Review of Carbon Neutral Fuels with Potential for Use in Modern Steam Locomotives

Brian McCammon **January 2007**

Introduction

Traditionally the fuels used in steam locomotives were derived from fossil resources. In the majority of cases, this fuel was coal in its various forms. However, there was also considerable usage of oil fuels and, less frequently, biomass based fuels such as log-wood and crop residues. Fossil fuels are still preferred for use in the world's remaining operational steam locomotive fleet principally because of the general difficulty of sourcing suitable alternatives.

A major advantage that steam locomotives have over other forms of primary rail traction (i.e. diesel[1] and gas turbine locomotives) is the fact that they can be fairly readily adapted to run on a variety of liquid and solid fuels. As the prices of fossil fuels escalate, it is appropriate to reconsider the possible use of these alternative fuels for steam locomotives and especially those which offer the highly desirable potential of "carbon neutral" operation. The purpose of this paper is to review the alternative fuels currently available and to clarify which of them is suitable for use in a modern steam locomotive. To ground this analysis, a brief consideration of the characteristics of the fossil fuels commonly used in steam locomotives will be helpful, see **Table 1.**

Table 1

Properties of Fossil Fuels

Characteristics	Units	Light Fuel Oil	Petrodiesel[2]	Coal[3]
Calorific Value	(MJ/kg)	43.7	45.9	28
Bulk Density	(kg/litre)	0.913	0.835	1.32
Flash Point	(°C)	103	75	>34
Pour Point	(°C)	-11	-50 to -10	NA
Sulphur Content	(%)	1.8	0.0005	<0.8–3
Ash Content	(%)	0.02	<0.01	5
Moisture Content	(%)	NA	NA	6
Storage life	(year)	Indefinite	Indefinite	Very lengthy
Range (5AT)	(km)	980	940	908
Current Cost	(GBP/km)	1.69	2.57	0.45

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[1] The term "petrodiesel" is used throughout the remainder of this paper to designate diesel fuel (sometimes called gas oil) produced from petroleum to differentiate it from 'biodiesel.'

[2] Data for oil fuels supplied by Caltex NZ Ltd

[3] Edbrooke, Figure 8, averaged by author. Price is CIF Northern Europe.

The figures given for Light Fuel Oil and Petrodiesel are for products derived from the crude oil used in the New Zealand refinery. However, the figures for the products derived from other crude oils should not vary greatly from these. The figures for coal are averages only of those coals suitable for steam locomotives.

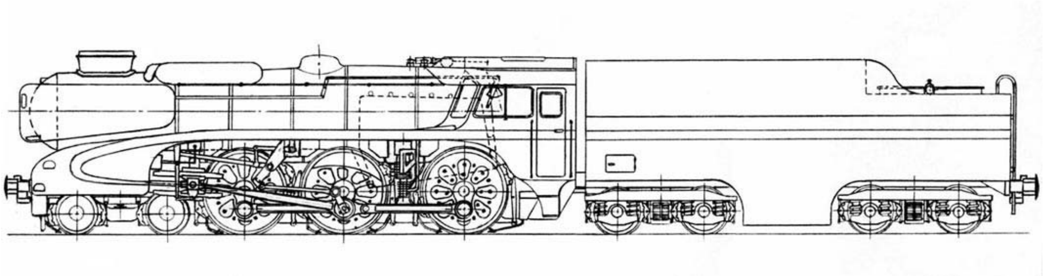
The pour point for petrodiesel varies with the additives used for very cold conditions.

The calorific values of the fossil fuels are higher than raw biomass feedstocks. Typically, these have values less than half of those for fossil fuels.

The 5AT Advanced Technology Steam Locomotive as the Reference Environment

In the following analysis the proposed Class 5AT advanced technology steam locomotive (operating under representative average mainline service conditions) is taken as the reference locomotive. This machine, which is shown in the drawing below, is a conventional reciprocating engine with two outside cylinders and a 4-6-0 wheel arrangement. It was originally conceived by David Wardale - the world-leading steam locomotive engineer. The prototype 5AT locomotive will be fuelled by ordinary petrodiesel fuel as this is widely available on the rail networks on which this locomotive is intended to operate.[4]

The 5AT is being designed specifically for hauling steam charter and rail cruise trains on the mainline and its design incorporates the best available existing technology. It is considered to be the next stage in the evolution of the steam locomotive and will provide a 100% increase in thermal efficiency compared to latter-day mid 20th Century steam designs. Full details of the locomotive are available at the project website www.5at.co.uk.



The Class 5AT Advanced Technology 4–6–0 for High Speed Charter Service D Wardale, February, 2005

To achieve the designed performance of this machine, the boiler requires that the firebox releases useable heat energy of about 342 MJ per km under representative average main line service conditions irrespective of the fuel used to fire it. The unit, MJ/km, is analogous to “litres/100km” of a motor car and it is used as such in the fuel comparisons below. The 5AT tender is being designed to have a fuel tank capacity of 7 tonnes of petrodiesel fuel. This has a density of 0.835 so that the fuel tank will have a volume of 8.4 m^3. This volume of petrodiesel fuel will give a fuel range under representative mainline service conditions of 940 km. The water tank will have a volume of 46.3 m^3 giving a water range under the same conditions of 620 km.

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[4] Wardale, 2006, for detailed discussion.

Comparison of Carbon Neutral Fuels Suitable for Modern Steam

There are a large number of biomass feedstocks available. These can be broadly categorised under the processes required to extract or convert the solar energy stored in the feedstocks. The categories which will be considered in this comparison are Anaerobic Digestion, Fermentation/Distillation, Direct Combustion and Transesterification.

Anaerobic Digestion

Anaerobic digestion of organic matter produces copious amounts of methane (with some by-product gases such as CO_2) and, by using properly designed digesters; this process can be harnessed to provide commercial quantities of pure methane. The feedstocks which can be used in these types of digesters include animal manures, green crops and wet wastes (e.g. sewerage). The methane generated in the digester plus the methane obtained from landfills can be used in a number of different ways. These include the fuel to fire a steam boiler, a gas turbine or used in the production of methanol. Methane, being the simplest hydrocarbon, actually produces more heat per unit mass than other complex hydrocarbons including the fossil fuels.

Methane (CH_4) and its Derivatives

The properties of methane and its derivatives are given in **Table 2** on the following page.

As a greenhouse gas, methane has a global warming potential over 100 years of 21. What this means is that when averaged over 100 years, each kg of methane warms the earth 21 times as much as the same mass of carbon dioxide.

The following points have to be considered in deciding whether methane and its derivatives would be satisfactory fuels for firing steam locomotives.

Gaseous Methane
Due to its low density, gaseous methane is completely unsatisfactory for firing a steam locomotive.

Liquid Natural Gas
LNG obtained from methane produced from biomass feedstocks, would be carbon neutral as a fuel. Using LNG as a fuel could provide a steam locomotive with an acceptable range but there are a number of other factors which would need to be considered and which could militate against the use of this fuel on a steam locomotive.

Table 2

Properties of Methane and its Derivatives[5]

Characteristics	Units	Methane (Gas)	LNG	Methanol
Calorific Value	(MJ/kg)	53	61	20
Bulk Density	(Kg/litre)	0.0007	0.41	0.792
Flash Point	(°C)	-188	-188	11
Pour Point	(°C)	NA	NA	NA
Sulphur Content	(%)	Not known	Not known	Not known
Ash Content	(%)	<0.01	<0.01	<0.01
Moisture Content	(%)	NA	NA	NA
Storage life[6]	(year)	Indefinite	Indefinite	Indefinite
Fuel Range (5AT)	(km)	<1 km	580 km	See p 5
Current Cost	(GBP/km)	NA	NA	NA

1. If LNG was obtained from the vast stores of methane held in the Earth's crust it would not be carbon neutral.

2. LNG is fairly readily transported but in a steam locomotive problems could arise with handling the associated pressures and temperatures in the fuel tank. The Maximum Transport Pressure for LNG has been set at 25 kPa for maritime and road transport[7] and any steam locomotive would need to conform to this regulation. The problem at this pressure is in retaining the liquid temperature at approximately -160 degrees Celsius. This problem has been solved in other forms of transport by holding the liquid in special cryogenic tanks of double wall, high-nickel steel construction with extremely efficient insulation between the walls. Such a tank would need to be incorporated in the tender of the 5AT locomotive which could raise more problems in the tender design and in obtaining the required range. Doubtless, the rail safety authorities would need considerable convincing that such a fuel was safe to use in a railway environment.

3. In its liquid state methane is not explosive. For an explosion to occur, the liquid must first vaporise and then mix with air in the proper proportions (the explosive range is 5% to 15% methane) and then be ignited afterwards. Accidents are rare but when they do occur, they

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[5] Data for these fuels were obtained from www.wikipedia.org

[6] The storage figures given for these fuels assume ideal storage conditions. This is not always the case.

[7] See the page on LNG in www.wikipedia,org

have been catastrophic and have involved a substantial number of deaths.[8]

The conclusion is that without significant further development (particularly regarding its storage and handling) LNG is not suitable for steam locomotives required to operate over a reasonable geographic range.

Methanol (CH_3OH)

There are a number of problems in using methanol as a fuel in a steam locomotive.

1. The production of methanol is a complex and costly process.

2. The largest use of methanol is in the production of other chemicals, particularly formaldehyde from which products as diverse as plastics, plywood, paint, explosives and permanent-press textiles are produced. Another major use is in the production of synthetic petrol.

3. The flash point for methanol is 11 °C and its boiling point is 64.7 °C. These properties make it too volatile to be used as fuel in the firebox of a steam locomotive. For a related discussion, see the section on ethanol below.

4. Methanol is slightly acidic and is corrosive to some metals including aluminium.

All of these reasons militate against its use as a fuel in steam locomotives. Having said that, however, methanol plus an alkaline catalyst such as sodium methoxide is used in the transeseterification process for the production of biodiesel; for a detailed discussion see the section on Biodiesel.

Fermentation/Distillation

Ethanol (C_2H_5OH)

Ethanol is produced as a result of natural fermentation. In Brazil where it is produced from fermentation of sugar it is widely used as a substitute for petrol. In the USA, the Renewable Fuel Standard (RFS) requires that 15 billion litres (4 billion US gallons) of "renewable fuel," i.e. a blend of ethanol and petrol, be used by 2006 rising to 28 billion litres per annum by 2012.

At current prices in the USA, ethanol costs about US$0.40 per litre to manufacture but ethanol is exempt from the US$0.13 per litre Federal Gasoline Tax. This makes this fuel very competitive with petrol. However, the production price is sensitive to the market prices for corn, the common feedstock for ethanol production in North America.

Ethanol or ethanol-petrol blends are unsatisfactory fuels for direct firing of steam boilers because of their low flash point and high volatility. Typically petrol has a flashpoint of -46 °C the flashpoint for ethanol is 13 °C and both

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[8] Details of some of these accidents can be found in the page on LNG in www.wikipedia.org

have low boiling points, 32 °C and 78 °C respectively. With the heat associated with a firebox, it would be extremely difficult, if not impossible, to accurately control the ignition point of these fuels. There would be a grave danger of pre-ignition within the burner jets with the possibility of the fuel starting to burn down the feed pipes from the burner jet[9].

Table 3

Properties of Ethanol

Characteristics	Units	Ethanol[10]
Calorific Value	(MJ/kg)	26.8
Bulk Density	(Kg/litre)	0.789
Flash Point	(°C)	13
Pour Point	(°C)	<-90
Sulphur Content	(%)	NA
Ash Content	(%)	NA
Moisture Content	(%)	<4
Storage life	(year)	Some Years
Range (5AT)	(km)	See p 7
Current Cost	(GBP/km)	NA

An important property of any liquid fuel which is to be used in a firebox of a steam locomotive is the cetane number, a measure of the burning rate of fuels in compression ignition engines. For use as fuel in a steam locomotive, the cetane number of any proposed carbon neutral fuels needs to be less than 55, the current CN of petrodiesel, to be certain of achieving the slow burning property required. All the liquid fuels considered in this analysis fall within this criterion.

Notwithstanding these difficulties, there are a large number of research projects currently exploring the possibilities of using ethanol as a wider range of fuel-stock than as a substitute for petrol.

- The transport manufacturer, Scania, have designed petrodiesel engines to run on modified ethanol. Pure ethanol has, what Scania describe as an *ignition improver additive*, added to it. This additive presumably modifies the cetane number of the ethanol to a figure which will allow the compression ignition system of the petrodiesel engine to operate satisfactorily[11].

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[9] Information from Caltex Oil , NZ, Ltd.

[10] Data obtained from www.wikipedia.org

[11] Track and Wheel, 2006, p 22.

- The Otago Daily Times, a New Zealand newspaper, reported on the 24 January 2007 that two New Zealand Crown Research Institutes, Scion and AgResearch in conjunction with the San Diego based Diversa Corporation are initiating a research programme to apply Diversa's enzymes to New Zealand grown tree-stocks to convert the wood into sugars. These would then be fermented and distilled to produce ethanol and other products

- It was reported in the New York Times of the same day that President Bush was pushing for the adoption of E85 (this is 85% ethanol blended with 15 % petrol) ethanol petrol blend, up from the E20 blend which has been common in North America until now. He also called for a mandatory requirement that makers of fuel produce 100 billion litres of alternative fuels a year by 2017, replacing about 15% of the projected petrol usage in that year.

Until this experimental work culminates in workable and sustainable outcomes, then the use of ethanol and its blends as a fuel source for firing a steam locomotive cannot be considered. However, this situation may change in the future. It should be noted that there are grave concerns in the mid-western states of the USA and in Mexico at the increasing costs of corn for human food-stocks. This is occurring because of the increased prices being offered by energy users for this agricultural product.

Direct Combustion

In this process the solar energy stored in the raw biomass feedstocks is directly converted to heat energy by combustion in air within a suitable firing enclosure, in the case of a steam locomotive this is the firebox. There are only a limited number of biomass feedstocks which can be utilised in this process. Currently, suitable feedstocks are those consisting of the ligno-cellulose group.

The Ligno Cellulose Group of Feedstocks

This group of feedstocks consists of forest arisings (the forest residues after harvesting the desired quality stem wood), wood process residues, crop residues, vegetative crops, woody crops and municipal solid waste. All of these feedstocks in their unprocessed state have widely varying moisture contents and this has a marked effect on the total heat content of the feedstock that is possible to recover from the combustion process. In each case some proportion of this heat content must be used to evaporate the water that is present in the feedstock and is unavailable to perform useful work. This relationship in symbols is:

$$LHV = HHV - LV$$

Where:

LHV represents Lower Heat Value (i.e. heat available for useful work)
HHV represents Higher Heat Value (i.e. gross calorific value of the feedstock)
LV represents the latent heat of vaporisation used to evaporate the water in the feedstock.

Woody Biomass

The term "woody biomass" covers the feedstocks obtained from forest arisings, residues from wood processing plants, short rotation forest crops and other woody crops. Sims notes that,

> **. . .** A common feature of these feedstocks is that they tend to change over time owing to changes in the wood process technologies used on a site, competition from other markets for the available resources, and changes in logging and harvesting practices. The nature of typical woody biomass feedstocks (high moisture content, variable ash contents, high volatiles and relatively low calorific values), along with their inherent variability and unpredictable characteristics, means that careful attention must be paid to matching the fuel type to the design and operation of the conversion plant system.[12]

While these remarks were not particularly relevant to traditional steam locomotives because of their inherent low efficiencies, it is imperative that attention be given to them to achieve the optimisation required under the modern steam regime.

A number of forestry crops are grown specifically for bioenergy use. These include short rotation forest crops. Examples are coppiced species like willow and poplar, and eucalyptus. The best species of trees for these crops are those that are fast growing and therefore produce high energy levels in terms of GJ/hectare/year. A large proportion of the nutrient uptake in a forest is recycled through the leaves or needles via litter fall and at harvest relatively few nutrients are removed from the site. Thus, there is minimal deterioration of the topsoil quality with this regime[13].

In terms of calorific values there is little difference to choose between softwoods and hardwoods; typically this is around 18 MJ/kg, but hardwoods have the advantage of higher bulk densities which enable a greater weight of (wood) fuel to be carried on a steam locomotive.

While roundwood logs and wood chunks have been used to fire traditional steam locomotives in a number of countries, logwood will not be suitable for modern steam traction because they cannot be handled by the mechanical

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[12] Sims, 2002, p 42.

[13] Sims, (2002), p 33, provides a more extensive discussion of this point.

stokers which would be fitted to these types of locomotive. Dependent on their size, wood chips may be suitable for handling by mechanical stokers.

Unprocessed sawdust poses difficulties both with stoking and on the fire grate itself. Furthermore, the moisture content and the bulk density of most of these feedstocks would severely curtail the fuel range of the locomotive. Nevertheless, a mix of processed sawdust and wood chips densified into wood pellets can provide a much more suitable fuel.

Wood-Burning Steam Locomotive in Thailand[14]

In the following table of typical bulk densities and moisture content for various woody biomass feedstocks, the lower ends of the ranges given are typical for softwoods and the upper end for hardwoods.

Table 4

Bulk Densities and Moisture Content of Woody Biomass[15] With Potential for Use in a Steam Locomotive

Type of biomass	Moisture Content (% wet basis)	Bulk Density (Kg/m^3)
Kiln dry wood chips	10 – 15	160 – 250
Kiln dry wood chunks	10 – 15	200 – 310
Kiln dry sawdust	10 – 15	240 – 370
Wood briquettes	7 – 14	900 – 1100
Wood pellets	7 – 14	500 – 700
Coal for comparison	6 – 10	700 – 800

From Ralph E.H. Sims, (2002)

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[14] Original source unknown.

[15] Sims, 2002, p 15.

In this range of feedstocks, there are only three which have potential for use in a modern steam locomotive, see **Table 5** below**.**

Table 5

Properties of Selected Woody Biomass Feedstocks[16]

Characteristics	**Units**	**Kiln Dried Wood Chips**	**Wood Pellets**	**Wood Briquettes**
Calorific Value LHV	(MJ/kg)	16	18	18
Bulk Density	(kg/litre)	0.25	0.7	1.1
Flash Point	(°C)	NA	NA	NA
Pour Point	(°C)	NA	NA	NA
Sulphur Content	(%)	<0.01	<0.01	<0.01
Ash Content	(%)	4	0.75	0.75
Moisture Content	(%)	15	14	14
Storage life	(year)	<2 Years	Some years	Some years
Range (5AT)	(km)	98	310	486
Current Cost	(GBP/km)	1.03	2.05	2.05

There are a number of problems with these fuels.

The maximum fuel range using **kiln dried wood chips** would be unsatisfactory for most operation, although it may be suitable as a fuel on short dedicated railways.

With **wood pellets**, the reduced range compared to petrodiesel fuel could be acceptable over short, restricted routes. However, increases in range could be obtained by modifying the tender to provide extra fuel capacity at the expense of water volume. If the capacity of the fuel hopper was doubled with a corresponding reduction in the volume of the water tank, then:

Fuel range	620 km
Reduced water capacity	37.9 m^3
Reduced water range	508 km

These reductions in range may not be acceptable to some operators. However, it may be possible to lengthen the tender to accommodate additional fuel but leave the water capacity unchanged. This decision would need to be discussed with the vehicle designers and the railway network managers. The locomotive (engine and tender) may be too long for the turntables at the locomotive depots.

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[16] Sims, 2002, Ch 1.

With the specified tender fuel capacity (8.4 m^3), **wood briquettes** would provide a greater range (486 km). Modifications to the tender would be necessary to bring the range up to the levels provided by petrodiesel fuel.

The use of these fuels derived from woody biomass raises the question as to whether an unmodified conventional (coal) mechanical stoker could be employed to deliver the fuel from the tender to the firebox. This would need investigation by the locomotive's designers.

The **lignin** component of these feedstocks requires comment. The lignin content varies over a very wide range with the tree species and the age of the tree. As a general rule a species produces a higher ratio of lignin to cellulose in the early years of a trees growth. While it has greater heat energy content than cellulose (26.2MJ/kg as against 17.8 MJ/kg), it can only be obtained from the lignin cellulose complex by a two stage process of hydrolysis to break down the feedstock into its components. Lignin, in conjunction with the acids and enzymes required for the hydrolysis, is the residue (called **black liquor**) of this process. This residue can be directly combusted and it is used as a boiler fuel in the steam generating plants of paper mills, the main users of the process to separate lignin from cellulose. The emissions which result after combustion are environmentally harsh and would normally be scrubbed out in the exhaust stack of an industrial plant. Such scrubbing equipment is impractical to fit into a steam locomotive because of the limited space within the smokebox (the combustion-gas/exhaust-steam mixing chamber at the front of locomotive boilers). Thus, lignin as a fuel source will not be considered further in this analysis.

Crop Residues

Within the ligno cellulose group of biomass feedstocks, there are a number of crop residues that have been used (and in some isolated cases still are used) for the firing of traditional steam locomotives. In general all of these residues suffer from the drawbacks of high transports costs from the growing areas and low bulk densities.

Bagasse is the residue of the sugar extraction process from sugar cane crops. There are substantial quantities of this material available in the sugar cane growing areas of the world and it has been used as a fuel for the processing mills and the steam locomotives operating on a few of the narrow gauge railways used in the cane fields. These railways can be very extensive. In Queensland, Australia, for example, the 31 sugar mills own, operate and maintain 4100 km of narrow gauge (610 mm) railway using small petrodiesel locomotives for traction. Some years ago this traction was provided by steam locomotives fired by coal and occasionally oil. Bagasse is a waste product for the mills so that it is obtained at no cost. The transport and processing costs of this feedstock are also very minimal, especially in view of the fact that the collection and transport of this residue to the mill is essentially free. However because of the very low bulk density of the material and its comparatively low calorific value of about 10 MJ/kg, it is impractical to transport it to areas much outside where it is grown and harvested. Even so, there are large surpluses of this residue which require being 'wasted efficiently' (i.e. burnt) to prevent embarrassing and dangerous accumulations of the material around the mill complexes. These surpluses would be better utilised in firing boilers for electricity generation, as they are in some places, and then exporting the electricity for use over the wider local areas around the mills. The problem with this is that normally there is no access to a transmission line distribution system. However there are many economic and political problems to be overcome before this solution to the surplus wastes can be widely achieved so that we can expect the burning of most of these wastes to continue into the foreseeable future.

Cereal Straw is the residue from the harvesting of grain crops and such crops as peas. Until the advent of high density baling techniques, these wastes were disposed of by stubble fires, but are now used for firing industrial boilers where appropriate, and for composting and soil regeneration. Although this residue can be regarded as waste there is sufficient demand for it that it has a reasonable commercial value. The bulk density of straw, even in high density bales, is still only about 350 kg/m^3 with a moisture content of 10 – 15%. The average cropping yield of this residue is 2.5 to 5 tonnes per hectare and it has a typical heating value of 10 to 16 GJ/tonne. To put this into perspective, 1 tonne of straw equates to approximately 0.5 tonne of coal or 0.3 tonne of petrodiesel. These figures are fairly typical for most biomass feedstocks, but to provide a reasonable fuel range on a modern steam locomotive, cereal straw would require further densifying into briquettes or pellets, and this would add further to the costs.

Rice husks are one of the commonest crop residues in the world. They make up about 25% of the harvested grain on a weight basis. For example, Indonesia produces about 8 million tonnes of this residue annually. They have been used to fuel steam locomotives operating in the rice growing areas of the world but the low bulk density prevents their export out of the growing areas. The husks have a relatively high silica content which can cause problems with the ash and possible slagging within the firebox. Currently, there is no densifying technology available for this material but because of the homogeneous nature of the material, it is better suited to more efficient conversion processes such as gasification rather than to Direct Combustion.

Coconut Shells have been used in the past as a fuel for steam locomotives but required hand firing because of the size of the shells. In its raw form, this feedstock is not suitable for use in a modern steam locomotive. However, with suitable processing of the shells in a hammer mill, it is possible to reduce the half shells into smaller pieces which could be fed with a mechanical stoker. The material has very low moisture content and, although no figures are available, the calorific value is unlikely to be any greater than for oven dry wood, say 18MJ/kg. The major drawback to any extension of the use of this fuel is that the coconut growing areas are in the tropical areas, primarily in the Eastern hemisphere, and the costs of sea transport to the UK or Europe would make its use there uneconomic. The use of this residue would be better confined to fire boilers for local power generation or for firing locally operated modern steam locomotives

The conclusion to be drawn is that the majority of unprocessed crop residues are unsatisfactory fuels for modern steam locomotives required to operate over wide networks of interlocking routes. Crop residues commonly available in Britain and Europe have bulk densities which would require far too many re-fuelling stops to be acceptable. The transport costs of those residues with suitably high bulk densities from the cropping areas to the areas where they could be utilised would be prohibitive. However, these residues might be acceptable for fuel use within the general cropping areas. Such residues have the advantage of very low purchase cost because they are essentially waste products.

Transesterification

Vegetable oils have a high viscosity and consequently are not suitable as a replacement fuel in modern petrodiesel engines. To produce such a replacement fuel (biodiesel) from vegetable oils requires a reduction in viscosity which is achieved by reacting the oil with an alcohol (either methanol or ethanol) in the presence of an alkaline catalyst. This process produces a methyl (or ethyl) ester of the vegetable oil with glycerine as the major by-product. This reduction of the viscosity of the vegetable oil by separating out the glycerine from the vegetable oil molecule is known as **transesterification**[17].

Vegetable Oils

There are a number of crops from which these oils are produced. They are suitable for conversion to biodiesel through the transesterification process (see later), but, potentially, could also be directly used to fire a steam locomotive. Note that vegetable oils need to be vaporised by a steam jet in the burner to allow ignition (in the same way as for petrodiesel fuel.) Moreover, constituent gums and fats can be deposited on the burner combustion head causing boiler lock-outs[18] so that particular attention must be paid to the design and adjustment of the burner.

Ideally, these feedstocks would need to be widely grown and processed within the geographic range to be served by the locomotive. There are some, notably palm oil, which have the required properties for use as a steam locomotive fuel, but which are more difficult and expensive to transport over long distances because of their physical characteristics.

The oil yields for the various feedstocks used in the production of bio-fuels are shown in **Table 6.**

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[17] Robertson, 2006, p 3.

[18] The term “boiler lockout” is used to describe boiler unreliability which can occur from a variety of causes even to the point where combustion ceases entirely.

Table 6
Oil Yields[19]

Feedstock	Litres/hectare/year
Soybean	375
Rapeseed	1,000
Mustard	1,300
Jatropha	1,590
Palm oil	5,800
Algae	95,000

The figures given above assume one harvest per year except for algae which is harvested on a continuing basis.

The characteristics of the current, most widely cultivated oils are given in the following table.

Table 7
Properties of the Most Widely Cultivated Vegetable Oils[20]

Characteristics	Units	Refined Soybean Oil	Rapeseed Oil	Crude Palm Oil
Calorific Value	(MJ/kg)	34.5	34.6	34.9
Bulk Density	(Kg/litre)	0.9269	0.914	0.89
Flash Point	(°C)	284	275	>250
Pour Point	(°C)	-12	-18	Semi-solid at room temp.
Sulphur Content	(%)	<0.01	<0.01	<0.01
Ash Content	(%)	0.17	0.02 @ 1000 °C	<0.02 @ 1000 °C
Moisture Content	(%)	NA	NA	NA
Storage life	(year)	<1 Year	<1 Year	<1 Year
Range	(km)	785	780	760
Current Cost	(GBP/km)	3.51	4.19	2.99

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[19] Data obtained from www.wikipedia.org

[20] Data for these oils obtained from www.wikipedia.org

Soybean oil is a by-product of the processing of soybeans. The apparent low cropping yield of the oil component occurs because only about 20% of the seeds of the dry plant are oil while the remainder is a mix of heat-stable protein, carbohydrate and a small percentage of ash. It is a native plant of Eastern Asia but is now extensively grown in many areas of the world and is an important global crop. World production is in excess of 230 million tonnes per annum. The large majority of the products of soybean processing are used in food production and processing industries but there is a substantial proportion used in industrial products including oils, soap, cosmetics, resins, plastics, inks, crayons, solvents, clothing and biodiesel. Much of the oil produced is used for cooking and there are large quantities of the waste oil to be disposed of annually. For example, restaurants in the United States annually produce about 1.15 billion litres of waste vegetable oil, the bulk of which is soybean oil. To put this volume of waste vegetable oil into perspective, the estimated annual transportation and heating oils from all sources used in the United States is 870 billion litres. The waste cooking oil produced annually in the USA, is less than 0.2% of the total annual usage. However, waste soybean oil has been occasionally used to directly fire steam locomotives but the competing demands for this waste product means that it can only ever be regarded as a suitable fuel if it can be obtained at a favourable price (including transport charges to the re-fuelling depots).

Rape Seed Oil is crushed from rape (or canola) seeds. Rapeseed (*Brassica napus*) is very widely cultivated for the production of animal feed, vegetable oil for human consumption, and biodiesel. It grows best in the temperate regions from Latitude 42° to Latitude 56° but will grow in the lower latitudes providing the soils and rainfall are suitable for its growth. In Europe, the average cropping yield for rape is 6.9 tonnes per hectare giving 1 tonne of rape seed oil, 2 tonnes of rape cake and 3.9 tonnes of rapeseed straw. The rape cake is normally processed into animal feed meals and the straw is normally ploughed back into the ground. However both these products have substantial gross energy content, the rape cake at 38.64 GJ/ha and the rape straw at 56.55 GJ /ha. With suitable further processing both these residues could be used as fuels but their market value as animal feed generally makes them uncompetitive for use as a fuel. Only rapeseed oil will be considered in this analysis

Palm oil is a form of edible vegetable oil obtained from the fruit of the palm oil tree. It is intensively cultivated in the tropical areas and it may have now surpassed soybean oil as the most widely produced vegetable oil in the world. It is widely used as a cooking oil, to make margarine and is a component of many processed foods. It is relatively high in saturated fats and is thus semi-solid at room temperature. It is this latter characteristic which makes it unsuitable for a steam locomotive fuel in its crude form within the temperate zones of the world unless kept above its melting point (e.g. by steam heating). However with suitable processing it makes an excellent basis for biodiesel. The Malaysian government is encouraging the establishment of processing plants for the production of 100,000 tonnes of biodiesel annually from palm oil. This is due to the higher prices of fossil fuel, increasing demand for alternative sources of energy in the face of Peak Oil and to mitigate the effects of global warming. On the 23 November 2006, Australia's first palm oil based biodiesel plant was opened in Darwin. When fully operational in 2007 this plant should produce 140 million litres of biodiesel annually. In both the Philippines and Indonesia there are substantial clearances of rain forest taking place for the planting of oil palms for the production of this oil. Many organisations have grave concerns over these policies.

Algae provide the greatest potential cropping yield for any of the natural oils as seen from **Table 6**. The technology for growing and harvesting algae is still under development but it appears that equivalent yields could be obtained from much reduced areas of land than from any of the other alternatives. If the early promises of this crop are realised, it will be the only sustainable source of alternative carbon neutral fuels to meet the world wide demand. It has been estimated that using a species of algae with up to 50% oil content would only require 28,000 km^2 or 0.3 % of the land area of the U.S.A to produce enough biodiesel for all the transportation fuel that the country currently utilises. However, in its unprocessed form it is not suitable as a steam locomotive fuel.

No figures for the properties of this crop are available for this analysis.

Biodiesel

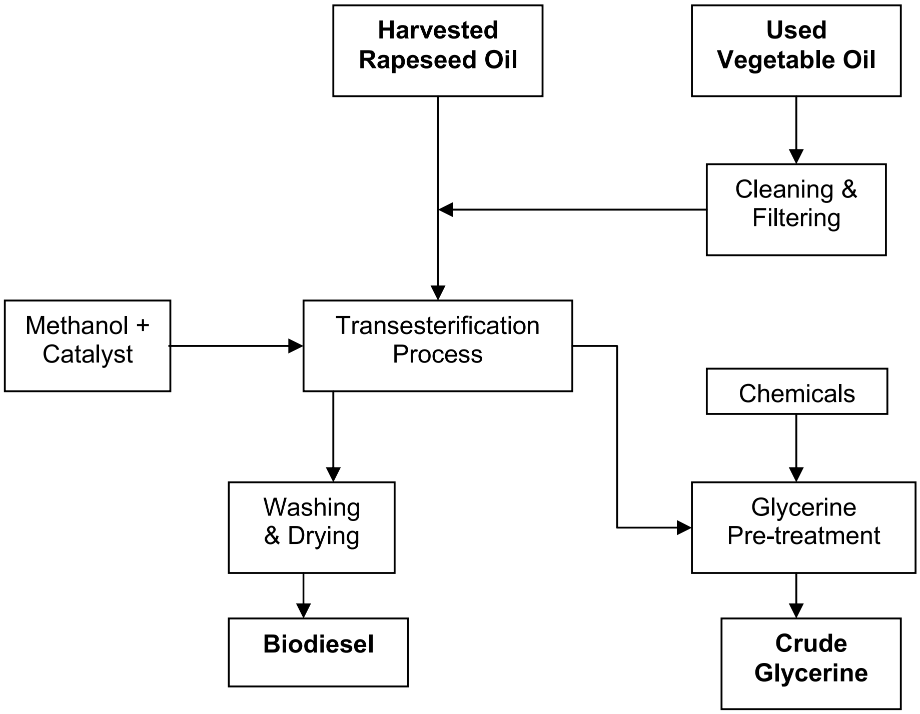
The term 'biodiesel' refers to alkyl esters made from the transeseterification of both animal fats and vegetable oils. Most biodiesel fuels currently on the market are blends of this product and ordinary petrodiesel. In the following description B100 is taken to mean the undiluted end product resulting from the transesterification process and, say, B20 describes a petrodiesel product containing 20% biodiesel and 80% petrodiesel.

Biodiesel is biodegradable and non-toxic, and has significantly fewer emissions than petrodiesel when it is burned. Primarily, it is seen as a substitute for petrodiesel as a fuel for petrodiesel engines but it can also be used as a heating fuel in domestic and commercial boilers, which would include firing steam locomotives. Andrew J. Robertson, in his paper, "Biodiesel Heating, Sustainable Heating for the Future," describes laboratory research and field trials using pure, B100 biodiesel and biodiesel blends as a heating fuel in oil fired boilers. He suggests that B20 biodiesel could reduce UK household CO_2 emissions by 1.5 million tonnes per year and this volume of biodiesel could be produced from around 330,000 hectares of arable land for the necessary crops.

Biodiesel can be distributed using today's infrastructure and its use and production is increasing rapidly. Fuel stations are beginning to make this fuel blended with petrodiesel available at the pump and an increasing number of transport companies use it as an additive in their fuel. It is more expensive than the current costs of petrodiesel but this will be offset with the increasing prices for petrodiesel as Peak Oil starts to impact on prices in the near future.

Advocates of biodiesel claim that improving technology and increasing production will drive the price of biodiesel down but this is doubtful. What is overlooked in these optimistic scenarios is that most of the cost to the consumer occurs before the feedstocks leave the farm gate. The production of biomass feedstocks other than wastes, is a sophisticated agricultural enterprise with its accompanying high costs. Some of the factors which must be taken into account are; the annualised capital cost of the very large land areas required; the fertilizer costs to make up the soil nutrients removed with the biomass harvesting; harvesting costs including transport to the processor; costs of tillage, costs of seeds, herbicides and pesticides; and the costs of labour and energy required in the enterprise. These costs vary widely from country to country and from year to year. For annual energy crops, if the prices fall in comparison with other crops, the farmers can easily change to the higher value crops which will cause the energy prices to be extremely volatile. For perennial crops, the farmers do not have the same flexibility.

The Biodiesel Production Process[21]



In effect these costs are equivalent in principle to the extraction costs of both oil and coal. The processing costs for biodiesel are equivalent in principle to the refining costs for petroleum based products and not much different in monetary terms. The distribution costs of biodiesel would be little different to petrodiesel.

In terms of the objectives of this paper, namely to consider the potential of carbon neutral fuels for use in modern steam locomotives, there is little point in considering anything other than biodiesel B100 as the most suitable biodiesel fuel on the grounds that the blends with kerosene or petrodiesel are not carbon neutral.

The pertinent characteristics of biodiesel are dependent on the feedstock used. The figures given in **Table 8** are typical only. The common international standard for biodiesel is EN 14214 and there are many national standards as well.

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[21] Robertson, 2006, p 3.

Table 8
Properties of Biodiesel[22]

Characteristics	Units	Biodiesel
Calorific Value	(MJ/kg)	37
Bulk Density	(Kg/litre)	0.90
Flash Point	(°C)	101
Pour Point	(°C)	<-10
Sulphur Content	(%)	<0.01
Ash Content	(%)	Not known
Moisture Content	(%)	NA
Storage life	(year)	Some Years
Range (5AT))	(km	820
Current Cost	(GBP/km)	3.87

Notes:-

1. The high flash point requires research into the design of the burner to allow this fuel to be used in a modern steam locomotive.

2. At ambient temperatures below 13 °C, B100 biodiesel will fail to ignite. This unreliability can be overcome by the use of a fuel pre-heat burner which preheats the fuel within the burner housing to around 70 °C. This reduces the fuel viscosity to a level that enables the fuel to atomise and combust effectively.[23]

3. Dependent on the ambient temperature, the main fuel tank may require heating. Biodiesel B100 (pure biodiesel) does not cause boiler lockouts through gelling if the temperature of the fuel at entry to the burner is 25 °C or greater. Robertson suggests that the holding tank be kept at a temperature greater than this to be certain of boiler reliability.

4. The burner will need to be designed to have the potential for high pressure at the jet[24] because the gums and fats in the fuel will require the flame to be lifted off the burner combustion head. Failure to achieve this will cause the gums and fats to deposit on the mouth of the burner head with subsequent boiler unreliability to the point of lockout within a few hours.

5. Biodiesel is biodegradable and is susceptible to water contamination and contamination from storage tank corrosion. If water is present in a heated tank

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[22] Data obtained from www.wikipedia.org

[23] Robertson, 2006, p 8.

[24] This operational parameter is known as "fan static."

> the conditions may suit the growth of bacteria triggering the growth of algae. This can occur within a very short time. This is also a problem with long-term storage of petrodiesel. However, with careful and well maintained storage, the storage life can be measured in years, even many years.

Table 9 on the following page summarises the essential properties of all those fuels covered in the above analysis which are currently seen as suitable for firing modern steam locomotives. The figures quoted in this table are drawn from the other tables in the body of the paper.

Table 9

Fuels Suitable for Modern Steam Locomotives: Summary of Their Essential Properties

Fuel	Calorific Value (MJ/kg)	Bulk Density (Kg/litre)	Flash Point (°C)	Ash Content (%)	Cetane Number	Storage Life (Years)	Fuel Range (km)	Current Cost (GBP)	
								per tonne	per km
Light Fuel Oil	43.7	0.913	103	0.02	Not published [1]	Indefinite	980	216 [4]	1.69
Petrodiesel	45.9	0.835	75	<0.01	55 [1]	Indefinite	940	345 [5]	2.57
Coal	28	1.32	>34	5	NA	Very lengthy	908	37 [6]	0.45
Methane (gas)	53	0.0007	-188	<0.01	Not published	Some years	<1	NA [10]	NA
LNG	61	0.41	-188	<0.01	Not published	Some years	614	NA [10]	NA
Methanol	20	0.792	11	<0.01	Not published	Some years	See p 4	NA [10]	NA
Ethanol	26.8	0.789	13	NA	Not published	Some years	See p 7	NA [10]	NA
Kiln dried wood chips	16	0.25	NA	4	NA	<2 years	98	54 [7]	1.03
Wood pellets	18	0.7	NA	0.75	NA	Some years	310	108 [7]	2.05
Wood briquettes	18	1.1	NA	0.75	NA	Some years	486	108 [7]	2.05
Refined soybean oil	34.5	0.927	284	0.17	37.9 [2]	<1 year	785	354 [8]	3.51
Rapeseed oil	34.6	0.914	275	0.02	37.6 [2]	<1 year	780	415 [8]	4.19
Crude palm oil	34.9	0.89	>250	<0.02	42 [2]	<1 year	760	304 [8]	2.99
Biodiesel	37	0.90	101	Not known	>51 [3]	Some years	820	420[9]	3.87

Notes to this Table

1. Information provided by Caltex NZ Ltd
2. Information obtained from Darren Hill's website
3. From EN 14214
4. Price provided by Caltex NZ Ltd
5. Information obtained from Ministry of Economic Development, NZ
6. Price obtained from e-coal.com for 12 January, 2007.
7. UK prices supplied by Solid Energy NZ Ltd
8. Prices from Oil World
9. Price averaged over 6 recent entries on the BulkOil website
10. No prices obtained for these unsuitable fuels

Comments on Quoted Prices

The fuel prices quoted in the tables reflect the market position in the period, mid-January to mid-February, 2007. The objective is to provide a snapshot in time of the relative costs of those fuels suitable for firing a modern steam locomotive. The fuels market is extremely volatile and is subject to a wide range of influences. It would therefore be unwise to use the quoted figures for budget planning. It is strongly recommended that intending operators of modern steam locomotives regularly review fuel price trends (at least on a quarterly basis.) While many organisations already do this, it will become increasingly important if the world swings to carbon neutral fuels for its transportation needs.

The volatility of the market for fossil fuels is largely driven by economic factors and those of international politics. These same factors are drivers for the markets in bio-fuels but there are two further complicating factors; firstly, the normal risks associated with any agricultural enterprise and, secondly, (and perhaps of greater importance) the possible conflicts which could arise between the use of agricultural land for growing energy crops versus the use of the same land for the production of food. These factors will only exacerbate the volatility of this market over that for fossil fuels.

It should be noted that the prices quoted in this analysis for raw vegetable oils, biodiesel and coal are the quoted international prices CIF to Antwerp, Rotterdam or Amsterdam (ARA) for January/February, 2007. No allowance has been made for onwards freight or landing costs, because of their widely varying nature. The transport infrastructure for liquids is well established and can be easily planned for on a case by case basis. In the case of coal due consideration would need to be made of the additional costs of its distribution and loading.

The fuel prices quoted in this analysis were obtained from a range of sources, see notes on **Table 9**.

Conclusions and Recommendations

As might be expected the most suitable choice of carbon neutral fuel will depend on a number of variable factors. These include calorific values, fuel availability and costs (which differ from location to location), safety considerations and the duties that the locomotive is called on to perform. For the more arduous duties, modern steam locomotives need to be capable of operating at their maximum continuous power for long periods of time. As David Wardale pointed out in his address to the conference held at the U.K. National Railway Museum, York in December 2006, to achieve the high efficiencies required for optimal performance of a modern steam locomotive, fuels of high calorific value are a necessity.[25]

Steam locomotives require regular replenishment of both fuel and water supplies. Therefore, an appropriate infrastructure is essential in order to provide facilities at strategic intervals to re-supply the locomotive en-route. The geographic spacing and complexity of this infrastructure depends on a) the locomotive's on-board storage capacity for fuel and water, b) the fuel type being used and c) the locomotive's

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[25] Wardale, 2006. p 2.

average fuel and water consumption. Where there is no fixed infrastructure, road-tankers could be utilised to deliver supplies to pre-arranged locations on the rail network.

Solid fuels are less easy to transport and handle than liquids and also tend to have higher ash contents (particularly coal which differs widely in quality and composition). The ash disposal facilities required under the traditional steam regime were labour intensive and involved an unpleasant working environment. These facilities could be greatly improved by quenching and dumping the ash without the crew having to get under the locomotive. However, there still remains the problem of disposal of the dumped ashes. Because of these two factors it is suggested that in most cases it would be preferable to use a liquid fuel although the use of wood briquettes and pellets (where they are readily available and suited to the operational duties) could be a satisfactory alternative.

The Gas Producer Combustion System (GPCS) provides a more efficient combustion of solid fuels and its use on steam locomotives was pioneered by Livio Dante Porta the outstanding Argentinean steam locomotive engineer who died in 2003. GPCS involves the provision of secondary air inlets above the bed of the fire and the admission of some exhaust steam through the firebed. The chemistry involved in GPCS is quite complex but its overall effect is to produce large quantities of combustible gases (particularly carbon monoxide) immediately above the firebed. These gases are then burnt with air from the secondary air intake. Overall a higher heat output is obtained from a given quantity of fuel. In particular, the lower primary air flow (through the grate) leads to less fuel carry-over. This is particularly important for renewable fuels such as wood, as it has a lower density than coal.

GPCS can be employed to cater for a wide range of solid fuels. The firebox of the 5AT can be adapted for GPCS although there would be some reduction in combustion efficiency compared to the combustion of petrodiesel fuel; about 10% in the case of coal firing.[26] Solid fuel alternatives to coal would require considerable development work to obtain optimum results.

A number of carbon neutral liquid fuels listed in Table 8 would appear to provide an acceptable fuel range for the 5AT. These include refined soybean oil, rapeseed oil and crude palm oil. Based on their calorific values and densities all three are anticipated to give an approximate range of around 800 kilometres (assuming the locomotive is operating under representative average mainline service conditions) compared with petrodiesel which will give a range of about 950 km. Under the same conditions B100 biodiesel would provide a smaller range of around 820 km. Palm oil, being semi solid at colder temperatures, would require steam heating to keep it in its liquid state, if it was used outside the tropics.

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[26] Ibid, No. 7.4.

Development work is essential to adapt the burner on the 5AT for the individual fuels and to determine the optimum conditions for operation. Similar work is currently being undertaken by Nigel Day on one of the locomotives on the Mount Washington Cog Railroad. Used soybean oil, (obtained as a waste product from restaurants) and after conversion to B100 biodiesel has been utilised as a fuel with successful results.[23] However a significant problem has arisen of "char" build up on the burner after relatively short periods of use which necessitates frequent cleaning to alleviate it. The photograph below showing the char build-up on Rutherford's burner is an example of this effect. The scope of the burner development work for the 5AT would need to include research to find suitable fuel additives and to ascertain optimum burner parameters to cure the problem.


[27]

Char Build-up on a Burner Mouth

A perceived advantage of the steam locomotive compared to the other primary forms of rail traction is its potential capability to burn these natural oils (soybean, rapeseed, palm, and even used cooking oils) without further processing. However, the work which has been done by Day at Mt Washington indicates that a considerable research effort will be required before the full potential of these raw fuel stocks can be realised. The volume of natural fats, including glycerine, which is naturally present in these oils would pose considerable problems in both forced draught and steam atomising burners with the current burner technology. Any attempt to modify the raw vegetable oils to improve their potential capability as furnace fuels by removing these fats, leads inexorably to the transesterification process and the production of B100 biodiesel.

In summary it is concluded that modern steam locomotives as exemplified by the 5AT could, with appropriate development, be adapted to run on carbon neutral fuels. The fuel selected would need to be governed by fuel availability at the specific geographic location and with due consideration given to the costs and logistics of providing it at the point of use. Generally liquid based bio fuels are to be preferred to solid bio fuel options.

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[27] Photo from Robertson, 2006, p12, showing the char build-up on the burner mouth. Nigel Day, in using a different design of burner, experienced a similar effect. The solution which Robertson found was to lift the flame off the burner mouth by increasing the pressure in the jet. No scientific explanation for this effect is known at this stage.

Acknowledgements

The author wishes to thank the following people for their suggestions and help in the preparation of this paper; Dr Alan Fozard, UK; John Hind, UK; Dr David Pawson, UK; Chris Newman, China; and Malcolm Cluett, Australia. Also thanks to Nigel Day, USA, and Shaun McMahon, Patagonia, for helpful discussions.

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There is an extensive literature available on this subject, much of it online. For the purposes of this paper, the general technical discussions found in the online encyclopedia at www.wikipedia.org have been used.

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