A Life Cycle Assessment (LCA) of Alternative Fuels in Transport Operation

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A Life Cycle Assessment (LCA) of Alternative Fuels in Transport Operation

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Abstract: This paper compares conventional and alternative vehicle fuels on a life cycle assessment (LCA) basis and is the first UK study to consider the use of landfill gas (LFG) against other fuels on a life cycle basis, inclusive of a vehicle cycle. The vehicles considered, 1.8t van, a 10t bus and a 16t HGV [all Unladen Vehicle Weights (UVW)] are based on typical Public Service Vehicles (PSVs). Results show that, on a life cycle basis, LFG powered vehicles compare favourably with gas-powered vehicles and generally cause less pollution that the liquid-fuel powered vehicles, with electric vehicles generally producing the least pollution overall. The results are normalised to reflect the impact made by each fuel and vehicle combination to Global Warming Potential (GWP) and Human Toxicity (HT).

1. Introduction

Alternative fuels are not new; as early as 1900 there were 1681 steam, 1575 electric, and only 936 petrol cars made, Motavalli[1]. As technology advanced the market demand for steam engines dried up and by 1911 a complete switch to petrol power had occurred. Today, the market demand for petrol and diesel is increasing. All petrol and diesel produced for UK consumption today has been refined and modified in accordance with the British Standards Institute (BSI) and the European Commission (Directive 2001/27/EC). At present the US and UK vehicle markets are dominated by petrol and diesel and so-called alternative fuels such as Liquefied Petroleum Gas (LPG), Compressed and Liquefied Natural Gas (CNG, LNG), Electric, Biofuels and Landfill Gas (LFG) are available but account for only about 2% of total fuel consumption, in all US vehicle types, Chang[2]. A similar situation holds in the UK. The inclusion of LFG arises from the symmetry of using a product of organic wastes to power PSVs, including waste collection vehicles.

Approximately 600 million vehicles were on the road in 1995, almost 80% of them passenger cars, the remainder consists of HGVs and Buses. This number will probably reach one billion before 2010, IEA[3]. In 1950, in the UK, there were only just under 2 million cars registered. By 1998 this number had risen to over 21.6 million. The car has replaced the bus as the predominant form of transport, 82% of journeys by mileage are in cars. Its flexibility and convenience has led to traffic growth across all areas, with a displacement of rail as the dominant form of freight transport to HGVs, which has led to a

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three-fold increase in HGV use, from 11 billion vehicle kilometres in 1950 to 32 billion vehicle kilometres in 1998. Approximately four-fifths of domestic inland freight transport (in terms of goods carried) now travels by road, CVTF[4]. Vehicle use is rising faster than vehicle stock and more than 99% of today's energy supply for road transport in developed countries is from crude oil (69% petrol, 30% diesel), IEA[3].

Crude oil is refined to produce, petrol, diesel and other commodities. The combustion of these hydrocarbon (HC) fuels in an ICE produces gaseous emissions including: Carbon Dioxide (CO_2), Carbon Monoxide (CO), Nitrogen Oxides (NOx), Hydrocarbons (HC) and Particulate Matter (PM). These emissions can have a harmful impact on local and global air quality and human health.

Air pollution is a problem in major cities throughout the world. International comparisons of urban air quality suggest that the concentrations found in cities across the UK are similar to those found in similar sized cities elsewhere in Northern Europe. At a national level, road transport is the single most important source of most pollution, with the exception of Sulphur Dioxide (SO_2) and Volatile Organic Compounds (VOCs). Cars are the most dominant source of road transport emissions, contributing between 50 to 90% of the share of CO_2, CO and NOx and are a less important source of PM, of which the largest source is HGVs, Holman[5].

Many transport related LCAs have focused upon cars due to their larger impact on local and global air quality, however the present paper focuses upon the use of conventional and alternative fuels in PSVs such as vans, HGVs and Buses. There is little information available to the public on the large vehicles. Moreover any future switch to alternative fuels will require proven technology with a relatively large fleet of vehicles. The use of LFG plus other alternative fuels can be demonstrated in these larger vehicles, as some local authorities and businesses are willing to try alternatives, although the majority are sceptical and need financial inducements to pilot schemes.

One pilot scheme, which investigates pollution reduction from existing and new vehicles as part of a much larger review and assessment of air quality, is underway across Merseyside (UK), Suceava (Romania) and Potenza (Italy). The Clean Accessible Transport for Community Health (CATCH) project, led by Merseytravel in the UK, aims to promote sustainable mobility in order to improve air quality. The project is part of the European Commissions Life-Environment Programme.

2. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA), in the present context, is an environmental management tool used to understand and compare how a product or service is provided 'from cradle to grave', a term used to describe the life cycle of a product from its first derivatives to its end-use e.g. Oil derived from an oil field, refined into petrol and used within a vehicle, Forbes *et al*[6]. The technique examines every stage of a product's life cycle, from raw materials acquisition, through manufacture, distribution, use, reuse/recycling and final disposal. Ideally, every operation or unit process within a stage is included. The inputs and outputs are aggregated over the life cycle. The environmental issues are then evaluated. A typical LCA consists of four stages: Goal Definition and Scope, Inventory

Analysis, Life Cycle Impact Assessment and Interpretation, as defined by the International Standardisation Organisation (ISO14040). Simplified and complex LCAs exist specific to particular applications, all of which follow the same basic procedure i.e. Nicolay[7] produced a simplified LCA for the automotive sector comparing diesel, petrol, electric vehicles. Further details on LCA studies can be found within DETR[8], Rosselot and Allen[9], Sheenan *et al*[10]. A LCA differs from other environmental management tools as integration over time is considered together with the stages a product will pass through over its lifetime, ETSU[11]. By adopting a holistic approach, LCAs avoid the problem of changing environmental impacts. Any positive and negative impacts through a product's life system are combined to produce a net impact; the significance of which becomes apparent when comparing various vehicle and fuel combinations.

The scope of the LCA defines the system boundaries. In theory a full LCA would include all upstream and downstream processes associated with the production and use of the vehicles and vehicle fuels. The LCA is comparing alternative vehicle fuels, not alternative vehicles fuelled by the same vehicle fuel.

Two linked cycles exist, see Figure 2:

- Fuel Cycle (F1-F6) and Vehicle Cycle (V1-V4)

The fuel cycle consists of six stages (F1-F6) and the vehicle cycle contains four stages (V1-V4). Both cycles can be used descriptively to document each stage within the life cycle of any fuel and vehicle combination. This includes the life cycle of traditional and alternative fuels. Within each stage, the emissions are under examination. Other LCA studies have produced fuel and vehicle cycles, premier amongst them being the GREET Model 1.5a, Wang[12,13]. To-date, the GREET model is the most widely used LCA, from a transport view, in the US; with a European version of the GREET model under preparation. Other LCA studies world-wide use the model as a template for their own work, see Deluchi[14], Gaines *et al*[15], General Motors Corporation[16], Hackney *et al*[17] and Wang[12,13].

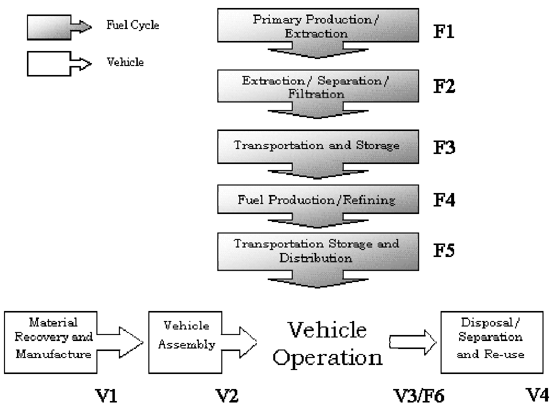

Figure 2: LCA Fuel and Vehicle Cycle

On completion of the building blocks that make up an LCA, the criterion for each vehicle and fuel cycle stage is summed to provide an overall value for further assessment. An overall life cycle emission in the vehicle stage for producing and operating a diesel car may be different than the emission as a result of producing and operating a petrol car. The following formula is derived to calculate life cycle emissions

$$E = \sum_{i=1}^{6} Fi + \sum_{i=1}^{4} Vi \tag{1}$$

where, E is the overall emission, Fi is the fuel cycle emission consisting of 6 stages and Vi is the vehicle cycle emission consisting of 4 stages.

2.1 Emissions

The emissions from each stage are either calculated or collected from various literature sources. For example, The Digest of UK Energy Statistics (DUKES) is produced annually by the Department of Trade and Industry (DTI)[19] and collates information provided by the manufacturing industry. All oil and gas usage within the UK is documented within, together with energy consumption levels, electricity supply and demand, import and export of oil and gas, combined heat and power and other solid fuel industries. With a prior knowledge of the mass inputs and outputs of fuels, emissions from each stage with the fuel cycle can be estimated.

Emissions are used to compare and contrast alternative fuels on a LCA basis. The direct and indirect emissions released as a result of the use of PSVs is of great interest to government agencies, local authorities and the public. It is for these reasons that the present study focuses solely upon emissions. Other impacts could be added within the framework, including: eco-toxicity, eutrophication, work conditions, etc.

In the assessment of conventional (petrol and diesel) and alternative fuels, nine fuel cycle are considered which represent the range of commercially available fuels in the UK in the year 2000. Some fuels are derived from petroleum based fuels and others from Natural Gas (NG) and Landfill Gas (LFG), see Figure 3.

(1) Petrol (2) Diesel (3) LPG	Petroleum Based Fuels
(4) NG to CNG (5) NG to LNG	Natural Gas Based Fuels
(6) Electric (7) Green Electric	Electric Based Fuels
(8) LFG to CNG (9) LFG to LNG	Landfill Gas Based Fuels

Figure 3: Fuel Options

3. Fuel and Vehicle Cycles

Hydrocarbon fuels (petrol, diesel and gas) and electricity are compared from the initial extraction through to final combustion/use within an engine. Emissions are calculated in (g/t) of fuel delivered and used in the end-use (F6) stage; with slight differences for electric vehicles modelling to cover the remotely generated emissions as the vehicles, in use, produce almost zero emissions. There are four stages to consider in the review of the vehicle cycle. They are used to clarify the calculation and accumulation of a set of characteristic emissions arising from the generation, use and disposal of a public service vehicle. Modifications can be made and any other vehicle could be modeled, provided the database is available. The combination of the fuel and vehicle cycles produces the Life Cycle Emissions Model (LCEM), further details can be seen in Finnegan (2003)[20] and Finnegan and Tickell[21].

4. The Life Cycle Emissions Model (LCEM)

The LCA model consists of a combined fuel and vehicle cycles to produce total emissions, enabling each combination to be assessed in relation to its competitors.

The calculations of emissions released through each stage of the LCA are representative of the associated auxiliary processes that occur through each stage. If one examines the fuel cycle of crude to petrol, the emissions associated with the extraction of crude oil in the F1 stage are derived from the turbines, flares, vents and boilers. The F2 stage emissions are derived from pumping operations and so on, per tonne of fuel used in the final F6 stage. These final F6 stage emissions are the result of the combustion of a tonne of fuel (e.g. petrol).

The vehicle cycle auxiliary emissions are generated in much the same way. However, the V1 emissions represent what is released in the processes of extracting the mass of material required to build a vehicle. The V2 emissions are associated with the releases to assemble a vehicle, with the V3 and V4 emissions representative of the emissions that result from vehicle use (minus fuel) and disposal, respectively.

The LCEM has been used to calculate the total life cycle emissions for each fuel and vehicle combination. The fuel cycle emissions, through the F1-F5 stages, are representative of a tonne of fuel delivery and used in the F6 stage. In this way all emissions, through each stage, can be represented by the units g/t of fuel. The vehicle cycles are different, since they cover the emissions associated with the construction of one vehicle.

In general, the F6 stage emissions contribute the most to the total life cycle emissions for each fuel and vehicle combination, with the exception of electric vehicles. Moreover, the cumulative F1 to F5 emissions are smaller that the F6 emissions and the total vehicle cycle emissions contribution to the life cycle emissions are minimal. The F6 calculations were made with the use of the Transport Research Laboratory (TRL) UK Road Emissions Database. This is the only UK database to include vans, HGVs and buses, which are the vehicles chosen to represent public service vehicles. Depending upon the operational characteristics of each vehicle the F6 emissions can be highly variable. Each vehicle, whether operating in the inner city or suburbs, will have different average speeds. Therefore, on review of the total emissions from each vehicle, the user must be cautious when comparing results.

4.1. The use of LCEM in the EC CATCH study – an example of procedure

Within the CATCH project the emissions from 89 Euro II ARRIVA buses (10% of fleet) are under review and assessment. Each bus was retrofitted with a particulate filter to reduce Particulate Matter (PM), Hydrocarbons (HC) and Carbon Monoxide (CO) by some 90-95%. Stage two of the emissions reduction from existing vehicles will come from the introduction of the Exhaust Gas Recirculation (EGR) hardware to reduce NOx (in progress). At present the buses reach the Euro IV standards for PM, HC and CO and with the successful installation of the proposed EGR system a similar Euro standard will be achieved for NOx. If one assumes that all emissions from the ARRIVA buses in operation across Merseyside (UK) reach the Euro IV specification, it then becomes possible to compare like-with-like in the LCEM.

Table 1 compares the theoretical life cycle CO_2 emission from the use of a Euro IV diesel, LPG, NG-CNG and LFG-CNG bus in operation across Merseyside, with assumed operational characteristics of average speed (16kph), distance traveled per day (140km), average diesel mpg (8), total operational days per year (300) and operational lifetime use (10 years).

TABLE 1. Life Cycle Bus CO_2 emission

Euro IV Bus	Total CO_2 Emissions (kg)			
	Diesel	LPG	NG-CNG	LFG-CNG
Fuel Cycle	490680[a]	446400[a]	393186[a]	384469[a]
Vehicle Cycle	16640	16640	16640	16640
Total	507320[b]	463040	409826	401109

[a]of which 95% is derived from the combustion of fuel in the end-use (F6) stage
[b]in theory 507 tonnes of CO_2 are released over the life cycle use of a Euro IV specification ARRIVA bus

A complete analysis of life cycle emissions from all fuels and vehicles can be seen in Finnegan[21].

5. Life Cycle Results

Life cycle results for each of the fuel and vehicle combinations are subject to a procedure of normalisation and weighting. The normalization results only, are presented in this paper. The Environmental Design of Industrial Products (EDIP) methodology, developed by Wenzel *et al*[22,23], was chosen due to its holistic approach and ability to adapt to different situations and applications. The method also enables a user to compare any product on a common basis and weight the relative impacts.

The EDIP method has been used in an environmental diagnosis and impact assessment of televisions, refrigerators, high-pressure cleaners, pumps and electro-hydraulic activation units. To-date, the only study which applies the EDIP methodology in the assessment of alternative fuels, is that of Tan and Culaba[24]. They combine the EDIP methodology with the GREET model developed by Wang[12,13], in the examination of air pollution and resource depletion of conventional and alternative fuels (biofuels and natural gas). In this study, seven fuels were evaluated within a passenger vehicle on a life cycle basis. The main results implied that the use of NG as an automotive fuel provides little or no environmental benefit.

5.1. The EDIP Methodology

A comparison is made based upon the potential environmental impact each vehicle has on society. The use of a vehicle produces emissions through the combustion of fuel and through the construction and use of the vehicle itself. Elements of an inventory of these fuel and vehicle cycles have been built, upon which an environmental impact assessment can be made. The combination of the cycles produces values that represent the total emissions from the use of a vehicle though its operational life, a so-called "cradle-to-grave" analysis. These total emissions can then be categorised against other fuel and vehicle cycles and against an average person's contribution to an environmental impact, such as Global Warming Potential (GWP) or Human Toxicity (HT). These are the processes of normalisation and weighting. The estimation of emissions is largely a technical matter and consideration of their impact on, for example, global climate change is relatively straightforward. The other impact chosen, as an example of procedures, is HT and here the process is more complex, see Finnegan[20].

Although local, regional and global pollution levels are increased through the release and interaction of many compounds across micro and macro time periods, for the purpose of this paper; the only impacts to GWP are considered. The system boundaries of any LCA have to be drawn in order to limit the scope of investigation. Without boundaries a complete assessment can extend indefinitely.

5.2. EDIP Results

The normalised results presented in this paper reflect the complete life cycle global impacts of the PSVs, in relation to the impact from the average persons' contribution to GWP in Denmark and the World, subject to the simplifications outlined in Finnegan[21]. Each vehicle and fuel combination can be compared and contrasted against each other. The relative impact of each can then be investigated, together with the identification of the stage with the highest contribution to the impact in question.

5.3. Global Warming Potential (GWP)

The normalised GWP results for the PSVs are presented in Figure 4. The results show that the lowest contribution to GWP is from a Green Electric Van (15 years operation) with the highest impact from a Diesel fuelled Euro 4 Bus (10 years operation). These results represent the percentage contribution from the average persons' total annual release of the gases that contribute to GWP in the World in 1990 i.e. the manufacture, use and disposal of a diesel bus operating for 10 years contributes to the equivalent GWP output of 3.27 people (per year) in 1990.

In comparison to a conventional petrol fuelled van, the results show, see Figure 4, that diesel GHG emissions (of which CO_2 plays the most significant role) are reduced by approximately 5%, CNG by approximately 30%, LPG by approximately 25% and electric vehicles by approximately 75%. In contrast, the work of Wang (1999b), on Light Duty Vehicles (LDVs) in the US, has revealed that GHG emissions in the use stage (F6 equivalent), in comparison to conventional gasoline in 1999, are reduced by approximately 27% for diesel LDVs, approximately 12% for LPG vehicles, approximately 10% for CNG vehicles and between 40-70% reductions are achievable with the use of electric vehicles (dependent upon the region of charging). .

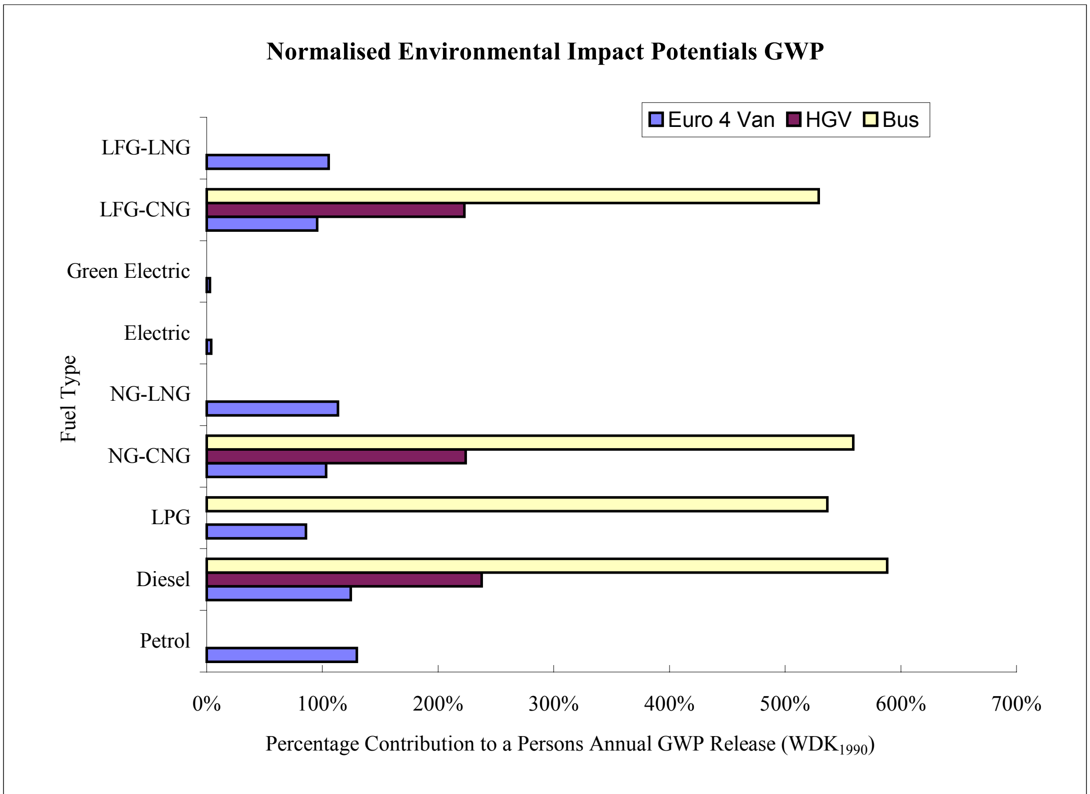

Figure 4: Normalised Impact Potentials

A 100% contribution represents the average GWP release for each person in the World. Excluding all other GWP emissions, such as the use of household products, burning of fossil fuels, use of electricity, heating and general living, the use of the van alone contributes to 30% above of the annual World average set for 1990.

7. Conclusions and Closure

This paper can only outline the structure and output of Finnegan[20]. The combination of the fuel and vehicle cycles has shown that the contributions to CO_2 are much larger than the other compounds and the end-use stage F6 has the largest impact to the total results. The electric vehicles are clearly less damaging than their liquid and gaseous equivalents and the use of a HGV and bus contributes to higher releases of all compounds. LFG vehicles compare favourably to the other fuel types. The analysis of the HGV has shown that a diesel HGV releases similar amounts of emissions in comparison to a NG-CNG and LFG-CNG HGV, with the LFG vehicle releasing less CO_2, offset by the large increase in CH_4.

The life cycles of the bus have the largest releases of CO_2. This is due to the operational characteristics chosen for the bus, not the vehicle size. During start/stop conditions and at low speeds, buses release more pollution per km traveled in comparison to vans and HGVs, which tend to operate at a more constant speed with fewer stops. Should a van, HGV and bus operate under exactly the same conditions the results would be very different. For the operational cycles chosen, the LFG-CNG bus compares favourably to the diesel bus and poorly in comparison to the LPG bus.

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