0	1	1	1	9000	5022.222	287.226	90	-0.05672	-0.122	0	99.41939	0	0	0	0	0	0.1247	0.1588	3005.9		0.1213	0.1591	3016.26
273.2026	1	0	1	1	1	9000	5033.333	287.209	90	-0.08766	-0.183	0	99.41939	0	0	0	0	0	0.1280	0.1585	2995.54		0.1247	0.1588	3005.90
274.2026	1	0	1	1	1	9000	5044.444	287.186	90	-0.1186	-0.244	0	99.41939	0	0	0	0	0	0.1313	0.1583	2985.19		0.1280	0.1585	2995.55
275.2027	1	0	1	1	1	9000	5055.556	287.155	90	-0.15984	-0.305	0	99.41939	0	0	0	0	0	0.1347	0.1580	2974.83		0.1313	0.1583	2985.47
276.2027	1	0	1	1	1	9000	5066.667	287.118	90	-0.1908	-0.366	0	99.41939	0	0	0	0	0	0.1380	0.1577	2964.47		0.1347	0.1580	2974.85
277.2027	1	0	1	1	1	9000	5077.778	287.074	90	-0.22689	-0.427	0	99.41939	0	0	0	0	0	0.1413	0.1575	2954.12		0.1380	0.1577	2964.49
278.2027	1	0	1	1	1	9000	5088.889	287.023	90	-0.26299	-0.488	0	99.41939	0	0	0	0	0	0.1446	0.1572	2943.76		0.1413	0.1575	2954.15
279.2027	1	0	1	1	1	9000	5100	286.965	90	-0.29908	-0.55	0	99.41939	0	0	0	0	0	0.1480	0.1569	2933.23		0.1446	0.1572	2943.80
280.2028	1	0	1	1	1	9000	5111.111	286.901	90	-0.33002	-0.611	0	99.41939	0	0	0	0	0	0.1514	0.1567	2922.88		0.1480	0.1569	2933.28
281.2028	1	0	1	1	1	9000	5122.222	286.83	90	-0.36612	-0.672	0	99.41939	0	0	0	0	0	0.1547	0.1564	2912.52		0.1514	0.1567	2922.94
282.2028	1	0	1	1	1	9000	5133.333	286.752	90	-0.40221	-0.733	0	99.41939	0	0	0	0	0	0.1580	0.1562	2902.16		0.1547	0.1564	2912.59
283.2028	1	0	1	1	1	9000	5144.444	286.667	90	-0.43831	-	0	99.41939	0	0	0	0	0	0.1613	0.1559	2891.81		0.1580	0.1562	2902.25

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
											0.794														
284.203	1	0	1	1	1	9000	5155.556	286.575	90	-0.47436	-0.855	0	99.41939	0	0	0	0	0	0.1647	0.1556	2881.45		0.1614	0.1559	2892.17
285.203	1	0	1	1	1	9000	5166.667	286.477	90	-0.50534	-0.916	0	99.41939	0	0	0	0	0	0.1680	0.1554	2871.09		0.1647	0.1556	2881.56
286.203	1	0	1	1	1	9000	5177.778	286.372	90	-0.54143	-0.977	0	99.41939	0	0	0	0	0	0.1713	0.1551	2860.74		0.1680	0.1554	2871.22
287.2031	1	0	1	1	1	9000	5188.889	286.26	90	-0.57753	-1.038	0	99.41939	0	0	0	0	0	0.1746	0.1548	2850.38		0.1713	0.1551	2860.89
288.2032	1	0	1	1	1	9000	5200	286.141	90	-0.61362	-1.099	0	99.41939	0	0	0	0	0	0.1780	0.1546	2840.02		0.1747	0.1548	2850.54
289.2032	1	0	1	1	1	9000	5211.111	286.016	90	-0.64456	-1.16	0	99.41939	0	0	0	0	0	0.1813	0.1543	2829.67		0.1780	0.1546	2840.20
290.2033	1	0	1	1	1	9000	5222.222	285.883	90	-0.6858	-1.221	0	99.41939	0	0	0	0	0	0.1846	0.1540	2819.31		0.1813	0.1543	2829.87
291.2034	1	0	1	1	1	9000	5233.333	285.744	90	-0.71674	-1.282	0	99.41939	0	0	0	0	0	0.1880	0.1538	2808.95		0.1846	0.1540	2819.53
292.2035	1	0	1	1	1	9000	5244.444	285.598	90	-0.75283	-1.343	0	99.41939	0	0	0	0	0	0.1913	0.1535	2798.6		0.1880	0.1538	2809.19
293.2036	1	0	1	1	1	9000	5255.556	285.446	90	-0.78369	-1.404	0	99.41939	0	0	0	0	0	0.1946	0.1532	2788.24		0.1913	0.1535	2799.11
294.2037	1	0	1	1	1	9000	5266.667	285.286	90	-0.82501	-1.465	0	99.41939	0	0	0	0	0	0.1979	0.1530	2777.88		0.1946	0.1533	2788.53
295.2038	1	0	1	1	1	9000	5277.778	285.12	90	-0.85594	-1.526	0	99.41939	0	0	0	0	0	0.2013	0.1527	2767.53		0.1980	0.1530	2778.19
296.204	1	0	1	1	1	9000	5288.889	284.947	90	-0.89203	-1.587	0	99.41939	0	0	0	0	0	0.2046	0.1524	2757.17		0.2013	0.1527	2767.87
297.2041	1	0	1	1	1	9000	5300	284.767	90	-0.92812	-1.648	0	99.41939	0	0	0	0	0	0.2079	0.1522	2746.81		0.2046	0.1525	2757.53
298.2042	1	0	1	1	1	9000	5311.111	284.581	90	-0.95905	-1.709	0	99.41939	0	0	0	0	0	0.2112	0.1519	2736.46		0.2079	0.1522	2747.19
299.2044	1	0	1	1	1	9000	5322.222	284.388	90	-0.99514	-1.77	0	99.41939	0	0	0	0	0	0.2146	0.1516	2726.1		0.2113	0.1519	2736.87
300.2046	1	0	1	1	1	9000	5333.333	284.187	90	-1.03638	-1.832	0	99.41939	0	0	0	0	0	0.2180	0.1514	2715.57		0.2146	0.1517	2726.55
301.2047	1	0	1	1	1	9000	5344.444	283.981	90	-1.06215	-1.893	0	99.41939	0	0	0	0	0	0.2213	0.1511	2705.22		0.2180	0.1514	2716.04
302.205	1	0	1	1	1	9000	5355.556	283.767	90	-1.10329	-1.954	0	99.41939	0	0	0	0	0	0.2246	0.1508	2694.86		0.2213	0.1512	2705.97
303.2052	1	0	1	1	1	9000	5366.667	283.546	90	-1.13947	-2.015	0	99.41939	0	0	0	0	0	0.2284	0.1504	2683.81		0.2247	0.1509	2695.39
304.2054	1	0	1	1	1	9000	5377.778	283.319	90	-1.1704	-2.076	0	99.41939	0	0	0	0	0	0.2338	0.1494	2670.63		0.2285	0.1504	2684.37

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
305.2056	1	0	1	1	1	9000	5388.889	283.085	90	-1.20648	-2.137	0	99.41939	0	0	0	0	0	0.2392	0.1484	2657.46		0.2339	0.1494	2671.22
306.2059	1	0	1	1	1	9000	5400	282.844	90	-1.24256	-2.198	0	99.41939	0	0	0	0	0	0.2446	0.1474	2644.28		0.2393	0.1484	2658.09
307.2061	1	0	1	1	1	9000	5411.111	282.597	90	-1.27349	-2.259	0	99.41939	0	0	0	0	0	0.2500	0.1464	2631.11		0.2447	0.1474	2644.93
308.2064	1	0	1	1	1	9000	5422.222	282.342	90	-1.31472	-2.32	0	99.41939	0	0	0	0	0	0.2554	0.1454	2617.93		0.2501	0.1464	2631.80
309.2067	1	0	1	1	1	9000	5433.333	282.081	90	-1.34564	-2.381	0	99.41939	0	0	0	0	0	0.2608	0.1444	2604.76		0.2555	0.1454	2618.65
310.2069	1	0	1	1	1	9000	5444.444	281.813	90	-1.38172	-2.442	0	99.41939	0	0	0	0	0	0.2662	0.1434	2591.58		0.2609	0.1444	2605.52
311.2073	1	0	1	1	1	9000	5455.556	281.539	90	-1.41251	-2.503	0	99.41939	0	0	0	0	0	0.2716	0.1424	2578.41		0.2663	0.1435	2592.60
312.2077	1	0	1	1	1	9000	5466.667	281.257	90	-1.45387	-2.564	0	99.41939	0	0	0	0	0	0.2769	0.1414	2565.23		0.2716	0.1424	2579.24
313.208	1	0	1	1	1	9000	5477.778	280.969	90	-1.48479	-2.625	0	99.41939	0	0	0	0	0	0.2823	0.1404	2552.06		0.2770	0.1414	2566.09
314.2083	1	0	1	1	1	9000	5488.889	280.674	90	-1.52086	-2.686	0	99.41939	0	0	0	0	0	0.2877	0.1394	2538.88		0.2824	0.1404	2552.96
315.2087	1	0	1	1	1	9000	5500	280.372	90	-1.55693	-2.747	0	99.41939	0	0	0	0	0	0.2931	0.1384	2525.7		0.2878	0.1394	2539.82
316.2091	1	0	1	1	1	9000	5511.111	280.063	90	-1.593	-2.808	0	99.41939	0	0	0	0	0	0.2985	0.1374	2512.53		0.2932	0.1384	2526.68
317.2095	1	0	1	1	1	9000	5522.222	279.748	90	-1.62392	-2.869	0	99.41939	0	0	0	0	0	0.3039	0.1364	2499.35		0.2986	0.1375	2513.54
318.2099	1	0	1	1	1	9000	5533.333	279.426	90	-1.65998	-2.93	0	99.41939	0	0	0	0	0	0.3093	0.1354	2486.18		0.3040	0.1365	2500.40
319.2104	1	0	1	1	1	9000	5544.444	279.097	90	-1.69605	-2.992	0	99.41939	0	0	0	0	0	0.3148	0.1344	2472.79		0.3094	0.1355	2487.27
320.2109	1	0	1	1	1	9000	5555.556	278.761	90	-1.73196	-3.053	0	99.41939	0	0	0	0	0	0.3201	0.1334	2459.61		0.3149	0.1345	2474.14
321.2114	1	0	1	1	1	9000	5566.667	278.418	90	-1.76818	-3.114	0	99.41939	0	0	0	0	0	0.3255	0.1324	2446.44		0.3203	0.1334	2460.78
322.2119	1	0	1	1	1	9000	5577.778	278.069	90	-1.79909	-3.175	0	99.41939	0	0	0	0	0	0.3309	0.1314	2433.26		0.3257	0.1324	2447.65
323.2124	1	0	1	1	1	9000	5588.889	277.713	90	-1.83515	-3.236	0	99.41939	0	0	0	0	0	0.3363	0.1304	2420.08		0.3311	0.1314	2434.51
324.2129	1	0	1	1	1	9000	5600	277.35	90	-1.87121	-3.297	0	99.41939	0	0	0	0	0	0.3417	0.1294	2406.91		0.3365	0.1304	2421.37
325.2135	1	0	1	1	1	9000	5611.111	276.98	90	-1.90726	-3.358	0	99.41939	0	0	0	0	0	0.3471	0.1284	2393.73		0.3419	0.1294	2408.24
326.2141	1	0	1	1	1	9000	5622.222	276.604	90	-1.93817	-	0	99.41939	0	0	0	0	0	0.3525	0.1274	2380.56		0.3473	0.1284	2395.10

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
											3.419														
327.2147	1	0	1	1	1	9000	5633.333	276.22	90	-1.97937	-3.48	0	99.41939	0	0	0	0	0	0.3579	0.1264	2367.38		0.3527	0.1274	2381.98
328.2153	1	0	1	1	1	9000	5644.444	275.83	90	-2.01028	-3.541	0	99.41939	0	0	0	0	0	0.3633	0.1254	2354.21		0.3581	0.1265	2368.84
329.216	1	0	1	1	1	9000	5655.556	275.434	90	-2.04099	-3.602	0	99.41939	0	0	0	0	0	0.3687	0.1244	2341.03		0.3635	0.1255	2355.92
330.2167	1	0	1	1	1	9000	5666.667	275.03	90	-2.08238	-3.663	0	99.41939	0	0	0	0	0	0.3740	0.1234	2327.86		0.3689	0.1245	2342.58
331.2173	1	0	1	1	1	9000	5677.778	274.62	90	-2.11328	-3.724	0	99.41939	0	0	0	0	0	0.3794	0.1224	2314.68		0.3743	0.1235	2329.44
332.218	1	0	1	1	1	9000	5688.889	274.202	90	-2.15447	-3.785	0	99.41939	0	0	0	0	0	0.3848	0.1214	2301.51		0.3797	0.1225	2316.32
333.2188	1	0	1	1	1	9000	5700	273.778	90	-2.18537	-3.846	0	99.41939	0	0	0	0	0	0.3902	0.1204	2288.33		0.3851	0.1215	2303.19
334.2195	1	0	1	1	1	9000	5711.111	273.348	90	-2.21626	-3.907	0	99.41939	0	0	0	0	0	0.3956	0.1194	2275.15		0.3905	0.1205	2290.04
335.2203	1	0	1	1	1	9000	5722.222	272.91	90	-2.25745	-3.968	0	99.41939	0	0	0	0	0	0.4010	0.1184	2261.98		0.3959	0.1195	2276.92
336.2211	1	0	1	1	1	9000	5733.333	272.466	90	-2.28834	-4.029	0	99.41939	0	0	0	0	0	0.4056	0.1173	2246.68		0.4013	0.1185	2263.79
337.2219	1	0	1	1	1	9000	5744.444	272.015	90	-2.32438	-4.09	0	99.41939	0	0	0	0	0	0.4095	0.1161	2229.04		0.4060	0.1174	2248.53
338.2229	1	0	1	1	1	9000	5755.556	271.557	90	-2.36021	-4.151	0	99.41939	0	0	0	0	0	0.4133	0.1148	2211.4		0.4098	0.1162	2231.13
339.2237	1	0	1	1	1	9000	5766.667	271.092	90	-2.39645	-4.213	0	99.41939	0	0	0	0	0	0.4172	0.1136	2193.47		0.4137	0.1149	2213.34
340.2246	1	0	1	1	1	9000	5777.778	270.621	90	-2.42734	-4.274	0	99.41939	0	0	0	0	0	0.4210	0.1124	2175.83		0.4176	0.1137	2195.44
341.2256	1	0	1	1	1	9000	5788.889	270.143	90	-2.46337	-4.335	0	99.41939	0	0	0	0	0	0.4248	0.1112	2158.19		0.4214	0.1125	2177.84
342.2265	1	0	1	1	1	9000	5800	269.658	90	-2.4994	-4.396	0	99.41939	0	0	0	0	0	0.4287	0.1100	2140.55		0.4252	0.1113	2160.25
343.2275	1	0	1	1	1	9000	5811.111	269.166	90	-2.53543	-4.457	0	99.41939	0	0	0	0	0	0.4325	0.1088	2122.91		0.4291	0.1101	2142.65
344.2285	1	0	1	1	1	9000	5822.222	268.667	90	-2.57145	-4.518	0	99.41939	0	0	0	0	0	0.4363	0.1075	2105.27		0.4329	0.1089	2125.05
345.2295	1	0	1	1	1	9000	5833.333	268.162	90	-2.60233	-4.579	0	99.41939	0	0	0	0	0	0.4402	0.1063	2087.63		0.4368	0.1077	2107.44
346.2306	1	0	1	1	1	9000	5844.444	267.65	90	-2.63835	-4.64	0	99.41939	0	0	0	0	0	0.4440	0.1051	2069.99		0.4406	0.1064	2089.85
347.2318	1	0	1	1	1	9000	5855.556	267.131	90	-2.67413	-4.701	0	99.41939	0	0	0	0	0	0.4478	0.1039	2052.35		0.4445	0.1052	2072.43

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
348.2329	1	0	1	1	1	9000	5866.667	266.605	90	-2.71039	-4.762	0	99.41939	0	0	0	0	0	0.4516	0.1027	2034.7		0.4483	0.1040	2054.65
349.234	1	0	1	1	1	9000	5877.778	266.073	90	-2.74126	-4.823	0	99.41939	0	0	0	0	0	0.4555	0.1015	2017.06		0.4522	0.1028	2037.03
350.2352	1	0	1	1	1	9000	5888.889	265.533	90	-2.78241	-4.884	0	99.41939	0	0	0	0	0	0.4593	0.1003	1999.42		0.4560	0.1016	2019.44
351.2364	1	0	1	1	1	9000	5900	264.987	90	-2.81328	-4.945	0	99.41939	0	0	0	0	0	0.4631	0.0991	1981.78		0.4599	0.1004	2001.83
352.2377	1	0	1	1	1	9000	5911.111	264.434	90	-2.84929	-5.006	0	99.41939	0	0	0	0	0	0.4670	0.0978	1964.14		0.4637	0.0992	1984.23
353.2389	1	0	1	1	1	9000	5922.222	263.875	90	-2.88015	-5.067	0	99.41939	0	0	0	0	0	0.4708	0.0966	1946.5		0.4676	0.0980	1966.62
354.2402	1	0	1	1	1	9000	5933.333	263.308	90	-2.9213	-5.128	0	99.41939	0	0	0	0	0	0.4746	0.0954	1928.86		0.4714	0.0968	1949.03
355.2416	1	0	1	1	1	9000	5944.444	262.735	90	-2.95216	-5.189	0	99.41939	0	0	0	0	0	0.4785	0.0942	1911.22		0.4753	0.0956	1931.42
356.243	1	0	1	1	1	9000	5955.556	262.155	90	-2.98789	-5.25	0	99.41939	0	0	0	0	0	0.4823	0.0930	1893.58		0.4791	0.0943	1913.99
357.2444	1	0	1	1	1	9000	5966.667	261.568	90	-3.02415	-5.311	0	99.41939	0	0	0	0	0	0.4861	0.0918	1875.94		0.4830	0.0931	1896.22
358.2458	1	0	1	1	1	9000	5977.778	260.975	90	-3.05501	-5.372	0	99.41939	0	0	0	0	0	0.4899	0.0906	1858.3		0.4868	0.0919	1878.61
359.2473	1	0	1	1	1	9000	5988.889	260.375	90	-3.091	-5.434	0	99.41939	0	0	0	0	0	0.4938	0.0893	1840.37		0.4907	0.0907	1861.01
360.2488	1	0	1	1	1	9000	6000	259.767	90	-3.13213	-5.495	0	99.41939	0	0	0	0	0	0.4977	0.0881	1822.73		0.4946	0.0895	1843.12
361.2503	1	0	1	1	1	9000	6011.111	259.154	90	-3.15784	-5.556	0	99.41939	0	0	0	0	0	0.5015	0.0869	1805.09		0.4984	0.0883	1825.50
362.2519	1	0	1	1	1	9000	6022.222	258.533	90	-3.19896	-5.617	0	99.41939	0	0	0	0	0	0.5053	0.0857	1787.45		0.5023	0.0871	1807.91
363.2535	1	0	1	1	1	9000	6033.333	257.905	90	-3.23495	-5.678	0	99.41939	0	0	0	0	0	0.5092	0.0845	1769.81		0.5061	0.0858	1790.30
364.2551	1	0	1	1	1	9000	6044.444	257.271	90	-3.26579	-5.739	0	99.41939	0	0	0	0	0	0.5130	0.0833	1752.17		0.5100	0.0846	1772.69
365.2568	1	0	1	1	1	9000	6055.556	256.63	90	-3.30147	-5.8	0	99.41939	0	0	0	0	0	0.5168	0.0821	1734.53		0.5139	0.0834	1755.24
366.2585	1	0	1	1	1	9000	6066.667	255.982	90	-3.33774	-5.861	0	99.41939	0	0	0	0	0	0.5206	0.0809	1716.89		0.5177	0.0822	1737.48
367.2603	1	0	1	1	1	9000	6077.778	255.328	90	-3.36858	-5.922	0	99.41939	0	0	0	0	0	0.5245	0.0796	1699.25		0.5215	0.0810	1719.86
368.262	1	0	1	1	1	9000	6088.889	254.666	90	-3.40969	-5.983	0	99.41939	0	0	0	0	0	0.5283	0.0784	1681.6		0.5254	0.0798	1702.26
369.2638	1	0	1	1	1	9000	6100	254	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5292	0.0786	1684.62

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
370.2656	1	0	1	1	1	9000	6111.111	253.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
371.2674	1	0	1	1	1	9000	6122.222	252.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
372.2692	1	0	1	1	1	9000	6133.333	252	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
373.271	1	0	1	1	1	9000	6144.444	251.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
374.2729	1	0	1	1	1	9000	6155.556	250.667	90	-3.42993	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5304	0.0782	1679.85
375.2747	1	0	1	1	1	9000	6166.667	250	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
376.2765	1	0	1	1	1	9000	6177.778	249.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
377.2783	1	0	1	1	1	9000	6188.889	248.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
378.2801	1	0	1	1	1	9000	6200	248	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
379.2819	1	0	1	1	1	9000	6211.111	247.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
380.2837	1	0	1	1	1	9000	6222.222	246.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
381.2855	1	0	1	1	1	9000	6233.333	246	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
382.2873	1	0	1	1	1	9000	6244.444	245.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
383.2892	1	0	1	1	1	9000	6255.556	244.667	90	-3.42993	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5304	0.0782	1679.85
384.291	1	0	1	1	1	9000	6266.667	244	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
385.2928	1	0	1	1	1	9000	6277.778	243.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
386.2946	1	0	1	1	1	9000	6288.889	242.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
387.2964	1	0	1	1	1	9000	6300	242	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
388.2982	1	0	1	1	1	9000	6311.111	241.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
389.3	1	0	1	1	1	9000	6322.222	240.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
390.3018	1	0	1	1	1	9000	6333.333	240	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
391.3036	1	0	1	1	1	9000	6344.444	239.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
392.3055	1	0	1	1	1	9000	6355.556	238.667	90	-3.42993	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5304	0.0782	1679.85
393.3073	1	0	1	1	1	9000	6366.667	238	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
394.3091	1	0	1	1	1	9000	6377.778	237.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
395.3109	1	0	1	1	1	9000	6388.889	236.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
396.3127	1	0	1	1	1	9000	6400	236	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
397.3145	1	0	1	1	1	9000	6411.111	235.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
398.3163	1	0	1	1	1	9000	6422.222	234.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
399.3181	1	0	1	1	1	9000	6433.333	234	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
400.3199	1	0	1	1	1	9000	6444.444	233.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
401.3217	1	0	1	1	1	9000	6455.556	232.667	90	-3.42993	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5304	0.0782	1679.85
402.3235	1	0	1	1	1	9000	6466.667	232	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
403.3253	1	0	1	1	1	9000	6477.778	231.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
404.3271	1	0	1	1	1	9000	6488.889	230.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
405.3289	1	0	1	1	1	9000	6500	230	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
406.3307	1	0	1	1	1	9000	6511.111	229.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
407.3325	1	0	1	1	1	9000	6522.222	228.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
408.3343	1	0	1	1	1	9000	6533.333	228	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
409.3361	1	0	1	1	1	9000	6544.444	227.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
410.338	1	0	1	1	1	9000	6555.556	226.667	90	-3.42993	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5304	0.0782	1679.85
411.3398	1	0	1	1	1	9000	6566.667	226	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
412.3416	1	0	1	1	1	9000	6577.778	225.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
413.3434	1	0	1	1	1	9000	6588.889	224.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
414.3452	1	0	1	1	1	9000	6600	224	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
415.347	1	0	1	1	1	9000	6611.111	223.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
416.3488	1	0	1	1	1	9000	6622.222	222.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
417.3506	1	0	1	1	1	9000	6633.333	222	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
418.3524	1	0	1	1	1	9000	6644.444	221.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
419.3543	1	0	1	1	1	9000	6655.556	220.667	90	-3.42993	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5304	0.0782	1679.85
420.3561	1	0	1	1	1	9000	6666.667	220	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
421.3579	1	0	1	1	1	9000	6677.778	219.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
422.3597	1	0	1	1	1	9000	6688.889	218.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
423.3615	1	0	1	1	1	9000	6700	218	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
424.3633	1	0	1	1	1	9000	6711.111	217.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
425.3651	1	0	1	1	1	9000	6722.222	216.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
426.3669	1	0	1	1	1	9000	6733.333	216	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
427.3687	1	0	1	1	1	9000	6744.444	215.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
428.3706	1	0	1	1	1	9000	6755.556	214.667	90	-3.42993	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5304	0.0782	1679.85
429.3724	1	0	1	1	1	9000	6766.667	214	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
430.3742	1	0	1	1	1	9000	6777.778	213.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
431.376	1	0	1	1	1	9000	6788.889	212.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
432.3778	1	0	1	1	1	9000	6800	212	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
433.3796	1	0	1	1	1	9000	6811.111	211.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
434.3814	1	0	1	1	1	9000	6822.222	210.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
435.3832	1	0	1	1	1	9000	6833.333	210	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
436.385	1	0	1	1	1	9000	6844.444	209.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
437.3868	1	0	1	1	1	9000	6855.556	208.667	90	-3.42993	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5304	0.0782	1679.85
438.3886	1	0	1	1	1	9000	6866.667	208	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
439.3904	1	0	1	1	1	9000	6877.778	207.333	90	-3.43538	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.71
440.3922	1	0	1	1	1	9000	6888.889	206.667	90	-3.43024	-6	0	99.41939	0	0	0	0	0	0.5294	0.0781	1676.69		0.5303	0.0782	1679.70
441.3939	1	0	1	1	1	9000	6900	206.016	90	-3.35316	-5.703	0	99.41939	0	0	0	0	0	0.5107	0.0840	1762.58		0.5303	0.0782	1679.57
442.3955	1	0	1	1	1	9000	6911.111	205.399	90	-3.1784	-5.402	0	99.41939	0	0	0	0	0	0.4918	0.0900	1849.62		0.5115	0.0841	1765.30
443.3969	1	0	1	1	1	9000	6922.222	204.816	90	-3.00359	-5.102	0	99.41939	0	0	0	0	0	0.4730	0.0959	1936.38		0.4925	0.0901	1852.16
444.3981	1	0	1	1	1	9000	6933.333	204.266	90	-2.83386	-4.802	0	99.41939	0	0	0	0	0	0.4542	0.1019	2023.14		0.4736	0.0961	1938.75
445.3992	1	0	1	1	1	9000	6944.444	203.749	90	-2.66408	-4.502	0	99.41939	0	0	0	0	0	0.4353	0.1079	2109.89		0.4547	0.1020	2025.33
446.4002	1	0	1	1	1	9000	6955.556	203.265	90	-2.49403	-4.201	0	99.41939	0	0	0	0	0	0.4164	0.1138	2196.94		0.4358	0.1080	2112.08

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)	Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
447.401	1	0	1	1	1	9000	6966.667	202.815	90	-2.31923	-3.901	0	99.41939	0	0	0	0	0	0.3951	0.1195	2276.45	0.4168	0.1139	2198.74
448.4017	1	0	1	1	1	9000	6977.778	202.398	90	-2.14932	-3.601	0	99.41939	0	0	0	0	0	0.3686	0.1244	2341.25	0.3953	0.1196	2278.05
449.4023	1	0	1	1	1	9000	6988.889	202.015	90	-1.97422	-3.3	0	99.41939	0	0	0	0	0	0.3420	0.1293	2406.26	0.3688	0.1245	2342.64
450.4028	1	0	1	1	1	9000	7000	201.665	90	-1.80424	-3	0	99.41939	0	0	0	0	0	0.3155	0.1342	2471.06	0.3421	0.1294	2407.45
451.4032	1	0	1	1	1	9000	7011.111	201.348	90	-1.63422	-2.7	0	99.41939	0	0	0	0	0	0.2890	0.1392	2535.86	0.3156	0.1343	2472.07
452.4036	1	0	1	1	1	9000	7022.222	201.065	90	-1.45902	-2.399	0	99.41939	0	0	0	0	0	0.2624	0.1441	2600.87	0.2891	0.1392	2536.68
453.4038	1	0	1	1	1	9000	7033.333	200.815	90	-1.28895	-2.099	0	99.41939	0	0	0	0	0	0.2359	0.1490	2665.67	0.2624	0.1441	2601.53
454.404	1	0	1	1	1	9000	7044.444	200.599	90	-1.1137	-1.799	0	99.41939	0	0	0	0	0	0.2162	0.1515	2721.18	0.2359	0.1491	2666.17
455.4042	1	0	1	1	1	9000	7055.556	200.415	90	-0.94866	-1.499	0	99.41939	0	0	0	0	0	0.1998	0.1528	2772.11	0.2162	0.1516	2721.80
456.4043	1	0	1	1	1	9000	7066.667	200.266	90	-0.7683	-1.198	0	99.41939	0	0	0	0	0	0.1834	0.1541	2823.21	0.1998	0.1528	2772.36
457.4044	1	0	1	1	1	9000	7077.778	200.149	90	-0.60331	-0.898	0	99.41939	0	0	0	0	0	0.1670	0.1554	2874.15	0.1834	0.1541	2823.37
458.4044	1	0	1	1	1	9000	7088.889	200.066	90	-0.428	-0.598	0	99.41939	0	0	0	0	0	0.1506	0.1567	2925.08	0.1670	0.1554	2874.23
459.4044	1	0	1	1	1	9000	7100	200.016	90	-0.25783	-0.297	0	99.41939	0	0	0	0	0	0.1342	0.1580	2976.19	0.1506	0.1567	2925.11
460.4044	1	0	1	1	1	9000	7111.111	200	90	-0.08251	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1342	0.1580	2976.19
461.4044	1	0	1	1	1	9000	7122.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.61
462.4044	1	0	1	1	1	9000	7133.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.61
463.4044	1	0	1	1	1	9000	7144.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.61
464.4045	1	0	1	1	1	9000	7155.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.88
465.4045	1	0	1	1	1	9000	7166.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.61
466.4045	1	0	1	1	1	9000	7177.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.61
467.4045	1	0	1	1	1	9000	7188.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.61
468.4045	1	0	1	1	1	9000	7200	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.61
469.4045	1	0	1	1	1	9000	7211.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.61
470.4045	1	0	1	1	1	9000	7222.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61	0.1180	0.1593	3026.61

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
471.4045	1	0	1	1	1	9000	7233.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
472.4045	1	0	1	1	1	9000	7244.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
473.4046	1	0	1	1	1	9000	7255.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
474.4046	1	0	1	1	1	9000	7266.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
475.4046	1	0	1	1	1	9000	7277.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
476.4046	1	0	1	1	1	9000	7288.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
477.4046	1	0	1	1	1	9000	7300	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
478.4046	1	0	1	1	1	9000	7311.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
479.4046	1	0	1	1	1	9000	7322.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
480.4046	1	0	1	1	1	9000	7333.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
481.4046	1	0	1	1	1	9000	7344.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
482.4047	1	0	1	1	1	9000	7355.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
483.4047	1	0	1	1	1	9000	7366.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
484.4047	1	0	1	1	1	9000	7377.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
485.4047	1	0	1	1	1	9000	7388.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
486.4047	1	0	1	1	1	9000	7400	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
487.4047	1	0	1	1	1	9000	7411.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
488.4047	1	0	1	1	1	9000	7422.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
489.4047	1	0	1	1	1	9000	7433.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
490.4047	1	0	1	1	1	9000	7444.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
491.4048	1	0	1	1	1	9000	7455.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
492.4048	1	0	1	1	1	9000	7466.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
493.4048	1	0	1	1	1	9000	7477.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
494.4048	1	0	1	1	1	9000	7488.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
495.4048	1	0	1	1	1	9000	7500	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
496.4048	1	0	1	1	1	9000	7511.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
497.4048	1	0	1	1	1	9000	7522.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
498.4048	1	0	1	1	1	9000	7533.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
499.4048	1	0	1	1	1	9000	7544.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
500.4049	1	0	1	1	1	9000	7555.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
501.4049	1	0	1	1	1	9000	7566.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
502.4049	1	0	1	1	1	9000	7577.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
503.4049	1	0	1	1	1	9000	7588.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
504.4049	1	0	1	1	1	9000	7600	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
505.4049	1	0	1	1	1	9000	7611.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
506.4049	1	0	1	1	1	9000	7622.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
507.4049	1	0	1	1	1	9000	7633.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
508.4049	1	0	1	1	1	9000	7644.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
509.4049	1	0	1	1	1	9000	7655.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
510.4049	1	0	1	1	1	9000	7666.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
511.4049	1	0	1	1	1	9000	7677.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
512.4049	1	0	1	1	1	9000	7688.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
513.4049	1	0	1	1	1	9000	7700	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
514.4049	1	0	1	1	1	9000	7711.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
515.4049	1	0	1	1	1	9000	7722.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
516.4049	1	0	1	1	1	9000	7733.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
517.4049	1	0	1	1	1	9000	7744.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
518.405	1	0	1	1	1	9000	7755.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
519.405	1	0	1	1	1	9000	7766.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
520.405	1	0	1	1	1	9000	7777.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
521.405	1	0	1	1	1	9000	7788.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
522.405	1	0	1	1	1	9000	7800	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61

Timestamp	Link	Tag number	Base Type	Vehicle Type	Section Number	PosX (m)	PosY (m)	PosZ (m)	Bearing (deg from N)	Elevation (deg)	Gradient (deg)	Acceleration (mpss)	Speed (mph)	Angular Velocity (deg/sec)	Brake	Right Indicator	Left Indicator	Busboard	NOx (mg)	PM10 (mg)	Total Carbon (mg)		Amended NOx (mg)	Amended PM10 (mg)	Amended Total Carbon (mg)
523.405	1	0	1	1	1	9000	7811.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
524.405	1	0	1	1	1	9000	7822.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
525.405	1	0	1	1	1	9000	7833.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
526.405	1	0	1	1	1	9000	7844.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
527.4051	1	0	1	1	1	9000	7855.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
528.4051	1	0	1	1	1	9000	7866.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
529.4051	1	0	1	1	1	9000	7877.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
530.4051	1	0	1	1	1	9000	7888.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
531.4051	1	0	1	1	1	9000	7900	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
532.4051	1	0	1	1	1	9000	7911.111	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
533.4051	1	0	1	1	1	9000	7922.222	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
534.4051	1	0	1	1	1	9000	7933.333	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
535.4051	1	0	1	1	1	9000	7944.444	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
536.4052	1	0	1	1	1	9000	7955.556	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.88
537.4052	1	0	1	1	1	9000	7966.667	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
538.4052	1	0	1	1	1	9000	7977.778	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
539.4052	1	0	1	1	1	9000	7988.889	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61
540.4052	1	0	1	1	1	9000	8000	200	90	0	0	0	99.41939	0	0	0	0	0	0.1180	0.1593	3026.61		0.1180	0.1593	3026.61

Table E. 2 Example of PHEM post-processor inputs and outputs for +6% -6% alignment and vehicle speed of 160 kph

Appendix F: Details of machinery pairings

Bulk Excavation : Outputs / Cycle Time data

Excavator pairing 3: 45 T Exc and 35 T ADT

1	Approx Excavator Weight in Tonnes	45 TONS
2	Excavator Bucket Size	2.90 m3
3	Minutes Worked Per Hour	50 Mins
4	Cycle Time in Seconds	26 Seconds
5	No of Cycles per	115 No
6	Bulking Factor	100%
7	Maximum Theoretical Excavator Output (Dig & Cast to one side)	335 m3/Hr
9	Calculated Output Based on Cycle Time Loading Vehicles	281 m3/Hr
10	Load Capacity of Haulage Unit	35.0 TONS
11	Type of Material to Be Carried	2B - Dry Cohesive
12	Density of Material to Be Carried	2.00 T/m3
13	Haulage Unit Capacity Based on a Density of Material	17.4 m3
14	Spot Time Under Excavator	0.50 Mins
15	Time Allowed to Tip	0.50 Mins
16	Load Time for Dumptruck	2.60 Mins
17	Assumed Effective Hours Per Day	9.50 Hrs
18	Fuel consumption Excavator (litres/hour)	52
19	Fuel consumption ADT (litres/hour)	29
20	CO2 emission for road haul per m3 (kg/km)	0.200
21	Time taken to spread 10m3 with D7 (seconds)	75.00
22	Fuel consumption D7 Dozer (litres/hour)	34.20
23	Depth of layers for compaction (m)	0.30
24	No. Of passes	4.00
25	Width of roller (m)	2.13
26	Roller speed (m/s)	0.83
27	Roller output (m3/hr)	366.48
28	Transportation distance of lime (km)	80
29	Density of lime (t/m3)	0.88
30	CO2 emission for road haul per m3 of lime (kg/km)	0.09

The Figure below shows how Full the Dumptruck is - Try Changing the Size of the Dumptruck to optimise the Usage of the Dumptruck	
99.43%	**CHECK EXCAVATOR AND DUMPTRUCK SIZING**

Bulk Excavation : Outputs / Cycle Time data

Excavator pairing 2: 35 T Exc and 30 T ADT

1	Approx Excavator Weight in Tonnes	35 TONS
2	Excavator Bucket Size	1.85 m3
3	Minutes Worked Per Hour	50 Mins
4	Cycle Time in Seconds	26 Seconds
5	No of Cycles per	115 No
6	Bulking Factor	100%
7	Maximum Theoretical Excavator Output (Dig & Cast to one side)	213 m3/Hr
9	Calculated Output Based on Cycle Time Loading Vehicles	186 m3/Hr
10	Load Capacity of Haulage Unit	30.0 TONS
11	Type of Material to Be Carried	6M - 75mm Down
12	Density of Material to Be Carried	2.00 T/m3
13	Haulage Unit Capacity Based on a Density of Material	14.8 m3
14	Spot Time Under Excavator	0.50 Mins
15	Time Allowed to Tip	0.50 Mins
16	Load Time for Dumptruck	3.47 Mins
17	Assumed Effective Hours Per Day	9.50 Hrs
18	Fuel consumption Excavator (litres/hour)	36
19	Fuel consumption ADT (litres/hour)	29
20	CO2 emission for road haul per m3 (kg/km)	0.200
21	Time taken to spread 10m3 with D7 (seconds)	75.00
22	Fuel consumption D7 Dozer (litres/hour)	34.20
23	Depth of layers for compaction (m)	0.30
24	No. Of passes	4.00
25	Width of roller (m)	2.13
26	Roller speed (m/s)	0.83
27	Roller output (m3/hr)	366.48
28	Transportation distance of lime (km)	80
29	Density of lime (t/m3)	0.88
30	CO2 emission for road haul per m3 of lime (kg/km)	0.09

The Figure below shows how Full the Dumptruck is - Try Changing the Size of the Dumptruck to optimise the Usage of the Dumptruck	
98.67%	**CHECK EXCAVATOR AND DUMPTRUCK SIZING**

Bulk Excavation : Outputs / Cycle Time data

Excavator pairing 1: 25 T Exc and 30 T ADT

1	Approx Excavator Weight in Tonnes	25 TONS
2	Excavator Bucket Size	1.35 m3
3	Minutes Worked Per Hour	50 Mins
4	Cycle Time in Seconds	25 Seconds
5	No of Cycles per	120 No
6	Bulking Factor	100%
7	Maximum Theoretical Excavator Output (Dig & Cast to one side)	162 m3/Hr
9	Calculated Output Based on Cycle Time Loading Vehicles	146 m3/Hr
10	Load Capacity of Haulage Unit	30.0 TONS
11	Type of Material to Be Carried	2B - Dry Cohesive
12	Density of Material to Be Carried	2.00 T/m3
13	Haulage Unit Capacity Based on a Density of Material	14.9 m3
14	Spot Time Under Excavator	0.50 Mins
15	Time Allowed to Tip	0.50 Mins
16	Load Time for Dumptruck	4.58 Mins
17	Assumed Effective Hours Per Day	9.50 Hrs
18	Fuel consumption Excavator (litres/hour)	20
19	Fuel consumption ADT (litres/hour)	29
20	CO2 emission for road haul per m3 (kg/km)	0.200
21	Time taken to spread 10m3 with D7 (seconds)	75.00
22	Fuel consumption D7 Dozer (litres/hour)	34.20
23	Depth of layers for compaction (m)	0.30
24	No. Of passes	4.00
25	Width of roller (m)	2.13
26	Roller speed (m/s)	0.83
27	Roller output (m3/hr)	366.48
28	Transportation distance of lime (km)	80
29	Density of lime (t/m3)	0.88
30	CO2 emission for road haul per m3 of lime (kg/km)	0.09

The Figure below shows how Full the Dumptruck is - Try Changing the Size of the Dumptruck to optimise the Usage of the Dumptruck	
99.00%	**CHECK EXCAVATOR AND DUMPTRUCK SIZING**

Appendix G: Mass haul details

Scheme A1: Case 1 - No lime

MASS HAUL INFORMATION															Lime	
		From						To								
Item	Haulage	From external	Source Point	Road haul (m)	Deposition zone / Excavation zone	Material Type	Volume (m3)	Double handling	Deposition Zone / Excavation zone	Excavator Number	Site haulage Distance (m)	To external	End point	Road haul distance (m)	% of fill to be treated	% of lime added by dry weight
1	ADT				4		1463		3	1	200					
2	ADT				5		5641		2	1	600					
3	ADT				5		4410		3	1	400					
4	ADT				6		11715		3	1	600					
5	ADT				7		678		3	1	800					
6	ADT				7		7404		8	1	200					
7	ADT				10		236		8	1	400					
8	ADT				25		3358		20	1	1000					
9	ADT				24		39385		21	1	600					
10	ADT				25		20425		21	1	800					
11	ADT				23		20441		22	1	200					
12	ADT				24		467		22	1	400					
13	ADT				25		1837		27	1	400					
14	ADT				25		5856		28	1	600					
15	ADT				25		8994		29	1	800					
16	ADT				26		5040		29	1	600					
17	ADT				26		3963		30	1	625.535					
18	ADT				26		497		30	1	625.535					
19	ADT				Int SP1		32837		8	1	600					
20	ADT				Int SP1		40814		9	1	400					
21	ADT				Int SP1		20861		11	1	50					
22	ADT				Int SP1		62016		12	1	200					
23	ADT				Int SP1		158416		13	1	400					
24	ADT				Int SP1		127281		14	1	600					
25	ADT				Int SP2		265527		15	1	200					
26	ADT				Int SP2		256788		16	1	50					
27	ADT				Int SP2		102415		17	1	200					
28	ADT				Int SP2		73790		18	1	400					
29	ADT				Int SP2		67580		19	1	600					
30	ADT				Int SP2		75279		20	1	800					
31	Road	Yes		5000	Source 1		442225		Int SP1	1						
32	Road	Yes		5000	Source 2		841379		Int SP2	1						

	EXCAVATOR OUTPUTS		DURATIONS			CYCLE TIMES (ADT / ROAD WAGON)										No. of ADT's	No. of Road Wagons
Item	EXC (m3/hr)	GANG (m3/hr)	Hours	Working Hours	Days	Load time (ADT)	Speed (km/hr)	Haulage (min)	Obstruct (min)	Spot	Load	Cycle (min)	Cycles (50min)	Capacity	ADT's (Actual)	ADT'S (Rnd Up)	Road Wagons (Rnd Up)
1	162	146	10.02	9.5	2	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
2	162	146	38.64	9.5	5	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
3	162	146	30.21	9.5	4	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
4	162	146	80.24	9.5	9	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
5	162	146	4.64	9.5	1	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
6	162	146	50.71	9.5	6	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
7	162	146	1.62	9.5	1	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
8	162	146	23.00	9.5	3	4.58	16	3.75	0.0	0.50	0.50	13.08	3.82	14.9	2.6	3.0	0.0
9	162	146	269.76	9.5	29	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
10	162	146	139.90	9.5	15	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
11	162	146	140.01	9.5	15	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
12	162	146	3.20	9.5	1	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
13	162	146	12.58	9.5	2	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
14	162	146	40.11	9.5	5	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
15	162	146	61.60	9.5	7	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
16	162	146	34.52	9.5	4	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
17	162	146	27.14	9.5	3	4.58	14	2.68	0.0	0.50	0.50	10.94	4.57	14.9	2.2	3.0	0.0
18	162	146	3.40	9.5	1	4.58	14	2.68	0.0	0.50	0.50	10.94	4.57	14.9	2.2	3.0	0.0
19	162	146	224.91	9.5	24	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
20	162	146	279.55	9.5	30	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
21	162	146	142.88	9.5	16	4.58	10	0.30	0.0	0.50	0.50	6.18	8.09	14.9	1.2	2.0	0.0
22	162	146	424.77	9.5	45	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
23	162	146	1085.04	9.5	115	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
24	162	146	871.79	9.5	92	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
25	162	146	1818.68	9.5	192	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
26	162	146	1758.82	9.5	186	4.58	10	0.30	0.0	0.50	0.50	6.18	8.09	14.9	1.2	2.0	0.0
27	162	146	701.47	9.5	74	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
28	162	146	505.41	9.5	54	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
29	162	146	462.88	9.5	49	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
30	162	146	515.61	9.5	55	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
31	162	146	3028.94	9.5	319	4.58	0	0.00	0.0	0.50	0.50	5.58	8.96	14.9	1.1	0.0	2.0
32	162	146	5762.87	9.5	607	4.58	0	0.00	0.0	0.50	0.50	5.58	8.96	14.9	1.1	0.0	2.0

	Excavate			Site haul			Road haul		Place		Compact			Lime				
Item	Excavator hours	Excavator fuel (litres)	Excavator CO2 (kg)	ADT hours	ADT fuel (litres)	ADT CO2 (kg)	To site Road haul CO2 (kg)	From site Road haul CO2 (kg)	Dozer hours	Dozer CO2 (kg)	Compactor hours	Compactor fuel (litres)	Compactor CO2 (kg)	Quantity of lime required (tonnes)	Embodied CO2 in lime (kg)	Volume of lime required (m3)	CO2 from transportation of lime to site(kg)	CO2 from modification process(kg)
1	10.02	202.42	559	20.04	581.59	1606	0.00	0.00	3.048	287.91	3.99	71.86	198	0.00	0	0	0.00	0.00
2	38.64	780.47	2156	115.91	3363.74	9291	0.00	0.00	11.75	1110	15.39	277.06	765	0.00	0	0	0.00	0.00
3	30.21	610.15	1685	60.41	1753.13	4842	0.00	0.00	9.19	868	12.03	216.60	598	0.00	0	0	0.00	0.00
4	80.24	1620.84	4477	240.72	6985.67	19294	0.00	0.00	24.41	2305	31.97	575.39	1589	0.00	0	0	0.00	0.00
5	4.64	93.81	259	13.93	404.29	1117	0.00	0.00	1.41	133	1.85	33.30	92	0.00	0	0	0.00	0.00
6	50.71	1024.39	2829	101.42	2943.34	8130	0.00	0.00	15.43	1457	20.20	363.65	1004	0.00	0	0	0.00	0.00
7	1.62	32.65	90	3.23	93.82	259	0.00	0.00	0.49	46	0.64	11.59	32	0.00	0	0	0.00	0.00
8	23.00	464.60	1283	69.00	2002.38	5531	0.00	0.00	7.00	661	9.16	164.93	456	0.00	0	0	0.00	0.00
9	269.76	5449.16	15051	809.28	23485.33	64866	0.00	0.00	82.05	7751	107.47	1934.43	5343	0.00	0	0	0.00	0.00
10	139.90	2825.92	7805	419.69	12179.46	33640	0.00	0.00	42.55	4019	55.73	1003.19	2771	0.00	0	0	0.00	0.00
11	140.01	2828.14	7811	280.01	8126.00	22444	0.00	0.00	42.59	4023	55.78	1003.98	2773	0.00	0	0	0.00	0.00
12	3.20	64.61	178	6.40	185.65	513	0.00	0.00	0.97	92	1.27	22.94	63	0.00	0	0	0.00	0.00
13	12.58	254.16	702	25.16	730.27	2017	0.00	0.00	3.83	362	5.01	90.23	249	0.00	0	0	0.00	0.00
14	40.11	810.21	2238	120.33	3491.94	9645	0.00	0.00	12.20	1152	15.98	287.62	794	0.00	0	0	0.00	0.00
15	61.60	1244.38	3437	184.81	5363.13	14813	0.00	0.00	18.74	1770	24.54	441.75	1220	0.00	0	0	0.00	0.00
16	34.52	697.32	1926	103.56	3005.36	8301	0.00	0.00	10.50	992	13.75	247.54	684	0.00	0	0	0.00	0.00
17	27.14	548.31	1514	81.43	2363.14	6527	0.00	0.00	8.26	780	10.81	194.65	538	0.00	0	0	0.00	0.00
18	3.40	68.76	190	10.21	296.36	819	0.00	0.00	1.04	98	1.36	24.41	67	0.00	0	0	0.00	0.00
19	224.91	4543.20	12548	674.73	19580.75	54082	0.00	0.00	68.41	6462	89.60	1612.82	4455	0.00	0	0	0.00	0.00
20	279.55	5646.87	15597	559.10	16224.96	44813	0.00	0.00	85.03	8032	111.37	2004.62	5537	0.00	0	0	0.00	0.00
21	142.88	2886.25	7972	285.77	8292.96	22905	0.00	0.00	43.46	4105	56.92	1024.61	2830	0.00	0	0	0.00	0.00
22	424.77	8580.30	23699	849.53	24653.48	68093	0.00	0.00	129.20	12204	169.22	3045.98	8413	0.00	0	0	0.00	0.00
23	1085.04	21917.83	60537	2170.08	62975.79	173939	0.00	0.00	330.03	31175	432.26	7780.76	21490	0.00	0	0	0.00	0.00
24	871.79	17610.11	48639	2615.36	75897.83	209630	0.00	0.00	265.17	25048	347.31	6251.53	17267	0.00	0	0	0.00	0.00
25	1818.68	36737.30	101468	3637.36	105556.08	291546	0.00	0.00	553.18	52254	724.53	13041.62	36021	0.00	0	0	0.00	0.00
26	1758.82	35528.20	98129	3517.64	102082.02	281951	0.00	0.00	534.98	50534	700.69	12612.39	34835	0.00	0	0	0.00	0.00
27	701.47	14169.75	39137	1402.95	40713.47	112451	0.00	0.00	213.36	20155	279.46	5030.21	13893	0.00	0	0	0.00	0.00
28	505.41	10209.30	28198	1010.82	29334.05	81021	0.00	0.00	153.73	14521	201.35	3624.27	10010	0.00	0	0	0.00	0.00
29	462.88	9350.11	25825	1388.63	40298.05	111303	0.00	0.00	140.79	13299	184.40	3319.26	9168	0.00	0	0	0.00	0.00
30	515.61	10415.31	28767	1546.83	44888.97	123983	0.00	0.00	156.83	14814	205.41	3697.40	10212	0.00	0	0	0.00	0.00
31	3028.94	61184.55	168992	0.00	0.00	0	442225.00	0.00	921.30	87027	1206.68	21720.31	59991	0.00	0	0	0.00	0.00
32	5762.87	116409.97	321524	0.00	0.00	0	841379.00	0.00	1752.87	165577	2295.84	41325.14	114140	0.00	0	0	0.00	0.00

Scheme A1: Case 2 - 20% of fill treated with 2% lime

MASS HAUL INFORMATION

		From						To							Lime	
Item	Haulage	From external	Source Point	Road haul (m)	Deposition zone / Excavation zone	Material Type	Volume (m3)	Double handling	Deposition Zone / Excavation zone	Excavator Number	Site haulage Distance (m)	To external	End point	Road haul distance (m)	% of fill to be treated	% of lime added by dry weight
1	ADT				4		1463		3	1	200				20%	2%
2	ADT				5		5641		2	1	600				20%	2%
3	ADT				5		4410		3	1	400				20%	2%
4	ADT				6		11715		3	1	600				20%	2%
5	ADT				7		678		3	1	800				20%	2%
6	ADT				7		7404		8	1	200				20%	2%
7	ADT				10		236		8	1	400				20%	2%
8	ADT				25		3358		20	1	1000				20%	2%
9	ADT				24		39385		21	1	600				20%	2%
10	ADT				25		20425		21	1	800				20%	2%
11	ADT				23		20441		22	1	200				20%	2%
12	ADT				24		467		22	1	400				20%	2%
13	ADT				25		1837		27	1	400				20%	2%
14	ADT				25		5856		28	1	600				20%	2%
15	ADT				25		8994		29	1	800				20%	2%
16	ADT				26		5040		29	1	600				20%	2%
17	ADT				26		3963		30	1	625.535				20%	2%
18	ADT				26		497		30	1	625.535				20%	2%
19	ADT				Int SP1		32837		8	1	600				20%	2%
20	ADT				Int SP1		40814		9	1	400				20%	2%
21	ADT				Int SP1		20861		11	1	50				20%	2%
22	ADT				Int SP1		62016		12	1	200				20%	2%
23	ADT				Int SP1		158416		13	1	400				20%	2%
24	ADT				Int SP1		127281		14	1	600				20%	2%
25	ADT				Int SP2		265527		15	1	200				20%	2%
26	ADT				Int SP2		256788		16	1	50				20%	2%
27	ADT				Int SP2		102415		17	1	200				20%	2%
28	ADT				Int SP2		73790		18	1	400				20%	2%
29	ADT				Int SP2		67580		19	1	600				20%	2%
30	ADT				Int SP2		75279		20	1	800				20%	2%
31	Road	Yes		5000	Source 1		442225		Int SP1	1						
32	Road	Yes		5000	Source 2		841379		Int SP2	1						

	EXCAVATOR OUTPUTS		DURATIONS			CYCLE TIMES (ADT / ROAD WAGON)										No. of ADT's	No. of Road Wagons
Item	EXC (m3/hr)	GANG (m3/hr)	Hours	Working Hours	Days	Load time (ADT)	Speed (km/hr)	Haulage (min)	Obstruct (min)	Spot	Load	Cycle (min)	Cycles (50min)	Capacity	ADT's (Actual)	ADT'S (Rnd Up)	Road Wagons (Rnd Up)
1	162	146	10.02	9.5	2	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
2	162	146	38.64	9.5	5	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
3	162	146	30.21	9.5	4	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
4	162	146	80.24	9.5	9	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
5	162	146	4.64	9.5	1	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
6	162	146	50.71	9.5	6	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
7	162	146	1.62	9.5	1	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
8	162	146	23.00	9.5	3	4.58	16	3.75	0.0	0.50	0.50	13.08	3.82	14.9	2.6	3.0	0.0
9	162	146	269.76	9.5	29	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
10	162	146	139.90	9.5	15	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
11	162	146	140.01	9.5	15	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
12	162	146	3.20	9.5	1	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
13	162	146	12.58	9.5	2	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
14	162	146	40.11	9.5	5	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
15	162	146	61.60	9.5	7	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
16	162	146	34.52	9.5	4	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
17	162	146	27.14	9.5	3	4.58	14	2.68	0.0	0.50	0.50	10.94	4.57	14.9	2.2	3.0	0.0
18	162	146	3.40	9.5	1	4.58	14	2.68	0.0	0.50	0.50	10.94	4.57	14.9	2.2	3.0	0.0
19	162	146	224.91	9.5	24	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
20	162	146	279.55	9.5	30	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
21	162	146	142.88	9.5	16	4.58	10	0.30	0.0	0.50	0.50	6.18	8.09	14.9	1.2	2.0	0.0
22	162	146	424.77	9.5	45	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
23	162	146	1085.04	9.5	115	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
24	162	146	871.79	9.5	92	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
25	162	146	1818.68	9.5	192	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
26	162	146	1758.82	9.5	186	4.58	10	0.30	0.0	0.50	0.50	6.18	8.09	14.9	1.2	2.0	0.0
27	162	146	701.47	9.5	74	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
28	162	146	505.41	9.5	54	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
29	162	146	462.88	9.5	49	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
30	162	146	515.61	9.5	55	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
31	162	146	3028.94	9.5	319	4.58	0	0.00	0.0	0.50	0.50	5.58	8.96	14.9	1.1	0.0	2.0
32	162	146	5762.87	9.5	607	4.58	0	0.00	0.0	0.50	0.50	5.58	8.96	14.9	1.1	0.0	2.0

	Excavate			Site haul			Road haul		Place	
Item	Excavator hours	Excavator fuel (litres)	Excavator CO2 (kg)	ADT hours	ADT fuel (litres)	ADT CO2 (kg)	To site Road haul CO2 (kg)	From site Road haul CO2 (kg)	Dozer hours	Dozer CO2 (kg)
1	10.02	202.42	559	20.04	581.59	1606	0.00	0.00	3.048	287.91
2	38.64	780.47	2156	115.91	3363.74	9291	0.00	0.00	11.75	1110
3	30.21	610.15	1685	60.41	1753.13	4842	0.00	0.00	9.19	868
4	80.24	1620.84	4477	240.72	6985.67	19294	0.00	0.00	24.41	2305
5	4.64	93.81	259	13.93	404.29	1117	0.00	0.00	1.41	133
6	50.71	1024.39	2829	101.42	2943.34	8130	0.00	0.00	15.43	1457
7	1.62	32.65	90	3.23	93.82	259	0.00	0.00	0.49	46
8	23.00	464.60	1283	69.00	2002.38	5531	0.00	0.00	7.00	661
9	269.76	5449.16	15051	809.28	23485.33	64866	0.00	0.00	82.05	7751
10	139.90	2825.92	7805	419.69	12179.46	33640	0.00	0.00	42.55	4019
11	140.01	2828.14	7811	280.01	8126.00	22444	0.00	0.00	42.59	4023
12	3.20	64.61	178	6.40	185.65	513	0.00	0.00	0.97	92
13	12.58	254.16	702	25.16	730.27	2017	0.00	0.00	3.83	362
14	40.11	810.21	2238	120.33	3491.94	9645	0.00	0.00	12.20	1152
15	61.60	1244.38	3437	184.81	5363.13	14813	0.00	0.00	18.74	1770
16	34.52	697.32	1926	103.56	3005.36	8301	0.00	0.00	10.50	992
17	27.14	548.31	1514	81.43	2363.14	6527	0.00	0.00	8.26	780
18	3.40	68.76	190	10.21	296.36	819	0.00	0.00	1.04	98
19	224.91	4543.20	12548	674.73	19580.75	54082	0.00	0.00	68.41	6462
20	279.55	5646.87	15597	559.10	16224.96	44813	0.00	0.00	85.03	8032
21	142.88	2886.25	7972	285.77	8292.96	22905	0.00	0.00	43.46	4105
22	424.77	8580.30	23699	849.53	24653.48	68093	0.00	0.00	129.20	12204
23	1085.04	21917.83	60537	2170.08	62975.79	173939	0.00	0.00	330.03	31175
24	871.79	17610.11	48639	2615.36	75897.83	209630	0.00	0.00	265.17	25048
25	1818.68	36737.30	101468	3637.36	105556.08	291546	0.00	0.00	553.18	52254
26	1758.82	35528.20	98129	3517.64	102082.02	281951	0.00	0.00	534.98	50534
27	701.47	14169.75	39137	1402.95	40713.47	112451	0.00	0.00	213.36	20155
28	505.41	10209.30	28198	1010.82	29334.05	81021	0.00	0.00	153.73	14521
29	462.88	9350.11	25825	1388.63	40298.05	111303	0.00	0.00	140.79	13299
30	515.61	10415.31	28767	1546.83	44888.97	123983	0.00	0.00	156.83	14814
31	3028.94	61184.55	168992	0.00	0.00	0	442225.00	0.00	921.30	87027
32	5762.87	116409.97	321524	0.00	0.00	0	841379.00	0.00	1752.87	165577

	Compact			Lime				
Item	Compactor hours	Compactor fuel (litres)	Compactor CO2 (kg)	Quantity of lime required (tonnes)	Embodied CO2 in lime (kg)	Volume of lime required (m3)	CO2 from transportation of lime to site(kg)	CO2 from modification process(kg)
1	3.99	71.86	198	11.70	8544	10	72.67	10.78
2	15.39	277.06	765	45.13	32943	40	280.21	41.55
3	12.03	216.60	598	35.28	25754	31	219.06	32.48
4	31.97	575.39	1589	93.72	68416	83	581.93	86.28
5	1.85	33.30	92	5.42	3960	5	33.68	4.99
6	20.20	363.65	1004	59.23	43239	52	367.79	54.53
7	0.64	11.59	32	1.89	1378	2	11.72	1.74
8	9.16	164.93	456	26.86	19611	24	166.81	24.73
9	107.47	1934.43	5343	315.08	230008	278	1956.42	290.08
10	55.73	1003.19	2771	163.40	119282	144	1014.60	150.44
11	55.78	1003.98	2773	163.53	119375	144	1015.39	150.55
12	1.27	22.94	63	3.74	2727	3	23.20	3.44
13	5.01	90.23	249	14.70	10728	13	91.25	13.53
14	15.98	287.62	794	46.85	34199	41	290.89	43.13
15	24.54	441.75	1220	71.95	52525	63	446.77	66.24
16	13.75	247.54	684	40.32	29434	36	250.36	37.12
17	10.81	194.65	538	31.70	23144	28	196.86	29.19
18	1.36	24.41	67	3.98	2902	4	24.69	3.66
19	89.60	1612.82	4455	262.70	191768	231	1631.16	241.86
20	111.37	2004.62	5537	326.51	238354	288	2027.41	300.61
21	56.92	1024.61	2830	166.89	121828	147	1036.26	153.65
22	169.22	3045.98	8413	496.13	362173	437	3080.60	456.77
23	432.26	7780.76	21490	1267.33	925149	1117	7869.20	1166.79
24	347.31	6251.53	17267	1018.25	743321	897	6322.60	937.47
25	724.53	13041.62	36021	2124.22	1550678	1871	13189.87	1955.69
26	700.69	12612.39	34835	2054.30	1499642	1810	12755.77	1891.33
27	279.46	5030.21	13893	819.32	598104	722	5087.39	754.32
28	201.35	3624.27	10010	590.32	430934	520	3665.47	543.49
29	184.40	3319.26	9168	540.64	394667	476	3356.99	497.75
30	205.41	3697.40	10212	602.23	439629	531	3739.43	554.45
31	1206.68	21720.31	59991	0.00	0	0	0.00	0.00
32	2295.84	41325.14	114140	0.00	0	0	0.00	0.00

Scheme A1: Case 1 - 40% fill treated with 2% lime

MASS HAUL INFORMATION

Item	Haulage	From: From external	From: Source Point	From: Road haul (m)	From: Deposition zone / Excavation zone	From: Material Type	From: Volume (m3)	To: Double handling	To: Deposition Zone / Excavation zone	To: Excavator Number	To: Site haulage Distance (m)	To: To external	To: End point	To: Road haul distance (m)	Lime: % of fill to be treated	Lime: % of lime added by dry weight
1	ADT				4		1463		3	1	200				40%	2%
2	ADT				5		5641		2	1	600				40%	2%
3	ADT				5		4410		3	1	400				40%	2%
4	ADT				6		11715		3	1	600				40%	2%
5	ADT				7		678		3	1	800				40%	2%
6	ADT				7		7404		8	1	200				40%	2%
7	ADT				10		236		8	1	400				40%	2%
8	ADT				25		3358		20	1	1000				40%	2%
9	ADT				24		39385		21	1	600				40%	2%
10	ADT				25		20425		21	1	800				40%	2%
11	ADT				23		20441		22	1	200				40%	2%
12	ADT				24		467		22	1	400				40%	2%
13	ADT				25		1837		27	1	400				40%	2%
14	ADT				25		5856		28	1	600				40%	2%
15	ADT				25		8994		29	1	800				40%	2%
16	ADT				26		5040		29	1	600				40%	2%
17	ADT				26		3963		30	1	625.535				40%	2%
18	ADT				26		497		30	1	625.535				40%	2%
19	ADT				Int SP1		32837		8	1	600				40%	2%
20	ADT				Int SP1		40814		9	1	400				40%	2%
21	ADT				Int SP1		20861		11	1	50				40%	2%
22	ADT				Int SP1		62016		12	1	200				40%	2%
23	ADT				Int SP1		158416		13	1	400				40%	2%
24	ADT				Int SP1		127281		14	1	600				40%	2%
25	ADT				Int SP2		265527		15	1	200				40%	2%
26	ADT				Int SP2		256788		16	1	50				40%	2%
27	ADT				Int SP2		102415		17	1	200				40%	2%
28	ADT				Int SP2		73790		18	1	400				40%	2%
29	ADT				Int SP2		67580		19	1	600				40%	2%
30	ADT				Int SP2		75279		20	1	800				40%	2%
31	Road	Yes		5000	Source 1		442225		Int SP1	1						
32	Road	Yes		5000	Source 2		841379		Int SP2	1						

Item	EXCAVATOR OUTPUTS: EXC (m3/hr)	EXCAVATOR OUTPUTS: GANG (m3/hr)	DURATIONS: Hours	DURATIONS: Working Hours	DURATIONS: Days	CYCLE TIMES (ADT / ROAD WAGON): Load time (ADT)	Speed (km/hr)	Haulage (min)	Obstruct (min)	Spot	Load	Cycle (min)	Cycles (50min)	Capacity	ADT's (Actual)	No. of ADT's: ADT'S (Rnd Up)	No. of Road Wagons: Road Wagons (Rnd Up)
1	162	146	10.02	9.5	2	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
2	162	146	38.64	9.5	5	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
3	162	146	30.21	9.5	4	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
4	162	146	80.24	9.5	9	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
5	162	146	4.64	9.5	1	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
6	162	146	50.71	9.5	6	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
7	162	146	1.62	9.5	1	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
8	162	146	23.00	9.5	3	4.58	16	3.75	0.0	0.50	0.50	13.08	3.82	14.9	2.6	3.0	0.0
9	162	146	269.76	9.5	29	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
10	162	146	139.90	9.5	15	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
11	162	146	140.01	9.5	15	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
12	162	146	3.20	9.5	1	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
13	162	146	12.58	9.5	2	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
14	162	146	40.11	9.5	5	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
15	162	146	61.60	9.5	7	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
16	162	146	34.52	9.5	4	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
17	162	146	27.14	9.5	3	4.58	14	2.68	0.0	0.50	0.50	10.94	4.57	14.9	2.2	3.0	0.0
18	162	146	3.40	9.5	1	4.58	14	2.68	0.0	0.50	0.50	10.94	4.57	14.9	2.2	3.0	0.0
19	162	146	224.91	9.5	24	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
20	162	146	279.55	9.5	30	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
21	162	146	142.88	9.5	16	4.58	10	0.30	0.0	0.50	0.50	6.18	8.09	14.9	1.2	2.0	0.0
22	162	146	424.77	9.5	45	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
23	162	146	1085.04	9.5	115	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
24	162	146	871.79	9.5	92	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
25	162	146	1818.68	9.5	192	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
26	162	146	1758.82	9.5	186	4.58	10	0.30	0.0	0.50	0.50	6.18	8.09	14.9	1.2	2.0	0.0
27	162	146	701.47	9.5	74	4.58	10	1.20	0.0	0.50	0.50	7.98	6.27	14.9	1.6	2.0	0.0
28	162	146	505.41	9.5	54	4.58	12	2.00	0.0	0.50	0.50	9.58	5.22	14.9	1.9	2.0	0.0
29	162	146	462.88	9.5	49	4.58	14	2.57	0.0	0.50	0.50	10.72	4.66	14.9	2.1	3.0	0.0
30	162	146	515.61	9.5	55	4.58	14	3.43	0.0	0.50	0.50	12.44	4.02	14.9	2.4	3.0	0.0
31	162	146	3028.94	9.5	319	4.58	0	0.00	0.0	0.50	0.50	5.58	8.96	14.9	1.1	0.0	2.0
32	162	146	5762.87	9.5	607	4.58	0	0.00	0.0	0.50	0.50	5.58	8.96	14.9	1.1	0.0	2.0

Item	Excavate: Excavator hours	Excavate: Excavator fuel (litres)	Excavate: Excavator CO2 (kg)	Site haul: ADT hours	Site haul: ADT fuel (litres)	Site haul: ADT CO2 (kg)	Road haul: To site Road haul CO2 (kg)	Road haul: From site Road haul CO2 (kg)	Place: Dozer hours	Place: Dozer CO2 (kg)
1	10.02	202.42	559	20.04	581.59	1606	0.00	0.00	3.048	287.91
2	38.64	780.47	2156	115.91	3363.74	9291	0.00	0.00	11.75	1110
3	30.21	610.15	1685	60.41	1753.13	4842	0.00	0.00	9.19	868
4	80.24	1620.84	4477	240.72	6985.67	19294	0.00	0.00	24.41	2305
5	4.64	93.81	259	13.93	404.29	1117	0.00	0.00	1.41	133
6	50.71	1024.39	2829	101.42	2943.34	8130	0.00	0.00	15.43	1457
7	1.62	32.65	90	3.23	93.82	259	0.00	0.00	0.49	46
8	23.00	464.60	1283	69.00	2002.38	5531	0.00	0.00	7.00	661
9	269.76	5449.16	15051	809.28	23485.33	64866	0.00	0.00	82.05	7751
10	139.90	2825.92	7805	419.69	12179.46	33640	0.00	0.00	42.55	4019
11	140.01	2828.14	7811	280.01	8126.00	22444	0.00	0.00	42.59	4023
12	3.20	64.61	178	6.40	185.65	513	0.00	0.00	0.97	92
13	12.58	254.16	702	25.16	730.27	2017	0.00	0.00	3.83	362
14	40.11	810.21	2238	120.33	3491.94	9645	0.00	0.00	12.20	1152
15	61.60	1244.38	3437	184.81	5363.13	14813	0.00	0.00	18.74	1770
16	34.52	697.32	1926	103.56	3005.36	8301	0.00	0.00	10.50	992
17	27.14	548.31	1514	81.43	2363.14	6527	0.00	0.00	8.26	780
18	3.40	68.76	190	10.21	296.36	819	0.00	0.00	1.04	98
19	224.91	4543.20	12548	674.73	19580.75	54082	0.00	0.00	68.41	6462
20	279.55	5646.87	15597	559.10	16224.96	44813	0.00	0.00	85.03	8032
21	142.88	2886.25	7972	285.77	8292.96	22905	0.00	0.00	43.46	4105
22	424.77	8580.30	23699	849.53	24653.48	68093	0.00	0.00	129.20	12204
23	1085.04	21917.83	60537	2170.08	62975.79	173939	0.00	0.00	330.03	31175
24	871.79	17610.11	48639	2615.36	75897.83	209630	0.00	0.00	265.17	25048
25	1818.68	36737.30	101468	3637.36	105556.08	291546	0.00	0.00	553.18	52254
26	1758.82	35528.20	98129	3517.64	102082.02	281951	0.00	0.00	534.98	50534
27	701.47	14169.75	39137	1402.95	40713.47	112451	0.00	0.00	213.36	20155
28	505.41	10209.30	28198	1010.82	29334.05	81021	0.00	0.00	153.73	14521
29	462.88	9350.11	25825	1388.63	40298.05	111303	0.00	0.00	140.79	13299
30	515.61	10415.31	28767	1546.83	44888.97	123983	0.00	0.00	156.83	14814
31	3028.94	61184.55	168992	0.00	0.00	0	442225.00	0.00	921.30	87027
32	5762.87	116409.97	321524	0.00	0.00	0	841379.00	0.00	1752.87	165577

Item	Compact: Compactor hours	Compact: Compactor fuel (litres)	Compact: Compactor CO2 (kg)	Lime: Quantity of lime required (tonnes)	Lime: Embodied CO2 in lime (kg)	Lime: Volume of lime required (m3)	Lime: CO2 from transportation of lime to site(kg)	Lime: CO2 from modification process(kg)
1	3.99	71.86	198	23.41	17088	21	145.35	21.55
2	15.39	277.06	765	90.26	65887	80	560.43	83.10
3	12.03	216.60	598	70.56	51509	62	438.13	64.96
4	31.97	575.39	1589	187.44	136831	165	1163.87	172.57
5	1.85	33.30	92	10.85	7919	10	67.36	9.99
6	20.20	363.65	1004	118.46	86479	104	735.58	109.07
7	0.64	11.59	32	3.78	2756	3	23.45	3.48
8	9.16	164.93	456	53.73	39221	47	333.61	49.47
9	107.47	1934.43	5343	630.16	460017	555	3912.84	580.17
10	55.73	1003.19	2771	326.80	238564	288	2029.20	300.87
11	55.78	1003.98	2773	327.06	238751	288	2030.78	301.11
12	1.27	22.94	63	7.47	5455	7	46.40	6.88
13	5.01	90.23	249	29.39	21456	26	182.50	27.06
14	15.98	287.62	794	93.70	68398	83	581.79	86.26
15	24.54	441.75	1220	143.90	105050	127	893.54	132.49
16	13.75	247.54	684	80.64	58867	71	500.72	74.24
17	10.81	194.65	538	63.41	46288	56	393.72	58.38
18	1.36	24.41	67	7.95	5805	7	49.38	7.32
19	89.60	1612.82	4455	525.39	383536	463	3262.31	483.71
20	111.37	2004.62	5537	653.02	476708	575	4054.81	601.22
21	56.92	1024.61	2830	333.78	243656	294	2072.51	307.30
22	169.22	3045.98	8413	992.26	724347	874	6161.20	913.54
23	432.26	7780.76	21490	2534.66	1850299	2233	15738.41	2333.57
24	347.31	6251.53	17267	2036.50	1486642	1794	12645.19	1874.93
25	724.53	13041.62	36021	4248.43	3101355	3743	26379.74	3911.39
26	700.69	12612.39	34835	4108.61	2999284	3620	25511.53	3782.66
27	279.46	5030.21	13893	1638.64	1196207	1444	10174.79	1508.64
28	201.35	3624.27	10010	1180.64	861867	1040	7330.93	1086.98
29	184.40	3319.26	9168	1081.28	789334	953	6713.98	995.50
30	205.41	3697.40	10212	1204.46	879259	1061	7478.86	1108.91
31	1206.68	21720.31	59991	0.00	0	0	0.00	0.00
32	2295.84	41325.14	114140	0.00	0	0	0.00	0.00

Appendix H: Earthworks mass haul for viaduct and embankment

MASS HAUL INFORMATION							
		From			To		
Item	Haulage	Source Zone	Material Type	Volume (m3)	Deposition Zone	Excavator Number	Haulage Distance
1	ADT	1	Emb	168	1	3	200
2	ADT	1	Emb	13956	3B	3	500
3	ROAD	1	Emb	52729	SPILE	3	4300
4	ADT	2	Emb	10509	3	3	400
5	ROAD	2	Emb	13248	SPILE	3	4300
6	ADT	3	Emb	1854	3	3	200
7	ROAD	3	Emb	2369	SPILE	3	4300
8	ADT	3A	Emb	2494	3A	3	200
9	ROAD	3A	Emb	4093	SPILE	3	4300
10	ADT	3B	Emb	14268	3B	3	200
11	ADT	5A	Emb	4067	5	3	400
12	ADT	5A	Emb	6793	5A	3	200
14	ADT	5A	Emb	5752	8	3	500
15	ROAD	5A	Emb	4236	SPILE	3	4300
16	ADT	5A	ROCK	21175	PCESSw	2	1500
17	ADT	5B	Emb	1061	5B	3	200
18	ROAD	5B	Emb	578	SPILE	3	4300
19	ADT	5B	ROCK	1628	PCESSw	2	1500
20	ADT	6	Emb	1089	7B	3	300
21	ADT	6	Emb	290	SPILE	3	4300
22	ADT	6	ROCK	818	PCESSw	2	1500
24	ADT	7A	Emb	1803	7A	3	200
25	ADT	7A	Emb	1605	8	3	400
26	ADT	7A	Emb	842	SPILE	3	4300
27	ADT	7A	ROCK	4261	PCESSw	2	1000
28	ADT	7B	Emb	45	7A	3	300
29	ADT	7B	Emb	522	SPILE	3	4300
31	ADT	8	Emb	1500	8	2	200
32	ADT	8	ROCK	1500	PCESSw	2	1000
33	ADT	9	Emb	2042	8	3	400
35	ADT	9	ROCK	2502	PCESSw	2	800
36	ADT	9A	Emb	7167	8	3	400
37	ADT	9A	Emb	277	9A	3	200
38	ADT	9A	ROCK	7444	PCESSw	2	800
39	ADT	9B	Emb	22764	8	3	400
40	ADT	9B	Emb	3304	13	3	800
41	ADT	9B	ROCK	26068	PCESSw	2	200
42	ADT	10	Emb	7123	8	3	600
43	ADT	10	ROCK	7183	PCESSw	2	200
44	ADT	11	Emb	35248	8	3	800
45	ADT	11	Emb	13158	13	3	400
46	ADT	11	Emb	2581	15	3	700
47	ADT	11	ROCK	13257	PCESSw	2	400
48	ROAD	12	Emb	19260	SPILE	3	1500
49	ADT	12	ROCK	7135	PCESSw	2	600
50	ADT	13	Emb	448	13	3	200
51	ROAD	13	Emb	50	SPILE	3	3000
52	ROAD	14	Emb	1729	SPILE	3	1200
53	ROAD	14	Emb	202	SPILE	3	2000
54	ADT	15	Emb	3543	15	3	200
55	ROAD	15	Emb	398	SPILE	3	3000
56	ADT	16	Emb	322	16	3	200
57	ROAD	16	Emb	31600	SPILE	3	600
58	ROAD	16	Emb	3547	SPILE	3	3000
59	ADT	16A	Emb	1699	16	3	300
60	ROAD	16A	Emb	1592	SPILE	3	600
61	ROAD	16A	Emb	355	SPILE	3	3000
62	ADT	16B	Emb	3473	16B	3	200
63	ADT	16B	Emb	8002	18	3	500
64	ROAD	16B	Emb	12300	SPILE	3	800
65	ROAD	16B	Emb	868	SPILE	3	3000
66	ADT	17	Emb	3417	17	3	200
67	ADT	17	Emb	16477	18	3	400
68	ADT	18	Emb	6600	18	3	200
69	ROAD	20	Emb	85388	SPILE	3	800
70	ROAD	21	Emb	16959	SPILE	3	100
71	ROAD	23	Emb	16959	SPILE	3	400
72	ROAD	24	Emb	5290	SPILE	3	700

73	ADT	24	Emb	7704	24	1	200
74	ADT	24A	Emb	874	24A	1	200
75	ADT	25	Emb	1360	25	1	200
76	ADT	26	Emb	13221	25	1	300
77	ADT	26	Emb	261	26	1	200
78	ADT	27	Emb	579	27A	1	200
79	ADT	27A	Emb	7846	27A	1	200
80	ADT	27C	Emb	1667	27C	1	200
81	ADT	28	Emb	3667	27A	1	300
82	ADT	28	Emb	121	28	1	300
83	ADT	29A	Emb	12386	27B	1	300
84	ADT	29B	Emb	4970	27B	1	600
85	ADT	30A	Emb	4036	27A	1	400
86	ADT	30A	Emb	4714	27B	1	400
87	ADT	30A	Emb	2382	30A	1	200
88	ADT	30B	Emb	3737	27C	1	400
89	ADT	30B	Emb	643	30B	1	200
90	ADT	31A	Emb	16342	27A	1	600
91	ADT	31A	Emb	2382	27B	1	600
92	ADT	31A	Emb	1521	27C	1	600
93	ADT	31A	Emb	2580	30A	1	400
94	ADT	31B	Emb	425	SPILE	3	800
95	ADT	33A	Emb	3025	27C	1	800
96	ADT	33A	Emb	2413	31B	1	600
97	ADT	33A	Emb	1369	32A	1	400
98	ADT	33A	Emb	1441	33A	1	200
99	ADT	33A	Emb	288	34A	1	400
100	ADT	33A	Emb	8915	SPILE	3	1000
101	ADT	33B	Emb	320	33B	1	200
102	ADT	34A	Emb	953	SPILE	3	1000
103	ADT	34B	Emb	1791	32B	1	600
104	ADT	ProcessW	Emb	0	SPILE	3	1500

Embankment option

MASS HAUL INFORMATION							
		From			To		
Item	Haulage	Source Zone	Material Type	Volume (m3)	Deposition Zone	Excavator Number	Haulage Distance
1	ADT	1	Emb	168	1	3	200
2	ADT	1	Emb	13956	3B	3	500
3	ROAD	1	Emb	52729	SPILE	3	4300
4	ADT	2	Emb	10509	3	3	400
5	ROAD	2	Emb	13248	SPILE	3	4300
6	ADT	3	Emb	1854	3	3	200
7	ROAD	3	Emb	2369	SPILE	3	4300
8	ADT	3A	Emb	2494	3A	3	200
9	ROAD	3A	Emb	4093	SPILE	3	4300
10	ADT	3B	Emb	14268	3B	3	200
11	ADT	5A	Emb	4067	5	3	400
12	ADT	5A	Emb	6793	5A	3	200
13	ADT	5A	Emb	327	7B	3	400
14	ADT	5A	Emb	5752	8	3	500
15	ROAD	5A	Emb	4236	SPILE	3	4300
16	ADT	5A	ROCK	21175	PCESSw	2	1500
17	ADT	5B	Emb	1061	5B	3	200
18	ROAD	5B	Emb	578	SPILE	3	4300
19	ADT	5B	ROCK	1628	PCESSw	2	1500
20	ADT	6	Emb	1089	7B	3	300
21	ADT	6	Emb	290	SPILE	3	4300
22	ADT	6	ROCK	818	PCESSw	2	1500
23	ADT	6A	Emb	412	6A	3	200
24	ADT	7A	Emb	1803	7A	3	200
25	ADT	7A	Emb	1605	8	3	400
26	ADT	7A	Emb	842	SPILE	3	4300
27	ADT	7A	ROCK	4261	PCESSw	2	1000
28	ADT	7B	Emb	45	7A	3	300
29	ADT	7B	Emb	522	SPILE	1	4300
30	ADT	7B	ROCK	479	PCESSw	3	1000
31	ADT	8	Emb	1500	8	2	200
32	ADT	8	ROCK	1500	PCESSw	2	1000
33	ADT	9	Emb	2042	8	3	400
34	ADT	9	Emb	460	9	3	200
35	ADT	9	ROCK	2502	PCESSw	2	800
36	ADT	9A	Emb	7167	8	3	400
37	ADT	9A	Emb	277	9A	3	200
38	ADT	9A	ROCK	7444	PCESSw	2	800
39	ADT	9B	Emb	22764	8	3	400
40	ADT	9B	Emb	3304	13	3	800
41	ADT	9B	ROCK	26068	PCESSw	2	200
42	ADT	10	Emb	7123	8	3	600
43	ADT	10	ROCK	7183	PCESSw	2	200
44	ADT	11	Emb	35248	8	3	800
45	ADT	11	Emb	13158	13	3	400
46	ADT	11	Emb	2581	15	3	700
47	ADT	11	ROCK	13257	PCESSw	2	400
48	ADT	12	Emb	19260	19	3	1500
49	ADT	12	ROCK	7135	PCESSw	2	600
50	ADT	13	Emb	448	13	3	200
51	ROAD	13	Emb	50	SPILE	3	3000
52	ADT	14	Emb	1729	19	3	1200
53	ROAD	14	Emb	202	SPILE	3	2000
54	ADT	15	Emb	3543	15	3	200
55	ROAD	15	Emb	398	SPILE	3	3000
56	ADT	16	Emb	322	16	3	200
57	ADT	16	Emb	31600	19	3	600
58	ROAD	16	Emb	3547	SPILE	3	3000
59	ADT	16A	Emb	1699	16	3	300
60	ADT	16A	Emb	1592	19	3	600
61	ROAD	16A	Emb	355	SPILE	3	3000
62	ADT	16B	Emb	3473	16B	3	200
63	ADT	16B	Emb	8002	18	3	500
64	ADT	16B	Emb	12300	19	3	800
65	ROAD	16B	Emb	868	SPILE	3	3000
66	ADT	17	Emb	3417	17	3	200

67	ADT	17	Emb	16477	18	3	400
68	ADT	18	Emb	6600	18	3	200
69	ADT	20	Emb	85388	19	1	800
70	ADT	21	Emb	16959	19	1	100
71	ADT	23	Emb	16959	19	1	400
72	ADT	24	Emb	5290	19	1	700
73	ADT	24	Emb	7704	24	1	200
74	ADT	24A	Emb	874	24A	1	200
75	ADT	25	Emb	1360	25	1	200
76	ADT	26	Emb	13221	25	1	300
77	ADT	26	Emb	261	26	1	200
78	ADT	27	Emb	579	27A	1	200
79	ADT	27A	Emb	7846	27A	1	200
80	ADT	27C	Emb	1667	27C	1	200
81	ADT	28	Emb	3667	27A	1	300
82	ADT	28	Emb	121	28	1	300
83	ADT	29A	Emb	12386	27B	1	300
84	ADT	29B	Emb	4970	27B	1	600
85	ADT	30A	Emb	4036	27A	1	400
86	ADT	30A	Emb	4714	27B	1	400
87	ADT	30A	Emb	2382	30A	1	200
88	ADT	30B	Emb	3737	27C	1	400
89	ADT	30B	Emb	643	30B	1	200
90	ADT	31A	Emb	16342	27A	1	600
91	ADT	31A	Emb	2382	27B	1	600
92	ADT	31A	Emb	1521	27C	1	600
93	ADT	31A	Emb	2580	30A	1	400
94	ADT	31B	Emb	425	SPILE	1	800
95	ADT	33A	Emb	3025	27C	1	800
96	ADT	33A	Emb	2413	31B	1	600
97	ADT	33A	Emb	1369	32A	1	400
98	ADT	33A	Emb	1441	33A	1	200
99	ADT	33A	Emb	288	34A	1	400
100	ADT	33A	Emb	8915	SPILE	1	1000
101	ADT	33B	Emb	320	33B	1	200
102	ADT	34A	Emb	953	SPILE	1	1000
103	ADT	34B	Emb	1791	32B	1	600
104	ADT	ProcessW	Emb	42457	19	1	1500

TOTAL MOVED BY …..

Road	**82673.00**	**12%**
ADT	**634255.00**	**88%**
	716928	

Construction material CO_2 data extracted from Arup CO2ST appraisal tool

Material	Unit	CO_2 per unit (kg)		
		Materials	Plant	Transportation
In situ concrete mix reference 40/20, total volume exceeding 6m3	m^3	318.5	25.3	12.1
High yield steel deformed type 2 bar reinforcement nominal size 20mm and over not exceeding 12 metres in length	tonnes	1,728.5	10.2	152.0
Formwork Class F1 vertical more than 300mm wide	m^2	5.1	0.1	10.3

Appendix J: Bridge dimensions

Description	Viaduct	Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5	Bridge 6	Bridge 7	Bridge 8		
Deck											
Total span (c/l length)	170.00 m	68.33 m	47.50 m	28.00 m	28.00 m	31.00 m	43.00 m	31.22 m	52.50 m		
Overall width (measured square to c/l)	27.10	17.33 m	49.00 m	13.40 m	13.40 m	9.90 m	22.10 m	43.00 m	12.85 m		
Depth (m)	0.250	0.250	0.250	0.250	0.250	0.250	0.200	0.200	0.200		
Spans (no.)	3	2	1	1	1	1	2	1	2		
Steel (tn/m3)	0.270	0.250	0.230				0.250				
Deck Support											
Beam type	Str. Steel	Str. Steel	Str. Steel				U10				
Top width (m)	0.300	0.300	0.300				1.361				
Depth (mm)	0	0	0				1400				
Mass (tn/m)	0.000	0.000	0.000				1.594				
Str. Steel (tn/m2)	0.280	0.280	0.270				0.270				
Beams (no. per width)	8	2	12				11				
Cantilever slabs											
Width (m)	1.00	1.48	1.05				0.75				
Depth (m)	0.25	0.25	0.25				0.20				
Steel (tn/m3)	0.270	0.250	0.250				0.250				
Abutments											
Average Height (m)	5.00	1.70	5.25				3.40				
Wall thickness (m)	2.00	0.40	1.50				1.00				
Skew angle (deg)	17	52	10				19				
Steel (tn/m3)	0.18	0.18	0.18				0.18				
Abutment Foundations											
Width (m)	7.60	3.10	6.40				3.50				
Depth (m)	2.00	1.00	1.00				0.80				
Excavation depth (m)	0.00	0.00	3.40				0.90				
Steel (tn/m3)	0.160	0.160	0.160				0.160				
Abutments Piles											
Diameter											
Depth (m)											
Centres (m)											
Steel (tn/m3)											
Wing walls											
Length (m)	6.00	15.00	7.80				7.70				
Average Height (m)	2.00	1.80	3.90				2.00				
Wall thickness (m)	0.4	0.4	0.4				0.55				
Steel (tn/m3)	0.180	0.180	0.180				0.180				
Transition Slab											
Length (m)											
Depth (m)											
Steel (tn/m3)											
Piers											
Average Height (m)	25.00	6.85					7.40				
Columns per base	3	2					6				
Length (m)	2.60	1.20					1.20				
Width (m)	2.60	2.75					1.50				
Steel (tn/m3)	0.20	0.18					0.20				
Pier Foundations											
Width (m)	5.00	5.00					4.00				
Depth (m)	2.00	1.20					1.00				
Exc depth (m)	4.00	1.20					1.60				
Steel (tn/m3)	0.160	0.160					0.160				
Pier Piles											
Diameter											
Depth (m)											
Centres (m)											
Steel (tn/m3)											

%	No.	Description	Quantity	Unit	Rate	Cost	Material (Embodied)		Transport		Labour & Plant	
	000_00_00	<Select>	-	unit	0.00	-	0.00	-	0.00	-	0.00	-
	200_01_03	General, heavy density wooded	-	ha	4,960.91	-	0.00	-	0.00	-	4,900.96	-
	200_01_01	General Site Clearance	2	ha	1,240.23	2,616.88	0.00	-	0.00	-	1,225.24	2,585.26
	300_01_01	Four rail fencing 1.4m high with timber posts	2,000	m	22.86	45,727.06	0.96	1,927.80	0.01	29.72	4.14	8,288.36
	400_01_01	Safety barrier N2 W2 designed to impact one side only straight or curved exceeding 120 metres radius.	2,000	m	79.06	158,118.76	97.55	195,090.52	0.35	702.37	2.69	5,387.96
	400_01_26	Rigid concrete barrier H2 W2 designed to impact on both sides straight or curved exceeding 120 metres radius.	1,000	m	54.84	54,836.43	122.28	122,284.80	9.71	9,706.58	12.71	12,714.17
	400_02_02	P4 terminal	202	no	914.33	184,693.93	943.28	190,542.56	3.40	685.99	59.27	11,972.04
	400_02_01	P1 terminal	202	no	567.38	114,609.95	471.64	95,271.28	1.70	343.00	42.33	8,551.46
	500_01_01	150 mm internal diameter drain design group 5 in trench depth to invert not exceeding 2 metres, average depth to invert 1.0 metres	2,000	m	55.16	110,327.96	18.93	37,867.85	1.97	3,939.10	10.95	21,897.66
	500_01_11	300 mm internal diameter drain design group 5 in trench depth to invert not exceeding 2 metres, average depth to invert 1.0 metres	-	m	120.28	-	55.86	-	4.92	-	15.59	-
	500_05_04	Chamber specified design group Type 3b PC manhole 1500mm dia with cover and frame depth to invert exceeding 1 metre but not exceeding 2 metres	40	no	1,660.67	66,426.70	1,786.26	71,450.26	80.51	3,220.29	399.21	15,968.52
	500_05_11	Precast concrete trapped gully with cover and frame	-	no	278.47	-	347.99	-	12.62	-	3.60	-
	500_01_02	150 mm internal diameter drain design group Z in trench depth to invert not exceeding 2 metres, average depth to invert 1.0 metres	-	m	73.25	-	77.70	-	5.20	-	12.94	-
	600_01_01	Excavation of acceptable material Class 5A	-	m3	2.34	-	0.00	-	0.00	-	1.43	-
	600_01_02	Excavation of acceptable material excluding Class 5A in cutting and other excavation	-	m3	3.11	-	0.00	-	0.00	-	1.90	-
	600_01_05	Excavation of unacceptable material Class U1 in cutting and other excavation	-	m3	3.11	-	0.00	-	0.00	-	1.90	-
	600_02_01	Extra over excavation for excavation in hard material in cutting and other excavation	-	m3	55.28	-	0.00	-	0.00	-	33.73	-
	600_04_01	Deposition of acceptable material in embankments and other areas of fill	-	m3	0.89	-	0.00	-	0.00	-	1.02	-

600_05_01	Disposal of acceptable material excluding Class 5A	-	m3	40.06	-	0.00	-	0.00	-	29.95	-
600_05_03	Disposal of unacceptable material Class U1	-	m3	40.06	-	0.00	-	0.00	-	29.95	-
600_06_02	Imported 6F3 material in capping	-	m3	23.48	-	30.46	-	14.11	-	2.44	-
600_06_01	Imported acceptable material in embankments and other areas of fill	-	m3	24.59	-	45.89	-	14.11	-	2.03	-
600_07_01	Compaction of acceptable material in embankments and other areas of fill	-	m3	1.17	-	0.00	-	0.00	-	1.26	-
600_13_01	Topsoiling 100mm thick to surfaces sloping at 10 or less to the horizontal	4,000	m2	2.82	11,275.65	0.00	-	0.00	-	3.22	12,880.45
3000_02_01	Grass seeding by conventional sowing to surfaces sloping at 10 degrees or less to the horizontal.	4,000	m2	0.68	2,724.39	0.10	401.88	0.00	3.41	0.01	41.92
600_13_02	Topsoiling 100mm thick to surfaces sloping at more than 10 to the horizontal	-	m2	3.13	-	0.00	-	0.00	-	3.58	-
3000_02_02	Grass seeding by conventional sowing to surfaces sloping at more than 10 degrees to the horizontal.	-	m2	0.74	-	0.10	-	0.00	-	0.01	-
700_01_01	Granular Type 1 sub-base Type SB1 in carriagway, hardshoulder and hardstrip.	3,504	m3	37.32	130,775.91	38.63	135,374.97	21.48	75,279.74	5.41	18,945.55
700_02_01	Heavy duty macadam with 28mm aggregate base Type BC1 120mm thick in carriageway hardshoulder and hardstrip.	-	m2	16.18	-	85.71	-	2.46	-	2.90	-
700_02_02	Heavy duty macadam with 28mm aggregate base Type BC1 150mm thick in carriageway hardshoulder and hardstrip.	-	m2	19.92	-	107.14	-	3.08	-	3.48	-
700_02_03	Heavy duty macadam with 28mm aggregate base Type BC1 180mm thick in carriageway hardshoulder and hardstrip.	-	m2	22.97	-	128.56	-	3.69	-	3.73	-
700_02_04	Heavy duty macadam with 28mm aggregate base Type BC1 200mm thick in carriageway hardshoulder and hardstrip.	-	m2	25.18	-	142.85	-	4.10	-	3.98	-
700_02_05	Heavy duty macadam with 28mm aggregate base Type BC1 230mm thick in carriageway hardshoulder and hardstrip.	15,800	m2	27.71	437,875.17	164.27	2,595,534.53	4.72	74,509.17	3.98	62,819.46
700_02_06	Heavy duty macadam with 28mm aggregate base Type BC1 250mm thick in carriageway hardshoulder and hardstrip.	-	m2	31.39	-	178.56	-	5.13	-	4.93	-
700_02_08	Heavy duty macadam with 20mm aggregate binder course Type BC1 50mm thick in carriageway hardshoulder and hardstrip.	-	m2	8.71	-	35.71	-	1.03	-	2.15	-

700_02_09	Heavy duty macadam with 20mm aggregate binder course Type BC1 60mm thick in carriageway hardshoulder and hardstrip.	-	m2	9.55	-	42.85	-	1.23	-	2.15	-
700_02_10	Heavy duty macadam with 20mm aggregate binder course Type BC1 70mm thick in carriageway hardshoulder and hardstrip.	-	m2	10.40	-	50.00	-	1.44	-	2.15	-
700_02_11	Heavy duty macadam with 20mm aggregate binder course Type BC1 80mm thick in carriageway hardshoulder and hardstrip.	15,000	m2	11.24	168,647.06	57.14	857,083.50	1.64	24,604.02	2.15	32,304.31
700_02_24	Concrete pavement, grade C30, 20mm agg, 180mm deep	-	m2	26.66	-	83.20	-	4.64	-	3.73	-
700_02_25	Concrete pavement, grade C30, 20mm agg, 220mm deep	-	m2	29.41	-	95.94	-	5.65	-	3.73	-
700_02_26	Concrete pavement, grade C30, 20mm agg, 260mm deep	-	m2	32.16	-	108.67	-	6.66	-	3.73	-
700_02_27	Concrete pavement, grade C30, 20mm agg, 300mm deep	-	m2	37.50	-	121.41	-	7.68	-	4.97	-
700_02_13	Thin surface course system to Clause 942 Type WC1 20mm thick in carriageway hardshoulder and hardstrip.	-	m2	4.69	-	14.28	-	0.41	-	1.33	-
700_02_15	Thin surface course system to Clause 942 Type WC1 25mm thick in carriageway hardshoulder and hardstrip.	-	m2	5.17	-	17.86	-	0.51	-	1.33	-
700_02_17	Thin surface course system to Clause 942 Type WC1 35mm thick in carriageway hardshoulder and hardstrip.	-	m2	6.83	-	25.00	-	0.72	-	1.66	-
700_02_19	Thin surface course system to Clause 942 Type WC1 40mm thick in carriageway hardshoulder and hardstrip.	-	m2	8.00	-	28.57	-	0.82	-	1.99	-
700_02_21	Thin surface course system to Clause 942 Type WC3 50mm thick in carriageway hardshoulder and hardstrip.	14,600	m2	10.00	146,007.92	35.71	521,392.46	1.03	14,967.45	2.48	36,280.23
1100_01_03	Precast concrete kerb, Type HB2, laid straight or curved exceeding 12 metres radius	-	m	16.55	-	44.17	-	2.68	-	0.99	-
1100_04_01	Footway specified design group Type 1 250mm thick	-	m2	23.43	-	33.46	-	2.23	-	9.54	-
1100_01_11	Precast concrete edgings, Type EF, laid straight or curved exceeding 12 metres radius	-	m	9.45	-	21.15	-	1.49	-	0.66	-
1100_04_02	Paved area specified design group Type 1 250mm thick	2,500	m2	23.43	58,578.51	33.46	83,645.95	2.23	5,571.56	9.54	23,861.42
1200_01_01	Retroreflective traffic sign as non-lit sign unit, sign face not exceeding 0.25 square metres in area on one tubular steel post	10	no	172.31	1,723.06	245.31	2,453.13	9.02	90.19	1.32	13.24

1200_01_04	**Retroreflective traffic sign as non-lit sign unit, sign face exceeding 10 square metres but not exceeding 11 square metres in area on three tubular steel posts**	1	no	3,290.96	3,290.96	2,402.34	2,402.34	31.38	31.38	17.88	17.88
1200_03_26	**Intermittent line in white thermoplastic screed 100 mm wide with 6 metre line and 3 metre gap**	2,000	m	0.58	1,166.60	0.70	1,398.60	0.00	5.35	0.39	785.19
1300_01_06	**Steel road lighting column of 10 metre nominal height with planted base and single bracket arm having a projection of 1.5m with a cut off luminaire incorporating a 250w SON-T+ lamp and lamp control gear**	25	no	1,314.95	32,873.76	309.66	7,741.60	1.28	31.88	79.66	1,991.45
1400_02_02	**Trench for cable not exceeding 300mm wide in depth not exceeding 1.5 metres in verges and central reserves**	1,000	m	13.45	13,451.75	0.00	-	0.00	-	4.35	4,348.24
1400_03_04	**16mm2 2 core XPLE/SWA/MDPE cable with copper conductors in trench depth not exceeding 1.5 metres.**	1,000	m	8.58	8,583.64	2.23	2,229.91	0.01	7.37	0.04	41.92
1400_04_08	**Single way cut out termination to 16mm2 2 core XPLE/SWA/MDP cable in road lighting column**	25	no	31.22	780.55	0.00	-	0.00	-	0.47	11.79
000_00_00	**<Select>**	-	unit	0.00	-	0.00	-	0.00	-	0.00	-

					TOTALS
Total CO2	4,924,094	213,729	281,708		5,419,531
Pavements CO2	4,109,385	189,360	150,350		4,449,095
			% of overall CO2 contribution from pavements =		82%