
Carbon costs and savings of Greenways: creating a balance sheet for the sustainable design and construction of cycling routes

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Abstract: A modal shift to cycling has the potential to reduce carbon emissions in the transport sector. However, the carbon footprint of constructing new cycling routes, particularly greenways, has not been previously considered and has the potential to negate carbon savings of the modal shift of many commuters. This paper, using a case study of a greenway in Ireland, describes a methodology for calculating the carbon costs and savings associated with cycle route construction. By carrying out a life cycle assessment (LCA), the case study greenway was found to embody 67.6 tCO₂e/km; the carbon savings of shifting one passenger kilometre travelled (PKT) from driving a car to cycling were found to average 134 gCO₂e. In the case study, a shift of 115 commuters per year (253,000 PKT) is required to 'balance' or offset the carbon footprint of one 10 km asphalt greenway (assuming a 20 year life cycle). The methodology presented can be used to ensure the efficient and sustainable design of cycle networks internationally.

Keywords: greenways; cycling routes; carbon footprint; carbon emissions; carbon costs; carbon savings; modal shift; life cycle assessment; LCA; sustainable transport; asphalt; sustainable design; environment; environment and sustainable development.

Reference to this paper should be made as follows: Manton, R., Duggan, A., Goggins, J. and Clifford, E (2014) 'Carbon costs and savings of Greenways: creating a balance sheet for the sustainable design and construction of cycling routes', *Int. J. Environment and Sustainable Development*, Vol. 13, No. 1, pp.3–19.

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This paper is a revised and expanded version of a paper entitled 'Use of carbon calculation tools for sustainable cycle network design' presented at 7th Conference on Sustainable Development of Energy, Water and Environment Systems, Ohrid, Republic of Macedonia, 1–7 July 2012.

1 Literature review

1.1 Background and policy

The development of cycle networks in rural and urban areas is seen as increasingly important for reasons including:

- 1 reducing the carbon footprint of the transport sector
- 2 potential for health benefits
- 3 improving quality of life
- 4 the development of sustainable tourism.

In 2009, the European Parliament included EuroVelo (the 45,000 km European cycle network) in the trans-European transport network. This means that structural funding may be made available for the completion of cycle routes which in turn places emphasis on efficient route design. Internationally, efforts have been made to reduce unsustainable transport habits, with promotion of cycling to the fore.

In Ireland, for example, there are currently 535 cars per 1000 population over 15 years old, up from 459 in 2001 (CSO, 2012a). 1.1 million people (61% of the commuting population) drive a car to work daily while only 40,000 people (2.4% of the

commuting population) cycle (CSO, 2012b). This is despite the fact that 30% of commutes are less than 5 km – a reasonable cycling distance (DoT, 2009). To encourage a modal shift in cycling to 10% of commuter trips, the Irish government has introduced a range of measures including the establishment of a National Cycle Network (NCN). The NCN will connect all urban settlements in Ireland and open up extensive rural routes. The key user groups of the NCN will be commuters, cycle tourists and leisure cyclists. The NCN will comprise a range of cycle route types including:

- 1 on-road
- 2 cycle lanes
- 3 greenways (traffic-free cycle trails) (NRA, 2010).

Due to the large carbon emissions associated with car usage, a modal shift to low carbon or carbon-free transport, such as cycling, is desirable. However, the carbon cost of constructing new cycling routes, particularly greenways, has not been previously considered. This cost has the potential to negate the carbon savings made by the modal shift of many commuters. This will be particularly relevant in rural areas where a greenway has been constructed, yet usage is relatively low, i.e., the carbon cost is distributed over few passenger kilometres travelled (PKT). What is therefore needed is a methodology which calculates the carbon costs and the potential carbon savings of cycling routes and through comparison of the two values, yields a decision on the environmental viability of the route.

1.2 Life cycle assessment

To evaluate the environmental impact of construction projects, an environmental life cycle assessment (LCA) is performed. This is a tool used to quantify and evaluate the environmental impact associated with a product, process or activity by identifying and quantifying energy and material uses and releases into the environment as embodied carbon or embodied energy. A LCA includes four phases according to BSI (2006):

- 1 goal and scope definition
- 2 life cycle inventory (LCI)
- 3 life cycle impact assessment
- 4 interpretation.

Phase 1 includes definition of the system boundaries, which determine the range of impacts considered that are directly linked to the product. Ideally the system boundaries are set from the extraction of raw materials until the end of the product's lifetime (cradle-to-grave), which would include stages such as manufacturing, transportation and decommissioning (or demolition) at the end of its life (BSI, 2006). Due to the uncertainties after product manufacture, it has become common practice to calculate the embodied carbon for materials as all the carbon released as greenhouse gases until the product leaves the factory gate (cradle-to-gate) (Hammond and Jones, 2011). In this study, carbon emissions associated with the construction processes (e.g., machinery used to place and compact the material) have been added to the embodied carbon due to transport, giving a cradle-to-site boundary condition. Wastage from building

construction/installation and disposal of waste should also be included for this boundary condition, although this was excluded by Mendoza et al. (2012) due to uncertainties over waste disposal. The addition of embodied carbon due to maintenance and decommission would be required to achieve a cradle-to-grave boundary.

1.3 Embodied carbon and carbon dioxide equivalents

The embodied carbon (a.k.a. carbon footprint) of a material can be used as an indicator for LCA. It is taken as the total carbon released over its life cycle (Hammond and Jones, 2011). Embodied carbon is measured in carbon dioxide equivalents (CO₂e), which not only includes carbon dioxide (CO₂), but also other greenhouse gases as set out in the Kyoto Protocol, such as methane (CH₄), nitrous oxide (N₂O) and PFCs (IPCC, 2007). The CO₂e of a gas is found by multiplying the mass of the gas by the associated global warming potential (GWP) (IPCC, 2007). GWP is based on the relative amount of heat that is trapped in the atmosphere by a greenhouse gas, where CO₂ has a GWP of 1. It should be noted that values for CO₂e are higher than CO₂ values for materials due to the inclusion of other greenhouse gas emissions (CH₄, N₂O, PFCs). For example, CO₂e values are on average 6% higher than CO₂ values for construction materials in the UK (Hammond and Jones, 2011). In this paper, a process-based method (Goggins et al., 2010) will be employed to assess the embodied carbon.

1.4 Carbon emissions of Irish transport

Ireland's greenhouse gas emissions in 2011 were 57.34 Mt carbon dioxide equivalents (Mt CO₂e), where 11.29 Mt CO₂e or 19.7% of these emissions were a result of the transport sector (EPA, 2012). Although, due to economic factors, this represents a decrease since 2008, the figure is more than double the 1990 level of 5.2 Mt CO₂e (EPA, 2012). The average commuting occupancy of Irish cars is 1.1, and the carbon dioxide emissions for an average Irish passenger car are approximately 160 g CO₂e/km (CSO, 2012b; NRA, 2011a; DECC and Defra, 2011). The emissions of CH₄, N₂O and other greenhouse gases emitted by cars are relatively insignificant (DECC and Defra, 2011). Thus an overall figure of 160 gCO₂e/km can be used. Emissions from all Irish passenger cars totalled 5.8 Mt CO₂e in 2009 – a 96% increase on 1990 (Hammond and Jones, 2011; NRA, 2011a). Vehicle emissions can be increased by poor road condition and therefore in rural areas, where road conditions tend to be poorer and greenways may be constructed, vehicle emissions may be greater than the national average.

1.5 Carbon savings of a modal shift to cycling

Cycling is not a zero emissions mode of transport and recent research has shown that carbon dioxide emissions as a result of cycling are approximately 11 gCO₂/km. Given that the maximum occupancy of a bicycle is almost always one person (the use of tandems, child seats, trailers being relatively insignificant etc.), the value may be expressed as 11 gCO₂/PKT (Walsh et al., 2008). These emissions include cyclists' exhalation (5 gCO₂/PKT) and the embodied emissions of the manufacture of the bicycle (6 gCO₂/PKT). The emissions of CH₄ and N₂O are negligible in cyclists' exhalation, therefore a figure of 5 gCO₂e/PKT can be used. For the embodied emissions of bicycle manufacture, an aluminium frame has been assumed and emissions have been distributed

over the lifespan distance of the bicycle. For aluminium, there is an 11% difference between embodied emissions values in CO₂ and CO₂e (8.24 kg CO₂/kg and 9.16 kg CO₂e/kg) (DECC and Defra, 2011). As the majority of the bicycles mass is accounted for by aluminium, a 11% increase has been applied to 6 gCO₂/PKT, yielding a figure of 6.7 gCO₂e/PKT. Summating gives a total of 11.7 gCO₂e/PKT for the embodied emissions of cycling. Though embodied emissions of potential increased food consumption were not considered in this study, it is likely that this would not be significant.

Nonetheless, cycling emits far less carbon than driving a car and has great potential as an alternative mode of transport. This is due to the characteristics of cycling, which include:

- 1 it is a cheap mode of transport
- 2 investment costs for infrastructure are much lower than for other modes
- 3 travel by bicycle can be time effective in congested urban areas
- 4 the economic impacts and the health benefits of cycling (Massink et al., 2011).

Although the potential for modal shift lies predominantly with commuter cyclists, leisure cycling routes can also encourage a modal shift to cycling on commuter routes.

1.6 Carbon footprint of cycling routes

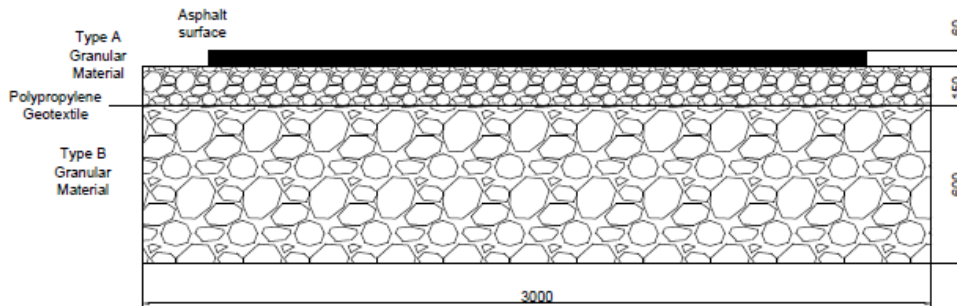
Similar to international routes, the NCN will comprise a range of cycle route types including:

- 1 on-road
- 2 cycle lanes
- 3 greenways (traffic-free cycle trails) (NRA, 2010).

Route types 1 and 2 are laid out on the road pavement; their formation normally consists of signage and line painting (pavements improvements can be necessary on occasion). Thus, no major construction takes place and the carbon emissions of constructing these route types can be considered to be minimal. A greenway, on the other hand, is a traffic-free trail typically constructed on disused railways, canal towpaths and riverbanks (Sustrans, 2009).

The preferred greenway surfacing is asphalt and the path is generally laid down in three layers. These include the surface layer, the base/sub-base layer and the capping layer with depths of 60 mm, 150 mm and up to 600 mm respectively (Sustrans, 2009; Manton and Clifford, 2012) (Figure 1 and Figure 2). The capping layer is required in soils of poor bearing capacity (e.g., peatland) and must be of sufficient depth to support construction, maintenance and possibly emergency vehicles. A geotextile, placed between the sub-base and capping layer, may be necessary to separate poor underlying soils such as peat with the base material (Sustrans, 2009; Manton and Clifford, 2012). This method has been used in greenways such as the Great Western Greenway in County Mayo, Ireland, where poor soils were frequently encountered (Figure 2).

Figure 1 Typical greenway cross-section



Source: Adapted from Sustrans (2009)

Figure 2 Great Western Greenway, County Mayo, Ireland (see online version for colours)



Source: Connor and Philbin (2010)

The carbon footprint of greenways can be divided into:

- 1 embodied carbon of materials
- 2 transport to site
- 3 machinery: site preparation and construction
- 4 loss of carbon from carbon sinks, such as peat.

These have been modelled for roads using tools such as asPECT and PaLATE (WRAP, 2011; CGDM, 2007).

1.7 Embodied carbon of peat

The majority of the NCN in Ireland will be constructed in rural areas. Given Ireland's large peatland areas (approximately 14% of land surface (Ward et al., 2007)) and given the prioritisation of using state owned lands, the issue of constructing on peat will be an important in the Irish context. Peat has a high carbon content ranging from 49% to 62% of its dry weight (SNH, 2003). Near-intact peatlands also slowly take in carbon from the atmosphere and nationally may take in as much as 210,474 tCO₂/yr (57,492 tC/yr) from the atmosphere (Renou-Wilson et al, 2011).

Given the low bearing capacity of peat, extraction and replacement may be required. Excavated peat, which has been under anaerobic conditions, starts releasing CO₂ and other gases when exposed to the atmosphere and aerobic conditions (Lindsay, 2010). A basic methodology of calculating the embodied carbon of peat is presented in this paper, based on the methodology given by Duggan et al. (2012). The removal of other carbon sinks, such as trees, bushes and organic topsoil, has not been considered in this methodology.

1.8 LCA of transport infrastructure

In recent years, transport engineers have begun to quantify embodied energy and embodied carbon of materials used in transport infrastructure projects. Angelopoulos et al. (2009) and Milachowski et al. (2011) calculated the environmental impact of constructing roads and Chau et al. (2011) examined the embodied energy of sections of a UK rail tunnel. The embodied carbon for construction of asphalt roads using a hot construction method is given as 32.8 kgCO₂e/m² in Hammond and Jones (2011). Furthermore, Hammond and Jones (2011) present embodied carbon values of 12.3 kgCO₂e/m² and 54 kgCO₂e/m² for maintenance and operation of the road respectively; over 40 years. Typical road operation includes streets and traffic lights (95% of total energy), road clearing, sweeping, gritting and snow clearing (Stipple, 2001).

Mendoza et al. (2012) applied a LCA methodology to the design and management of pedestrian pavements in urban environments. As a result of these LCA studies, methodologies have been presented for urban pedestrian, road and rail construction that can inform methodologies for cycle infrastructure. However, there are currently no guidelines determining construction-related emissions for use in the planning and design stages of greenways. The methodology presented below aims to create such guidelines based on the LCA method reviewed in this section.

2 Methodology

This research evaluates the carbon footprint due to the construction of greenways (carbon costs) and the required modal shift to cycling (carbon savings) necessary to 'balance' or offset these costs. This may be considered the 'goal' of our life-cycle assessment. This methodology identifies, based on a case-study, the emissions associated with various stages of the routes construction. This can allow better design and construction to reduce the emissions associated with various route options. Such a methodology can form part of an overall cycle route design matrix and be used when assessing the merits of one

proposed route over another. This methodology includes a LCA approach as outlined in BSI (2006) and has been applied to the 42 km Great Western Greenway in County Mayo, Ireland (Mayo County Council, 2012).

Given that the actual in-situ profile of the case study greenway changed frequently as various on-site conditions were encountered all equations are presented in a general manner and then applied to the typical greenway cross section. Once a life cycle inventory of embodied carbon intensities for materials, transport and machinery has been set up, the embodied carbon of a greenway can be calculated. This is divided into four parts and this section is laid out as such.

2.1 Embodied carbon of materials

A typical greenway comprises three layers:

- 1 asphalt
- 2 Type A granular material
- 3 Type B granular material.

Type A granular material (known as Type 1 in the UK) comprises gravel, crushed rock or recycled crushed mixed concrete aggregates. Type B granular material is crushed rock (NRA, 2011b; BSI, 2010). A polypropylene geotextile is generally used to prevent mixing with the subgrade and regrowth of vegetation. Having estimated the mass of each material required, the embodied carbon of each layer can be calculated as follows [equation (1)].

$$EC_{layer} = Vol_{layer} \times \rho \times \frac{EC_{material}}{1,000} \quad (1)$$

where EC_{layer} is the total embodied carbon intensity for the material in the layer in tonnes (tCO₂e) Vol_{layer} is the volume of the layer (m³), ρ is the density of the material (kg/m³) and $EC_{material}$ is the embodied carbon of the material (kgCO₂e/kg).

The volume of the layer (m³) over a given section of route being considered can be taken as [equation (2)].

$$Vol_{layer} = L_{layer} \times d_{layer} \times B_{layer} \quad (2)$$

where d_{layer} (m) and B_{layer} (m) are the average depth and breadth of the layer over a particular section of length, L_{layer} , (m).

2.2 Embodied carbon due to transport

The carbon emissions associated with transporting construction materials can be significant; particularly so in the case of heavy materials, such as stone. Equation (3) expresses the embodied carbon due to transport of construction materials:

$$EC_{transport} = \frac{Dist}{1,000} \times \left((W \times EC_{full}) + (n \times EC_{empty}) \right) \quad (3)$$

where the embodied carbon for transport, $EC_{transport}$ (tCO₂e) is calculated from the embodied carbon of the truck for the transport of construction material to site, EC_{full} (kg CO₂e/t-km), multiplied by the distance from gate-to-site, Dist (km), and the mass of the material transported, $W(t)$. This is then added to the embodied carbon for the empty return journey for the truck, EC_{empty} (kg CO₂e/km), multiplied by the number of trips, n , and Dist (km). The number of trips, n , is calculated by dividing the mass of the material by the capacity of the truck.

2.3 Embodied carbon due to machinery

To construct the greenway, a variety of machinery is used. For the purposes of this paper, the carbon emissions of excavators, dump trucks and rollers are considered. The consumption of fuel by these machines is considered only and the embodied carbon associated with the manufacture of the machines is omitted. In the initial stage of construction, it may also be necessary to cut and to fill sections to ensure gradients remain within tolerances.

The amount of excavation will depend on the strength of the soil, the profile of the route, verge and drainage requirements, and the soil's potential to support the structure's self weight. Embodied carbon from the use of excavators to clear soil and vegetation, $EC_{excavator}$ (tCO₂e) is based on the volume of soil, $Vol_{material}$ (m³), the working rate of the excavator, rate (m³_{material}/h), the fuel consumption of the excavator, FC (l/h) and the embodied carbon of the fuel (in this case diesel was assumed), $EC_{diesel-e}$ (kgCO₂e/l). This is expressed in equation (4).

$$EC_{excavator} = \left(\frac{Vol_{soil}}{Rate} \right) \times FC \times \frac{EC_{diesel-e}}{1,000} \quad (4)$$

Dump trucks are included in EC calculations as they place the materials in the excavations for the capping layer and sub-base layer. The carbon cost of this vehicle, $EC_{dumptruck}$, (tCO₂e) is a function of the pavement length, L (km), the mass of materials, W (t) and the embodied carbon for the dump truck per tonne kilometre, $EC_{vehicle}$ (kgCO₂e/t-km). This is expressed in equation (5).

$$EC_{dumptruck} = L \times W \times \frac{EC_{vehicle}}{1,000} \quad (5)$$

For the top layer, a paver lays the asphalt which is sometimes fed by a dump truck. A vibrating roller is then used to compact the layer. The carbon cost of a vibrating roller EC_{roller} (tCO₂e) is calculated from the drum width, D_{width} (m), the pavement width, P_{width} , (m) the pavement length, L (km), the number of times of compaction, $Comp_{number}$ and the embodied carbon of diesel for a vehicle between 1.74 and 3.5 tonnes in weight, $EC_{diesel-r}$ (kgCO₂e/km). This is expressed in equation (6).

$$EC_{roller} = \left(\text{Roundup} \left(\frac{P_{width}}{D_{width}} \right) \right) \times L \times Comp_{number} \times \frac{EC_{diesel-r}}{1,000} \quad (6)$$

where the term 'Roundup' indicates P_{width}/D_{width} rounded up to the nearest whole number.

2.4 Loss of carbon from peat

Excavated peat can be dried for agricultural purposes or dried and burnt as a fuel where it will lose 100% of its carbon. However, peat placed in peat disposal areas or in restoration of a peatland will likely retain a high proportion of its carbon (Nayak et al., 2008). Loss of carbon from excavated peat, EC_{peat} (tCO₂e) is calculated using the carbon content of the peat $pC_{drypeat}$ (%), the dry soil bulk density $\gamma_{drypeat}$ (g/cm³), the volume of excavated peat, Vol_{peat} (m³) and the percentage of carbon lost from the peat – pC_{lost} (%). A factor of 44/12 is used to convert the molecular mass of carbon to CO₂ and is expressed in tCO₂.

Further conversion to tCO₂e was not calculated by Nayak et al. (2008). The short term release of methane as peat is excavated can be difficult to estimate and can vary significantly between sites and construction practice. It is likely to be relatively limited compared to the overall carbon dioxide emissions. Excavated peat left on the surface will likely be exposed to aerobic conditions, therefore long term methane emissions, as a result of excavation, may be limited as anaerobic conditions are required for CH₄ production (Sundh et al., 2000; Roulet et al., 1993). Martikainen et al. (1993) has also shown that N₂O emissions are negligible from nutrient-poor peatlands. As a result, CH₄ and N₂O emissions are not considered in this study and the unit tCO₂e is therefore used. equation (7) is adapted from Nayak et al. (2008).

$$EC_{peat} = \frac{44}{12} \times \frac{pC_{drypeat}}{100} \times \gamma_{drypeat} \times Vol_{peat} \times \frac{pC_{lost}}{100} \quad (7)$$

3 Results and discussion

3.1 Carbon savings

Table 1 shows that for each trip shifted from a car of average occupancy (in Ireland) to bicycle, the carbon avoided is 134 gCO₂e/km. Major potential for modal shift exists amongst commuters with daily journeys of 5 km or less. To meet the Irish government's sustainable transport target, 150,000 people will be required to shift from driving a car to cycling by 2020 (DoT, 2009). This amounts to approximately 2,200 km per commuter (10 km per day for 220 working days/year), and a total of 330 million PKT per year. The avoided greenhouse gases in the form CO₂e in such a scenario is quantified in Table 1.

Table 1 Avoided carbon due to a modal shift from a car trip to a bicycle trip

<i>Mode of transport</i>	<i>Embodied carbon of trip (gCO₂e/km)</i>	<i>Average occupancy</i>	<i>Carbon emissions of trip (gCO₂e/PKT)</i>
Car	160 ¹	1.1 ²	145
Bicycle	11 ³	1	11
Avoided carbon (gCO ₂ e/km)			134
Avoided carbon (tCO ₂ e/million PKT)			134
Avoided carbon (tCO ₂ e) if Ireland's targets are met			44220

Source: ¹NRA (2011a), ²CSO (2012b) and ³Walsh et al. (2008)

This avoided carbon accounts for just under 0.8% of current Irish passenger car emissions. The figure is limited as commuters already travelling by car are unlikely to

cycle more than 5 km to work and therefore longer distance commuters will most likely continue to travel by car.

3.2 Carbon costs

The major carbon cost associated with the construction of greenways is the embodied carbon of the materials used. Tables 2 and 3 show that the embodied carbon (cradle-to-gate) for the construction materials used in the case study, which comprised a 3 m-wide greenway, is 46.36 tCO₂e/km. These results are based on the materials and quantities preferred by the literature and used in the Great Western Greenway in County Mayo, north-west Ireland. Values for the embodied carbon of Type A and Type B granular materials were acquired in kgCO₂/t and converted to kgCO₂e/t by increasing the value by 6%, as recommended by Hammond and Jones (2011) and MPA (2009). Mitigation measures exist that can reduce this embodied carbon and these are discussed in the conclusions.

Table 2 Mass of materials required for a typical 1 km of 3 m-wide section of the case study greenway

<i>Material</i>	<i>Depth of layer (m)^{1,2}</i>	<i>Volume (m³)</i>	<i>Density (kg/m³)</i>	<i>Mass required (t)</i>
Asphalt	0.06	180	2,243	403.74
Type A granular material	0.15	450	1,600	720
Type B granular material	0.6	1,800	1,600	2,880
Geotextile	/	3,000 (m ²)	120 (g/m ²)	0.36

Source: ¹Sustrans (2009) and ²Manton and Clifford (2012)

Table 3 Embodied carbon of materials used in a typical 1 km long, 3 m-wide section of the case study greenway

<i>Material</i>	<i>Mass required (t)</i>	<i>Embodied carbon (kgCO₂e/t)</i>	<i>Embodied carbon (tCO₂e)</i>
Asphalt	403.74	71 ¹	28.67
Type A granular material	720	4.54 ²	3.27
Type B granular material	2,880	4.58 ²	13.19
Geotextile	0.36	3,430 ¹	1.23
Total			46.36

Source: ¹Hammond and Jones (2011) and ²MPA (2009)

The embodied carbon of the greenway due to transportation of the materials is estimated in Table 4. The vehicles used are assumed to be heavy goods vehicles (HGVs) in excess of 17 tonnes and are assumed to be full on the outward journey and empty on the return journey. 100% full HGVs have an embodied carbon of 0.1205 kgCO₂e per tonne-kilometre and an average payload of 9.42 tonnes (DECC and Defra, 2011). Empty HGVs have an embodied carbon of 0.7925 kgCO₂e per kilometre over an empty return journey (DECC and Defra, 2011). The distance travelled was estimated based on the locations of quarries in relation to the Great Western Greenway. Such information could be available at planning stage. Gravel and crushed rock are often available locally in Ireland and excavated rock may also be used.

Table 4 Embodied carbon due to transport of materials in the case study greenway

<i>Material</i>	<i>Mass required</i>	<i>Distance</i>	<i>n</i>	<i>EC out</i>	<i>EC in</i>	<i>EC</i>
	(<i>t</i>)	(<i>km</i>)		(<i>kgCO₂e/t-km</i>) ¹	(<i>kgCO₂e/km</i>) ¹	
Asphalt	403.74	60	43	0.1205	0.7925	4.96
Type A	720	20	77	0.1205	0.7925	2.96
Type B	2880	20	307	0.1205	0.7925	11.81
Geotextile	0.36	60	1	0.1205	0.7925	0.05
Total						19.78

Source: ¹DECC and Defra (2011)

The embodied carbon of the greenway due to machinery can be difficult to estimate. Table 5 shows the embodied carbon of each machine in kgCO₂e per litre, per tonne-kilometre or per kilometre. The embodied carbon of diesel is 2.668 kgCO₂e/l, while dump trucks used are assumed to be average laden HGVs, which have an embodied carbon of 0.1292 kgCO₂e per tonne-kilometre (DECC and Defra, 2011). The vibrating roller is put into the category of vehicles whose weight lies between 1.74 and 3.5 tonnes and, therefore, has an embodied carbon figure of 0.27 kgCO₂e/km (DECC and Defra, 2011).

Table 5 Embodied carbon of each machine

<i>Vehicle</i>	<i>Embodied carbon</i>
Excavator	2.668 (kgCO ₂ e/l)
Dump truck	0.1292 (kgCO ₂ e/t-km)
Roller	0.27 (kgCO ₂ e/km)

Source: DECC and Defra (2011)

Excavation to a depth of 600 mm for a 3 m wide by 1,000 m long section requires the excavation of 1,800 m³ of material. A 21 tonne excavator has a fuel consumption of 16 l/h and a working rate of about 84.7 m³/h (Langdon, 2010; LandPro, 2012). The roller used was assumed to be a 2.75 tonne Wacker hydrostatic vibratory roller with a drum width of 1.2 m. It was estimated, on average, to pass over the 3 m by 1,000 m section twice. Using equations (3) to (5) the embodied carbon of the greenway due to machinery used has been estimated as 1.46 tCO₂e/km and is shown in Table 6.

Table 6 Embodied carbon estimated due to machinery

<i>Operation</i>	<i>Vehicle</i>	<i>Embodied carbon</i> (<i>tCO₂e/km</i>)
Clearance and excavation	Excavator	0.907 ^{2,3}
Placement of surface/base	Dump truck, roller	0.057 ¹
Placement of sub-base and geotextile	Dump truck, roller	0.098 ¹
Placement of capping	Dump truck	0.372 ¹
Total		1.43

Source: ¹DECC and Defra, 2011, ²Langdon (2010) and ³Landpro (2012)

Table 7 gives the total carbon footprint of constructing a typical greenway, which is 63.3 tCO₂e/km. This figure excludes the release of any carbon dioxide and other greenhouse gases that may have been stored in organics due to carbon sequestration, but subsequently released back into the atmosphere due to its removal or disturbance during construction. It may be seen that the embodied carbon due to construction materials is the main contributing factor, accounting for 73.3% of the total. The second largest contributor is that due to the transport of materials, account for 24.4%. Machinery usage during the construction of the greenway, meanwhile, accounts for just 2.3%. Additional carbon costs not considered include maintenance, drainage channels, fencing, signs and work on structures such as bridges.

Table 7 Total carbon footprint of a typical greenway

	<i>Embodied carbon (tCO₂e/km)</i>	<i>%</i>
Materials	46.36	68.6
Transport of materials	19.78	29.3
Machinery	1.43	2.1
Total	67.6	

The total embodied carbon of constructing a typical greenway estimated in this study is thus 22.5 kgCO₂e/m² for cradle-to-site, which is two-thirds that of the embodied carbon of constructing an asphalt road using a hot construction method (32.8 kgCO₂e/m²) (Hammond and Jones, 2011). However, it must be noted that the value for asphalt road construction in Hammond and Jones (2011) is for a cradle-to-gate boundary profile. Thus, if transport of material to site is ignored in the calculations of embodied carbon for a typical greenway, then greenways account for half that of an asphalt road built using a hot construction method.

3.3 Potential additional emissions due to peat removal

A further consideration for the embodied carbon of greenways is carbon loss of the material removed, particularly if this material is peat. If peat is burnt or dried, 100% of the carbon content of the peat is released. If the above 3 m wide by 1,000 m long section of greenway was constructed on peat and 1800 m³ of peat was excavated and burnt or dried, assuming a dry density of 0.1g/cm³ (100 kg/m³) (Nayak et al., 2008) and 50% carbon content (Müller et al., 2010), the carbon emissions alone (i.e., excluding CH₄ and N₂O) would be approximately 330 tCO₂/km, or at least 550% of the total carbon footprint due to construction materials, transport and machinery.

This figure illustrates the importance of the use of peat disposal areas, peatland restoration and good construction techniques. Further research is required to resolve the design issues presented by peat with a view to minimising the requirement for peat excavation.

3.4 Balance sheet

By equating the carbon costs and savings in a basic balance sheet, the number of commuters required to shift from driving a car to cycling can be calculated. Equation (8) demonstrates this, where $EC_{Greenway}$ (kgCO₂e/km) is the embodied carbon of the

greenway, $L_{Greenway}$ is the length of the greenway, $Dist_{commute}$ is the average commuting distance, $Commutes_{annually}$ is the number of commutes completed per year (around two per day for 220 days), and $LC_{Greenway}$ is the life cycle of the greenway. The number of 5 km commuters required to shift from the car to the bicycle based on the embodied carbon of a 10 km typical asphalt greenway with a life cycle of 20 years is 115 per year, as shown in Table 8.

$$Commuters_{required} = \frac{EC_{Greenway} \times L_{Greenway}}{CO_{2,avoided} \times Dist_{commute} \times Commutes_{annually} \times LC_{Greenway}} \quad (8)$$

Table 8 Sample calculation of commuters required to shift

Embodied carbon (kgCO ₂ e/km)	67,600
Length of greenway (km)	10
CO ₂ e avoided (kgCO ₂ e/km)	0.134
Commute distance (km)	5
Commutes (/year)	440
Life cycle of greenway (years)	20
Commuters required to shift from car to bicycle per year	115

4 Discussion and conclusions

With provision of cycling infrastructure both in rural and urban environments becoming increasingly important, tools that can aid the route selection process are required. While a modal shift to cycling has clear potential to reduce carbon emissions in the transport sector, has economic benefits and can lead to positive health impacts; the carbon cost of constructing new cycling routes, particularly greenways should be considered during the route selection stage of cycling network development. This paper describes a methodology, based on a LCA approach, of assessing and comparing the potential carbon cost that can be associated with the construction of various route options. The main conclusions that can be interpreted are:

- 1 In the case study presented, the 3 m wide greenway embodied 67.6 tCO₂e/km or 22.5 kgCO₂e/m². This is 30% that of a single lane rural road (225 tCO₂ per lane km) and 13.5% of a railway line (500 tCO₂ per single track km) (Transport Scotland, 2009; Hammond and Jones, 2011). It should be noted that the values for the single lane rural road and railway line do not account for other greenhouse gases other than carbon dioxide. However, accounting for other greenhouse gases would only increase these values by approximately 6% on average (Hammond and Jones, 2011).
- 2 Considering the embodied carbon of transport infrastructure per square metre, greenways account for two-thirds that of an asphalt road built using a hot construction method. However, such roads require greater width, verges, sight-lines etc. and therefore the overall embodied carbon of a road corridor is far greater than that of a greenway, as shown in point 1 above.
- 3 Construction materials comprise 69% of the embodied carbon in a greenway.

- 4 Transport of construction materials comprises 29% of the embodied carbon in a greenway.
- 5 Emissions from on-site construction machinery comprise 2.1% of the total embodied carbon in a greenway.
- 6 Given an assumed design life cycle of 20 years for the greenway; 115 commuters annually, commuting an average of 10 km/day, would be required to shift from the car to the bicycle in order to cancel out the carbon footprint of a 10 km greenway.

Using this methodology, it is recommended the following considerations could significantly reduce or offset the carbon footprint of greenways:

- 1 Use of recycled asphalt and demolition waste along with the investigation of the use of novel materials in the surface layer of greenways.
- 2 Use of locally recycled materials and local crushed rock and gravel in the sub-base and capping layers, thereby minimising transport of materials.
- 3 The use of novel materials in the base/sub-base layer and the capping layers could offer a more sustainable solution. Given the reduced loads on cycle lane foundations solutions such as tyre bales offer potential.
- 4 Use of existing road infrastructure, (e.g., local roads or other assets) where possible, to reduce the length of greenway constructed.
- 5 Promotion of greenways once constructed to ensure large usage and modal shift.
- 6 Encouraging modal shift from high carbon releasing transport, e.g., old cars and SUVs to cycling, walking and public transport. The presence of a greenway, by increasing the numbers of leisure cyclists could indirectly stimulate greater modal shifts.
- 7 Access to these greenways by public transport and provision of bicycle hire on site can further improve their carbon efficiency by reducing trips by car to the facility.

Further research is underway to quantify carbon costs not considered in the above case study, including maintenance, drainage channels, fencing, benches, signs, work on structures such as bridges, removal of carbon sinks and mode of travel to the greenway. This will allow for a cradle-to-grave approach. The existing ground conditions should also be considered, particularly when the cycle route is being constructed on peat. Novel designs could be used to minimise the volumes of peat removed – these may include the development of floating cycle lanes. This technique is commonly used for forestry and wind farm access roads in Ireland.

The methodology developed in this paper may be used in an overall design matrix for the comparison of route options, yielding an efficient and environmentally friendly design of cycle networks. The metric, once optimised, can be applied to cycle routes planned and constructed internationally.

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