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## Use of carbon calculation tools for sustainable cycle network design

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### ABSTRACT

In recent years European cycling has undergone a renaissance with various initiatives including the establishment of EuroVelo and the proposed European trans-border cycling infrastructure. Significant advances on this infrastructure have been made with 45,000 km of bike paths completed. In Ireland, to encourage a modal shift among commuters to cycling, and help boost facilities for leisure cyclists and cycle tourism, the Irish Government has proposed the establishment of a 2,000 km National Cycle Network (NCN). The NCN will be modelled on international networks such as the Vias Verdes (Spain), Landelijk Fietsroutes (Netherlands) and D-Netz (Germany) and the Sustrans NCN (UK). It will comprise a range of cycle route types including: (i) on-road, (ii) cycle lanes, and (iii) greenways (traffic-free cycle trails).

While a modal shift to cycling has clear potential to reduce carbon emissions in the transport sector the climate cost of constructing new cycling routes, particularly greenways, has not been previously considered. Carbon emissions during rural cycle lane construction, have the potential to negate the carbon savings made by the modal shift of many commuters. This paper, using a case study, describes a methodology for calculating the potential carbon emissions associated with cycle lane construction. It was found that the embodied carbon of on-road cycle routes and cycle lanes were generally not significant. On the other hand, the case study greenway was found to embody 60.4 tCO<sub>2</sub>e/km. The carbon savings of shifting a Passenger Kilometre Travelled (PKT) from driving a car to cycling were found, in Ireland, to average 134 gCO<sub>2</sub>e/PKT. Therefore, in the example presented, a shift of 102 commuters per year (224,400 PKT) are required to offset the carbon footprint of one 10 km asphalt greenway. The metric presented can (i) be used, at design stage to compare proposed routes in terms of their embodied carbon and (ii) be integrated in a wider design matrix to ensure the efficient and sustainable design of cycle networks internationally.

### LITERATURE REVIEW

#### Background and policy

The development of cycle networks in rural and urban areas is seen as increasingly important for reasons including: (i) reducing the carbon footprint of the transport sector, (ii) the potential for health benefits, (iii) improving quality of life and (iv) 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 structural funding can be made available for the completion of cycle routes which in turn places emphasis on efficient route design. Internationally, efforts are also being made to reduce unsustainable transport habits, with provision of cycling being to the fore.

In Ireland, for example, there are currently 435 cars per 1000 population, a 109% increase since 1990 [1, 2]. 1.1 million people (58% of the commuting population) drive a car to work daily while only 36,000 people (2% of the commuting population) cycle. This is despite the fact that 30% of commutes are less than 5 km – a reasonable cycling distance [3]. 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: (i) on-road, (ii) cycle lanes, and (iii) greenways (traffic-free cycle trails) [4].

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 climate 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).

Evaluating the carbon emissions in the construction of cycle route pavements can be one of the key parameters used in the route selection and design phases of cycle networks. Figures and methodologies have been presented for other transport forms, such as road and rail construction. Currently there are no guidelines on how to determine the potential emissions at the planning and design stages. Thus, for the effective comparison of route options, a metric for the carbon impact of each route is necessary.

This research evaluates the potential carbon savings of a modal shift to cycling in PKT and the carbon emissions of the construction of cycling routes. This paper proposes a metric that estimates the carbon emissions and potential savings associated with each route. Such a metric can form part of an overall cycle route design matrix work which is currently being separately developed as part of this research.

### **Embodied carbon and carbon dioxide equivalents**

Embodied carbon of a material can be taken as the total carbon released over its life cycle [5]. Ideally the boundaries would be 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. 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) [5]. However, by including the embodied carbon due to transport, the Cradle-to-Site embodied carbon has been considered in this paper.

Embodied carbon is measured in carbon dioxide equivalents (CO<sub>2</sub>e), which not only include carbon dioxide, but also other greenhouse gases as set out in the Kyoto protocol, such as methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and PFCs [6]. The carbon dioxide equivalent of a gas is

found by multiplying the mass of the gas by the associated global warming potential (GWP) [6]. GWP is based on the relative amount of heat that is trapped in the atmosphere by a greenhouse gas, where CO<sub>2</sub> has a GWP of 1. Values for CO<sub>2</sub>e are approximately 6% higher than values for CO<sub>2</sub> for materials used in the UK [5].

### **Carbon emissions of Irish transport**

Ireland's greenhouse gas emissions in 2010 were 61.64 Mt carbon dioxide equivalents (Mt CO<sub>2</sub>e) and 11.77 Mt CO<sub>2</sub>e or 19.1% of these emissions were a result of the transport sector [7]. Although, due to economic factors, this represents a decrease since 2008, the figure is more than double the 1990 level of 5.2 Mt CO<sub>2</sub>e [8]. The average occupancy of Irish cars when commuting is 1.1, with the carbon dioxide emissions for an average Irish passenger car being approximately 160 g CO<sub>2</sub>/km [2, 9]. The emissions of CH<sub>4</sub>, N<sub>2</sub>O and other greenhouse gases emitted by cars are relatively insignificant thus an overall figure of 160 gCO<sub>2</sub>e/km can be used [10]. Emissions from all Irish passenger cars totalled 5.8 Mt CO<sub>2</sub> in 2009 - a 96% increase on 1990 [9].

### **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 gCO<sub>2</sub>/PKT. These emissions include emissions due to cyclists' exhalation and the embodied emissions of the manufacture of the bicycle [11]. The emissions of CH<sub>4</sub> and N<sub>2</sub>O are assumed to be negligible and an overall figure of 11 gCO<sub>2</sub>e/PKT can be used. Though embodied emissions of potential increased food consumption were not considered in this study, it is likely 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: (i) it is a cheap mode of transport, (ii) investment costs for infrastructure are much lower than for other modes, (iii) travel by bicycle can be time effective in congested urban areas, and (iv) the economic impacts and the health benefits of cycling [12].

### **Carbon footprint of cycling routes**

Similar to international routes, the NCN will comprise a range of cycle route types including: (i) on-road, (ii) cycle lanes, and (iii) greenways (traffic-free cycle trails) [4]. Route types (i) and (ii) are laid out on the road pavement; their formation normally consists of signage and line painting. 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 [13].

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 [13, 14] (Figure 1 and Figure 2). The capping layer is required in soils of poor bearing capacity 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 [13, 14]. This method has been used in greenways such as

the Great Western Greenway in County Mayo, Ireland, where poor soils were frequently encountered.

The carbon footprint of greenways can be divided into: (i) embodied carbon of materials, (ii) transport to site, (iii) machinery: site preparation and construction, and (iv) loss of carbon from peat, where construction in peat areas is planned along the route. These have been modelled for roads using tools such as asPECT and PaLATE [15, 16]. The removal of carbon sinks, such as trees, bushes and organic topsoil, has not been considered in this methodology.

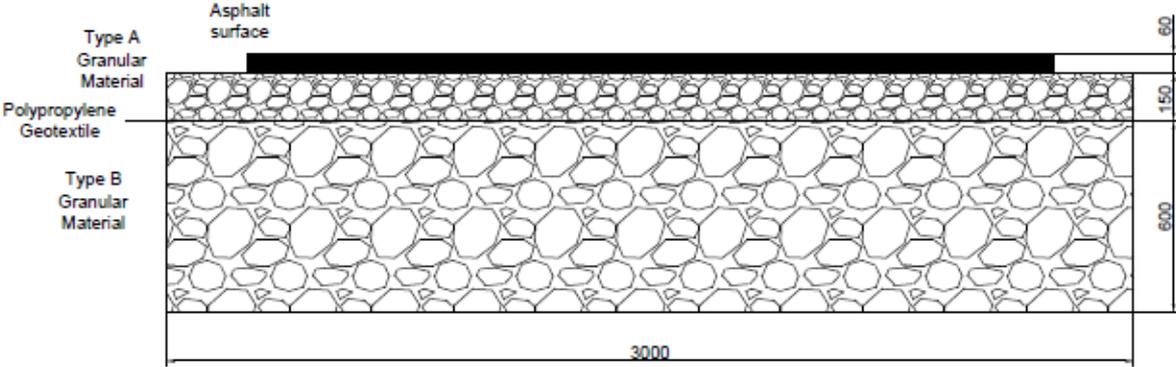


Figure 1. Typical greenway cross section. Adapted from [13]



Figure 2. Great Western Greenway, County Mayo, Ireland [17]

**Embodied carbon of peat**

The majority of the NCN in Ireland will be constructed in rural areas. Given Ireland’s large bogland areas (approximately 14% of land surface [18]) and given the prioritisation of using state owned lands, the issue of constructing on peat will be an important in the Irish context.

The peat in bogs has a high carbon content ranging from 49% to 62% of its dry weight [19]. Near-intact boglands also slowly take in carbon from the atmosphere and nationally may take in as much as 210,474 tCO<sub>2</sub>/yr from the atmosphere [20].

Given the low bearing capacity of peat, extraction and replacement may be required. Excavated peat, which has been under anaerobic conditions, starts releasing CO<sub>2</sub> and other gases when exposed to the atmosphere and aerobic conditions [21]. A basic methodology of calculating the embodied carbon of peat is presented in this paper, based on the methodology given by Duggan et al. [22].

## METHODOLOGY

This section presents the methodology for estimating the embodied carbon of a typical greenway. The embodied carbon of a greenway can be divided into four parts and this section is laid out as such. All equations are presented in a general manner and are applied to a case study of the 42 km Great Western Greenway in County Mayo, Ireland [23].

### (i) Embodied carbon of materials

A typical greenway comprises three layers: (i) asphalt, (ii) Type A granular material, and (iii) Type B granular material. Type A granular material comprises of gravel, crushed rock or recycled crushed mixed concrete aggregates. Type B granular material is crushed rock [24]. 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, and includes the embodied carbon from Cradle-to-Gate (Eq 1).

$$EC_{layer} = Vol_{layer} \times \rho \times \frac{EC_{material}}{1000} \quad (1)$$

Where  $EC_{layer}$  is the total embodied carbon intensity for the material in the layer (tCO<sub>2</sub>e) including transport from Cradle-to-Gate,  $Vol_{layer}$  is the volume of the layer (m<sup>3</sup>),  $\rho$  is the density of the material (kg/m<sup>3</sup>) and  $EC_{material}$  is the embodied carbon of the material (kgCO<sub>2</sub>e/kg).

The volume of the layer (m<sup>3</sup>) over a given section of route being considered can be taken as (Eq 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).

### (ii) 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. The Gate-to-Site boundary profile can be expressed as:

$$EC_{transport} = Dist \times W(t) \times \frac{EC_{vehicle}}{1000} \quad (3)$$

Where the embodied carbon for transport,  $EC_{transport}$  (tCO<sub>2</sub>e) is dependent on the distance from Gate-to-Site, Dist (km), the mass of the material transported, W (t), and the embodied carbon emissions intensity for the transport vehicle per tonne kilometre,  $EC_{vehicle}$  (kg CO<sub>2</sub>e/t-km).

### (iii) 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. 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 soils potential to support the structure's self weight. Embodied carbon from the use of excavators to clear soil and vegetation,  $EC_{excavator}$  (tCO<sub>2</sub>e) is based on the volume of soil,  $Vol_{material}$  (m<sup>3</sup>), the working rate of the excavator, Rate (m<sup>3</sup> material/h), the fuel consumption of the excavator, FC (l/h) and the embodied carbon of the fuel (in this case diesel was assumed),  $EC_{diesel}$  (kgCO<sub>2</sub>e/l). This is expressed in Equation 4.

$$EC_{excavator} = \left( \frac{Vol_{soil}}{Rate} \right) \times FC \times \frac{EC_{diesel}}{1000} \quad (4)$$

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,  $EC_{dumptruck}$ , (tCO<sub>2</sub>e) 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,  $EC_{vehicle}$  (kgCO<sub>2</sub>e/t-km). This is expressed in Equation 5.

$$EC_{dumptruck} = L \times W \times \frac{EC_{vehicle}}{1000} \quad (5)$$

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  $EC_{roller}$  (tCO<sub>2</sub>e) 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,  $EC_{diesel}$  (kgCO<sub>2</sub>e/km). This is expressed in Equation 6.

$$EC_{roller} = \left( Roundup \left( \frac{P_{width}}{D_{width}} \right) \right) \times L \times Comp_{number} \times \frac{EC_{diesel}}{1000} \quad (6)$$

### (iv) 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 bogland will likely retain a high proportion of its carbon [25]. Loss of carbon from excavated peat,  $EC_{peat}$  (tCO<sub>2</sub>) is calculated using the carbon content of the peat  $pC_{drypeat}$  (%), the dry soil bulk density  $BD_{drypeat}$  (g/cm<sup>3</sup>), the volume of excavated peat,  $Vol_{peat}$  (m<sup>3</sup>) 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 CO<sub>2</sub>. This figure will exclude CH<sub>4</sub> and N<sub>2</sub>O and is therefore expressed in tCO<sub>2</sub>. Equation 7 is adapted from work carried out by Nayak et al. [25].

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

## RESULTS AND DISCUSSION

### (a) Carbon savings

Table 1 shows that for each trip shifted from a car of average occupancy to bicycle, the carbon avoided is 134 gCO<sub>2</sub>e/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 [3]. 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 carbon 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

Mode of Transport	Embodied Carbon of trip (gCO <sub>2</sub> e/km)	Average Occupancy	Carbon emissions of trip (gCO <sub>2</sub> e/PKT)
Car	160 <sup>[9]</sup>	1.1 <sup>[2]</sup>	145
Bicycle	11 <sup>[11]</sup>	1	11
Avoided carbon (gCO <sub>2</sub> e/km)			134
Avoided carbon (tCO <sub>2</sub> e/million PKT)			134
Avoided carbon (tCO <sub>2</sub> e) if Ireland's targets are met			44220

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 will continue to travel by car.

### (b) 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 for the case study, which comprised a 3 m-wide greenway, is 46.36 tCO<sub>2</sub>e/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 kgCO<sub>2</sub>/t and converted to kgCO<sub>2</sub>e/t by increasing the value by 6%, as recommended by [5, 26]. 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

Material	Depth of layer (m) <sup>[13,14]</sup>	Volume (m <sup>3</sup> )	Density (kg/m <sup>3</sup> )	Mass required (t)
Asphalt	0.06	180	2243	403.74
Type A granular material	0.15	450	1600	720
Type B granular material	0.6	1800	1600	2880

Geotextile	/	3000 (m <sup>2</sup> )	120 (g/m <sup>2</sup> )	0.36
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Table 3. Embodied carbon of materials used in a typical 1 km of 3 m-wide section of the case study greenway

Material	Mass required (t)	Embodied Carbon (kgCO <sub>2</sub> e/t)	Embodied Carbon (tCO <sub>2</sub> e)
Asphalt	403.74	71 <sup>[5]</sup>	28.67
Type A granular material	720	4.54 <sup>[26]</sup>	3.27
Type B granular material	2880	4.58 <sup>[26]</sup>	13.19
Geotextile	0.36	3430 <sup>[5]</sup>	1.23
<b>Total</b>			<b>46.36</b>

The embodied carbon of the greenway due to transportation of the materials is estimated in Table 4. The vehicles used are assumed to be average laden Heavy Goods Vehicles (HGVs), which have an embodied carbon of 0.1292 kgCO<sub>2</sub>e per tonne-kilometre [10]. 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

Material	Mass required (t)	Distance (km)	Embodied Carbon (kgCO <sub>2</sub> e/t-km) <sup>[10]</sup>	Embodied Carbon (kgCO <sub>2</sub> e)
Asphalt	403.74	60	0.1292	3.13
Type A granular material	720	20	0.1292	1.86
Type B granular material	2880	20	0.1292	7.44
Geotextile	0.36	60	0.1292	0.003
<b>Total</b>				<b>12.44</b>

The embodied carbon of the greenway due to machinery is difficult to estimate. Table 5 shows the embodied carbon of each machine in kgCO<sub>2</sub>e per litre, per tonne-kilometre or per kilometre. The embodied carbon of diesel is 3.1761 kgCO<sub>2</sub>e/l, while dump trucks used are assumed to be average laden HGVs, which have an embodied carbon of 0.1292 kgCO<sub>2</sub>e per tonne-kilometre [10]. 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 0.271 kgCO<sub>2</sub>e/km [10].

Excavation to a depth of 600 mm for a 3 m wide by 1000 m long section requires the excavation of 1800 m<sup>3</sup> of material. A 21 tonne excavator has a fuel consumption of 16 l/h and a working rate of about 84.7 m<sup>3</sup>/h [27, 28]. The roller used is assumed to be a 2.75 tonne Wacker hydrostatic vibratory roller with a drum width of 1.2m [29]. It was assumed, on average, to pass over the 3 m by 1000 m section twice. Using Eqns 3, 4 and 5 the embodied

carbon of the greenway due to machinery used has been estimated as 1.6 tCO<sub>2</sub>e/km and is shown in Table 6.

Table 5. Embodied carbon of each machine [10]

Vehicle	Embodied Carbon
Excavator	3.1761 (kgCO <sub>2</sub> e/l)
Dump truck	0.1292 (kgCO <sub>2</sub> e/t-km)
Roller	0.271 (kgCO <sub>2</sub> e/km)

Table 6. Embodied carbon estimated due to machinery

Operation	Vehicle	Embodied Carbon (tCO <sub>2</sub> e/km)
Clearance and excavation	Excavator	1.08 <sup>[10,27,28]</sup>
Placement of surface/base	Dump truck, Roller	0.054 <sup>[10,29]</sup>
Placement of sub-base and geotextile	Dump Truck, Roller	0.095 <sup>[10,29]</sup>
Placement of capping	Dump Truck	0.372 <sup>[10]</sup>
Total		1.6

Table 7 gives the total carbon footprint of a typical greenway. 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 materials is the main contributing factor, accounting for 72.4% of the total. The second largest contributor is that due to the transport of materials, account for 25.1%. Machinery, meanwhile, accounts for just 2.5%. 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

	Embodied Carbon (tCO <sub>2</sub> e/km)	%
Materials	46.36	76.8
Transport of materials	12.44	20.6
Machinery	1.6	2.6
Total	60.4	100

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 x 1000 m section was constructed on peat and

1800 m<sup>3</sup> of peat was excavated and burnt or dried, assuming a dry density of 0.1g/cm<sup>3</sup> (100 kg/m<sup>3</sup>) [25] and 50% carbon content [30], the carbon emissions alone (i.e. excluding CH<sub>4</sub> and N<sub>2</sub>O) would be about 330 tCO<sub>2</sub>/km, or at least 550% of the total carbon footprint due to materials, transport and machinery. This figure illustrates the importance of the use of peat disposal areas, bogland 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.

### (c) Environmental metric

Equation 8 gives a basic metric for the environmental evaluation of greenways, where  $EC_{Greenway}$  (kgCO<sub>2</sub>e/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 potential to cancel out the embodied carbon of greenways exists in the shifting of commuters from cars to bicycles. Table 8 calculates 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.

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

Table 8. Sample calculation based on environmental metric

Embodied Carbon (kgCO <sub>2</sub> e/km)	60400
Length of greenway (km)	10
CO <sub>2</sub> e avoided (kgCO <sub>2</sub> 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	102

## 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 climate 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 of assessing and comparing the potential carbon cost of various route options. Based on the metric and the case study the main conclusions are:

1. In the case study presented the 3 m wide greenway contained about 60.4 tCO<sub>2</sub>e/km, assuming a Cradle-to-Site boundary profile. This is about 25% of a single lane rural road and 11% of a railway line [31]
2. The materials comprise approximately 77 % of the embodied carbon in a greenway.

3. Transport of construction materials comprises approximately 21% of the embodied carbon in a greenway.
4. On-site construction machinery comprises less than 3% of the total embodied carbon in a greenway.
5. 102 commuters annually would be required to shift from the car to the bicycle for their daily commute in order to cancel out the carbon footprint of a 10 km greenway.

By analysing the developed metric, the following six basic methods could significantly reduce or offset the carbon footprint of greenways:

1. Use of existing road infrastructure, e.g. local roads, for cycling routes rather than constructing greenways.
2. Encourage modal shift from high carbon releasing transport, e.g. old cars and SUVs to cycling, walking and public transport.
3. Use of recycled asphalt and the investigation of novel materials in the surface layer of greenways.
4. Use of recycled and local crushed rock and gravel in the sub-base and capping layers, thereby minimising transport of materials.
5. Promotion of greenways once constructed to ensure large usage and modal shift.
6. 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 and the removal of carbon sinks. This will allow a Cradle-Grave approach. The existing ground conditions should also be considered, particularly when the cycle route is being constructed on peat.

The environmental metric developed by 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 being planned and constructed internationally.

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