# 1. Background

## *1.1 Introduction*

This report responds to a brief from the Australian Greenhouse Office (AGO) to undertake:

- a comparison of road transport fuel emissions through a full fuel-cycle analysis of greenhouse gas emissions and emissions affecting air quality; and
- for each fuel, an assessment of current and near future (i.e., to 2006):
  - viability and functionality;
  - health related issues (including occupational health and safety issues); and
  - environmental issues (including ecologically sustainable development) not related to greenhouse or air quality issues.

The full Terms of Reference are given in Appendix 1.

Information in this report may be used by the Australian Greenhouse Office when considering the appropriateness of recommending the inclusion of additional fuels under the Diesel and Alternative Fuels Grants Scheme. Thus, it incorporates a desk study and literature review of existing Australian and overseas data concerning the emissions characteristics of alternative and conventional fuels that are or may be suitable for use in road vehicles weighing 4.5 tonnes gross vehicle mass (GVM) or more. The Prime Minister indicated under the *Measures for a Better Environment* Statement of May 1999 that the Chief Executive of the AGO may certify additional fuels under the DAFGS. The scheme is designed to maintain price relativity as at 1 July 2000 between diesel and alternative fuels so as not to discourage the use of cleaner fuels.

The AGO requires an analysis that will:

- conduct a full fuel-cycle analysis of emissions for on-road transport fuels;
- determine whether any fuel has significant potential to compromise vehicles' compliance with gazetted ADR standards for the period to 2006 (inclusive);
- examine the viability and functionality of the fuels;
- examine significant health (and occupational health and safety) related issues from the use of the fuels; and
- examine other significant environmental issues resulting from the use of the fuels including ecologically sustainable development.

These points broadly cover the criteria for determining the appropriateness of certifying a new fuel under the DAFGS.

### *1.1.1 Approach*

This study consists of a literature review and a desk analysis of existing Australian and overseas studies that assess the emissions characteristics of fifteen fuels. Three classes of emissions are considered:

- Greenhouse gases, which comprise carbon dioxide, nitrous oxide, hydrofluorocarbons, methane, sulfur hexafluoride, and perfluorocarbons.
- Air pollutants, which comprise carbon monoxide, oxides of nitrogen, sulfur dioxide, non-methanic volatile organic compounds, and particles.
- Air toxics, which include compounds such as benzene, aldehydes (formaldehyde and acetaldehyde), 1,3 butadiene, polycyclic aromatic hydrocarbons (PAH), toluene, and xylene.

This study was completed over a five month period from March to July 2001.

### *1.1.2 Previous Work*

This study extends the work undertaken by Beer et al. (2000) in their life-cycle emissions analysis of alternative fuels for heavy vehicles. It does so, with a focus on the Australian context, by i) examining more recent investigations and incorporating their data, if relevant, ii) examining some new fuels that were not examined in the earlier study, and iii) examining more upstream pathways for fuels that were examined in the earlier study.

## *1.2 Life-Cycle Analysis (LCA)*

A general introduction to life-cycle analysis may be found in Graedel & Allenby (1995), while the international standards on LCA, contained in the 14040 series (International Standards Organisation, 1998) provide a basic framework in which to undertake LCA. When LCA is applied to the emissions from the use of different transport fuels, both combustion and evaporative emissions need to be included, as well as the full life cycle of the fuel. A full life-cycle analysis of emissions takes into account not only the direct emissions from vehicles (which are referred to as downstream emissions) but also those associated with the fuel’s:

- Extraction
- Production
- Transport
- Processing
- Conversion
- Distribution

These are referred to as upstream emissions. In the context of automobile fuels they are also referred to as pre-combustion emissions.

The Bureau of Transport and Communications Economics (1994) uses the term ‘full fuel cycle’ for the situation that takes into account emissions from all energy used in achieving a given transport task with a particular fuel. The full fuel cycle contrasts with the more basic analysis of tailpipe emissions.. A life-cycle basis for estimating fuel emissions for a particular fuel takes into account emissions in vehicle manufacture and vehicle life, whereas a full life-cycle analysis sets the system boundaries much wider and incorporates emissions from the associated infrastructure. The term ‘well to wheel emissions’ is also used in the analysis of automotive fuels.

Life-cycle analysis is often used to determine the amount of upstream energy used to construct a particular object. The term ‘embodied energy’ has achieved widespread use to denote such energy. However, the term ‘embodied emissions’, to cover the full fuel-cycle emissions of gases or pollutants, would be a misnomer, because emissions are emitted, not embodied. Thus, in this report, we use the term exbodied emissions to refer to the cumulative life cycle of emissions (including combustion) associated with a fuel.

Emissions related to vehicle manufacture, maintenance and disposal, and road building are relevant to total transport emissions, but they are not likely to vary significantly with the nature of the fuel used. The infrastructure associated with refuelling will, however, vary with the different alternative fuels.

### *1.2.1 System Boundary for LCA*

Some elements of the production system are excluded from the study, for two reasons:

- the process is considered small enough to ignore, given the aims of the study; and

- the impacts of the process belong to a different product system entirely, which is the case with waste products which attract little or no revenue in their disposal.

Figure 1.1 shows a simplified outline of the system elements for the fuels studied, and places a boundary around those included in the study. Capital equipment and infrastructure are universally excluded from the study, based on its expected low contribution to the overall environmental impact of the fuel used. The impacts derived from capital goods are expected to be similar for each of the fuels studied. Though the capital goods in fuels delivery and filling could have substantial impacts if a radically different filling infrastructure is required, the full context of the market segment and expected market penetration of the fuel would need to be known to determine this impact. These factors are beyond the scope of the study so the filling infrastructure has also been excluded from quantitative calculations.

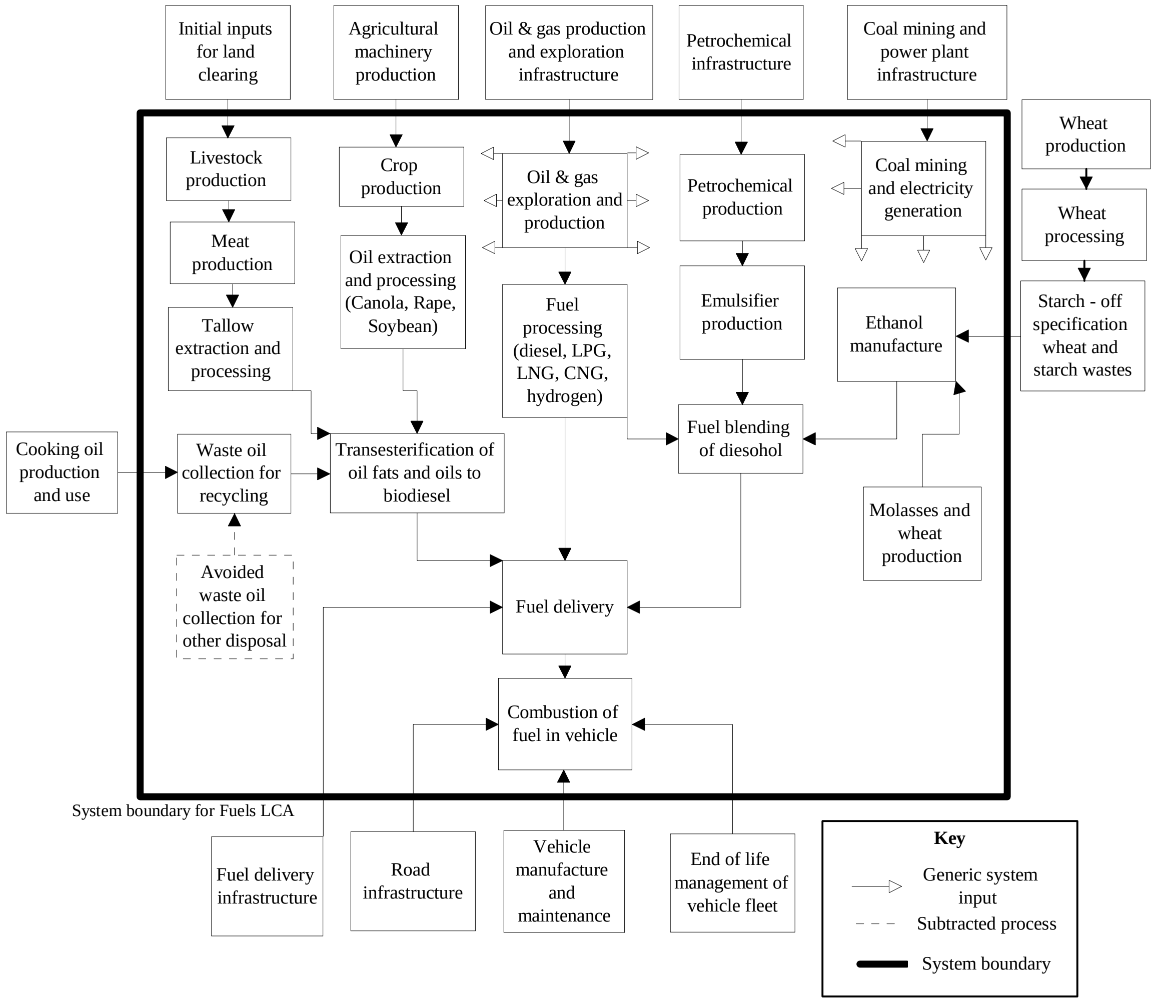


**Figure 1.1**
**System boundaries in fuels LCA – note not all fuels studied are included in diagram and different allocation procedures have been employed for individual fuels – see fuel chapters for full details.**

When considered as waste products, waste cooking oil and waste wheat products are outside the system boundary due to their low value as a waste product. Should these wastes gain in value as demand increases then an alternative approach is required, that is depicted in subsequent calculations as an alternative allocation abbreviated as alt. alloc.

***Allocation of burdens for co-products and by-products***

Many of the feedstocks for fuels used in this study are either co-produced with other products or are from by-products and wastes from other production processes. A methodology needs to be applied to determine the appropriate environmental impacts of these co-produced materials. The two main options available for dealing with co-production are to split emissions between the product streams – known as allocation, or to expand the study to take account of the potential flow-on effects of providing a new use for the co-product, on systems currently using the co-product, which is known as system boundary expansion. The two basic approaches are shown in Figure 1.2.

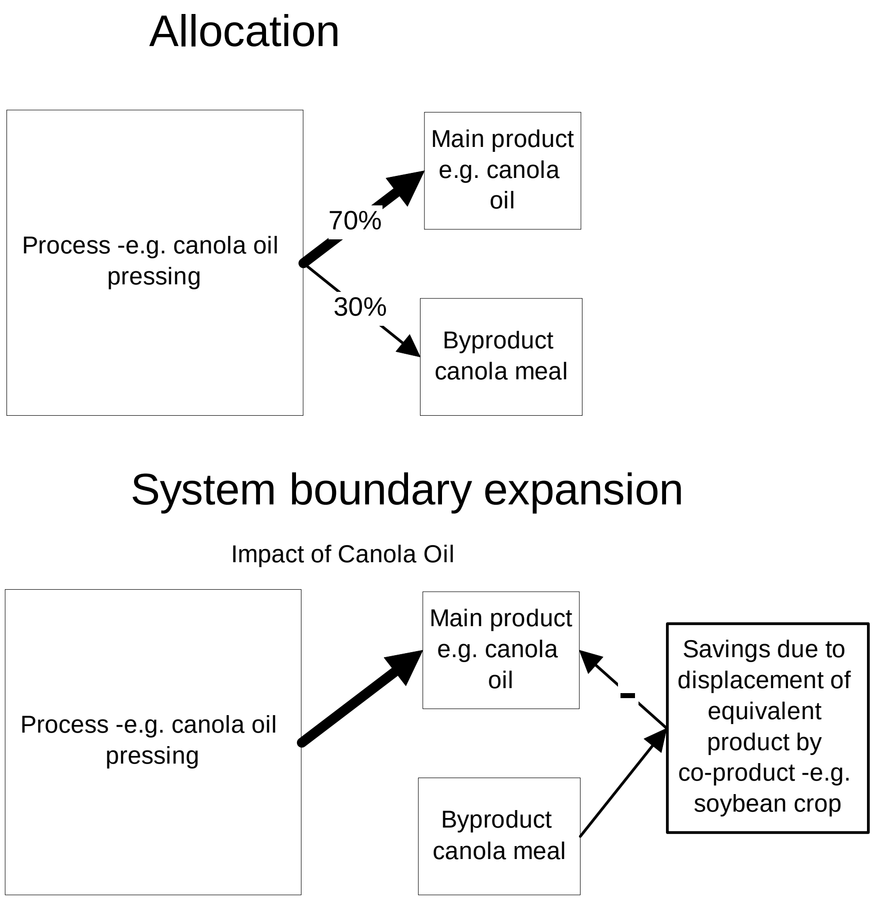


**Figure 1.2**
**Approaches to allocation in life-cycle analysis**

The international standard on life cycle assessment (International Standards Organisation, 1997) states that allocation should be avoided where possible through the use of system boundary expansion. Where this is not possible allocation should be undertaken using either causal relationships, based on economic, or physical properties of the co-products.

The problem with system boundary expansion is that it requires a good knowledge of the market forces that result in the product substitution. It is also complicated by the factor that many co-products are competing with other co-products, so expanding the system boundary for canola meal may find that soy meal is the likely replacement material. This product has the same allocation issues as canola meal. It is necessary then to follow the product substitution chain back to a point where a “determining” or “main” product is found which can expand or contract its production in line with system dynamics. This is different to by-products which are assumed to be able only to alter the market in which they are utilised and the level of utilisation.

## Part 1 Background Information

Weidema (1999) has developed four simple rules for determining expanded system boundary allocation based on the level of utilisation of the by-product (or waste).

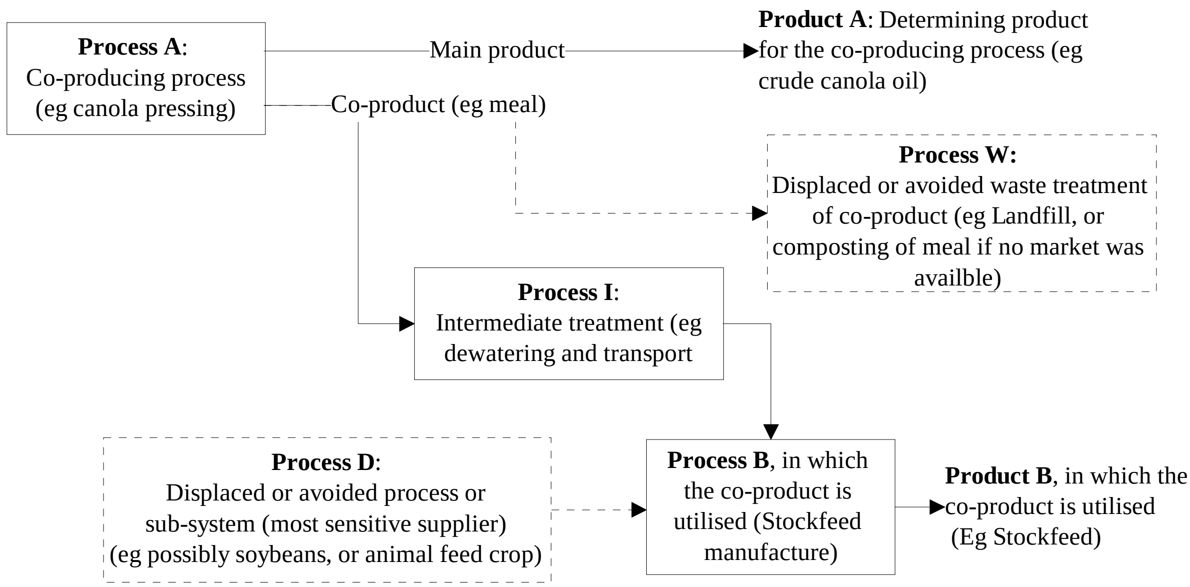


**Figure 1.3**
**Model for system boundary expansion – Adapted from (Weidema, 1999)**

Using the model of Figure 1.3 for reference Weidema (1999) developed the following four rules for ascribing process impact to different products. These are:

1)*"The co-producing process shall be ascribed fully (100%) to the determining product for this process (product A)"* (eg all impact of canola growing and crushing ascribed to the canola crude oil).

2)*"Under the conditions that the non-determining co-products are fully utilised in other processes and actually displace other products there, product A shall be credited for the processes, which are displaced by the other co-products, while the intermediate treatment (and other possible changes in the further life cycles in which the co-products are used, which are a consequence of differences in the co-products and the displaced products) shall be ascribed to product A"* (eg crude canola oil is given credit for avoided soybean production (or other equivalent crop) but also bears the impacts of dewatering and transporting the meal to the stockfeed production process).

If the two conditions stated in rule no. 2 are not fulfilled, rule no. 3 and 4 apply, respectively:

3)*"When a non-determining co-product is not utilised fully (i.e. when part of it must be regarded as a waste), but at least partly displaces another product, the intermediate treatment shall be ascribed to product B, while product B is credited for the avoided waste treatment of the co-product"* (eg if canola meal was not fully utilised and some of it was being landfilled for want of a market, then the dewatering and transport would be part of the stock feed life cycle, but the stockfeed life cycle in turn receives credits for avoided landfill impacts from landfilling of the canola meal). Crude canola oil is given all impacts of production and landfilling of the meal (as any increase in production will probably have 100% of meal to landfill as the market for meal is saturated under this scenario.)

4) "*When a non-determining co-product is not displacing other products, all processes in the entire life cycle of the co-product shall be fully ascribed to product A*" (eg if the canola meal is applied to land, but provided little value and does not displace fertiliser use, all the impacts are ascribed to crude canola oil and no credits are given).

In this study system boundary expansion has been used wherever the fuel is produced from the non-determining co-product (molasses, LPG and tallow). In three instances co-products have been considered so close to waste that no prior emissions have been allocated (forest waste, starch waste in diesohol, and waste oil). Where a determining product is used as a fuel such as for canola, rape and soybean crops, economic allocation was applied due to difficulties and additional work in applying expanded system boundaries.

***Compliance with ISO14040 series standard on Life-Cycle Assessment***

In general the methodologies applied in this study are in compliance with the ISO 14040 series standards[1]. In particular we have endeavoured to follow the standard on the following points:

**Allocation procedures:** For multi-product systems we have opted first to try expanding the system boundary to eliminate the need for allocation. Where this has not been practical, allocations have been made on energy content (e.g. in refineries) or economic value (e.g. agricultural products). Sensitivity studies have been undertaken using alternative allocation procedures where there is some question over the appropriateness of the allocation procedure and where an alternative method is possible.

**Indicators:** The two main indicators being examined in the project are global warming and air quality. In the case of comparative assertions released to the public, the standard allows for calculation of indicator results (characterisations) that are internationally accepted. The greenhouse indicator is clearly internationally accepted, with the characterisation factors[2] being developed by the IPCC. For the air quality indicator, the use of such an indicator is not uncommon internationally. However, international acceptance of the characterisation factors that are used is unlikely given the local nature of the air quality impacts and the fact that the values are based on this local situation. Compliance on this point is unclear.

**Peer review:** The project has had three types of peer review: an internal peer review process within CSIRO, review by the Australian Greenhouse Office as the commissioner of the study, and stakeholder review through a stakeholder forum held on 7 June, and subsequent focussed roundtables on 25 June and 26 June. During July 2001 Australian Government stakeholders reviewed the draft report, and their input was incorporated into the final report.

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[1] The series include ISO 14040 (International Standards Organisation, 1997) giving a general framework, ISO 14041(International Standards Organisation, 1998) which outline inventory assessment, ISO 14042 (International Standards Organisation, 2001) which outlines impact assessment and ISO14043 (International Standards Organisation, 2001) which outlines interpretation.

[2] The characterisation factors are considered in this report to be part of the third mandatory stage of impact assessment [see page 3 of International Standards Organisation, 2001a] as they apply to one damage endpoint — human health effects from urban air pollution. The values could be considered as weighting factors and thus part of impact weighting [stage three of the optional impact assessment process, which is not allowed by the standard in the case of a comparative assertion released to the public.]

***Recent life-cycle studies of fuels or transport***

The earlier report of Beer et al. (2000) reviewed the detailed studies of Sheehan et al. (1998) on the life-cycle of biodiesel in an urban bus, and of Wang and Huang (1999) who examined the full fuel cycle of natural gas, as well as the European IEA/AFIS work. The Flemish research organisation VITO undertook a comparative life-cycle assessment of biodiesel in Europe (Ceuterick and Sprinckx, 1999). There are a number of life cycle analyses of individual fuels that are reviewed or referenced in the appropriate chapters.

MacLean et al. (2000) used US information to examine the life-cycle emissions of alternative fuels when used in petrol-driven vehicles.

### *1.2.2 Life-Cycle Analysis Modelling*

Life-cycle analysis was done using SimaPro 5.0 software. SimaPro 5.0 is an open structure program that can be used for different types of life-cycle assessments. The production stage, the use stage and the end-of-life scenario can be specified in as much detail as necessary by selecting processes from the database and by building process trees, which can be drawn by the program. The results are presented in scores or graphs, varying from a list of substances (inputs and outputs), characterised scores, normalised scores or evaluated scores.

An alternative life-cycle model for alternative fuels, much used in the United States, is the GREET model developed at Argonne National Laboratories. Appendix 2 compares GREET and SimaPro, and provides an explanation of the structure of SimaPro process trees.

## *1.3 Structure of the Report*

This report examines the alternative fuels with respect to their life-cycle emissions of greenhouse gases and air pollutants. Each fuel is considered in a separate chapter that examines: Full Fuel-Cycle Analysis; Viability and Functionality; Health Issues; and Environmental Impact and Benefits. Wherever possible the emissions are provided on a quantitative basis as a result of values available in the literature.

The report consists of three main parts. Part 1 consists of 15 chapters, each of which provides a *summary* of the salient points of each fuel, with a graphical representation of the emissions from the fuel, the reference fuel, and similar fuels, together with a representation of the uncertainty associated with the emissions. There is no summary description of Low Sulfur Diesel because it is the reference fuel against which all subsequent heavy vehicle fuels are examined.

Part 2 consists of *detailed* chapters on each fuel. These provide a literature review for each fuel, a description of the upstream and tailpipe emissions along with an explanation of the assumptions made in the quantitative modelling, the numerical results on which the graphical information in Part 1 is based as well as the uncertainty estimates. In addition, each chapter provides details of the viability and functionality, health effects, environmental issues and expected future emissions associated with each fuel.

Part 3 consists of supporting chapters that discuss possible weighting methodologies for examining air quality emissions, and the modelling approach for the estimates of future emissions.

We have used a hierarchy of data quality to assess the data on emission profiles from different vehicle types. Australian experimental data on emissions from heavy vehicles is used wherever possible. Recent overseas data on heavy vehicles is reviewed and, where appropriate, used in the SimaPro model.

The comparison between different fuels is done on the basis of both the mass of emissions per energy used (g/MJ), and the mass of emissions per kilometre of distance travelled. The mass of emissions per kilometre travelled is the environmentally most meaningful figure, though it is subject to greater variability than the mass per unit energy. Arriving at the emissions per kilometre involves three steps:

**Life-Cycle Analysis of Emissions**

This first step produces an estimate of the greenhouse gas and air quality emissions from each fuel expressed as the mass of emissions per unit of energy - kg/MJ.

**Fuel combustion**

This characterises the fuel in terms of its energy per unit volume in units of MJ/L

**Performance**

This characterises the fuel in terms of the per-kilometre emissions.

An alternative way of examining this is to examine the units associated with the quantities:

g/km = (g/kWh)x (1/engine efficiency) x (kWh/MJ) x (MJ/kg) x (kg/L) x (L/km).

The first term (g/km) is the final performance result that this report examines. The emissions are expressed on a per kilometre basis. One arrives at this by considering the product of the engine emissions (g/kWh), the fuel combustion characteristics (MJ/kg), the fuel density (kg/L) and the vehicle fuel economy (L/km). Each one of these four terms will display variability, so that the uncertainty associated with the emissions will be the sum of the percentage uncertainties associated with each of the four terms.

We have retained the use of g/kWh (even though it is dimensionally equivalent to g/MJ) to emphasise that the output of an engine dynamometer refers to the usable work, rather than the energy content of the fuel. The theoretical Carnot efficiency of a diesel engine is 64%, though the efficiencies of actual diesel engines are lower.

Whereas the first four steps given above can be undertaken on the basis of static tests of motors and theoretical calculations on fuel properties, performance is determined in this study on the basis of fuel economy, expressed in units of L/km. Ideally this is based on road tests using vehicles with alternative fuels. Such road tests are very difficult and expensive to carry out so that most emission tests are actually carried out either as static tests or on a chassis dynamometer.

Static tests require the engine to be removed from the chassis, and then tested over a lengthy test protocol. Chassis dynamometer tests involve the drive wheels of the vehicle being placed over a set of rollers, and the vehicle being driven in a representative test cycle while the emissions are collected and then analysed. The dynamometer must have sufficient rotating inertia to simulate the mass of the vehicle in acceleration and deceleration manoeuvres. Most tests are performed on unladen vehicles because of limited dynamometer inertia.

Fuels will be presented in terms of emissions per tonne-km in the case of trucks, and emissions per passenger-km in the case of buses. Presentation in this form will minimise the variations in emissions that arise from payload variations, rather than fuel variations. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116). Adjustments, such as those due to the extra weight of CNG tanks, have been made to these figures in some situations.

The quantitative results provide an estimate for the mean emission factor. Because of the large variability in the results of emission tests on conventional and alternative fuels, a statistical approach needs to be adopted. The uncertainty for each fuel needs to be estimated, and comparison with the reference fuel made on the basis of the statistical variability. The method of uncertainty analysis that was adopted is explained in Appendix 3.

**Table 1.1**
**Summary of information sources used for the quantitative evaluation of each fuel**

| Chapter | Fuel | Upstream | Tailpipe |
|---|---|---|---|
| **Diesel fuels** | | | |
| 1 – This is the reference fuel; thus there is no summary in Part 1 | Low Sulfur Diesel (LSD) | Australian petroleum refinery with hydro-desulfurisation unit | Diesel NEPM |
| 2 | Ultra Low Sulfur Diesel (ULSD) | Australian petroleum refinery with hydro-desulfurisation unit | Diesel NEPM Supplementary Study |
| 3 | Fisher-Tropsch Diesel (FTD) | Wang and Huang (1999) | Norton et al. (1998) |
| **Biodiesel fuels** | | | |
| 4 | Biodiesel (BD100) | Sheehan et al. (1998) and Ceuterick and Spirinckx (1999) | Sharp (1998) Tier 1 testing |
| 5 | Canola | Australian agricultural data | No data available due to the unsuitability of the fuel |
| **Ethanol fuels** | | | |
| 6 | Hydrated Ethanol | Kadam et al. (1999) | Skaraborg ethanol buses (CADETT, 1998) |
| 7 | Diesohol (E15D) | APACE data | Swedish data provided by APACE |
| **Gaseous fuels** | | | |
| 8 | Compressed Natural Gas (CNG) | Wang and Huang (1999) | Data from Andrew provided by ANGVC |
| 9 | Liquefied Natural Gas (LNG) | Wang and Huang (1999) | Data from Andrew provided by ANGVC |
| 10 | Autogas (LPG) | Standard refinery and natural gas operations | Nylund and Lawson (2000) |
| 11 | HD-5 Propane (LPG HD5) | Standard refinery and natural gas operations | Millbrook trials London bus data |
| **Light vehicle fuels** | | | |
| 12 – Reference fuel | Premium Unleaded Petrol (PULP) | Standard refinery | MacLean (1998, 2000) |
| 13 | Anhydrous Ethanol | As for hydrated ethanol | MacLean (1998, 2000) |
| 14 | Petrohol (E10P) | Combines PULP and anhydrous ethanol | MacLean (1998, 2000) |
| **Other fuels** | | | |
| 15 | Hydrogen | Spath and Mann (2001) | Assumed no emissions |

## *1.4 Sources of Quantitative Information*

The quantitative calculations in the report are based on a variety of sources, summarised in Table 1.1. These sources were used, in conjunction with the extensive data set held by RMIT Centre for Design. This data set consists of emissions and energy use involved in Australian manufacturing. The upstream sources in Table 1.1 were used to provide default values when no Australian data was known, and the assumptions were examined during focussed roundtable discussions held with stakeholders, who examined the biodiesel, gaseous, and other fuels. Details of stakeholder interactions are given in Appendix 4.

## *1.5 Emissions from Diesel Engines*

There are some generalisations concerning the emissions from diesel vehicles resulting from different fuels. These include:

- the less volatile and more aromatic the fuel, the higher the exhaust particle emissions;
- oxygenated fuels produce fewer particles due to more complete combustion, providing that other fuel-related qualities, e.g. cetane number, remain constant; and
- significant evaporative emissions may result from use of volatile fuels such as LPG or ethanol.

The presence of impurities such as sulfur will result in extra particle formation (in the form of sulfate). In regard to fuel consumption, provided the fuel is within the normal specification range, then for a given engine technology and transport task, fuel economy will be related to the energy content of the fuel.

However, it must be borne in mind that measurements of exhaust pollutants on chassis dynamometers show considerable variation between similar vehicles that can mask small changes that might result from using a different fuel. The reasons are that, for pollutants other than $CO_2$, we are dealing with trace amounts of unburnt fuel or combustion side reactions. These vary according to engine condition and maintenance and also, if non-steady state test cycles are used, the accuracy with which the cycles have been performed by the driver.

**Table 1.2**
**Change (percent) in heavy-duty diesel vehicle emissions with variations in diesel fuel properties**

| Fuel property | $CO_2$ | Particles | $NO_x$ | NMHC | CO |
|---|---|---|---|---|---|
| Density<br>855 to 828 g/L | +0.07 | -1.59 | -3.57 | +14.25 | +5.0 |
| Polyaromatics<br>8 to 1 percent | -0.60 | -3.58 | -1.66 | -4.02 | 0.08(NS) |
| Cetane number<br>50 to 58 | -0.41 | 0(NS) | -0.57 | -6.25 | -10.26 |
| T95<br>370 to 325$^o$C | +0.42 | 0(NS) | -1.75 | +13.22 | +6.54 |
| Sulfur<br>2000 to 500 ppm | - | -13.0 | - | - | - |

Source: Faiz et al. (1996) - not applicable; (NS) not significant; positive values indicate an increase in emissions; negative values indicate a decrease in emissions.

The European Programme on Emissions, Fuels and Engine Technologies (EPEFE) examined the effect of variations in European diesel fuel properties on emissions of light duty and heavy duty diesel engines. The heavy duty engines conformed to the Euro2 limits. The results are summarised in Faiz et al. (1996) and are reproduced in Table 1.2. They may also be found in Table 3.9 of Coffey (2000). Increasing cetane number and decreasing polycyclic aromatics are the two most significant variables in reducing heavy-duty diesel engine emissions. As Faiz et al. (1996) note, the absence of any effect on particulate matter (PM) emissions from changes in cetane number is different from the results of a number of US studies. This difference is most likely due to the higher cetane number of the EPEFE fuels (50 to 58) compared to the diesel fuels in the United States. Increasing cetane number from 50 to 58 seems to have little effect on PM emissions, but increasing it from 40 to higher levels such as 45 or 50 has a significant effect. Density and T95 are correlated as depicted in Table 1.2.

A subsequent program, the European automobile fuels programme (see http://europa.eu.int/comm/environment/autooil/), re-examined the Euro2 emissions data and extrapolated the results to estimate the performance of alternative fuels in Euro3 and Euro4 engines (Arcoumanis, 2000).

## *1.6 Greenhouse Gases and Other Emissions*

In 1998, transport emitted about 22% of the national anthropogenic $CO_2$ emissions of 312.1 Mtonnes, but only 16% of total greenhouse gas emissions of 456 Mtonnes $CO_2$-equivalents (National Greenhouse Gas Inventory Committee, 2000). About 89% of these emissions come from road transport, including cars, trucks and buses. Table 1.3 gives a breakdown of the relative greenhouse gas emissions from transport and road transport.

**Table 1.3**
**Australian greenhouse gas emissions from the transport sector and the road sub-sector in 1998**

| | $CO_2$ (Gg) | $CH_4$ (Gg) | $N_2O$ (Gg) | $CO_2$-equiv. (Gg) |
|---|---|---|---|---|
| Transport | 68433 | 23.18 | 11.91 | 72612 |
| Road Transport | 60753 | 20.48 | 11.69 | 64807 |

Source: National Greenhouse Gas Inventory Committee (2000)

In terms of the types of fuel used, current annual consumption is about 18,000 ML of automotive gasoline and about 12,500 ML of automotive diesel, with aviation using around 5,000 ML of turbine fuel. LPG and aviation gasoline consumption is relatively low. Strong growth is anticipated for aviation and road freight. Rail currently accounts for about 56% of non-urban freight (in net tonne-kms).

The greenhouse gases considered in this review are carbon dioxide, nitrous oxide, hydrofluorocarbons, methane, sulfur hexafluoride, and perfluorocarbons. This particular group of greenhouse gases is sometimes called the Kyoto Protocol group of greenhouse gases, because they comprise the list of greenhouse gases specified in that protocol. The transport sector generates both ‘direct’ and ‘indirect’ greenhouse gases. Direct gases are radiatively active. Those emitted by transport include carbon dioxide, methane, nitrous oxide, and CFCs. The indirect greenhouse gases include carbon monoxide, other oxides of nitrogen and non-methanic volatile organic carbons. These do not have a strong radiative effect in themselves, but influence atmospheric concentrations of the direct greenhouse gases by, for example, oxidising to form $CO_2$ or contributing to the formation of ozone, a potent direct greenhouse gas. Present international agreement is to ignore such gases in the calculation of $CO_2$-equivalent greenhouse gases.

The concept of a global warming potential (GWP) has been used to enable different greenhouse gases to be compared with each other and expressed in $CO_2$-equivalents. The GWP factors reflect the different extent to which gases absorb infrared radiation and the differences in the time scales on which the gases are removed from the atmosphere. The GWP is used in the National Communications required by the UN Framework Convention on Climate Change. The Kyoto Protocol has adopted GWPs (with 100-year time horizon) as the basis for defining equivalences between emissions of different greenhouse gases during the 2008-2012 commitment period. These GWPs are given in Table 1.4.

The Kyoto Protocol requires calculations of greenhouse gases to be made on the basis of fossil-fuel derived carbon dioxide. Carbon dioxide that is generated as a result of the combustion of a renewable fuel (such as canola oil) is not to be included in greenhouse gas inventories.

**Table 1.4**
**100-year greenhouse gas warming potentials**

| Gas | GWP |
|---|---|
| Carbon dioxide | 1 |
| Methane | 21 |
| Nitrous Oxide | 310 |
| Sulfur Hexafluoride | 23900 |
| CFC-11 | 3800* |
| $CF_4$ | 6500 |
| $C_2F_6$ | 9200 |

*Direct only. Other estimates include indirect effects

With vegetable oils and ethanol derived from biomass, carbon dioxide emitted during combustion of the fuel is offset by that absorbed by the plant from the atmosphere during growth. However, greenhouse debits arise on the path from crop to canola or ethanol consumption in vehicles. The use of agricultural chemicals, fuelling of farm machinery, transport of the crop, processing of the crop, drying of liquid wastes and transport of canola or ethanol may all involve the use of fossil fuels and hence emissions of $CO_2$. Denitrification of fertilisers applied to the crop is also a major problem because $N_2O$, which has a high GWP, will be emitted.

These greenhouse debits are site specific because they depend on the crop grown, the source of fuel used to process the crop, and any additional release of greenhouse gases from the soil above natural levels.

### *1.6.1 Air Pollutants*

The air pollutants to be considered are carbon monoxide, oxides of nitrogen, sulfur dioxide, non-methanic hydrocarbons (NMHC), and particles with diameter less than 10 μm (PM10). These air pollutants are generated by transport vehicles, depending on the nature and composition of the fuel that is used, the type and age of the vehicle, the nature of the drive cycle, and the degree to which the vehicle is properly tuned.

Elevated concentrations of sulfur dioxide are not an issue in urban Australia (Manins et al., 2001). The only population centres to exceed the one hour standard of the ambient air quality NEPM are Mount Isa and Kalgoorlie, and in those locations the exceedances are caused by industrial emissions, not transport emissions. Accordingly, this report does not quantify sulfur dioxide emissions, but notes where they may be an issue.

NMHC exhaust emissions from conventional vehicles consist primarily of simple hydrocarbons (excluding methane). NMHC emissions from alcohol-based vehicles contain a greater proportion of very reactive and toxic compounds called aldehydes. Particles, smoke and NMHCs are composed of a mixture of many different compounds. Some of these compounds are toxic. Examples are benzene, formaldehyde, lead, chromium and benzo-a-pyrenes. In addition, alcohol blended fuels have potential evaporative emissions including unburnt alcohol.

There is a relatively small number of studies on air toxics in Australia. A greater difficulty is that there is no agreed Australian methodology for evaluating health risks associated with air toxics. This study reviews work on air toxics emissions from the fuels where such work exists, but generally had to use total hydrocarbon emissions as indicative of likely air toxics and their impact.

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# 2. Ultra Low Sulfur Diesel Summary

## *2.1 Background*

Ultra low sulfur diesel (ULSD) is diesel fuel that meets either the Euro4 fuel specifications for diesel fuel, or the fuel specifications proposed by the Commonwealth for implementation in 2006. To date, the only Euro4 fuel specification that has been established is for sulfur. Directive 98/70/EC of the European Communities in 1998 set the maximum sulfur level from 2005 as being 50 ppm. Euro3 specifications for other parameters such as the cetane number, cetane index, density, T95, and PAH levels, apply until replaced by revised specifications. These limits are shown in Table 2.1.

**Table 2.1**
**Ultra low sulfur diesel fuel quality specifications (Environment Australia, 2000a, 2000b)**

| Fuel parameter | Euro 3 (applicable from 2000) | Euro 4 (applicable from 2005) | Commonwealth (1 January 2006) |
|---|---|---|---|
| Sulfur (ppm) | 350 (max) | 50 | 50 (max) |
| Cetane number | 51 (min) | - | - |
| Cetane index | 46 (min) | - | 50 (min) |
| Density at 15$^o$C (kg/m$^3$) | 845 (max) | - | 820 to 850 |
| Distillation T95 ($^o$C) | 350 (max) | - | 360 (max) |
| PAH (% by mass) | 11 (max) | - | 11 (max) |

Diesel fuel is generally derived from light virgin gas oil that is produced from the distillation of crude oil. The distillation is conducted in Australian refineries. Low sulfur diesel is produced in refineries with a hydrodesulfurisation unit. ULSD requires either a hydrocracker, or the use of higher pressures in the hydrodesulfurisation unit (hydrofining). As at March 2001 Western Australia and Queensland had passed legislation mandating a diesel sulfur content of 500 ppm or less.

## *2.2 Results*

Two modes of ULSD manufacture are examined. The first assumes that 50% of Australian ULSD production comes from hydrocracking, and the other 50% from hydrofining. The second (marked as 100% reprocessing) assumes that all ULSD comes from hydrofining.

### *2.2.1 Greenhouse gas emissions*

Figure 2.1 depicts the greenhouse gas emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116).

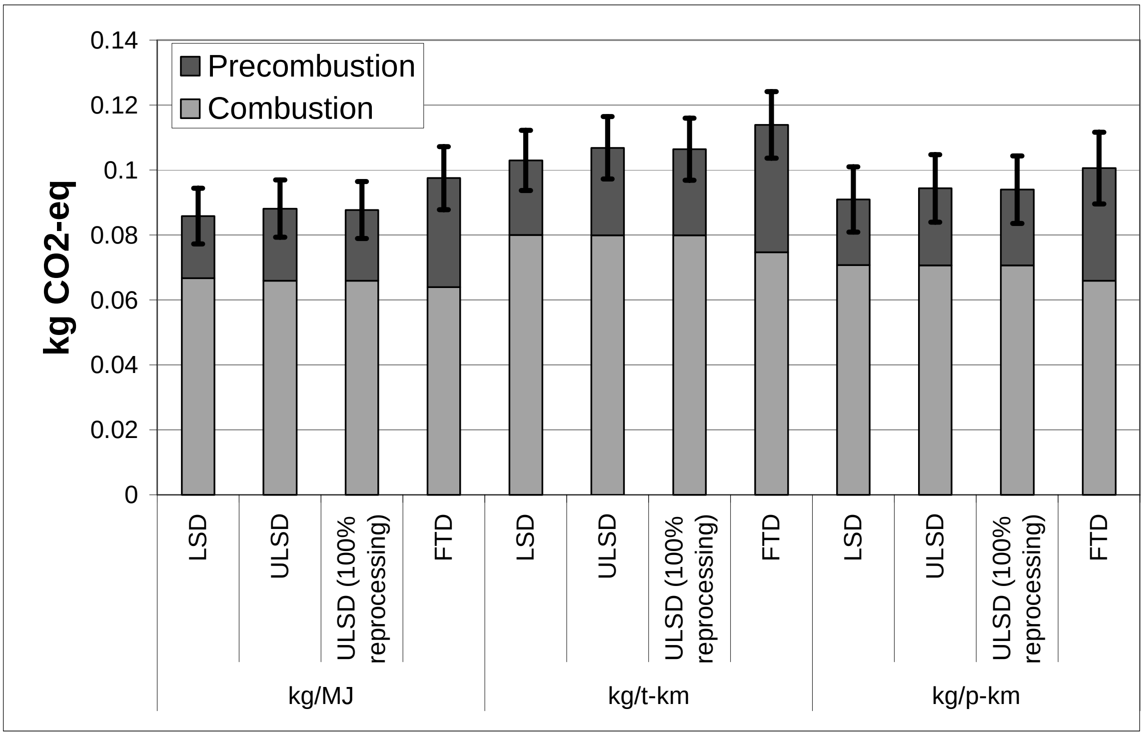


**Figure 2.1**
**Exbodied emissions of greenhouse gases for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance**

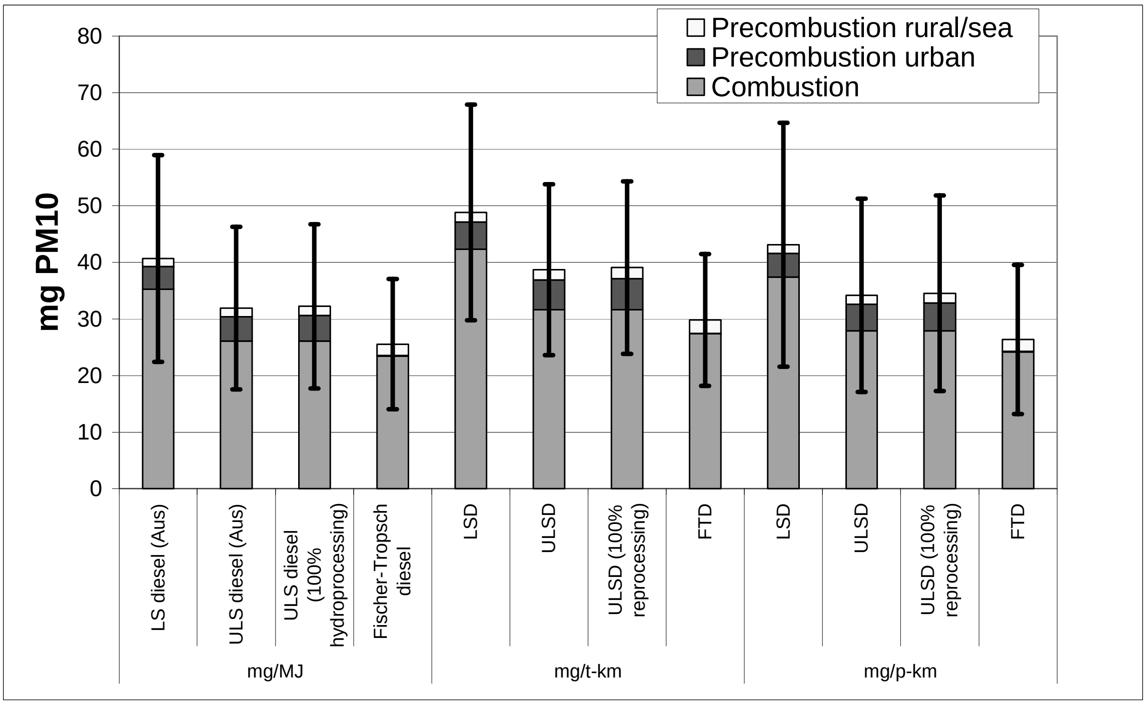


**Figure 2.2**
**Exbodied emissions of particulate matter for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance**

### *2.2.2 Particulate matter emissions*

Figure 2.2 depicts the particulate matter (PM10) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger basis for buses using the same energy intensities previously noted.

### *2.2.3 Emissions of oxides of nitrogen*

Figure 2.3 depicts the oxides of nitrogen (NOx) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger basis for buses using the same energy intensities previously noted.

### *2.2.4 Hydrocarbons*

Figure 2.3 depicts the oxides of non-methanic hydrocarbon (HC) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger basis for buses using the same energy intensities previously noted.

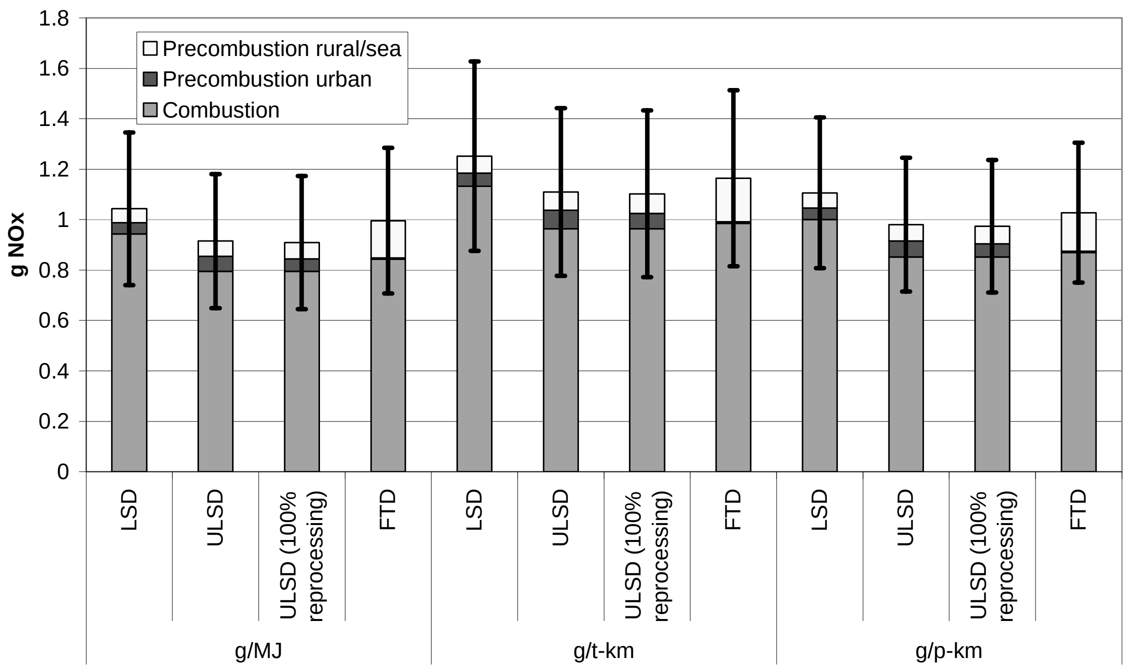


**Figure 2.3**
**Exbodied emissions of oxides of nitrogen for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance**

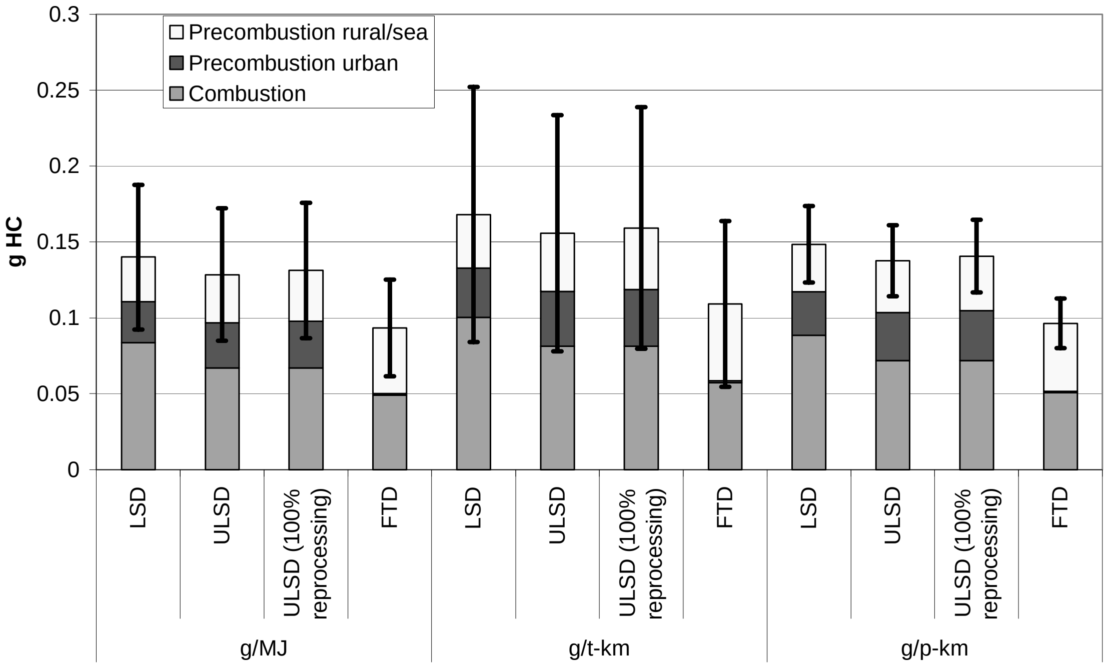


**Figure 2.4**
**Exbodied emissions of hydrocarbons for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance**

## *2.3 Viability and Functionality*

There is a need to match the fuel with the appropriate vehicle technology. The major benefits of the move to ULSD are provided by the ability to use advanced technology in the engine and the catalyst. These components are often sensitive to sulfur. We expect vehicle emissions to be lower than those presented in the results section when ULSD is used with the appropriate Euro4 fuelled engines. Using ULSD in a Euro2 vehicle provides only marginal improvement in tailpipe emissions over low sulfur diesel. However, the emissions from a Euro4 vehicle with advanced on-board diagnostics and a particulate trap will be dramatically better.

## *2.4 Health Effects*

Epidemiological evidence indicates that decreasing particle emissions reduces morbidity and reduces hospital admissions as a result of respiratory illness. At present, diesel engines are a major source of fine particles – diesel exhaust releases particles at a rate about 20 times greater than that from petrol-fuelled vehicles. Thus the combination of ULSD and particulate traps on vehicles using ULSD will have the beneficial effect of reducing the emissions of particles. ULSD upstream particulate and HC emissions are similar to LSD. ULSD tailpipe HC emissions are similar to LSD and have little effect on emissions of VOCs and aldehydes. ULSD reduces particulate emissions compared to LSD.

OH&S issues associated with ULSD are the same as those associated with LSD (the reference fuel).

## *2.5 Environmental Issues*

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on the environment arising from the introduction of low sulfur diesel and ULSD. The combination of ULSD and oxygenating catalysts or "de-NOx" catalysts will enable emissions of smog precursors to diminish, thus improving urban air quality. The upstream environmental issues associated with ULSD are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

*ESD issues*

The modern western economy is based on petroleum products, of which diesel is one. The current concern over climate change highlights the burning of fossil fuels as one of the main causes. Examined from the ESD perspective of equity, efficiency and ecological integrity, even if one argues that the fossil fuel economy is economically efficient, it is more difficult to argue that it encourages equity or ecological integrity. Climate change, and global warming in particular, pose threats to inter-generational equity.

*Sustainability*

Crude oil supplies are sustainable in the medium term (to at least 2020), though Australian imports will need to rise as the Victorian oil fields start to decline in production. The key sustainability issues for diesel fuel depend on global oil supply.

*Groundwater contamination*

Diesel is refined from crude oil. Spills of crude oil, especially during transport in oil tankers at sea, pose an environmental hazard that contaminates marine life and bird life. Environmental damage from diesel itself can also occur, especially from leaks at service stations and refuelling depots that have been known to contaminate groundwater supplies.

## *2.6 ADR Compliance*

Ultra low sulfur fuel is being introduced specifically to enable the introduction of technology to meet Euro4 fuel specifications. The ADR have been based on this fuel so that, by definition, there should be no potential to compromise vehicles' compliance with gazetted ADR standards.

## *2.7 Summary*

The advantages of ultra-low sulfur diesel are:

- ULSD contains little sulfur and few aromatics. In a properly tuned engine this is expected to lead to lower particle exhaust emissions.
- The low sulfur content means that oxidation catalysts will be more efficient.
- The existing diesel infrastructure can be used, unchanged, for ultra-low sulfur diesel.
- Low-sulfur diesel can be used in existing diesel engines.
- Diesel is one of the safest of the automotive fuels.

The disadvantages of ultra-low sulfur diesel are:

- Diesel exhaust (including ULSD exhaust) is treated by the US EPA as an air toxic.
- Because of the extra processing energy, ULSD produces more exbodied greenhouse gases than LSD.

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# 3. Fischer-Tropsch Diesel

## *3.1 Introduction*

Fischer-Tropsch diesel (FTD) is a synthetic fuel produced from the conversion of natural gas into a diesel fuel. The fuel thus formed is superior to crude-oil based diesel in certain ways, principally the high cetane number and the zero sulfur content. It is also known as GTL diesel, where the acronym refers to “gas to liquid” conversion. Gas to liquid fuels conversion is of relevance to Australia, because of the large natural gas deposits in the north-west shelf.

This study is required to use Australian data where available. At the time of writing SASOL-Chevron was not in a position to submit emissions data that would be applicable to its production of FTD and the use of FTD in Australia. It is recommended that a separate study be undertaken when that data becomes available

## *3.2 Results*

### *3.2.1 Greenhouse gas emissions*

Figure 3.1 depicts the greenhouse gas emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116).

The extra processing required to make synthetic diesel means that the exbodied emissions of greenhouse gases are greater from FTD than from LSD, even though there are lower tailpipe emissions.

### *3.2.2 Particulate matter emissions*

Figure 3.2 depicts the particulate matter (PM10) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Particulate emissions of FTD are markedly lower than those of LSD.

### *3.2.3 Emissions of oxides of nitrogen*

Figure 3.3 depicts the oxides of nitrogen (NOx) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

The upstream processing required to produce FTD means that its NOx emissions are greater than those of LSD, even though the tailpipe emissions are lower.

### *3.2.4 Emissions of hydrocarbons*

Figure 3.4 depicts the emissions of non-methanic hydrocarbon (HC) estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

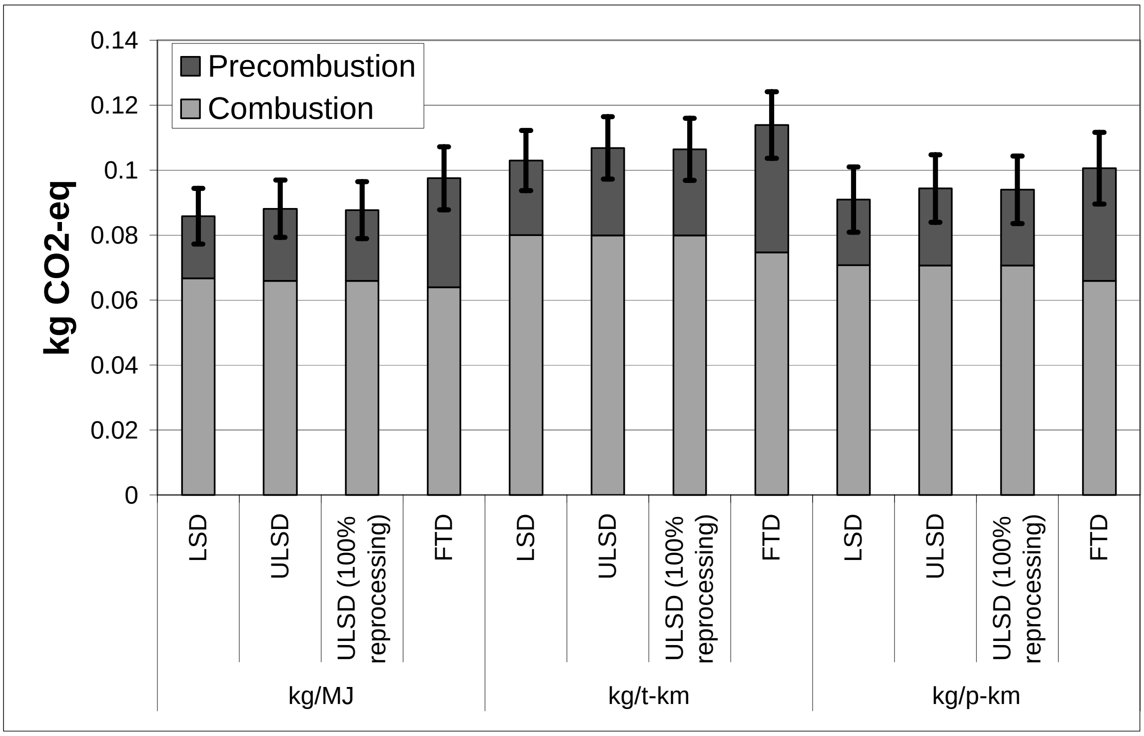


**Figure 3.1**
**Exbodied emissions of greenhouse gases for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance.**

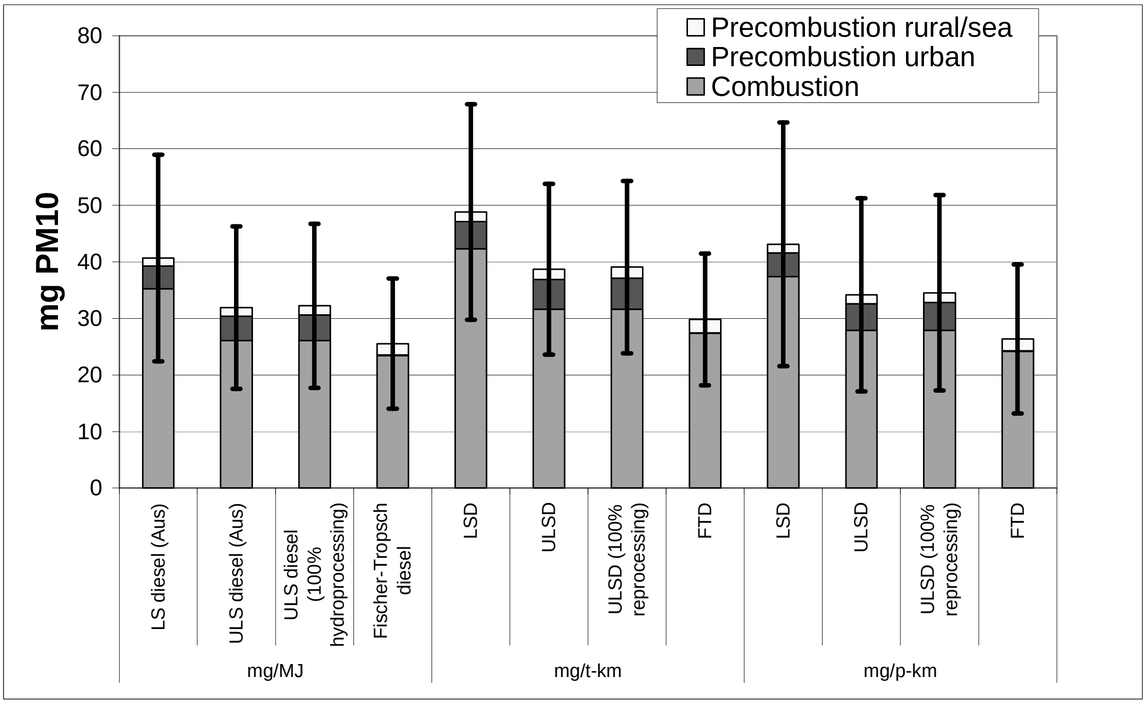


**Figure 3.2**
**Exbodied emissions of particulate matter for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance.**

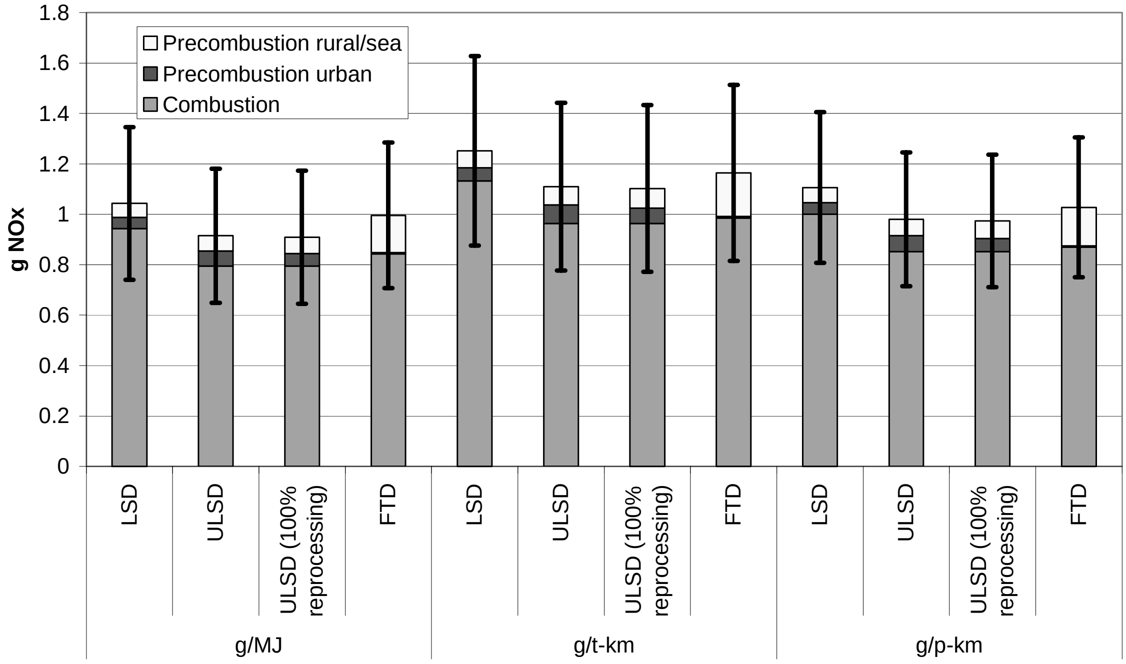


**Figure 3.3**
**Exbodied emissions of oxides of nitrogen for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance.**

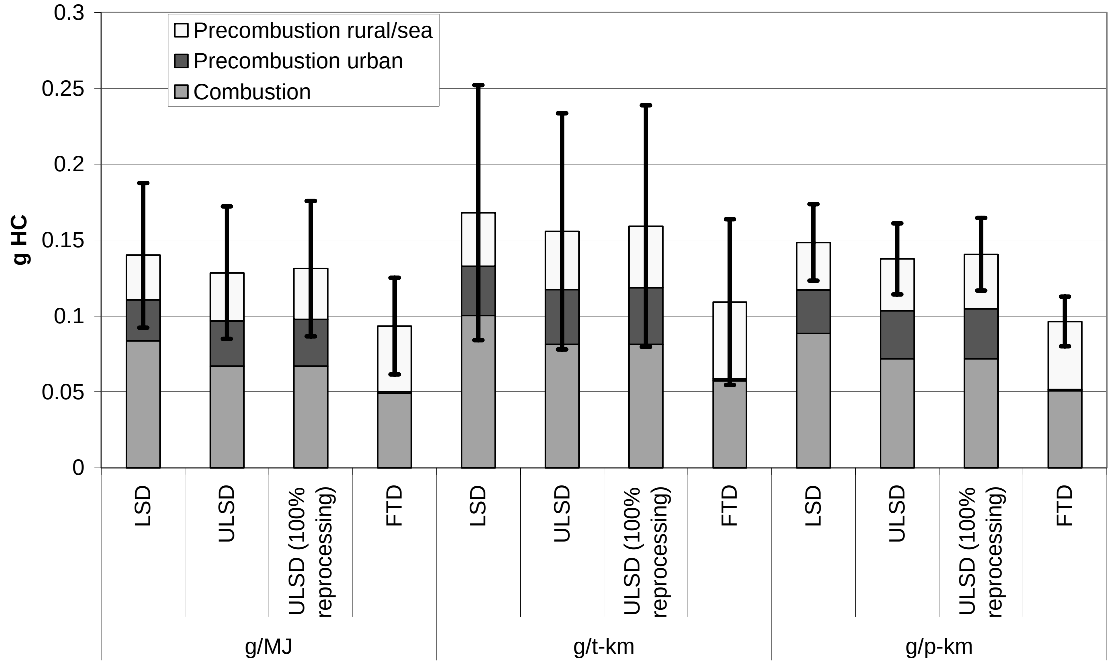


**Figure 3.4**
**Exbodied emissions of hydrocarbons for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance.**

## 3.3 Viability and Functionality

FT diesel has the same viability and functionality as diesel fuel.

## 3.4 Health Issues

FT diesel is an extremely low sulfur diesel, with sulfur content less than 10ppm. The health benefits, when compared to the low sulfur diesel reference fuel will be at least those of ultra low sulfur diesel (ULS). There are claims that there are 20% reductions in aromatics from the tailpipes of vehicles using such extremely low sulfur diesel fuels.

FT diesel upstream emissions of both particulates and HC are substantially less than for LSD. FT diesel tailpipe emissions of both particulates and HC are marginally less than for LSD.

## 3.5 Environmental Impact and Benefits

Greene (1999) comprehensively reviews the environmental issues involved with GTL fuels. The environmental impacts are the same as those for diesel fuel, with the benefit of lower air pollutant emissions and increased resource security through a lowered dependence on imported oil. An FTD plant does not produce undesirable co-products, unlike a refinery, which produces heavy fuel oil and coke.

*ESD issues*

Gas to liquids conversion is based on the use of natural gas, which is a fossil fuel. The current concern over climate change highlights the burning of fossil fuels as one of the main causes. Examined from the ESD perspective of equity, efficiency and ecological integrity, even if one argues that the fossil fuel economy is economically efficient, it is more difficult to argue that it encourages equity or ecological integrity. Climate change and global warming pose threats to inter-generational equity.

*Sustainability*

FTD is made from natural gas. Australian known reserves of natural gas are estimated to last for the next 90 years, ensuring a sustainable, indigenous supply of natural gas as the feedstock for the FTD.

*Groundwater contamination*

FT diesel does not require the transport of crude oil. Environmental damage from any liquid hydrocarbon can occur, especially from leaks at refuelling depots that may contaminate groundwater supplies.

## 3.6 ADR Compliance

Ultra low sulfur fuel is being introduced specifically to enable Euro4 fuel specifications to be met. The ADR have been based on this fuel. There should thus be no potential for an even lower sulfur fuel such as FT diesel to compromise vehicles' compliance with gazetted ADR standards.

## 3.7 Summary

The advantages of FT diesel are:

- FT diesel contains virtually no sulfur or aromatics. In a properly tuned engine this is expected to lead to lower particle exhaust emissions.
- The absence of sulfur means that oxidation catalysts and particulate traps will operate at maximum efficiency.
- The existing diesel infrastructure can be used, unchanged, for Fischer-Tropsch Diesel.
- FT diesel can be used in existing diesel engines.

- Diesel is one of the safest of the automotive fuels.
- An FT plant does not produce any of the less desirable co-products from a refinery, such as heavy fuel oil or coke.
- Provided an FT plant uses an oxygen feed, it produces a pure $CO_2$ stream that provides an option for the collection and sequestration of $CO_2$.

The disadvantages of FT diesel are:

- Diesel exhaust (including FT diesel exhaust) is treated by the US EPA as an air toxic.
- Because of the extra processing energy, FT diesel produces more exbodied greenhouse gases than any of the conventional or alternative fuels studied in this report.

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