1. Weighting Methodologies for Emissions from Transport Fuels

1.1 Introduction

1.1.1 Scope of Work

This chapter responds to a request from the Australian Greenhouse Office (AGO) to develop a weighting scheme for air quality that enables all emissions affecting air quality to be weighted and combined into a single measure of air quality. The international agreement on the use of the GWP as a weighting factor for different greenhouse gases means that it is straightforward to calculate the greenhouse gas emissions in CO_2-equivalents, and this measure can be used to compare the greenhouse gas emissions performance of different alternative fuels. There is no similar agreement in relation to other gases that fall under the general category of air pollutants.

The chapter explores alternative approaches to address the question of how to weight emissions that affect air quality. A range of models are presented that should only be considered as being illustrative of possible approaches and how they would be implemented. In section 1.4 and 1.5, the purpose of examining these models is to promote discussion about possible models and methodologies for weighting fuels, rather than a debate about the merits of each fuel.

No conclusions are meant to be drawn from the analysis of the fuels themselves in sections 1.4 and 1.5. Another approach might have been to refer to fuels “A”, “B” and “C” rather than specific fuels. However, this approach might have been considered to be too abstract. In summary, each example should be examined in terms of the merits of the model and the methodology by which it weights emissions rather than the outcome for each fuel.

Section 1.6 applies a weighting methodology as specified by Environment Australia.

1.2 Background

The air that we breathe is a mixture of many different gases. It is a mixture of 78% nitrogen, 21% oxygen, slightly under 1% argon, and about 0.037% carbon dioxide. These percentages are based on units for the gases that comprise volume mixing ratios.

We can represent such a mixture mathematically. In this case:

$$A = \Sigma w_i E_i \qquad (1)$$

where A represents air, w represents the proportions of each gas (0.78, 0.21, 0.00963, 0.00037), and E is the volume mixing ratio of each of the gases. The symbol Σ represents summation, in this case over four gases.

This simple example illustrates the difficulties that are involved in any weighting scheme. Firstly, there needs to be a decision on the choice of weights (w in this case). Secondly, there needs to be a decision as to the appropriate units for the gases (percentages by volume, in this case). Thirdly, there needs to be a decision on the number of entities to be summed.

The example given above, for air, is straightforward because its composition can be determined by direct experiment. There is another straightforward example, namely that of greenhouse gases. International agreement has been reached on how to combine greenhouse gases. Before proceeding to the more difficult case of air quality weighting schemes, the weightings used for greenhouse gases will be reviewed.

1.3 Greenhouse Gases

The Australian National Greenhouse Gas Inventory (NGGIC, 2000) follows the international agreement that Greenhouse gas emissions will be weighted using IPCC 100 year global warming potentials as given in Table 1.1.

Table 1.1
100 years global 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

This means that a measure of greenhouse gases, called the carbon dioxide equivalent (CO_2-e), is computed as:

$$CO_2\text{-e} = CO_2 + 21\ CH_4 + 310\ N_2O + 23900\ SF_6 + \ldots \qquad (2)$$

where the weights are as given in Table 1.1, and the gases are measured in units of mass per unit time, tonnes per year being a representative example.

1.4 Air Quality

There is no agreement on how to combine air pollutants. This section reviews existing available weighting methodologies.

1.4.1 Air quality indexes

Air pollution control authorities have found it useful, when presenting air quality information to the public, to use an Air Quality Index — or an Air Pollution Index — as a means of combining information on all of the pollutants.

Table 1.2
Victorian air pollution index categories

Air quality category	Associated colour	Index range
Very Good	Blue	0-33
Good	Green	34-66
Fair	Yellow	67-99
Poor	Red	100-149
Very Poor	Black	150 or higher

(Source: http://www.epa.vic.gov.au/aq/abindex.htm)

Australian authorities typically use the ratio of pollutant concentration to pollutant standard level as the basis from which to construct an air quality index. Victoria, for example, expresses the index value as a percentage that is calculated for ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, fine particles (PM10) and visibility. The maximum of these figures is taken as the index value for the relevant monitoring station, and one of five colour-coded air quality categories (from blue to black) is chosen on the basis of the index, as shown in Table 1.2.

In this case the weights, *w*, are given by

$$w = 100/(\text{value of the NEPM standard}) \qquad (3)$$

so that the measure of the pollutant, E, need to be expressed in the same units as the NEPM standard. Air pollution indexes in Australia are not based on a sum of weighted pollutants, unlike Equation (1), but are set equal to the maximum value of the weighted pollutants.

1.4.2 Stage 1 Alternative Fuels Study Method

The Stage 1 alternative fuels study (Beer et al., 2000) developed a weighting scheme to rank various alternative fuels. The scheme was based on two major criteria:

1. Health effects guided the choice of the weights, *w*.
2. The quantities being evaluated (*E*) were the **ranked score** for the pollutant.

Emissions of carbon monoxide do not cause problems in Australia, so that the study believed that it did not need to be considered in evaluating alternative fuels. NOx and NMHC (i.e. THC less methane) together are important because they are the precursors of smog. . NOx (in the form of NO_2) is linked to respiratory illness. Particulate matter is of concern because of the epidemiological evidence that particulate matter has short-term and long-term health effects, including mortality, such that a 10 $\mu g/m^3$ increase in PM10 is associated with a 1% increase in mortality.

These air pollution and health considerations indicated that fuel emissions should be considered in two classes – those used primarily in urban areas (e.g. buses), and those used primarily in rural areas (e.g. trucks). Urban vehicles need to have low emissions of NOx, THC and particulate matter. However, as smog is not a problem in rural areas, the THC and NOx levels of emission are not as important as the particulate emissions. This is especially the case as the NEPM for Ambient Air Quality seeks equal protection for all Australians. Though it may be argued that rural particulate emissions are not important because of the occurrence of natural dust, there are theories that health effects arising from inhalation of particulate matter arise only when carbonaceous particles, such as those from combustion, are inhaled. Accordingly it was recommend in Beer et al. (2000) that rural and highway air quality evaluation include particles, particularly as many small country towns sit alongside major transport routes.

Ranking (including uncertainty)

The Stage 1 study ranked the emissions according to their average characteristics in terms of global warming and pollution impact, and assigned its rank value to each gas as a score.. To allow for variation in the emission results, the gases were ranked for one standard deviation above and below their average emissions and again scored. The three scores were summed, and the final ranking based on this sum.

This method is straightforward when calculating the rankings on the basis of greenhouse gases (expressed in CO_2-equivalents). In relation to air quality, the ranking was less straightforward. Because of the concern for human health and well-being, particulate matter is believed to pose the greatest health risk. Hydrocarbons pose a health risk in the long term, as a number of compounds are carcinogenic. In addition hydrocarbons are considered to be one of the precursors for the formation of ozone, and reductions in hydrocarbon are the most effective way of reducing ozone. Oxides of nitrogen are also ozone precursors, and NO_2 poses a health risk at high concentrations (which are rarely found in Australian cities). Finally, carbon monoxide poses a health risk at concentrations that do not occur in Australia.

It was thus decided to weight the air pollutants on the basis of their health risk.

Air pollution health risk

The NEPM for Ambient Air Quality (National Environment Protection Council, 1998) provides estimates of the short-term health effects of the criteria pollutants.

CO – Loss of 1 day's earning for 50,000 people at a cost of $6 million. (National Environment Protection Council, 1998: p.52)

NO_2 – 10 to 15% of the population display respiratory symptoms at a cost of $5 million. (National Environment Protection Council, 1998: p. 61)

O_3 – Up to 10 deaths per year in Australia, with total costs up to $810 million. (National Environment Protection Council, 1998: p.75-76)

PM - Up to 2,400 deaths per year in Australia, with an associated health cost of $17.2 billion. (National Environment Protection Council, 1998: pp.122 & 127)

In the absence of more detailed information, the health effects related to ozone (O_3) are ascribed equally to NOx and hydrocarbons. (National Environment Protection Council, 1998: p. 78)

In addition, hydrocarbons have long-term health effects that were examined by Hearn (1998) for Melbourne. If we extrapolate his figures to all of Australia then there are approximately 1250 to 1785 deaths per annum as a result of hydrocarbons (excluding deaths ascribed to the particulate matter in the hydrocarbons).

Insufficient is known about the source of the particulate matter to determine how much of it is attributable to traffic, and how much of the health effects are attributable to traffic. Industry emits particles, but these are generally in the larger size ranges. Present evidence indicates that most health effects result from the smaller sizes below PM10. Traffic emits most particles in the PM2.5 size range. Information on emissions alone does not provide insights into the contribution of traffic to airborne concentration of particles other pollutants will form secondary particulate matter. This report has examined particulate matter emissions as PM10.

The main health risk for Australians arises from particulate matter and from hydrocarbons. Given the considerable uncertainties associated with these estimates of mortality, and the costs of morbidity, the health risk weighted air quality rankings were as follows:

The summed score for particulate matter was multiplied by 2, the summed score for hydrocarbons was multiplied by 1, the summed score for NOx was multiplied by 0 (i.e it was ignored because less than 0.2% of health effects are related to NOx),, and the summed score for carbon monoxide was multiplied by 0 (i.e it was also ignored because less than 0.2% of health effects are related to CO),, and the totals added together to produce a final air quality score, as shown in Table 1.3.

Table 1.3
Fuel scores and final ranking in relation to air quality; the lowest value denotes the lowest emissions

Fuel	**CityPM**	**CityHC**	**City NOx**	**CityAQ**	**CityAQ**	**Hwy PM**	**HwyHC**	**Hwy NOx**	**HwyAQ**	**HwyAQ**
				Score	**Rank**				Score	**Rank**
Weight	2	1	0			2	1	0		
Diesel	28	25	24	81	**10**	14	17	17	45	**5**
LSD	15	15	20	45	**4**	16	10	15	42	**4**
LSD+W5	21	10	19	52	**5**	20	11	24	51	**7**
ULS	18	19	14	55	**7**					
ULS+W5	21	14	13	56	**8**					
LPG	9	4	4	22	**1**					
CNG	3	18	7	24	**2**	7	3	7	17	**1**
LNG	6	32	33	44	**3**	3	18	3	24	**2**
E95	15	24	7	54	**6**	8	24	8	40	**3**
BD20/35	29	17	30	75	**9**	16	14	20	46	**6**
BD100	33	20	27	86	**11**	24	11	14	59	**8**

1.4.3 Load-based licensing valuation methods

As a result of the NSW load-based licensing legislation, there has been substantial activity devoted to assigning the load valuation to be placed on airborne pollutants. The Environment Protection Authority (1997) produced a table of results, based on cost-benefit analyses of health effects, which are reproduced in Table 1.4. The pollutants are intended to deal with motor vehicle emissions. The dollar values are determined on the basis of the mean of valuations for US and European conditions.

Table 1.4
Valuation of airborne pollutants from motor vehicles (Environment Protection Authority, 1997)

Pollutant	**Valuation ($/kg)**
Particles	1.81
CO	0.025
NO_X	1.49
Total hydrocarbons (THC)	0.96

Thus, in some respects the valuation weighting method – being based on health risk weightings, agrees with the philosophy of the Stage 1 weighting method. It may be noted that when expressed in dollars per tonne, the numerical value for particles is approximately equal to the annual number of deaths in Australia attributed to particulate matter. With this in mind, some of the actual values appear curious. NOx, for example, appears to have a much higher value than one would expect on the basis of expected Australian health effects. However, applying the weights directly to mass emissions (rather than ranked scores) leads to a far more significant difference. To appreciate this difference, Table 1.5 has used the results of Beer et al. (2000: Table 3.1) to determine load valuations for tailpipe emissions of urban buses. Because of the combination of high NOx emissions (on a g/km basis) and a high NOx valuation, the resulting load valuation rankings are dominated by NOx.

Table 1.5
Load valuation (c/km) for tailpipe emissions from urban buses

Fuel	CO (g/km)	THC (g/km)	NOx (g/km)	PM (g/km)	c/km
Biodiesel	7.68	0.84	17.2	0.6	2.77
CNG	0.66	2.75	9.87	0.05	1.75
Diesel	1.88	1.1	15	0.47	2.43
E95	14.6	4.85	7.83	0.21	1.71
LNG	9.05	2.45	32.5	0.01	5.10

1.4.4 Index-based weighting (hazard-quotient method)

By analogy with the construction of an air pollution index, it is possible to construct a fuels emission index based on the emission standards specified under either the Australian Design Rules or the European emission standards. This task will now be undertaken on the basis of the Euro4 ETC standards for heavy vehicles.

The Euro4 standards are based on vehicle emissions in units of g/kWh, which have been converted to g/MJ. The standards are given in Table 1.6.

Table 1.6
Euro4 emissions standards (g/MJ) for heavy vehicles

Pollutant	CO	NMHC	NOx	PM	CH_4
g/MJ	1.11	0.015	0.97	0.0083	0.31

Beer et al. (2000), in Table A4.1 of their Appendix 4, provide a table of emissions for buses expressed in g/MJ. The diesel fuel in this study was regular diesel used in US buses with engines that corresponded to Euro2 standards. These are reproduced in Table 1.7. These values enable one to construct a fuels emission index based on the sum of the ratios. The ratios are determined by the ratio of the emission to the Euro4 standard. These are given in Table 1.8. The introduction of advanced technologies will lead to improvements in all of the fuels.

Table 1.7
Tailpipe emissions from urban buses (g/MJ)

Fuel	CO (g/MJ)	THC (g/MJ)	NOx (g/MJ)	PM (g/MJ)	c/km
Biodiesel	0.521	0.054	1.176	0.041	0.001
CNG	0.027	0.111	0.398	0.002	0.101
Diesel	0.092	0.055	0.736	0.023	0.001
E95	0.641	0.213	0.345	0.009	0.004
LNG	0.382	0.113	1.332	0.001	0.102

Table 1.8
Fuels emission index for each pollutant, and the summed index

Fuel	CO (g/km)	THC (g/km)	NOx (g/km)	PM (g/km)	CH_4	Sum
Biodiesel	0.5	3.6	1.2	4.9	0.0	10.2
CNG	0.0	7.4	0.4	0.2	0.3	8.4
Diesel	0.1	3.7	0.8	2.8	0.0	7.3
E95	0.6	14.2	0.4	1.1	0.0	16.2
LNG	0.3	7.5	1.4	0.1	0.3	9.7

1.5 Air Toxics

Nolan-ITU (2001) reviewed and extended the valuation of airborne pollutants based on the NSW 1998 proposed pollution controls. They recommend a value of $0.96/kg for methane (apparently equating methane with total hydrocarbons). They obtained substantially different valuations for a number of the pollutants. Particulate matter increased to a value of $9.40/kg and oxides of nitrogen increased to $3.82/kg. The most dramatic change was in the valuation for hydrocarbons. The valuation for total hydrocarbons according to the 1998 proposed pollution controls was set at $3.52/kg, but the value for chlorinated and aromatic hydrocarbons was set at $5,873/kg.

The reason for this is that the term chlorinated and aromatic hydrocarbons is being used to encompass those chemicals that cause cancer. The US EPA designated toxics emitted from conventional automobile exhaust and evaporative emissions are benzene, 1,3-butadiene, formaldehyde, acetaldehyde, and polycyclic aromatic hydrocarbons. The US EPA also designated diesel particulate matter to be an air toxic. The Environment Australia list of priority air pollutants under the air toxics program does not include diesel exhaust, but consists of 32 pollutants, including the other ones in the US EPA list.

MacLean (1998) and MacLean & Lave (2000) calculate weighted emissions of toxics from conventional and alternative fuels. Their weighting scheme is based on the occupational health and safety based threshold limit value (in mg/m^3) for 1,3-butadiene as 4.4 mg/m^3 , a value for benzene as 1.6 mg/m^3, formaldehyde as 0.9 mg/m^3, acetaldehyde as 360 mg/m^3, and diesel particulate matter as 0.15 mg/m^3. They did not examine polycyclic aromatic hydrocarbons as such. Thus, according to these values, the diesel particulate matter is the most toxic and acetaldehyde is the least. Their results for the total emissions (in grams) over the life of a vehicle are shown in Tables 1.9 and 1.10, where Table 1.9 shows the unweighted emissions (ie the weights are unity), and Table 1.10 shows the weighted emissions.

Table 1.9
Vehicle exhaust toxic emissions (grams per lifetime) from conventional and alternative fuels (Maclean, 1998)

Fuel	Benzene	1,3-butadiene	Formaldehyde	Acetaldehyde	Diesel PM	Aggregate toxics
Petrol	1540	112	252	168	-	2072
E85	161	18	672	3010	-	3861
CNG	4	0	175	20	-	199
Diesel					12,000	12,000

Table 1.10
Weighted vehicle exhaust toxic emissions (grams sulfuric acid equivalent per lifetime) from conventional and alternative fuels (Maclean, 1998)

Fuel	Benzene	1,3-butadiene	Formaldehyde	Acetaldehyde	Diesel PM	Aggregate toxics
Petrol	963	25	280	0.5	-	1268
E85	101	42	747	8.4	-	860
CNG	3	0	194	0.1	-	197
Diesel					80000	80000

The calculation of toxic risk from vehicle emissions has received considerable attention in California. The procedure adopted by the Office of Environmental Health Hazard Assessment (OEHHA) is to derive the toxic risk by using unit risk factors as the weighting coefficients (Marty, 2000). Table 1.11 gives values of these toxic risk factors for emissions that are liable to occur from alternative transport fuels as reported by OEHHA (1999).

Table 1.11
Unit risk factors for carcinogenic air toxics

	Benzene	1,3-butadiene	Formaldehyde	Acetaldehyde	Diesel PM	Polyclic Aromatic Compounds
$(\mu g/m^3)^{-1}$ (Swedish study)	$8 x10^{-6}$	$300 x10^{-6}$	$100 x10^{-6}$	$2 x10^{-6}$	$70 x10^{-6}$	$2.8 x 10^{-2}$
$(\mu g/m^3)^{-1}$ (OEHHA, 1999)	$2.9 x 10^{-5}$	$1.7x10^{4-}$	$6.0x10^{-6}$	$2.7x10^{-6}$	-	-
ppm (OEHHA, 1999)	$9.3x10^{-5}$	$3.7x10^{-4}$	$7.0x10^{-6}$	$4.8x10^{-6}$	-	-

An analysis from Sweden that is reported by Ospital (2000) followed a similar procedure but used substantially different unit risk factors, as also shown in Table 1.11. These values were then applied to the emissions from various alternative fuelled buses. Table 1.12 gives the comparison between the results using the Californian risk factors and the Swedish risk factors when the risk weighted emissions are normalised to that of uncontrolled ultra-low sulfur diesel, as used in Sweden.

Table 1.12
Relative Potency Weighted Emissions (Ospital, 2000)

Fuel/Treatment	Relative emissions using OEHHA risk factors	Relative emissions using risk factors from the Swedish study
Diesel	100	100
Diesel with catalyst	85	31
Diesel with particulate filter	10	37
Diesel, DPF+EGR	7.5	38
Ethanol with catalyst	4.9	88
CNG “Average”	6.1	110
CNG “BAT”	3.1	55

1.6 ADR and Fuel Quality Review Method

According to information received from Environment Australia, the Regulatory Impact Statements accompanying the 1999 Australian Design Rules for Vehicle Emissions and the Fuel Quality Standard Bill (2000) used economic weightings for the criteria pollutants determined by the NSW Environment Protection Authority. Environment Australia requested that we examine the results using these weightings as given in Table 1.13 (where it has been assumed that all NOx transforms to NO_2).

Table 1.13
ADR/FQR weights ($/tonne)

Pollutant	PM	HC	NOx	CO
$/tonne	$17,600	$1,440	$1,385	$12

These weights were examined with the results from the life-cycle analysis. The results of their application to low sulfur diesel in trucks are given in Table 1.14, and are shown for all of the fuels examined in this study in Table 1.15.

Table 1.14
ADR/FQR weights applied to exbodied emissions from low sulfur diesel

Pollutant	PM	HC	NOx	CO	
Weights	$17,600	$1,440	$1,385	$12	$/tonne
Emissions	0.428	2.62	11.0	2.71	g/km
Weighted emissions	7533	3773	15235	32.5	μ$/km

The results of Table 1.13 and Table 1.14 occasioned considerable comment when discussed with stakeholders during a forum held in June 2001. Some stakeholders (primarily representing biodiesel producers) felt that the weight assigned to PM was too high. Others (ANGVC, EPA Victoria) felt that the weighting assigned to PM was too low. We agree with the latter group. On the basis of the weightings that we were asked to use, fuels that decrease their NOx emissions are favoured over fuels that decrease particulate matter emissions. This weighting assigns greater value to the reduction of urban smog than to the preservation of human health. This is not in accord with current Australian air quality objectives as encapsulated in the desired environmental outcome of the Ambient Air Quality NEPM, namely the adequate protection of human health and well-being.

Environment Australia has requested that the following statement be included regarding the weightings:

> "Environment Australia recognises the lack of certainty in the results of the weighting exercise. These results have value in indicating the relative impact of various fuels on emissions of concern to the Commonwealth. Ultimately, however, future policy development will require the Commonwealth to determine the most cost-effective means of addressing priority pollutants/air toxics. For this reason, the Commonwealth would be concerned if stakeholders took the results of Part 3 as solely determinative of future policy directions."

Table 1.15
Weighted emissions obtained (in µ$/km) for trucks using alternative fuels on the basis of exbodied emissions

Fuel and processing method	HC	NOx	CO	PM10	Total
LS diesel (Aus)	2173	15581	33	7716	25502
ULS diesel (Aus)	1963	13712	41	6058	21773
ULS diesel (100% hydroprocessing)	1938	13504	41	6039	21521
Fischer-Tropsch diesel	1531	15117	30	4834	21512
Biodiesel (canola)	2072	17860	20	5235	25188
Biodiesel (soybean)	2461	17694	26	5145	25327
Biodiesel (rape)	2087	18109	20	5343	25559
Biodiesel (tallow-expanded sys. boundary)	2029	17805	20	5221	25075
Biodiesel (tallow-eco.allocat.)	864	16321	864	4833	22883
Biodiesel (waste oil)	860	16294	17	4828	21998
Biodiesel (waste oil 10% original oil value)	874	16363	17	4828	22083
CNG (Electric compression)	422	2123	1	211	2758
CNG (NG compression)	461	2308	2	228	2998
LNG (from existing transmission line)	454	3210	2	103	3768
LNG (Shipped from north west shelf)	455	3235	2	108	3799
LNG (perth)	490	3797	2	451	4739
LPG (Autogas)	1595	2114	5	1703	5417
LPG (HD5)	1632	6256	5	1245	9137
LSdiesohol	2046	14310	36	6010	22402
Ethanol azeotropic (molasses-expanded sys.bound.)	1160	14072	39	5510	20781
Ethanol azeotropic (molasses-economic allocation)	1200	12227	127	5059	18613
Ethanol azeotropic (wheat starch waste)	1121	12945	39	5062	19167
Ethanol azeotropic (wheat)	2102	15831	135	5716	23784
Ethanol azeotropic (wheat) fired with wheat straw	8255	15277	299	9416	33247
Ethanol azeotropic (woodwaste)	5317	12662	168	7445	25592
Ethanol azeotropic (ethylene)	9608	16800	46	5952	32407
PULP	593	619	27	1628	2867
E10PULP (molasses-exp.sys.bound.)	482	599	23	1626	2731
E10PULP (molasses-eco.allocat.)	482	573	24	1619	2699
E10PULP (wheat starch waste)	481	574	23	1624	2703
E10PULP (wheat)	495	614	24	1626	2760
E10PULP (wheat WS)	605	605	27	1691	2928
E10PULP (wood waste)	563	567	25	1663	2819
E10PULP (ethylene)	602	628	23	1630	2883
E85PULP (molasses-exp.sys.bound.)	457	810	29	1588	2884
E85PULP (molasses-eco.allocat.)	465	474	45	1505	2489
E85PULP (wheat starch waste)	449	477	29	1576	2531
E85PULP (wheat)	628	1002	47	1588	3264
E85PULP (wheat WS)	2019	876	84	2427	5405
E85PULP (wood waste)	1489	400	60	2068	4018
E85PULP (ethylene)	2005	1176	30	1637	4848
Hydrogen (from natural gas)	516	787	2	128	1432

1.7 Discussion

The choice of any weighting scheme for road transport emissions must meet two criteria of acceptability. The scientific aspects of the scheme must be acceptable, and the public policy aspects of the scheme must be acceptable.

The ambient air quality NEPM declared that "the desired environmental outcome of this Measure is ambient air quality that allows for the adequate protection of human health and well-being." Ever since then it has been accepted that health-risk weighting of pollutants is the most appropriate weighting scheme. However, the science in this area is changing rapidly (Beer, 2000) so that weightings that were deemed appropriate in 1997 or 1998 may no longer be deemed appropriate today. In particular, in Table 1.4, and even more so in Table 1.15 and 1.16, the relatively high weighting (as expressed by a high price) for NOx and the relatively low weighting for particulate matter do not agree with the present consensus of the Australian health effects of the criteria pollutants as summarised in section 1.4.2. This also reflects the current view in the US. In the appendix to Ospital (2000) the California EPA states that: "It is possible to use the total PM emissions on a mass basis as a rough surrogate for the non-cancer health effects related to particulate matter emissions from both conventionally and alternatively fuelled engines".

Australian public policy in this area is also in a state of rapid flux. Environment Australia released the final draft of its Air Toxics State of Knowledge report[1] in late 2000. Both the NEPC and the EnHealth Council continue to examine the way to use risk assessment within Australia. This means that there are no agreed Australian unit risk factors to use for cancer risk. In addition, it is uncertain whether there are sufficient data on emissions from Australian conventional and alternative fuelled vehicles to enable adequate speciation of air toxics to take place.

Given the present state of knowledge in this area, the weightings adopted in the Stage 1 report, as described in section 1.4.2 of this chapter, reflect the present understanding. Cancer risks are assigned to the total hydrocarbons. The practice of using total hydrocarbons emissions as an indication of air toxics and their impacts has severe limitations. The composition of the mixture of hydrocarbons in exhaust will vary with fuel. Where total hydrocarbons is used as an indicator for relative importance of air toxic emissions the results are indicative only. Particulate matter is weighted according to recent epidemiological results. The relative magnitude of the final weighted values should be in the same proportion to the mortality attributable to each pollutant. Given that the ratio of HC to PM is in the expected ratio of 1 to 2, we conclude that in the ADR/FQR weightings (given in Table 1.14) the NOx weighting appears to be far too high in comparison to the HC and PM weightings.

However, we suspect that all the air quality valuations are too low. Representative valuations for CO_2 range from \$5 per tonne to \$500 per tonne. If we use a value of \$50 per tonne (the geometric mean of the range of estimates)[2], and note that a typical bus emits 1,300 g/km of CO_2, then the valuation associated with exbodied greenhouse gases is µ\$65,000/km for greenhouse gases emitted using low sulfur diesel, compared to about µ\$25,000/km for criteria pollutants emitted from low sulfur diesel. Surveys of the Australian public regularly reveal that air quality is considered to be a much higher environmental priority than greenhouse gases. This seems to indicate that weightings that lead to a total valuation for air quality that is about one-third that of greenhouse gases are unlikely to be correct weightings.

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[1] http://www.environment.gov.au/epg/airtoxics/sok_final_draft.html

[2] This figure has been chosen by the consultants as being a representative one for calculations. It has not been endorsed by the Australian Greenhouse Office and should not be taken to indicate a policy position on the part of the AGO.

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2. Modelling Emission Standards and Driving Conditions

2.1 Modelling the Influence of Future Emission Standards

2.1.1 Introduction

The terms of reference require an examination of the fuels to determine whether each fuel is likely to meet future Australian Design Rules for vehicular emissions. This point has been examined for each fuel in Parts 1 and 2 but is explored in more technical detail in this chapter.

An approximate method for including the effect of future emission standards was developed for the technical study on fuels technology related to the Auto Oil 2 Program. The final report by Arcoumanis (2000) was released in December 2000 by the EC's Directorate-General for Energy. This was a survey of best available information on emissions and energy efficiency for a more limited range of fuels than are considered here. It introduced the concept of emission factors related to a base of Euro2, the same base that has been followed in this work where possible. The emission factors are developed from consideration of a range of influences of alternative fuels on combustion and other engine characteristics.

2.1.2 Methods

In this project an attempt is made to estimate future emission factors by considering the changes that may occur in the near future that could influence engine and vehicle technology, and the interaction of this with the fuel. For each regulated pollutant, CO, HC, NOx, PM and for CO_2 factors have been estimated, and then these are multiplied by the ratio of the new emission standard to Euro2 for each of the regulated pollutants. For CO_2, since there are no regulated emissions standards in place at this time, the Euro3/Euro2 and Euro4/Euro2 factors were considered as unity.

No allowance has been made for the different implementation times of the Euro standards in Australia to Europe. The time lags have been regarded as technology transfer times. However, experience with emission control equipment has indicated that the lags often allow the Australian implementation of more mature technology which might be expected to improve the emission factors. Here these benefits are assumed to be the same for the low sulfur diesel reference fuel and the alternative fuel technology.

The implication in the methodology is that in the absence of any special problems or benefits the reduction in alternative fuel performance will be similar to the reduction for a given pollutant as expected from the change in the emission standards.

Engine parameters that have an effect on exhaust emissions have been divided into the following groups (Arcoumanis, 2000):

1. Engine breathing - this determines the amount of mixture/air entering the cylinders and participating in combustion which controls the mass of exhaust pollutants.
2. Mixture preparation - which influences the local fuel air ratio in the engine and has influence on pollutant formation and emissions exiting from the exhaust.
3. Combustion - this influences the formation of pollutants in the cylinder as a function of the local thermodynamic conditions.
4. Exhaust after treatment - this determines the percentage of formed pollutants escaping in the atmosphere.
5. Engine/fuel compatibility - which determines the degree of positive or negative interaction of the given of alternative fuel with components of the fuel injection system.

6. Engine deterioration in use - this depends on the maintenance standards and the state of the engines exhaust emissions and any variation with time that may vary from the standard low sulfur diesel fuel.

It is important to note that the multiplying parameter n_{total} is a product of parameters just described. Thus for a fuel where the n_{total} coefficient is 0.8, this value would express that this particular alternative fuel has some advantage compared with the low sulfur diesel reference fuel. Conversely, a coefficient of 1.5 would indicate a major difficulty with respect to the pollutants being considered. The parameter EF given the following tables thus represents the final merit of an alternative fuel including the expected reduction factor of the changed emission standards. In order to make this clear the first table presented shows the Euro factors being the ratio of Euro4 to Euro2.

In summary the following equation forms the basis for the model

$$\mathbf{EF_{Euro3/4} = EF_{Euro2} \cdot n_{total} (R_{Euro3/4}/R_{Euro2})} \quad (1)$$

where

$n_{total} = n_{br.}\, n_{mp.}\, n_{cmb.}\, n_{ea.}\, n_{fc}$

and

n_{br} = engine breathing coefficient

n_{mp} = mixture preparation coefficient

n_{cmb} = combustion coefficient

n_{ea} = exhaust after-treatment coefficient

n_{fc} = fuel/engine compatibility coefficient

$R_{Euro\ 3/4}$= regulated emission limit for a particular pollutant for Euro3/4 (in Europe in 2000/5 and Australia in 2005/8)

R_{Euro2} = regulated emission limit for a particular pollutant in 2002 (Euro2)

2.1.3 Emission factors for Euro3 and Euro4

Most of the coefficients in Equation 2.1, for the fuels given in Tables 2.1 –2.7, have values taken from the Auto-Oil II program (Arcoumanis, 2000). Where necessary, errors or inconsistencies in that work have been rectified. For some tables new factors have been generated based on the team's knowledge and this review of the literature.

The tables which follow are restricted to Factors for Heavy Duty Vehicles and Buses. Only the last table refers to PULP plus E10 for passenger cars and Light Duty Vehicles.

2.1.4 Concluding remarks

This section has evaluated, through the process used in the Auto Oil II program, the prospects and difficulties that alternative fuels may suffer as a consequence of tightening emissions standards through Euro3 and Euro4 from a base of Euro2. These results have been tabulated and presented in each Chapter of Part 2 under the heading "Expected Future Emissions".

Most fuels (including BD30) continue their relative advantages during the period of these tighter emission standards. The apparent exceptions are 100% biodiesel (PM > Euro3, NOx > Euro3 and Euro4), ethanol (THC > Euro3 and Euro4) and possibly diesohol.

Table 2.1
Future emission factors for heavy duty vehicles and buses for CNG/LNG

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**0.3**		**0.9**		**0.2**		**0.1**		**1.0**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	0.9	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	0.9	0.60	1.1	0.71	0.9	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.2	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	0.972	1.0	1.1	1.0	0.9	1.0	1
Euro 3 EF			**0.16**		**0.52**		**0.16**		**0.06**		**1.00**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.1	0.50	1.0	0.13	1.1	1
	n_{ea}	1.1	n_{total}	1.1	n_{total}	0.9	n_{total}	0.9	n_{total}	1.0	n_{total}
	n_{fc}	1.1	1.21	1.1	1.21	1.0	0.99	0.9	0.81	0.9	0.99
Euro 4 EF			**0.14**		**0.46**		**0.10**		**0.01**		**0.99**

Source: Arcoumanis(2000)

Table 2.2
Future emission factors for heavy duty vehicles and buses for LPG

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**0.4**		**0.5**		**0.3**		**0.3**		**1.1**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	0.9	0.71	1.0	0.67	0.9	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.1	1.1	1.0	0.9	1.0	1	1.0	0.9
Euro 3 EF			**0.21**		**0.33**		**0.19**		**0.20**		**0.99**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	0.9	1
	n_{ea}	1.0	n_{total}	0.9	n_{total}	1.1	n_{total}	0.9	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	0.90	1.0	1.10	0.9	0.81	1.0	0.9
Euro 4 EF			**0.15**		**0.19**		**0.17**		**0.03**		**0.99**

Table 2.3
Future emission factors for heavy duty vehicles and buses for 100% biodiesel

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**0.8**		**0.7**		**1.0**		**1.0**		**1.0**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.1	0.71	0.9	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.1	1.1	1.1	1.21	1.1	0.99	1.0	1
Euro 3 EF			**0.42**		**0.46**		**0.86**		**0.66**		**1.00**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.1	0.50	0.9	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1.1	1.0	0.9	1.0	1
Euro 4 EF			**0.30**		**0.29**		**0.55**		**0.12**		**1.00**

Table 2.4
Future emission factors for heavy duty vehicles and buses for diesohol

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**1.1**		**1.1**		**0.8**		**0.6**		**0.4**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.0	0.71	1.0	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 3 EF			**0.58**		**0.66**		**0.57**		**0.40**		**0.40**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 4 EF			**0.41**		**0.46**		**0.40**		**0.08**		**0.40**

Table 2.5
Future emission factors for heavy duty vehicles and buses for E85

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**1.1**		**1.1**		**0.8**		**0.6**		**0.4**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.0	0.71	1.0	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 3 EF			**0.58**		**0.66**		**0.57**		**0.40**		**0.40**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 4 EF			**0.41**		**0.46**		**0.40**		**0.08**		**0.40**

Table 2.6
Future emission factors for heavy duty vehicles and buses for hydrogen (Combustion Engine)*

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**0.05**		**0.02**		**0.2**		**0.01**		**0.01**	
Euro 3	n_{br}	0.9		0.9		0.9		0.9		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	0.9	0.53	0.9	0.60	1.1	0.71	0.2	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	0.765	1.0	0.765	1.0	0.935	1.0	0.17	1.0	1
Euro 3 EF			**0.02**		**0.01**		**0.13**		**0.00**		**0.01**
Euro 4	n_{br}	0.9		0.9		0.9		0.9		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.1	0.50	0.2	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	0.85	1.0	0.85	1.0	0.935	1.0	0.17	1.0	1
Euro 4 EF			**0.02**		**0.01**		**0.09**		**0.00**		**0.01**

* Fuel Cell vehicles assumed to emit only water vapour.

Table 2.7
Future emission factors for passenger cars and light duty vehicles for PULP

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**0.4**		**0.4**		**0.4**		**0.4**		**0.4**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.0	0.71	1.0	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 3 EF			**0.21**		**0.24**		**0.29**		**0.27**		**0.40**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 4 EF			**0.15**		**0.17**		**0.20**		**0.05**		**0.40**

Table 2.8
Future emission factors for passenger cars and light duty vehicles for E10PULP

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**1.1**		**1.1**		**0.8**		**0.5**		**1.0**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.1	R_3/R_2	1.1	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.0	0.71	1.0	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.1	n_{total}	1.1	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1.1	1.0	1.21	1.0	1.1	1.0	1	1.0	1
Euro 3 EF			**0.64**		**0.80**		**0.63**		**0.33**		**1.00**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.1	R_4/R_2	1.1	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.1	n_{total}	1.1	n_{total}	0.9	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1.1	1.0	1.21	1.0	1.1	1.0	0.9	1.0	1
Euro 4 EF			**0.45**		**0.56**		**0.44**		**0.06**		**1.00**

2.2 Modelling the Influence of Driving Conditions.

2.2.1 Introduction

The terms of reference require an examination of the fuels to determine approaches that would enable the downstream emissions from fuel and technology combinations to be approximated without conducting a large scale tailpipe emissions testing program.

This section of the chapter provides an initial appreciation of the effect of a range of urban and rural driving conditions on the greenhouse gas emissions of selected fuels. All of the results in the comparison of emissions with the base line diesel fuel have been made using data from the Euro 2 test schedule for vehicles or engines. The weighting applied to the 13 modes of this engine test schedule is somewhat arbitrary, reflecting a simplistic allocation of engine load and speed. The reference vehicles are a conventional diesel engined, standard 59 seat bus and a 45 tonne articulated truck..

2.2.2 Modelling methodology

The model used for the analysis is a deterministic one, of the engine mapping type. The computer program, MEEDAM (Model for Emissions and Energy Dissipation for Analysis of Missions) is a derivative of the main-frame models first used in late 1980's (Khatib and Watson, 1986) and developed for the SAE-A, as a commercial package, to allow operators when purchasing new trucks to be informed on the relative fuel efficiency of variants available from the manufacturer.

Central to the model are measured maps of engine performance, which describe an engine's emission or fuel rate use over the usable range of torque (positive and negative) and engine speed. The engine maps comprise emission rates of hydrocarbons, oxides of nitrogen, carbon monoxide or particulates and fuel rate for energy consumption simulation. Here, only steady state maps are employed, although when available maps in speed and torque time-derivative domains may be included. In comparative (sensitivity) analyses this limitation is not as important as in the calculation of absolute values of fuel consumption and CO_2 emissions. In any event, at the end of a period of ten or more minutes driving, the net contribution of the transient fuel supply is quite small, perhaps 3% of the total (Trayford and Watson, 1999).

An outline of the model is presented in Figure 2.1. At a given vehicle speed and acceleration the first step is the calculation of the instantaneous wheel torque and the selected gear ratio. The wheel torque is calculated from the rolling resistance, aerodynamic drag, inertial forces (linear and rotating). The transmission losses and engine auxiliaries' torque are added to the wheel derived torque to define the instantaneous engine speed and torque and thus the fuel rate is calculated from the map

Gear selection to simulate a manual transmission is made by an algorithm that uses shift points as a function of vehicle speed and acceleration.

For an automatic transmission the gear ratio selected is a function of engine speed and torque ratio to allow for torque converter slip, the coefficients for which came from an analysis of bus four speed automatic performance.

The final drive efficiency is a function of rotational speed and torque transmitted. More details of example applications are to be found in references Watson and Alimoradian (1989) and Watson (1995).

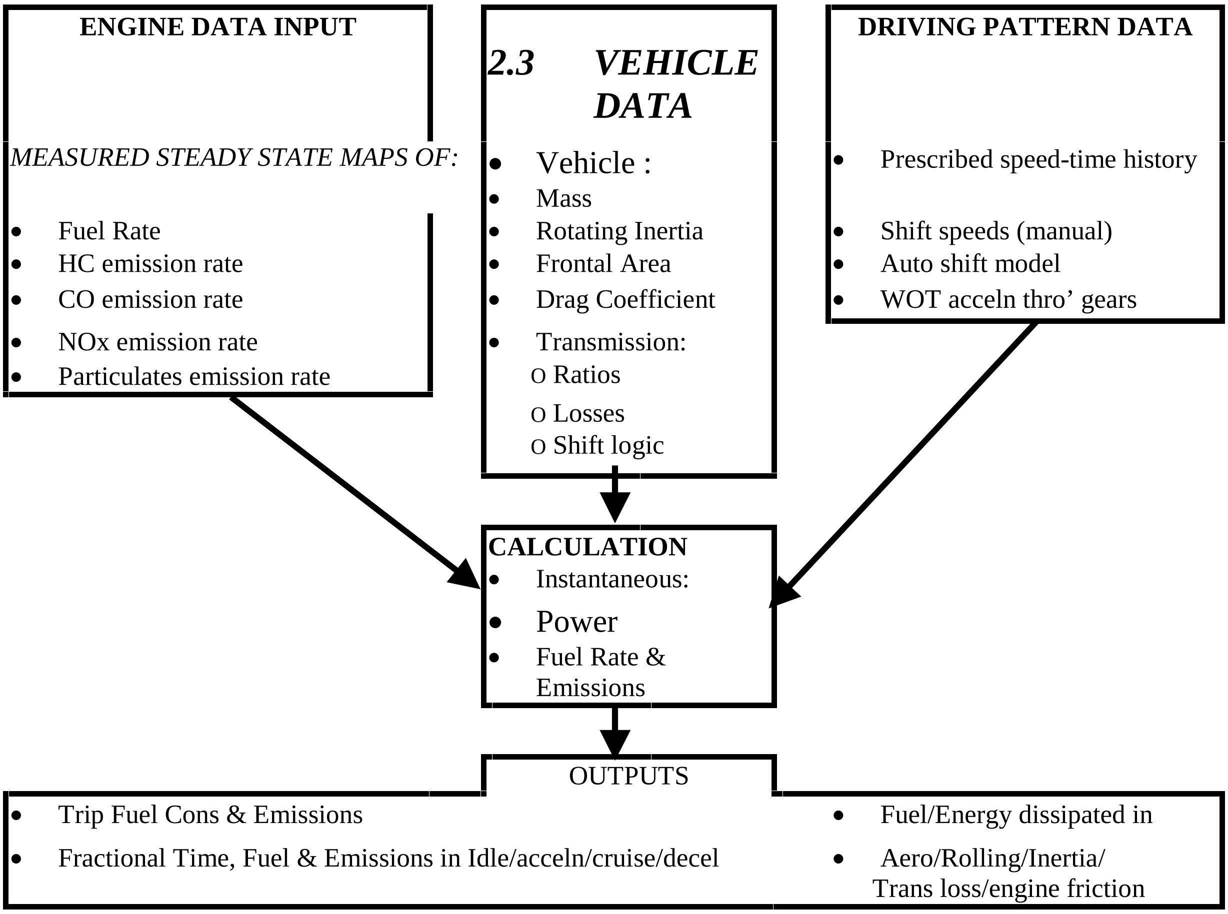


Figure 2.1
Model inputs and outputs

The model includes allowance for road gradient and wind speed and direction. Both of these effects have considerably more effect on trucks and buses than is found in passenger cars, because of their relatively poor power in proportion to size and weight.

Two examples follow to illustrate the effect of the change in liquid fuel composition and the change of fuelling system (liquid to gas).

2.2.3 Results of changed fuel - diesohol example

The test results in this section refer to earlier diesohol trials and are used for illustrative purposes only. Current emissions data for diesohol is provided in Parts 1 and 2.

The data for this comparison were obtained from the NSW EPA for the diesohol bus trial, which was conducted in 1993/4. The buses used in the test and simulated in the model were Renault/Mack buses operated by Action Buses in Canberra. The thirteen mode Euro 2 test was modified slightly by the EPA to produce the database, which nonetheless allowed the development of the relevant engine maps for modelling.

Figure 2.2 shows the CO_2 emissions rate for the bus No. 977 operated on diesohol fuel compared with diesel for a range of established test cycles. The average speed of these cycles forms the base of the graph. The cycles include the fuel consumption cycle AS2877 City and AS2877 Highway normally used for car and light commercial vehicles testing. However, experience has shown that buses can also perform satisfactory on these cycles. Also included are an urban truck and a highway truck cycle based on measurements made in Sydney and Melbourne and the interstate highways between Brisbane, Sydney and Melbourne in the period 1986/7. (Khatib 1987).

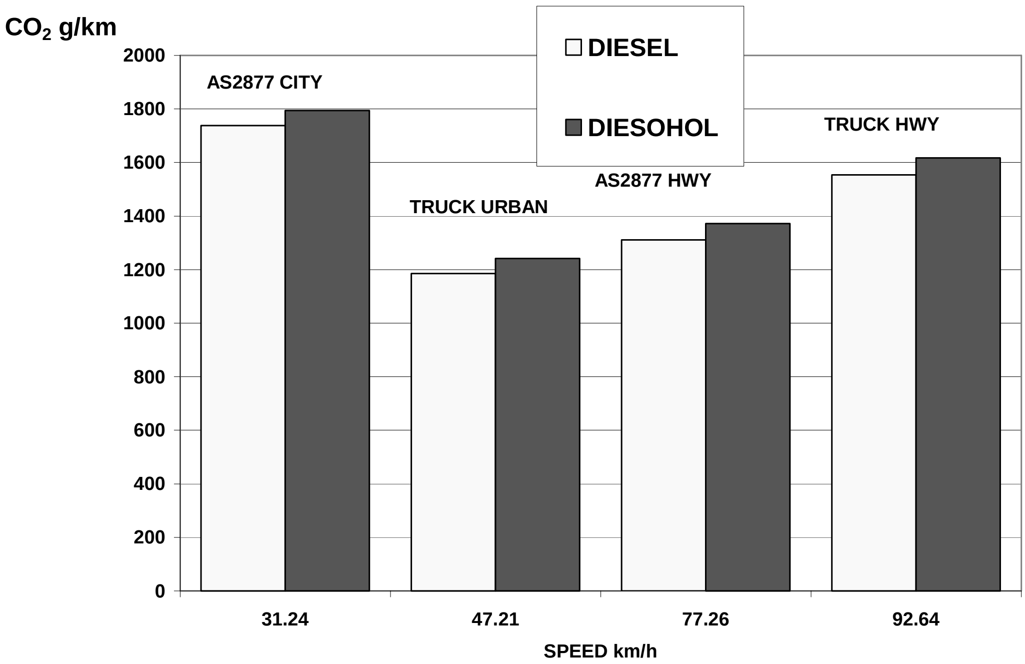


Figure 2.2
Variation in CO_2 emissions for the simulated bus over AS2877 and truck cycles for diesohol and reference diesel fuel

In Figure 2.3 a similar set of values are presented on the basis of driving as measured recently as part of the Diesel NEPM developed two years ago NEPC (1997). These cycles are disaggregated into congested, residential, arterial and highway driving. All were based on driving in Sydney.

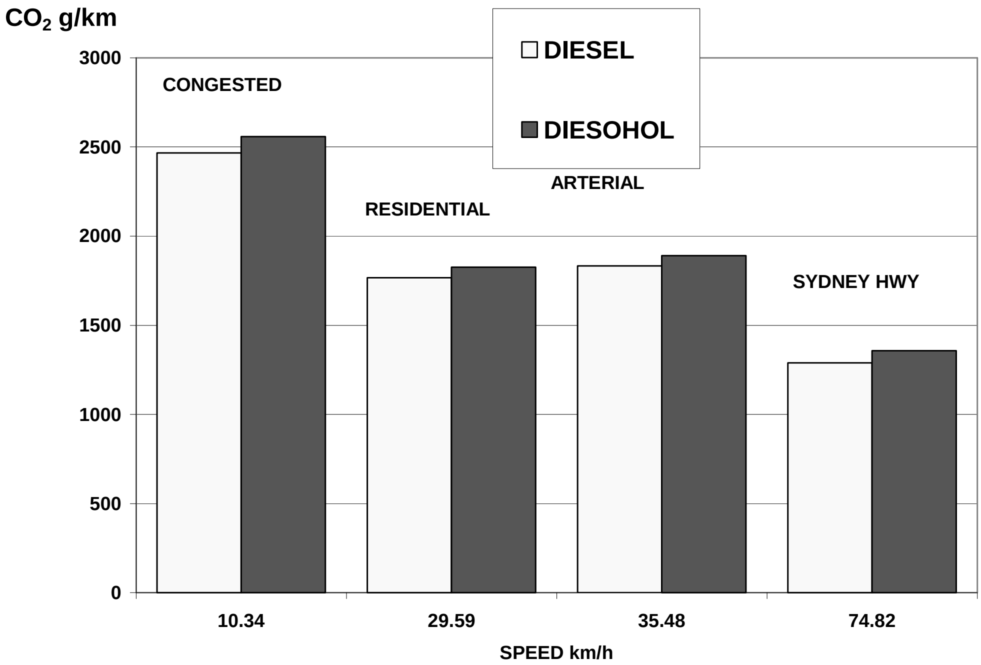


Figure 2.3
Variation in CO_2 emissions for the simulated bus over CUEDC developed as part of the diesel NEPM

It can be seen in each of the figures under all conditions that the diesohol bus has slightly higher CO_2 emissions than the diesel reference bus.

These sample results are now expressed as a ratio in Figure 2.4 - the ratio of the CO_2 emissions in the diesohol mode is compared with the CO_2 emissions in the diesel mode. It can be observed that the ratio varies between 1.031 to 1.053 with an average value of 1.038. The average value for the weighted Euro 2 cycle was 1.034.

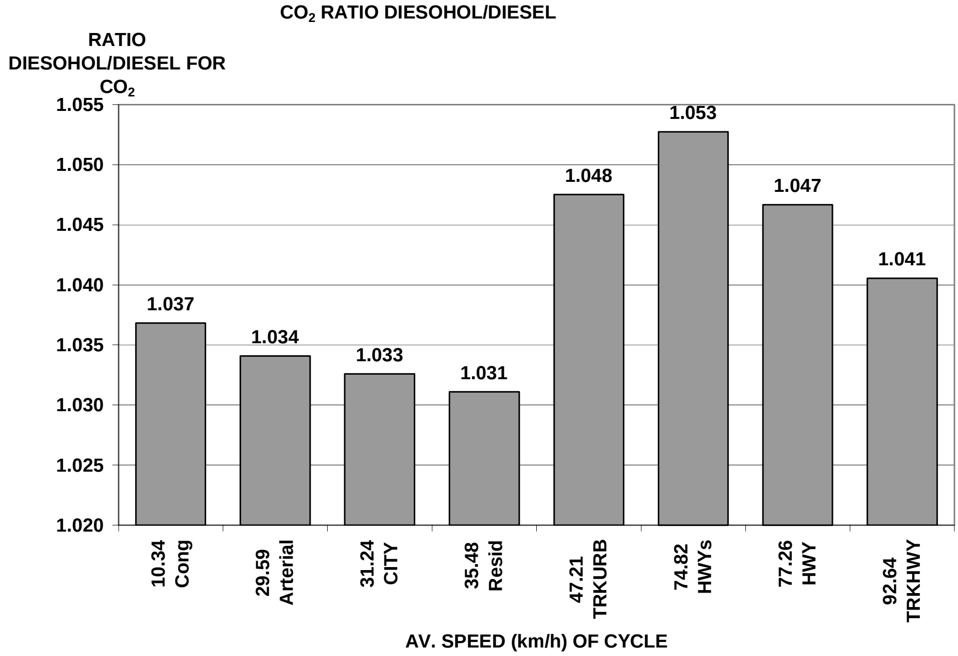


Figure 2.4
Ratios in CO_2 emissions for diesohol compared with diesel fuel the simulated bus over the eight cycles

It may be thought that the variation in CO_2 emissions with driving is very small. However, it should be recalled that diesohol comprises only 15% which replaces only about 9% of diesel fuel energy. Thus, with a 9% replacement in energy a 2% variation in CO_2 emissions is nearly 25% variation in the replaced CO_2.

Similar ratios are plotted for NOx and smoke emissions in figures 2.5 and 2.6 respectively. There is a general trend for these to be lower in the urban conditions and higher in highway driving. Overall there is a slight increase in NOx and a small reduction in exhaust smoke and therefore particulates.

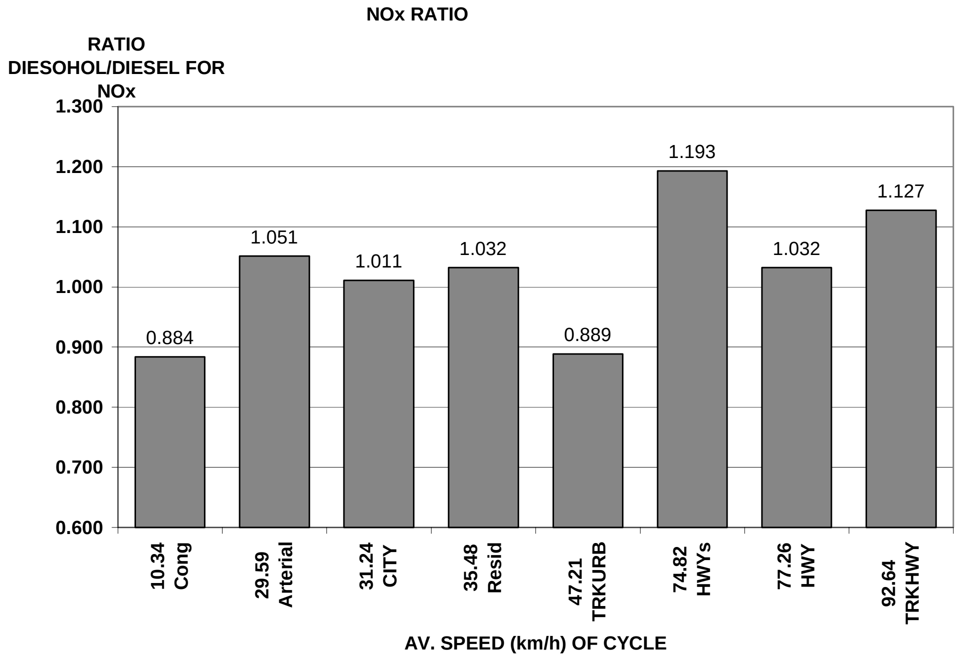


Figure 2.5
Ratios in NOx emissions for diesohol compared with diesel fuel the simulated bus over the eight cycles

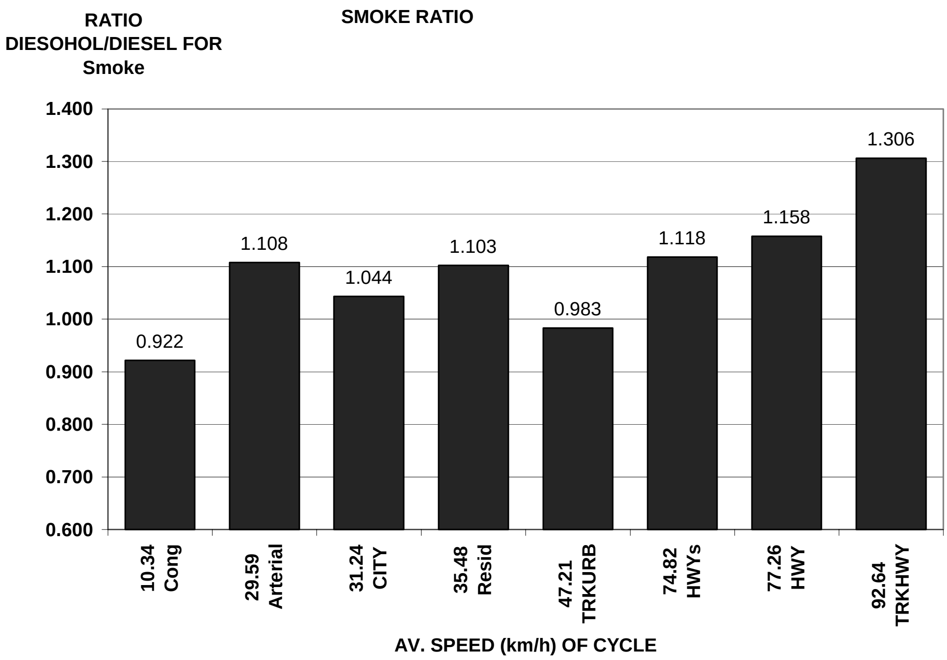


Figure 2.6
Ratios in Smoke emissions for diesohol compared with diesel fuel the simulated bus over the eight cycles

2.2.4 Results for changed fuel supply system, example - dual fuel CNG

This simulation is for an articulated truck with a minimum GVM of 15 tonnes and a maximum of 45 tonnes. It is powered by a 450HP engine sourced from the US and drives through a 12 speed transmission and dual axle drive.

As no Euro 13 mode data was available in the open literature for a spark ignited CNG vs diesel comparison, the simulation was performed for a dual fuel engine with 65% CNG substitution of gas for diesel over the 13 mode test schedule with the standard's weighting factors.

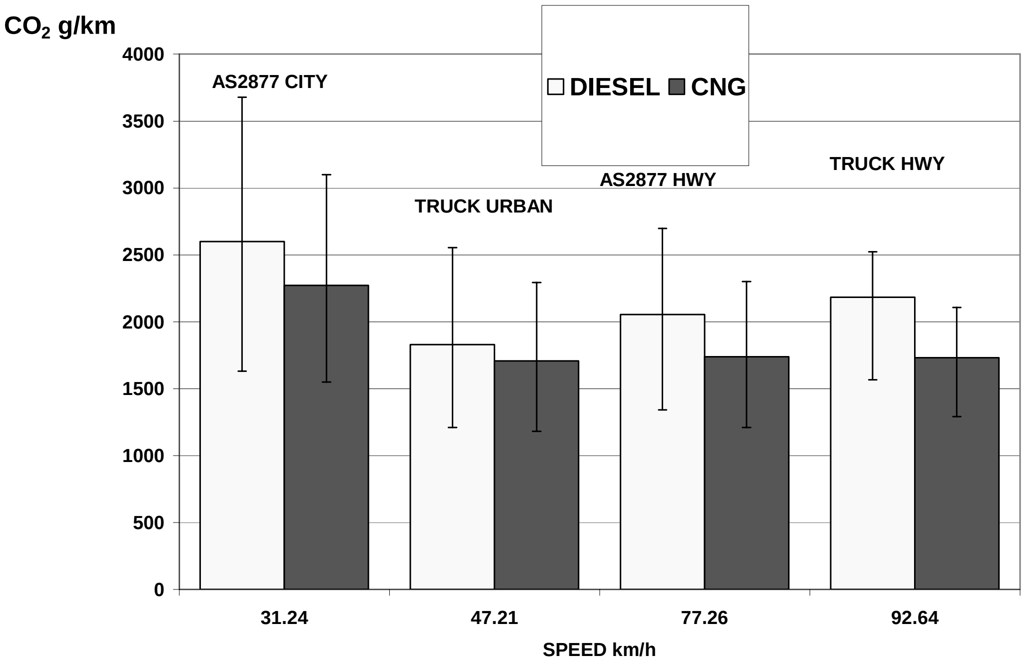


Figure 2.7
Variation in CO_2 emissions for the simulated truck over AS2877 and truck cycles for dual fuel CNG and reference diesel fuel

The bars are for 30 tonnes half-laden condition. The error bars show the 45 tonne and 15 tonne conditions.

The results in Figure 2.7 show CO_2 emissions for the simulated truck over AS2877 and truck cycles for the dual fuel CNG and LSD diesel fuel. The major bars are for 30 tonnes half laden condition, whilst the error bars show the 45 tonne fully laden and 15 tonne unladen conditions. It is noticeable that there is a significant variation of emission with load condition and relatively small variation with speed except for the aggressive-for-a-truck car city cycle. Indeed in the unladen condition the reduction in CO_2 is 7% compared with 18% under full load. This trend is expected as the CNG substitution tends to increase in proportion to the power output.

Similar conclusions may be drawn for the CUEDC cycles in Figure 2.8

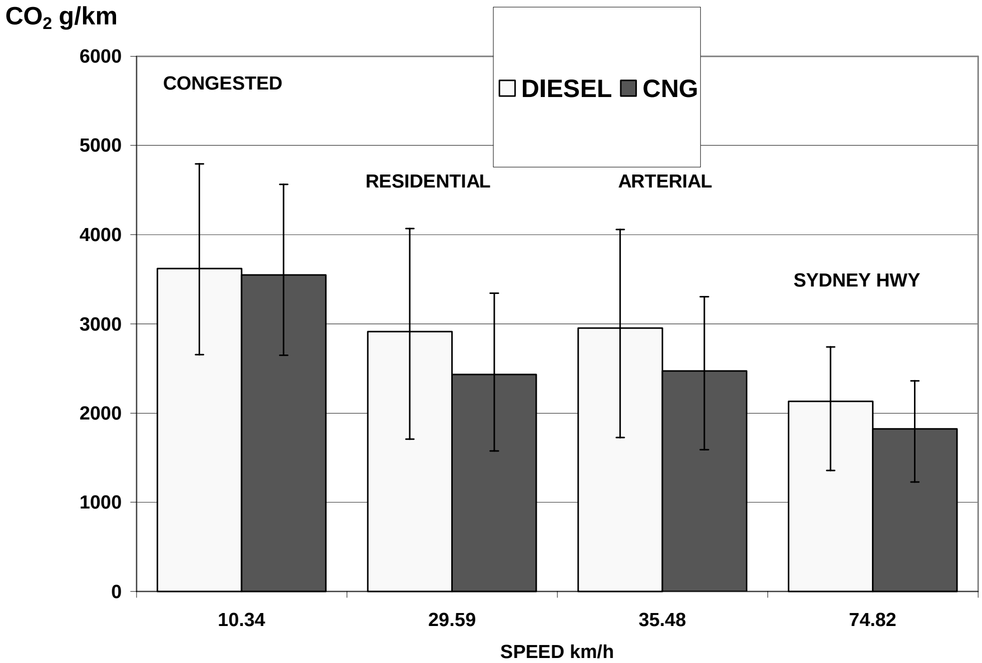


Figure 2.8
Variation in CO2 emissions for the simulated truck over CUEDC developed as part of the diesel NEPM. for dual fuel CNG and reference diesel fuel

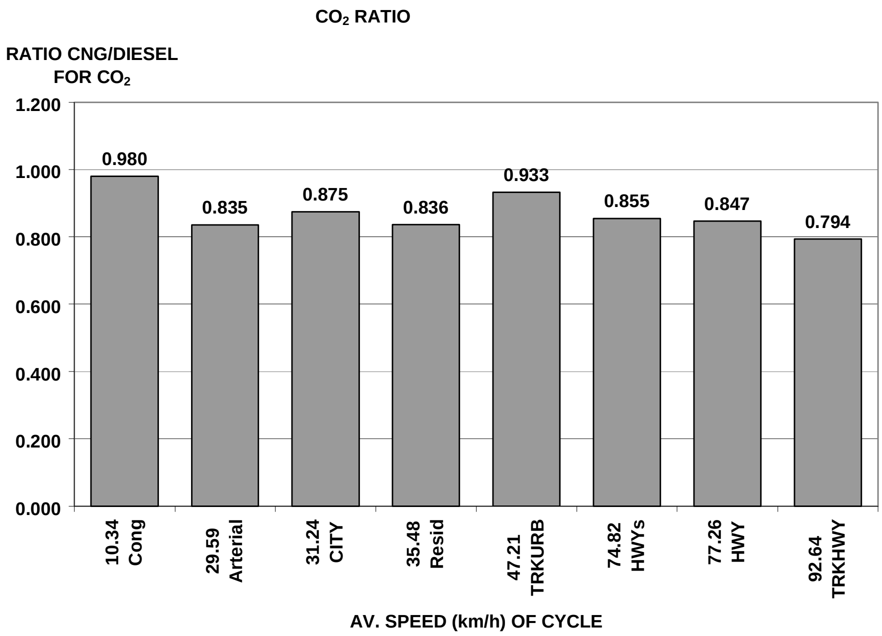
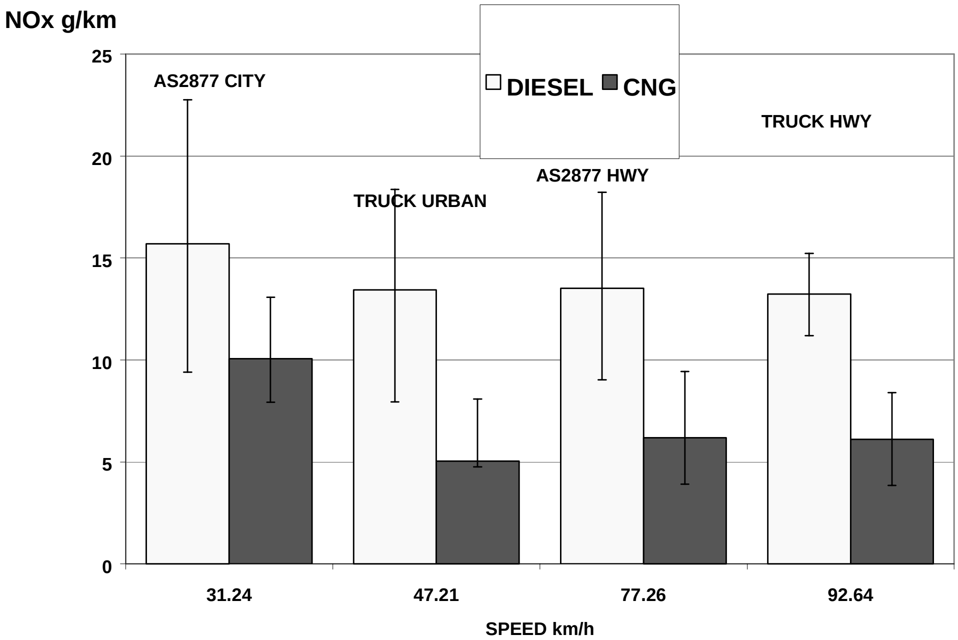


Figure 2.9
Ratios in CO_2 emissions for dual fuel CNG compared with diesel fuel for the simulated truck over the eight cycles

The bars are for 30 tonnes half laden condition. The error bars show the 45 tonne and 15 tonne conditions.

Figure 2.9 shows ratios in CO_2 emissions for dual fuel CNG/diesel fuel for the simulated truck over the eight cycles for a vehicle mass of 30 tonnes. The reduction in combustion CO_2 is about 16% on average.

Figure 2.10



Variation in NOx emissions for the simulated truck over AS2877 and truck cycles for dual fuel CNG and reference diesel fuel

The bars are for 30 tonnes half laden condition. The error bars show the 45 tonne and 15 tonne conditions.

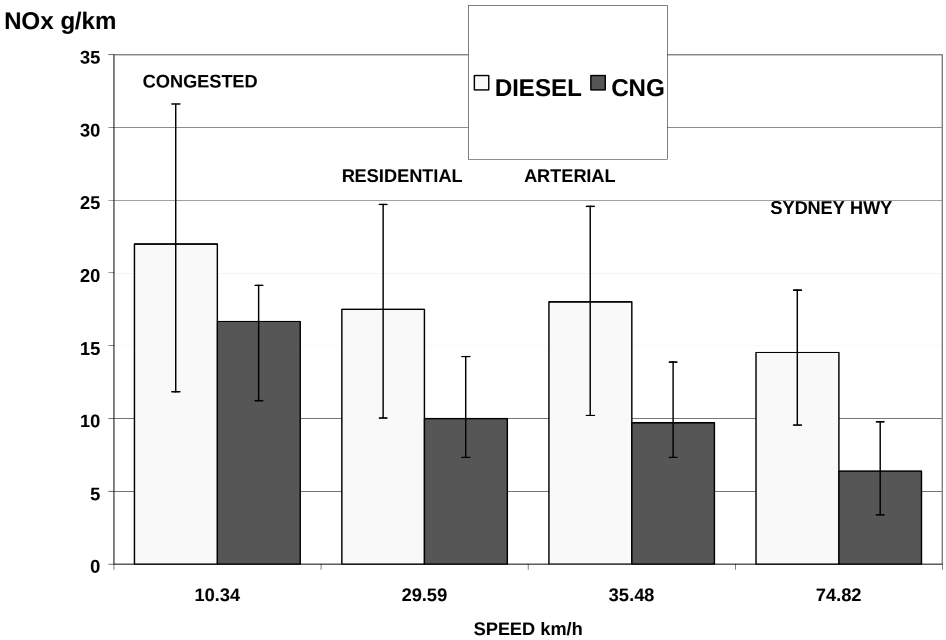


Figure 2.11
Variation in CO_2 emissions for the simulated truck over CUEDC developed as part of the diesel NEPM. for dual fuel CNG and reference diesel fuel.

The bars are for 30 tonnes half laden condition. The error bars show the 45 tonne and 15 tonne conditions.

The NOx emissions in Figures 2.10 and 2.11 demonstrate more pronounced reductions in NOx emissions with increased vehicle mass with reductions in excess of 40% under the fully laden condition. The ratios of CNG dual fuel to diesel at the 30 tonne mass condition are shown in Figure 2.12 where the trend for reducing NOx with increasing speed is evident. This of course means that the NOx emission benefit is not so great where it matters most in urban areas.

Unfortunately the data on CNG dual fuel did not cover particulate emissions.

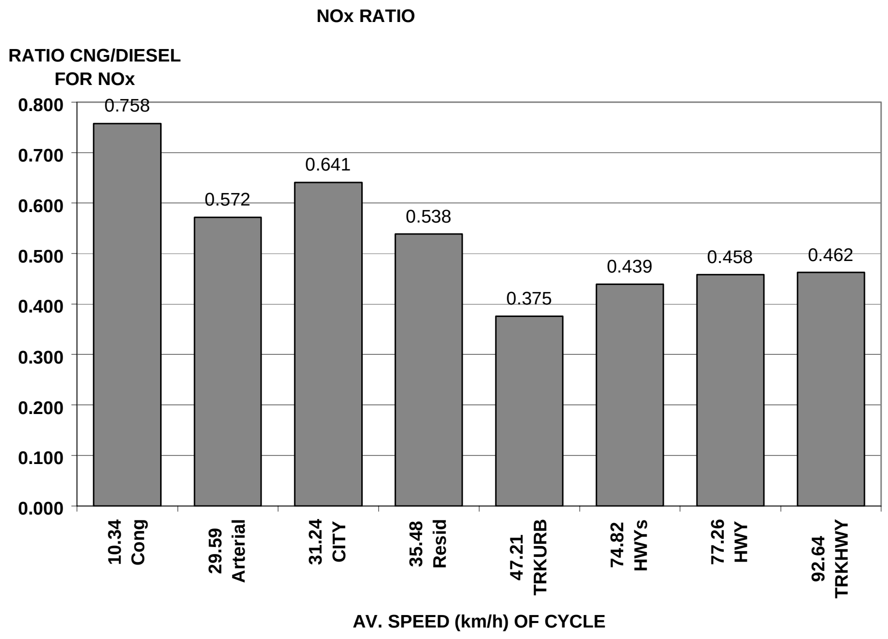


Figure 2.12
Ratios in NOx emissions for dual fuel CNG compared with diesel fuel for the simulated truck over the eight cycles

2.2.5 Conclusions

In this section we have examined two examples of alternative fuels application to heavy-duty vehicles, a bus and a truck. In the first example the impact of a change fuel composition (to dieshol) which showed that the CO_2 emissions might increase somewhat more in real world driving from the expected increase in the Euro 2 steady state test. However the increase is small, and other tests have shown an opposite trend,

In contrast the example of a changed fuel application of CNG to a large truck the real world CO_2 emissions were somewhat better than expected from the Euro 2 base.

Whilst this has only been a limited illustration of the available methodology for modelling these changes, the method does provide a workable basis for the estimation of emissions from alternative fuel vehicles in a range of driving circumstances which include interstate highway and urban situations including congested and free driving conditions. This information should be useful for those involved in undertaking analysis of transport emission sources or CO_2 emissions inventories.

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