EFFET DU TRACÉ SUR LES ÉMISSIONS DE CO_2 D'UNE INFRASTRUCTURE ROUTIERE PENDANT SON CYCLE DE VIE

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RÉSUMÉ

Le cycle de vie d'un projet d'infrastructure comprend les phases de planification, de conception, de construction, d'exploitation, d'utilisation et de déclassement. La capacité à influer sur les quantités de carbone diminue au fur et à mesure de l'avancement du projet d'une phase à l'autre. Dans le cas d'un projet de nouveau tronçon de route de 25 km au Royaume-Uni, les émissions de CO_2 produites par les véhicules utilisant la route pendant la « phase d'utilisation » représentent 94 % du total des émissions de CO_2 du projet sur une période de 60 ans. La présente étude examine le tracé de la route, qui est une décision prise à un stade précoce du projet (lors de la phase de planification), afin de comprendre de quelle manière il peut avoir un effet positif sur les émissions de CO_2 associées à la phase d'utilisation.

Afin de comprendre l'effet du tracé vertical tout au long du cycle de vie, les quantités de CO_2 ont été calculées au cours des phases tant de construction que d'utilisation. Une méthodologie a été mise au point pour calculer la quantité de CO_2 résultant des travaux de terrassement. Un modèle d'émission instantanée PHEM a été utilisé pour calculer la quantité de CO_2 dégagée par les véhicules utilisant une route.

L'évaluation d'un terrain théorique et d'un projet en cours a permis de démontrer les avantages potentiels d'une modification du tracé d'une route. Les avantages tout au long de la durée de vie dépendent de la composition du parc automobile, du trafic routier et de la durée de la phase d'utilisation.

1. INTRODUCTION

The life cycle of any infrastructure project can be divided into the phases shown in Figure 1. By considering all phases in terms of carbon it can be said that a Whole Life Carbon approach has been taken.

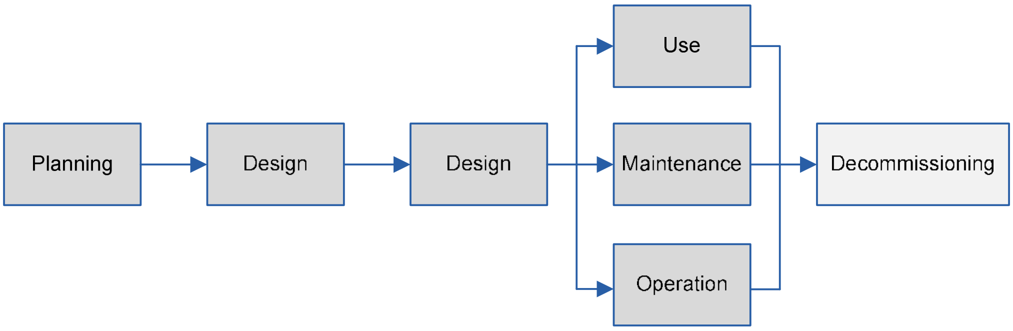

Figure 1 - Life cycle phases of infrastructure projects

The planning stage is when decisions can be made to reduce the Whole Life Carbon; by considering the impact of different design options at the different phases of the life cycle.

The ability to influence carbon decreases as the project progresses through the life cycle. 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 a whole life carbon evaluation 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.

Assessing carbon in only one phase of the life cycle could result in one design option being favourable over another. Yet the apparently favourable option could yield higher carbon emissions when it enters a different phase of the life cycle.

The CO_2 assessment undertaken for a new major motorway scheme in the UK, considered both the construction phase and the use phase. The CO_2 critical phase was identified as the use phase – covering the CO_2 emitted from the vehicles using the highway [1]. The CO_2 resulting from the construction of the pavement, structures and earthworks totalled 532,977 tonnes, yet the use phase emits 124,375 tonnes of CO_2 in the opening year [1]. Over a 60-year period, the use phase overshadows the construction phase, as shown in Figure 2.

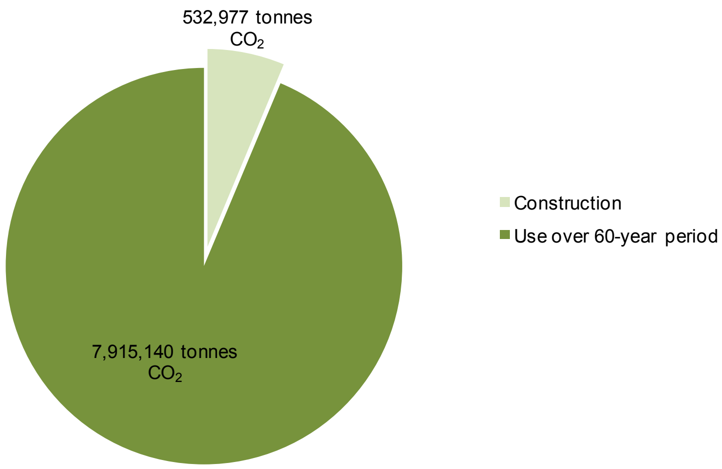

Figure 2 – Comparison of the construction and use phases [1]

The use phase proved to be the major contributor to the overall motorway project CO_2 and is, therefore, the key phase to target to achieve CO_2 reductions. However, from a designer's perspective, the use phase can be difficult to influence. This paper considers the decisions that can be made at the planning stages of a highway project that could result in CO_2 benefits throughout the remainder of the life cycle.

The CO_2 from the use phase results from the combustion of fuel by vehicles, which is directly influenced by the gradient of the highway; determined by the vertical alignment that is chosen at the early project stages. The vertical alignment is often dictated by the earthworks balance of the site, with the goal to keep earthworks to a minimum. Despite the motorway project requiring a substantial earthworks operation, it contributed only 4% to the overall construction CO_2. Raising the question: should designers expend more CO_2 during construction on low CO_2 intensive earthworks to achieve an alignment that will result in lower CO_2 emissions in the use phase?

The Integration of the Measurement of Energy Usage into Road Design project [2] was designed to reduce the energy used in the construction of roads and the energy used by the vehicles using the roads. The outcome of the project was Joulesave, a software package to be used in conjunction with road design software. Taking a similar 'first principle' approach, this paper also explores the effect of the vertical alignment on CO_2 emissions in both the construction phase and the use phase, and enables the potential benefits and payback periods to be estimated so that total whole life carbon is reduced.

2. Approach

To understand the effects of the vertical alignment through the life cycle, the CO_2 in both the construction and use phase has to be calculated. The methodology to calculate the CO_2 from the earthworks operations and the CO_2 from the vehicles using the highway is described below.

2.1 Earthworks

The CO_2 emitted from construction activities consists of three components, namely from the manufacture of construction materials; from the transport of materials, labour and plant to and from a site; and from the plant used during construction. For most construction activities, CO_2 embodied in the building materials is the majority of the construction CO_2. When quantities of these materials are known, it is simple to apply embodied CO_2 coefficients to arrive at a CO_2 value for the activity. Most currently adopted methods therefore use data from a standard academically-derived inventory of embodied CO_2 in building materials; the Inventory of Carbon and Energy [3].

Traditionally earthworks have been a construction activity which used mostly natural materials, manual labour and horse-power and which had a very low carbon footprint. Modern earthworks construction, however, is a highly mechanised activity but earthworks construction still remains a low carbon activity today - at least relative to other construction activities. This is because earthworks still mainly uses excavated natural materials (whereas, as discussed above, most construction materials are manufactured and have significant amounts of embodied CO_2). The majority of the carbon footprint of earthworks results from the fuel used to power the earthworks construction plant and from the lorries used to haul materials to and from sites.

An outcome of a recent research project was a tool to calculate the CO_2 associated with bulk earthworks [4]. Such a tool is necessary as the earthworks on each project (i.e. the combination of ground conditions, haulage distances and quantities) are unique and so standardised CO_2 values for earthworks operations are frequently not representative between projects. The tool has been used to assess the earthworks associated with the theoretical alignments and case studies presented within this paper.

2.2 Vehicle emissions

As a result of a comprehensive review of the available emission models, it was decided that an instantaneous emission model was to be used to research the effect of alignment on life cycle CO_2 emissions of highway infrastructure. Instantaneous models are the most accurate in quantifying vehicle emissions; by requiring and using detailed input data.

The input vehicle data includes the vehicle speed, engine load (speed x acceleration) and operating gradient. This data enables instantaneous models to interpolate fuel consumption and emissions from steady-state engine maps for every second of a given driving cycle. Figure 3 shows an example of an engine map for CO emissions.

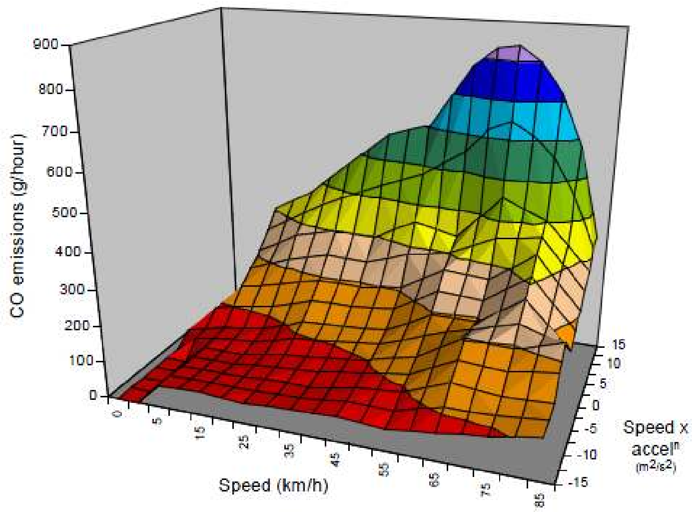

Figure 3 - Example of an engine map

The instantaneous emission model used is PHEM (Passenger car and Heavy Duty Emission Model). Although originally developed by the Graz University of Technology, it has become available through various European research projects*. The model comprises 31 driving cycles, 7 road gradients, 30 vehicle classes and 5 legislative emission levels – resulting in over 30,000 emission factors per emission type.

* COST 346 and ARTEMIS projects

With speed, acceleration and gradient input to the appropriate PHEM engine map the actual power demand from the engine and engine speed are simulated. The simulation of the actual power demand of the engine is based on the driving resistances and the transmission losses. The engine speed is calculated using the transmission ratios and a gear-shift model.

3. Theoretical alignments

3.1 Effect on individual vehicles

To understand the effect of differing gradients on the fuel consumed by vehicles a theoretical hill has been used; the dimensions of the hill are shown in Figure 4.

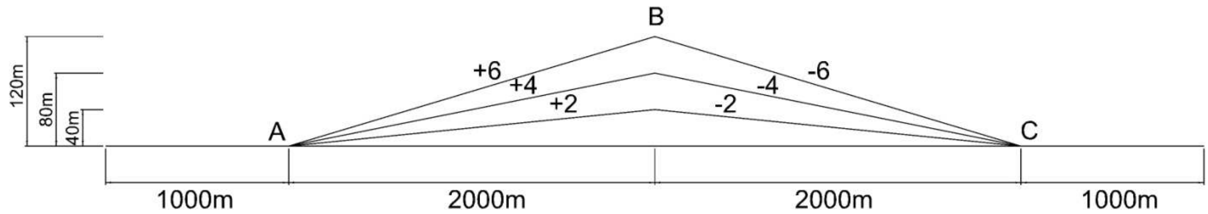

Figure 4 - Dimensions of theoretical symmetrical hill

The hill could be considered to be of large proportions with uphill (AB) and downhill (BC) sections of 2000m in length. However, 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.

The 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. Although the design speed is 120kph, vehicle speeds of up to 160kph have been considered.

Figure 5 shows the normalised CO_2 for a petrol car over the symmetrical alignment (shown in Figure 4) across a speed range of 50kph to 160kph. The CO_2 for each speed has been normalised to the CO_2 produced by a petrol car travelling over a level alignment at that speed. At speeds around 120kph, less fuel is consumed by a petrol car traversing the hill compared to a petrol car travelling on the level alignment. For a petrol car over the steepest alignment at 110kph the total CO_2 emission is 1141g – equating to 228g/km. On the level alignment at the same speed the total CO_2 emission is 1154g – equating to 231g/km.

The Internal Combustion Engine varies hugely in efficiency dependent on the operating requirements, and for this reason it is entirely reasonable for fuel consumption figures to be counter-intuitive. For example, a vehicle traversing a hill can require less fuel than a vehicle on a level road of equal length; because more of the available torque is utilised, meaning the engine would work more efficiently. In the case of a hill - although the fuel consumption would increase on the incline, the decrease seen on the decline could offset the additional fuel required for the incline.

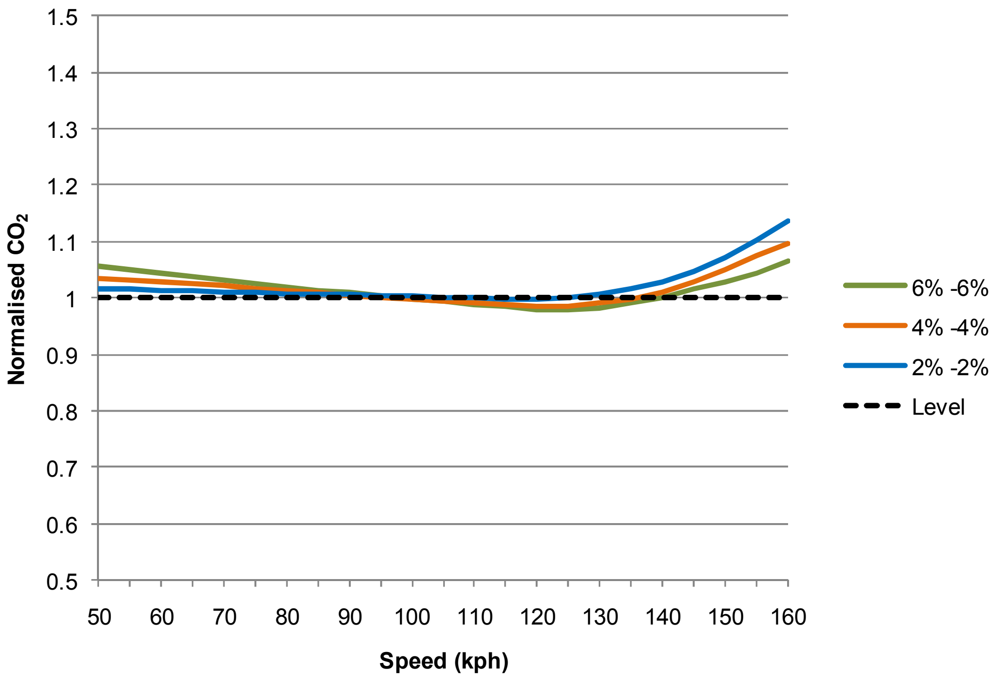

Figure 5 - Normalised CO_2 for a petrol car over different alignments

Figure 6 shows the normalised CO_2 for a fully-laden heavy goods vehicle (HGV) over the symmetrical alignment across a speed range of 50kph to 100kph. Again, the CO_2 for each speed has been normalised to the CO_2 produced by a fully-laden HGV travelling over a level alignment at that speed. In most cases the graded alignment results in more fuel consumed and hence higher CO_2 emissions. For a fully-laden HGV over the steepest alignment at 90 kph the total CO_2 emission is 5889g – equating to 1178g/km. On the level alignment at the same speed the total CO_2 emission is 5217g – equating to 1044g/km.

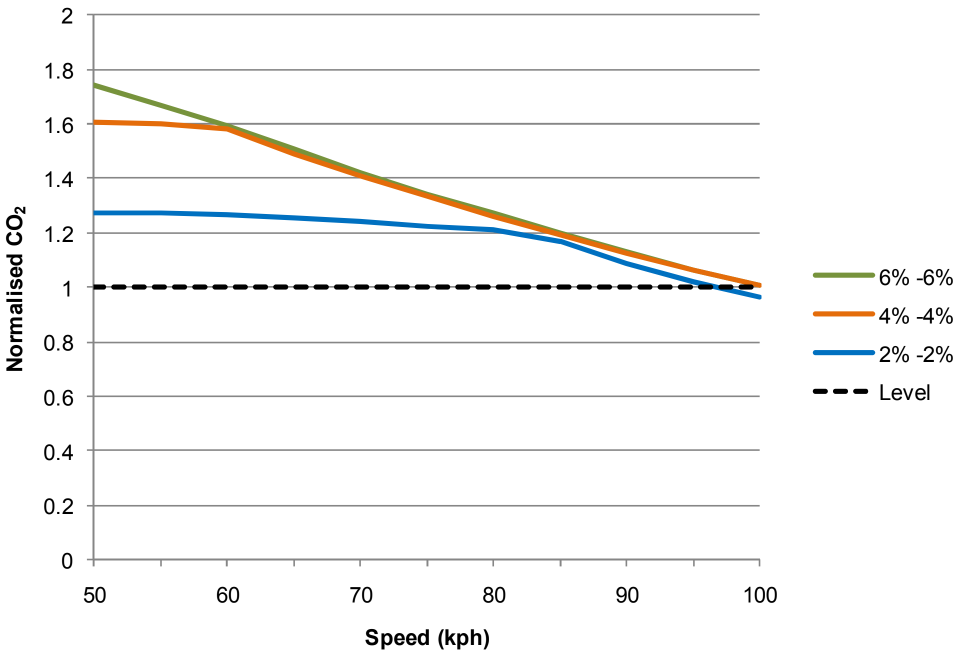

Figure 6 - Normalised CO_2 for fully-laden HGV over different alignments

For the fully-laden HGV as it traverses the most steeply graded alignment, the large increase in CO_2 emissions on the incline is not sufficiently offset by the decrease on the decline – resulting in most graded alignments yielding higher CO_2 emissions.

In addition to a petrol car and fully-laden articulated HGV, the following were also analysed:

- Diesel car
- LGV
- Rigid HGV (unladen, half-laden and fully-laden)
- Articulated HGV (unladen and half-laden)

The bars in Figure 7 show emissions at 90kph over the level alignment for the different vehicle types. The ranges between the minimum and maximum emissions are indicated by the black range-bars. It demonstrates the lesser variations in emissions resulting from alignment changes on the lighter vehicles such as the cars and LGVs. Articulated HGVs are influenced greatly, with large variations in CO_2 emissions ensuing from changes in alignment.

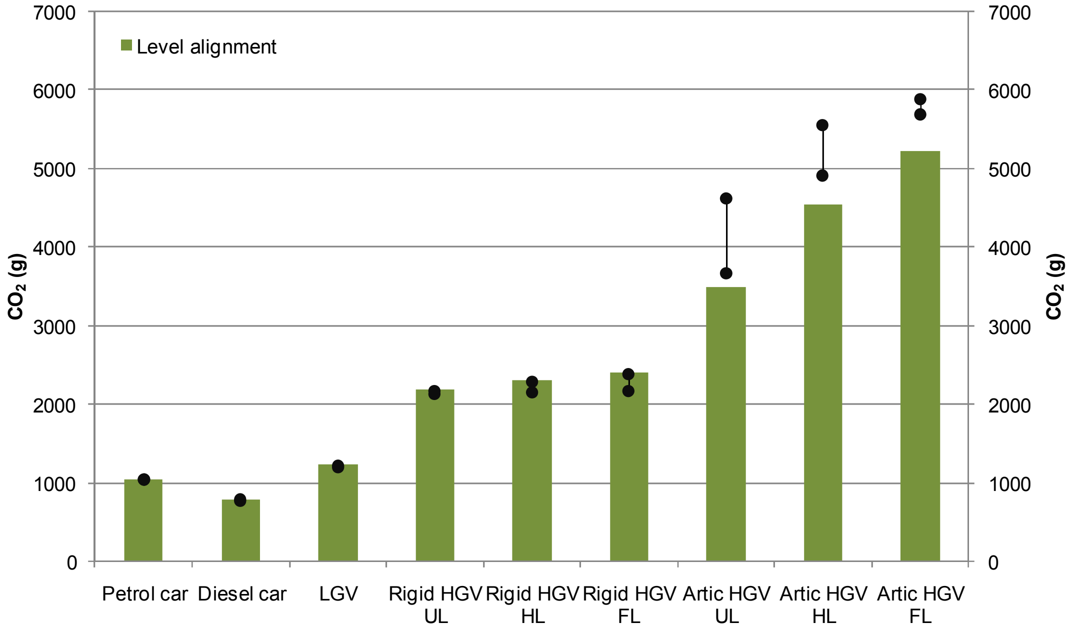

Figure 7 – Variation across all alignments at 90kph

3.2 Effect on vehicle fleets

Vehicles have been individually analysed to understand the effect of different alignments on various vehicle types over a range of speeds. However, due to traffic comprising a variety of vehicle types travelling at different speeds, the impact of alignment on typical fleets has also been analysed. For the purpose of this assessment the fleet composition reflects the composition on UK motorways in 2010 [4] and is given in Table 1.

Table 1 – Fleet composition on UK motorways

Vehicle type	Percentage
Petrol car	60.69%
Diesel car	15.6%
LGV	12.4%
Rigid	4.1%
Artic	7.3%

The speeds used reflect the speeds on UK motorways in 2010 [4] and are given in Table 2.

Table 2 – Vehicle speeds on UK motorways

Speed	Percentage travelling at speed (%)			
	Cars	LGV	Rigid HGV	Artic HGV
Under 50 mph	3	3	9	8
50-59 mph	13	13	71.33	89.5
60-64 mph	13	13	6.67	1.5
65-69 mph	19	18	4.33	0.5
70-74 mph	21	20	4	0.5
75-79 mph	16	16	2.33	-
80-89 mph	13	14	1.67	-
90 mph and over	2	3	0.67	-

The fleet mix and speed breakdown were applied to the average motorway flow in the UK in 2010 of 84,852 vehicles per day [4]. Current road building will have an impact in the future and so three possible scenarios have been considered:

- Scenario 1 – Business as usual, assuming the current fleet mix and engine technology
- Scenario 2 – Low carbon future, assuming passenger vehicles are electrically powered and freight vehicles are fuelled by biodiesel as set out in the 2050 Pathways Analysis [6].
- Scenario 3 – Lower speed limits, assuming lower speed restrictions are enforced to reduce CO_2 emissions. All speeds were reduced by 10kph.

Figure 8 shows the CO_2 for each scenario on each alignment normalised to the CO_2 emissions released on the level alignment; the detrimental impacts on CO_2 emissions of the graded alignments are apparent.

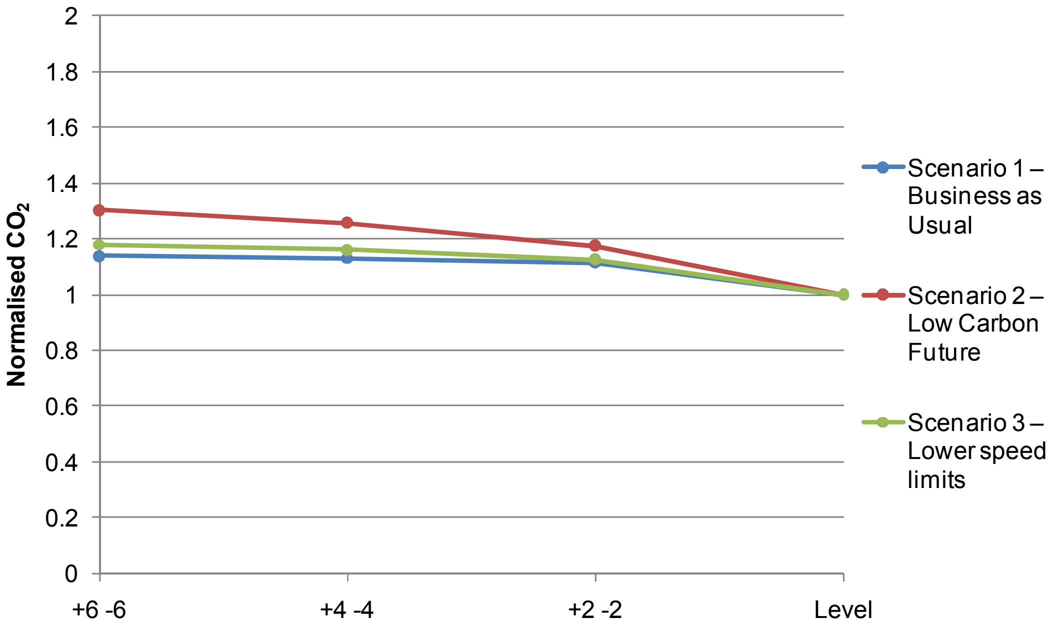

Figure 8 - CO_2 for each scenario normalised to the CO_2 emissions released on the level alignment

The CO_2 emissions values for each scenario are presented in Table 3, along with 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 3 - CO_2 emissions for each scenario

Scenario	Daily CO_2 emissions (tonnes)				Maximum percentage saving	Maximum annual saving (tonnes)
	+6 -6	+4 -4	+2 -2	Level		
Scenario 1 – Business as Usual	124	123	121	109	12%	5,505
Scenario 2 – Low Carbon Future	40	39	36	31	23%	3,435
Scenario 3 – Lower speed limits	121	119	116	103	15%	6,709

Emissions are greatly reduced in Scenario 2 between the steepest and level highway due to the entire fleet comprising of HGVs – the vehicle type most influenced by gradients.

3.3 Effect on earthworks

The earthworks volumes required to intersect the different vertical alignments with the terrain shown in Figure 4 have been calculated and are shown in Table 4.

Table 4 - Earthworks volumes associated with the different vertical alignments

Alignment	Cut (m^3)	Fill (m^3)	Balance (m^3)
Level	37,106,391	35	37,106,357
+2 -2	16,449,252	35	16,449,218
+4 -4	4,665,586	35	4,665,552
+6 -6	36,478	113	36,365

The earthworks volumes are based on a three-lane UK motorway with 1:2 cutting slopes. CO_2 has been estimated based on the use of mid-range earthmoving plant; a 45 tonne excavator in conjunction with a 35 tonne articulated dump truck. It was assumed that the spoil was hauled to locations either side of the cutting for stockpiling. To cover the possibility that the surplus spoil cannot be accommodated on site, the CO_2 associated with its possible removal from site has also been estimated. The removal calculations are based on the use of a 45 tonne excavator in conjunction with a typical road lorry. The CO_2 estimated for the excavation and haul to the stockpile site and the potential haul off site are given in Table 5.

Alignment	CO2 (tonnes)		
	Excavation and haul to stockpile site	Haul off site	Total
Level	96,517	218,961	315,479
-2 +2	42,216	96,998	139,214
-4 +4	11,735	27,467	39,202
-6 +6	75	208	283

Table 5 - CO_2 estimated for earthworks operations

3.4 Impact of earthworks through the life cycle

In previous sections the effect of different vertical alignments on vehicle fleets has been illustrated, alongside the CO_2 impact of achieving such alignments through bulk earthwork operations.

Considering the business as usual scenario (Scenario 1), with the vehicle flow of 84,852 per day, CO_2 emissions can be reduced by 5,505 tonnes per year through the adoption of a level highway over the graded theoretical highway. The CO_2 associated with the earthworks required to construct this alignment, if the excavated material is to remain on site, is 96,517 tonnes. The annual reduction in CO_2 therefore allows the additional CO_2 expended at the construction stage to be recovered over approximately 18 years, as shown in Figure 9.

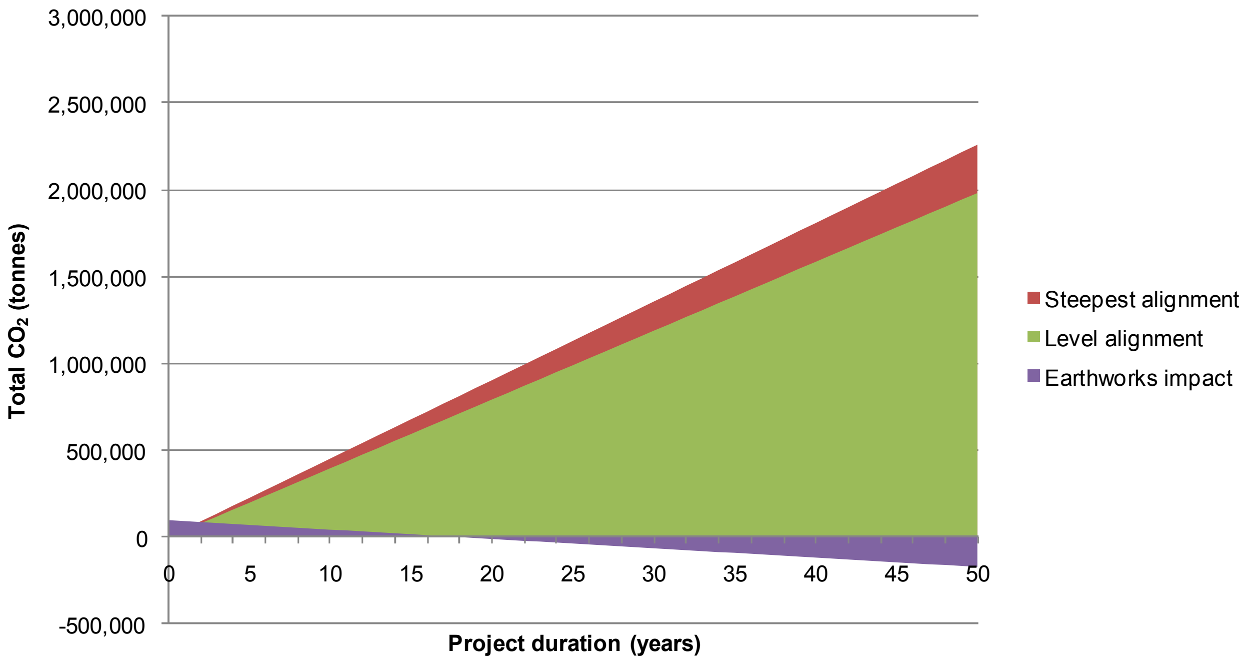

Figure 9 – Payback period for additional earthworks

4. Case study

An actual highway project in the UK, the construction of a dual carriageway, with six possible alignments has been assessed. The vertical alignments and the horizontal alignments are shown in Figure 10.

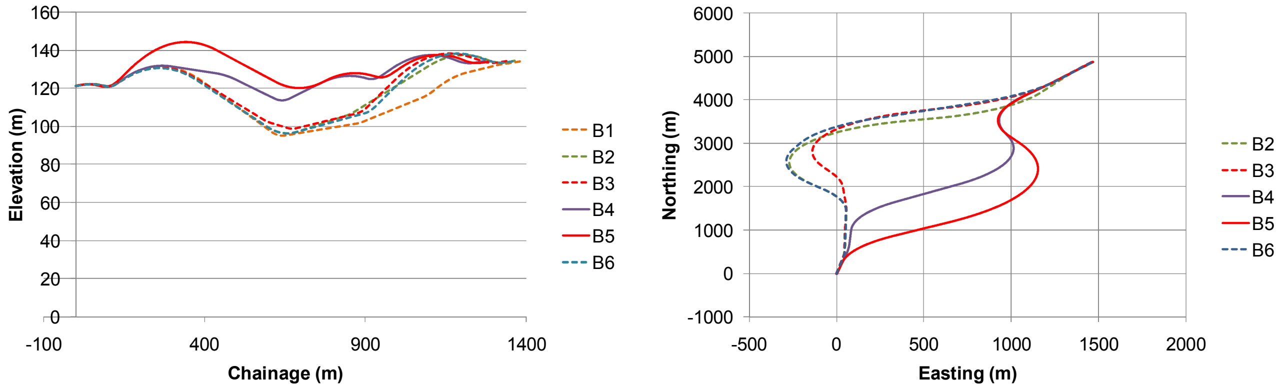

Figure 10 – Possible alignments for highway project

For the purpose of this assessment the fleet composition reflects the composition on UK dual carriageways in 2010 [4], and is given in Table 6. The fleet mix shown was applied to the vehicle flows modelled for this specific highway scheme; approximately 7000 vehicles in each direction.

Table 6 – Fleet mix on dual carriageways

Vehicle types	Percentage
Petrol car	63.6%
Diesel car	16.3%
LGV	13.3%
Rigid	3.4%
Artic	3.4%

The speeds used reflect the speeds on UK dual carriageways in 2010 [4] and are given in Table 7.

Table 7 – Vehicle speeds on dual carriageways

Speed	Percentage (%)			
	Cars	LGV	Rigid HGV	Artic HGV
Under 30 mph	0	0	0	0
30-39 mph	1	0	1.4	1
40-49 mph	3	3	15	17
50-59 mph	17	18	66.7	78.5
60-64 mph	16	16	7.7	2
65-69 mph	21	20	3.4	0.5
70-79 mph	32	32	4.4	0.5
80 mph and over	10	11	1.4	0.5

The northbound and southbound routes were assessed separately; the total CO_2 associated with each route in each direction is shown in Figure 11. Also shown are the CO_2 emissions on a per km basis. Route 4 produces the least total emissions; which could be explained by it being the shortest route. However, when normalised to the route length it is also the most efficient route, giving a CO_2 emission across the entire fleet of 2,934 kg/km. Through the choice of Route 4 over the highest emitting route (Route 1), approximately 31,600 tonnes could be reduced over a 60 year use period – an 8.5% reduction.

Route 4 has been identified as the most efficient route, and will therefore be focused upon and the vertical alignment amended to attempt to achieve further efficiency in the use phase. The additional CO_2 required in the construction phase has also been considered.

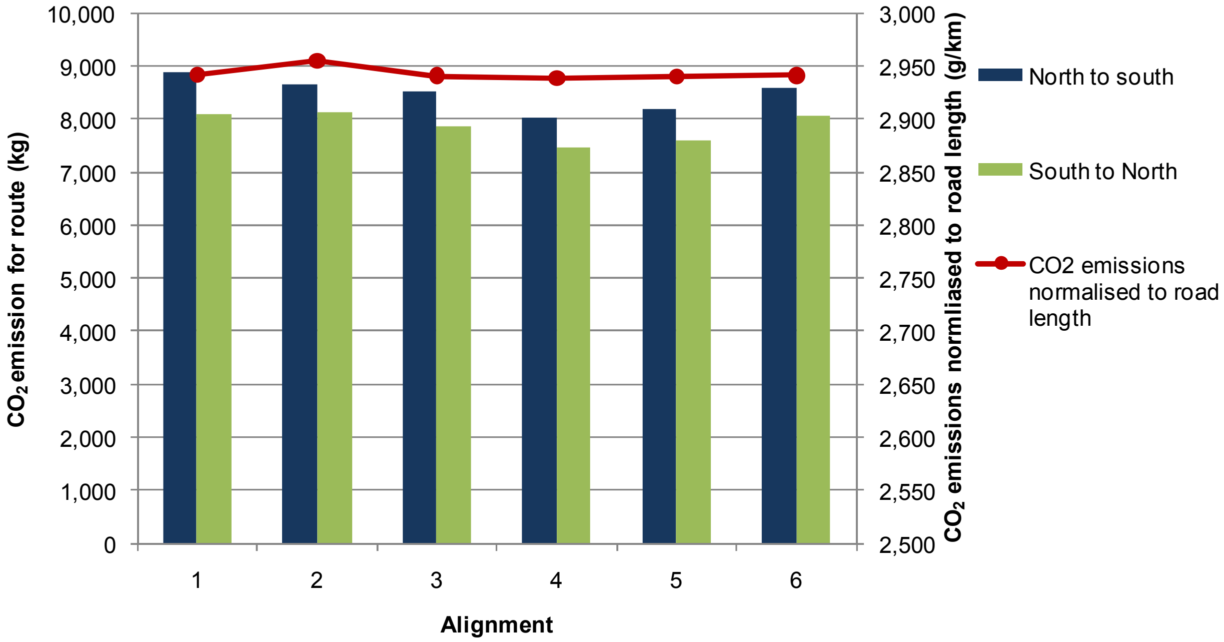

Figure 11 - CO_2 emissions for all alignments

Route 4 has been amended as shown in Figure 12; the undulating valley section has been levelled. However, a graded section between chainage 0+000m and 1+000m still remains.

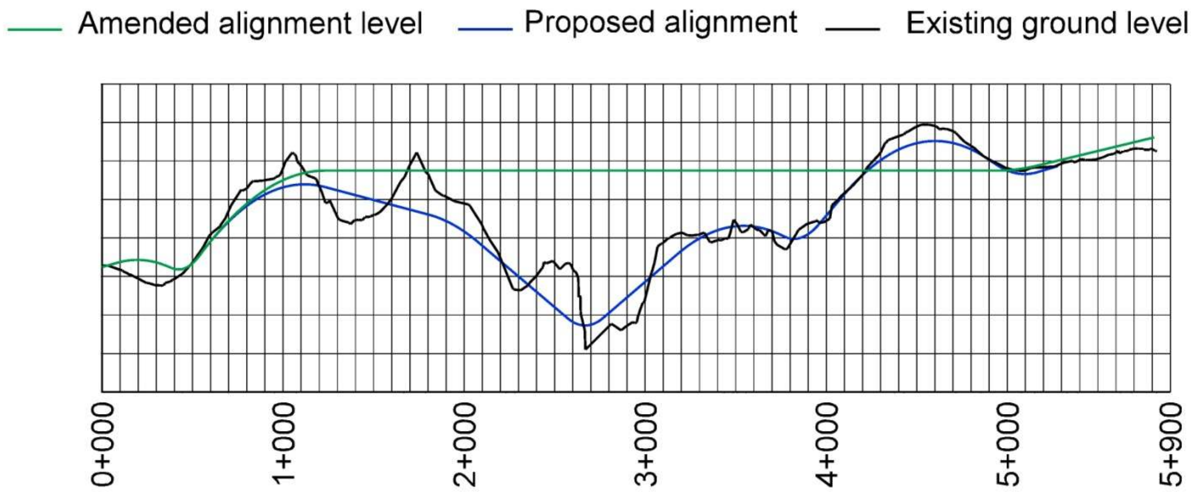

Figure 12 – Route 4 vertical alignments

The emissions were assessed over the amended vertical alignment. Similar to the theoretical alignment the lighter vehicles were less affected, with the heavier vehicles resulting in a greater change. Figure 13 shows the CO_2 emissions associated with the proposed alignment and amended alignment – both normalised to the CO_2 that would be emitted if the alignment were completely level. The differences shown are small, with maximum variations from the level alignment being approximately 5%. The North to South direction results in higher emissions than South to North due to the uphill section. Conversely, the resultant downhill section on the South to North direction results in lower emissions than the level alignment.

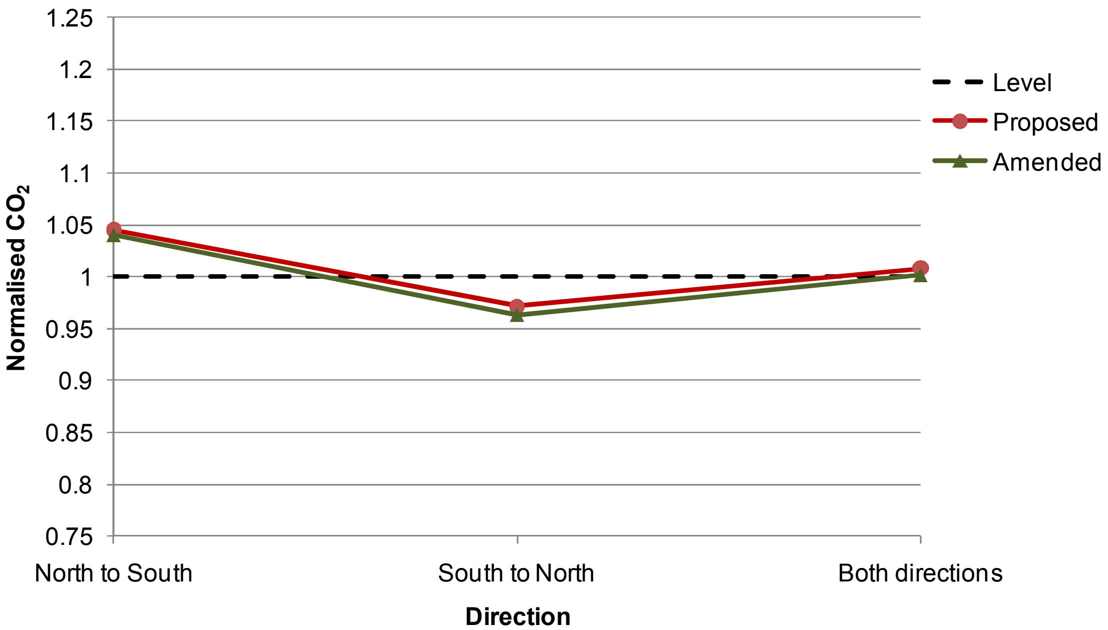

Figure 13 – CO_2 emissions associated with the proposed and amended vertical alignments

The total decrease across the fleet from the proposed alignment to the amended alignment, over a 60 year period is 2,310 tonnes per year.

The CO_2 expended for the additional earthworks required for the amended alignment has been considered, to understand whether the potential CO_2 reductions in the use phase are worth the additional CO_2 in the construction phase. The earthwork volumes associated with the proposed and amended alignments are shown in Table 8, with a range of CO_2 values associated with the anticipated earthworks operation. Ranges have been presented to demonstrate the potential variation in earthworks CO_2; dependent on the plant selection, use of lime as an additive, and the origin of the fill material – whether it can be sourced on-site or has to be imported to site.

Table 8 – Earthworks associated with vertical alignments

Alignment	Cut volume (m^3)	Fill volume (m^3)	CO_2 Range (tonnes)
Proposed vertical alignment	132,954	63,596	190 – 1,093
Amended vertical alignment	153,900	1,437,509	2,636 – 25,191

The estimated CO_2 associated with the additional earthworks required to achieve the amended alignment is between 2,636 and 25,191 tonnes. The optimistic end of the range, 2,636 tonnes, is slightly higher than the potential CO_2 emission savings in the use phase over a 60 year period.

5. Discussion

A whole life approach has been taken to consider the long-term impacts of the alignment choice of highways. The main construction activity that determines the vertical alignment is the earthworks operation. Varying magnitudes of earthworks operations and their associated CO_2 have been considered, to enable the potential benefit of a more level alignment during the use phase to be understood.

For the theoretical alignment that has been considered, over a 60-year period, the level alignment under the Business as Usual scenario could reduce CO_2 emissions by 330,300 tonnes – a 12% reduction. The estimated CO_2 associated with the earthworks operation required to take the theoretical terrain to the level alignment was, in the optimistic case, 96,517 tonnes. In this case, the high vehicle flow means that the benefits resulting in the use phase would quickly offset the additional CO_2 expended in the construction phase, over a period of about 18 years.

The vehicle flow is a fundamental factor, as demonstrated by the case study. The dual carriageway that has been assessed is expected to carry a traffic flow of around 7,000 vehicles in each direction per day. As a result, the consequential CO_2 reductions of the amended alignment, which were 0.7% less than the proposed alignment before amendments, would take many years to offset the additional CO_2 expended through the earthworks. Over 60 years of use a decrease of 2,310 tonnes of CO_2 would be expected, which is similar to the additional CO_2 required for the earthworks. Should the vehicle flow be 30,000 vehicles per day in each direction rather than 7,000 then it would take 16 years to offset the additional earthworks CO_2.

The dual carriageway case study had six possible alignments. The assessment of all six showed the alignment with the highest emissions was Route 1 at 6,195 tonnes per year. The lowest was Route 4 at 5,668 tonnes per year. With the amendments made to Route 4, this reduced further to 5,629 tonnes per year - giving a total difference of 9.1%.

The emission values over the alignments have been calculated assuming that the vehicles travel at constant speeds; the impact of traffic interactions has not been considered. The effect of traffic interaction, particularly on uphill sections, would be expected to exaggerate the overall result as slower moving heavier vehicles would impede the more agile vehicles – further increasing the detrimental impact of graded alignments on fuel consumption and hence CO_2 emissions. The impact of traffic interaction is a subject for further study.

6. Conclusion

The ability to influence carbon decreases as the project progresses through the life cycle. The ideal time to act on carbon is during the planning and design phases – when decisions are taken that have effects which manifest throughout the life cycle. This paper has considered the potential CO_2 reductions that can be achieved through such a Whole Life Carbon approach.

Assessing carbon in only one phase of the life cycle can result in one design option being favoured over another. Yet the option that is apparently most favourable for one phase could generate higher carbon emissions when it enters the subsequent phase. This is highlighted by both the theoretical highway example and the case study considered. Both examples required a more CO_2 intensive construction phase to achieve alignments that resulted in less CO_2 in the use phase. The important issue is whether the additional CO_2 expended in the construction phase results in a worthwhile reduction in the use phase. If the earthworks operation results in an increase that requires a long period of use for it to be offset then a decision should be made based on the payback period length.

CO_2 emissions, one of a number of issues that should be considered when adopting a sustainable approach, may not rate as highly as other issues that result from the amendment of an alignment. For example, a large earthworks embankment may reduce emissions in the use phase, but may also have detrimental social impacts for the life of the highway, for instance, in terms of noise or community severance. A considered integrated approach should be taken to the assessment of highway infrastructure, taking into account the different phases over the lifetime of the highway and understanding the impact had in each.

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