DIESEL PARTICULATE MATTER AND ASSOCIATED ENVIRONMENTAL CONCERNS, HEALTH RISKS AND TRADEOFFS

Prepared for

The Onroad Diesel Emissions
Evaluation Task Force

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EXECUTIVE SUMMARY

Diesel particulate matter emissions from on-road diesel vehicles and their potential impact on human health in the Lower Fraser Valley are the focus of this study. The major findings from the study are summarized below.

Potential Health Impacts from Exposure to Diesel Particulate Matter

- The California Air Resources Board (CARB) has reviewed all of the epidemiological studies involving exposure to diesel particulate matter and concluded that diesel particulate is carcinogenic, and that a reasonable estimate of the cancer risk factor for continuous exposure to diesel particulate matter over a 70 year lifetime is about 300 cases of cancer per million population per 1 $\mu g/m^3$ average concentration of diesel $PM_{2.5}$ in the ambient air. Based on the scientific data, a threshold diesel particulate concentration for carcinogenic effects has not been identified.
- The CARB review also concluded that chronic non-cancer health effects (i.e. non-lethal) are unlikely to result from a lifetime exposure to below an average ambient air concentration of 5 $\mu g/m^3$ of diesel $PM_{2.5}$.
- The US EPA is presently preparing a health assessment for diesel particulate emissions that is expected to be finalized in 2000 following review by the Clean Air Scientific Advisory Committee of the Science Advisory Board.
- Insufficient data are presently available to make any conclusions about the potential significance from a health effects perspective of suggestions from very limited engine dynamometer testing that higher particle number concentrations are produced with current diesel engines than pre-1990 diesel engines.

Diesel Particulate Emissions and Ambient Air Concentrations in the Lower Fraser Valley

- From the 1998 emission inventory, it is estimated that the emissions of PM_{10} and $PM_{2.5}$ in the Lower Fraser Valley are as follows:

Source and Type of Particulate	PM_{10} (tonnes/year)	$PM_{2.5}$ (tonnes/year)
All particulate and all sources	10,708	6,475
Diesel particulate from:		
all mobile sources	967	874
on-road & off-road vehicles	662	594
on-road vehicles	375	330
heavy duty on-road trucks and buses	332	293
all buses (public transit, commercial and school buses)	19	17

- Diesel particulate emissions from heavy duty on-road trucks and buses are forecast to decrease by about 45% over the period from 2000 to 2010-2015 as a result of fleet turn-over, which introduces newer lower-emitting vehicles into the fleet, and the inspection and maintenance program for heavy duty vehicles (AirCare On-Road Program). Emissions of diesel particulate matter from heavy duty on-road vehicles is forecast to trend upward again after 2015, assuming emission standards stay at their current levels.

- The average ambient regional PM_{10} concentration is currently about 13-15 $\mu g/m^3$ and is forecast to remain approximately within this range to 2020 with implementation of the 1994 Air Quality Management Plan.
- The current regional average concentration of diesel PM_{10} and $PM_{2.5}$ from on-road diesel vehicle emissions is estimated to be about 1 $\mu g/m^3$, based on the annual diesel particulate emissions from on-road vehicles, and on the assumption that these emissions disperse to the same extent as observed regionally for carbon monoxide emissions from on-road vehicles.
- Average ambient concentrations of diesel $PM_{2.5}$ from all on-road and off-road sources in several Eastern U.S. urban areas range from 0.5 to 1.6 $\mu g/m^3$. The average diesel particulate concentration in Los Angeles is about 1.5 $\mu g/m^3$. While there is no ambient air monitoring data for total diesel $PM_{2.5}$ in the GVRD, estimates in this study suggest that average diesel particulate concentration in the Lower Fraser Valley is similar in magnitude to that observed in some large U.S. cities.
- Preliminary “screening-level” air quality modeling indicates that a resident living adjacent to a road with a large amount of heavy duty diesel truck and bus traffic may be exposed to a maximum 24-hour average diesel $PM_{2.5}$ concentration of about 2.4 $\mu g/m^3$ at the roadside and about 0.7 $\mu g/m^3$ at 20 m away from the road centreline. This excludes the potential contribution of diesel particulate emissions from other nearby roads. Maximum 24-hour average $PM_{2.5}$ concentrations were predicted to decrease to below 0.25 $\mu g/m^3$ at distances of 150 m or more from the road centreline. More in-depth analysis would be required to verify these preliminary findings.

Risk Assessment for Diesel Particulate Matter from On-road Vehicles

- Applying the CARB cancer risk factor to the estimated regional ambient average diesel $PM_{2.5}$ concentration of 1 $\mu g/m^3$ from on-road vehicles yields a cancer risk factor of 300 per million population over a 70 year lifetime exposure. This equates to a probability of about 8 excess cases of cancer per year in the approximately 2 million population of the GVRD (300 per million x 2 million population/70 year lifetime). This cancer risk is projected to decrease by about half by the 2010 to 2015 period as a result of replacement of the older existing trucks and buses in the on-road fleet with vehicles meeting current, lower engine emission standards.
- Since emissions from all commercial, public transit and school buses in the region are about 5% of the diesel particulate emissions from on-road vehicles, the cancer risk attributable to these vehicles is currently 15 per million population

over a 70 year lifetime exposure, or 1 new cancer case every two years. This risk factor will probably remain roughly constant through to the 2010 to 2015 period if lower vehicle emissions from introduction of cleaner, new diesel buses in the fleet are countered by increases in the number of buses.

- The preliminary air quality modeling results indicate that the CARB reference concentration of 5 $\mu g/m^3$ for adverse non-cancer health effects from long-term exposure would not be exceeded in the Lower Fraser Valley even in the most impacted areas adjacent to major arterial roads with a high volume of diesel truck and bus traffic.

Interpretation of the Acceptability of the Health Risk Estimates for the GVRD

- As the cancer risk associated with exposure to diesel particulate matter from on-road diesel vehicles was predicted to be 300 cases per million population for continuous exposure over a 70 year lifetime, and this is above levels of 1 to 10 cases per million population often deemed to represent a threshold of significance when evaluating environmental public health risks, an appropriate level of priority and risk management should be applied to diesel particulate emissions.
- The cancer risk from exposure to diesel particulate matter predicted in this study appears to be a small component of the current total lifetime risk from cancers of all kinds, which is about 200,000 to 250,000 in a million population over a 70 year lifetime.
- The 45% decline in diesel particulate emissions from current levels forecast to occur by 2010-2015 is relevant to future management as it will result in a corresponding reduction in the cancer risk over that period.

Next Steps

- Implementation of a continuous monitoring program for PM_{10} or, preferably, $PM_{2.5}$, together with chemical analysis of particulate matter samples, is recommended for at least a one year period to determine ambient diesel particulate matter concentrations in the region. It is suggested that sampling be done within a road transportation corridor having a high level of heavy duty truck traffic and at a site expected to be representative of regional average concentrations. (Section 4.4 provides an outline of the recommended program.)
- Information on the health impacts of diesel particulate matter should be monitored periodically to keep abreast of the latest science, including the comprehensive health impact assessment for diesel particulate matter being conducted by the US EPA that is expected to be finalized in 2000.
- The GVRD should work together with other agencies and levels of government to encourage programs that will reduce future diesel particulate matter emissions from heavy duty vehicles in the region, including, for example, consideration of alternative fuel and future diesel heavy duty vehicle technologies reviewed in this study.

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ABBREVIATIONS

bhp	brake horsepower
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent mass emission of carbon dioxide, methane and nitrous oxide based on respective global warming potentials of 1, 21 and 310.
DPM	Diesel particulate matter
g	gram
H_2	Hydrogen
HC	Hydrocarbons
HDDV	Heavy duty diesel vehicle
kg	Kilogram
LDV	Light duty gasoline or diesel vehicle
LDGT	Light duty gasoline truck
LDDT	Light duty diesel truck
LDGV	Light duty gasoline vehicle
LDDV	Light duty diesel vehicle
LFV	Lower Fraser Valley
LNG	Liquified natural gas
LPG	Liquified petroleum gases (i.e. propane)
m^3	cubic meter
m	meter
MC	Motor cycle
mi	Mile
ng	nanogram (10^{-9} gram
NMHC	Nonmethane hydrocarbons
NO_x	Nitrogen dioxide
PM	Total particulate matter
PM_{10}	Particulate matter with an aerodynamic diameter of 10 microns or less
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of 2.5 microns or less
ppm	Parts per million
RfC	Daily reference concentration for chronic morbidity health effects
S	Sulphur
t	tonne (metric tonne, or 1000 kilograms)
yr, or y	Year
μg	microgram (10^{-6} grams)

1. INTRODUCTION

1.1 BACKGROUND

Diesel engines are in common use in heavy duty trucks and urban buses because of their attractive performance characteristics and low operating cost. However, diesel engines are also a source of a wide range of organic and inorganic gaseous and particulate matter emissions. Particles in diesel engine exhaust are of particular concern because of their very small diameter and the mixture of chemicals they contain, such as elemental carbon, many toxic organic compounds, adsorbed gases and trace metals. Diesel particulate emissions from heavy duty vehicles and their potential impact on human health in the Lower Fraser Valley are the focus of this study.

Some of the key characteristics of diesel particulate matter (EPA, 1999b) are as follows:

- individual particles consist of a porous core of elemental carbon with a large surface area, on which organic compounds are adsorbed.
- the major organic constituents are hydrocarbons (C_{14}-C_{35}), polyaromatic hydrocarbons and nitro-polyaromatic hydrocarbons.
- particles contain sulphate and nitrate compounds and trace levels of metals.
- typically greater than 90% of the particle mass is less than 2.5 µm in diameter.
- the particle size distribution has two pronounced peaks, one in the 0.005-0.05 µm range, with an average diameter of about 0.02 µm, referred to as nuclei mode particles, and the second in the 0.05 -1 µm range, with an average of 0.2 µm, referred to as accumulation mode particles. Larger particles are sometimes referred to as course mode particles. Nuclei mode particles are formed by nucleation from condensing liquids, ash present in the fuel, or incomplete combustion of the fuel and formation of solid particles. Accumulation mode particles are those formed by incomplete combustion, by aggregation of the nuclei mode particles, or by enlargement of these particles through condensation of vapour phase constituents in the exhaust stream.
- Continued growth and aggregation of the particles leads to coarser particle sizes and these have diameters in the 1-10 µm range.
- The nuclei mode contains 1%-20% of the particle mass and from 50-90% of the particle number. Note that the size distribution of particles is sensitive to the measurement technique applied and most published data was obtained from engines operated under steady state conditions not transient conditions typical of normal vehicle operation.
- Elemental carbon comprises about 60-80% of the diesel particulate mass, depending on the engine, fuel properties and operating conditions, and is characteristic of fuel combustion particulate.

Scientific and regulatory assessments of the health impacts of diesel exhaust have been conducted in the US in recent years, or are nearing completion. The California Office of Environmental Health Hazard Assessment prepared a detailed analysis of the literature in 1998 (CARB/OEHHA, 1998a,b). Based on the assessment the California Air Resources Board declared diesel exhaust to be carcinogenic. The Health Effects Institute prepared an assessment of the association between diesel emissions and lung cancer in 1999 (HEI, 1999). In November, 1999, the US Environmental Protection Agency (EPA) released a draft health assessment document for diesel emissions, which is subject at the present time to review by the EPA's Science Advisory Board, Clean Air Scientific Advisory Committee.

The emissions, ambient concentrations and potential impacts of inhalable (PM_{10}) and fine particulate matter are important considerations for the maintenance of air quality and visibility in the Lower Fraser Valley, particulate matter and odours from large diesel vehicles has been a frequent complaint during stakeholder consultations during the formulation of regional air quality plans. One of the responses to this issue has been the implementation of the AirCare On-Road (ACOR) program, which tests and requires repair of high emitting heavy duty trucks operating in the region.

Emissions from on-road vehicles are a significant contributor to the total emissions from all sources in the Lower Fraser Valley and a large part of the emissions from the mobile source sector. Diesel fueled on-road vehicles are a significant source of fine and inhalable particulate emissions. The GVRD contracted this study of diesel particulate from on-road vehicles to improve the understanding of the basis for current concerns about the health impacts of diesel particulate matter, to provide preliminary information on the potential health impact of diesel particulate emissions, to outline an ambient monitoring program that may be appropriate, and to provide information regarding the options and potential impacts of alternative fuel/vehicle technology choices for the public transit bus fleet.

1.2 STUDY OBJECTIVES

The objectives of the study were as follows:

- Prepare an overview of the current scientific literature on the health effects of diesel particulate matter and summarize the basis for assessing the cancer and non-cancer health risks;
- Develop screening level predictions of the maximum diesel particulate concentrations to which people may be exposed adjacent to roadways;
- Review the potential health impacts of diesel particulate emissions in the regions and, more specifically, the significance of emissions from the future urban bus fleet;
- Based on the assessment of the potential health impacts of diesel particulate emissions, recommend an appropriate ambient air quality monitoring program; and
- Prepare an overview of the current and emerging diesel and alternative fueled heavy duty truck and urban bus technologies, with consideration of tradeoffs, emissions characteristics and status of the technology.

2. REVIEW OF CURRENT KNOWLEDGE OF HEALTH IMPACTS FOR DIESEL PARTICULATE

Several recent scientific and regulatory assessments of diesel exhaust have provided a basis for summarizing health impacts of diesel particulate matter (DPM). In support of a decision by the California Air Resources Board (CARB) to declare diesel exhaust a toxic air contaminant, the California Office of Environmental Health Hazard Assessment prepared a detailed analysis of the literature in 1998 (CARB/OEHHA, 1998a,b). The Health Effects Institute prepared an assessment of the association between diesel emissions and lung cancer in 1999 (HEI, 1999). The US Environmental Protection Agency (EPA) is in the process of preparing a health assessment document for diesel emissions. EPA's documentation is available for review as of November 1999[1], but it may not be cited until it has been evaluated by the EPA's Science Advisory Board, Clean Air Scientific Advisory Committee (SAB/CASAC). This review is expected to be completed in early 2000. These documents and the recent primary literature provided the material on which this summary is based. Diesel particulate matter is generally accepted as a surrogate for total diesel exhaust and is treated as such here.

Most epidemiological studies of the effects of urban particulate matter have not separated diesel-generated particles from those emitted by automobiles. The inference that diesel particles have been responsible for the observed outcomes rests on evidence from animal exposures, and more recently from experiments in which human volunteers have inhaled particles generated by diesel engines. Animal data indicate that diesel particles cause inflammation in the lung, enhance the effect of a subsequently inhaled allergen, and are carcinogenic. Human exposures (to about 300 micrograms/m^3 of PM_{10}) confirm that these particles cause inflammation with mobilization of enzymes that may have effects on other organs (Sandstrom et al., 1999; Rudell et al., 1996). There are also preliminary human studies indicating that diesel exhaust exposure enhances the effect of a subsequently administered allergen (Svartengren et al., 1999), which confirms the animal data mentioned above. These observations are in accord with the epidemiological associations noted below. However, recently reported observations (Rudell et al., 1999) have indicated that diesel exhaust still caused an inflammatory response in human volunteers after a particle trap was used that removed 50% of the particles. This remains to be explained.

2.1 HEALTH EFFECTS ASSOCIATED WITH EXPOSURE TO PARTICULATE POLLUTION

The evidence relating particulate matter exposure to adverse health effects is primarily epidemiological. It has been shown in many studies in at least 35 different regions on five continents that there is an association between the level of PM (usually measured as PM_{10}) and the following health outcomes:

- Daily respiratory and cardiovascular mortality (Wilson and Spengler, 1996);
- Hospital admissions for acute respiratory disease (Wordley et al,1997; Schwartz, 1996);
- Hospital admissions for cardiovascular disease (Burnett et al, 1995);
- Emergency visits for acute asthma in adults and children (Schwartz et al, 1993);
- Fluctuations in the pulmonary function of asthmatic children (Vedal, 1998; Pope et al, 1992; Neas et al, 1999);
- Cough incidence in asthmatic children (Vedal et al, 1998);
- Family practice consultations for asthma and respiratory disease (Median et al, 1997; Hajat et al, 1999).

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[1] Available on the EPA website at http://www.epa.gov/ncea/diesel.htm.

All of the above outcomes have been shown to be associated with changes in PM_{10} or $PM_{2.5}$ level on a daily basis.

Additional observations have included the following:

- More respiratory symptoms in those exposed to higher levels of particulate (Brunekreef, 1997):
- Lower lung function in children exposed to higher levels (Van Vliet, 1997);
In two large populations in the US followed for at least 17 years, a lower survival was observed in regions with higher PM_{10} and $PM_{2.5}$ pollution (see below):
In one study of non smoking Seventh Day Adventists, higher PM_{10} levels were associated with an increased risk of lung cancer (Abbey et al, 1999);
- In one recent study, higher levels of pollution (including particulate pollution) were associated with an increased prevalence of asthma (Baldi et al, 1999), but other comparisons have not indicated that asthma prevalence is affected by pollution.
- Exposure to diesel particles is believed to increase the risk of lung cancer. Most of this evidence is based on analyses of occupationally exposed populations (Bhatia et al, 1998).

In summary, these accumulated data are generally considered to be interpreted as indicating that PM_{10} is causative of the phenomena shown to be associated with its level.

2.2 ACUTE MORBIDITY

Increased exposure to diesel particles from freeways has been shown in studies from Holland to result in increased episodes of acute respiratory infection in children, and in lower lung function in those most heavily impacted (Brunekreef et al., 1997; Van Vliet et al., 1997). In these studies, the density of diesel traffic was recorded, and the adverse health outcomes were closely associated with exposure to higher levels of “Black Smoke” (in this setting, this reflects elemental carbon composition and is closely associated with diesel-generated particles).

Combustion particles in general have been shown to have an adverse impact on asthmatic children, and these studies include one conducted in Port Alberni (Vedal et al., 1998). In this environment, it was shown in addition that chronic respiratory symptoms were more prevalent in children living in a region of the town where PM_{10} values averaged about 50 micrograms/m^3, than they were in districts where the PM_{10} averaged less than 20 micrograms/m^3 as an annual average.

There have been few studies of family practice data. One conducted in Paris (Medina et al., 1997) showed convincing evidence of an association between air pollution levels and consultations, particularly for children with asthma. An earlier study in the same city over the winter had shown a strong association between ‘Black Smoke’ (a particulate index) and adult consultations for respiratory disease. This association has recently been confirmed in London England (Hajat et al., 1999) where consultation data was available for between 268,718 and 295,740 registered patients from 45-47 London practices from 1992-1994. In adults, a PM_{10} level increase from the 10th to the 90th percentile was associated with a 9.2% increase in consultations (this change in pollution was from 16.3 micrograms/m^3 to 46.4 micrograms/m^3). In summer, in children, significant increases in consultations for asthma also occurred in association with NO_2, SO_2, and CO levels. London has 17,500 diesel taxicabs, so the proportion of diesel generated particles is relatively high.

Recent studies of children in a summer camp (Neas et al., 1999) where the PM_{10} averaged about 30 micrograms/m^3, showed that the adverse effect of the particles was only weakly associated with the acidity of the particles, but depended on their mass. PM_{10} levels have also been shown to be associated with an increased incidence of pneumonia in the elderly (Wordley et al., 1997), and also with changes in heart rate in elderly people (Pope, et al., 1999) many of whom had cardiovascular abnormalities.

2.3 MORTALITY

The association of PM_{10} with mortality on a daily basis, has been confirmed by many studies in different locations. Both respiratory and cardiovascular causes are included. This association has been shown to exist in every urban location in which it has been tested, with the exception of Vancouver (S. Vedal and M. Brauer, pers comm., October 1998), where PM_{10} levels may be too low for the association to be detected. In some third world cities, like Santiago in Chile where 80% of the particles have been shown to be diesel-generated (Ostro, et al., 1996), the same associations with mortality are found as exist in Philadelphia or Chicago. In Bangkok, a recent comprehensive study showed that PM_{10} levels were, in addition to mortality, also strongly associated with hospital admissions for respiratory disease in children under the age of 16 (Hagler Bailly, 1998). This city also has a high percentage of diesel-generated particles.

2.4 LUNG CANCER

Studies of drivers of diesel trucks and of railroad employees with exposures to diesel emissions greater than occur in the general population, have in general showed an increased risk of lung cancer. A recent meta-analysis of 23 occupational studies (Bhatia et al., 1998) found that the risk ratio of lung cancer between those most exposed and those least exposed was about 1.3 (i.e., a 30% increase in incidence). The epidemiological data sets are very large and have involved long-term studies of hundreds of thousands of workers exposed to diesel particulate from a range of diesel engine powered equipment.

Another analysis of occupational data (Lipsett and Campleman, 1999) came to the same conclusion. The Health Effects Institute of Cambridge, Mass, concluded however that there were so many uncertainties about exposure, that no firm conclusion could be drawn (Health Effects Institute, 1999). A panel of experts convened in California reviewed all the occupational data, and came to the conclusion that diesel emissions should be regarded as carcinogenic (CARB/OEHHA, 1998). Since both of these reports were published, an increased risk of lung cancer has been reported in workers in German potash mines that use diesel vehicles (Saverin, et al., 1999), and in this cohort, smoking history was carefully determined. Other studies of diesel exhaust exposures in underground mines have also appeared (Stayner et al., 1998). The only two environmental epidemiological studies to be conducted have been reported in the past few months. One involved the general population of Stockholm and its suburbs (Pershagen, 1999) and the authors found an increased risk of lung cancer as the estimated exposure to diesel emissions increased. This has not yet been published in full. A second study in Germany came to the same conclusion (Bruske-Hohlfeld et al., 1999). Comparisons of lung cancer prevalence as between rural and urban environments have indicated a risk ratio of about 1.3 (30% increase) in urban populations (Cohen and Pope, 1995). A prospective study of non-smoking Seventh Day Adventists in California (Abbey et al., 1999) has indicated an increased risk of lung cancer associated with residence in areas with higher levels of PM_{10}.

Diesel exhaust has been shown to be carcinogenic in animals; it would seem prudent to conclude from current evidence that it is also carcinogenic in humans. A detailed analysis of the calculations of risk of lung cancer from diesel emissions that have been put forward is beyond the scope of this review; but the California Review (CARB/OEHHA, 1998a) concluded that the 95% upper confidence limit per million population per microgram of diesel exhaust particulate in a cubic meter of air exposure over a 70 year lifetime was between 280 and 1800 with a mean value of about 700. The Staff paper (CARB/OEHHA, 1998b) concluded that 3×10^{-4} per (microgram/m^3) was a reasonable estimate of unit risk expressed in terms of diesel particulate.

An editorial writer in the American Journal of Public Health (Stayner, 1999) recently concluded that there was enough evidence to indicate that protective steps ought to be taken. Not much is known about actual public exposure levels to diesel particles, but a recent study of adolescents in Harlem, using a biomarker (l-hydroxypyrene {l-HP}) in the urine for diesel exposure, concluded that in an upper quartile of their population, exposure levels must have been very significant (Northridge et al., 1999).

In view of the recent evidence that has appeared, it would seem prudent to agree with the California panel that diesel particles should be deemed to be carcinogenic.

2.5 PERSONAL EXPOSURE VERSUS AMBIENT LEVELS

There have been a number of studies to determine whether personal exposures approximate ambient levels. In general, personal PM_{10} exposures have been found to be higher than levels from ambient monitors, leading investigators to postulate a "personal cloud" that influences the individual sampler. In a study of Dutch schoolchildren (Janssen, 1998), one factor in the increased level of personal exposure was shown to be the dust in schoolrooms from surface soil. In Vancouver, a study of 16 subjects with chronic obstructive lung disease wore personal $PM_{2.5}$ monitors for seven 24-hour periods, randomly spaced approximately 1.5 weeks apart (Ebelt et al., 1999). There was a relatively low degree of correlation between personal exposure and ambient $PM_{2.5}$. However, the relationship between personal exposures and ambient levels of sulphates (SO_4) was much closer.

It is generally agreed that the smaller the particle, the closer will indoor concentrations match outdoor concentrations. With particles as small as 0.2 microns (a common size range for diesel-generated particles) indoor levels will closely reflect outdoor levels unless there are major indoor sources, such as tobacco smoke. It is probably fair to conclude that differences in ambient outdoor levels for $PM_{2.5}$ will be reflected in different levels of personal exposure, but individual variation will be significant.

2.6 DOES THE SIZE OF THE PARTICULATE MATTER?

There has been considerable research initiative to determine whether the effects are being exerted by particles in a particular size range. There is general agreement that in terms of mortality, particles less than 2.5 microns in size are more important than larger ones (Schwarz et al., 1996); and in some studies such as one on hospital admissions in Toronto (Thurston et al., 1994), Total Suspended Particulate (TSP) minus PM_{10} did not show any associations, whereas PM_{10} did. There has been experimental evidence pointing towards ultrafine particles (less than 0.1 microns). In Port Alberni, Vedal and his colleagues measured five different size ranges of particles, and found evidence that the important particle size for the effect on asthmatic children was between 0.5 and 5.0 microns (S. Vedal, private communication, November 1999). There are insufficient data to resolve this issue at the present time.

The California panel concluded that diesel particulate matter is an adequate surrogate for total diesel exhaust, which includes various gases as well as fine particles. Diesel particulate matter, then, is the generally accepted ambient air metric for exposure to diesel emissions.

2.7 WHAT IS KNOWN OF THE LONG-TERM EFFECTS OF REPETITIVE EXPOSURES TO RESPIRABLE PARTICULATE MATTER?

What we know of long term effects is based on three longitudinal datasets. The first is from the 17-year follow-up of individuals in six US cities with varying pollution levels (Dockery et al, 1993). These cities vary from one that is heavily polluted (Steubenville, Ohio), to one that is essentially rural (Topeka Kansas). The smoking history of all individuals is known, and the levels of PM_{10} in each community have been monitored for twelve years. What is found is a reduced survival expectancy in relation to the level of PM_{10} that exists in the community. The extensive data from this study are currently being re-examined and re-analysed.

A second analysis is from a prospective study started by the American Cancer Society twenty years ago. This determined the health status, and followed the smoking history of more than half a million Americans. Pope (Pope et al, 1995) analysed the data in terms of ambient pollution levels in the communities in which the individuals were living, and found evidence of a reduced survival and increased prevalence of respiratory and cardiovascular disease in communities with higher PM_{10} levels. These data are also currently being re-analysed.

The follow-up study of Seventh Day Adventists referred to in the paragraph above has demonstrated an increased risk of lung cancer in relation to PM_{10} levels in this cohort.

It seems probable that if PM_{10} is strongly associated with mortality, then it should also be exerting an effect on the prevalence of the same conditions with which it is associated. Although this is harder to show statistically (and the confounders in long term studies are different from those in time-series data), nevertheless it is biologically likely that an agent that is associated with acute mortality, would also produce long term chronic effects. It is also safe to assume that the induction of more severe or more frequent attacks of asthma, or episodic adverse effects on lung function in asthmatic children, are also adverse effects with a harmful effect on long term health, though the long term consequences have not been precisely characterized.

In summary, there is evidence of long term effects on survival. This evidence is more difficult to collect than are the daily “time-series” analyses.

2.8 DOES LIVING IN REGIONS OF HIGHER PARTICULATE POLLUTION AFFECT THE PREVALENCE OF DISEASE?

In the case of open coal burning leading to large particulate, acidic air pollution, this combined with cigarette smoking led to a higher prevalence of chronic obstructive lung disease. Comparisons between East and West Germany have indicated that the prevalence of asthma is not increased by that kind of air pollution. There are major differences between the prevalence of asthma in different countries and different regions (with high values usually recorded in the Southern Hemisphere). These differences are unexplained, but are usually attributed to different environmental factors.

However, a recent report from France comparing different regions in ten areas indicated that higher levels of particulate and SO_2 pollution were associated with higher prevalences of asthma (Baldi et al., 1999). There are too many variables involved in prevalence rates - and asthma is difficult to define precisely - for this to be of much value in establishing the effects of air pollution, but the French data suggest that the book is not closed on this issue.

2.9 WHAT IS THE MECHANISM OF EFFECT?

The US EPA argued before the Federal Court of Appeal (American Lung Assoc. et al, 1993) that a causal inference could not be drawn from the evidence of association unless the biological mechanism was understood. The Court, in its judgement, specifically disagreed with this position. In this they agreed with Bradford Hill in England who in 1965 (Hill, 1965) had stated that in his view, a causal inference could be drawn in the absence of mechanistic understanding.

There has been an intense research effort to determine the mechanism of effect of respirable particles at the generally quite low levels people are exposed to. At the present time, the following conclusions seem justified for this study from a review of current literature that covers diesel particulate, diesel exhaust, mixed PM_{10} in urban settings, carbon and crustal particles:

a) Inhaled particles are capable of inducing changes in other organs, particularly mobilization of neutrophil cells from the bone marrow in both animals (Terashima et al., 1997) and humans (Tan et al., 1999), an increase in blood viscosity (Peters et al., 1997), and some reduction in the volume of circulating red cells (Seaton et al., 1999). It is thought that these changes are induced by alveolar macrophages, which are the first cells to be affected when particles are deposited in the alveoli of the lung.

b) Inhaled particles can influence the electrocardiogram and produce changes in heart rate variability (Pope et al., 1999). These two effects combined with the changes in the blood may be responsible for the association between PM_{10} inhalation and deaths from heart disease.

c) The fact that inhaled particles produce an inflammatory response in the lung provides a sound basis for the aggravation of asthma, more severe respiratory infections, and an increased risk of pneumonia in the elderly.

d) Although the complete chain of events linking particle inhalation to mortality is not yet understood, the first requirement for biological plausibility has been met - namely the demonstration that particle inhalation, at ambient levels, can produce changes in remote organs.

2.10 HEALTH EFFECTS IN THE CONTEXT OF ECONOMIC COSTS

When decisions have to be made about transportation policy, there is bound to be pressure to reduce the uncertainty by calculations of economic benefit or penalty consequent upon whatever policy is being urged. Although a strong case can be made that diesel particles are adversely affecting health, both in the short term and in the long term, it is nevertheless difficult to have much confidence in economic estimates of these effects. This is because it is unclear what fraction of particle burden should be attributed to diesel emissions, and whether these particles are the dominant toxicological species in the urban air that everyone inhales. The present information does not permit a precise calculation of risk, though in respect of particulate pollution in general, these have been attempted for the US (Ostro and Chestnut, 1998).

On the other hand, if policy decisions are made that will increase public exposure to diesel particles, it is legitimate to argue that some consideration (even if not an economic one) should be given to the injurious effects of these particles as these are now understood. There is, in our opinion, enough evidence about diesel particles for those whose responsibility it is to protect the public from airborne environmental hazards, to decide on an appropriate surveillance scheme.

3. PREDICTION OF CONCENTRATIONS OF DIESEL PARTICULATE NEAR MAJOR ROADWAYS

3.1 RATIONALE, ANALYTICAL METHODOLOGY AND ASSUMPTIONS

Two different approaches for estimating the concentration of diesel particulate matter to which people could potentially be exposed were concluded to be needed for this study. The first approach leads to a conservative estimate of the maximum diesel particulate concentration and was developed by modelling the diesel particulate concentration near a major truck route. The predicted diesel particulate concentrations for this case reflect the upper range of potential ambient concentration for some people in the region. This chapter describes the methods used to estimate the maximum 24-hour average diesel particulate concentrations adjacent to a major truck route and the results that were obtained. The second approach developed an estimate of the regional average diesel particulate concentration using a ratiometric method as described in Chapter 4. The diesel particulate concentration predicted by this second approach reflects the annual average concentration that a person would be exposed to over a long time period, regardless of location relative to sources of diesel particulate matter emissions.

To predict ambient air quality impacts of diesel particulate emissions near a roadway, the CALINE3 dispersion model was used. This model is currently the model recommended by the United States Environmental Protection Agency (US EPA) for prediction of air quality impacts of highway (line) emission sources. This model is suitable for use in urban or rural areas and for simple (essentially flat) terrain. The model can reliably predict results out to approximately 150 m from a roadway. The model requires meteorological data, geographical parameters, as well as source emission information, which were developed as described below.

3.1.1 Meteorological Data

The model requires input parameters of wind speed, wind direction, stability, and mixing height and, with this data predicts hourly pollutant concentrations. Since the 24-hour averaging period is the basis for the provincial interim PM_{10} objective, an entire year (1996) of hourly meteorological data from the Vancouver International Airport was utilized to provide a reasonably long period of time over which 24 hour averages could be calculated. Rolling 24-hour averages were calculated from the 1-hour values by considering each 24 hour period of time in 1 hour steps from the beginning of the meteorological record. Wind speeds and wind directions are as reported by the monitoring station, while the atmospheric mixing height and stability were calculated from measured meteorological data using standard methods.

The model predictions at a particular point are determined by wind direction, and are inversely proportional to wind speed. As the model is unable to predict concentrations during calm conditions (a limitation of all Gaussian dispersion models), the mean hourly wind speed was set to 1 m/s for any hour in the data set when these conditions occurred. Calm conditions (wind speed below 1 m/s) occurred for 777 hours, or 8.8 %, of the 8784 hours in the 1996 meteorological data set used for modeling. For periods when the wind direction was missing, the wind direction was set to the previous wind direction. The 1996 meteorological data set for the Vancouver Airport station was found to have almost 100% data recovery for the year.

Wind blowing over the surface of the earth develops a turbulent, well mixed layer. This layer is referred to as the mixing layer, and the top of this layer is the mixing height. The mechanical mixing height was calculated for each hour of the year using the Benkley and Schulman approach. The roughness length for this study was presumed to be typical of an urban-type or forested area (100 cm).

The lowest level of the atmosphere can be classified into six characteristic stability types, known as the Pasquill-Gifford stability classes. These classes range from extremely unstable, to neutral, to stable conditions. Stability classification is a method of categorizing the level of turbulence in the atmosphere. Low levels of turbulence and a stable temperature gradient will restrict the dispersion of airborne pollutants. The amount of turbulence in the atmosphere varies with wind speed, solar insolation, and the roughness of the underlying surface. For the CALINE3 model, the stability categories were calculated using Turner's method (Turner, 1969).

3.1.2 Parameters

To be conservative in the estimation of the diesel particulate impact adjacent to a roadway, particulate concentrations were modeled for a truck route in the GVRD having a high traffic volume. For each piece of road that is modeled, CALINE requires the width and height of the road, which for this study was assumed to be two lanes in either direction, with a lane width of 3 m (approx. 10 ft). To account for the wake induced horizontal dispersion behind a moving vehicle, an additional 3 m on either side of the road was added, as recommended in the CALINE user guideline. Predictions of concentrations were made at points perpendicular to the road at incremental distances.

3.2 EMISSIONS CHARACTERISTICS FOR DIESEL VEHICLES

For modelling purposes, traffic flows along major roadways in the GVRD were examined. The CALINE3 model requires the number of vehicles passing on a link of road per hour, as well as an emission factor of particulate. The following is a description of how this information was determined.

The 1996 Screenline Survey: "1996 Vehicle Volumes, Classifications and Occupancies" (GVRD, 1997) has vehicle count information for various roads in Vancouver. Hourly information from this study on the number of vehicles, light trucks, and heavy trucks travelling on roadways in Vancouver was utilized. Traffic data measured at the mid-span of the Knight Street Bridge was selected for the analysis, as it is representative of a roadway having a high traffic volume, and a high proportion of heavy duty trucks in the vehicle population. The number of diesel vehicles travelling on the roadway was determined using the reported traffic data, which is summarized in Table 3-1 by hour of day and vehicle type.

The heavy truck traffic is high from 0700 hours (7:00 AM) through to 1500 hours (3:00 PM) , with peak truck traffic volumes occurring from 8:00-9:00 AM and 2:00-3:00 PM. Heavy duty gasoline and diesel fueled trucks comprise 3.3% of the total traffic volume. Passenger cars are the dominant vehicle category, comprising 93.0% of the traffic, while light trucks amount to 3.6% and other vehicles amount to 0.1%.

The percentage of passenger cars, light trucks and heavy trucks that are diesel fueled was needed to disaggregate the respective traffic count statistics measured at the Knight Street Bridge location and thereby estimate the number of diesel vehicles in each of these categories. The percentage of the fleet in each vehicle category was estimated using the vehicle kilometers traveled (VkmT) in the GVRD predicted by TransLink for the 1995 inventory of emissions from on-road vehicles (GVRD, 1998) and the 1990 annual mileage accumulation rates for each vehicle category. This input data and the calculated vehicle percentages are presented in Table 3-2. Applying the calculated vehicle percentages by fuel type for each vehicle category used in the traffic counts gives the vehicle split between gasoline and diesel vehicles presented in Table 3-3.

Some uncertainty in the estimate of the number of diesel fuelled vehicles is introduced by increases that are known to be occurring both in the annual VkmT driven in the Lower Fraser Valley and the annual mileage accumulation rates for each vehicle category since 1995 and 1990, respectively. The most notable shift is a significant increase in the number of light duty trucks, because of the popularity of vans and sport utility vehicles. The effect of any uncertainty in the diesel:gasoline split for passenger cars and light trucks on the calculated emission of diesel particulate from all diesel vehicles will be small because the emissions are small relative to those from heavy duty vehicles. In the US there has been a continuing trend towards increased use of diesel for heavy duty on-road vehicles that is likely also occurring in Canada. In this case, the estimated diesel:gasoline split, and the estimated emissions for heavy duty vehicles could be an underestimate. All considered, the estimated emission rates are most likely conservative for the vast majority of urban streets as the location used for the traffic data has one of the highest truck traffic volumes for a road of its type in the region.

Table 3-1 1996 Vehicle counts for the Knight Street Bridge Count Station (Conservative Modelling Case)

Time Period	Total Vehicles	Passenger Cars	Light Trucks	Heavy Trucks	Other	Total Diesel	Diesel Passenger Cars	Diesel Light Trucks	Diesel Heavy Trucks
6:00	4311	4071	98	130	12	131	45	2	84
7:00	6940	6551	161	215	13	214	72	3	139
8:00	7495	6921	300	263	11	252	76	6	170
9:00	5783	5271	252	250	10	225	58	5	162
10:00	5179	4700	239	234	6	208	52	5	152
11:00	5310	4766	290	250	4	220	52	6	162
12:00	5280	4740	286	248	6	218	52	6	161
13:00	5547	4976	305	260	6	229	55	6	168
14:00	6293	5646	346	296	5	260	62	7	192
15:00	7324	6829	280	207	8	214	75	6	134
16:00	7395	7021	215	146	13	176	77	4	95
17:00	7450	7149	162	127	12	164	78	3	82
18:00	5995	5744	129	110	12	137	63	3	71
19:00	4125	3946	92	82	5	98	43	2	53
20:00	2924	2796	65	57	6	69	31	1	37
21:00	3030	2896	68	61	5	73	32	1	40
22:00 - 6:00	7753	7208	280	253	12	249	79	6	164
Average	5773	5367	210	188	9	185	59	4	122
Percent of Vehicles	100	92.9	3.6	3.3	0.2	100	31.9	2.2	65.9

Source: GVRD, Strategic Planning Department, 1997. 1996 Vehicle Volumes, Classifications and Occupancies, Knight Street Bridge, Count Station 6.3.

Table 3-2 Estimated Vehicle Fleet Profile for the Lower Fraser Valley

Vehicle Type	Description	Million VkmT for 1995[1]	Vehicle Mileage Accumulation[2] (Average km/yr)	Estimated Vehicle Percentage
LDGV	Light Duty Gasoline Vehicles (passenger cars)	10105	14,001	70.72%
LDGT1	Light Duty Gasoline Trucks, up to 2720kg (includes vans & pickups)	3078	15,224	19.81%
LDGT2	Light Duty Gasoline Trucks, 2720kg - 3856 kg (includes heavier vans, pickups, some commercial trucks)	871	15,224	5.61%
HDGV	Heavy Duty Gasoline Vehicles	53	13,551	0.38%
LDDV	Light Duty Diesel Vehicles	112	14,001	0.78%
LDDT	Light Duty Diesel Trucks (includes types 1 & 2)	124	23,593	0.52%
HDDV	Heavy Duty Diesel Vehicles	629	87,484	0.70%
MC	Motorcycles	83	5,520	1.47%
All Vehicles		15054		100.00%

[1] 1995 LFV Emission Inventory, GVRD, 1998.

[2] Levelton Engineering, 1993, for the inventory of 1990 mobile source emissions in the Lower Fraser Valley.

Table 3-3 Estimated Percentage of Diesel and Gasoline Vehicles in the GVRD

Passenger Cars		Light Trucks		Heavy Trucks	
Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline
1.10%	98.90%	1.99%	98.01%	64.77%	35.23%

The percentages in Table 3-3 were applied to the number of vehicles, light trucks, and heavy trucks in Table 3-1 to estimate approximately the hourly number of diesel vehicles of each type. The estimated number of diesel vehicles is presented in the last four columns of Table 3-1, indicating at this site and roadway, the distribution of diesel vehicles is dominated by heavy duty trucks (65.9%), followed by diesel passenger cars (31.9%) and light duty diesel trucks (2.2%).

Emission factors for 1998 by vehicle classification, were supplied by the GVRD and are the same as used in the 1998 regional emission inventory. For diesel particulate exhaust, the emission factors are constant with speed.

A weighted emission factor was derived based on the number of types of vehicles. To account for the daily variance of traffic volumes, four separate emission factors and vehicle flows were modeled depending on the time of day. This was done to provide an improved estimate of 24-hour average concentrations. The emission factors and weighted emission factors for each period modeled are presented in Tables 3-4 and 3-5.

Table 3-4 Diesel Particulate Emission Factors Used for Emission Estimates

Particulate Size Range	Emission Factor (g/km)		
	LDDV	LDDT	HDDV
PM_{10}	0.160	0.182	0.495
$PM_{2.5}$	0.138	0.159	0.437

Table 3-5 Emission Factors For Each Hour in the Day Used for Modelling Ambient PM_{10} and $PM_{2.5}$ Concentrations

Time (beginning to ending)	$PM_{2.5}$ Weighted Emission Factor (g/km)	PM_{10} Weighted Emission Factor (g/km)	Number of Diesel Vehicles	Vehicles per Hour
6:00am to 9:00am	0.34	0.38	597	199
9:00am to 3:00pm	0.36	0.41	1360	227
3:00pm to 7:00pm	0.30	0.35	691	173
7:00pm to 6:00am	0.32	0.36	488	44

3.3 MAXIMUM PREDICTED 24-HOUR DIESEL PARTICULATE CONCENTRATIONS

Diesel particulate concentrations were predicted assuming an emission rate at 100% and 50% of that estimated using the traffic data discussed in Section 3.2 for a road having a high volume of heavy truck traffic The modeling analysis is preliminary and only suitable at this time for an order of magnitude indication of ambient PM_{10} and $PM_{2.5}$ diesel particulate matter concentrations that may occur, and of the change in peak concentration with distance away from a roadway.

The CALINE model was run to predict 1-hour average diesel particulate concentrations for each of the four representative time periods described in Section 3.2, each period including hours having similar traffic volumes. The predicted concentrations were subsequently combined to create a data set containing results for all of the hours in the one-year meteorological period considered in this study. The data set was analyzed to determine the maximum predicted 24-hour average particulate concentration as a function of distance from the roadway in increments of 10 m from the roadside to a distance of 150 m.

Maximum predicted 24-hour average diesel particulate matter concentrations for the calculated emission rates are presented in Figure 3-1 for PM_{10} and Figure 3-2 for $PM_{2.5}$ as a function of distance away from the centre of the roadway. At 100% of the assumed traffic volume, the maximum 24-hour diesel PM_{10} concentration was predicted to be about 2.8 $\mu g/m^3$, while the maximum 24-hour diesel $PM_{2.5}$ concentration was predicted to be about 2.4 $\mu g/m^3$. Peak concentrations occur at the roadside. Note that the concentrations shown are the maximum predicted values at each distance away from the road centreline during any rolling 24 hour period in the modeled year (1996). These maximum concentrations are predicted to occur very infrequently and will not occur simultaneously for all distances from the road.

Predicted diesel particulate concentrations are linearly proportional to emission rate. The higher values shown in Figures 3-1 and 3-2 apply to the case of 100% of the reported1996 Knight

Street Bridge traffic volume, while the lower values apply to 50% of this volume. These graphs may also be used to approximate the maximum diesel particulate concentrations adjacent to roads having different diesel particulate emission rates than those modelled as long as the concentrations are adjusted in proportion to the change in emission rate and the distribution of emissions over the day are similar.

Diesel PM_{10} and $PM_{2.5}$ concentrations decrease with increasing distance perpendicular to the roadway. The maximum predicted concentration decreases rapidly to about 39% of the peak roadside concentration at a distance of 10 m from the centreline, and to 27% of the peak roadside concentration at a distance of 20 m. The maximum predicted concentration decreases to about 9% of the roadside concentration at a distance of 150 m from the centreline. The downward trend of particulate concentration continues beyond this distance, however predicted concentrations become very uncertain because of potential interference from other road sources, the effects of buildings and other structures that may be present, and the limitations of the dispersion model.

The worst-case conditions for the predicted 24-hour concentrations are associated with persistent wind in the direction perpendicular to the road, an average wind speed of 6 km/hr, and low mixing heights.

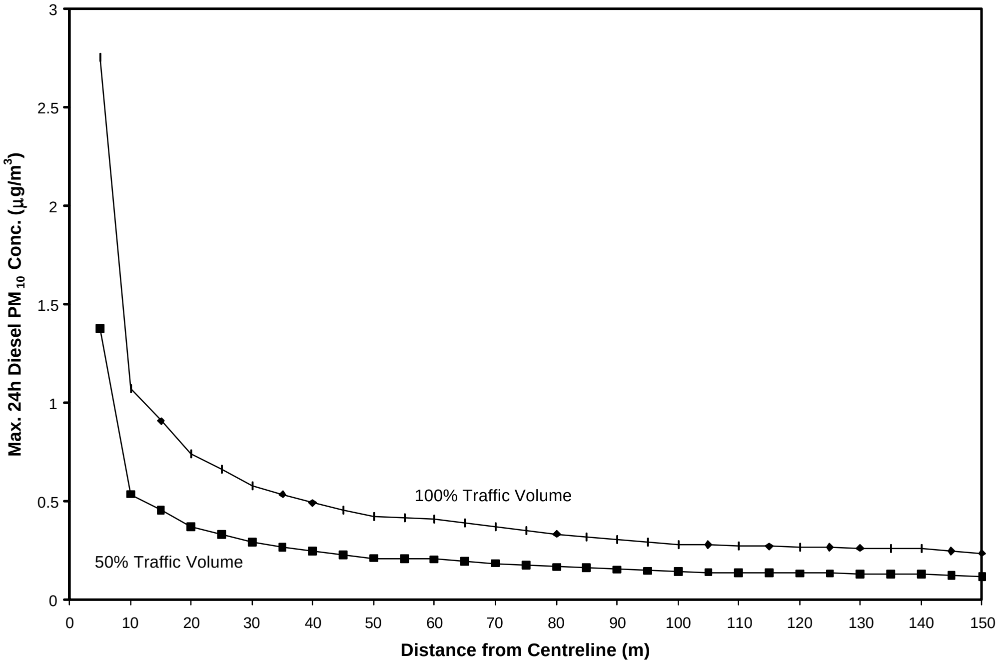

Figure 3-1 Maximum Predicted 24-hour Diesel PM$_{10}$ Concentration for a High Traffic Truck Route Versus Distance Away from the Roadway

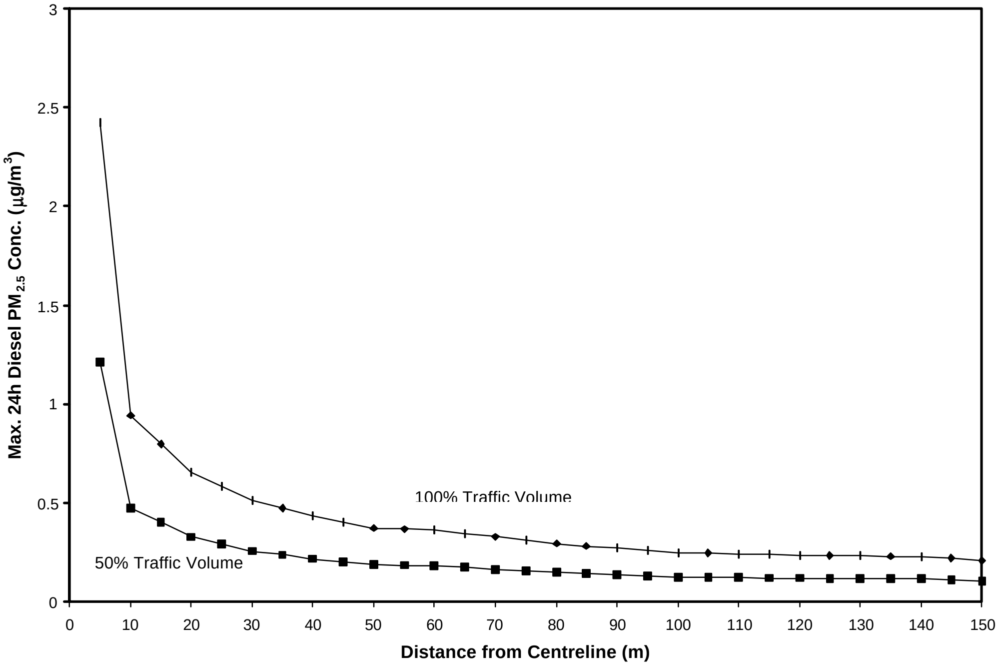

Figure 3-2 Maximum Predicted 24-hour Diesel PM$_{2.5}$ Concentration for a High Traffic Truck Route Versus Distance Away from the Roadway

4. INTEGRATION OF AVAILABLE DATA PERTAINING TO THE POTENTIAL FOR DIESEL PARTICULATE HEALTH IMPACTS

4.1 CONTRIBUTION OF DIESEL PARTICULATE TO TOTAL EMISSIONS

The most recent inventory of emissions in the Lower Fraser Valley was prepared for 1998 by the GVRD (1999). This inventory was developed as an interim update to the comprehensive emission inventory prepared for 1995 (GVRD, 1998) using a combination of detailed analysis of major source sectors and extrapolation of minor source sectors based on surrogates for changes in source activity levels. The next comprehensive emission inventory is scheduled to be completed for the year 2000.

The 1998 particulate emissions in the Lower Fraser Valley (GVRD, 1999) are as shown in Table 4-1.

Table 4-1 Total, Inhalable and Fine Particulate Matter Emissions in the Lower Fraser Valley in 1998

Sector	Particulate Matter					
	Total		PM_{10}		$PM_{2.5}$	
	tonnes	%	Tonnes	%	tonnes	%
POINT SOURCES	9,743	49.1%	3,818	35.7%	1,759	27.2%
AREA SOURCES	7,352	37.1%	4,219	39.4%	2,408	37.2%
MOBILE SOURCES	2,743	13.8%	2,671	24.9%	2,308	35.6%
Light-duty vehicles	384	1.9%	376	3.5%	229	3.5%
Heavy-duty vehicles	337	1.7%	337	3.1%	296	4.6%
Off-Road	2,022	10.2%	1,958	18.3%	1,783	27.5%
TOTAL, All Sources	**19,838**		**10,708**		**6,475**	

Based on a review of the reported particulate emissions for point and area source categories, emissions of diesel particulate from these sectors are expected to be small, and associated mainly with diesel fuel used as a standby fuel when natural gas supply is interrupted, or for space heating in areas where natural gas is not available.

As discussed in more detail later in this section, annual emissions of PM_{10} and $PM_{2.5}$ from diesel fueled mobile sources in the LFV total 967 tonnes and 874 tonnes, respectively. Assuming negligible diesel particulate emissions from the point and area source sectors, diesel particulate is estimated to be 4.9% of PM, 9.0% of PM_{10} and 13.5% of $PM_{2.5}$ emissions from all sectors, excluding road dust. If road dust emissions are included in the total for the region, the contribution from diesel particulate decreases to 1.4% of PM, 4.7% of PM_{10} and 9.9% of $PM_{2.5}$.

Table 4-2 summarizes the 1998 emissions of total particulate matter, PM_{10} and $PM_{2.5}$ from mobile sources in the Lower Fraser Valley, showing the emissions for each subsector by fuel type or fugitive source. Of the total particulate emissions from the mobile sector of 2,743 tonnes, 97.3% is PM_{10} (2,671 tonnes) and 84.1% is $PM_{2.5}$ (2,308) tonnes. Diesel fuel particulate from the mobile source sector amounts to 967 t of PM and PM_{10} (36.2% of the PM_{10} sector total) and 874 t of $PM_{2.5}$ (37.9% of the sector total). All diesel particulate emissions are less than 10 µm in size and over 90 % are typically less than 2.5 µm in size (CARB/OEHHA, 1998, 1998b; Singal and Pundir, 1996).

Table 4-2 Emissions of Particulate Matter and Diesel Particulate Matter from the Mobile Sector in the Lower Fraser Valley in 1998

Source Subsector	Emission (tonnes)					
	PM	% of Sector Total	PM_{10}	% of Sector Total	$PM_{2.5}$	% of Sector Total
1.On Road Vehicles						
Light-Duty						
Gasoline	341		333		191	
Diesel	43		43		37	
	384	14.0	376	14.1	229	9.9
Heavy-Duty						
Gasoline	5		5		3	
Diesel	332		332		293	
	337	12.9	337	12.6	296	12.8
Total						
Gasoline	346		338		195	
Diesel	375		375		330	
	721	26.3	713	26.7	525	22.7
2. Off-Road Vehicles						
Gasoline	42		40		37	
Diesel	287		287		264	
	329	12.0	327	12.2	301	13.0
3. Aircraft						
Kerosene and Jet Fuel	142	5.2	79	3.0	56	2.4
4. Rail						
Diesel Fuel	110		110		101	
Coal Dust	1191		1191		1095	
	1301	47.4	1301	48.7	1196	51.8
5. Marine Vessels						
Heavy Fuel Oil	55		55		51	
Diesel Fuel	195		195		179	
	250	9.1	250	9.4	230	10.0
Sector Total	2,743		2,671		2,308	
Total Diesel Particulate	967	35.3	967	36.2	874	37.9

Source: GVRD, 1999

The main sources of diesel particulate matter from the mobile source sector are summarized in Table 4-3, in decreasing order of magnitude. The largest source of diesel particulate emissions is heavy duty on-road vehicles, amounting to 34.3% of the PM_{10} and 33.5% of the $PM_{2.5}$. This category includes a wide range of vehicles over 8500 lbs. GVW, such as medium duty vehicles, delivery vans, Class 7 (26,001 – 33,000 lb. GVW) and Class 8 (>33,000 lb. GVW) diesel tractor/trailer units and diesel transit buses. The dominant group within the heavy duty truck category is Class 7 and 8 trucks, though the presently reported emission inventory does not show the contributions from transit buses separate from other heavy duty on-road vehicles.

In 1995, total bus travel in the region was 37.437 million kilometers (GVRD, pers comm., 1999) based on the data developed previously by TransLink for the 1995 emission inventory using the EMME/2 regional transportation model. This includes public transit, school and commercial bus operations. As most of the buses use diesel engines, diesel particulate emissions from all buses in 1998 are estimated to be 19.1 t of PM_{10} (0.510 g/km) and 17.1 t of $PM_{2.5}$ (0.457 g/km), assuming the travel distance for buses is similar for 1998 as in 1995. This is based on emission factors for buses determined by Levelton (1999b)[2]. At these emission levels, buses contribute 2.0% of the mobile sector diesel PM_{10} and $PM_{2.5}$ emitted in the region, and 5.8% of the particulate emitted from the heavy duty vehicle subsector.

Table 4-3 summarizes the contribution to the total diesel particulate emissions in the Lower Fraser Valley from off-road vehicles, marine vessels, rail, light duty on-road vehicles and aircraft. Light duty on-road vehicles contribute about 4.3% of the diesel PM_{10} emissions from the mobile sector, consistent with the small fraction of diesel vehicles in the light duty vehicle fleet.

Table 4-3 Diesel Particulate Matter Emissions in the Lower Fraser Valley from the Mobile Sector in Order of Magnitude

Rank	Subsector	LFV Diesel Particulate Emissions			
		PM_{10} (tonne)	% of Total	$PM_{2.5}$ (tonne)	% of Total
1	Heavy duty on-road vehicles	332	34.3	293	33.5
2	Off-road Vehicles	287	29.7	264	30.2
3	Marine vessels	195	20.2	179	20.5
4	Rail	110	11.4	101	11.6
5	Light duty on-road vehicles	43	4.4	37	4.2
6	Aircraft	0	0	0	0
	Totals	967	100	874	100

Figure 4-1 shows the diesel PM_{10} emission results from Table 4-3 in graphical form, illustrating the percentage contribution of each subsector and further subdividing the emissions from heavy duty vehicles to show the individual contributions from trucks and all buses.

The most recent backcast and forecast of annual PM_{10} and $PM_{2.5}$ emissions from heavy duty vehicles in the Lower Fraser Valley are those reported by Levelton (1998). The PM_{10} results for heavy duty vehicles and heavy duty diesel vehicles given in this reference are summarized in Table 4-4. $PM_{2.5}$ emissions were calculated as 88% of the PM_{10} emissions, consistent with the size distribution profile used in the US EPA Part 5 model. The emission forecast is based on TransLink projections of growth in vehicle kilometers traveled and emission factors predicted by the US Part 5 model. Emission factors for the truck fleet improve as old heavy duty trucks are assumed to be replaced over time with 1994 or later model trucks meeting the 1994 US exhaust emission standards. Also, emission factors have been adjusted to suit the sulphur content of diesel fuel meeting the BC fuel sulphur regulation and to reflect the reduction in emissions anticipated by the inspection and maintenance program that has been implemented for heavy

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[2] Determined using the same model (PART5) and input assumptions used by the GVRD for calculating emission factors for the overall heavy duty vehicle fleet for the 1998 emission inventory.

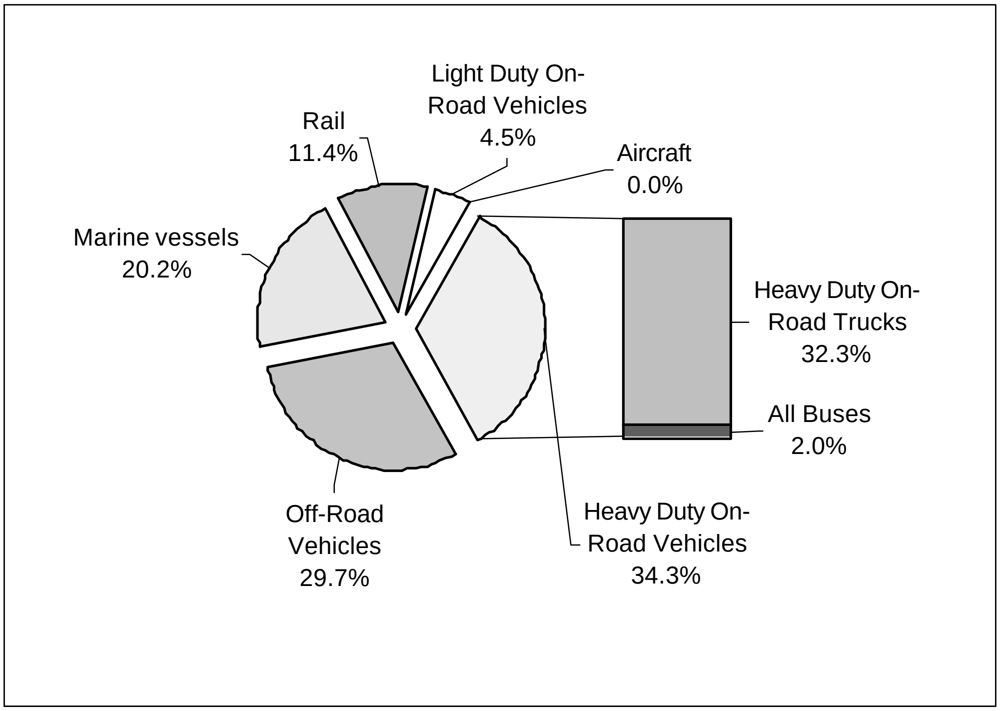


Figure 4-1 Subsector Contributions to Total Diesel PM_{10} Emissions in the Lower Fraser Valley

duty vehicles. Emission reductions achieved by this inspection and maintenance program were reported in the previous study to be 5.8% in 2000, increasing to 19.2% in 2015, then decreasing to 17.9% in 2020.

The recent GVRD inventory of 1998 PM_{10} emissions from heavy duty diesel vehicles of 332 tonnes is 15% higher than the Levelton (1998) forecast for 2000 of 288 tonnes shown in Table 4-4. This result suggests that the forecast emissions for later years may be under-estimates.

Table 4-4 Current and Forecast Emissions of PM_{10} and $PM_{2.5}$ from On-Road Heavy Duty Vehicles

Year	Emissions (tonnes)					
	PM_{10}			$PM_{2.5}$		
	HDGV[a]	HDDV	Total	HDGV	HDDV	Total
1995	6	413	419	6	363	369
2000	5	288	293	5	253	258
2005	4	155	159	4	136	140
2010	4	131	135	4	115	119
2015	4	129	133	4	114	118
2020	4	140	144	4	123	127

a HDGV, heavy duty gasoline vehicles; HDDV, heavy duty diesel vehicles.
Source: PM_{10} from Levelton, 1998; $PM_{2.5}$ calculated as 88% of PM_{10} emissions.

Relative to the emissions in 1995, diesel $PM_{2.5}$ and PM_{10} emissions from heavy duty diesel trucks and buses are forecast to decrease 68-69% by 2010-2015 as a result of fleet turnover and the inspection and maintenance program. Diesel particulate emissions are forecast to decrease 45% from 2000 to 2010-2015. Diesel particulate emissions from heavy duty diesel vehicles are forecast to once again begin to increase after 2015, assuming exhaust emission standards remain at the levels set for the 1994 model year. This is true for heavy duty trucks, which are the dominant source of heavy duty vehicle emissions, however, the particulate emission standard for buses were further reduced for the 1996 model year.

The contribution of heavy duty vehicles to total PM_{10} emitted by the mobile source sector in the Lower Fraser Valley is forecast to decrease from 10% in 2000 to about 3% in 2020, because of the decrease in emissions of diesel particulate matter from heavy duty vehicles combined with growth in emissions from other mobile sources.

4.2 RELEVANT INFORMATION AND TRENDS FROM REGIONAL PARTICULATE MONITORING

4.2.1 Ambient Monitoring Data for PM_{10} and $PM_{2.5}$

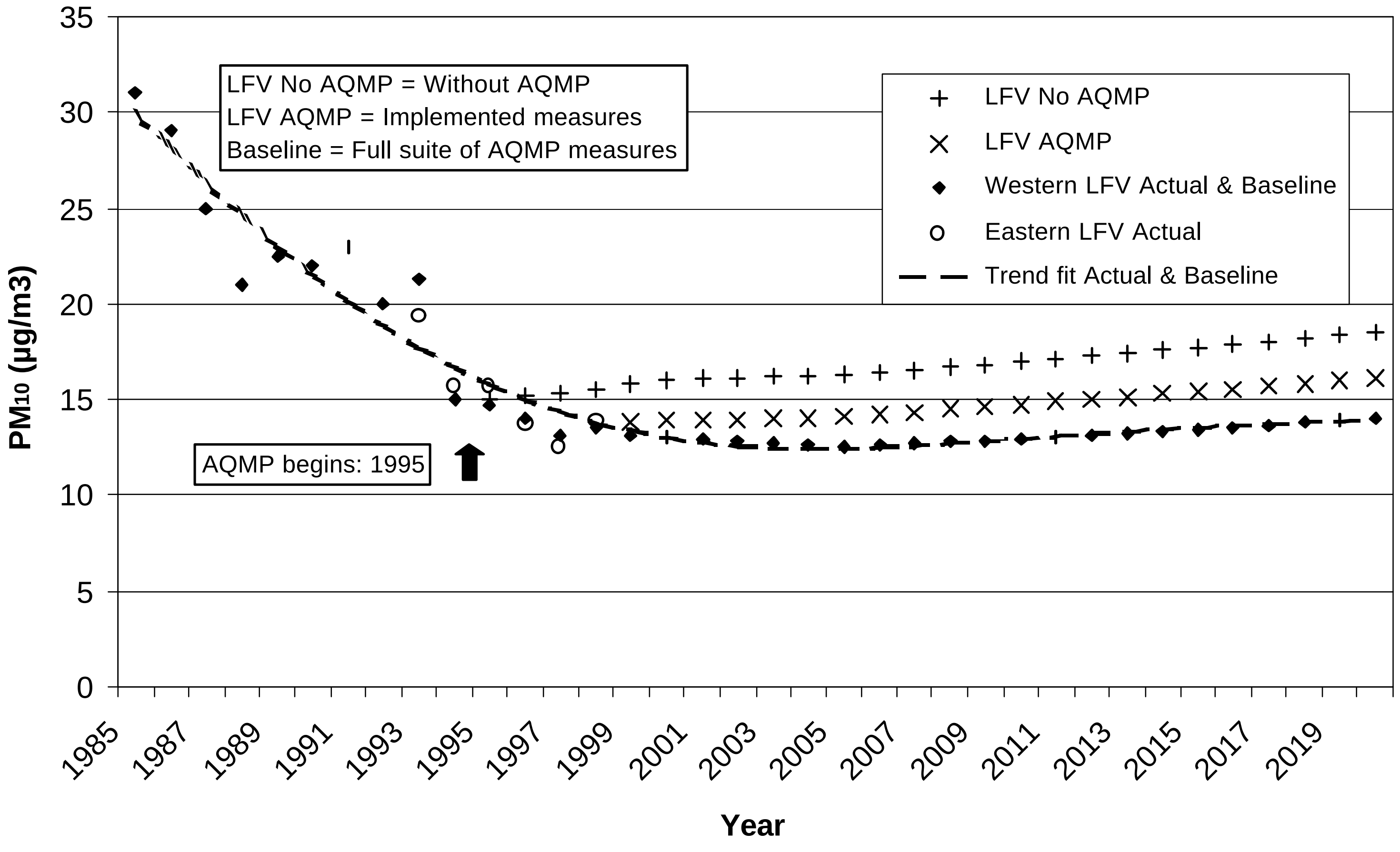
The regional monitoring network in the Lower Fraser Valley currently includes 13 continuous monitors for PM_{10} and 1 $PM_{2.5}$ continuous monitor. An additional 3 $PM_{2.5}$ monitors are planned for the near future. The most recent data and trends are summarized in the LFV *Ambient Air Quality Report* for 1998 (GVRD/FVRD, 1999). Mean levels of PM_{10} vary little from one monitoring station to another across the region. Other statistical characteristics of the PM_{10} monitoring data (e.g., maximum, minimum, standard deviation) also vary little from station to station. Levels have remained relatively constant over the past few years after a significant drop from the mid-1980s. The regional mean levels for PM_{10} are now between 13-15 $\mu g/m^3$. The relative contribution of diesel particulate matter (DPM) to the observed PM_{10} concentrations has not been determined, but it can be estimated approximately, as described below in Section 4.4.2.

Estimates from a related project currently in progress—the BC Clean Transportation Analysis Project—indicate the following trend forecast for the mean PM_{10} concentration in the region out to 2020 (Figure 4-2). Based on these data, it is expected that the regional mean level of PM_{10} will remain constant or drop slightly over the next few years and then rise very slowly between 2005 and 2020.

4.2.2 Estimate of the Contribution of Diesel Particulate Matter to Ambient PM_{10}

A number of research studies of fine particulate matter in the Lower Fraser Valley have attempted to apportion the source contributions to ambient particulate matter concentrations. Gasoline and diesel-fuelled vehicles both emit carbonaceous particles. It is difficult to distinguish the relative contributions of gasoline and diesel emissions to ambient PM_{10} or $PM_{2.5}$ concentrations, because the chemical parameters usually measured in field studies are insufficient to apportion the individual contributions to measured particulate matter levels. This has been the case to date in the LFV. Lowenthal et al. (1994) sum up the situation: "… it is not possible, given the available source profiles and large number of potential source types, to distinguish between diesel- and gasoline-based emissions in REVEAL $PM_{2.5}$ aerosols using CMB (chemical mass balance)." Another summary of the REVEAL source apportionment analysis and attempts to resolve vehicle emissions in collected field samples of $PM_{2.5}$ may be found in Pryor et al. (1997). The Cassiar Tunnel studies in 1993 and 1995 focused on determining how derived emission factors for gaseous pollutants related to those used in emission inventories, as described, for example, by Rogak et al. (1998). None of these studies was able to determine from measured ambient concentrations the gasoline/diesel particulate matter emission contributions.

Figure 4-2 LFV PM_{10} Measured & Forecast Levels—GVRD AQMP Measures
[Annual average Lower Fraser Valley (LFV) network concentrations]



As documented in an earlier report to GVRD on road dust emission estimates for the region (Levelton/Alchemy, 1998), an estimation method based on a carbon monoxide dispersion factor is believed to provide a reasonable estimate of the dispersion of other exhaust emissions from on-road vehicles. A high proportion of regional carbon monoxide (CO) emissions comes from the on-road vehicle fleet. Carbon monoxide is monitored at 18 sites throughout the LFV. The ratiometric method assumes that the ratio of measured CO concentrations to estimated CO emissions from the current emission inventory can be used to relate the estimated emissions of other pollutants emitted from vehicles to their otherwise unknown ambient concentrations. In this case, the average ambient concentration of diesel PM_{10} or $PM_{2.5}$ may be estimated by multiplying the corresponding annual emission of diesel PM_{10} or $PM_{2.5}$ (in tonnes per year, t/y) by the ratio of CO concentration (µg/m^3) to CO emissions (t/y). The calculation is shown in the following equation:

$$
\begin{aligned}
[\mathrm{DPM}]_{\mathrm{ambient}} &= \{[\mathrm{CO}]_{\mathrm{ambient}} / \text{CO emission rate (t/y)}\} \text{ X DPM emission rate (t/y)} \\
&= K_{\mathrm{local\ CO}} \text{ x DPM emission rate (t/y)},
\end{aligned}
$$

where DPM refers to diesel particulate matter from the on-road diesel vehicle fleet.

Table 4-5 shows the relevant data for the emission rate and concentration of CO in the Lower Fraser Valley. K_{local} is the CO dispersion factor needed for the above equation. It is assumed to characterize the local dispersion characteristics of emissions from the on-road vehicle fleet averaged over the entire region that is covered by monitors.

The CO ratio shown in the table has been adjusted for the local contribution of on-road vehicles taking into account an estimated background level. The CO ratio has remained essentially constant over a long period of time, although the estimated emissions have dropped by nearly 60% over the period shown in the table. This means that the measured ambient concentrations due to local sources have dropped in direct proportion to the emissions, lending credence to the approach.

The 1998 emission inventory for the region (see Section 4.1) estimates that total on and off-road motor vehicle diesel particulate emissions (expressed as $PM_{2.5}$)[3] are about 594 t/y, of which 330 t/y come from the on-road fleet (all light-duty diesel vehicles: cars and trucks and heavy-duty diesel vehicles: trucks and buses). Within this on-road fleet total, it is estimated that the total regional public transit, commercial and school diesel bus fleet would contribute about 17 t/y of $PM_{2.5}$ (see Section 4.1). When rail, aircraft and marine diesel emissions are added as contributors, the total emission of diesel particulate matter for 1998 comes to 874 t/y of $PM_{2.5}$ (see Table 4-2)

The CO ratiometric method applies only to the on-road fleet, so on this basis on-road diesel vehicles contribute about 1 µg/m^3 of diesel particulate matter to the regional average ambient PM_{10} or $PM_{2.5}$ concentration. This level is about 8% of the current total PM_{10} concentration. The total diesel particulate matter concentration may be higher due to contributions from other sources that cannot be estimated by this method. Total diesel particulate emissions are about 2.7 times the on-road vehicle emission, but some of the additional emissions, such as marine sources, occur at a considerable distance from human receptors. As an educated guess, the average total ambient loading of diesel particulate matter in the populated region due to all sources might be up to twice the estimate for on-road vehicles alone.

The contribution of on-road diesel vehicles to PM_{10} or $PM_{2.5}$ will decrease about 45% from the current level by 2010-2015 based on the most recent forecast of emissions from heavy duty

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[3] Diesel particulate matter emissions are approximately equal whether expressed as PM_{10} or $PM_{2.5}$.

diesel vehicles. On this basis, the contribution of on-road diesel particulate matter to the regional average ambient PM_{10} or $PM_{2.5}$ concentration will decrease from the estimated current level of 1 µg/m^3 to about 0.5 µg/m^3.

Table 4-5 Carbon Monoxide Dispersion Ratios for the Lower Fraser Valley

Basis	Estimated Regional Background Conc. (µg/m^3)	On-road Vehicle Emissions (t/y)*	Total emissions (t/y)	Avg Total Conc. (µg/m^3)	Avg Local Conc. (vehicles) (µg/m^3)	K_{local} (vehicles) (µg/m^3 per t/y)
CO 1995	160	162,003	183,614	749	520	3.208E-03
CO 1996	160	149,078	171,039	698	469	3.145E-03
CO 1997	160	137,184	159,501	697	462	3.367E-03
CO 1998	160	126,238	148,918	658	422	3.344E-03
CO 1990 (Levelton backcast)	160	293,583	317,411	1140	906	3.087E-03
S in Fuels Study data (1990)	160	304,700	335,573	1140	890	2.920E-03
				Avg. K_{local}	1995-1998	3.266E-03

* Using revised GVRD Scenario B baseline for the on-road fleet from the BC CTA study for 1995-1998 (Alchemy/Levelton, 2000)

There are insufficient data to estimate the current regional ambient $PM_{2.5}$ concentration, but typically, the ratio of $[PM_{2.5}]/[PM_{10}]$ is about 0.55. This suggests that diesel particulate matter from on-road vehicles comprises about 15% of ambient $PM_{2.5}$.

The California assessment estimated that in Los Angeles ambient diesel particulate matter averages about 1.5 µg/m^3, while EPA (1996b) data indicates $PM_{2.5}$ concentrations in Boston, Rochester, NY and Washington, DC are of similar magnitude, ranging from 0.5-1.6 µg/m^3. The preliminary estimates developed in this study suggest that the ambient diesel particulate matter concentration in the Lower Fraser Valley is possibly similar in magnitude to that observed in US cities.

The CALINE3 dispersion modelling results shown in Chapter 3 suggest a maximum value of ambient diesel particulate matter concentration beyond 150 m of roads carrying a high truck traffic volume that is lower than the estimated average value derived from the CO ratiometric method. The modelling results imply that an average ambient level of on-road diesel particulate matter would more likely be below 0.25 µg/m^3 than near 1 µg/m^3. This discrepancy suggests the possible range of uncertainty in an exposure estimate for health effects assessment. The higher value is assumed in our assessment to err on the conservative side. The CO ratiometric approach does not take into account removal processes that reduce particle concentrations relative to CO as the pollutants disperse, such as by dry deposition, washout or rain out, so it is expected that this estimation method may over-estimate the ambient concentration of diesel particulate matter. The dispersion modelling method makes some allowances for the effects of these processes.

At a distance of 20 m from the street centreline, the dispersion modelling predicts that the maximum 24-hour average diesel PM_{10} or $PM_{2.5}$ concentration from on-road vehicles would be about 27% of the roadside concentration. The maximum diesel PM_{10} or $PM_{2.5}$ concentration decreases to about 18% of the roadside level at a distance of 40 m, and 9% of the roadside concentration at 150 m from the centre of the road. This all suggests that a very conservative estimate[4] of the maximum 24-hour average concentration that a resident living near a street (i.e., at 20 m distance) with heavy diesel traffic might be exposed to would be between 0.7 (the modelled result) and 2 µg/m^3 (twice the ratiometric method result for the regional average).

The analysis of the potential impact of diesel particulate emissions on ambient PM_{10} and $PM_{2.5}$ concentrations can also be used to assess the significance of adding diesel buses to the current public transit bus fleet. The incremental contribution to emissions by a fleet of 1,000 new diesel transit buses designed to meet the current emission standard would be about 26 t/y of diesel particulate matter (see Table 5-4, Section 5-4 for emission calculation). The CO ratiometric method implies that this would add below 0.1 µg/m^3 to the mean ambient PM_{10} or $PM_{2.5}$ concentration, or about 10% of the estimated current ambient concentration of diesel particulate matter from on-road vehicles.

The exposure estimated from the modelling results shown in Chapter 3 represents a worst case, since the values are the maximum 24 hour averages at the indicated distances from the street that may occur infrequently during a 1 year period. The more typical 1-hour diesel particulate concentrations that contribute to the 24-hour averages are in the range of 0.2 to 0.6 µg/m^3 (about 50% of the time). The maximum 1-hour value in the modelling simulation was about 20 µg/m^3 at roadside—30 to 100 times the more typical maximum hourly values. The potential health significance of such peak values is not known, but it is clear that short-term roadside exposures can be quite high. We base our assessment of potential health effects in the next section on the longer-term average concentrations that would be characteristic of typical exposures across the region.

4.3 POTENTIAL FOR HEALTH IMPACTS FROM EXPOSURE TO DIESEL PARTICULATE IN THE LOWER FRASER VALLEY

The California health assessment cited in Chapter 2 (CARB/OEHHA, 1998a,b) proposed a daily reference concentration (RfC) for morbidity effects of diesel particulate matter concentration of 5 µg/m^3. This is not intended as a threshold value, but as an indicator of a concentration above which there is concern for possible chronic morbidity effects (respiratory irritation, etc.), including sensitive members of the general population.

The dispersion modelling results shown in Chapter 3 indicate that the peak concentration at the side of a Vancouver street with heavy diesel truck traffic is about 2.8 µg/m^3 of diesel PM_{10} averaged over 24 hours in the worst case. If this represents the maximum concentration to which a resident is exposed over 24 hours, the California RfC level would not be exceeded. This implies a relatively low level of concern for non-mortality effects in Vancouver. The California assessment also proposed a diesel particulate matter cancer risk factor of 3×10^{-4} lifetime (70 years) risk per µg/m^3 of exposure. That is, diesel particulate matter is estimated to increase the risk of contracting cancer by 300 in a million if a person is exposed to 1 µg/m^3 of diesel particulate matter for an entire 70-year lifetime. The current total lifetime risk of dying from cancers of all kinds is about 20-25%, or 200,000-250,000 in a million. The cancer risk factor is an upper bound estimate. To-date, both the US EPA and the Health Effects Institute in their reviews that post-date the California assessment found insufficient evidence to recommend a diesel particulate matter cancer dose-response factor.

If the 70-year lifetime risk is 3×10^{-4}, the annual risk (basis for estimating the approximate number of new cancer cases per year) is about 4×10^{-6} (4 in a million). For an exposed

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[4] This estimate is conservative for the region in general as it is based on a high diesel particulate emission rate associated with a busy truck route and the highest 24-hour average concentration predicted over a one year period.

population of 2 million (the approximate population of the LFV), this implies that about 8 new cases of cancer a year would be attributable to exposure to the estimated current average level of diesel particulate matter from on-road diesel vehicles (1 µg/m^3 from Section 4.2.2)[5]. Of these, about 5% (i.e., 1 case in 2 years) would be attributable to emissions from all diesel buses operating in the region, based on the relative emissions stated above.

The number of new cancer cases per year attributable to emissions from on-road heavy duty diesel vehicles is estimated to decrease to 4 by 2010-2015 as a result of the forecast decline of emissions from this source subsector (see Section 4.1 for information on the emission forecast).

4.4 RECOMMENDATIONS FOR AMBIENT MONITORING OF DIESEL PARTICULATE

The predicted air quality and health impacts of diesel particulate matter are sufficiently low based on the analysis in this study to not be an immediate health concern, but do warrant further study. Given the uncertainty in the estimated ambient concentrations together with the potential health impacts of diesel particulate matter, a focused monitoring program as outlined below is recommended for the Lower Fraser Valley:

- At a monitoring station located near a road or within a road transportation corridor where there is a high volume of heavy duty truck traffic, PM_{10} or, preferably, $PM_{2.5}$ should be monitored on a continuous basis for at least a one year period. Designated truck routes would be obvious candidate monitoring locations.
- If feasible, a second such monitoring study should be carried out at a site more representative of general regional exposure, i.e. well away from emissions of combustion particulate matter.
- Periodic samples of the collected fine particulate should be analyzed to determine the mass fraction of elemental and organic carbon. Elemental carbon is approximately 60-80% the mass of diesel particulate matter, however, there are numerous other sources, such as gasoline engine exhaust, combustion of wood and oil, charcoal barbecues, cigarette smoke and road dust. As diesel particulate is a major contributor to ambient elemental carbon emissions, measured ambient concentrations of elemental carbon can be used to determine an upper bound of diesel PM_{10} and $PM_{2.5}$. An improved estimate of diesel PM_{10} or $PM_{2.5}$ concentrations can be made using a combination of the measured values for elemental and organic carbon.
- Results from the monitoring program should be used to estimate the approximate fraction of the fine particulate that is from combustion of petroleum fuels and hence would be an upper limit of the concentration of diesel particulate matter.
- If the fraction of the fine particulate due to diesel fuel combustion is of concern, more detailed chemical analysis of samples of particulate matter for compounds indicative of diesel particulate should be conducted and utilized with chemical mass balance methods to estimate the ambient concentration of diesel particulate matter. The chemical analysis profiles typically used in chemical mass balance methods are: elemental carbon, organic carbon; trace metals; chemical species forming the organic carbon component; and total major ions.

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[5] Since historical levels of diesel particulate matter were probably higher, persons who have contracted cancer would have been exposed to higher levels and would have proportionately higher risk. Similarly, persons spending extended time nearer the source of diesel emissions (e.g., on or beside the street) would have higher peak exposures than typical residents. The average exposures of the latter group are not known.

5. ENVIRONMENTAL AND HEALTH RISKS/TRADEOFFS FOR ALTERNATIVE HEAVY DUTY TRUCKS AND BUSES

5.1 DIESEL ENGINE TECHNOLOGY AND EMISSION STANDARDS FOR HEAVY DUTY TRUCKS AND BUSES

The engine most commonly used for heavy duty trucks and buses is the diesel engine, which offers high energy efficiency and, hence, good fuel economy, together with a good power to weight ratio and attractive economics. The direct injected engine has become the standard diesel engine technology for highway applications, displacing the indirect injected engine and yielding a 15-20% reduction in fuel consumption (EPA, 1999b). Although very popular for urban bus applications, the 2-stroke diesel engine has been displaced by the 4-stroke engine primarily because of lower particulate emissions.

A driving force for improving the design of the diesel engine for heavy duty vehicle applications has been concern about the impacts of NO_x and particulate emissions, leading the US EPA to promulgate ever more stringent exhaust emission standards since 1990 (Table 5-1). The current NO_x exhaust emission standard of 4 grams/bhp-hr is one-third less than that required in 1990, and the standard will be further reduced as of the 2004 model year, reaching a level two-thirds below that required in 1990. Over this same period, the particulate matter standard has been reduced by 83% to 0.1 grams/bhp-hr for trucks, and by 92% to 0.05 grams/bhp-hr (0.07 grams/bhp-hr in use) for buses. The US EPA recently announced (October, 1999) its intention to further reduce the emission standards for NO_x and particulate matter from heavy duty vehicles beyond those planned for 2004, possibly taking effect in 2007. The EPA anticipates that this second phase of reduction in exhaust emission standards would reduce NO_x 75-90% and particulate matter 80-90%. Details of this plan are not yet available.

Table 5-1 US EPA Heavy-Duty Vehicle Emission Standards (grams/bhp-hr).

Model Year	NO_x[‡]	NOx+NMHC	PM[‡]		HC	CO
			Trucks	Buses		
1990	6.0	-	0.6	0.6	1.3	15.5
1991	5.0	-	0.25	0.1	1.3	15.5
1993	5.0	-	0.25	0.1	1.3	15.5
1994	5.0	-	0.1	0.07	1.3	15.5
1996	5.0	-	0.1	0.05**	1.3	15.5
1998	4.0	-	0.1	0.05**	1.3	15.5
2004 (proposed)	-	2.4* or 2.5* w/ limit on NMHC of 0.5 g/hp-hr	0.1	0.05**	see NO_x	15.5

* Applies to NO_x+NMHC combined.
** The in-use emission rate allowed is 0.07 g/bhp-hr.
‡ Averaging, banking and trading has been an option since 1991 to achieve the standards. Manufacturers have been subject to nonconformance penalties since 1990 for these pollutants.
Source: US EPA, 1997

Achievement of the current emission standards for heavy duty trucks and buses has been facilitated in part by reduction of the sulphur content of diesel fuel in BC and elsewhere in North America to not more than 0.05% by weight. A review of future diesel emission reduction technologies by the US EPA (1999b) indicates that the performance of emission control technologies being developed to meet the 2004 standards is improved by, or may require, diesel sulphur below 50 ppm (0.005%). Engine manufacturers have recommended diesel sulphur levels be reduced to below 30 ppm (0.003%) (Levelton et al, 1999).

Currently, the main technologies being researched and developed to meet the 2004 emission standards are:

- Cooled exhaust gas recirculation: reduces NO_x emissions, but requires appropriate control to not adversely affect emissions of hydrocarbon, particulate and CO. Low fuel sulphur levels are needed for cooled EGR to help avoid corrosion problems.
- Oxidation catalysts for treatment of the exhaust: oxidizes more than 70% of the hydrocarbons that contribute to the soluble organic fraction of particulate, resulting in a 15-30% reduction in the mass of particulate emissions.
- Lean NO_x catalysts: involves injection of a small amount of diesel fuel into the hot exhaust gases, and subsequent reaction over a platinum catalyst , reducing NO_x by 15-35%.
- Continuously regenerating particulate traps: reduces particulate emissions by collecting particulate on a ceramic or metallic filter material, which is then regenerated by burning the combustible portion. A continuously regenerating trap is capable of reducing particulate emissions by more than 80%, though a fuel sulphur level below 50 ppm is needed to avoid inhibiting the catalyst performance.

5.2 EFFECTS OF DIESEL ENGINE TECHNOLOGY AND SAMPLING CONDITIONS ON PARTICULATE EMISSIONS

In a very limited number of laboratory tests with a few engine designs, researchers have observed that, although the mass emissions of particulate matter was lower for newer engines than for older engines, the concentration of the number of particles was higher for the newer engines. Bagley et al (1996), and in subsequent related work, Kreso et al (1998) conducted steady-state engine dynamometer tests (at 75% and 25% load) to measure the mass and particle number concentrations of particulate emissions from Cummins 4 cycle engines made in three different model years: a 1988, 224 kW L10-300; a 1991, 231 kW L10-310; and a 1995, 246 kW M11-330E. Compared to the 1988 model engine, total diesel particulate emissions were reduced by 71% for the 1991 model engine and 72% for the 1995 model engine for tests at 75% load. These reductions were due to a reduction in the emissions of solids and, to a lesser extent, the soluble organic fraction, with negligible changes in the particulate sulphate emissions[6]. At this same load level, the total number concentration of particles increased by a factor of 34 for the 1991 engine, and by 22 for the 1995 engine, compared to the 1988 engine. The nuclei mode particles (nominally less than 0.05 µm diameter) increased by a factor of 57 for the 1991 engine and by a factor of 36 for the 1995 engine compared to the 1988 engine. Subsequent tests and analysis by other researchers and improvement in the understanding of the processes occurring in the exhaust gas during tests to measure particle number concentrations have raised many questions about the significance and interpretation of these test results, as discussed below.

Particle number emissions are strongly affected by the type of emission control technology used for NO_x and particulate matter. Kreso et al (1998) found that a relatively low exhaust gas circulation rate (EGR) of 10% reduced the number of particles by 92% when operating at 75% load with the 1995 engine tested. Under these conditions, total particulate matter emissions increased by 20%. EGR is expected to be an important future control technology to meet the proposed 2004 NO_x emission standards. Hawker et al (1998) tested the effect of a continuously regenerating diesel particulate filter on particulate emissions from a 169 kW direct injected diesel engine operated on fuel having a sulphur content of 7 ppm. This type of particulate after

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[6] Fuel sulphur was 100 ppm for tests with the 1988 and 1991 engines and 310 ppm for the 1995 engine. The effect of this change in fuel sulphur on emissions was not investigated.

treatment converts some of the NO in the exhaust gas to NO_2 over a platinum catalyst, which then continuously oxidizes particulate matter removed from the exhaust gas in a downstream filter. At 100% engine load, this control device reduced engine out particle number concentrations by a factor of 10 to 20 for 0.01-0.05 µm diameter particles and up to a factor of 100 for 0.1 µm diameter particles. Luders et al (1998) and Abdul-Khalek (1998) have tested the performance of conventional diesel particulate filters and observed a large increase in the number of nuclei mode particles downstream of the filter. Luders et al attributed this result to condensation of ultra fine sulphuric acid droplets under the dilution conditions used in the tests and concluded that without the particulate filter these particles would have condensed on particles already in the gas stream and not added to the particle number concentration.

The significance and interpretation of particle number emission results from steady-state engine dynamometer tests[7] are presently in question as they have been found to be very sensitive to conditions during the test. Conditions that favour the formation of substantially increased numbers of particles are lower dilution temperature, lower dilution ratio, longer residence time, higher humidity in the dilution gas and higher fuel sulphur content (Abdul-Khalek, 1998; Lapuerta et al, 1999). The changes in particle concentrations for different vintages of engine or configurations of emission controls may be simply due to the sampling conditions used for the tests, and further research into the significance of test conditions has been done (Abdul-Khalek et al, 1999; Luders et al, 1998) and is continuing.

Another important factor with regard to the use and interpretation of particle number concentration test results, is that the steady-state dynamometer engine test procedure and the dilution and sampling methods that have been used in published studies to date are probably not representative of in-use conditions for the engine or the dilution of emitted particulate matter. The US EPA (1999) anticipates that more than 90% of diesel particulate emissions are likely to occur during transient rather than steady-state load conditions. The effect of transient engine operation on particle number emissions has not been tested. Also, dilution of the diesel exhaust gas emitted to the atmosphere is on the order of 1000:1, which is much higher than the dilution levels of 10-15:1 used in experimental tests.

There is presently a high level of uncertainty associated with the significance and interpretation of measured particle number concentrations. This uncertainty exists because of the small number of tests that have been performed, the sensitivity of the test results to sampling methods and engine configuration, and differences between the test procedure and in-use engine operating conditions. It is not presently possible to draw a conclusion about the potential shift in particle number concentration as a result of the use of new diesel engine technologies in the 1990s, or the introduction of future engine technologies. Resolution of this issue must await further testing of diesel engine emissions and particle concentrations using methods that are representative of actual engine use and ambient mixing conditions.

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[7] The method commonly used by researchers to measure the number concentration of particles in diesel exhaust gases has been described by Pagan (1999) and consists of a dilution tunnel that mixes clean air with the engine exhaust gases to allow a homogeneous cooled sample to be extracted for counting particle numbers. The dilution tunnel conditions have varied in published tests, though typically the dilution ratio is 10 to 15:1and the temperature of the diluted gas sample is 20-50 C. A sampling probe inserted into the dilution tunnel draws a continuous sample which is further diluted with air, then injected into a scanning mobility particle sizer that classifies and counts the particles. The number of particles measured in the diluted sample of gas is typically corrected to the undiluted condition based on the dilution ratio of either carbon dioxide or nitrogen oxides in the exhaust gas.

5.3 CURRENT AND FUTURE ALTERNATIVE FUEL AND VEHICLE TECHNOLOGIES FOR HEAVY DUTY VEHICLES

A detailed review of the existing and developing alternative fuel/vehicle technologies for heavy duty vehicles has been conducted by Levelton et al (1999) for the Transportation Issue Table, with a focus on technologies that could lead to substantial reductions in greenhouse gas emissions. Table 5-2 summarizes the technologies identified in the study as having current and future potential for commercial application in two categories: heavy duty tractor/trailers (Class 7 & 8 trucks); and for urban buses.

Table 5-2 Current and Future Alternative Fuel/Vehicle Technologies

Heavy Duty Trucks	Development Status	Urban Buses	Development Status
Natural Gas: Spark Ignition cycle	C	Natural Gas: Spark-ignition cycle	C
Compression ignition cycle (high pressure direct injection)	E	Compression ignition cycle (high pressure direct injection)	E
Propane (spark ignition cycle)	C	Propane (spark ignition cycle)	C
Biodiesel (such as from processing of canola oil)	F	Biodiesel	F
Dimethyl Ether (synthesized from natural gas feedstock)	F	Dimethyl Ether	F
		Hybrid Diesel Electric	E
		Fuel Cell: Methanol fuelled	F/E
		Hydrogen fuelled	F/E

Legend for development status: C - Current commercial technology
E - Emerging commercial technology
F - Future technology

Of the fuel/vehicle technologies listed in Table 5-2 for heavy duty trucks, spark ignition engines fuelled with natural gas or propane have been tested and seen limited commercial application. The main limitations of spark ignition engines with these fuels is the lower fuel efficiency relative to a diesel engine (early engines were 15-30% less efficient, while current technologies are about 10-15% less efficient) and the additional space and weight for the fuel storage system. Biodiesel has been used successfully in blends with diesel fuel, and has potential for greater application, but there are major barriers, such as high price, the lack of supply, and no distribution infrastructure. Dimethyl ether is not a commercially available fuel, though has been of interest to some because of its excellent combustion characteristics in diesel engines and the potential to achieve lower particulate emissions.

A very promising new technology for heavy duty trucks is being developed locally by Westport Innovations (pers comm., 1999). With this technology, natural gas is injected at high pressure directly into the cylinder of a compression ignition (i.e. diesel type) engine following a pilot charge of diesel. The technology is expected to achieve an engine efficiency within a few percentage points of what can be achieved with diesel fuel.

The most promising commercial or near term fuel/vehicle technologies for urban bus applications are: natural gas, both current spark ignition technology and high pressure direct injection); hybrid diesel electric; and fuel cells (presently hydrogen fuelled is most advanced). The other potential technologies listed in Table 5-2 have the disadvantages discussed above for heavy duty trucks, or, in the case of propane, has not been attractive because of safety concerns, lower engine efficiency and the added space and weight of the fuel storage system.

5.4 EMISSION CHARACTERISTICS OF DIESEL AND ALTERNATIVE HEAVY DUTY VEHICLES

A very large number of tests of emissions from heavy duty vehicles have been published in different studies and on internet web sites. The EPA statistically analyzed emission data from chassis dynamometer tests of more than 200 diesel fuelled heavy duty truck and bus vehicles (about half were buses) reported in 20 different studies (EPA, 1999b) and developed overall trend profiles of g/mile emission rates for NO_x, particulate and total hydrocarbons. The EPA analysis indicates that diesel fueled engine exhaust emission rates for NO_x vary widely between tests, but on average have been decreasing slightly through the 1990s. Particulate and hydrocarbon emissions also vary widely from test to test and have decreased most significantly since 1990. The average emission rates for diesel truck and bus vehicles in1998 from the EPA analysis are as follows

Particulate matter	0.5 g/mile
NO_x	21 g/mile
Hydrocarbon	0.6 g/mile

A listing of many of the test results for urban buses developed using the central business district test cycle have been summarized in Appendix A. This summary includes tests of buses fueled by diesel fuel, natural gas and diesel electric power. By inspection of this partial list of test data, trends in the emission rates for buses and the differences in emissions associated with the fuel used are evident. Nominal emission rate values for the main fuel/vehicle urban bus technologies are summarized in Table 5-3. The values in this Table for diesel vehicles are similar for particulate matter and significantly higher for NO_x and hydrocarbons than the more broadly based statistical averages indicated above from the EPA.

Changes in diesel engine technology and fuel quality have resulted in about a 70% decrease in particulate emission rates, a 73% decrease in CO emission rates and no change in hydrocarbon emission rates since the early 1990s. Current particle trap technology appears to yield a 50% reduction in particulate emission rate. The test data examined in this study suggests NO_x emission rates have increased by 24% since the 1990s, though this is misleading as it is due to the variability in test results and the small data set examined for this study. The EPA result showing a slight decrease in NO_x emission rate in recent years is more realistic.

Test data is not available in the public domain for diesel engines that meet the 2004 EPA heavy duty vehicle standards, however, manufacturers are improving their engine designs to meet this challenge. Particulate emissions from future diesel engines are likely to remain near the lowest level presently achieved in tests with particle traps, as these meet the current standard. NO_x emission rates will need to decrease by about 45% while CO will remain the same. Perhaps a 50% decrease will occur for hydrocarbon emissions.

CNG buses reduce particulate emissions by 95% compared to a current diesel engine without a particle trap, or about 90% if a particle trap is used. Average NO_x emissions are reduced by about 10-30%, although results vary widely and in some cases CNG buses had higher NO_x emission rates than diesel buses. One cause of the wide variation in NO_x emission rates for CNG buses is variable air/fuel ratios. CO emission rates from CNG buses are about 20% less than that for a current diesel engine. About 5% of the total hydrocarbons from a CNG bus engine are non-methane hydrocarbons (NMHC), whereas most of the hydrocarbons from a diesel engine are NMHC. Consequently, CNG yields perhaps a 50% reduction in NMHC emissions compared to a diesel engine.

Table 5-3 Nominal Exhaust Emission Rates for Urban Buses Based on Central Business District Test Data for Diesel and Alternative fuels

Engine/Model Year	Particulate* (g/mile)	CO* (g/mile)	NOx* (g/mile)	NMHC* (g/mile)	HC* (g/mile)
Diesel Fuel					
Early 1990s	2.0	17.5	24.4	-	1.9
1998 est. w/o trap	0.6	4.8	30.2	-	1.9
1998 est. w/ trap	0.3				
Natural Gas- spark ignition, lean burn					
Early 1990	0.01	19.0	29.0	1.0	20.6
1998 est.	0.03	4.0	22.1	0.8	16.7
Hybrid Diesel Electric** (Orion Bus Ind.)					
2000-2005 w/ trap	0.03	0.13	11	-	0.09
2000-2005 w/ox. catalyst	0.3	1.8	10.7	-	0.22
Fuel Cell					
Hydrogen fuel	~0	~0	~0	~0	~0

* Estimated from data summarized in Appendix A from chassis dynamometer tests using the central business district test cycle.

** Based on only one chassis dynamometer test.

Limited test data is available for the Westport Innovations high pressure direct injected (HPDI) natural gas bus engine that is being tested for a one-year period with three buses at the University of Berkeley. Preliminary test data provided by Westport for the two cycle Westport 6V-92 retrofitted bus engine is available on a gram/bhp-h basis that can not be compared to the vehicle dynamometer results presented earlier for other engines/vehicles. The engine dynamometer tests show Westport technology yields a PM reduction of 65%, a CO increase of 48% and a NO_x reduction of 37% relative to a diesel engine of the same design. The fuel efficiency of the natural gas engine was only 4% lower than the baseline diesel fuelled engine. Westport is presently focusing more of its development and commercialization efforts on HPDI engine applications other than buses because of market size and partner participation, though remains very interested in pursuing this application of the technology.

Clark et al (1998) reported tests with Class 8 heavy duty trucks using conventional diesel engine and an engine fueled with liquified natural gas (LNG). The emission rates for the diesel engine were very similar to those estimated in this study for 1998 (Table 5-3). The LNG engine emitted 0.07 g/mile particulate, 7.1 g/mile CO, 5.2 g/mile NO_x and 0.6 g/mile NMHC, which is fairly similar, except for a much lower NO_x emission, to that for compressed natural gas (Appendix A).

Hybrid diesel electric buses utilize a smaller diesel engine in combination with a battery and electric motor in various possible configurations to suit the acceleration and cruising energy demands of the bus. Energy utilization is improved and emissions reduced by operating the diesel engine at a steadier load and taking advantage of regenerative braking. One of the developers of hybrid diesel electric buses is Orion Bus Industries, who has reported that mile/gallon fuel economy of its bus design is 70% higher (i.e. improved) than that of a conventional diesel fueled bus, though this is value is based on very limited testing. Data from one test of this bus design (Table 5-3) suggests that, compared to current diesel engine technology with a particle trap, emissions of particulate, CO, NO_x and HC are reduced by 90%, 95%, 60% and 95%, respectively. These emission levels are comparable to, or less than, that achievable with natural gas.

Hydrogen fuel cell technology yields the lowest vehicle emission rates as the principal product of combustion is water vapour. Some small amounts of pollutants are likely emitted, though these can be assumed to be negligible. Emissions do occur as a result of fuel manufacture, either from power generation if electrolysis of water is used, or from power generation, combustion and fugitive emissions if hydrogen is produced by reforming natural gas.

5.5 RELATIVE ENVIRONMENTAL MERITS OF ALTERNATIVE FUEL/VEHICLE TECHNOLOGIES FOR URBAN BUSES

The relative emission differences of future diesel and alternative fueled buses discussed in the previous section have been consolidated in Table 5-4 to illustrate the annual emission reductions potentially achievable on a per bus basis. The annual mileage accumulation rate is the same as was used in the earlier BC Transit Fuel Choice Study (Sypher, 1997). The emission reductions achievable with future diesel and alternative fuel/vehicle technologies shown in this table are nominal and intended to illustrate trends and order of magnitude differences, as the assumed g/mile rate are based on a very limited data set. Also, the future emissions for natural gas vehicle technology are based on current technology and have not been indexed to reflect potential technology advancements.

For assessing the health benefits associated with reducing particulate concentrations, Table 5-4 shows the approximate percent reduction in PM emissions relative to performance of engines designed to meet the current exhaust emission standards. Similarly, the emission of ozone precursors, calculated as NO_x+NMHC+CO/7, is used as an indicator of emissions of pollutants having ozone forming potential. It has been assumed that future diesel bus engines will include a particulate trap or similar controls to meet the proposed 2004 emission standards, and that the reduction in particulate emissions achieved by this control is 50%.The diesel electric hybrid bus is assumed to be configured without a particulate trap, though one could be used to achieve lower particulate emissions than that shown.

Considering the estimated emissions of PM and ozone precursors for the various alternative bus technologies, hydrogen fuel cell technology yields the lowest emissions and the largest emission reduction compared to current diesel engines. Which of the other technologies is more attractive from an emission point of view depends on the weighting given to particulate matter and ozone precursors, among other factors. The limited test data available for this study suggests that a natural gas bus has lower particulate emissions, but higher ozone precursor emissions than a diesel electric hybrid bus. Diesel engines meeting the 2004 emission standards could also yield significantly lower emissions than current engines. The bus engine technologies considered in this study differ in cost and the status of commercial development, which are both important factors for technology selection.

Tables 5-5 and 5-6 summarize the greenhouse gas emission rates in grams/mile for commercial and emerging alternative fuel/vehicle technologies for 2000 and 2010. These results were developed in a study by Levelton and coworkers (1999) which considered emissions over the full cycle from fuel production through refining, distribution and use in the vehicle. An underlying assumption in this analysis is that future engine technology will be optimized for the fuel used. The equivalent greenhouse gas emissions reported in these tables include carbon dioxide, methane and nitrous oxide in CO_2 equivalents, allowing for the global warming potential of each gas.

The lowest greenhouse gas emissions in 2010 for the options for heavy duty trucks shown in Table 5-5 are forecast to be achieved using liquified natural gas in a high pressure direct injection engine. Full cycle greenhouse gas emissions for heavy duty trucks are estimated to be lowest for liquified petroleum gases (i.e. propane).

Different fuel/vehicle technology options were considered to be most suitable for city transit buses. Vehicle and full cycle CO_2 equivalent emissions for commercial and emerging fuel/bus technology options are summarized in Table 5-6. For these options, the lowest greenhouse gas emissions from the vehicle in 2010 are achieved using hydrogen fuel cell technology. If the hydrogen for fuel cells is generated using 100% hydropower, substantially lower full cycle greenhouse gas emissions are achieved than that shown for electricity generated using the national utility fuel mix. With diesel electric hybrid buses, a 41% reduction in vehicle greenhouse gas emissions and a 40% reduction in full cycle greenhouse gas emissions can be achieved compared to use of low sulphur diesel in a diesel engine. Compressed natural gas is estimated to yield a 9% reduction in vehicle greenhouse gas emissions and an 11% reduction in full cycle greenhouse gas emissions compared to diesel.

Table 5-4 Summary of Approximate per Bus Emission Reductions for Diesel and Alternative Fuels based on Central Business District Test Data

Scenario*	PM	CO	NOx	NMHC	HC	NOx+NMHC+CO/7
Diesel Designed for Current Emission Standards						
g/mi	0.6	4.8	30.2	1.9	1.9	
Emission (kg/yr)	26	206	1298	82	82	1409
Diesel Engine Meeting 2004 Standards (assumes a particulate trap is used)						
g/mi	0.3‡	4.8	17	1	1	
Emission (kg/yr)	13	206	731	43	43	803
Emission Reduction (kg/yr)	13	0	567	39	39	606
Emission Reduction (%)	50	0	43.7	47.4	47.4	43.0
Natural Gas						
g/mi	0.03	4	22.1	0.8	16.7	
Emission (kg/yr)	1	172	950	34	718	1009
Emission Reduction (kg/yr)	25	34	348	47	-636	406
Emission Reduction (%)	95	16.7	26.8	57.9	-778.9	28.4
Diesel Electric Hybrid (assumes a particulate trap is not used)						
g/mi	0.3	0.13	11	0.09	0.09	
Emission (kg/yr)	13	6	473	4	4	478
Emission Reduction (kg/yr)	13	201	825	78	78	932
Emission Reduction (%)	50	97.3	63.6	95.3	95.3	66.1
Hydrogen Fuel Cell						
g/mi	0	0	0	0	0	
Emission (kg/yr)	0	0	0	0	0	0
Emission Reduction (kg/yr)	26	206	1298	82	82	1409
Emission Reduction (%)	100	100	100	100	100.0	100

* Assumed distance traveled per year = 69,000 km (Sypher, 1997)

‡ Assumes that some form of particulate control will be used at a control efficiency of 50% to off-set the adverse effects on particulate emissions of NO_x control measures needed to meet the 2004 exhaust standard. Hence the 2004 PM emission is calculated as 0.5*0.6=0.3 g/mi. This may be conservative as the 0.6 g/mi is approximately equivalent to the standard of 0.05 g/bhp-h.

Table 5-5 **Fuel-Cycle CO_2-Equivalent Emissions for Heavy Duty Class 8 Trucks in 2000 and 2010 (g/mile)**

	2000				2010			
Fuel / Vehicle Option ->	300 ppm S Diesel	50 ppm S Diesel	LNG	LPG	300 ppm S Diesel	50 ppm S Diesel	LNG	LPG
Vehicle operation	1715	1715	1377	1742	1662	1662	1331	1668
Fuel dispensing	3	3	295	4	3	3	278	4
Fuel storage and distribution	27	28	87	38	26	26	83	35
Fuel production	149	178	33	52	147	175	31	50
Feedstock transport	5	5	0	1	5	5	0	1
Feedstock and fertilizer production	137	138	41	63	137	137	39	61
Land use changes and cultivation	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
CH4 and CO2 leaks and flares	81	81	306	72	72	72	209	64
C in end-use fuel from CO2 in air	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Emissions displaced by coproducts	0	0	0	0	0	0	0	0
Sub total (fuel cycle)	2118	2147	2139	1972	2051	2080	1972	1883
% changes for each year (fuel cycle)	--	1	1	-7	--	1	-4	-8
Vehicle assembly and transport	15	15	15	15	15	15	15	15
Materials in vehicles (incl. storage)	77	77	76	77	75	75	74	75
Grand total	2209	2239	2230	2064	2141	2170	2062	1973
% changes for each year (grand total)	--	1	1	-7	--	1	-4	-8

Source: Levelton et al, 1999

Table 5-6 Fuel-Cycle CO_2-Equivalent Emissions for City Transit Buses in 2000 and 2010 (g/mile)

	2000						2010					
Fuel / Vehicle Option ->	300 ppm S Diesel	50 ppm S Diesel	300 ppm S Diesel Hybrid	CNG	H_2 (Natural Gas) Fuel Cell	H_2 (Electricity) Fuel Cell*	300 ppm S Diesel	50 ppm S Diesel	300 ppm S Diesel Hybrid	CNG	H_2 (Natural Gas) Fuel Cell	H_2 (Electricity) Fuel Cell*
Vehicle operation	2152	2152	1354	2009	0	0	2156	2156	1262	1964	0	0
Fuel dispensing	3	3	2	46	94	94	4	4	2	54	88	88
Fuel storage and distribution	34	35	22	112	7	7	34	34	20	110	5	5
Fuel production	187	223	118	47	1471	1736	190	227	111	46	1133	1477
Feedstock transport	6	6	4	0	84	0	6	6	4	0	65	0
Feedstock and fertilizer production	172	173	108	59	80	0	178	178	104	58	61	0
Land use changes and cultivation	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
CH4 and CO2 leaks and flares	102	102	64	177	130	0	94	94	55	161	92	0
C in end-use fuel from CO2 in air	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Emissions displaced by coproducts	0	0	0	0	0	0	0	0	0	0	0	0
Sub total (fuelcycle)	2657	2694	1672	2451	1866	1837	2661	2699	1557	2393	1445	1570
% changes for each year (fuelcycle)	--	1	-37	-8	-30	-31	--	1	-41	-10	-46	-41
Vehicle assembly and transport	14	14	17	15	15	15	14	14	18	15	15	15
Materials in vehicles (incl. storage)	75	75	87	76	76	76	73	73	85	74	73	73
Grand total	2746	2783	1776	2541	1957	1929	2748	2786	1660	2482	1532	1658
% changes for each year (grand total)	--	1	-35	-7	-29	-30	--	1	-40	-10	-44	-40

* Based on incremental electric power derived from the natural fuel mix for electricity generation.

Source: Levelton et al, 1999

6. DATA GAPS AND UNCERTAINTIES

The preliminary review of the diesel particulate matter issue conducted in this study utilized a variety of information on potential health effects of diesel particulate matter, regional concentrations of air contaminants, vehicle traffic volume, emission characteristics of diesel vehicles, and meteorological data. Although conservative approaches were used in the analysis of diesel particulate exposure in the region in order to determine if there was reason for concern, some level of uncertainty exists due to the inherent variability of the data and the estimation methodologies that were applied.

Significant data gaps and uncertainties that affect the analysis in this study are summarized below for use by the GVRD as guidance for future assessment and management of the issue:

- The analysis of potential human health effects from diesel particulate in the region in this study relied on the reference concentration for chronic morbidity effects and a cancer risk factor determined from work in California by the Air Resources Board and the Office of Environmental Health Hazard Assessment. The US EPA is in the process of preparing a health impact assessment document for diesel particulate matter, but this will not be finalized until early in 2000. The additional information made available when the EPA assessment has been completed should be examined to see if it significantly affects the preliminary assessment prepared in this study. This includes any further information on particle number emissions from in-use diesel vehicles and the significance of this in terms of health effects.
- The modeling of maximum concentrations of diesel particulate matter prepared in this study for a roadway having a high traffic volume of heavy-duty trucks was preliminary, but is expected to yield reliable order of magnitude values. Further more detailed modeling analysis would be needed if more accurate predictions of diesel particulate concentrations adjacent to a roadway are desired. Such modeling would have to take into account a longer meteorological record, effects of buildings and other flow disturbances and effects of road grade, queuing at intersections and other related issues.
- No data is available for the region on the concentration of diesel particulate in the ambient air. It would be beneficial for future assessment of the potential regional impacts of diesel particulate to undertake the monitoring program outlined in Chapter 4. This would fill an important gap in the available regional data and improve the reliability of future assessments of the potential impact of diesel particulate on human health near roadways and regionally.
- The nominal emission characteristics of diesel and alternative fueled urban buses used in Chapter 5 for the estimation of emissions of common contaminants are representative, but may not fully reflect the latest advances and on-road performance of some of the technologies. The main areas of uncertainty are the on-road emission characteristics of the most advanced commercially available diesel, natural gas and hybrid diesel electric urban buses.
- Very limited data is available on the particle number emissions from diesel engines and how these emissions vary with the vintage of the engine, emission control technology used, and in-use vehicle operation and exhaust dilution conditions. Further test data are needed on this issue to assess if advances in engine technologies to reduce particle mass emissions may also be shifting the size distribution and the magnitude of particle number emissions.

7. FINDINGS

7.1 KNOWLEDGE OF HEALTH IMPACTS

- The California Review (CARB/OEHHA, 1998a) concluded that the cancer risk over a 70 year lifetime and to a 95% upper confidence limit, was between 280 and 1800, with a mean value of about 700 per million population per microgram of diesel exhaust particulate in a cubic meter of air exposure. The CARB staff paper (CARB/OEHHA, 1998b) concluded that 3×10^{-4} per (µg/m^3) was a reasonable estimate of unit risk expressed in terms of diesel particulate. In view of the recent evidence that has appeared, it would seem prudent to agree with the California panel that diesel particles should be deemed to be carcinogenic.
- The California health assessment (CARB/OEHHA, 1998a,b) proposed a daily reference concentration (RfC) for morbidity effects of diesel particulate matter of 5 µg/m^3. This is not intended as a threshold value, but as an indicator of a concentration above which there is concern for possible chronic morbidity effects.

7.2 DIESEL PARTICULATE MATTER EMISSIONS AND PREDICTED AMBIENT CONCENTRATIONS

- Lower Fraser Valley $PM_{2.5}$ emissions from mobile sources in 1998 are estimated to total 874 tonnes, of which 594 tonnes (68%) are from diesel fuelled on and off road vehicles. The 1998 $PM_{2.5}$ diesel particulate emission from on-road vehicles is 330 tonnes, or 55% of the total diesel particulate from on and off road vehicles. The emission of diesel particulate matter from heavy duty vehicles is forecast to decrease by about 45% over the period from 2000 to 2010-2015.
- The estimated on-road diesel contribution to the regional average ambient PM_{10} or $PM_{2.5}$ concentration is estimated currently to be about 1 µg/m^3. This level is about 8% of the current regional average ambient PM_{10} concentration. The total concentration of diesel particulate matter from mobile sources may be higher due to contributions from off-road sources that cannot be estimated by the method applied in this study. Insufficient data are available to estimate the current regional $PM_{2.5}$ ambient concentration, but typically, the ratio of $[PM_{2.5}]/[PM_{10}]$ is about 0.55. This suggests that on-road diesel particulate matter comprises about 15% of the regional ambient average $PM_{2.5}$ concentration. For comparison, the California assessment estimated that in Los Angeles ambient diesel particulate matter averages about 1.5 µg/m^3, while US EPA data indicates diesel $PM_{2.5}$ concentrations in Boston, Rochester, NY and Washington, DC are of similar magnitude, ranging from 0.5-1.6 µg/m^3.
- Preliminary predictions of the maximum 24-hour average concentration of diesel particulate matter in the vicinity of a road carrying a high volume of truck traffic were developed using a dispersion model for designed for analysis of the air quality impacts of on-road vehicles. The maximum 24-hour average concentration of diesel particulate matter at the roadside was predicted to be about 2.8 µg/m^3 for PM_{10} and 2.4 µg/m^3 for $PM_{2.5}$, using hourly meteorological data from the Vancouver International Airport for 1996. Note that these maximum concentrations are predicted to occur infrequently and are the highest values predicted for all 24-hour periods in the modelled year.
- Ambient diesel PM_{10} and $PM_{2.5}$ concentrations decrease as distance increases perpendicular to the roadway. The maximum 24-hour average diesel particulate concentration decreases rapidly with distance, reaching about 39% of the peak concentration 10 m from the centreline and 27% at 20 m from the centreline. The maximum 24-hour average diesel PM_{10} was predicted to be 0.25 µg/m^3 at a distance of 150 m from the centreline, or 9% of the roadside

concentration. Predicted concentrations become very uncertain PM_{10} beyond 150 m from the road.

- Preliminary dispersion modelling suggests that a very conservative estimate of the maximum average concentration of diesel PM_{10} that a resident living near a street (i.e., at 20 m distance) might be exposed to between 0.7 (the modelled result) and 2 µg/m^3 (twice the ratiometric method result for the regional average).

7.3 POTENTIAL HEALTH RISKS ASSOCIATED WITH DIESEL PARTICULATE MATTER FROM ON-ROAD DIESEL VEHICLES

- The maximum predicted 24-hour average diesel PM_{10} concentration beside a road with high truck traffic was about 2.8 µg/m^3. This maximum concentration is well below the California reference concentration for diesel particulate matter of 5 µg/m^3 for lifetime exposure and, hence, chronic non-cancer chronic health impacts are unlikely to occur. This implies a relatively low level of concern for non-mortality effects in Vancouver.
- Using the CARB diesel particulate matter cancer risk factor of 300 in a million per average diesel particulate concentration of 1 µg/m^3 for an entire 70-year lifetime and the estimated diesel particulate matter concentration of 1 µg/m^3 yields an annual excess cancer risk of about 4 cases per million population. For an exposed population of 2 million (the approximate population of the LFV), this implies that about 8 new cases of cancer a year would be attributable to exposure to current levels of diesel particulate matter from on-road diesel vehicles. Of these, about 5% (i.e., 1 case in 2 years) would be attributable to the current commercial, public transit and school bus fleet, based on the relative emissions stated above. The current total lifetime risk of dying from cancers of all kinds is about 20-25%, or 200,000-250,000 in a million.
- The incremental contribution to emissions by a fleet of 1,000 new diesel transit buses meeting current exhaust emission standards would be about 26 t/y of diesel particulate matter. This would add below 0.1 µg/m^3, or below 10% to the estimated ambient diesel PM_{10} or $PM_{2.5}$ concentration from on-road vehicles.
- The current health impacts of diesel particulate matter are sufficiently low based on the analysis in this study to not be of a high level of concern relative to the current lifetime risk of cancer of all kinds. Also, the contribution of diesel particulate matter from heavy duty diesel vehicles to regional ambient average PM_{10} and $PM_{2.5}$ concentrations is predicted to decrease in proportion to the forecast decline in emissions. The cancer risk from diesel particulate emissions is above the guidelines of 1 to 10 per million population often deemed to indicate a nonsignificant cancer risk from environmental exposure.
- Given the uncertainty in the estimated low ambient concentrations together with the potential health impacts of diesel particulate matter, a focused monitoring program is recommended for two selected areas, one in an area representing a regional average and the other in an area exposed to high truck traffic emissions, such as beside a busy truck route. An outline of the monitoring program is given in Section 4.4. Monitoring should include continuous measurement of PM_{10}, or preferably $PM_{2.5}$, periodic determination of elemental and organic carbon concentrations in these samples, and estimation of the ambient concentration of diesel particulate matter.

7.4 DIESEL AND ALTERNATIVE HEAVY DUTY TRUCK AND BUS TECHNOLOGIES

- In a very limited number of steady-state laboratory tests with a few engine designs, researchers have observed that, although the mass emissions of particulate matter were lower for newer engines than for older engines, the concentration of the number of particles emitted was higher for the newer engines. These measurements apply to a diluted and cooled slip stream of the exhaust gases from a diesel engine. Conditions that favour the formation of substantially increased numbers of particles under laboratory test conditions have been observed to be lower dilution temperature, lower dilution ratio, longer residence time, higher humidity in the dilution gas and higher fuel sulphur content. Some tests indicate that many of the smallest particles are acidic water droplets with no solid core.

- There is presently a high level of uncertainty associated with the significance and interpretation of measurements of particle number emissions from heavy duty diesel engines. This uncertainty exists because of the small number of test that have been performed, the sensitivity of the test results to sampling methods and engine configuration, and differences between the test procedure and in-use engine operating conditions. Available data is insufficient to draw a firm conclusions about the potential shift in particle number concentration as a result of the use of new diesel engine technologies in the 1990s, or the introduction of future engine technologies. Resolution of this issue must await further testing of diesel engine emissions and particle concentrations using methods that are more representative of actual engine use and ambient mixing of exhaust gases.
- Current and future engine technologies for heavy duty trucks and urban buses are summarized in Table 7-1. A very promising new technology for heavy duty trucks is high pressure direct injection technology for natural gas fuel being developed locally by Westport Innovations. The technology is expected to achieve an engine efficiency within a few percentage points of what can be achieved with diesel fuel and yield cleaner engine emissions. The most promising commercial or near term alternative fuel/vehicle technologies for urban bus applications are: natural gas (both current spark ignition technology and high pressure direct injection); hybrid diesel electric; and fuel cells (presently hydrogen fuel cells are most advanced, though refueling infrastructure is a barrier to wide-spread use)

Table 7-1 Current and Future Alternative Fuel/Vehicle Technologies

Heavy Duty Trucks	Development Status	Urban Buses	Development Status
Natural Gas: Spark Ignition cycle	C	Natural Gas: Spark-ignition cycle	C
Compression ignition cycle (high pressure direct injection)	E	Compression ignition cycle (high pressure direct injection)	E
Propane (spark ignition cycle)	C	Propane (spark ignition cycle)	C
Biodiesel (such as from processing of canola oil)	F	Biodiesel	F
Dimethyl Ether (synthesized from natural gas feedstock)	F	Dimethyl Ether	F
		Hybrid Diesel Electric	E
		Fuel Cell: Methanol fuelled	F/E
		Hydrogen fuelled	F/E

Legend for development status: C - Current commercial technology
E - Emerging commercial technology
F - Future technology

- For assessing the health benefits associated with fuel/vehicle technology options, the potential reductions in emissions of particulate matter and precursors of ozone are believed to be the most important indicators.

Considering these two environmental indicators and focusing on commercial and emerging technologies for urban bus fleets, hydrogen fuel cell technology yields the lowest emissions compared to current diesel engine technology. Which of the other technologies is more attractive from an emission point of view depends on the weighting given to particulate matter and ozone precursors, among other factors. A natural gas bus appears to have lower particulate emissions, but higher ozone precursor emissions than a diesel electric hybrid bus. Diesel engines meeting the 2004 emission standards are expected to have significantly lower emissions than current engines.

- Of the commercial and emerging options identified for reducing greenhouse gas emissions from heavy duty trucks and buses by 2010, a recent study (Levelton et al, 1999) concluded that the lowest greenhouse gas emissions from the vehicle would be achieved using liquified natural gas for trucks and hydrogen fuel cells for buses. Hybrid diesel electric buses were estimated to yield a greater reduction in greenhouse gas emissions from the vehicle and the full fuel cycle than could be achieved using compressed natural gas.

7.5 NEXT STEPS

- Implementation of a continuous monitoring program for PM_{10} or, preferably, $PM_{2.5,}$ together with chemical analysis of particulate matter samples, is recommended for at least a one year period to determine ambient diesel particulate matter concentrations in the region. It is suggested that sampling be done within a road transportation corridor having a high level of heavy duty truck traffic and at a site expected to be representative of regional average concentrations.
- Information on the health impacts of diesel particulate matter should be monitored periodically to keep abreast of the latest science, including the comprehensive health impact assessment for diesel particulate matter being conducted by the US EPA that is expected to be finalized in 2000.
- The GVRD should work together with other agencies and levels of government to encourage programs that will reduce future diesel particulate matter emissions from heavy duty vehicles in the region, including, for example, consideration of alternative fuel and future diesel heavy duty vehicle technologies reviewed in this study.

8. REFERENCES

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APPENDIX A - PARTIAL SUMMARY OF EXHAUST EMISSION DATA FOR URBAN BUSES REPORTED IN THE LITERATURE

Table A-1 Transit Bus Central Business District Emission Test Results (g/mile)

Engine	Location	Engine Model Year	Buses Tested	PM	CO	NO_x	NMHC	HC
Compressed Natural Gas								
Cummins L10-240G[1]	Miami	1991	5	0.01	15.8	29.0	~ 1.0	20.6
Cummins L10-240G[1]	Tacoma	1992	5 with 2 replicates	0.01	21.8	30.4	~ 0.5	9.3
Cummins L10-260G[7]	New York	1993	5 with 2 replicates	0.03	1.56	12.02	~ 0.8	16.1
Cummins L10-260G[1]	Tacoma	1994	5	0.02	0.7	11.2	~ 0.8	15.5
Cummins L10[2]	Garden City, NY	1996	10	0.030	2.54	23.47	0.86	18.91
Detroit Diesel 50G[3]	Atlanta	1996	10	0.03	9.0	20.8	0.80	15.8
Diesel Fuel								
Cummins L10[1]	Miami	1990	5	1.99	23.5	22.0	-	1.9
Detroit Diesel 6V92TA	-	1990	1 with 6 replicates	1.06	13.74	16.84	-	1.08
Detroit Diesel 6V-92[4]	Miami	1990	6	2.53	16.0	26.7	-	2.1
Detroit Diesel 6V71 & 6V92[5]	Ottawa	1990& 1991	7	2.26	16.9	24.5	-	2.4
Cummins L10[1]	Tacoma	1991	5	1.74	11.2	24.6	-	2.4
Detroit Diesel 6V-92TA[4]	St. Paul	1991	9	1.05	9.5	25.3	-	3.35
Cummins LTA-10[6]	-	1992	2 with 4 replicates	1.15	15.1	19.7	-	1.97
Detroit Diesel 6V-92TA with particle trap[7]	Peoria	1992	3	0.44	Note 7	Note 7	-	Note 7
Detroit Diesel 6V-92TA with & without particle trap[7]	Peoria	1992	3 with 2 replicates	0.72	7.45	25.27	-	2.65
Detroit Diesel 6V-92TA[7] With particle trap	St. Paul	1993	1+ 4 with 2 duplicates	0.34	Note 7	Note 7	-	Note 7
Detroit Diesel 6V-92TA with & without particle trap[7]	St. Paul	1993	5 with 2 duplicates	0.81	6.68	26.4	-	2.11
Detroit Diesel 6V-92TA[7]	St. Paul	1993	10	1.05	9.5	25.3	-	3.35
Detroit Diesel S50[3]	Atlanta	1994	3	0.66	5.2	31.5	-	0.12
Cummins M-11[2]	Cincinnati	1996	10	0.69	4.22	28.66	-	1.89
Detroit Diesel 50[3]	Flint, MI	1996	7	0.3	4.9	30.4	-	-
Hybrid Diesel Electric								
Navistar T444 (Detroit Diesel 30) -Catalyzed particulate filter[8]	-	1996 (?)	Replicates with 2 calibration speeds	0.027-0.036	0.12-0.13	11.2-10.6	-	0.04-0.13
Navistar T444 (Detroit Diesel 30) - Particulate Oxidation Catalyst[8]	-	1996 (?)	Replicates	0.32	1.78	10.66	-	0.22

1. Motta et al., 1996. Tests in 1994 and 1995. The Diesel and 240G CNG engines had significant mileage accumulation (mostly greater than 50,000 miles); the 260G CNG engines had accumulated less than 20,000 miles.
2. Clark et al., 1998. Tests in 1997. Average mileage accumulation was 25,600 miles for CNG engines and 56,600 miles for diesels. Test weight was 35,877 for CNG and 33,449 lb for diesel. Average energy use was 42,919 BTU/mile for CNG and 31,247 BTU/mile for diesel.
3. Clark et al., 1997. Tests in 1997. All 1996 engines used the same 5-speed automatic transmission and had low mileage accumulation (25-45,000 miles), the 1994 engines used a 3-speed automatic transmission with 120-145,000 mileage accumulation. Fuel economy was 2.81 mile/USgal for CNG and 3.41 mile/USgal for diesel.
4. NREL, 1996
5. Environment Canada, after Alchemy/Levelton, 2000.
6. Wang et al, 1993. All tests done using the Central Business District driving cycle on a dynamometer. Tests were done with buses from several manufacturers.
7. Chandler, et al, 1996
8. Environment Canada, 1997. Central business district test cycle on a vehicle dynamometer. Fuel use averaged 5.82 mile/US gal.

Table A-2 Truck Emission Tests (g/mile)

Engine	Location	Model Year	Class 8 Tractors Tested	Fuel	PM	CO	NOx	NMHC	HC
Cummins L-10	Sacramento	1997	8	LNG	0.07	7.12	5.16	0.60	17.51
Cummins M-11	Sacramento	1996	4	Diesel	0.73	1.95	32.25	Not Reported	1.29

Clark et al., 1998. Tested in 1997. LNG tractors had accumulated 14,675 miles and were 300 hp. Diesel tractors had accumulated 175,650 miles and were 330 hp. Tests were done on a 5 mile route using a 42,000 lb load weight with 5 different acceleration, cruise and deceleration levels. Average energy use 21,164 BTU/mile.