Understanding the Carbon Footprint of Timber Transport in the United Kingdom

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Executive Summary

This study on “Understanding the Carbon Footprint of Timber Transport in the United Kingdom” was undertaken by North Energy Associates Ltd and Forest Research for the Confederation of Forest Industries (UK) Ltd (ConFor) on behalf of the Timber Transport Forum. Its aims have been to determine the contributions to, and significance of greenhouse gas (GHG) emissions associated with timber transport, and to explore possible interventions for reducing these emissions. It was a requirement of this study that it should mainly rely on existing sources of information and literature.

Estimates of direct GHG emissions due to fuel consumption of typical timber road haulage vehicles travelling on public roads have been derived travelling on public roads. These have been adjusted to account for the effects of topography and road type within forest. Subsequent direct GHG emissions for timber transport were found to be between 33% and 35% higher on forest roads compared with public roads.

Various interventions to reduce fuel consumption and GHG emissions have been investigated and it has been concluded that the most practical possibilities, consisting of modified driver behaviour and tyre pressure control systems, result in maximum savings in fuel consumption and direct GHG emissions of 15%. The use of biodiesel in timber road haulage vehicles, if practical, could reduce direct GHG emissions by between 49% and 83% depending on their source of supply.

Indirect GHG emissions related to vehicle manufacture and maintenance have been evaluated. Due to the assumed short working life of timber road haulage vehicles, equating to a total of 770,000 km, than the 1,000,000 km normally assumed for conventional road haulage vehicles, inclusion of vehicle manufacture adds between 13% and 18% to direct GHG emissions from timber transport. Vehicle maintenance, including complete tyre replacement annually, would increase direct GHG emissions by between 25% and 33%.

Other sources of indirect GHG emissions for timber transport, consisting of forest road construction and maintenance, and public road maintenance, have also been addressed. The relative significance of these contributions depends on specific assumptions about soil disturbance and carbon dioxide emissions from forest road construction, the life span of forest roads, the details of management strategies for maintaining forest roads, and the public road density which relates the length of such roads used for timber haulage to the area of forest from which timber is extracted.

Total GHG emissions for alternative modes of timber transport, including diesel freight trains, inland waterways and coastal shipping, have been evaluated, although their widespread use would clearly depend on practical and logistical considerations.

Total GHG emissions from existing timber transport have been set in context of timber production and use as sawn timber in construction and as fuel wood for heating. In order to do this, it was necessary to take into account GHG emissions from all relevant forestry operations as well as the potential displacement of other construction materials and the effects of end-of-life disposal, in the case of sawn timber, and the displacement of fossil fuels by fuel wood. Calculations have been performed using the specifically-developed Timber Transport Workbook.

Estimates indicate that overall GHG emissions are between – 570 and – 8,376 kg eq. CO_2 per tonne of sawn timber used in construction, depending on displacement and disposal assumptions, and between – 667 and – 666 kg eq. CO_2 per tonne of fuel wood for heating. GHG emissions associated with timber transport amount to 35 kg eq. CO_2 per tonne of sawn timber used in construction, and 14 kg eq. CO_2 per tonne of fuel wood for heating. In the context of total GHG emissions, excluding displacement, these contributions are relatively small, accounting for 6 % in the case of one tonne of sawn timber and 15% in the case of one tonne of fuel wood.

Sensitivity analysis has been conducted on these estimates using the Timber Transport Workbook. In particular, the effects of timber transport distance, vehicle fuel consumption savings and levels of forest and public road maintenance were investigated. Clear variations were apparent from this sensitivity analysis but the resulting impact on overall GHG emissions for sawn timber and fuel wood are relatively small.

Recommendations from this study are for:

- Further examination of potential interventions and their practical implementation for reducing direct GHG emissions from timber transport.

- A more detailed study into the actual working life of timber road haulage vehicles and their tyre replacement, with more detailed assessment of GHG emissions associated with vehicle and tyre manufacture and maintenance, if necessary.

- Further investigation of CO_2 emissions from soil disturbance during forest road construction, the life span of forest roads, and the extent and frequency of forest road maintenance.

- Searching information required for derivation of a more reliable estimation of public road density.

- More extensive evaluation of the effects of materials displacement and end-of-life disposal for sawn timber used in construction, and fossil fuel displacement for fuel wood used in heating and other energy end uses.

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1 INTRODUCTION

1.1 Background

There are numerous contributions to the total greenhouse gas[1] (GHG) emissions associated with the production and the supply of timber for material and fuel purposes. Viewed over the full life cycle, these include activities involved in original afforestation and subsequent regeneration; felling, removal and haulage; and processing into forest products, such as timber products (for construction, manufacturing, etc.) and wood chips and pellets (for energy production). Initial forest growth and eventual product both offer potential for carbon sequestration, although its realisation depends on specific circumstances and assumptions. In contrast to this, all forestry operations, transportation and timber processing can give rise to GHG emissions directly as a result of the consumption of fossil fuels and indirectly due to the use of chemicals, materials, plant, equipment, machinery, *etc*.

Various studies have assessed contributions to the total GHG emissions of selected parts of these timber product pathways. This has been possible by combining specialist knowledge of forest growth and carbon cycles, the relevant details of forest and timber operations, and the practical application of life cycle assessment (LCA) as the basic framework within which GHG emissions calculations are performed. Previously published LCA studies have not focused specifically on the relative contribution of timber transport to total GHG emissions of timber products. However, as a result of accumulated publication of relevant data over a period of time, it is now possible to set GHG emissions associated with timber transport in context of overall timber product production and supply. In addition, the relative significance of possible interventions which might reduce GHG emissions from timber transport can be investigated.

1.2 Aims and Objectives

The aims of this study, which has been undertaken by North Energy Associates Ltd and Forest Research for the Confederation of Forest Industries (UK) Ltd (ConFor) on behalf of the Timber Transport Forum, are as follows:

- To improve understanding of the contribution of timber haulage to the carbon footprint (in the form of associated GHG emissions) of the forestry and timber industries, and

- To enable the Timber Transport Forum (TTF) to form a better assessment of the significance, in terms of the carbon footprint, of interventions relating to timber transport in the United Kingdom (UK).

In order to accomplish these aims, the following objectives were established:

- To present the available carbon footprint data for definable segments that make up the roundwood (softwood) supply chain, with particular attention given to those components that influence roundwood haulage. The main elements that effect timber transport are highlighted in the original TTF scoping paper (TTF, 2009). It is expected that, ideally, results will be presented as "indicators" that would allow some manipulation of figures, such as by altering fuel performance data (km/l) or timber miles on forest or minor

[1] The prominent greenhouse gases addressed in most studies consist of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

roads. In addition to contributions from vehicle use to total GHG emissions, the consequences of investment in maintaining, improving or creating roads (forest roads, haul routes, minor public roads) will be investigated. Proposed discussion between the client and the consultant will determine the most appropriate presentation of supply chain segments and indicators based on the available data.

- To set the carbon footprint of roundwood haulage in the wider context of the forest industry by illustrating two typical roundwood supply chain scenarios consisting of the production and use of sawn timber and fuel wood.

- To consider the likely significance and sensitivity of data on the GHG emissions contributions of the elements of the roundwood haulage sector and suggest where further information collection would improve understanding.

It should be noted that this study was not intended to involve the generation of new data. Instead, the study relies on existing data from published and other sources. Where detailed data are not available, it was proposed that illustrative figures would be used to suggest the relative contribution of each element of the roundwood supply chain. Subsequent analysis was expected to determine which elements are likely to be particularly significant or sensitive to variable factors and, therefore, where further data gathering would be considered worthwhile.

1.3 Structure of the Report

Having established the background to this study and its aims and objectives, Section 2 describes the collection of relevant data from existing sources and the analysis of such data for current purposes. The derivation and presentation of relevant GHG emission indicators are addressed in Sections 3 to 6. In particular, direct GHG emissions are considered in Section 3 which includes the fuel performance of current road haulage vehicles and the likely effects of possible interventions to reduce direct GHG emissions. Infrastructure GHG emissions associated with road haulage vehicle manufacture and maintenance, forest and public road construction and maintenance are examined in Section 4, with details contained in Appendices A and B. Total GHG emissions of other modes of transport including rail and inland waterway barge transport are covered by Section 5. All other contributions to GHG emissions associated with the selected roundwood supply chain scenarios, including forest establishment and regeneration, roundwood harvesting and extraction, timber sawmilling and fuel wood preparation are investigated in Section 6, with details of forest operations contained in Appendix C. Comparative GHG emissions associated with the use of steel and concrete as alternatives to sawn timber, and fossil fuels as alternatives to fuel wood for heating are summarised in Section 7. Relative contributions of segments of the chosen roundwood supply chain scenarios are presented in Section 8. The main outcomes of sensitivity analysis conducted on chosen key parameters are presented in Section 9. Conclusions and recommendations are provided in Section 10.

2 DATA COLLECTION

A brief review of existing literature, in the form of relevant reports, studies and findings available both in the public domain and from internal sources, was conducted at the beginning of this study. This covered existing literature on the following general areas of interest:

- Direct GHG Emissions from Timber Haulage Vehicles:
  - Fuel performance of road haulage vehicles
  - Effects of interventions on fuel performance
- Indirect GHG Emissions of Infrastructure:
  - Road haulage vehicle manufacture and maintenance
  - Forest road construction and maintenance
  - Public road construction and maintenance
- Total GHG Emissions of Alternative Modes of Transport:
  - Rail, barge and ship transport
- Total GHG Emissions of Forest Systems:
  - Forest establishment and regeneration
  - Harvesting and extraction of forest products
  - Sawmilling of timber
  - Production and use of fuel wood
- Total GHG Emissions of Comparative Reference Systems:
  - Steel and concrete as alternatives to timber
  - Fossil fuels as alternatives to fuel wood for heating

Widespread literature searches were conducted and specific literature was also provided by the Timber Transport Forum. Relevant literature was assessed with regard to the relevance, quality and transparency of data presented. Data which provided or could be used to derive estimated GHG emissions associated with various operations, activities, etc., were collected and manipulated to produce suitable indicators for segments of the chosen roundwood supply chain scenarios. These indicators are measured in equivalent carbon dioxide (CO_2)[2] and presented in common units such as 'kg eq. CO_2 per tonne-kilometre (t-km)', 'kg eq. CO_2 per kilometre (km)' and 'kg eq. CO_2 per oven dried tonne (odt)'.

[2] In this report, the following? Global Warming Potentials were adopted for converting CH_4 (25) and N_2O (298)to equivalent CO_2 on the basis of a 100 year time horizon (Forster et al., 2007)

3 DIRECT EMISSIONS OF TIMBER HAULAGE VEHICLES

3.1 Fuel Performance of Road Haulage Vehicles

There are various sources of data on GHG emissions from transport, especially in relation to fuel performance. One of the main problems with these sources, however, is that they often categorise vehicles into vague groups and are measured in various units. This is particularly true for road haulage, where vehicles of various size classes are grouped together as either 'rigid' (typically size classes from 3 tonnes (t) to 32 t Gross Vehicle Weight (GVW)) and 'articulated' (size classes from 40 t to 44 t GVW). Direct GHG emissions due to fuel combustion by vehicles are usually measured in g CO_2 or eq. CO_2 per km travelled (see, for example, NETCEN, 2003; DEFRA, 2008) or g CO_2 or eq. CO_2 per MJ (mega joule; 10^6 J) of fuel consumed (Waldron et al., 2006). For GHG emission to be specifically representative of haulage, it is best to cite estimates in the form of 'per tonne-kilometre' (t-km), as this demonstrates the function of both weight transported and distance. Subsequent estimates represent the GHG emissions released when transporting one tonne of load one kilometre. In this report, transport GHG emissions are based on three main factors: the vehicle load, distance travelled and the GHG emissions per t-km. It should be noted that care needs to be applied in the interpretation of "distance travelled" when discussing any estimated transport GHG emissions. This is because some estimates refer to the actual distance over which a given load was moved whereas other estimates take account of the distance of return of the vehicle, especially if this was empty. For this reason, it is necessary to distinguish between "single trip" and "round trip" distance. In this study, it has been assumed that outward journeys are undertaken with a full load, and that there is no load on the return journey.

In a haulage system, vehicle loads may be expected to be already optimised for economics, logistics and safety. There are few advantages with overloading vehicles to increase volume transported as this can cause damage to both vehicles and roads (RHWP, 2002). Two specific road haulage vehicle sizes and payload capacities are normally assumed for timber haulage: 40 t GVW with a payload capacity of 25.5 tonnes, and 44 t GVW with a payload capacity of 28.5 tonnes (North Energy, 2009a). It is generally assumed that the load capacity of road timber transport is limited by the weight of the load rather than its volume, given the relatively high bulk density of fresh roundwood which is over 400 kg/m^3 (Whittaker et al., 2009). From earlier work, it is also assumed that there is a linear relationship between the fuel consumption of a road haulage vehicle, in litres (l) per km, and the weight of load carried relative to the payload capacity represented by the load factor (North Energy, 2009a), expressed as follows:

$$F_l = F_f \times 0.874 \times \{1 + [0.36 \times (L - 50)/100]\} \qquad \text{(Equation 1)}$$

where,

F_l = fuel consumption at a given load factor (l/km)

F_f = fuel consumption at full load (l/km)

L = load factor (%)

For a 40 t GVW road haulage vehicle, F_f is taken to be 0.332 l/km and for a 44 t GVW vehicle, F_f equals 0.376 l/km. For comparison with other estimates, it is necessary to convert results for Equation 1 into fuel performance expressed in miles per UK gallon (mpg). On this basis, fuel performance derived using Equation 1 declines by 0.080 mpg per tonne of payload carried. This is comparable with a decrease of 0.112 mpg per tonne, which was calculated experimentally (Coyle, 2007). Goodyear testing data indicate that every 10,000 pound (lb) increase in load leads to a 5% drop in fuel efficiency (Goodyear, 2008). This is comparable with equivalent results generated with Equation 1 for 40 t and 44 t GVW road haulage vehicles which suggest that every 10,000 lb increase in load causes a reduction in fuel efficiency, measured in km/l, of between 4.9% and 5.4%.

As with the load, distances travelled by a road haulage vehicle can also be expected to be optimised with consideration to any restrictions on passage through the local area. The TTF provides maps of routes agreed with local authorities that address road and environmental damage, and community and safety issues (TTF, 2010; RHWP, 2002). A recent survey of Timber Miles suggested that the average timber haulage distance was 51 miles (82 km) (or 102 mile/164 km round trip; FR, 2007). The RUTT report, based on timber haulage in Dumfries and Galloway, suggested that 20% of this journey would be on a forest road, and between 20% and 50% of the total trips are unloaded (FCS, 2008). Based on the estimate of 50%, it was assumed here that outward trips are fully loaded with empty return trips.

Unlike load and distance, GHG emissions 'per t-km' are much more sensitive to a range of factors some of which might be considered to be less controllable. These factors ultimately affect the fuel consumption of the vehicle. The combined impact of these factors changes the fuel performance of the vehicle, normally expressed in mpg. The mpg of the vehicle will usually be specified and certified when it is sold. However, on the road, the actual experienced mpg can be influenced by driving behaviour, traffic congestion, road conditions, use of onboard facilities (such as air conditioning, etc.) and engine warm-up with driving patterns (JAMA, 2008). Significantly for timber transport, the mpg is affected by off-road driving conditions and average speed.

In this study, basic direct GHG emissions of on- and off-road haulage will be developed for the two sizes of vehicle specified previously. Based on Equation 1, the 40 t GVW vehicle has a fuel performance of 7.5 mpg and the 44 t GVW vehicle has a fuel performance of 8.5 mpg, both at full load (North Energy, 2009a). Here, these are regarded as base case fuel performances which are assumed to be applicable to travel on a normal public road. Table 1 provides subsequent estimates of direct GHG emissions. These estimates are based on complete fuel combustion in the engine in accordance with assumptions made by the Inter-governmental Panel on Climate Change (IPCC) (Waldron et al, 2006). In order to reflect the majority of timber transport operating logistics, the overall estimates in Table 1 are based on a full load on the outward journey and an empty return journey (Killer et al, 2003).

Table 1 Base Case Direct Greenhouse Gas Emissions of Road Haulage

Vehicle Size (t GVW)	Full Load (t)	Fuel Consumption (l/km)			Unit Fuel Consump-tion for Round Trip (l/t-km)	Direct GHG Emissions			
		Outward Journey at Full Load	Return Journey Empty	Average for Round Trip		(kg CO_2/t-km)	(kg CH_4/t-km)	(kg N_2O/t-km)	(kg eq. CO_2/t-km)
40	25.5	0.332	0.231	0.319	0.0112	0.032	8.6×10^{-6}	2.4×10^{-7}	0.032
44	28.5	0.376	0.231	0.281	0.0110	0.032	8.8×10^{-6}	2.5×10^{-7}	0.032

It is generally known that haulage vehicles use more fuel when travelling on forest roads, yet there are few studies which have tested this. One practical study has examined fuel consumption on a public highway and on a forest road (Killer et al., 2003). Generally, haulage vehicles travel slower on forest roads and have lower fuel performance measured in mpg. Loaded vehicles also travel slower than empty ones, and fuel performance is reduced with load. Estimated fuel performance for a loaded and unloaded vehicle on a forest road is 2.39 mpg and 3.92 mpg, respectively, compared to 5.00 mpg and 6.88 mpg, respectively, on a public highway. Hence, travelling on a forest road reduces fuel performance, approximately, to 49% for a loaded vehicle and 57% for an unloaded vehicle. The resulting changes in fuel consumption of switching from a public highway to a forest road are 210% for a fully loaded vehicle and 175% for an empty vehicle.

The RUTT report (FCS, 2008) examines theoretical diesel fuel costs whilst travelling on forest and public roads. It was estimated that haulage vehicles travel faster on public roads (between approximately 43 and 14 miles per hour; mph) compared to forest roads (approximately 28 to 9 mph, Stiven, 2010). The report provides data on fuel costs (in £/km) on Type A, B and C forest roads and public roads with laden and unladen trucks, and results are reproduced in Table 2. Road topography is distinguished as ‘flat’, ‘rolling’ and ‘mountainous’ to represent different terrain. It has been assumed that the fuel cost results can be translated directly into the effects on fuel consumption of road haulage. In summary, fuel consumption is almost always higher and operational costs are always higher on forest roads compared to public roads. The exception is unladen vehicles on flat forest roads. As the terrain becomes more ‘extreme’, fuel consumption increases for both public and forest roads. Comparing loaded vehicles on flat public roads with ‘flat’, ‘rolling’ and ‘mountainous’ forest roads requires 6%, 70% and 196% more fuel, respectively. Loaded vehicles in general consume 37% (on a flat forest roads) to 92% (on a mountainous forest roads) more fuel than unloaded vehicles.

Table 2 Effect of Topography and Road Type on Road Haulage Costs (FCS, 2008)

Topography and Road Type	Operating Costs (£/km)				Fuel Costs (£/km)			
	Low		High		Low		High	
	Unladen	Laden	Unladen	Laden	Unladen	Laden	Unladen	Laden
Flat: Forest Road	2.16	2.31	2.16	2.31	0.41	0.56	0.41	0.56
Flat: Public (Trunk) Road	1.45	1.55	1.45	1.55	0.44	0.53	0.44	0.53
Rolling: Forest Road	2.18	2.46	2.26	2.72	0.41	0.68	0.49	0.90
Rolling: Public (Trunk) Road	1.66	1.79	1.67	1.86	0.38	0.50	0.38	0.55
Mountainous: Forest Road	2.33	2.93	2.55	3.75	0.56	1.08	0.74	1.57
Mountainous: Public (Trunk) Road	1.68	1.89	1.77	2.27	0.37	0.56	0.45	0.84

Using the information reproduced in Table 2, it is possible to adjust the base case direct GHG emissions for road haulage provided by Table 1. This can be achieved by assuming that the base case estimates in Table 1 represent “average” road haulage on predominantly flat public roads. It is then necessary to account for the likelihood that both public and forest roads used by timber transport more hilly than “average” flat public roads. Ideally, actual combinations of topography for timber transport would have to be taken into account for the adjustment in base case direct GHG emissions for road haulage. However, in the absence of such information, it was assumed for illustrative purposes that timber transport would be undertaken over an averaged combination of terrain consisting of one third flat roads, one third rolling roads and one third mountainous roads. Obviously these assumptions could be modified to derive adjustments for known combination of terrain.

Before presenting adjusted estimates of direct GHG emissions for timber transport, it necessary to accommodate another consideration. It is known that road haulage vehicles used in timber transport generally consume more fuel than conventional road freight vehicles and this is mainly due to aerodynamics of the drive cabin and the trailer (Killer et al., 2003). This effect will be aggravated at higher speeds, which is mostly applicable to timber transport on public roads. Currently, it is not practical to fit timber lorries with aerodynamic features as the overall dimensions of the vehicle change as it is loaded/unloaded (Killer et al., 2003). Aerodynamic trailers can save up to 10% of emissions from transport (Baker et al., 2009). It is possible that the effects of such aerodynamic improvements are accounted for in Equation 1, which represents typical road freight vehicles travelling on public roads, and, therefore, are already incorporated in Table 1. Consequently, it was assumed that a further adjustment, based on a 10% increase in fuel consumption, had to be incorporated into the estimates for timber transport on public roads. The overall effects on direct GHG emissions for timber transport by road are summarised in Table 3.

Table 3 Adjusted Base Case Direct Greenhouse Gas Emissions for Timber Transport by Road

Road Type and Topography	Vehicle Size (t GVW)	Full Load (t)	Unit Fuel Consumption for Round Trip (l/t-km)	Direct GHG Emissions			
				(kg CO_2/t-km)	(kg CH_4/t-km)	(kg N_2O/t-km)	(kg eq. CO_2/t-km)
Forest Road (33% flat, 33% rolling, 33% mountainous)	40	25.5	0.0180	0.052	1.4×10^{-5}	4.0×10^{-7}	0.052
	44	28.5	0.0183	0.052	1.4×10^{-5}	4.0×10^{-7}	0.053
Public Road (33% flat, 33% rolling, 33% mountainous)	40	25.5	0.0134	0.038	1.1×10^{-5}	3.0×10^{-7}	0.039
	44	28.5	0.0136	0.039	1.1×10^{-5}	3.0×10^{-7}	0.039

3.2 Effect of Interventions

3.2.1 Aerodynamics

As mentioned previously, the lack of suitable aerodynamic improvements on road haulage vehicles for timber transport probably increases fuel consumption and direct GHG emissions whilst driving on public roads by 10% over typical road freight vehicles. If practical features could be installed which would not interfere with the loading, unloading and operation of timber haulage vehicles, then similar savings might be expected during their use on public roads. However, this intervention is currently not considered to be appropriate, mainly due to likely damage of aerodynamic features during in-forest use.

3.2.2 Speed Reduction

Although the Department for Transport have released a set of workbooks and reports on transport emission factors that include the effect of speed (NETCEN, 2003; DfT, 2008), subsequent results are not provided in a useful form nor are the vehicle categories suitable for use in this particular study. Generally, as the speed of a vehicle increases, the engine must generate more power to overcome the force of drag, mainly due to the trailer. A 'general rule of thumb' is that, above 55 mph, every increase by 10 mph leads to a decrease in fuel performance by 1 mpg (Goodyear, 2008). Conversely, this implied that reducing speed would lead to fuel consumption savings (up to 20% (Goodyear, 2008)). Specific savings would depend on possible speed reductions which, in turn, would be influenced by economic and logistical considerations. However, since the average speed of timber a haulage vehicle on public roads is estimated to be between 43 and 14 mph (Stiven, 2010), such savings are not considered to be applicable.

3.2.3 Driver Behaviour

Attention to vehicle speed is one of many factors which are covered by driver behaviour. Other factors include smooth transitions between speeds, avoidance of sharp braking, when possible, gear selection appropriate for the terrain and appropriate adjustment to road, traffic and weather conditions. Because of the large number of factors relevant, along with the impact of human influence, it is difficult to quantify potential savings with any precision. However, it has been estimated that modifications in driver behaviour can reduce emission by up to 10% (Baker et al., 2009).

3.2.4 Tyre Pressure Control Systems

Tyre pressure control systems are particularly useful on timber haulage routes as they can protect both the vehicle from damage and the road surface from degradation, and in some circumstances reduce fuel consumption. The equipment is retrofitted to vehicles and can vary the tyre pressure whilst in motion. The technology aims to distribute the weight of the truck over a larger surface area which reduces damage to the road surface. It has also been estimated that automatic tyre pressure control systems can lead to an overall reduction in direct GHG emissions of between 3% and 8% (an average of 5% is assumed, Baker et al., 2009; DfT and SG, 2009).

3.2.5 Other Low Carbon Options

Other low carbon options are available for typical road freight vehicles. A range of low carbon technologies that can be retrofitted to vehicles has been examined and potentials for reductions in direct GHG emissions have been estimated (Baker et al., 2009). It has been concluded that the most effective options consisted of the use of aerodynamic trailers (10% savings, as discussed in Section 3.2.1), the adoption of hybrid vehicles (10-20% savings) and vehicle "platooning" (20% savings). However, it is not apparent that these options are readily applicable or relevant to current timber transport. Instead, the main interventions seem to be speed reduction, driver behaviour and automatic tyre pressure control. Assuming that savings from interventions applicable to timber haulage can be combined together (multiplicatively), the overall maximum effect on the direct GHG emissions of timber transport is illustrated in Table 4.

Table 4 Maximum Combined Effect of Driver Behaviour and Automatic Tyre Pressure Control on Direct Greenhouse Gas Emissions for Timber Transport by Road

Inter-Vention	Road Type and Topography	Vehicle Size (t GVW)	Full Load (t)	Unit Fuel Consump-tion for Round Trip (l/t-km)	Direct GHG Emissions			
					(kg CO_2/t-km)	(kg CH_4/t-km)	(kg N_2O/t-km)	(kg eq. CO_2/t-km)
Driver behaviour and automatic tyre pressure control = 15% saving	Forest Road (33% flat, 33% rolling, 33% mountainous)	40	25.5	0.015	0.044	1.2×10^{-5}	3.4×10^{-7}	0.044
		44	28.5	0.016	0.044	1.2×10^{-5}	3.4×10^{-7}	0.045
	Public Road (33% flat, 33% rolling, 33% mountainous)	40	25.5	0.011	0.033	8.9×10^{-6}	2.5×10^{-7}	0.033
		44	28.5	0.012	0.033	9.1×10^{-6}	2.5×10^{-7}	0.033

All these options have the added attraction that they save on fuel costs as well as reduce GHG emissions. However, there is another form of intervention which currently has no economic benefits but could substantially reduce direct GHG emissions. This involves using biodiesel instead of conventional diesel fuel derived from crude oil. There are two important considerations for this particular intervention. The first consideration is the practicality of sourcing sufficient quantities of biodiesel in the rural locations where most timber transport occurs. If current supply constraints can be overcome, the issue would then be the relative portion of biodiesel used; either as a blend or as 100% biodiesel. The second consideration is the original source of vegetable oil used as a biomass feedstock since this has a significant effect on the overall reductions in GHG emissions. Whilst this does not influence the GHG emissions due to fuel combustion by the vehicle, the original source of the vegetable oil affect the GHG emissions associated with biodiesel production.

The maximum effect of this intervention on road haulage for timber transport can be investigated by assuming that 100% biodiesel is used instead of conventional diesel from crude oil. It is necessary to adjust estimated fuel consumption due to differences in the energy content of biodiesel and conventional diesel. The net calorific value of biodiesel (33.1 MJ/l) is lower than that of conventional diesel (35.9 MJ/l) (RFA, 2009). This increases the unit fuel consumption of the road haulage vehicles by approximately 8%, assuming that there are no changes in the energy efficiency of the engine. For illustrative purposes, two sources of biodiesel are considered; biodiesel from UK oilseed rape and biodiesel from UK used cooking oil. Estimates similar to typical values quoted in the European Commission Renewable Energy Directive (EC, 2009) can be adopted for GHG emissions associated with biodiesel production from these sources of vegetable oil[3]. Finally, CH_4 and N_2O emissions from biodiesel combustion were assumed to be the same as those for the combustion of conventional diesel (BRE, 2000). Subsequent results which show substantial reductions in direct GHG emissions for timber transport are presented in Table 5.

[3] It should be noted that these estimates are consistent with the methodology adopted in the EC Renewable Energy Directive (EC, 2009); co-product allocation by energy content, GHG emissions associated with plant and equipment construction and maintenance excluded, and used cooking oil treated as a waste product with no GHG emissions associated with it provision prior to conversion to biodiesel.

Table 5 Effect of Using Biodiesel on Direct Greenhouse Gas Emissions for Timber Transport by Road

Inter-Vention	Road Type and Topography	Vehicle Size (t GVW)	Full Load (t)	Unit Fuel Consump-tion for Round Trip (l/t-km)	Direct GHG Emissions			
					(kg CO_2/t-km)	(kg CH_4/t-km)	(kg N_2O/t-km)	(kg eq. CO_2/t-km)
100% biodiesel from UK oilseed rape	Forest Road (33% flat, 33% rolling, 33% mountainous)	40	25.5	0.015	0.011	5.3×10^{-4}	1.5×10^{-2}	0.026
		44	28.5	0.016	0.011	5.3×10^{-4}	1.5×10^{-2}	0.027
	Public Road (33% flat, 33% rolling, 33% mountainous)	40	25.5	0.011	0.0081	3.9×10^{-4}	1.1×10^{-2}	0.020
		44	28.5	0.012	0.0083	4.0×10^{-4}	1.1×10^{-2}	0.020
100% biodiesel from UK used cooking oil	Forest Road (33% flat, 33% rolling, 33% mountainous)	40	25.5	0.015	0.0086	1.1×10^{-4}	4.4×10^{-5}	0.009
		44	28.5	0.016	0.0087	1.2×10^{-4}	4.4×10^{-5}	0.009
	Public Road (33% flat, 33% rolling, 33% mountainous)	40	25.5	0.011	0.0064	8.5×10^{-5}	3.3×10^{-5}	0.007
		44	28.5	0.012	0.0065	8.6×10^{-5}	3.3×10^{-5}	0.007

4 INDIRECT EMISSIONS OF INFRASTRUCTURE

4.1 Vehicle Manufacture and Maintenance

The Biomass Environmental Assessment Tool ($BEAT_2$) includes machinery construction and maintenance in GHG emissions calculations for biomass energy generation (BEAT, 2008). The GHG emissions for construction of vehicles were estimated using approximate multipliers. These were derived from input-output analysis of 51 different sectors of industries which enables the multipliers to represent total GHG emissions associated with the extended process chains involved in producing goods and services from original raw materials (Hetherington, 1996). These multipliers are expressed per unit of £value for relatively broad categories of products and services. Largely due to this, such multipliers are usually regarded as order-of-magnitude estimates of total GHG emissions factors. This is normally adequate for their applications in situations where contributions within any given process or activity are relatively small compared to those from direct fuel combustion, etc. Hence, they are often appropriate for the evaluating contributions from the provision of machinery, equipment, etc. (Whittaker et al., 2010), and they are used here for vehicle manufacture and maintenance.

Cost data for use with such multipliers were obtained from the RUTT report (FCS, 2008), which assumes that a 44 GVW forest haulage truck has an average cost of £150,000. This is adjusted for inflation to about £138,000 in 2004, using Price Indices for motor vehicles (Fice, 2010), so that the latest available cost multipliers for 2004 could be used (North Energy, 2006). The service life is lower than typical haulage vehicles as a result of work on forest roads which dramatically reduces the lifespan of a timber haulage vehicle (FCS, 2008) which is normally assumed to be 7 years (Killer et al., 2003). Vehicles engaged in mixed operations (with about 22,000 km/a on forest roads) are expected to have a working life span of 4 years, or total of 8,000 hours. Total driving intensity, in either case, is estimated to be 110,000 km/a. The RUTT report suggests that, after use for timber haulage, vehicles can be re-sold (overseas) and continue to be used for a total residual life of up to 7 years. Based on normal conventions, the total GHG emissions of manufacture are spread evenly over the total life of a product such as a vehicle. Hence, this approach was adopted in this study, using a total vehicle life of 7 years and a driving intensity of 110,000 km/a (Killer et al., 2003). Estimated total GHG emissions for vehicle manufacture were allocated per t-km travelled (assuming 50% load factor) and the result is shown in Table 6.

Few data are available on GHG emissions associated with maintenance over the lifetime of a vehicle. However, an annual estimate of 2.5% of total GHG emissions for initial manufacture was assumed for basic maintenance (Mortimer and Elsayed, 2001), with additional total GHG emissions for a full set of tyre replacements each year, costing about £3,235 (estimated 2004 price). Although this might be considered to be an extreme assumption (FCS, 2008), it has been suggested that forest haulage vehicles are particularly susceptible to tyre damage (Killer et al, 2003), and may require up to three full sets of tyres every year (TTF, 2010). The subsequent estimate of total GHG emissions associated with road haulage vehicle maintenance is included in Table 6.

Table 6 Greenhouse Gas Emissions for Road Haulage Vehicle Manufacture and Maintenance

	Contribution	Indirect GHG Emissions			
		(kg CO_2/t-km)	(kg CH_4/t-km)	(kg N_2O/t-km)	(kg eq. CO_2/t-km)
Mixed forestry operations and residual use	Manufacture	0.007	1.0×10^{-5}	5.2×10^{-7}	0.007
	Maintenance	0.013	2.2×10^{-5}	7.6×10^{-6}	0.013

4.2 Forest Road Construction and Maintenance

As forest roads are generally un-sealed, subjected to extreme loads, and penetrate extraordinary terrain, every step of their construction (i.e. planning to maintenance) needs to be well engineered to ensure user safety, vehicle access and surface durability. Roads must be constructed to specified gradients and with smooth surfaces to reduce rutting and degradation of the surface layers (Killer, no date).

In the UK, forest roads are generally constructed with two main layers of aggregate which are added on top of the existing sub-grade, which is the existing original ground that is exposed after shaping and excavating the road (Killer, no date). In terms of construction, there are two main types of forest road: overlay and formation roads. Overlay roads are constructed on softer sub-grade terrain, such as peat, and this involves creating a solid layer on which finer aggregate is applied. Formation roads are typically built on hard rock, and their construction mainly involves creating a single, or a series of layers of fine aggregate. In each case, the top layer is made from a durable stone that will not readily break down under wheel loading. It must also fall within a specified Aggregate Impact Value (AIV; between 30 and 20) so that it can be compacted, graded and rolled.

There are few sources in literature that examine forest road construction, particularly for the UK. One study has examined forest road construction in 'mountainous terrain' in the USA (Loeffler et al, 2009). This study mainly investigated the actual excavation of road paths through extreme terrain (i.e. cut-fill and bench road construction). The study did not provide details on building aggregate surfacing for the roads. The results from this study can be re-calculated according to direct and indirect GHG emissions for diesel fuel in the UK. Subsequent estimates of GHG emissions associated with the construction of a kilometre of forest road are summarised in Table 7. It is worth noting here that the maximum gradient of forest roads in the UK is 12.5%, and cross slope is 8% (Killer et al, 2003).

Table 7 Estimated Greenhouse Gas Emissions from Diesel Fuel Consumption During Forest Road Construction in the USA (Loeffler et al., 2009)

Details	Diesel Fuel (litres/km)	Quoted GHG Emissions (kg eq. CO_2/km)	Re-Calculated GHG Emissions (kg eq. CO_2/km)
Slopes<50%	4,318	9,782	12,456
Slopes>50%	23,887 – 58,530	54,311 – 133,368	68,908 - 168,843

Another study, based in Finland, concluded that the construction of 'permanent forest' roads was the highest source of GHG emissions for silvicultural and forest maintenance (Karjalainen and Asikainen, 1996). These roads are similar to those built in the UK. Using the raw data provided in this study, it was determined that a total of 41,153 litres diesel was consumed per kilometre 'permanent forest road', releasing 118,715 kg eq. CO_2/km, as shown in Table 8.

Table 8 Estimated Greenhouse Gas Emissions from Diesel Fuel Consumption During Forest Road Construction in Finland (Karjalainen and Asikainen, 1996)

Details	Diesel Fuel (litres/km)	Calculated GHG Emissions (kg eq. CO_2/km)
Excavating	765	2,207
Loading	68	196
Truck Haulage	40,320	116,312
Total	41,153	118,715

In a separate, internal study, a 'Forest Road Construction LCA' was developed using primary data collected by the Department of Civil Engineering of the Forestry Commission at Castle Douglas, Dumfries (Whittaker et al, 2008). Case study data on diesel fuel consumption, operational hours and materials used were provided for the construction and maintenance of both overlay and formation roads. The analysis covered excavating, loading, haulage, spreading, grading and rolling. Rock blasting was also included. This involved the use of ammonium nitrate-based explosives, which was not taken into account in the earlier published studies. In the case studies examined, road aggregate was provided from local quarries (less than 2 miles away). The resulting blasted rock was either used directly to create a sub-layer in overlay roads, or crushed to form the top layer. On average, for each kilometre of overlay road, 8,800 t of blasted rock and 1,200 t of crushed rock were required. For a formation road, only crushed rock is required, at a rate of approximately 5,469 t/km.

Given the transparency and greater detail of this internal study, it was decided that this provided the most suitable basis for evaluating the contribution of forest road construction and maintenance to total GHG emissions. Consequently, estimates for rock production are summarised in Table 9 and Table 10 provides a summary of total GHG emissions associated with operations and rock/aggregate consumption in the construction of overlay and formation roads. Full details are provided in Appendix A.

Table 9 Total Greenhouse Gas Emissions Associated with Production of Blasted and Crushed Rock

Rock Blasting	Value	Units	Total GHG Emissions (kg eq. CO_2/t blasted rock)
Diesel fuel for drilling	0.03	l/t blasted rock	0.09
Explosives	0.15	kg/t blasted rock	0.96
Total for rock blasting			**1.06**
Rock Crushing	Value	Units	Total GHG Emissions (kg eq. CO_2/t crushed rock)
Diesel fuel for excavator	0.18	l/t crushed rock	0.51
Diesel fuel for loading	0.22	l/t crushed rock	0.63
Diesel fuel for crushing	0.22	l/t crushed rock	0.65
Blasted rock	1.00	t blasted rock/t crushed rock	1.06
Total for rock crushing			**2.84**

Table 10 Total Greenhouse Gas Emissions Associated with Construction of Overlay and Formation Forest Roads

Overlay Road Construction	Value	Units	Total GHG Emissions (kg eq. CO_2/km)	%
Diesel fuel for loading roadstone	1,181.25	l/km road	3,408	13.6
Diesel fuel for hauling roadstone	2,406.25	l/km road	6,941	27.6
Diesel fuel for spreading roadstone	612.50	l/km road	1,767	7.0
Diesel fuel for grading	65.63	l/km road	189	0.8
Diesel fuel for rolling	40.63	l/km road	117	0.5
Total diesel fuel consumption	4,306.25	l/km road	12,422	49.5
Roadstone (blasted)	8,800	t/km road	9,285	37.0
Roadstone (crushed)	1,200	t/km road	3,407	13.6
Total material Inputs	10,000	t/km road	12,692	50.5
Total for overlay road construction			**25,115**	100.0
Formation Road Construction	Value	Units	Total GHG Emissions (kg eq. CO_2/km)	
Diesel fuel for loading roadstone	646.00	l/km road	1,864	8.3
Diesel fuel for hauling roadstone	1315.92	l/km road	3,796	16.9
Diesel fuel for spreading roadstone	334.96	l/km road	966	4.3
Diesel fuel for grading	65.63	l/km road	189	0.8
Diesel fuel for rolling	40.63	l/km road	117	0.5
Total diesel fuel consumption	2403.13	l/km road	6,932	30.9
Roadstone (crushed)	5,469	t/km road	15,526	69.1
Total for formation road construction			**22,459**	100.0

GHG emissions from soil disturbance due to road construction were also considered although this is an issue on which limited information is currently available. CO_2 emissions can arise from the exposure of carbon stocks in the soil. The magnitude of these emissions depends on the carbon content of the soil, which varies with soil type, and the extent of soil disturbance. It was necessary to base estimates of CO_2 emissions on assumptions about these considerations. To begin, it was assumed that forest road construction would avoid disturbing soils which have high carbon content, such as peaty soils. If a road had to be constructed over such soils, it would be laid across the surface so that, effectively, no significant CO_2 emissions from soil disturbance were caused. Consequently, this represents the extreme low case for soil CO_2 emissions. At the other extreme, roads constructed over non-peaty gley would involve soil disturbance. Such soils were assumed to have a carbon content of 150 t C/ha which, with a road width of 3 metres, equates to 45 kg C per m of road length. It was further assumed that the disturbed soil is left at either sides of the road and that, in the first year, 50% of the contained carbon would be released as CO_2. After this, it is assumed that the vegetation growing in this area stabilises the soil, thereby preventing subsequent emissions. Converting accordingly (44/12), CO_2 emissions from soil disturbance for this extreme high case were, therefore, estimated at 82.5 kg CO_2/m of road length. In the absence of relevant information on road locations and soil types, it was assumed that CO_2 emissions for soil disturbance lay between these two extreme cases. Hence, an average of 41.25 kg CO_2/m of road length has been used in subsequent calculations.

Another important consideration for which current information is limited concerns the "life span" of forest roads. It is necessary to spread the total GHG emissions of forest road construction, including soil emissions, over their life span. In the absence of specific data, it was assumed that this 'life span' is one complete forest rotation, which equals 50 years in this study. It is acknowledged that a forest road may be suitable for use after this period, and that some forest rotations, such as those for broadleaf species, are longer. Furthermore, the life span of a road will be enhanced through regular maintenance. However, no specific evidence could be accessed on these and other possible considerations. Hence, for illustrative purposes, it was decided to adopt a 50 year life span in subsequent calculations.

Forest road maintenance can either involve re-application of the top layer of aggregate, or just re-grading and rolling of the remaining aggregate layer. The latter occurs when the road is constructed with a purposely 'sacrificial layer' that gradually wears down to a finer consistency that is re-spread during maintenance events (Nicol, 2009). The two types of maintenance are compared here with the following assumptions: replenishing the road with crushed rock at a rate of 1,500 t/km (Whittaker et al, 2008), or simple re-grading and rolling. The estimated total GHG emissions associated with these examples of forest road maintenance are presented in Table 11.

Table 11 Summary of Greenhouse Gas Emissions for Forest Road Maintenance

Re-surfacing	Value	Units	Total GHG Emissions (kg eq. CO_2/km)
Diesel fuel for loading roadstone	270.00	l/km road	779
Diesel fuel for hauling roadstone	360.94	l/km road	1,041
Diesel fuel for spreading roadstone	91.88	l/km road	265
Diesel fuel for grading	65.63	l/km road	189
Diesel fuel for rolling	40.63	l/km road	117
Total diesel fuel consumption	829.06	l/km road	2,392
Roadstone (crushed)	1500	t/km road	4,259
Total for re-surfacing			**6,650**
Re-grading	Value	Units	Total GHG Emissions (kg eq. CO_2/km)
Diesel fuel for grading	65.63	l/km road	189
Diesel fuel for rolling	40.63	l/km road	117
Total for re-grading	**106.25**	l/km road	**307**

In terms of classification, there are three types of forest road: Types A, B and C. However, only the first two (Types A and B) are involved in timber haulage (FCE, 2000). These are identical in terms of construction, but they are maintained at different intervals, according to the frequency of their use. Type A roads are general arterial roads that are used frequently during the year. These are maintained at least once a year, or up to three times in some cases (FSC, 2008). Type B roads are infrequently used spur roads that provide access to stands (Mason et al, 2009). These are typically maintained in preparation of a felling event (Killer, 2008).

Wear and tear of forest roads can be minimised by reducing, or spreading the impact of loads across the road surface. This can be achieved by using tyre pressure control systems, wider or twin tyres or smaller loads. It is also important to reduce activity of non-road vehicles, such as forwarders or other track-wheeled machines, to prevent extra maintenance (Killer, no date). Certain driver behaviour can also reduce wear on forest roads, such as speed of travel and manoeuvring, and avoiding overloading vehicles and working in wet or icy weather (Killer, no date). However, in the absence of any detailed information on reductions in maintenance which might be achieved, this was not taken into account.

To encompass the effects of different forest road maintenance management strategies, two possible extreme cases were examined in this study. In the low case, it was assumed that all Type A roads are maintained once every year by means of re-grading, whilst in the high case, they are maintained twice each year by re-grading once and re-surfacing once. For Type B roads, in the low case, it was assumed that all such roads would be maintained, by re-grading only, before each harvest. In the high case, all Type B roads are assumed to be maintained twice each year; once before and once after each harvest with maintenance consisting of one re-surfacing and one re-grading.

Based on these assumptions, Table 12 summarises the total GHG emissions associated with construction and annual maintenance of forest roads. Estimates for original construction of both an overlay and formation road, and an average for both types combined, are presented in Table 12. The total GHG emissions from construction and annual maintenance include diesel fuel consumption for constructing the road and transporting the materials (aggregate) to the site, as well as materials consumed during road operations and the provision of these materials (e.g. explosives consumed during rock extraction). Average CO_2 emissions due to soil disturbance during excavation of existing forest to build roads are incorporated into the estimates for road construction.

Table 12 Summary of Total Greenhouse Gas Emission Associated with Forest Road Construction and Maintenance and Emissions Due to Soil Disturbance

Details	Total GHG Emissions			
	kg CO_2/km	kg CH_4/km	kg N_2O/km	kg eq. CO_2/km
Road Construction (overlay)	18,467	20.57	20.58	25,115
Road Construction (formation)	18,744	13.62	11.32	22,459
Road Construction (average)	18,606	17.09	15.95	23,787
Soil Disturbance (average)	41,250	-	-	41,250
Road Maintenance (re-surfacing)[(a)]	5,627	3.87	3.11	6,650
Road Maintenance (re-grading)[(a)]	304	0.08	0.00	307

Note
(a) Per maintenance event.

4.3 Public Road Construction and Maintenance

Very little information on the construction of public roads is available in the public domain, especially in relation to LCA. Road pavements are typically constructed of several material layers that are either granular (sand, gravel or crushed rock) or bound by concrete or bitumen. Some of these materials can be produced from wastes, such as fly ash from coal-fired power stations, or from recycling of used materials, such as recycled asphalt (Birgisdottir, 2005). A few references were found with some relevance to the LCA of public road construction and the information they contained has been considered accordingly.

One study of road construction in Finland examines the use of a range of materials such as sand, crushed rock, blast furnace slag, gravel, fly ash and cement and asphalt-concrete (Mroueh et al, 2000). In this study, road construction is investigated in great detail and fuel consumption for various machinery operations is recorded. However, results are not provided in a useable form, as they are mainly presented graphically, and, where numbers are given, no clear units or assumptions are stated. Some information for possible use in estimating GHG emissions is documented, such as the composition and depth of each layer of the road types studied and average transport distances for each material, along with a materials inventory. The study does conclude that diesel fuel used in construction contributed very little to the overall energy requirement, compared with manufacturing of cement and asphalt (25% and 57% of energy requirement, respectively). Maintenance data are provided 'per 50 years' of service, but the frequency of maintenance over this period of time is not specified. Tables 13 and 14 summarise relevant but limited results from this study for total energy requirements and carbon dioxide emissions, and materials requirements, respectively.

Table 13 Results for Public Road Construction in Finland (Mroueh et al, 2000)

Road Construction	Value	Units
Total energy requirements[(a)]	1,200,000	kWh/km
	4,320,000	MJ/km
Carbon dioxide emissions[(a)]	562,000	kg/km

Note

(a) Includes production of materials.

Table 14 Material Requirements for Public Road Construction in Finland (Mroueh et al, 2000)

Material	Amount (t/km)	Depth (mm)	Distance Transported (km)
Fly ash	6,540	350	10
Sand	22,940	200	50
Crushed aggregate	4,480	150	10
Asphalt	3,600	160	10
Average			34.4

Another study examined the life cycle energy requirements and carbon dioxide (as well as sulphur dioxide and oxides of nitrogen) emissions from creating a kilometre of a 4-lane highway, including construction, repair, re-pavement, demolition and recycling (Park et al., 2003). Some useful data are provided which can be used in subsequent analysis. It is assumed that over the life cycle of the road pavement (20 years), the road is repaired twice (in year 7 and 14) and then re-paved after 20 years. Total energy requirements and carbon dioxide emissions are recorded for the production of materials and machinery operations. Relevant results are illustrated in Table 15.

Table 15 Primary Energy Inputs and Carbon Dioxide Emissions from a Four-Lane Highway Construction, Maintenance, Repair and Final Demolition (Park et al, 2003)

Contribution	Energy Consumption		Carbon Dioxide Emissions	
	t of oil equivalent/km	MJ/km	t C/km[a]	kg CO_2/km
Manufacturing of Construction Materials	1,525.7	63,878,008	1,391.4	5,101,800
Construction	47.1	1,971,983	41.7	152,900
Road Re-Surfacing	69.3	38,962,361	31.7	3,115,778
Repair	930.6	2,901,452	849.8	464,722
Demolition of Old Surfacing	34.5	1,444,446	28.9	105,967

Note

(a) Original units, assume t C refers to tonne of carbon.

The majority of roads that were designed 20 to 30 years ago were built to modern standards and have pavements that should last up to 20 years. Newer roads have a lifespan of about 40 years (Mackenzie, 2010). Maintenance and resurfacing frequency depends on local traffic levels and available budgets. In the UK, the majority (70%) of roads local to forests are rural roads, and 52% of these are single track (Timber Transport Forum, 2010a). It is suggested in the RUTT report that, in the UK, public roads exposed to timber haulage have a life of 10 to 12 years (GTKP, 2010; FSC, 2008). However, because of the lack of necessary detailed information on public roads which are used by timber transport and due to fundamental problems in allocating GHG emissions between all traffic using such road, GHG emissions from public road construction were not taken into account in this study.

As the maintenance of a highway will be to a considerably higher specification to that of a single track road examined here, an attempt has been made to modify the results in Table 15 to reflect the main type of public road used by forest haulage vehicles. The frequency of maintenance has been reduced to once every 10 years. Additionally, the relative GHG emission associated with road maintenance has been adjusted according to the cost of maintaining a motorway (approximately £133,262/km/year based on average data) compared to a small 2-track bitumen road (£2,799/km/year, divided by two to get a single track road; GTKP, 2010). Although this analysis is somewhat approximate, it does enable the relative magnitude of public road maintenance to be indicated. A suitably adjusted estimate for the total GHG emissions associated with the maintenance of single track public roads is presented in Table 16.

Table 16 Total Greenhouse Gas Emission Associated with Single Track Public Road Maintenance (per maintenance event)

Contribution	Carbon Dioxide Emissions[a]	Methane Emissions[a]	Nitrous Oxide Emissions[a]	Total GHG Emissions[a]
	kg CO_2/km	kg CH_4/km	Kg N_2O/km	kg eq. CO_2/km[b]
Road Re-Surfacing	32,721	(c)	(c)	32,721

Notes

(a) Emissions per maintenance event.

(b) Approximate as methane and nitrous oxide emissions are not known.

(c) Emissions not known.

In summary, the GHG emissions associated with maintaining a single track public road are not well -documented. Instead, it has been necessary to derive an approximate estimate of these emissions. Overall, the total GHG emissions per maintenance event are approximately 5 times higher than those for maintaining a forest road, (33,843 kg eq. CO_2/km compared to 6,650 kg eq. CO_2/km) per maintenance event. However, there are differences in intervals between maintenance for public and forest roads. Hence, maintenance frequency has to be examined as part of subsequent sensitivity analysis (see Section 10).

4.4 Road Density

The contribution of forest road construction and forest and public road maintenance to total GHG emissions associated with timber transport depends on the road density of the area under consideration. The road density determines the length of roads that are used in hauling timber from, in effect, one hectare of forest land. To calculate this, it is necessary to know the total area of a given forest and the specific length of roads that are used by vehicles which are hauling timber from that forest. In this study, estimates of forest road density were derived for Dumfries and Galloway for illustrative purposes. Actual forest road density data were obtained from Forest Research Geographical Information Service Division to provide figures for the length of road by types (Types A and B) in each forest district in Great Britain (GB) (see Appendix B). The forest road density of Type A and B roads in Dumfries and Galloway is 0.003 and 0.002 km/ha, respectively. This is compared with the average forest road density of the whole of GB of Type A and B roads of 0.005 and 0.011 m/ha, respectively (Whittaker et al, 2010).

Estimates of the density of public roads which are specifically used for timber haulage are more difficult to assess. This cannot be achieved using general statistics on public roads for a given region as many roads may not be used by timber haulage vehicles, thereby causing possible over-estimation of the GHG emissions contribution to timber transport. The detailed information required is not currently available and, consequently, a default value for the timber haulage-specific public road density, based on results from the Timber Miles Survey (FR, 2007), was used for illustrative purposes in this study. This public road density is based on Dumfries and Galloway in which timber transport on public roads account for 80% of the total distance of 51 miles (82 km), equating to 41 miles or 67 km on public roads. Taking into account the total forest area served in Dumfries and Galloway, the resulting timber haulage-specific public road density is estimated to be 0.0004 km/ha.

5 TOTAL EMISSIONS FOR ALTERNATIVE MODES OF TRANSPORT

The choice of alternative timber transport modes on associated total GHG emissions can be explored using published data on freight transport by rail (diesel), inland waterway (barge) and coastal shipping.

Approximately 90% of freight transported by rail is hauled with diesel locomotives and the remainder electric (McInnon, 2010). The direct GHG emissions per t-km for electric trains depend on the mix of sources used to generate electricity. Currently, in the UK, electric rail transport releases twice the amount of equivalent carbon dioxide emissions as those of diesel rail transport. However, electric freight rail transport is rarely an option for timber transport in the UK. Table 17 provides estimated GHG emissions for rail freight transport, based on trains with a total payload of 1,400 tonnes (NNFCC, 2009b).

Statistics of freight transport on inland waterways are limited, although this mode has received increasing interest of late as a form of relatively cheap, low carbon transport. If this facility is available for use then significant GHG emissions can be achieved. Data from NNFCC, 2007d was used to generate GHG emission indicators. Table 17 summarises estimated GHG emissions for freight transport by inland waterways, assuming a barge with a payload capacity of 400 tonne running on fuel oil (North Energy, 2009c).

Data from the TimberLINK Environmental Benefits Review (Girnary and Brightman, 2010) were used for estimating the fuel consumption and GHG emissions of coastal shipping. The TIMBERLink Review examines timber-specific transport via coastal shipping. It is estimated that the fuel consumption for loading material into the ship for transport is 35 l/h. The assumed ship load capacity is not provided but it can be assumed that the ship has a payload of between 1,200 t and 1,400 t, based on the two examples provided in the TIMBERLink Review. It was estimated that, in 2009/10, 150,000 t of timber were transported by ship and that 70,000 l of fuel were consumed in loading and unloading this cargo (Girnary and Brightman, 2010). This corresponds to 0.47 l of fuel to unload and load each tonne of timber into a cargo ship. Fuel is also used for loading and unloading with the other modes of transport; although it is recognised that loading and unloading a ship may be more fuel intensive than loading a train, for example. A fuel consumption of 18.18 l/nautical mile, or 9.8 l/km is assumed for shipping (Girnary and Brightman, 2010). This information was combined with estimated GHG emissions associated with capital equipment and maintenance (North Energy, 2009c) to obtain the estimate of total GHG emissions for coastal shipping presented in Table 17.

Table 17 Total Greenhouse Gas Emissions for Alternative Modes of Freight Transport

Mode of Transport	Carbon Dioxide Emissions (kg CO_2/t-km)	Methane Emissions (kg CH_4/t-km)	Nitrous Oxide Emissions (kg N_2O/t-km)	Total GHG Emissions (kg eq. CO_2/t-km)
Diesel Train				
Fuel	0.0117	3.7×10^{-6}	4.0×10^{-6}	0.0130
Capital Equipment	0.0003	8.6×10^{-7}	9.2×10^{-9}	0.0003
Maintenance	0.0055	1.5×10^{-5}	1.6×10^{-7}	0.0055
Totals	**0.0175**	**1.9×10^{-5}**	**4.2×10^{-6}**	**0.0192**
Inland Waterway Transport				
Fuel	0.0153	4.8×10^{-6}	5.2×10^{-6}	0.0170
Capital Equipment	0.0054	9.2×10^{-6}	3.3×10^{-7}	0.0057
Maintenance	0.0004	7.4×10^{-7}	2.6×10^{-8}	0.0004
Totals	**0.0211**	**1.5×10^{-5}**	**5.6×10^{-6}**	**0.0231**
Coastal Shipping				
Fuel	0.0046	1.5×10^{-6}	1.6×10^{-6}	0.0052
Capital Equipment	0.00026	7.2×10^{-7}	7.7×10^{-9}	0.00028
Maintenance	0.00002	5.8×10^{-8}	6.2×10^{-10}	0.00002
Totals	**0.0049**	**2.2×10^{-6}**	**1.6×10^{-6}**	**0.0054**
Loading/Unloading	Carbon Dioxide Emissions (kg CO_2/t)	Methane Emissions (kg CH_4/t)	Nitrous Oxide Emissions (kg N_2O/t)	Total GHG Emissions (kg eq. CO_2/t)
Fuel	0.0358	9.8×10^{-6}	2.8×10^{-7}	0.0361

6 TOTAL EMISSIONS OF FOREST SYSTEMS

6.1 Forest Establishment and Harvesting

In order to set the contribution of timber transport to total GHG emissions in context, it is necessary to examine other sources of GHG emissions associated with timber production and use. For this, it is assumed that the silivicultural system taking place is conventional clear-fell and re-stocking (Whittaker et al, 2010). Re-stocking, or new forest establishment, takes place between 1 and 5 years after the previous clear-fell event and involves basic land preparation and planting. Land preparation involves mounding and herbicide applications, and, sometimes, installation of fencing to protect the newly established saplings from herbivore grazing. It is assumed that no fertiliser is applied. Previous information on site establishment (Matthews and Mortimer, 2000) has been updated with more recent data. Mounding is generally carried out by an excavator (for the purposes of this paper a 20t machine is assumed), which has a diesel fuel consumption requirement of 18 to 20 l/h and a work rate of approximately 6.75 h/ha (Murgatroyd, 2008). For consistency, data for forest establishment data was derived from a published source, which may not represent all current practices, but does provide a full set of data (Matthews and Mortimer, 2000). According to this source, the herbicide application rate is low at 0.06 kg active ingredient/ha and this is assumed to be applied using a typical agricultural 100 hp tractor, consuming 24 l/h of diesel fuel with a work rate of 1.2 h/ha (Nix and Hill, 2004; Matthews and Mortimer, 2000). Tree seedlings are planted by hand at a density of approximately 1,300 seedlings/ha (Matthews and Mortimer, 2000). As a worse-case scenario, it is assumed that all the forests are fenced to protect the young stand from grazing herbivores. Fencing requirements include the use of wood, steel and preservative for a 30 ha plot (Matthews and Mortimer, 2000). Primary energy consumption and GHG emissions from site preparation and establishment are listed in Appendix C.

Fuel consumption for timber and fuel wood harvesting was based on data provided by Forest Research, which updates estimates (Matthews and Mortimer, 2000). Saw log and fuel wood harvesting involves felling, de-limbing and de-barking (carried out by one machine) and then transporting to the roadside by a forwarder. The remaining forest residues can also be collected up into brash bales for use as fuel wood, although currently this is not widely carried out in the UK due to economic constraints and lack of available technology. There are also sustainability issues with removing this material from the forest floor, as it is often used to create ‘brash mats’ for passing machinery to avoid damage to the forest floor (Brierley et al., 2004). It was assumed however, that a small portion of forest residues are collected at the final clear-fell event for use as biomass energy. Brash baling has a diesel fuel requirement of 2 l per bale which weighs approximately 500 kg, therefore resulting in fuel consumption of 4 l/t.

Fuel requirements were estimated for harvesting at 3.64 l per oven dry tonne (odt) of biomass (based on a fuel requirement of 1.2 litres/m^3 of biomass), and for forwarding at 2.73 l/odt (based on a fuel requirement of 0.9 litres/m^3 of biomass). This assumes a density of 0.33 odt/m^3 and a moisture content of 50%, so that fuel requirements for harvesting and forwarding are 7.27 l/t and 5.45 l/t of biomass, respectively. GHG emissions from harvesting and forwarding are summarised in the Appendix C. Subsequent estimates of total GHG emissions for forest site establishment and harvesting, on a “per hectare area” basis are summarised in Table 18.

Table 18 Total Greenhouse Gas Emissions for Forest Site Establishment and Harvesting

Contribution	Carbon Dioxide Emissions	Methane Emissions	Nitrous Oxide Emissions	Total GHG Emissions
	kg CO_2/ha	kg CH_4/ha	kg N_2O/ha	kg eq. CO_2/ha
Site Establishment	1063.17	0.13	0.03	1071.11
	kg CO_2/t	kg CH_4/t	kg N_2O/t	kg eq.CO_2 /tonne
Harvesting (Roundwood, whole trees and saw logs)	20.79	0.006	0.0002	20.98
Brash Baling	11.43	0.003	0.0001	11.54
Forwarding (all)	15.59	0.004	0.0001	15.73

6.2 Yield of Forest Products

In this conventional clear-fell system, it is assumed that fuel wood and saw logs are extracted from the same site. Fuel wood is in the form of whole trees extracted as early thinnings, small roundwood harvested from the forest as late thinnings and as bales of forest residue brash. The first two thinnings that take place in about year 25 and 30 are removed as whole trees. These are not believed to be utilisable for anything apart from fuel wood. After this, the diameter of the stem means that they are suitable for pulpwood production and, therefore, from about year 30 onwards, roundwood is harvested. For softwood plantations, the majority of this roundwood is assumed to be sold to the pulp market (85%) and the remaining is available for the biomass energy market. Some saw logs are harvested from particularly large thinnings but the majority are harvested at the final clear-fell event, taking place, on average, between year 45 and 70. Additionally, it is assumed, to maximise fuel wood production from forestlands, that brash is harvested during the clear-fell event, harvesting a maximum of 25% of the remaining forest residues as brash bales, with the remainder being left to protect the site surface from passing machinery.

For calculating the yield of saw logs, roundwood and, therefore, fuel wood from a site, the yield of each forest product type was obtained from Forest Research BSORT model (Matthews and Duckworth, 2005). The BSORT model provides yields in odt/ha for above and below biomass and is based on allometric equations that estimate crown biomass and woody root biomass for different tree species (McKay et al, 2003). A series of 'availability coefficients' were also used to estimate the quantities of saw logs, pulp wood and fuel wood would be available from a site in order to allocate GHG emissions from site establishment to each tonne of product. This can either be done by price, mass or by the relative energy contents of each product.

To illustrate results, an example has been chosen for a typical commercial forest stand of Sitka Spruce, yield class 12, which was clear-felled after 50 years. During the whole rotation, there were 6 harvesting/thinning events. Whilst this may not represent all actual practice, this example is based on data provided by Forest Research which reflects default values in the BSORT model. Table 19 summarises resulting yields of each product which can be extracted from this site according to the BSORT model. In subsequent GHG emissions calculations, allocation between these products is accomplished using relative prices, with a price ratio of 4:2:1 for sawlogs:pulpwood:biomass (BEAT, 2008).

Table 19 Summary of Yield of Forest Products from a Commercial Stand of Sitka Spruce (yield class 12)

Age (years)	Saw log (odt/ha)	Pulpwood (odt/ha)	Biomass (odt/ha)		
			Roundwood	Branches	Whole Trees
25	0	0	0	0	24.2
30	0.1	0	0	0	20.1
35	2.3	8.4	1.5	0	0
40	4.7	6.4	1.1	0	0
45	6.4	5.0	0.9	0	0
50	81.4	19.2	3.4	10.5	0
Total	95.0	39.1	6.9	10.5	44.2
Relative Price	4	2	1		
Allocation per Hectare (%)	73.1	15.0	11.9		

The carbon content of timber varies between approximately 45% and 55% of the oven dry weight and is conventionally taken as being 50% (Matthews, 1993). In order to determine the actual carbon content of a piece of wood, it is necessary to take into account its moisture content. At felling, the moisture content is approximately 50%. Therefore, the carbon content per tonne is 250 kg, or (multiply by 44/12) 916.67 kg eq. CO_2/t.

6.3 Sawmilling Wood

Current information on the energy consumption and GHG emissions of processing wood in a saw mill is not well documented. There is limited research on this aspect of sawmilling, and what information is available is not transparent. In this study, information on this was mostly provided from Forest Research, which has carefully examined and analysed available data and secondary sources along with internal expert knowledge of mass and volume flows of wood in GB sawmills. Subsequent estimates for producing sawn timber are summarised in Table 20.

Table 20 Greenhouse Gas Emission of Producing Sawn Timber and Particle Board (FR, 2010; Frhward, 2010).

Product	Units	Processing of Timber into Sawn Timber		
		Harvesting and Sawmilling	Harvesting Only	Sawmilling Only
Sawn Timber	t eq. CO_2/m^3	0.142	0.007	0.135
	t eq. CO_2/t[(a)]	0.403	0.020	0.382

Notes

(a) Assuming a density of 0.400 odt/m^3 and moisture content of 12%.

6.4 Fuel Wood Production

There have been many LCA studies that examine the use of wood as a source of fuel. Wood can be chipped or pelleted and used for either heat and/or electricity production at both small and large scales. There are currently a number of wood chip supply chains in operation in the UK, many of which source forest residues. For illustration purposes in this study, it is assumed that forest residues are chipped and used as a source of fuel for heat production.

GHG emissions from chipping are based on fuel trials at the Forestry Commission, resulting in diesel fuel consumption of, on average, 1 l/m^3 of roundwood chipped (BEAT, 2008). Whole trees are assumed to have roughly the same density as roundwood (approximately 0.400 odt/m^3). However, brash bales are of a lower density (approximately 0.231 odt/m^3) and, therefore, chipping requirements are higher compared to roundwood (1.7 litres/odt wood chips). It was assumed that the wood is chipped at 25% moisture content, corresponding to 0.7 litres/tonne wood chips from roundwood/whole trees and 1 litres/tonne wood chips from brash bales.

Table 21 Total Greenhouse Gas Emissions Associated with Fuel Wood Production

Source of Wood Chips	Carbon Dioxide Emissions (kg CO_2/t)	Methane Emissions (kg CH_4/t)	Nitrous Oxide Emissions (kg N_2O/t)	Total GHG Emissions (kg eq. CO_2/t)
Chipping Roundwood/Whole Trees	2.12	6×10^{-4}	2×10^{-5}	2.14
Chipping Forest Residues/Brash Bales	2.76	8×10^{-4}	2×10^{-5}	2.78

7 EMISSIONS OF COMPARATIVE REFERENCE SYSTEMS

7.1 Construction Materials

Previous LCA studies have suggested that the GHG emissions associated timber products are lower than those for alternative materials, such as cement and steel, for which timber can potentially substitute (Matthews et al, 2007). Such comparison has to be considered carefully, however, as one tonne of sawn timber cannot directly substitute one tonne of cement or steel. The whole construction must be considered and the relative consumption of timber and other building materials compared in each case. Estimates are available from the Building Research Establishment for displaced GHG emission savings from substituting steel and cement with sawn timber. However, these estimates are difficult to interpret and they are not transparent. Hence, Forest Research provided the results of their own analysis of displacing steel, concrete and brick cladding by timber (FR, 2010) and subsequent GHG emissions savings are reproduced in Table 22.

Table 22 Total Greenhouse Gas Emission Savings of Sawn Timber Displacing Alternative Building Materials (FR, 2010)

Displacement	Total GHG Emissions Savings	
	t eq. C/odt of timber	t eq. CO_2/t of timber[(a)]
Sawn Timber Displacing Steel	0.40	1.67
Sawn Timber Displacing Concrete	0.46	1.93
Sawn Timber Displacing Brick Cladding	1.69	7.04

Note
(a) Assuming timber with a moisture content of 12%.

It has been suggested that carbon can be sequestered in timber products. Increasing the use of timber products as either building materials or products effectively creates a store of carbon. There are qualifications and constraints on this concept, however, and this has been explained thoroughly elsewhere (Matthews et al, 2007). Basically, there can only be a certain number of ways that timber products can be used, and carbon sequestration by these products is determined by their carbon content and their service life. It has been shown that a stack of fuel wood sequesters more carbon (7.5 t C/a) than a wooden hut (0.3 t C/a), as long as the fuel wood is replenished each year from sustainable forestry so the annual outflow of carbon is balanced with the annual inflow (Matthews et al, 2007). At the same time, the annual inflow of carbon cannot exceed the annual productivity of the forest. Therefore, there is a limit to carbon sequestration in products. To take this into account here, the average lifespan of a building incorporating timber has been assumed to be 50 years (Matthews et al, 2007). Consequently, every tonne of timber used for construction will sequester 0.032 t CO_2/a (assuming 12% moisture content and carbon content of 0.44 t C/t of timber).

The eventual method of disposal at the end of the life of the building is crucial in determining the full life cycle GHG emissions balance of the materials it incorporates. If waste wood is recovered after demolition and incinerated, then the contained carbon will, ultimately, be released as carbon dioxide. However, if the incineration plant includes energy recovery, then fossil fuels may be displaced by the heat and/or electricity generated, effectively, from the wood waste. Alternatively, if the demolition material, including waste wood, is sent to a landfill site which has energy recovery, fossil fuels may also be displaced. However, the actual balance of GHG emissions depends on a number of considerations such as the amount and type of fossil fuels displaced and the extent of methane leakage from the breakdown of waste wood in the landfill site.

These and other factors have to be taken into account during the evaluation of overall GHG emissions associated with the use of timber as a construction material. In common with most other studies, it is assumed here that the construction timber is derived from sustainable forests. This means that the carbon dioxide eventually released during end-of-life disposal (either via incineration or landfilling) is balanced by the carbon dioxide absorbed during the growth of trees planted as replacements for timber originally extracted from the forest. On this basis, the overall GHG emissions associated with end-of-life disposal options can be established (BEAT, 2008) and the estimates are presented in Table 23.

Table 23 Overall Greenhouse Gas Emissions from Disposal of Sawn Timber at End of Life

Disposal Option	Type of Emission	Overall Greenhouse Gas Emissions[a]			
		Carbon Dioxide Emissions (kg CO_2/t)	Methane Emissions (kg CH_4/t)	Nitrous Oxide Emissions (kg N_2O/t)	Total GHG Emissions (kg eq. CO_2/t)
Incineration (no energy recovery)	Emissions/Total	-	0.16	0.05	18.21
Incineration (with energy recovery)[b]	Emissions	-	0.16	0.05	18.21
	Savings	-718.28	-1.93	-0.03	-774.45
	Total	-718.28	-1.77	0.02	-756.24
Landfill (with energy recovery)[b]	Emissions	-	57.5	0.00	1437.50
	Savings	-336.32	-0.91	-0.01	-362.7
	Total	-336.32	56.59	-0.01	1074.8

Notes
(a) Assumes conversion efficiency of 30%
(b) Assuming thermal energy efficiency of 30% for energy recovery.

7.2 Heating Fuels

For comparative purposes, it is assumed here that wood chips derived from biomass in the forest are used for heat production, by means of a boiler, to displace natural gas. At 25% moisture content, wood chips from forest residues have a net energy content of 13.21 GJ/t, and sawmill residues (at 12% moisture content) have a net energy content of 15.92 GJ/t (BEAT, 2008). The conversion efficiency to heat is assumed to be 90%, based on a specialised wood chip burner (Bradford, 2008). The assumed efficiency for a natural gas boiler is 72% on the basis that this is old and being replaced by a more efficient boiler. Assuming that wood chips are derived from sustainable forests, carbon dioxide emissions from their combustion are discounted. However, relatively small emissions of methane and nitrous oxide from combustion are taken into account, at a rate of 0.00001 kg CH_4 and 0.000003 kg N_2O per MJ of fuel combusted (Jungmeier, 2003). Based on these assumptions, Table 24 provides a comparison between the GHG emissions per unit heat provided from the combustion of fuel wood, in the form of wood chips, and natural gas.

Table 24 Comparison of Greenhouse Gas Emissions from Fuel Wood Natural Gas Combustion

Type of Heating Fuel	GHG Emissions from Fuel Combustion			
	Carbon Dioxide Emissions (kg CO_2/MJ)	Methane Emissions (kg CH_4/MJ)	Nitrous Oxide Emissions (kg N_2O/MJ)	Total GHG Emissions (kg eq. CO_2/MJ)
Fuel Wood (wood chips)	-	1×10^{-5}	3×10^{-6}	0.001
Natural Gas	0.06	7×10^{-5}	2×10^{-7}	0.062

8 TIMBER SUPPLY CHAIN SCENARIOS

8.1 Basic Scenarios

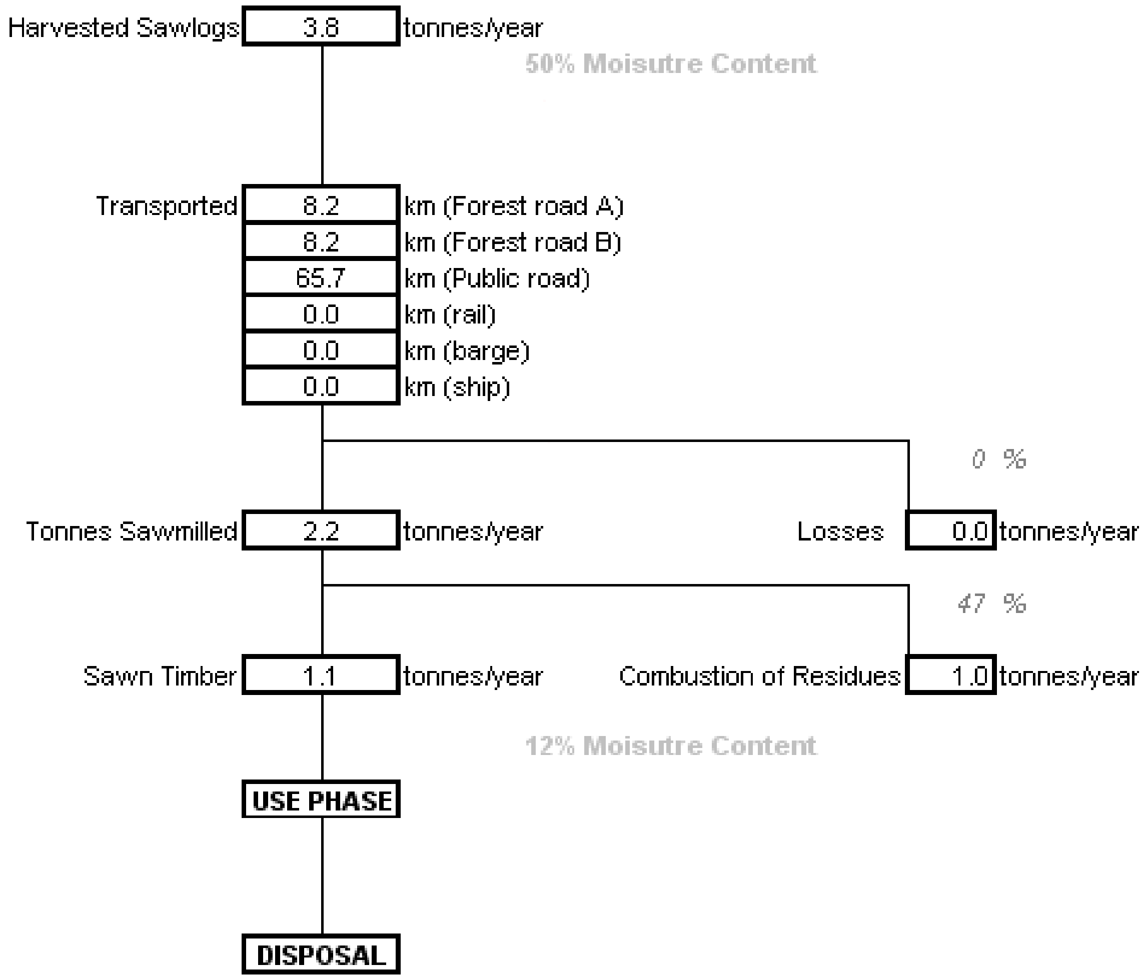
Data collected from existing sources have been used to calculate full life cycle GHG emissions for two complete timber supply chain scenarios; production and use of sawn timber as an alternative to concrete and steel in construction, and fuel wood production and use in heating as an alternative to fossil fuel heating. In addition to the ‘production’ phase for these scenarios, the ‘use’ phase is also included, as compliant with PAS 2050 (BSI, 2008). Furthermore, the end-of-life, or ‘disposal’ phase is taken into account for sawn timber for construction. The evaluation of full life cycle GHG emissions for these two scenarios in this manner enables the contribution from timber transport to be set in context. For complete evaluation, it is necessary to include direct GHG emissions from the fuel consumption of road haulage vehicles under different driving conditions, and indirect GHG emissions associated with the manufacture and maintenance of these vehicles, construction and maintenance of forest roads and the maintenance of public roads which they use. All these and other contributions can be determined using the results assembled and documented previously (see Sections 3 to 7).

It will have been noted that these results have, so far, been presented in units relevant to stages in the timber life cycle. These results have to be combined together so that they represent the GHG emissions of the full life cycle. This can be achieved by specifying flow charts for both of the scenarios under consideration here. Such flow charts identify the stages in each life cycle and quantify the amounts of timber associated with each of these stages. It is, of course, possible to formulate different flow charts which have different stages and quantities of timber involved.

8.2 Sawn Timber in Construction

The full life cycle for sawn timber used in construction consists of the following stages; forest establishment and cultivation, saw log harvesting, transportation by road haulage vehicles on forest roads and public roads, sawmilling, use in construction and, after the life of the building comes to an end, disposal by incineration or landfilling of waste wood from the demolition site. This full life cycle for annual sawn timber production from 1 hectare of forest is illustrated in Figure 1 (see also Appendix D). For every t of 'green' saw logs (50% moisture content) that enters the saw mill, approximately 0.55 t of sawn timber (at approximately 12% moisture content) is produced. Approximately 47% of the original saw logs are lost as slab wood (43%) and sawdust (4%). This material is assumed to be a waste product of saw log processing and this is consumed on-site for heat production. This can, effectively, displace fossil fuels and, as such, it is included in subsequent evaluation.

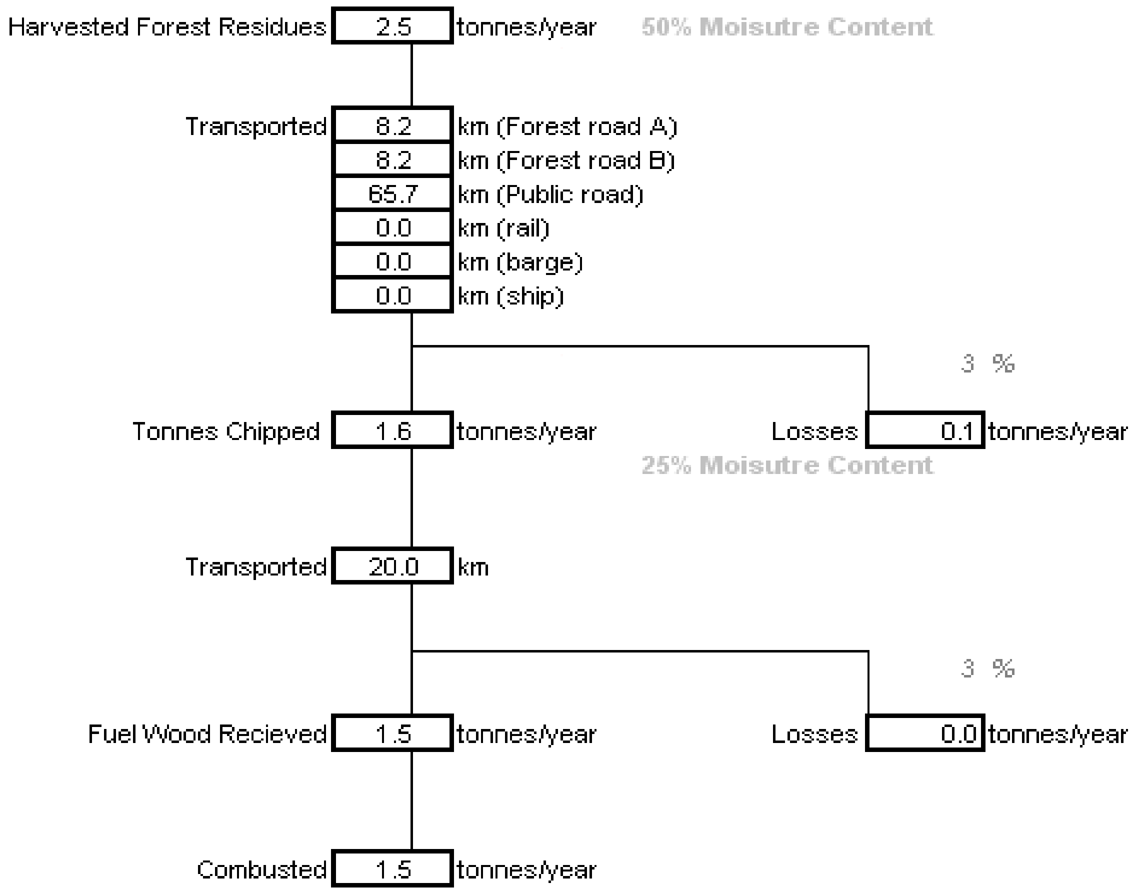
Figure 1 Flow Chart for the Production, Use and Disposal Phase of sawn Timber Used as a Construction Material



8.3 Fuel Wood for Heating

The flow chart for the full life cycle of annual fuel wood production from 1 hectare of forest and subsequent use in heating is shown in Figure 2 (see also Appendix D). The full life cycle consists of the following stages; forest establishment and cultivation, forest residue harvesting, transportation by road haulage vehicles on forest roads and public roads, chipping, further transportation to the site of use and, finally, combustion. It is assumed that forest residues at 50% moisture content are transported from the site of harvesting in the forest to a central chipping plant along forest and public roads. At the chipping plant, the residues are left to dry and then chipped at about 25% moisture content.

Figure 2 Flow Chart for the Production and Delivery of Fuel Wood for Heating



After this, the wood chips are delivered to a consumer to produce heat. It is assumed that the wood chips are delivered in 26 GVW tipper trucks, which are more suitable for local use than those used to transport timber. The transport of wood chips is volume-limited as they have a low bulk density of 0.240 t/m^3 (Biomass Energy Centre, 2010). This means that the full hold of the vehicle is filled before the weight limit of the vehicle is reached. This size of tipper truck is assumed to have a volume capacity of 33 m^3 (Whittaker et al., 2009). Hence, the outward load factor of a fully-laden tipper truck is 47%. It is assumed that the truck is empty on the return journey to the chipping plant. It is also assumed that local transport takes place to deliver the chips, at no more than 20 km. On this basis, GHG emissions for the delivery of wood chips with such tipper trucks has been derived from a standard source (North Energy, 2009) and estimates are summarised in Table 25.

Table 25 Total Greenhouse Gas Emissions Associated with Fuel Wood Delivery

Stage	Carbon Dioxide Emissions (kg CO_2/t-km)	Methane Emissions (kg CH_4/t-km)	Nitrous Oxide Emissions (kg N_2O/t-km)	Total GHG Emissions (kg eq. CO_2/t-km)
Transport of Wood Chips	0.002	6×10^{-7}	2×10^{-8}	0.002

9 RESULTS

9.1 Greenhouse Gas Emissions of Sawn Timber in Construction

Combining the results derived for individual life cycle stages (from Section 3 to 7) with the flow chart information (from Section 8.2), total GHG emissions for the use of sawn timber in construction can be obtained. A number of options can be considered which affect subsequent results and these can be illustrated by means of the best case (high net GHG emissions savings) and worst case (low net GHG emissions savings). Figure 3 displays the best-case in which sawn timber displaces brick cladding and, at the end of the life of the building, waste wood is disposed of by incineration with energy recovery. Individual contributions, either positive or negative, to GHG emissions are added cumulatively in Figure 3. The final result with this best case is that overall emissions amount to – 8376.2 kg eq. CO_2/t of sawn timber.

Figure 3 Cumulative Greenhouse Gas Emissions for Sawn Timber Used in Construction: Best Case

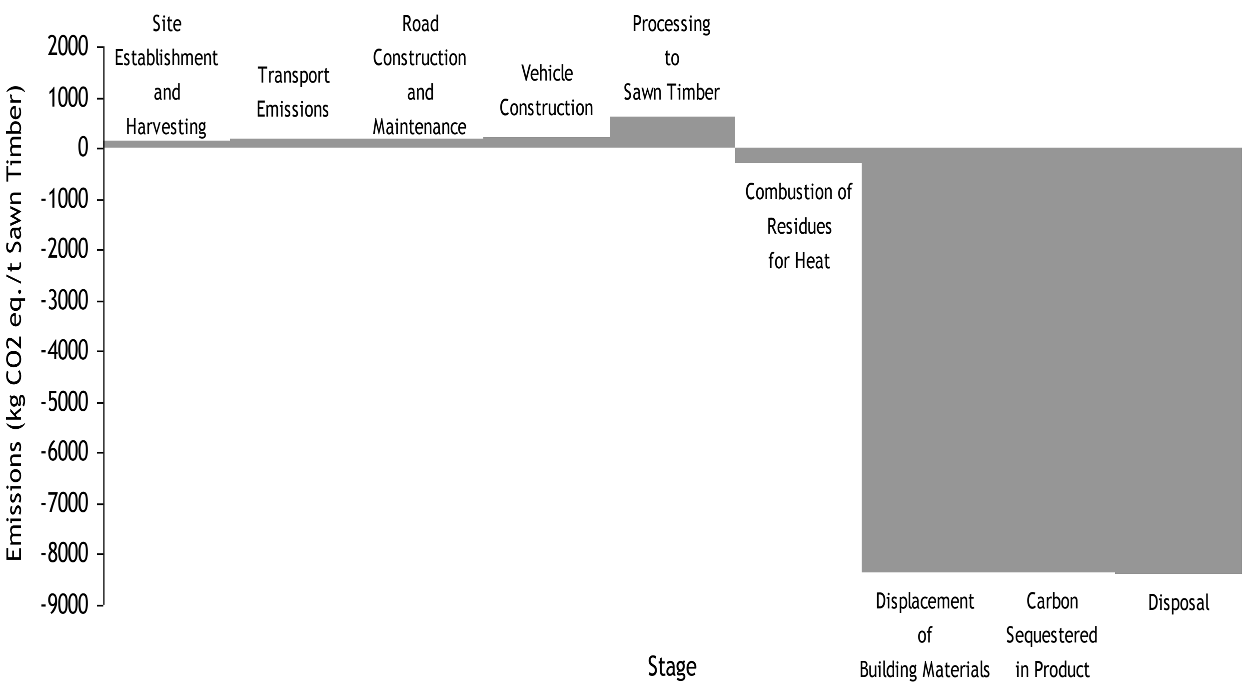
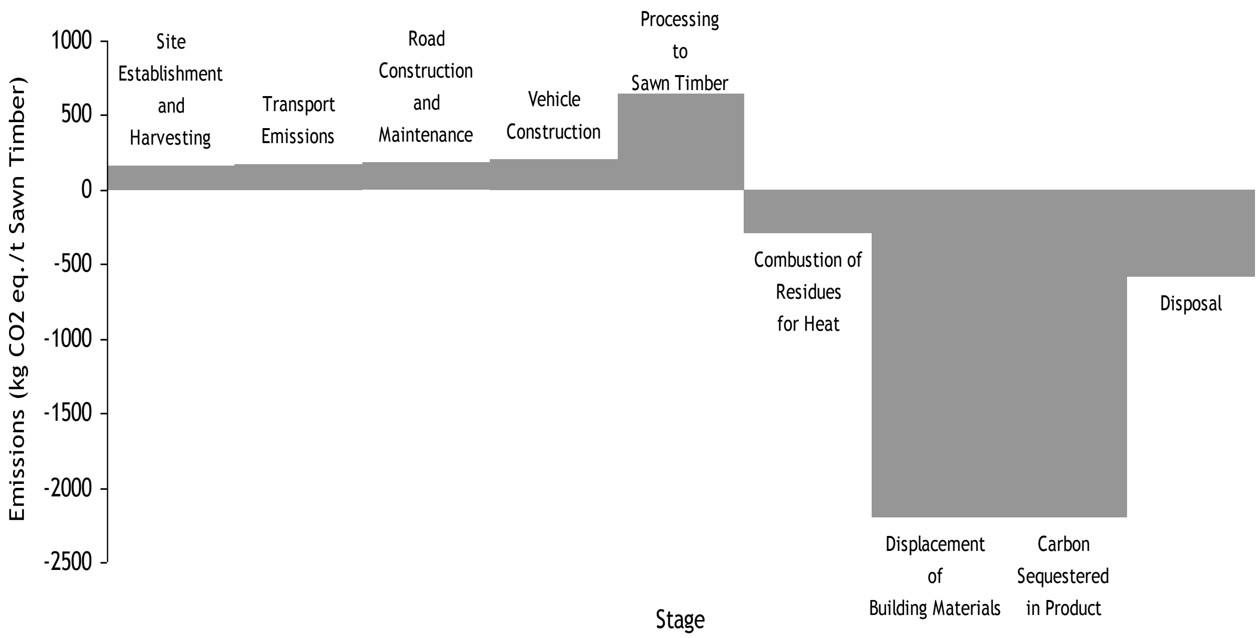


Figure 4 shows the cumulative GHG emissions of the worst case in which sawn timber replaces steel in construction and, after the end of the life of the building, wood waste is disposed of into landfill with energy recovery (with associated CH_4 emissions from the landfill site and avoided GHG emissions from displaced grid electricity). This worst case also assumes that forest roads are subjected to a high maintenance strategy (see Section 4.2). The final result with this worst case is that overall GHG emissions amount to – 569.6 kg eq. CO_2/t of sawn timber.

Figure 4 Cumulative Greenhouse Gas Emissions for Sawn Timber Used in Construction: Worst Case



From these results, it can be seen that assumptions about materials substitution and end-of-life disposal have a significant effect on magnitude of net GHG emissions savings. However, it should be noted that, in both cases, savings are apparent. Within this context, the relative contributions from timber transport are very small. This is demonstrated further in Table 26 which summarises GHG emissions per year for one hectare of forest and GHG emissions per tonne of sawn timber. The results in Table 26 are based on the assumption that the average round trip distance for timber haulage vehicles is 102 miles (164 km) of which 20% is on forest roads (Type A and B roads equally) and 80% on public roads. It is assumed that a low case maintenance management strategy has been adopted for the forest roads and that public roads used by timber transport are re-surfaced every 10 years. On this basis, total GHG emissions from timber transport on forest and public roads amount to 34.7 kg eq. CO_2 per t of sawn timber[4] (see Table 27). This is equivalent to approximately 6% of the total GHG emissions of 568.7 kg eq. CO_2 per t of sawn timber, excluding avoided emissions from the use of sawmill waste as a fuel, substitution of other construction materials and end-of-life disposal, and carbon sequestration.

[4] It should be noted that, of these total GHG emissions for sawn timber, 17.0 kg eq. CO_2 per t is due to fuel consumption and that the relatively high contribution from vehicle manufacture and maintenance is as a result of their relatively short working life and the need for regular tyre replacement.

Table 26 Summary of Contributions to Greenhouse Gas Emissions for Sawn Timber Used in Construction

Contribution	Total GHG Emissions	
	(kg eq. CO_2/a)	(kg eq. CO_2/t sawn timber)
Site Establishment	15.7	13.7
Harvesting	139.5	121.9
Fuel Consumption of Timber Transport on Forest Roads	2.8	2.4
Construction of Forest Roads	1.8	1.6
Soil Disturbance during Forest Road Construction	3.1	2.7
Maintenance of Forest Roads	2.0	1.8
Fuel Consumption of Timber Transport on Public Roads	16.7	14.6
Maintenance of Public Roads	1.8	1.6
Road Haulage Vehicle Construction and Maintenance	11.5	10.0
Sawmilling	437.3	382.3
Combustion of Sawmill Residues	18.5	16.1
Sub-Totals	**650.6**	**568.7**
Use of Sawmill Waste as a Fuel	- 927.8	- 811.0
Avoided Emissions:		
- Substitution of Steel	- 1906.6	- 1,666.7
- Substitution of Concrete	- 2211.7	- 1,933.3
- Substitution of Brick Cladding	- 8055.6	- 7,041.7
End-of-Life Disposal Emissions:		
- incineration without energy recovery	20.83	18.2
- incineration with energy recovery	- 43.4	- 38.0
- landfilling with energy recovery	1614.3	1,411.1
Sequestered Carbon in Sawn Timber	-0.04	-0.03

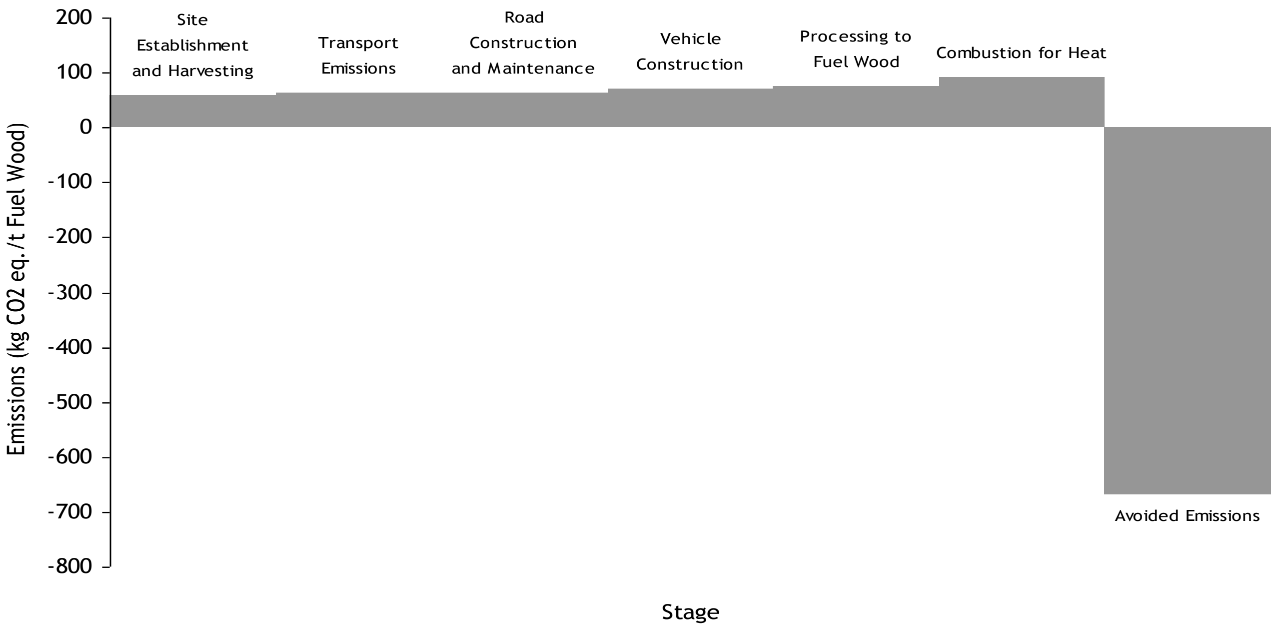
Table 27 Total Greenhouse Gas Emissions from Sawn Timber Transport

	Total Greenhouse Gas Emissions	
	(kg eq. CO_2/t sawn timber)	(%)
Fuel Consumption on Forest and Public Roads	17.0	49.0
Road Haulage Vehicle Construction and Maintenance	10.0	28.8
Construction of Forest Roads	1.6	4.6
Soil Disturbance during Forest Road Construction	2.7	7.8
Maintenance of Forest Roads	1.8	5.2
Maintenance of Public Roads	1.6	4.6
Totals	**34.7**	**100**

9.2 Greenhouse Gas Emissions of Fuel Wood for Heating

Combining the results derived for individual life cycle stages (from Section 3 to 7) with the flow chart information (from Section 8.3), total GHG emissions for the use of fuel wood for heating can be obtained. Again, a number of options can be considered which affect subsequent results and these can be illustrated by means of the best case (high net GHG emissions savings) and worst case (low net GHG emissions savings). Figure 5 shows best case for the cumulative GHG emissions from fuel wood production including forest establishment and harvesting, transport, chipping, chip delivery and combustion for heat. The avoided GHG emissions by displacing natural gas for heating are included. As with sawn timber (see Section 9.1), it is assumed that the average round trip distance for timber haulage vehicles is 102 miles (164 km) of which 20% is on forest roads (Type A and B roads equally) and 80% on public roads. In this instance, a low case maintenance management strategy is adopted for the forest roads and public roads used by timber transport are assumed to be re-surfaced every 10 years. Price allocation has an effect on results since fuel wood commands a lower price relative to that for saw logs. Hence, a smaller proportion of total GHG emissions is allocated to fuel wood relative to sawn timber. The overall GHG emissions for this best case for fuel wood production and use for heating amount to – 667 kg eq. CO_2/t of fuel wood. In the worst case, all the above assumptions are incorporated apart from adoption of high case maintenance strategy for forest roads. As shown in Figure 6, this results in little difference in overall GHG emissions which amount to – 666 kg eq. CO_2/t of fuel wood.

Figure 5 Cumulative Greenhouse Gas Emissions for Fuel Wood (Wood Chips) Used in Heating: Best Case



As previously, a relatively small contribution of timber transport to overall GHG emissions is apparent for fuel wood, although it is somewhat higher than that for sawn timber. This is demonstrated in Table 28 which summarises GHG emissions per year for one hectare of forest and GHG emissions per tonne of fuel wood. The results in Table 28 are based on the assumption that the average round trip distance for timber haulage vehicles is 102 miles (164 km) of which 20% is on forest roads (Type A and B roads equally) and 80% on public roads. It is assumed that a low case maintenance management strategy has been adopted for the forest roads and that public roads used by timber transport are re-surfaced every 10 years. On this basis, total GHG emissions from timber transport (fuel consumption, vehicle manufacture and vehicle maintenance) on forest and public roads amount to 13.65 kg eq. CO_2 per t of fuel wood (see Table 29). This is equivalent to approximately 15% of the total GHG emissions of 92.97 kg eq. CO_2 per t of fuel wood, excluding avoided emissions from displacement of natural gas for heating.

Figure 6 Cumulative Greenhouse Gas Emissions for Fuel Wood (Wood Chips) Used in Heating: Worst Case

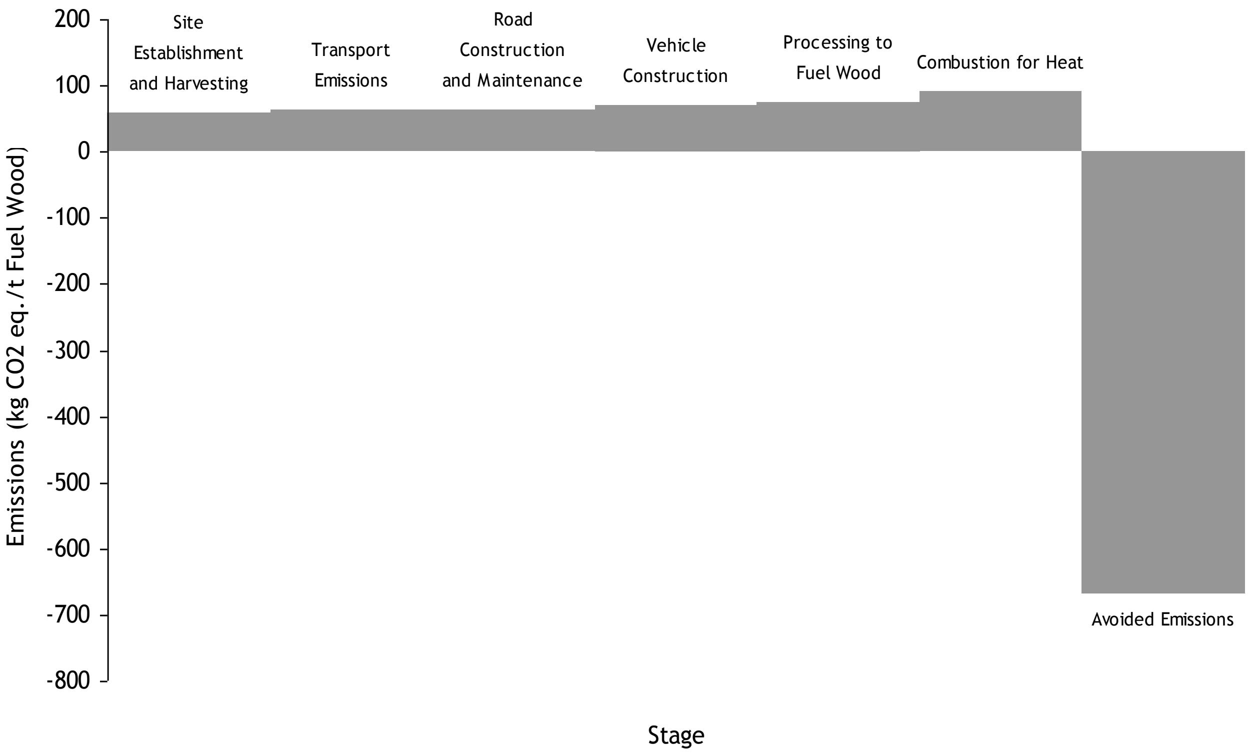


Table 28 Summary of Contributions to Greenhouse Gas Emissions for Fuel Wood Used in Heating

Contribution	Total GHG Emissions	
	(kg eq. CO_2/a)	(kg eq. CO_2/t fuel wood)
Site Establishment	2.54	1.64
Harvesting	86.55	55.97
Fuel Consumption of Timber Transport on Forest Roads	1.81	1.17
Construction of Forest Roads	0.16	0.10
Soil Disturbance during Forest Road Construction	0.27	0.18
Maintenance of Forest Roads	0.32	0.21
Fuel Consumption of Timber Transport on Public Roads	10.81	6.99
Maintenance of Public Roads	0.30	0.19
Road Haulage Vehicle Construction and Maintenance	7.43	4.81
Chipping	5.38	3.48
Wood Chip Delivery	2.63	1.70
Combustion of Wood Chips	23.36	15.11
Sub-Totals	**143.77**	**92.97**
Avoided Emissions by Displacing Natural Gas	- 1,173.28	- 758.71
Overall Emissions	- 1029.51	- 665.74

Table 29 Total Greenhouse Gas Emissions from Fuel Wood Transport

	Total Greenhouse Gas Emissions	
	(kg eq. CO_2/t fuel wood)	(%)
Fuel Consumption on Forest and Public Roads	8.16	59.8
Road Haulage Vehicle Construction and Maintenance	4.81	35.2
Construction of Forest Roads	0.10	0.7
Soil Disturbance during Forest Road Construction	0.18	1.3
Maintenance of Forest Roads	0.21	1.5
Maintenance of Public Roads	0.19	1.4
Totals	**13.65**	**100**

10 SENSITIVITY ANALYSIS

10.1 Timber Transport Workbook

A MS Excel workbook, referred to as the Timber Transport Workbook (Timber Transport Workbook v14.xls), was established to assist the estimation of GHG emissions associated with sawn timber and fuel wood production and use. This provided the basis for the estimates illustrated previously in this study. The workbook was also developed to support sensitivity analysis into the effect of various key variables on the total GHG emissions. Basic information on the Timber Transport Workbook is provided in Appendix E. Sensitivity analyses were performed on the effects of transport distance, timber haulage vehicle fuel consumption savings, and the level of road maintenance on total GHG emissions and results are presented here. Particular attention should be given to the adopted scale of the vertical axes of the graphical presentation of results of these sensitivity analyses since these have been modified to reveal effects which may be small relative to the magnitude of overall GHG emissions.

10.2 Effect of Transport Distance

As the average transport distances increase for a timber haulage vehicle, the overall GHG emissions per tonne of sawn timber or fuel wood increase, as shown in Figures 7 and 8, respectively. This is due to an increase in fuel consumption for the total journey, and the greater proportion of the vehicles working life which is allocated to transporting one tonne of sawn timber or fuel wood. It can be deduced that, with every one kilometre increase in transport distance, GHG emissions increase by 0.07 kg eq. CO_2 per tonne of sawn timber and fuel wood (with mixed transport).

Figures 7 and 8 illustrate the influence on overall GHG emissions of travelling on forest and public road. This is demonstrated by assuming 100% travelling on forest roads, 10% travelling on public roads and, more realistically, travelling 20% on forest roads and 80% on public roads (FCS, 2008) Previously, it was indicated that transport fuel consumption and subsequent GHG emissions are higher on forest roads than on public roads (see Section 3.1). This is observed in Figures 7 and 6, although differences are very small.

Figure 7 Effect on Transport Distance on Overall Greenhouse Gas Emissions per Tonne of Sawn Timber: Best Case

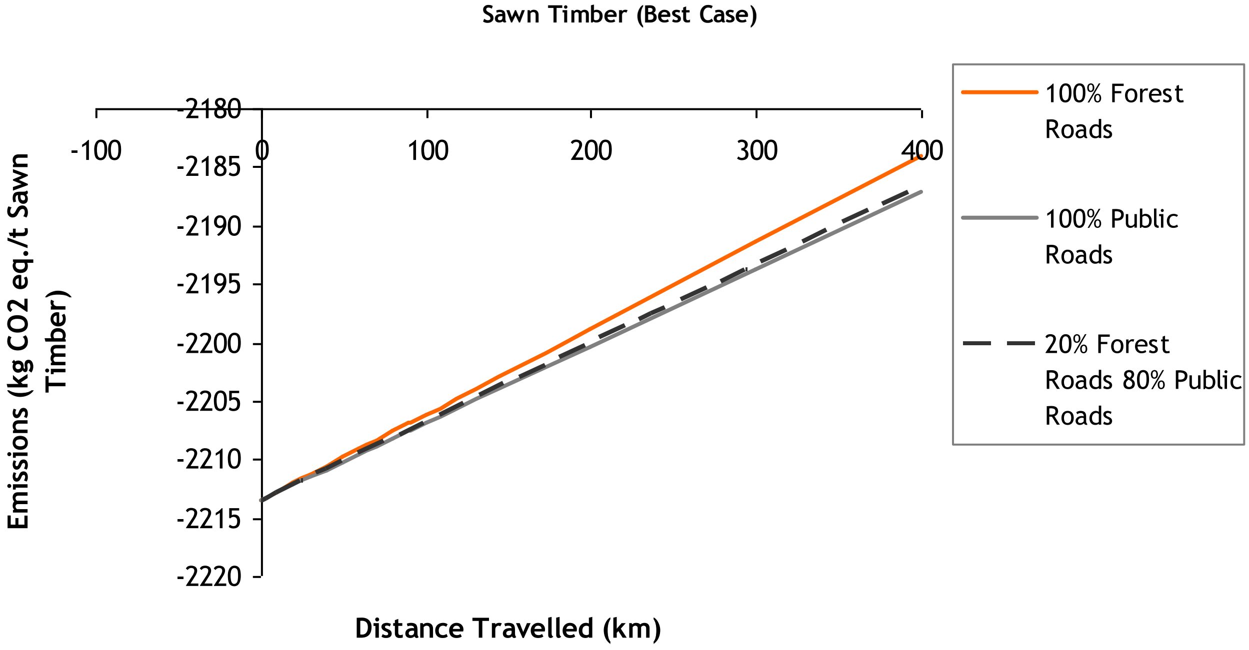
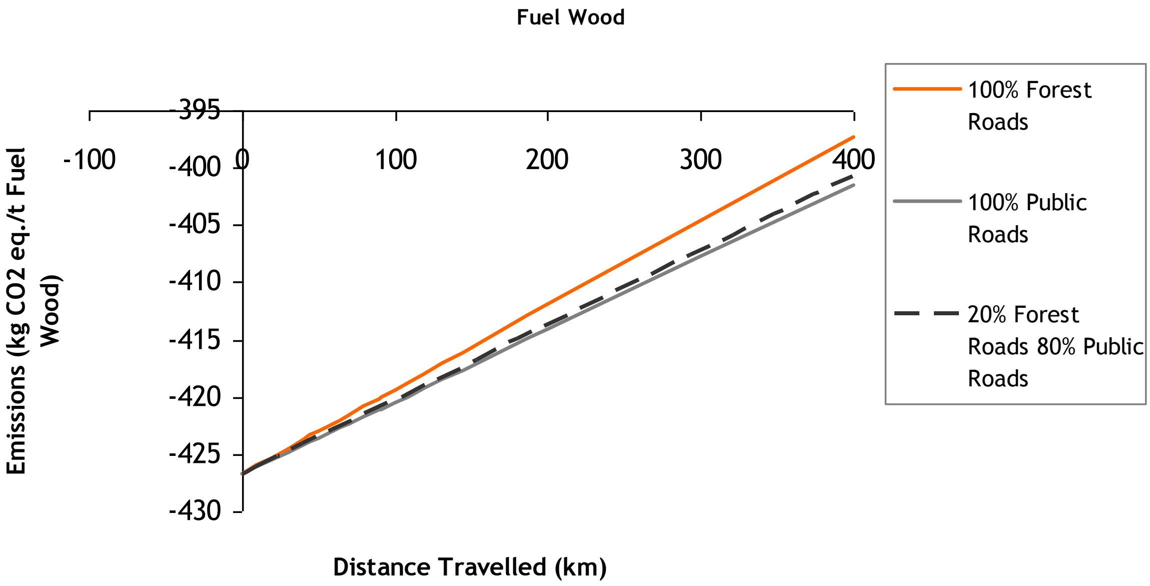


Figure 8 Effect of Transport Distance on Overall Greenhouse Gas Emissions per Tonne of Fuel Wood



10.3 Fuel Consumption Savings

Figures 8 and 9 show the effect of transport fuel consumption savings on overall GHG emissions for sawn timber and fuel wood, respectively. Potential savings up to 60% are considered for illustrative purposes, whilst this study assumes that 15% savings are achievable for timber haulage vehicles: 10% from driver behaviour and about 5% from tyre pressure control (see Section 3.2). Fuel savings have only a relatively small effect on the overall GHG emissions. It can be deduced that, with every 1% increase in such savings, overall GHG emissions are reduced by 0.20 kg eq. CO_2 per tonne of sawn timber and 0.10 CO_2 per tonne of fuel wood.

Figure 9 Effect of Fuel Consumption Savings on Overall Greenhouse Gas Emissions for Sawn Timber: Best Case

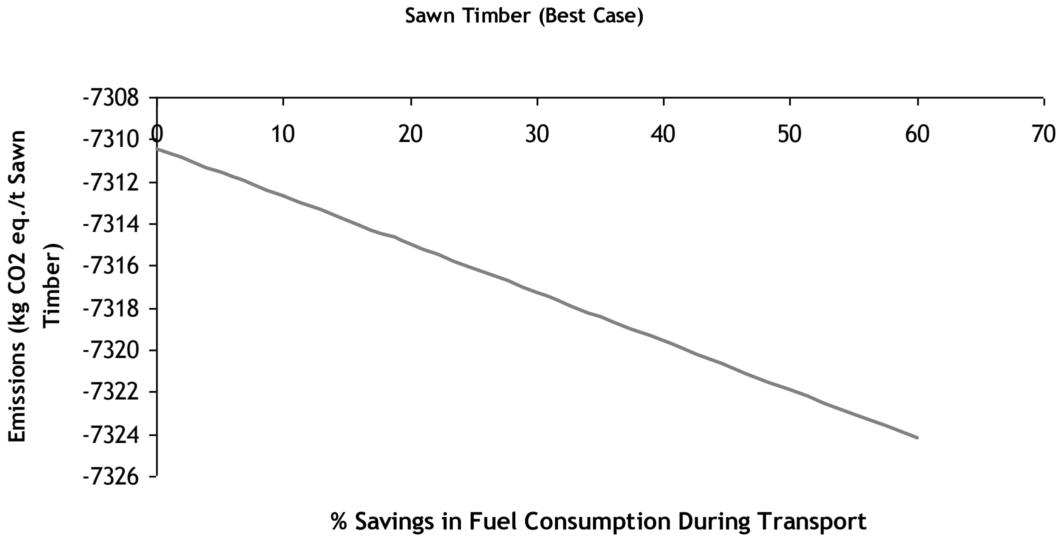
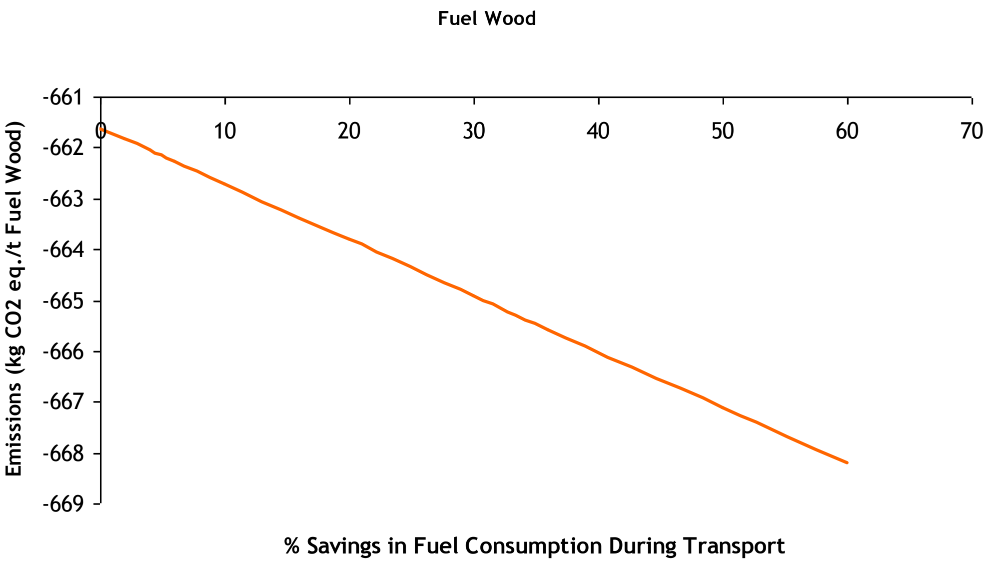


Figure 10 Effect of Fuel Consumption Savings on Overall Greenhouse Gas Emissions for Fuel Wood



10.4 Level of Road Maintenance

The fuel wood production and use for heating has been was chosen to illustrate the sensitivity of the overall emissions to forest and public road maintenance. Figure 11 shows the effect of forest road maintenance on the overall GHG emissions per tonne of fuel wood by examining the number of maintenance events with the low case, based on re-grading each time, and the high case, based on re-surfacing each time. In this instance, only the effect on Type A roads is considered, as these are used more often than Type B roads. In terms of GHG emissions, re-grading is a much less intensive operation compared to re-surfacing. Re-grading requires a grader and roller to make several passes over the road surface until it is smooth, whereas re-surfacing requires provision of blasted and crushed stone. As the frequency of maintenance increases over a rotation, overall GHG emissions also increase. However, this effect is much more prominent when road maintenance consists of re-surfacing. In the study, it is assumed that Type A roads are maintained every year, either being re-graded (low case) or re-surfaced (high case) each time.

Figure 12 shows how the level of public road maintenance affects overall GHG emissions for fuel wood. In this instance, the level of road maintenance is represented by how frequently the road is re-surfaced. The default value for this frequency of 10 years has been adopted in this study. The Timber Transport Workbook was used to determine how overall GHG emissions per tonne of fuel wood vary with changes in this frequency up to 60 years. Figure 12 demonstrates that the subsequent relationship is asymptotic. Whilst overall GHG emissions are relatively insensitive to maintenance frequency exceeding 20 years, they are very sensitive to frequencies below this value. However, this sensitivity needs to be set within the context of the magnitude of overall GHG emissions.

Figure 11 Effect of Levels of Forest Road Maintenance on Overall Greenhouse Gas Emissions for Fuel Wood

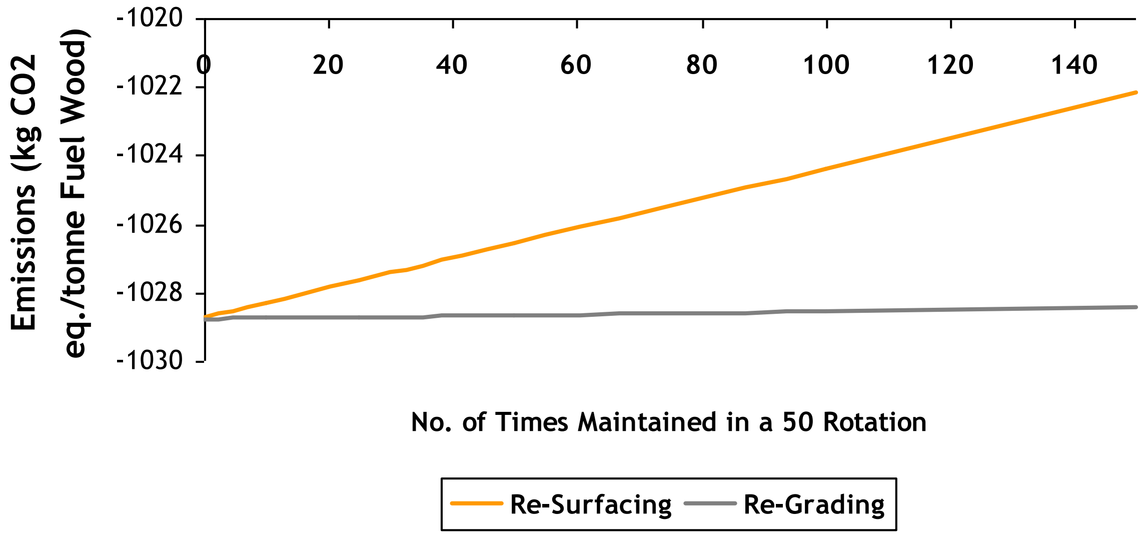
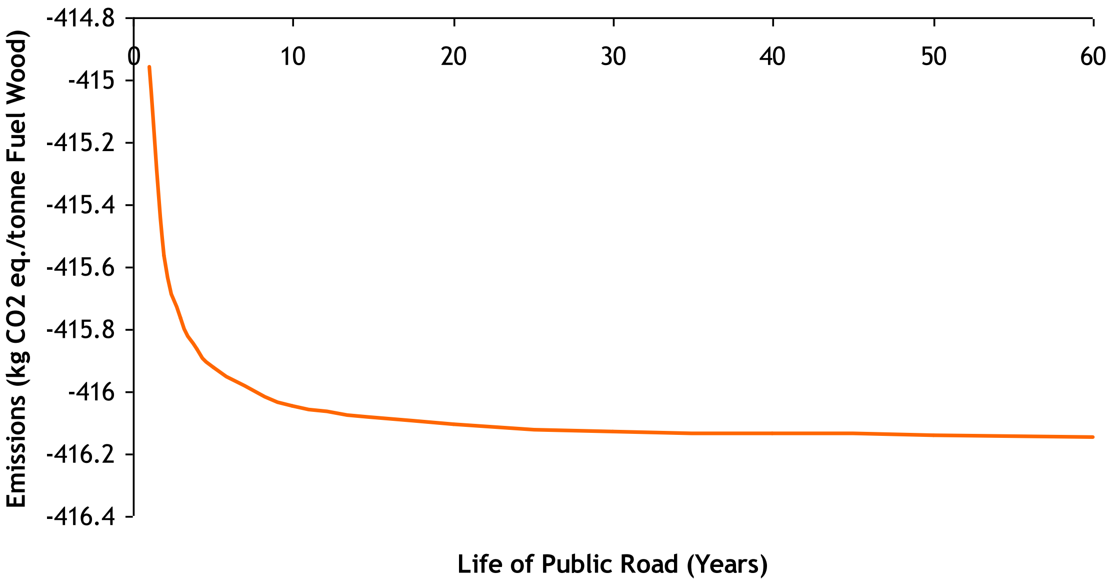


Figure 12 Effect of Levels of Public Road Maintenance on Overall Greenhouse Gas Emissions for Fuel Wood



11 CONCLUSIONS AND RECOMMENDATIONS

Timber transport is a vital component in managing forests and utilising the resulting produce as either a source of construction material or sustainable fuel. Using existing literature, this study has examined the GHG emissions of timber transport which arise from vehicle fuel consumption, vehicle manufacture, vehicle maintenance, forest road construction and maintenance, and public road maintenance. Using a basic formula, vehicle fuel consumption and direct GHG emissions, expressed in terms of kg eq. CO_2/t-km, have been derived for timber road haulage vehicles, with typical sizes of 40 and 44 t GVW, travelling on public roads. These have been adjusted to account for the effects of topography and road type so that estimated GHG emissions for timber transport on average forest could be determined. On this basis, GHG emissions for timber transport were found to be between 33% and 35% higher on forest roads compared with public roads.

Various interventions to reduce fuel consumption and GHG emissions were investigated including improving vehicle aerodynamics, applying speed reductions, modifying driver behaviour and installing automatic tyre pressure control. Based on limited available information, it was concluded that only modifications to driver behaviour and installation automatic tyre pressure control might currently be practical for timber transport. It was estimated that these interventions, combined together, might realise maximum savings in fuel consumption and GHG emissions of 15%. The more radical possibility of adopting low carbon options, such as using biodiesel, was also explored. This indicated that, potentially, large reductions in GHG emissions could be achieved depending on the specific source of the biodiesel. Assuming that 100% biodiesel could be used in timber road haulage vehicles, then GHG emissions reductions of between 49% and 50% could be realised with biodiesel sourced from UK oilseed rape and between 82% and 83% with biodiesel derived from used cooking oil.

In addition to direct GHG emissions from vehicle fuel consumption, indirect GHG emissions related to vehicle manufacture and maintenance were evaluated. Although based on less precise and specific existing data, approximate estimates for these particular contributions to total GHG emissions for timber transport were obtained. This indicated that inclusion of vehicle manufacture would add between 13% and 18% to the GHG emissions from timber road haulage vehicle fuel consumption. For maintenance, this would increase GHG emissions from fuel consumption by between 25% and 33%. These are quite significant contributions especially when compared with those estimated previously for conventional road haulage vehicles. One reason for such differences is the assumed shorter working life of timber road haulage vehicles which was assumed to be 7 years at 110,000km/a (770,000 km/life) in contrast to an assumption of 10 years and 100,000 km/a (1,000,000 km/life) for a conventional road haulage vehicle. The relative contribution to GHG emissions from maintenance is also higher because it is assumed that this is related to GHG emissions from vehicle manufacture and due to the assumed need for complete tyre replacement every year.

The other main sources of indirect GHG emissions for timber transport are forest road construction and maintenance, and public road maintenance. A very detailed internal study on 'Forest Road Construction LCA' was accessed to determine the GHG emissions associated with the construction and maintenance of different types of forest road. An approximate average estimate of CO_2 emissions from soil disturbance was added to these originally estimated GHG emissions from forest road construction. It was noted that estimates of CO_2 emissions from soil disturbance depend on a number of considerations including assumptions about the location of forest roads, the types of soil which may or may not be disturbed, the carbon content of these soils, and the mechanism by which this carbon is released as CO_2. The allocation of total GHG emissions from forest road construction to timber extracted was also found to be very dependent on the assumed life span of forest roads which, in this study, was taken to be one complete forest rotation of 50 years. GHG emissions from forest road maintenance were also evaluated based on re-grading and re-surfacing, with combinations of these representing low and high cases for forest road maintenance management strategies.

Relevant information on public road construction and maintenance was very limited. Whilst GHG emissions from public road construction were excluded from this study for practical reasons, those from public road maintenance were approximated using existing data. The contribution of all GHG emissions from forest road construction and maintenance, and public road maintenance to timber extracted from the forest depends on road density which relates length of roads used for hauling timber to an unit area (1 ha) of forest land. Statistical information was available on forest road densities although its application to GHG emissions from forest road maintenance depends on assumptions about the extent and frequency of such maintenance. Only a speculative estimate could be derived for the public road density due to the lack of relevant data.

For comparative purposes, total GHG emissions for alternative modes of timber transport were assembled from published sources. These modes included diesel freight train, inland waterways and coastal shipping. The GHG emissions from timber loading and unloading for these modes of transport were also estimated. In general, these alterative modes of transport have lower total GHG emissions than those of timber road haulage vehicles. However, their widespread use would clearly depend on practical and logistical considerations.

Total GHG emissions from timber transport were set in context of timber production and use by considering complete forest systems, consisting, in this instance, of sawn timber used in construction and fuel wood for heating. In order to do this, it was necessary to take into account all forestry operations, including establishment, harvesting and extraction, and timber product processing, such as sawmilling or chipping. Additionally, for sawn timber, its potential displacement of other construction materials, such as steel, concrete and brick cladding, had to be addressed as was as the effects of end-of-life disposal, including incineration without energy recovery and landfilling with and without energy recovery, and carbon sequestration. For fuel wood, the displacement of natural gas for heating was considered. Allocation between timber products was taken into account and calculations were performed using the specifically-developed Timber Transport Workbook.

Overall GHG emissions from sawn timber and fuel wood depend on certain assumptions, especially in relation to construction material displacement and end-of-life disposal for sawn timber. However, it was demonstrated that significant GHG emissions benefits can be achieved by using sawn timber in construction and fuel wood for heating. In both instances, there are substantial net GHG emissions savings, as indicated by large, negative estimates of overall GHG emissions. Within the context of total GHG emissions, excluding displacement, the contributions of timber transport are relatively small, accounting to 6% in the case of one tonne of sawn timber and 15% in the case of one tonne of fuel wood.

Sensitivity analysis was conducted on these estimates using the Timber Transport Workbook. In particular, the effects of timber transport distance, vehicle fuel consumption savings and levels of forest and public road maintenance were investigated. Clear variations were apparent from this sensitivity analysis but the resulting impact on overall GHG emissions for sawn timber and fuel wood are relatively small.

Based on these results, the following recommendations can be drawn from this study:

- In order to determine the possible fuel and direct GHG emissions savings for timber transport, potential interventions and their practical implementation need to be examined in more detail.

- The practicality of using biodiesel in timber transport, as a means of realising substantial reductions in direct GHG emissions, especially if derived from appropriate sources, should be explored further.

- A more detailed study into the actual working life of timber road haulage vehicles, especially in terms of total distance travelled, and details of their maintenance, particularly tyre replacement, is required.

- If current assumptions are supported or extended by such a study, then more detailed assessment of the GHG emissions associated with timber road haulage vehicles and tyre manufacture will be needed.

- Further examination is required into CO_2 emissions from soil disturbance during forest road construction, including data on the co-location of these roads and the soil types over which they are laid, the carbon content of these soil types and actual CO_2 release mechanisms.

- The likely life span of forest roads needs to be established more thoroughly in order to determine the contribution of construction to total GHG emissions more accurately.

- Further investigation is needed into the actual extent and frequency of forest road maintenance.
- More reliable information is required on public road density which relates the length of these roads which are used for hauling timber to areas of forest from which it is extracted.
- In order to set GHG emissions from timber transport into complete context, more extensive evaluation of the effects of materials displacement and end-of-life disposal is required for sawn timber used in construction and fossil fuel displacement for fuel wood used in heating and other energy end uses.

APPENDIX A: BASIC DATA FOR FOREST ROAD CONSTRUCTION AND MAINTENANCE

Table A1 Primary Energy and Greenhouse Gas Emissions from Production of Blasted and Crushed Stone (Whittaker et al, 2008)

Rock Blasting	**Value**	**Units**	**Notes**	**Primary Energy**	**Greenhouse Gas Emissions**		
Diesel fuel consumption:				MJ/tonne blasted rock	kg CO_2/tonne blasted rock	kg CH_4/tonne blasted rock	kg N_2O/tonne blasted rock
Drilling	0.03	litres/tonne	Based on a fuel consumption of 441 litres for drilling, based on a total usage of 19 hours for setting up and idling when blasting 14040 tonnes rock[(a)].	1.30	0.09	0.00002	0.000001
Material inputs:							
Explosives	0.14	kg/tonne blasted rock	Based on total usage of 4164 Kg of explosives when extracting 14040 tonnes rock. Assume this is ammonium nitrate-based. Assumes 46% concentration of ammonium nitrate[(b)].	5.47	0.31	0.002	0.002
TOTAL Rock Blasting				***6.77***	***0.40***	***0.002***	***0.002***
Rock Crushing				**Primary Energy**	**Greenhouse Gas Emissions**		
Diesel fuel consumption:				MJ/tonne crushed rock	kg CO_2/tonne crushed rock	kg CH_4/tonne crushed rock	kg N_2O/tonne crushed rock
Excavator	0.18	litres/tonne	Based on a diesel fuel consumption of 1408 litres diesel when excavating 8000 tonnes of rock.	7.28	0.50	0.0001	0.000004
Loading	0.22	litres/tonne	Based on a diesel fuel consumption of 1747.2 litres diesel when loading crusher with 8000 tonnes of rock.	9.04	0.62	0.0002	0.000005
Crushing	0.22	litres/tonne	Based on a diesel fuel consumption of 1792 litres diesel when crushing 8000 tonnes of rock.	9.27	0.64	0.0002	0.000005
Material inputs:							
Blasted rock	1.00	tonne/tonne blasted rock	Assumes minimal losses.	6.77	0.40	0.002	0.002
TOTAL Rock Crushing				***32.35***	***2.17***	***0.002***	***0.002***

Notes

(a) Energy requirements and emissions for diesel fuel based on diesel fuel in United Kingdom in 1996 (BRE, 2000), and assumes a calorific value of 37.27 MJ/litre (Elsayed et al, 2003).

(b) Energy requirements and emissions based on that of ammonium nitrate fertilisers (North Energy Associates, 2008) assuming a 46% concentration (http://www.freepatentsonline.com/4701227.html).

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Table A2 Diesel Fuel Requirements and Aggregate Usage for Construction of One Kilometre of an Overlay Construction Forest Road (Whittaker et al, 2008)

Overlay Road Construction	Value	Units	Notes	Primary Energy	Greenhouse Gas Emissions		
				MJ/km	kg CO_2/km	kg CH_4/km	kg N_2O/km
Diesel fuel consumption[a]							
Loading Roadstone	1181.25	litres/km road	Based on a work rate of 28 hours for loading 3200 tonnes of rock and a fuel consumption of 13.5 litres/hour for loading dumpers with rock.	48867.96	3376.73	0.92	0.026
Haulage	2406.25	litres/km road	Based on a work rate of 56 hours for hauling 3200 tonnes of rock, and a fuel consumption of 13.75 litres/hour for a short-medium haulage (500m-5.5km) of rock.	99545.84	6878.53	1.88	0.053
Spreading Roadstone	612.50	litres/km road	Based on a work rate of 28 hours for spreading 3200 tonnes of rock and a fuel consumption of 7 litres/hour for spreading rock with a D5 Bull Dozer.	25338.94	1750.90	0.48	0.013
Grading	65.63	litres/km road	Based on a work rate of 2 hours for grading a 320 m stretch of road and a fuel consumption of 10.5 litres/hour for grading.	2714.89	187.60	0.05	0.001
Rolling	40.63	litres/km road	Based on a work rate of 2 hours for rolling a 320 m stretch of road and a fuel consumption of 6.5 litres/hour for rolling.	1680.64	116.13	0.03	0.001
TOTAL Diesel Fuel	***4306.25***	***litres/km road***		***178148.27***	***12309.89***	***3.37***	***0.095***
Material Inputs							
Roadstone (blasted)	8800	tonnes/km road	Based on a usage of 2816 tonnes of blasted rock for a road of length 320 metres.	59546.28	3551.44	14.62	18.01
Roadstone (crushed)	1200	tonnes/km road	Based on a usage of 384 tonnes of crushed rock for a road of length 320 metres.	38819.57	2605.60	2.57	2.47
TOTAL for Material Inputs	***10000***	***tonnes/km road***		***98365.85***	***6157.04***	***17.20***	***20.49***
TOTAL per km road				**276514.12**	**18466.93**	**20.57**	**20.58**

Note

(a) Energy requirements and emissions for diesel fuel based on diesel fuel in United Kingdom in 1996 (BRE, 2000), and assumes a calorific value of 37.27 MJ/litre (Elsayed et al, 2003).

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Table A3 Diesel Fuel Requirements and Aggregate Usage for Construction of One Kilometre of a Formation Construction Forest Road (Whittaker et al, 2008)

Formation Road Construction	Value	Units	Notes	Primary Energy	Greenhouse Gas Emissions		
				MJ/km	kg CO_2/km	kg CH_4/km	kg N_2O/km
Diesel fuel consumption (a)							
Loading Roadstone	646.00	litres/km road	Based on a work rate of 28 hours for loading 3200 tonnes of rock and a fuel consumption of 13.5 litres/hour for loading dumpers with rock.	26724.66	1846.65	0.51	0.014
Haulage	1315.92	litres/km road	Based on a work rate of 56 hours for hauling 3200 tonnes of rock, and a fuel consumption of 13.75 litres/hour for a short-medium haulage (500m-5.5km) of rock.	54439.13	3761.69	1.03	0.029
Spreading Roadstone	334.96	litres/km road	Based on a work rate of 28 hours for spreading 3200 tonnes of rock and a fuel consumption of 7 litres/hour for spreading rock with a D5 Bull Dozer.	13857.23	957.52	0.26	0.007
Grading	65.63	litres/km road	Based on a work rate of 2 hours for grading a 320 m stretch of road and a fuel consumption of 10.5 litres/hour for grading.	2714.89	187.60	0.05	0.001
Rolling	40.63	litres/km road	Based on a work rate of 2 hours for rolling a 320 m stretch of road and a fuel consumption of 6.5 litres/hour for rolling.	1680.64	116.13	0.03	0.001
TOTAL diesel fuel	***2403.13***	***litres/km road***		***99416.56***	***6869.59***	***1.88***	***0.053***
- Material Inputs							
Roadstone (crushed)	5469	tonnes/km road	Based on a usage of 384 tonnes of crushed rock for a road of length 320 metres.	176912.12	11874.50	11.73	11.27
TOTAL for Material Inputs	***5469***	***tonnes/km road***		***176912.12***	***11874.50***	***11.73***	***11.27***
TOTAL per km road				**276328.68**	**18744.09**	**13.62**	**11.32**

Note

(a) Energy requirements and emissions for diesel fuel based on diesel fuel in United Kingdom in 1996 (BRE, 2000), and assumes a calorific value of 37.27 MJ/litre (Elsayed et al, 2003).

Table A4 Primary Energy Requirements and Greenhouse Gas Emissions for Maintaining One Kilometre of Forest Roads (Whittaker et al, 2008)

Resurfacing	**Value**	**Units**	**Notes**	**Primary Energy**	**Greenhouse Gas Emissions**		
Diesel fuel consumption				MJ/km	kg CO_2/km	kg CH_4/km	kg N_2O/km
Loading Roadstone	270.00	litres/km road	Based on a work rate of 28 hours for loading 3200 tonnes of rock and a fuel consumption of 13.5 litres/hour for loading dumpers with rock.	11169.82	771.82	0.21	0.006
Haulage	360.94	litres/km road	Based on a work rate of 56 hours for hauling 3200 tonnes of rock and a fuel consumption of 13.75 litres/hour for a short-medium haulage (500m-5.5km) of rock.	14931.88	1031.78	0.28	0.008
Spreading Roadstone	91.88	litres/km road	Based on a work rate of 28 hours for spreading 3200 tonnes of rock and a fuel consumption of 7 litres/hour for spreading rock with a D5 Bull Dozer.	3800.84	262.63	0.07	0.002
Grading	65.63	litres/km road	Based on a work rate of 2 hours for grading a 320 m stretch of road and a fuel consumption of 10.5 litres/hour for grading.	2714.89	187.60	0.05	0.001
Rolling	40.63	litres/km road	Based on a work rate of 2 hours for rolling a 320 m stretch of road and a fuel consumption of 6.5 litres/hour for rolling.	1680.64	116.13	0.03	0.001
TOTAL diesel fuel	***829.06***	***litres/km road***		***34298.07***	***2369.97***	***0.65***	***0.018***
Material Inputs							
Roadstone (crushed)	1500.00	tonnes/km road	Based on a usage of 384 tonnes of crushed rock for a road of length 320 metres	48524.47	3257.00	3.22	3.09
TOTAL Material Inputs	***1500.00***	tonnes/km road		***48524.47***	***3257.00***	***3.22***	***3.09***
TOTAL				**82822.53**	**5626.97**	**3.87**	**3.11**
Re-grading							
Diesel fuel consumption							
Grading	65.63	litres/km road	Based on a work rate of 2 hours for grading a 320 m stretch of road and a fuel consumption of 10.5 litres/hour for grading.	2714.89	187.60	0.05	0.001
Rolling	40.63	litres/km road	Based on a work rate of 2 hours for rolling a 320 m stretch of road and a fuel consumption of 6.5 litres/hour for rolling.	1680.64	116.13	0.03	0.001
TOTAL	***106.25***	***litres/km road***		***4395.53***	***303.73***	***0.08***	***0.00***

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APPENDIX B: DETAILS OF FOREST ROAD DENSITY

Table B1 Density of Forest Roads in Great Britain (Whittaker et al, 2010)

Road Density	Forest Size (ha)	Road length (metres)		Density (m/ha)	
Forest		Class A	Class B	Class A	Class B
101 Sherwood	10302.2	6557.1	130325.9	0.6	12.7
103 East Anglia	21472.6	22901.8	188667.8	1.1	8.8
104 Northants	6442.7		80877.4	0.0	12.6
112 Kielder	49728.5	560808.0	193500.0	11.3	3.9
113 North West England	10135.7	163039.8	79918.3	16.1	7.9
117 North York Moors	16921.3	45237.0	307544.8	2.7	18.2
302 South East England	18599.7	653.6	218173.0	0.0	11.7
304 New Forest	17813.6		217350.4	0.0	12.2
312 West Midlands	10715.1		178239.5	0.0	16.6
314 Peninsula	12704.7	35190.5	210104.3	2.8	16.5
317 Forest of Dean	13036.9	1457.6	278457.4	0.1	21.4
410 Coed y Gororau	18293.2	104690.6	439044.6	5.7	24.0
413 Coed y Mynydd	28302.3	186333.8	502235.8	6.6	17.7
416 Coed y Cymoedd	23648.2	121750.4	358616.9	5.1	15.2
418 Llanymddri	29117.9	123770.3	531778.8	4.3	18.3
501 West Argyll	44768.5	197652.5	360656.9	4.4	8.1
503 Lorne	29034.1	174743.3	80578.5	6.0	2.8
504 Tay	28947.8	23408.6	397591.5	0.8	13.7
511 Moray	18948.5	147180.5	184093.7	7.8	9.7
513 Buchan	28486.7	114344.1	146861.1	4.0	5.2
516 Dornach	37594.3	103443.4	244445.4	2.8	6.5
517 Inverness	23192.4	205758.5	134975.4	8.9	5.8
518 Fort Augustus	27916.3	163745.9	172802.9	5.9	6.2
519 Locaber	20124.4	137912.5	122465.3	6.9	6.1
701 Cowal & Trossachs	32524.5	234905.5	404479.2	7.2	12.4
704 Scottish Lowlands	27321.6	120535.7	185014.2	4.4	6.8
710 Galloway	59137.8	473437.4	404737.7	8.0	6.8
714 Ae	24936.7	279371.5	257470.2	11.2	10.3
715 Scottish Borders	20407.6	193493.3	168352.5	9.5	8.2
			Average	5.0	11.2
			Max	16.1	24.0
			Min	0.0	2.8

APPENDIX C: BASIC DATA FOR FOREST OPERATIONS

Table C1 Summary of Primary Energy Consumption and Greenhouse Gas Emissions for Forest Site Preparation and Establishment

	Value	Units	Notes	Primary Energy	Greenhouse Gas Emissions		
Diesel Fuel Consumption				MJ/ha	kg CO_2/ha	kg CH_4/ha	kg N_2O/ha
Mounding	4779.88	MJ/ha	Based on a 20 Tonne Daewoo Excavator consuming 18 to 20 litres diesel per hour. Based on a work rate of 0.08 to 0.1 ha/hour (Murgatroyd, 2008)	5305.66	366.62	1.0E-01	2.8E-03
Herbicide Application	1101.60	MJ/ha	Based on a agricultural tractor of 100 hp, and PTO of 85% and engine efficiency of 0.25 and work rate of 1.2 hour/ha (Matthews and Mortimer, 2000).	1222.78	84.49	2.3E-02	6.5E-04
Material Inputs							
Herbicides	0.06	kg a.i/ha	Matthews and Mortimer, 2000	6.23	0.29	1.1E-03	9.3E-03
Seedlings	29.40	seedlings/ha	Matthews and Mortimer, 2000	38.78	1.67	1.8E-04	3.6E-04
Fencing:							
Support Posts	55.00	kg/ha	Based on a 30 ha plot (6 ha * 5 ha) and with 0.75kg of support wood per metre	27.72	2.26	3.3E-06	5.2E-08
Straining Wire	7.33	kg/ha	Based on a 30 ha plot (6 ha * 5 ha) and with 0.1kg of straining wire per metre of fence (Matthew and Mortimer, 2000)	1006.13	46.27	1.2E-04	1.9E-06
Straining Posts	0.37	kg/ha	Based on a 30 ha plot (6 ha * 5 ha) and 0.005kg of straining posts per metre of fence (Matthew and Mortimer, 2000)	0.18	0.02	2.2E-08	3.4E-10
Bracing Struts	0.73	kg/ha	Based on a 30 ha plot (6 ha * 5 ha) and with 0.01kg of bracing struts per metre of fence (Matthew and Mortimer, 2000)	0.37	0.03	4.4E-08	6.9E-10
Wire Netting	73.33	kg/ha	Based on a 30 ha plot (6 ha * 5 ha) and with 1kg of wire nettling per metre of fence (Matthew and Mortimer, 2000)	10061.33	462.73	1.2E-03	1.9E-05
Nails and Staples	0.73	kg/ha	Based on a 30 ha plot (6 ha * 5 ha) and with 0.01kg of nails and staples per metre of fence (Matthew and Mortimer, 2000)	22.73	0.91	2.7E-06	4.2E-08
Preservative	18.33	kg/ha	Based on a 30 ha plot (6 ha * 5 ha) and with 0.25kg of paint per metre of fence (Matthew and Mortimer, 2000)	1833.33	25.85	2.2E-04	3.4E-06
Total				**19525.26**	**991.13**	**0.13**	**0.01**

Table C2 Summary of Primary Energy Consumption and Greenhouse Gas Emissions for Harvesting and Forwarding Saw Logs and Roundwood

Step	Value	Units	Notes	Primary Energy	Emissions		
				MJ/tonne	kg CO_2/tonne	kg CH_4/tonne	kg N_2O/tonne
Harvesting	7.27	litres/tonne	Assumes a diesel consumption of 1.2 litres/m3 for harvesting (Murgatroyd, 2008) and a density of 0.33odt/m3, and moisture content of 50%	300.87	20.79	0.006	0.0002
Brash Baling	4.00	litres/tonne	Assumes a diesel consumption of 2 litres/bale for brash baling (Murgatroyd, 2008) and an average bale weight of 500 kg, and moisture content of 50%	165.48	11.43	0.003	0.0001
Forwarding	5.45	litres/tonne	Assumes a diesel consumption of 0.9 litres/m3 for forwarding (Murgatroyd, 2008) and a density of 0.33odt/m3, and moisture content of 50%	225.65	15.59	0.004	0.0001
Total				**526.52**	**36.38**	**0.010**	**0.0003**

APPENDIX D: FLOW CHARTS FOR BASIC SCENARIOS

Figure D1 Flow Chart and Sources of Greenhouse Gas Emissions and Sinks of Sequestered/Avoided Greenhouse Gas Emissions for Sawn Timber Used in Construction (Best Case Scenario)

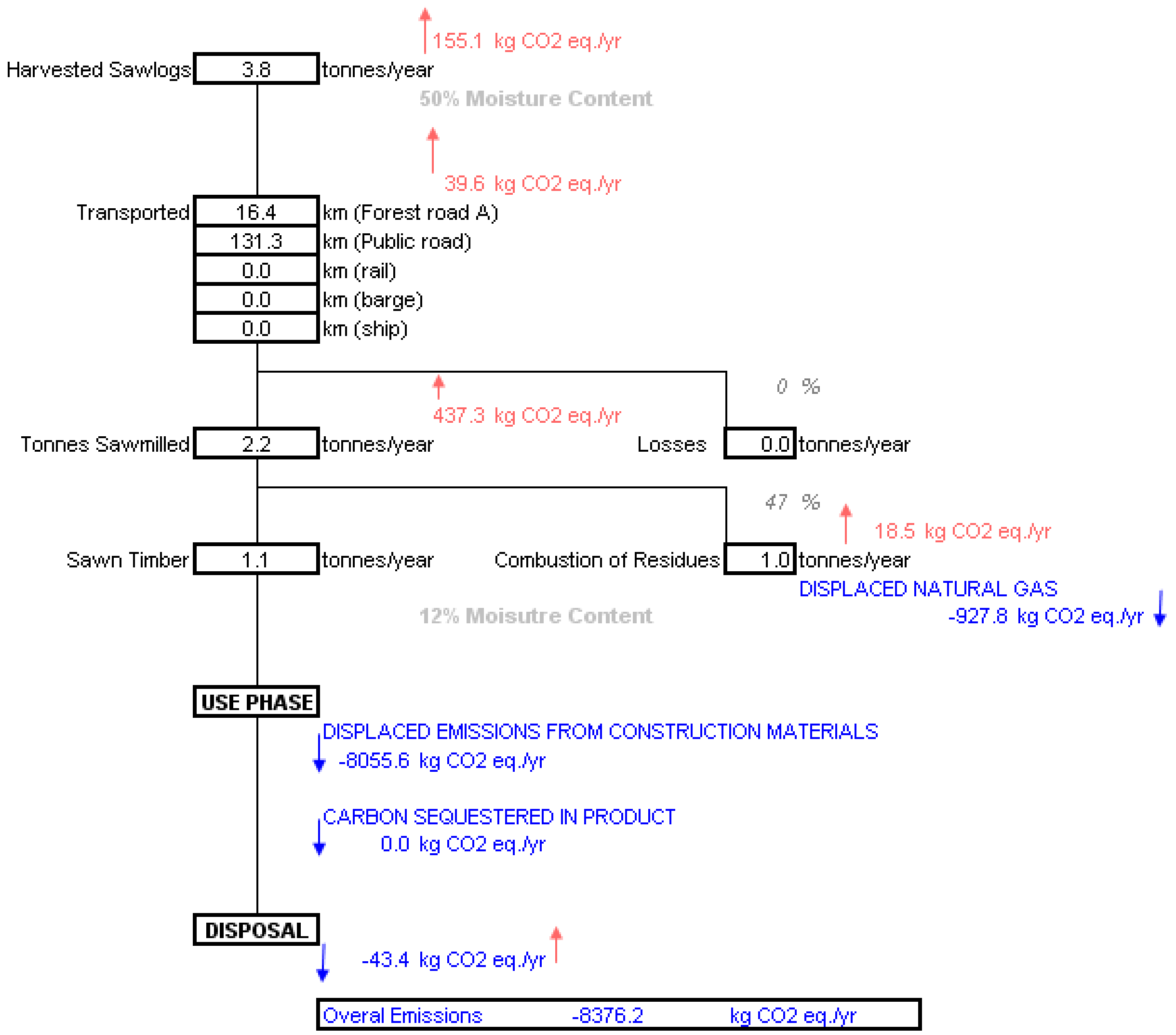
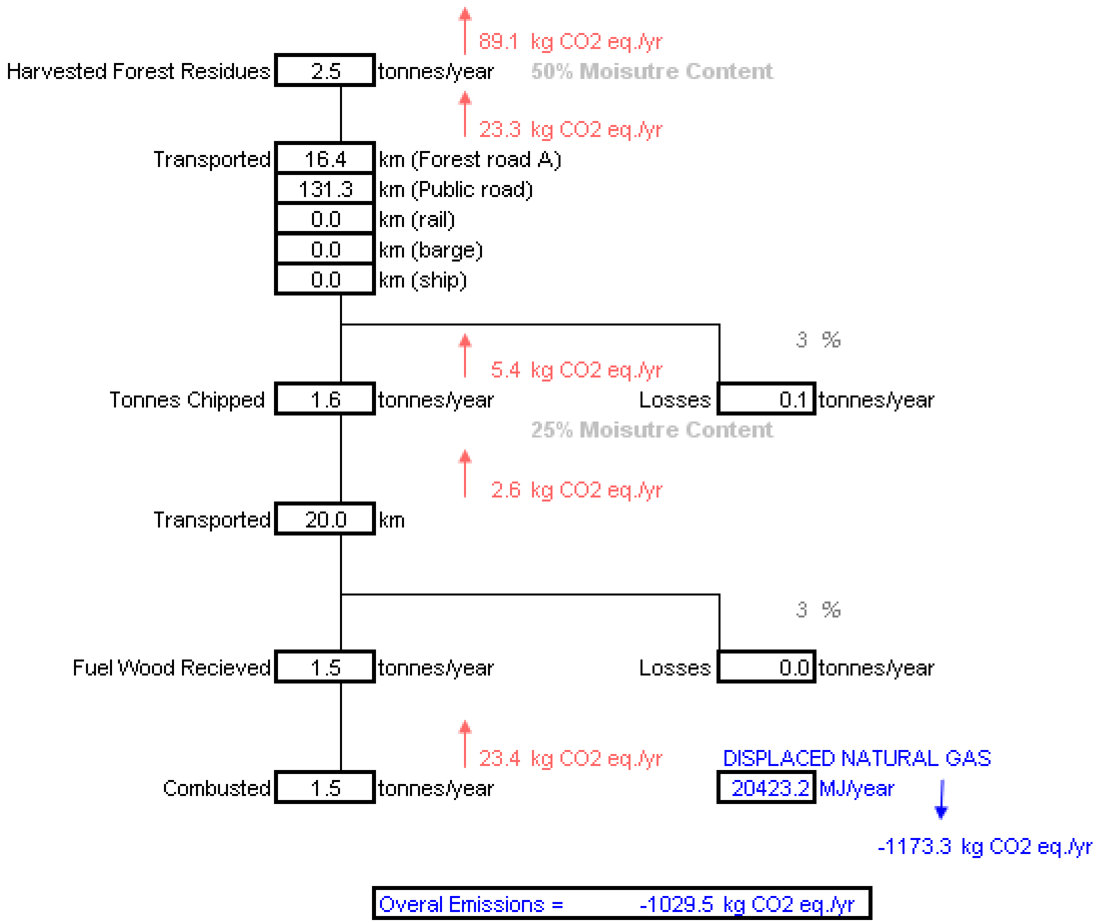


Figure D2 Flow Chart and Sources of Greenhouse Gas Emissions and Avoided Greenhouse Gas Emissions for Fuel Wood Used for Heating



APPENDIX E: TIMBER TRANSPORT WORKBOOK

The Timber Transport Workbook was formulated to assist the calculation of total GHG emissions associated with the production and use of sawn timber in construction and fuel wood for heating. It was primarily prepared for internal use and was not intended for widespread use by general users. Hence, it is not a completely “user-friendly” workbook such as others produced by North Energy Associates Ltd. As the development of complete user-friendly features requires considerable time and effort, this could not be done within the limitations of this study. However, this workbook is still accessible for use and the following information assists with this by providing a basic introduction to the main components of this workbook and how the input parameters can be manipulated to test the sensitivity of results.

Flow Charts (Grey Worksheet Tabs)

The Flow Charts provide a pictorial summary of the results of the analysis, as demonstrated in Figures 1 and 2 in sections 8.2 and 8.3 for saw log and fuel wood production, respectively. It provides a summary of the quantities of timber and transport distances involved in the supply chain, and the emissions or carbon savings that occur at each stage. The user cannot change the values on this page as this is used for presentation only.

Summary Sheets (Red Worksheet Tabs)

A separate Summary Sheet is provided for the saw log and fuel wood production chains. It is on these pages that the user can alter the input parameters to test for sensitivities in the results. On each sheet, the flow chain of producing timber, transporting it and then processing it into sawn timber or fuel wood is handled step by step, and the GHG emissions (in kg CO2 eq./year) are calculated.

The results are presented in a table at the bottom of the flow chart, and graphically to the right of the flow chart. Also, a result for the total GHG emissions per year is provided. Results from this page directly feed into the Flow Chart page.

Input parameters that can be tested/manipulated by the user include (blue boxes only):

- Number of forest rotations studied
- Number of hectares
- Truck size (40 or 44 GVW)
- Fuel (diesel, biodiesel from oilseed rape or biodiesel from used cooking oil)
- Transport distances covered on each road type (forest road Type A or B, or public roads)
- Maintenance intensity of forest roads (low or high)
- Life time of public road (time between maintenance events)
- Allocation of timber haulage vehicles to road maintenance (%)

- Alternative modes of transport (train, barge, shipping)
- Chip transport (for fuel wood only)
- Losses during transport (%)
- Displacement of materials (steel, cement, brick cladding, sawn timber only)
- Disposal options (incineration (with and without energy recovery), or landfill with energy recovery, sawn timber only)

Red boxes represent where calculations are made and should not be altered. Notes are provided that explain how the default parameters are calculated.

Calculation Sheets (White Worksheet Tabs)

The Calculation Sheets are a series of worksheets where the original calculations and indicators are developed for various stages of the supply chains. It is not recommended that these are changed by the user. There are separate calculation sheets for:

- Forest road construction
- Public road maintenance
- Transport emissions
- Vehicle construction
- Forest operations
- Sawn timber production
- Fuel wood production
- Forest product yield

There is also a list of references from which the data were derived/calculated.

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