# TRUCK TRANSPORT EMISSIONS MODEL

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# ABSTRACT

In the past, transportation related economic analysis has considered agency related costs only. However, transportation managers are moving towards more holistic economic analysis including road user and environmental costs and benefits. In particular, transportation air pollution is causing increasing harm to health and the environment. Transport managers are now considering related emissions in transport economical analyses, and have established strategies to help meet Kyoto Protocol targets, which specified a fifteen percent reduction in Canada's emissions related to 1990 levels within 2008-2012.

The objectives of this research are to model heavy vehicle emissions using a emissions computer model which is able to assess various transport applications, and help improve holistic economic transport modeling. Two case studies were evaluated with the model developed.

Firstly, the environmental benefits of deploying weigh-in-motion systems at weigh stations to pre-sort heavy vehicles and reduce delays were assessed. The second case study evaluates alternative truck sizes and road upgrades within short heavy oilfield haul in Western Canada.

The model developed herein employed a deterministic framework from a sensitivity analysis across independent variables, which identified the most sensitive variables to primary field state conditions. The variables found to be significant included idling time for the weigh-in-motion case study, road stiffness and road grades for the short heavy haul oilfield case study.

According to this research, employing Weigh-in Motion (WIM) at weigh stations would reduce annual Canadian transportation $CO_2$ emissions by nearly 228 kilo tonnes, or 1.04 percent of the Canadian Kyoto Protocol targets. Regarding direct fuel savings, WIM would save from 90 to 190 million litres of fuel annually, or between $59 and $190 million of direct operating costs.

Regarding the short heavy oil haul case study, increasing allowable heavy vehicle sizes while upgrading roads could decrease the annual emissions, the fuel consumption, and their associated costs by an average of 68 percent. Therefore, this could reduce each rural Saskatchewan municipality's annual $CO_2$ emissions from 13 to 26.7-kilo tonnes, which translates to 0.06 and 0.12 percent of the Canadian Kyoto Protocol targets or between $544,000 and $ 1.1 million annually.

Based on these results, the model demonstrates its functionality, and was successfully applied to two typical transportation field state applications. The model generated emissions savings results that appear to be realistic, in terms of potential Kyoto targets, as well as users cost reductions and fuel savings.

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## TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# 1.0 INTRODUCTION

## 1.1. BACKGROUND

The objectives of road transportation are to ensure the safe and cost effective transport of people and goods, to protect life, health, property and the environment as well as to contribute to the economic growth and the development of society. Inherent to road transportation economical considerations are savings associated with road users, road agencies, and the society as a whole. This is collectively referred to as holistic whole life cycle financing of transport.

Road transport related emissions are generated directly from road construction, vehicle manufacture, fossil fuel extraction, production and distribution, as well as vehicle operations. Because of the significant impacts that vehicle operations emissions have on human health, animals, vegetation, buildings, and the environment, as outlined in the Kyoto Protocol (1997), environmental costs are now being recognized as significant costs of transport activities and these costs need to be included in transportation investments and management decisions. As a result, world transportation agencies are beginning to include environmental costs in addition to conventional road agency and road user costs, in order to protect the environment and optimize the holistic social utility of transport. By including environmental impact costs, road agencies will be able to explicitly evaluate alternative environmentally sustainable transportation systems that account for the reduction of greenhouse gas emissions and air pollution. Only by adopting a holistic transportation economic framework, will eventual proactive emissions prevention and mitigation systems be further developed to significantly reduce environmental health damage resulting from transportation activities.

To calculate savings in fuel consumption, and therefore, emissions generation, reductions in environmental costs involved with transportation must be quantified. However, transportation costs related to air pollution are identified as external, variable, and non-market (Bein 1997). External (or indirect) means there are several steps between an activity and its ultimate outcome. Variable costs are incremental and result from an incremental change in consumption, and so reflect costs that can be reduced by decreased consumption. Non-market goods are those that are not regularly traded in the market, such as clean air. Because of these characteristics, emissions related costs are difficult to quantify, and it has been common practice to ignore them in transport economic decisions, and or to incorporate them qualitatively rather than quantitatively.

Given these characteristics, it is better to quantitatively approximate environmental costs to avoid the tendency to value environmental damage as being irrelevant to the specific analysis being performed. However, valuing non-market goods is often a difficult and indirect science. One technique for quantifying non-market goods is through measuring the value of marginal change in these resources in terms of damage costs, or control or prevention methods (Victoria Transport Policy Institute 2003).

Air pollution costs is one of the most often cited external costs resulting from transport activities. External air pollution costs comprise both human health and environmental damage. Therefore, quantifying air pollution costs requires information about vehicle emissions rates, the impacts that these pollutants have on human mortality, morbidity, crop damage, wildlife, aesthetics, climate, *et cetera*, as well as unit values on each of these impacts (Bein 1997).

One method for calculating the financial aspects of emissions costs is directly quantifying fuel consumption. For the case of this research, a fuel based emissions model for heavy trucks was used. Specifically, the model combines vehicle activity data through volume of fuel consumed, with emissions factors normalized to fuel consumption, such as mass of pollutant emitted per unit volume of fuel burned (Dreher and Harley 1998).

To ensure that non-market environmental goods have consistent values, it is necessary to have uniform reference values of costs per unit of impact or incremental impact reduction (Bein 1997). Transportation project evaluation increasingly incorporates shadow prices of non-market costs and benefits, such as valuation of travel-time savings, accident reductions and environmental impacts.

Under the Kyoto Protocol, Canada is committed to reduce its overall greenhouse gas (GHG) emissions by 15 percent below 1990's levels during the 2008-2012 period (Wilson 2003). Reduction in emissions produced by various modes of transportation is one of the most significant components in meeting the Kyoto target. Whole transportation emissions in Canada accounted for 26 percent of the total GHG emissions production in 2001. Road transportation contributed 71 percent of these GHG emissions, 32 percent of which were from heavy duty vehicles. Therefore, heavy trucks accounted for 43 mega tonnes of GHG emissions, or 6 percent of the total Canada GHG emissions in 2001 (Nix 2003).

In addition, heavy freight vehicles account for a large portion of the vehicle kilometres traveled combined with relatively low fuel mileage as compared to private vehicles. Therefore, reducing emissions produced by heavy vehicles would significantly lower the overall production of transportation emissions. However, truck traffic has been increasing significantly over recent years due to the increasing of trade, as well as the need for suppliers to deliver goods just-in-time, in order to optimize logistics costs. To illustrate, in Canada, about 671,000 commercial trucks were registered in 2001 (Nix 2003).

There are significant short-heavy haul operations related to heavy industry within Canada. An inherent disadvantage to short-heavy haul is the relatively high proportion of idle time during loading and unloading, as well as stop-and-go operational conditions. In addition, short heavy haul is often concentrated in resource-based regions operating on undeveloped non-structural roads. This results in lower overall vehicle fuel efficiency due to increased road roughness and low structural road stiffness, which increases dynamic load effects, and rolling resistance of heavy trucks. All these factors further reduce fuel efficiency and significantly increase emissions.

As a result, from a road transport policy perspective designed to minimize social impacts, there is a need to calculate the environmental benefits of changing policies related to commercial vehicle operations. For that reason, the development of a mechanistic based commercial vehicle operations emissions model with the ability to encode different heavy truck haul field state conditions will significantly improve the ability to quantify the economics related to alternative transport policies in terms of emissions costs.

## 1.2. RESEARCH GOAL

The goal of this research is to improve the holistic economic modeling of transport related activities, and to help transportation agencies optimize transport policy decisions including emission reduction and environmental impact.

## 1.3. RESEARCH OBJECTIVE

The objective of this research is to develop a deterministic-mechanistic model with the ability to quantify heavy truck fuel consumption and vehicle emission costs across alternative commercial vehicle operations policies.

## 1.4. RESEARCH HYPOTHESIS

The hypothesis of the research is that innovative heavy haul transport logistics management and road structural upgrades can significantly reduce emission costs associated with transport activities.

## 1.5. SCOPE

The scope of this research includes consideration of the following:

- Literature review regarding all aspects of direct vehicle operations emissions, including investigation of emissions unit rates resulting from fuel consumption, as well as financial costs associated with heavy vehicle emissions from agencies worldwide;

- Identification and quantification of typical ranges in emission rates across typical Canadian heavy truck types and drive train types;

- Identification and quantification of independent field state variables related to heavy truck emission rates including vehicle size and weight, fuel type used, engine characteristics, usage, speed, road grades, road structural stiffness, start-stop application, and idle time;

- Development of a commercial transport emission modeling framework;

- Sensitivity analysis of the independent variables considered in the model in terms of total fuel emissions and fuel consumption;

- Quantification of dependent variables, including rolling resistance, grade resistance, fuel rate, emissions rates, and emissions unit costs across different vehicle weights and dimensions, as well as road structural types;

- Validation of model across typical line haul-long distance hauls and comparison of the model results with emissions unit costs from recognized global organizations;

- Application of the model through quantification of emissions resulting from typical Canadian road transport operations and field state conditions including weigh station advances such as weigh-in-motion pre-sorting.

- Application of short heavy resource haul innovations within Western Canada including road structural upgrades and increased heavy vehicle weights and dimensions regulations;

- Investigation of the estimated health and environmental costs across transport related emissions calculated in this research;

- Recommendations for deployment of future road modeling improvements, weight enforcement technologies, as well as short-heavy resource haul road transport management policy directions, based on environmental impacts of transport related emissions.

## 1.6. WORK PLAN

The work plan of this research included four project elements:

- Literature review and theoretical background;
- Emissions model formulation;
- Model validation, and;
- Model applications.

### 1.6.1. Literature Review and Theoretical Background

A literature review was performed with respect to two primary areas: quantification of heavy vehicle emission unit rates under typical field state conditions as well as economical estimates related to the impact of emissions. The literature investigation was limited to publications on heavy duty diesel truck emissions as well as emissions cost data accumulated by agencies worldwide and the methods used to monetize the environmental impacts of vehicle emissions. The heavy vehicle emissions considered in the research were carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), particulate matter (PM), and carbon dioxide ($CO_2$).

Investigation into past research and the theoretical background drew upon several sources of information. An internet search was performed to identify numerous publications of vehicles emissions related materials. A library search was used to assist in the initial stages of the computerized literature search. The relevant published literature was reviewed and is summarized herein.

### 1.6.2. Emissions Model Formulation

A model was developed to evaluate costs and benefits of alternative commercial vehicles policies and road structural upgrades. Independent variables were quantified and encoded into the model. The independent variables considered are organized into the following categories:

- Road characteristics;
- Truck characteristics;
- Truck field operations;
- Engine characteristics, and;
- Emissions rates and units costs.

These independent variables resulted in several dependent variables related to the following categories:

- Truck performance;
- Truck efficiency;
- Engine efficiency, and;
- Total emissions quantity.

Emissions costs, related to the impact of heavy truck emissions on the environment, were then identified. The intangible environmental costs included a significant amount of research into historically published information from agencies worldwide. All the characteristics were input in Decision Programming Language (DPL), Decision Analysis Software used to calculate the expected value and distribution of the environmental costs across the range of transport parameters.

### 1.6.3. Model Validation – Long Haul Emissions Calculations

In Canada, the only published emissions values available are those estimated for long haul transport. Therefore, the emissions model developed in this research was validated using Canadian long haul operational parameters and included truck characteristics, road characteristics, and engine characteristics.

Based on the deterministic model developed in this research, a sensitivity analysis was performed to determine the variables most affected by field state conditions generated in application of the model. For both the weigh-in-motion application across Canada and the short heavy haul industry application, a probabilistic distribution was then applied to each variable determined in the model.

Using the mechanistic model developed in this research, Canadian $CO_2$ emissions rates and volumes were calculated and compared to the following national published emissions rates and volumes for long haul transport in Canada:

- Environment Canada (Greenhouse Gas Emissions in Canada – 1990-2000);
- FHWA (Federal Highway Cost Allocation Study – 1997);
- Victoria Policy Institute (Transportation cost and benefit analysis – June 2003);
- Transportation Research Board (Estimating the benefits and costs of public transit project – TCRP Report 78 – 2002);
- Transportation Research Record (TRB 1999);
- IBI Group (Inclusion of environmental costs in transportation pricing. – 1996);
- Australian Greenhouse Office (25th Australian Transport Research Forum – October 2002);

- European Commission (Transportation cost and benefit analysis – June 2003), and;
- Delucchi et al. (Reports from UC Davis Institute of Transportation Research – University of California - 1996).

### 1.6.4. Model Applications

Two model applications were conducted within this research. An application of weigh in motion (WIM) for weigh stations across Canada, and road upgrade and heavy vehicle weights and dimensions as applied to short heavy oilfield haul application in Western Canada. The first application quantified the benefits associated with the installation of WIM systems as pre-sorting systems at weigh stations in Canada and the US. The second application involved evaluating increased truck weights and strengthening road structures in short heavy industrial haul applications. The environmental benefit framework developed and validated in this research was used to quantify the environmental benefits of the estimates of emissions and direct fuel savings across the independent variables as applied in the commercial vehicle operation case studies presented. Environmental benefits were translated into the percentage of reduction of emissions and fuel in terms of quantities and costs.

#### 1.6.4.1. Long Haul Case Study: Weigh-in-Motion Pre-Sorting at Weigh Stations

Heavy vehicle operational data were collected from different worldwide research papers. The environmental benefit model developed was used to analyze the impact on emissions levels related to implementation of WIM systems at weigh stations, and the resulting benefits were determined in terms of reduction in heavy vehicle idle time.

#### 1.6.4.2. Short Heavy Haul Case Study: Heavy Oil Field Operations

Typical heavy oil transport information was assembled from rural municipalities to provide the basis for modeling the impact that road upgrades would have in road structural integrity, as well as increased weights and dimensions as applied to short heavy oilfield haul. The model was applied to the implementation of larger and more efficient trucks weights and dimension policies. The different operational efficiency aspects of each type of truck were identified as well as the impacts of the road performance. Based on total heavy oil produced in Western Canada in 2004 (CAPP Statistical Handbook 2004), the results were then multiplied by 50 to capture all heavy oil operations within Western Canada. The model could also be applied in other concentrated heavy hauls, such as forestry, mining, or aggregates.

### 1.6.5. Research Findings, Summary, Conclusion and Recommendations

This thesis set out to document the development of a vehicle emissions model. The model was demonstrated by quantifying the reduction of emissions across two case studies as a function of the variables considered in the model. The incremental reduction in terms of heavy diesel truck emissions and direct fuel savings were then explicitly measured in both cases.

## 1.7. LAYOUT OF THE THESIS

Chapter 1.0 includes the introduction and background, research objectives, scope and methodology of the research. Chapter 2.0 provides a summary of the literature review related to Canadian heavy diesel truck emissions rates and cost estimates. Chapter 3.0 presents the modelling of environmental benefits of various combinations of field state conditions and innovative transport solutions. Chapter 4.0 presents the validation of the model with the example of long heavy hauls. Chapter 5.0 consists of two applications of the model. Weigh-in-motion installation at weigh stations was the first case study to analyse the impacts of the commercial vehicle operations at weigh stations, with particular focus on heavy trucks idling emissions reduction. The model was then applied to short heavy oil haul within a typical Rural Municipality in order to quantify the impact of upgrading the road structural stiffness as well as the truck size and weight limits to decrease emissions. Chapter 6.0 provides a summary and conclusions of the findings of this research and includes application examples of the emissions model developed in this research as it relates to new transport policies for Canadian road transport.

# 2.0 LITERATURE REVIEW

## 2.1. INTRODUCTION

This chapter presents the literature review and theoretical background related to vehicle emissions in the following sections:

- Evolution of Canadian freight transportation;
- Kyoto Protocol;
- Definition of emissions damage;
- Quantification of volumes of emissions;
- Transport emissions in Canada;
- Methodologies for quantifying emissions;
- Road transport financial values, and;
- Model formulation.

## 2.2. EVOLUTION OF TRANSPORTATION EMISSIONS IN CANADA

Transportation accounts for approximately 26 percent of total GHG generated in Canada (Nix 2003). More precisely, transportation is responsible for 30 percent of carbon dioxide ($CO_2$), 62 percent of total nitrogen oxides (NOx), and 42 percent of volatile organic compound (VOC) (Wilson 2003), as illustrated in Figure 2.1. In 1990, $CO_2$ emissions accounted for 95.4 percent of the total GHG emissions produced by the transportation sector, or 146,000 kilo tonnes. A reduction of 15 percent below 1990 emissions levels by 2008-2012 would mean a net reduction of 21,900 kilo tonnes of $CO_2$.

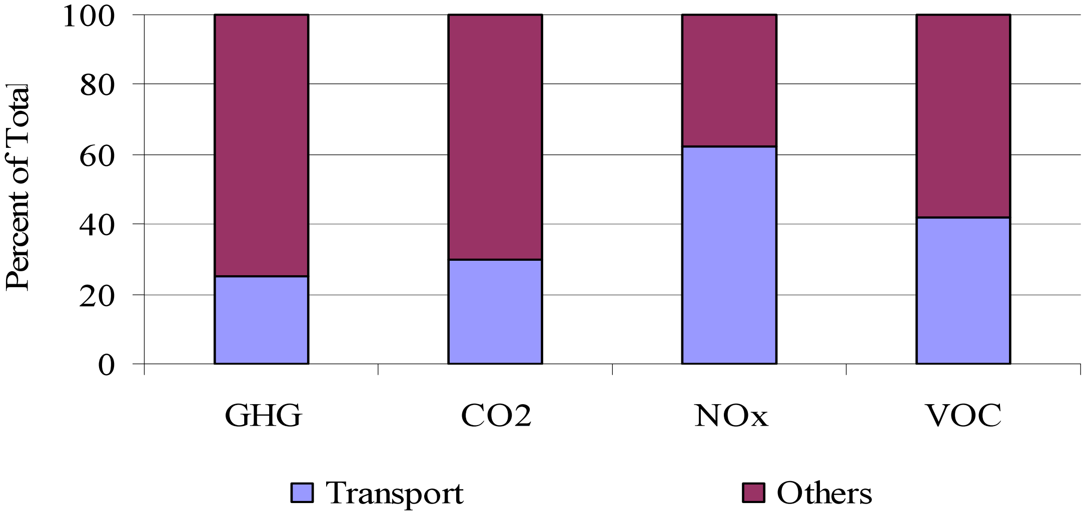

**Figure 2.1: Distribution GHG in Canada (Wilson, 2003)**

Due to their efficiency, diesel engines are the most common internal combustion engines used by commercial trucks. However, internal combustion engines are suspected of causing significant global climate changes (Taylor 2001). Also, because of their high number, diesel engines are large contributors to air pollution resulting in a damaging impact on health and the environment. In 2001, of the total emissions generated by transportation, road transport in Canada represents 71 percent of transportation GHG generated emissions, with 32 percent of the road emissions produced by heavy truck freight (Environment Canada 2001), as illustrated in Figure 2.2 and Figure 2.3.

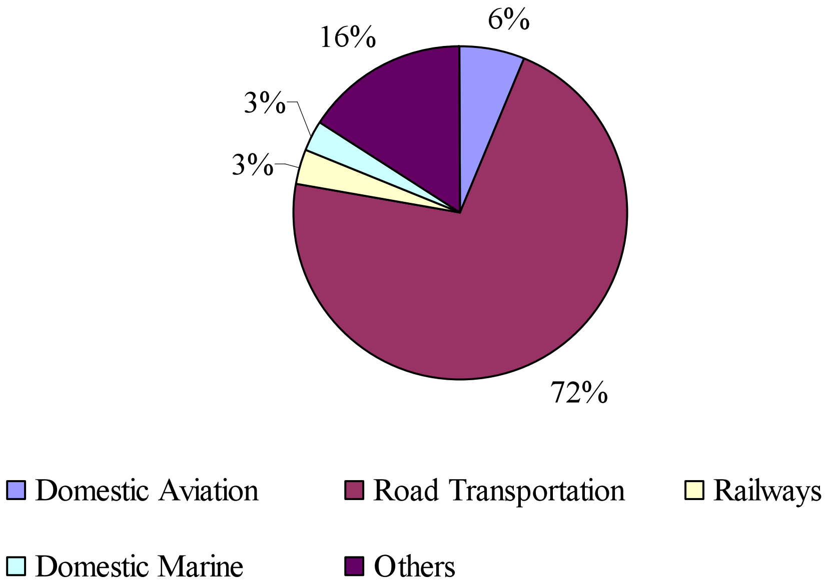

**Figure 2.2: Transportation GHG Distribution in Canada (Environment Canada, 2003)**

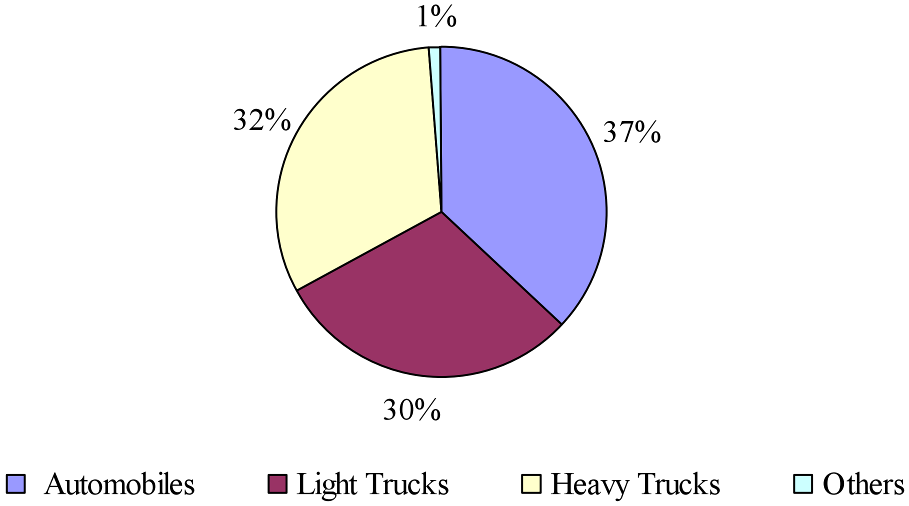

**Figure 2.3: Road Transportation GHG Distribution in Canada (Environment Canada, 2003)**

Over the past decade, technologies in commercial vehicle engine and chassis designs have improved fuel efficiency and have reduced emissions by 80 percent since the 1970's (Taylor 2001). To illustrate, a 39,500 kilogram truck can travel 2.3 times more tonne-kilometres (t-km) using the same amount of fuel in 2001 as compared to 1975. One of the primary reasons for the improved efficiency is the fact that most domestic freight is transported by trucks with six axles or more. Moreover, freight on an eight-axle B-train operating at 62,500 kilograms (net to tare ratio of approximately 2.0) uses 36 percent less fuel hauled per t-km than that on a five-axle semi-trailer operating at 31,000 kilograms gross vehicle weight (net to tare ratio of 1.0) (Taylor 2001).

To further illustrate, the net to tare ratio of a 5-axle tractor semi-trailer is ((31,600 kgs – 18,000 kgs)/18,000 kgs) 0.75, while that of an eight-axle B-train is ((62,500 kgs – 22,000 kgs)/22,000 kgs) 1.8. Given these economies of scale in transport efficiency, Canada has been proactive in permitting significant increases in all allowable heavy truck weights and dimensions. This has led to the allowance of larger and heavier trucks on many Canadian roads, such as the 8-axle B-train, as illustrated in Figure 2.4.

**Figure 2.4: Eight - Axle B-Train Double**

Despite these recent technological advances in commercial transport vehicles, road transport still produces a significant amount of air emissions. The primary reason for this includes the overall increased t-km traveled by trucks over the past two decades, and the North American modal shift in transport of goods from rail to road. Truck traffic is also continuously increasing due to market globalization, social expectation for just-in-time delivery, dispersed production facilities, and reduced warehousing. Therefore, more trucks are required to be at the right place at the right time to satisfy increasing social needs.

Countries such as the United States, Canada, Australia, and the United Kingdom have long been leaders in innovative commercial truck weights and dimensions policies. This is especially true in Canada, due to its significant geographic size, and a primary component of the Canadian economy being export of bulk commodities. Canada has, therefore, undertaken proactive technical and economic analysis on standards for heavy commercial trucks weights and dimensions to improve truck transport economy.

Increased vehicle weight limits have significantly improved transport productivity and have lowered the relative road related transportation costs in Canada. To illustrate,

Figure 2.5 shows the energy and emissions incentives to deploy larger and heavier trucks. Based on the general trend of increasing truck weights and dimensions, the relationship is that fuel consumption rate decreases as truck weights and dimensions increase for dense freight transport (over 200 kilogram per cubic meter).

Therefore, freight transported on an eight-axle B-train operating at 62,500 kg uses 36 percent less fuel per tonne hauled than would have been accomplished on a five-axle tractor-semi trailer operating at 31,600 kg (Taylor 2001).

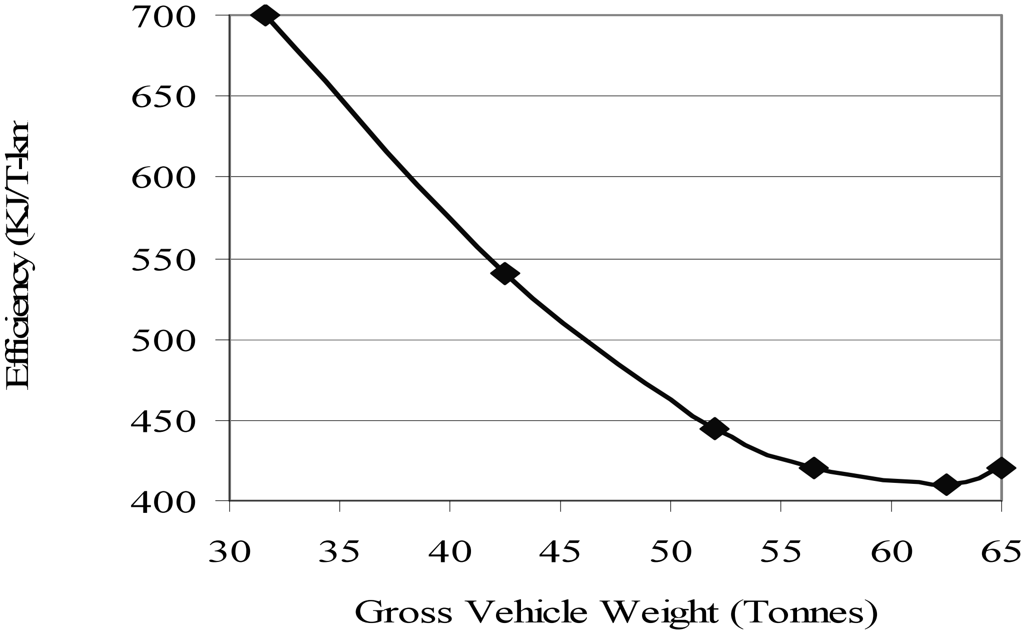

**Figure 2.5: Energy Efficiency versus Gross Vehicle Weight for Conventional Canadian Trucks (Taylor, 2001)**

Europe has implemented similar policies to improve transport efficiency. As an example, in 1994, the United Kingdom allowed six axle articulated vehicles and drawbar–trailer combination units to operate at a gross vehicle weight (GVW) of 44 tons, while the present gross vehicle weight for an articulated truck with five or more axles was limited to 38 tons. Thus, it was thought that there would be economic and environmental benefits in allowing and encouraging more use of 6 axle trucks able to operate up at 44 tons. Six axle trucks with a capacity of 44 tons would be able to carry an increase of five tons more (14 percent for GVW) payload over the conventional 38 ton five axle trucks. In 1995, there were 75,300 articulated trucks registered at 38 tons in the UK, with an average net capacity of approximately 24 tons (net/tare ratio of 24/14 = 1.7). A 44 ton GVW truck payload is 29 tons (net/tare ratio 29/15 = 1.9). An application of the payload ratio to the present number of vehicles would result in

(75,300x 24/29 =) 62,317 vehicles of 44 tons GVW and therefore, a maximum potential decrease of about 13,000 heavy trucks in the UK (UK Department of Transport 2002).

Bulk commodity goods haul such as fuel, grains, or aggregates, would be able to fully exploit the 44 ton limit. Knowing that the estimated proportion of vehicles carrying bulk dense goods in the UK is over 50 percent, it is therefore estimated that the operating fleet in the UK could be reduced by 6,500 vehicles (50 percent of 13,000), or 9 percent reduction of the number of trucks registered in 1995, over a period of time by a policy implementation of 44 ton limit. A reduction of about 6,500 vehicles would result in benefits in terms of reduced congestion, improved safety, fuel savings with resultant savings in emissions, and cost and efficiency savings for industry. Fuel consumption has been estimated to decrease by about 200 million litres (6 percent) with commensurate reductions in nitrous oxide and other particulate emissions (UK Department of Transport 2002).

Given recent developments in Europe and North American Transport, it is clear that it may be possible to further reduce emissions by improving heavy vehicle designs and therefore, increase the size and weights of commercial vehicles.

## 2.3. KYOTO PROTOCOL

On 16 December 2002, Canada was the 99th country to ratify the Kyoto Protocol in order to reduce total greenhouse gas (GHG) emissions to six percent below 1990 levels within the time frame of 2008-2012. The Kyoto Protocol was established in 1997 by the United Nations and is designed to take necessary measures to limit the impact of the greenhouse gases on the environment. The Kyoto Protocol was founded at the *United Nations Framework Convention on Climate Change* (UNFCCC) adopted after the *Earth Summit* in June 1992, at Rio de Janeiro, Brazil. Article 2 of the Declaration of Rio asserts that:

> *The final objective of this Conventio (...) is to stabilize, according to this convention significant arrangements, greenhouse gases concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.*

In 1997 in Kyoto, Japan, representatives of 160 countries agreed on reducing six primary greenhouse gas emissions (including carbon dioxide $CO_2$, methane $CH_4$, and nitrogen dioxide $N_2O$) by 5.2 percent on average relative to 1990 levels, between 2008 and 2012. Specifically, major industrialized countries, such as the USA, must reduce their emissions by seven percent, Canada by six percent; and European Union by eight percent. The Kyoto agreement would come into effect after it has been ratified by at least 55 countries.

The environmental effects of industrialization are well known today. These effects include climate change through gas emissions, such as greenhouse gases, health and non-health impacts, noise, non-renewable energy consumption, and irreversible land use due to pollution, as well as water pollution. The major contributors of gas emissions that are hazardous to the environment include:

- Production related heavy industry;
- Transportation;
- Generation and distribution of energy;
- Agriculture;
- Forestry;
- Mining and;
- Solid waste management sector.

Concerning transportation, Kyoto Protocol (1997) requires that:

> *Countries involved in the convention must achieve their quantified emission limitation and reduction in order to promote sustainable development. They shall implement and/or elaborate policies and*

> *measures in accordance with their national circumstances, such as measures to limit and / or reduce emissions of greenhouse gases in the transport sector, and limitation and / or reduction of methane emissions through recovery and use in waste management, as well as in production, transport and distribution of energy.*

During the period 1990-2000, Canada's total GHG's increased by 9 percent (Environment Canada 2001). Therefore, as of 2000, Canada must decrease GHG's by 15 percent below recorded 1990 levels by 2008-2012 (Wilson 2003). To illustrate, in 1990, Canada estimated 608,000 kilo tonnes of GHG emissions, in terms of carbon dioxide equivalent ($CO_2$ equivalent), released in the atmosphere. Reduction of 15 percent would equal 91,200 kilo tonnes. Carbon dioxide ($CO_2$) itself accounted for 77.6 percent of these overall greenhouse gas emissions, or 472,000 kilo tonnes. Therefore, a 15 percent reduction in $CO_2$ will equal 70,800 kilo tonnes of reduced emissions. In 1990, the transportation sector produced 153,000 kilo tonnes of $CO_2$ equivalent, with 95.4 percent for $CO_2$ itself or 146,000 kilo tonnes. A reduction of 15 percent in the transportation sector will equal 22,950 kilo tonnes of $CO_2$ equivalent, and 21,900 kilo tonnes of $CO_2$ (Environment Canada 2001).

Strategies have been suggested in the transportation sector in Canada to decrease emissions and meet the desired Kyoto targets. In order to reduce the emissions and make the Canadian transportation strategies sustainable, a variety of measures must be implemented. They include, among others, demand management, operation management, pricing policies, vehicle technology improvement, clean fuel, transportation planning, and integrated land use. Another way to decrease emissions and thus, their environmental costs, may be to increase the size of commercial trucks, therefore realizing savings in vehicle-kilometres traveled and fuel through reduced tare weight of the vehicle.

## 2.4. DEFINITION OF EMISSIONS CAUSING ENVIRONMENTAL DAMAGES

In 2001, Canadian heavy duty vehicles produced a significant quantity of carbon dioxide ($CO_2$) which accounts for 98.6 percent of the total greenhouse gas emissions generated by heavy vehicles (Environment Canada 2001). Although the Kyoto Protocol focuses only on greenhouse gas emissions, heavy vehicles produce other emissions that seriously harm human health: carbon oxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and particulate matter (PM). Damages resulting from these emissions are divided into three categories: air pollution damage, fine particle damage, and global warming (Bein 1997).

### 2.4.1. Air Pollution Damage

Roadside and local air pollution impacts are the most significant emissions impact as measured in the immediate area where the emissions have occurred (Bein 1997). They are generated by transport vehicles, depending on the nature and composition of the fuel that is used, the type and age of the vehicle, the vehicle operational parameters, and the degree to which the vehicle drive train is properly tuned. Emission impacts include human mortality (death) and morbidity (illness), reduced agricultural production, reduced visibility, corrosion of materials, increasing cleaning costs and other damage to the natural environment. Primary air pollutants from transportation include carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC).

#### 2.4.1.1. Carbon Monoxide (CO)

When carbon or hydrocarbon fuels are burned with insufficient oxygen, some of the carbon is incompletely oxidized and forms carbon monoxide (CO). CO is a colorless, tasteless, poisonous gas that contributes to ground-level ozone formation and converts to methane ($CH_4$). Exposure to high concentration of CO can have negative health effects, such as impaired perception and thinking, slow reflexes, drowsiness, unconsciousness, and even death (Bein 1997).

$CH_4$ is produced during the use of fossil combustibles. The combustion of $CH_4$ generates by-products responsible for the atmospheric pollution, such as smog (Bein 1997). This pollution has a significant impact on people who suffer from cardiovascular diseases and respiratory system problems, such as asthma, chronic bronchitis, or allergies.

#### 2.4.1.2. Nitrogen Oxides (NOx)

Nitrogen oxides (NOx) are produced in the greatest quantity early in the combustion process of fossil fuels (Bein 1997). This gas results from the reaction between nitrogen and free oxygen at high temperature close to the flame front. The rate of NO formation in diesel engines is a function of oxygen availability, and increases exponentially with flame temperature. It has virtually no direct affect on human health, but NO will convert to nitrogen dioxide ($NO_2$), which reacts with volatile organic compounds (VOC's) to produce ozone ($O_3$) (Bein 1997). $NO_2$ irritates the respiratory system and, with prolonged exposure, increases susceptibility to viral infections such as influenza. These health impacts are most prevalent in urban areas. NOx also contributes to the formation of secondary fine particulate matter in the air and to acid precipitations. $NO_2$ gas also plays a special role in visibility problems: $NO_2$ absorbs blue light, creating the yellow to reddish-brown appearance of urban smog.

#### 2.4.1.3. Hydrocarbons (HC)

Hydrocarbons are generated from the fractions of fuels and lubricants with lower boiling points and from partially combusted fuels. A higher proportion of diesel hydrocarbon emissions occur primarily at light loads of the truck. The major source of light-load HC emissions is excessive air-fuel mixing, which results in air-fuel mixtures that are too lean to burn. Motor vehicles emit about 10 percent of hydrocarbon pollutants from running losses, 30 percent from other evaporative losses, and 60 percent from exhaust (Bein 1997). HC reacts with NOx to form ground-level ozone (Bein 1997).

### 2.4.2. Fine Particulates

Most of the particulate mass generated from transport consists of heavy hydrocarbons adsorbed or condensed in the form of soot. This is referred to as the soluble organic fraction (SOF) of the particulate matter. The SOF is derived partly from the lubricating oil, partly from unburned fuel, and partly from compounds formed during combustion.

The most damaging impacts of particulates are those on human health. Exposure to airborne particles can interfere with the normal functioning of the respiratory system and may cause heart problems and cancers. Larger particles, especially carbon, are believed responsible for most of the soiling in urban areas, and are the primary cause of visibility impairment from regional haze conditions (Bein 1997).

Transportation activities generate particles ranging from relatively large and visible particles, such as smoke and road dust, to microscopic particles. While the larger particles are a cleaning nuisance, particles smaller than 10 μm (denoted as $PM_{10}$) are the most harmful, because they stay in the atmosphere for several weeks even in the rainy season, are inhalable and can penetrate human, animal and plant tissue (Bein 1997). The finest particle fractions ($PM_{2.5}$ smaller than 2.5 μm) contain both solids and aerosols. Composition of particles ranges from road surface materials; tire rubber, carbon and vehicle brake lining, to organic compounds from fuel, metals from the wear of vehicle parts, and sulphuric acid aerosols. The finer fractions contain more toxic trace elements than the coarse fractions. Fine particles have been identified as a major health risk. In general, the smaller the particles, the greater the health risks.

### 2.4.3. Global Warming

The threat of global warming (also called climate change or enhanced greenhouse effect) arises from the increasing concentrations in the atmosphere of gases that trap solar heat rather than letting it escape into space after reflecting from the surface of the earth (Bein 1997). This greenhouse effect is necessary to make the earth habitable, but increasing concentrations in the atmosphere of greenhouse gases may cause significant climatic change and result in ecological turmoil in future decades. Indeed, global warming and climatic changes could result in significant socioeconomic and environmental impacts including droughts and floods, reduced agricultural and forest production, desertification, species extinction and ecological system damage (IPCC 1995).

The transport sector generates both direct and indirect greenhouse gases. Direct greenhouse gases are radioactive. Those emitted by transport vehicles include carbon dioxide, methane, nitrous oxide, and flurochemicals. The indirect greenhouse gases include carbon monoxide, other oxides of nitrogen and nonmethanic volatile organic carbons. These do not have a strong radioactive effect in themselves but influence atmospheric concentrations of the direct greenhouse gases by, for example, oxidizing to form $CO_2$ or contributing to the formation of ozone, a potent direct greenhouse gas.

The contribution of greenhouse gases to global warming, called global warming potential is measured in comparison to the contribution made by $CO_2$, defined as 1.0 (IPCC 1995). Global warming potential factors reflect the different extent to which gases absorb infrared radiation and the differences in the time scales on which the gases are removed from the atmosphere. The global warming potential is used in the national or international communications as required by the United Nation Framework Convention on Climate Change. The Kyoto Protocol has adopted global potential warming (with 100-year time horizon) as the basis for defining equivalences between emissions of different greenhouse gases during the 2008-2012 commitment periods. To measure greenhouse gases, carbon dioxide equivalents (CO2-e) are computed as (Bein 1997):

$$CO_2\text{-}e = CO_2 + 21\, CH_4 + 310\, N_2O + 23900\, SF_6 + \ldots \qquad 1$$

Road transportation is a major source of $CO_2$, responsible for about one-quarter of non-biomass emissions of $CO_2$ (Bein 1997). Over a long time period, the present contribution of methane and nitrous oxide from transportation would add about 10 percent to the global warming potential of $CO_2$. The Kyoto Protocol requires calculations of greenhouse gases to be made on the basis of fossil-fuel derived carbon dioxide. Table 2.1 shows the global warming potential of each gas on a $CO_2$ equivalency basis (Bein 1997).

**Table 2.1: 100-Year Greenhouse Gas Warming Potentials (Bein, 1997)**

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

### 2.4.4. Diesel Engine Efficiency Impact on Emissions

Various characteristics influence the combustion efficiency of diesel engines (Faiz et al. 1996):

- Air-fuel ratio;
- Air-fuel mixing;
- Fuel injection and combustion timing;
- Charge temperature, and;
- Charge composition.

The air-fuel ratio has a significant effect on the emission rate for HC and PM in the combustion chamber. The fact that fuel and air must mix before burning, means that a substantial amount of excess air is needed to ensure a complete combustion of the fuel within the limited time allowed by the power stroke. The minimum air-fuel ratio for complete combustion is about equal to 15/1 or the smoke limit that establishes the maximum amount of fuel that can be burned per stroke, and thus the maximum power output of the engine (Faiz et al. 1996).

The rate of air-fuel mixing between the compressed charge in the cylinder and the amount of injected fuel is among the most important factors in determining diesel performance and emissions generation. The mixing rate during the ignition delay determines how much fuel is burned in the premixed burning phase. The higher the mixing rate, the greater the amount of fuel burning in the premixed burning phase, and the higher the noise and NOx emissions. The more rapid and complete the mixing, the greater the amount of fuel, the higher the efficiency, and the lower the PM emissions (Faiz et al. 1996).

Concerning fuel injection and combustion timing, the earlier the fuel is injected, the less compression heating will have occurred, and the longer the ignition delay. The longer the ignition delay, the more time for air and fuel to mix, increasing the amount of fuel that burns in the premixed combustion phase. More fuel burning at, or just before top-dead-center of the cylinder, can also increase the maximum temperature and pressure attained in the cylinder. Both of these effects tend to increase $NO_x$ emissions. On the other hand, earlier injection tends to reduce PM and light-load truck HC emissions (Faiz et al. 1996).

The process of compressing the intake air in turbo-charged engines increases its temperature. Reducing the temperature of the compressed air charge with air to air coolers going to the cylinder has benefits in terms of reduced PM and NOx (Faiz et al. 1996).

Higher compression ratio results in a higher temperature for the compressed charge, and thus in a shorter ignition delay and higher flame temperature. The effect of a shorter delay is to reduce NOx emissions, while the flame temperature would be expected to increase them. Engine fuel economy, cold starting, and maximum cylinder pressures are also affected by the compression ratio (Faiz et al. 1996).

## 2.5. QUANTIFICATION OF TRANSPORT RELATED EMISSIONS

Emission volumes vary with the activity type and the vehicle performance. Factors considered in this research that affect the rates of vehicle emissions are:

- Fuel type;
- Vehicle configuration, weights and dimensions;
- Field operations;
- Vehicle engine and drive train characteristics;
- Road roughness;
- Road stiffness;
- Vehicle rolling resistance, and;
- Idling emissions.

### 2.5.1. Fuel Type

A variety of fuel types can power automobiles. Alternative fuels tend to reduce some types of emissions, but in most cases their total benefits are modest, and many increase other harmful emissions such as $CO_2$ or PM. (Victoria Transport Policy Institute 2003). For instance, bio-diesel fuels are supposed to be the lowest GHG’s emitters but also generate considerable amounts of PM (Beer et al. 2000).

### 2.5.2. Vehicle Configuration, Weights and Dimensions

Vehicle configuration (mass and dimension) has an impact on vehicle emission levels. Generally, the larger the truck, the higher the emission rates. But, it may be hypothesized that if a truck can carry increased payload, it would decrease the number of trucks on the road, and thus, decrease the total amount of emissions from an overall society perspective (Taylor 2001). In addition, older vehicles that lack current emission control systems, and vehicles that are poorly tuned, tend to have high emissions rates. (Victoria Transport Policy Institute 2003). Therefore, vehicle age should be incorporated into a vehicle emissions model.

### 2.5.3. Vehicle Field Operations - Applications

Start-up and shut-down cycle emissions generated from heavy trucks can be significantly different from routine operations according to the specific field applications. For example, emission rates for most pollutants are higher when engines are cold, and tend to significantly increase under stop-and-go conditions, and at very low and/or very high speeds. Short heavy hauls are subjected to the relatively high proportion of slow travel speeds, acceleration and deceleration due to the poorer road conditions, and increased idle time during loading and unloading, as well as including stop-and-go travel conditions. This is especially true for diesel engines of larger trucks. As well, in contrast to rural operations, urban operations generally consume more fuel than rural operations and thus, involve more emission generation.

Fuel efficiency between private cars and commercial heavy trucks can be very different. A private car consumes between 0.07 and 0.14 litre per kilometre (20 to 40 miles per gallon), whereas a truck consumes between 0.4 and 0.7 litre per kilometre (4 to 7 miles per gallon). This latter figure is considerably more when the comparison is based on the total amount of fuel consumed annually. In Canada, there are about 671,000 commercial heavy vehicles that log approximately 100,650 billion kilometres annually (671,000 x 150,000 kilometres each), and there are about 10.2 million cars driving 306,000 billion kilometres annually (10.2 million x 30,000 kilometres each) (Nix 2003). The resulting range of fuel consumed is 21 to 43 trillion litres for private cars, and 40 to 71 trillion litres for commercial heavy trucks, as presented in Figure 2.6. Figure 2.6 shows that, despite their lower number, commercial heavy trucks consume nearly twice as much fuel per year compared to private cars.

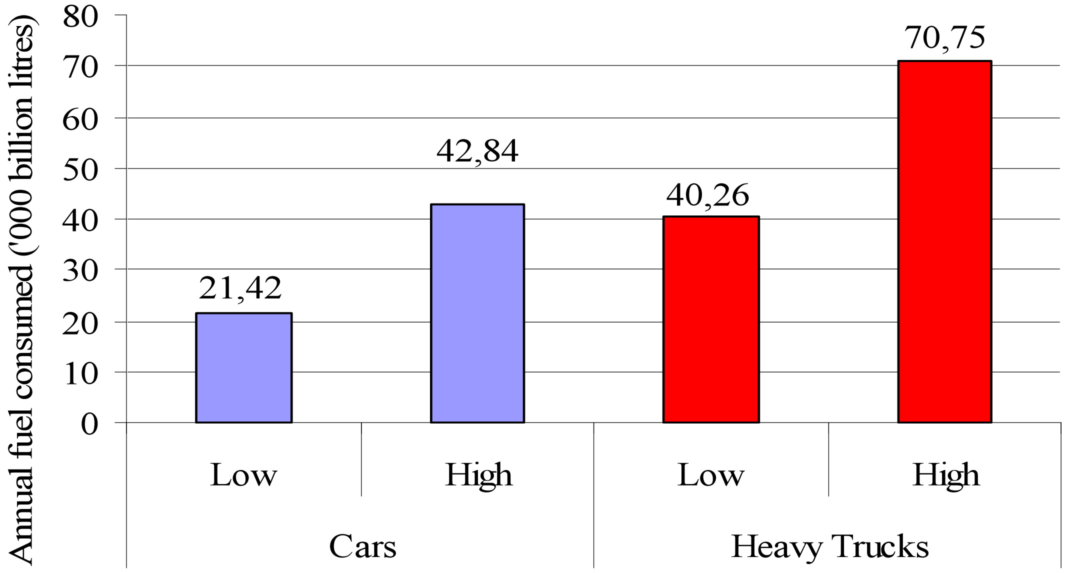

**Figure 2.6: Fuel Consumption Range by Type of Vehicles in Canada (Transport Canada, 2003)**

### 2.5.4. Engine Characteristics

Emission levels are typically higher for larger horsepower engines. However, the use of technology in advanced electronic controls, diagnostics, and driver management systems introduce not only added operational efficiency, but also control engine performance efficiency and reduction of vehicle emissions. Therefore, an advanced heavy diesel truck engine would tend to emit fewer emissions than a common medium diesel truck engine.

Direct injection of heavy duty diesel trucks typically generate higher power output and better fuel economy but are considerably noisier. Compared to gasoline spark-ignition engines, heavy-duty diesel engines have lower CO and HC emissions, but higher NOx emissions. Diesel engines are, however, up to 100 percent more energy efficient in terms of litres consumed per kilometre travelled, compared to gasoline engines (Nix 2003). However, PM emissions in diesel engines are considerably higher than those recorded from gasoline engines. To reduce the PM emissions of diesel engines, there is a need for modifying the engine and combustion process.

### 2.5.5. Road Roughness

Road roughness is defined as *a distortion of the pavement surface that contributes to an undesirable or uncomfortable ride* (Hudson 1978) and, in the case of commercial truck operations, may induce vehicle accelerations or decelerations, having an increased effect on emissions outputs (Barth and Tadi 1996). Pavement roughness is typically measured in terms of the International Roughness Index (IRI), defined as a specific mathematical transform of a true profile in terms of mm/m, and is becoming the international standard in measurement and analysis of pavement roughness (TAC 1997). Roughness has a significant influence on heavy vehicle dynamic loading because the engine requires more energy to overcome the deformed pavement.

Figure 2.7 shows typical IRI ranges for different road types and conditions (Sayers 1986).

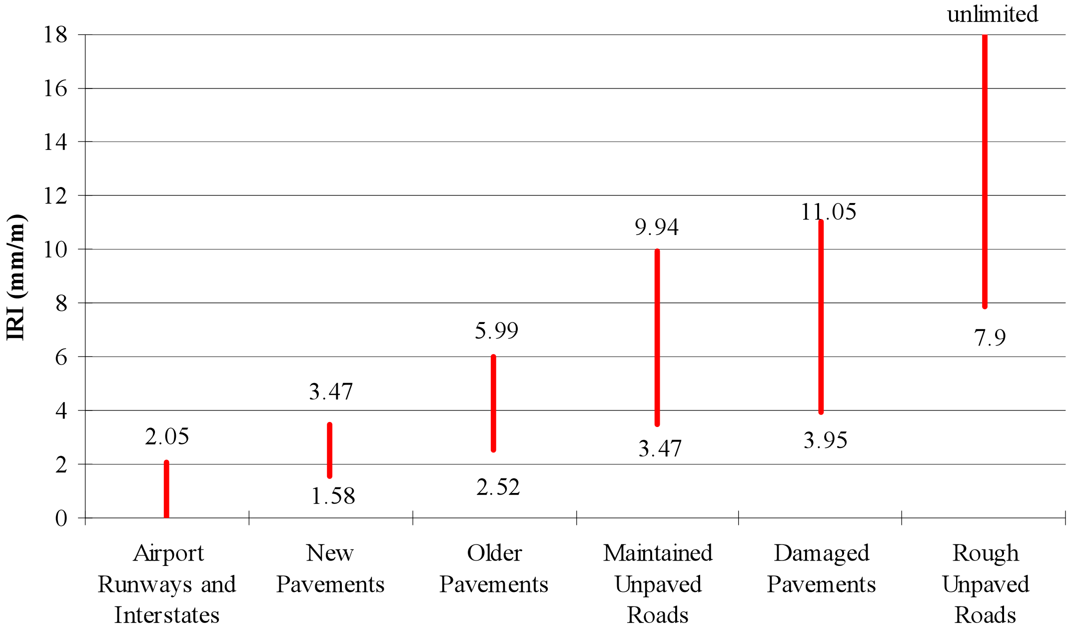

**Figure 2.7: IRI Scale for Road Types and Condition (Sayers, 1986)**

As seen in Figure 2.7, IRI can range from 0.0 to approximately 3.5 for new airfields and pavements. However as pavements age and become increasingly rough, IRI can increase over to 10.0.

### 2.5.6. Road Stiffness and Vehicle Rolling Resistance

Road stiffness is an important factor in vehicle rolling resistance and, therefore, emissions levels. Roads are typically designed and built to support heavy trucks. Stiffness is the relationship between induced stress and resulting strain as a function of time and loading. Lower road stiffness typically increases rolling resistance. Road stiffness is an important component in the ride quality and strength of roads and has an impact on truck fuel consumption and thus, gas emissions. Rolling resistance is primarily influenced by the tire-road interface, as a function of tire contact and the properties of the tire, such as pressure, size, and material type, as well as the surface characteristics of the road and vehicle speed. Heavy trucks consume significant fuel in overcoming rolling resistance. Table 2.2 and Figure 2.8 demonstrate typical amounts of the pollutants emitted by diesel trucks (Bein 1997).

**Table 2.2: Emissions Rates of Motor Vehicles in Urban and Rural Driving (Bein, 1997)**

| **Truck, diesel (GVW) Metric tonnes** | **Urban Driving (grams/vehicle-kilometre)** | | | **Rural Driving (gram/vehicle-kilometre)** | | |
|---|---|---|---|---|---|---|
| | **NOx** | **HC** | **$SO_2$** | **NOx** | **HC** | **$SO_2$** |
| **3.5-9.0.** | 3.8 | 0.8 | 0.9 | 3.3 | 0.6 | 0.9 |
| **5.0-13.0.** | 11.0 | 1.9 | 1.0 | 11 | 1.9 | 1.0 |
| **13.5-18.0** | 13.8 | 1.6 | 1.2 | 13.8 | 1.6 | 1.2 |
| **18.0-20.0** | 15.3 | 1.4 | 1.3 | 15.3 | 1.4 | 1.3 |
| **20.0-24.0** | 16.4 | 1.3 | 1.4 | 16.4 | 1.3 | 1.4 |
| **Over 24.0** | 21.1 | 1.8 | 1.9 | 21.1 | 1.8 | 1.9 |

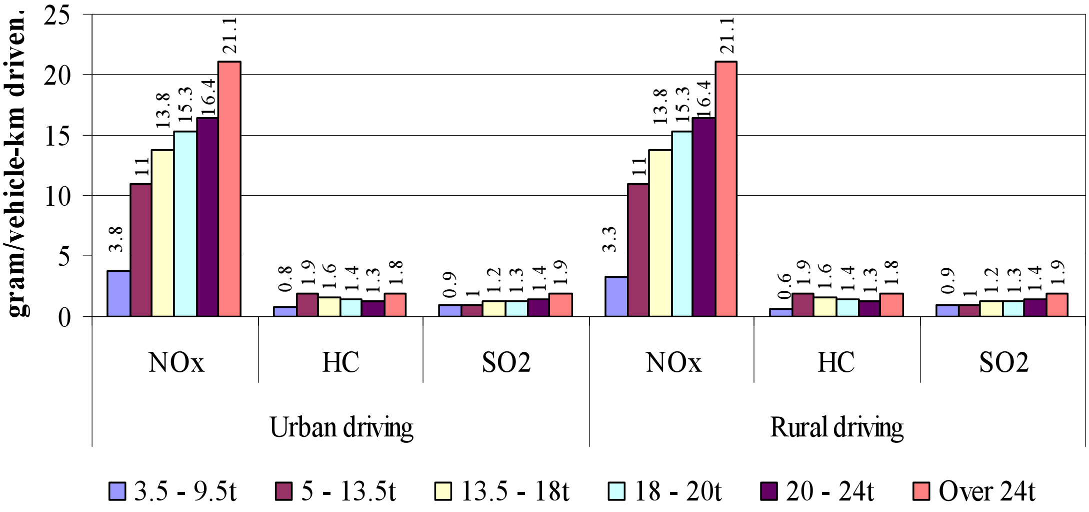

**Figure 2.8: Emissions Rates of Motor Vehicles based on GVW (Bein, 1997)**

Truck emissions differ only slightly between urban and rural driving, except for trucks in the 3.5 to 9.5 tonnes GVW class.

Based on a study by Canadian transport data assembled from Transport Canada (Bein 1997), Table 2.3 shows the superior fuel-efficiency per tonne-kilometre associated with lower emissions of a B-train configuration compared to a semi-truck. Table 2.3 shows that a B-train with a payload of 44.20 tonnes consumes less fuel, and therefore, produces less emission than a semi-truck with a payload of 31.50 tonnes.

**Table 2.3: 1995 Environmental Performances of Canadian Freight Truck Types (Bein, 1997)**

| Vehicle | Net Payload, (MT) | Fuel | NOx | CO | VOC | PM | $CO_2$ | Tires/ Million (t-km) | Load Factor |
|---|---|---|---|---|---|---|---|---|---|
| | | (Grams/tonne-kilometre) | | | | | | | |
| **Semi-truck** | 31.50 | 19.38 | 0.55 | 1.75 | 0.146 | 0.012 | 61.38 | 1.98 | 0.65 |
| **B-train** | 44.20 | 17.60 | 0.51 | 1.58 | 0.138 | 0.011 | 56.00 | 2.04 | 0.65 |

### 2.5.7. Idling Emissions

Commercial vehicles typically operate in idling conditions from five to eight hours a day (Environmental Protection Agency 2004). Idling aims at keeping the engine and fuel warm, especially in cold weather as commonly experienced in northern climates, cooling the truck's cab compartment in southern climates and/or summer conditions, as well as waiting for inspection in weigh stations. A heavy truck consumes an average of 3.63 litres of fuel per hour of idling (Environmental Protection Agency 2004). Table 2.4 shows the Environmental Protection Agency (EPA) idling emissions outputs for heavy diesel vehicles in summer and winter. Winter idling emissions are usually higher than summer idling emissions.

**Table 2.4: Idling Emission for Heavy Diesel Vehicles (EPA, 1999)**

| | Winter Conditions (-1°C) | | Summer Conditions (24°C) | |
|---|---|---|---|---|
| **Emissions** | **grams/hour** | **grams/min** | **grams/hour** | **grams/min** |
| HC | 12.60 | 0.21 | 12.50 | 0.17 |
| CO | 94.60 | 1.58 | 94.00 | 1.18 |
| NOx | 56.70 | 0.94 | 55.00 | 1.42 |
| PM | 2.57 | 0.04 | 2.57 | 0.04 |

Table 2.5 and Table 2.6, and Figure 2.9 through Figure 2.13 illustrate heavy diesel truck idle emissions standards from the California emissions inventory model with accessory load and without accessory load across idling applications, respectively (California Air Resources Board 2002). EMFAC2002 is an on-road emission model used in California and includes two basic modules: emissions factors and vehicle activity. Emissions factors describe the characteristics of vehicles under different ambient and driving conditions. They have been developed from a thousand emissions tests on both new and used vehicles in California. Vehicle activity is an estimate of travel and vehicle demography for each area within the state.

Regarding idle emissions, the EMFAC2002 staff estimated the idle emission factors by using data of a heavy duty diesel trucks population from the US. They divided this heavy duty diesel truck population in diverse model year's groups, as represented in Table 2.5 and Table 2.6. The average idling emissions rates of these trucks were assumed to be applicable to all model year's groups. However, it is important to note that no discernable relationship between the $CO_2$ emissions and the engine model was found and therefore, the $CO_2$ data of all the model years were evaluated together in a single group (California Air Resources Board 2002).

As illustrated, idling emissions are higher when the vehicle has accessory loads on the engine relative to no accessory loads. Since 1975, PM emissions have decreased by 87.4 percent, CO emissions by 53 percent, and HC emissions by 78.6 percent. This is the result of the constant improvement of diesel engines combustion efficiency, as explained in section 2.4.4. NOx emissions have increased between the 1975-1989 period and the 1990-2006 period by 189 percent, due to the increasing use of diesel engine that is a significant source of NOx emissions (Faiz et al. 1996).

**Table 2.5: Idle Emission Factors by Emission by Year without Accessory Load (EMFAC, 2002)**

| Model-Year Group | PM (grams/hr) | NOx (grams/hr) | CO (grams/hr) | HC (grams/hr) | $CO_2$ (grams/hr) |
|---|---|---|---|---|---|
| **2007+** | 0.09 | 84 | 18 | 6 | 4366 |
| **2004-2006** | 0.85 | 84 | 18 | 6 | 4366 |
| **1998-2003** | 0.85 | 84 | 18 | 6 | 4366 |
| **1994-1997** | 1.13 | 84 | 20 | 8 | 4366 |
| **1991-1993** | 1.50 | 84 | 23 | 9 | 4366 |
| **1990** | 2.00 | 84 | 25 | 12 | 4366 |
| **1987-1989** | 2.00 | 29 | 25 | 12 | 4366 |
| **1984-1986** | 2.65 | 29 | 28 | 14 | 4366 |
| **1980-1983** | 3.53 | 29 | 31 | 18 | 4366 |
| **1977-1979** | 4.68 | 29 | 35 | 22 | 4366 |
| **1975-1976** | 5.72 | 29 | 37 | 26 | 4366 |
| **Pre-1975** | 6.73 | 29 | 40 | 29 | 4366 |

**Table 2.6: Idle Emission Factors by Emissions by Year with Accessory Load (EMFAC, 2002)**

| Model-Year Group | PM (grams/hr) | NOx (grams/hr) | CO (grams/hr) | HC (grams/hr) | $CO_2$ (grams/hr) |
|---|---|---|---|---|---|
| **2007+** | 0.28 | 165 | 90 | 12 | 9140 |
| **2004-2006** | 2.77 | 165 | 90 | 12 | 9140 |
| **1998-2003** | 2.77 | 165 | 90 | 12 | 9140 |
| **1994-1997** | 3.69 | 165 | 100 | 15 | 9140 |
| **1991-1993** | 4.89 | 165 | 111 | 18 | 9140 |
| **1990** | 6.51 | 165 | 123 | 22 | 9140 |
| **1987-1989** | 6.51 | 57 | 123 | 22 | 9140 |
| **1984-1986** | 8.63 | 57 | 137 | 28 | 9140 |
| **1980-1983** | 11.49 | 57 | 152 | 34 | 9140 |
| **1977-1979** | 15.24 | 57 | 169 | 43 | 9140 |
| **1975-1976** | 18.64 | 57 | 182 | 50 | 9140 |
| **Pre-1975** | 21.92 | 57 | 193 | 56 | 9140 |

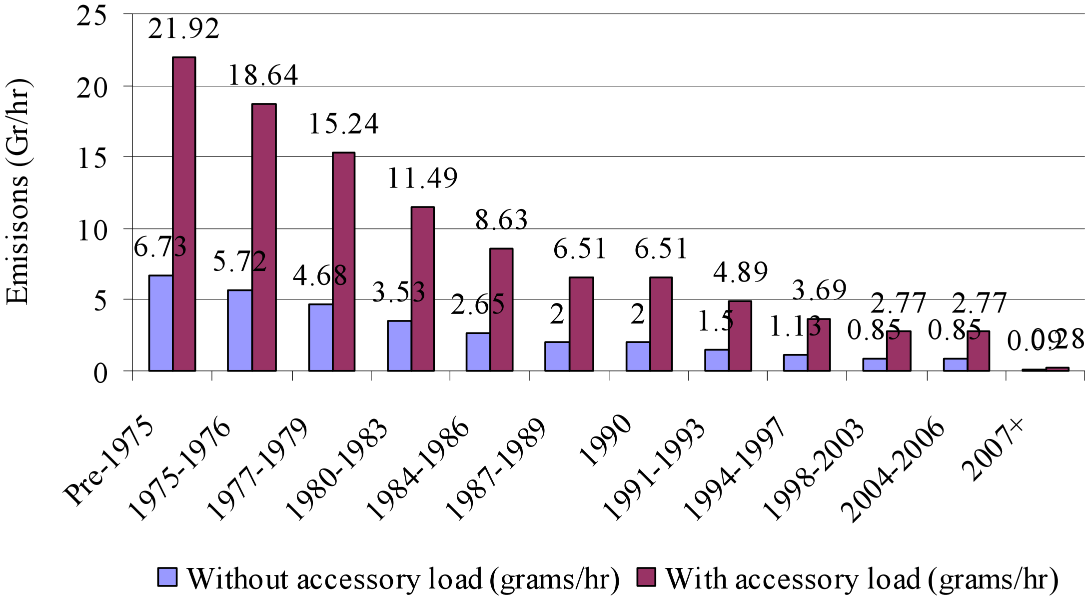

Figure 2.9: Comparison of Idle PM Emissions with and without accessory load by year (EMFAC, 2002)

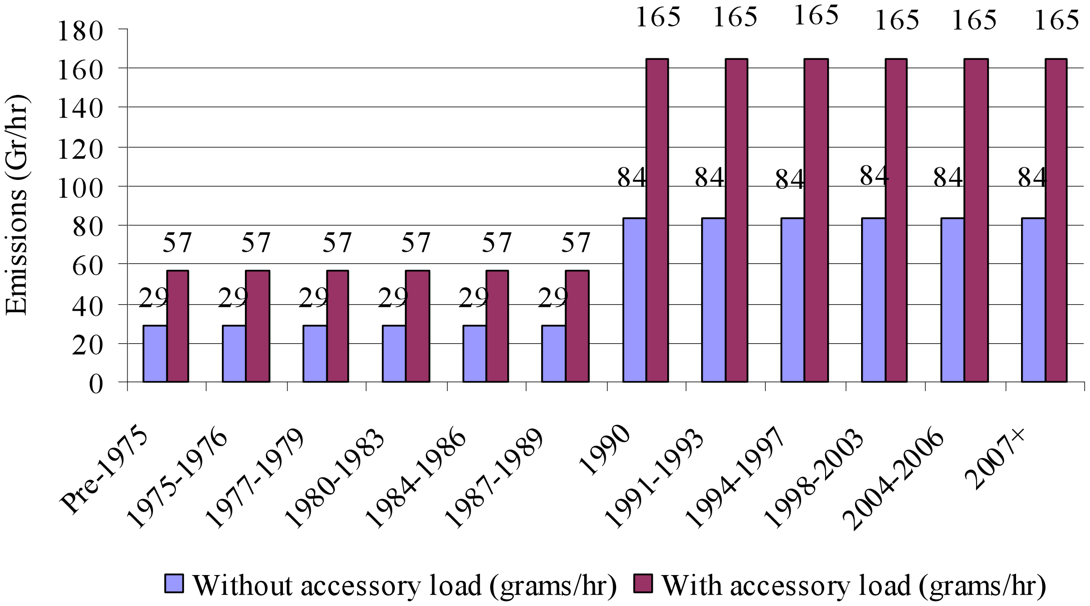

Figure 2.10: Comparison of Idle NOx Emissions with and without accessory load by year (EMFAC, 2002)

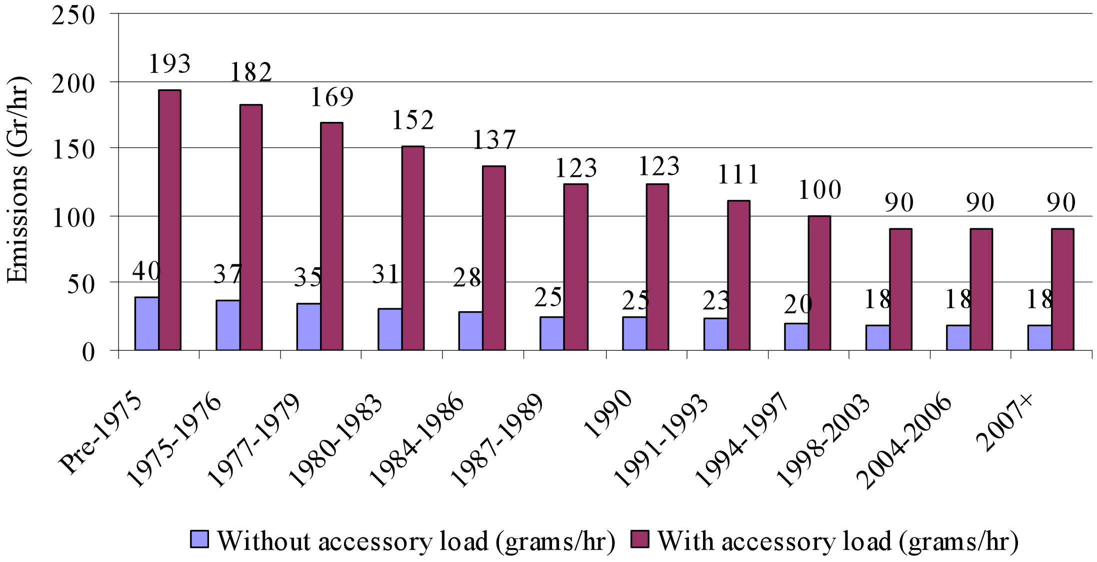

**Figure 2.11: Comparison of Idle CO Emissions with and without accessory load (EMFAC, 2002)**

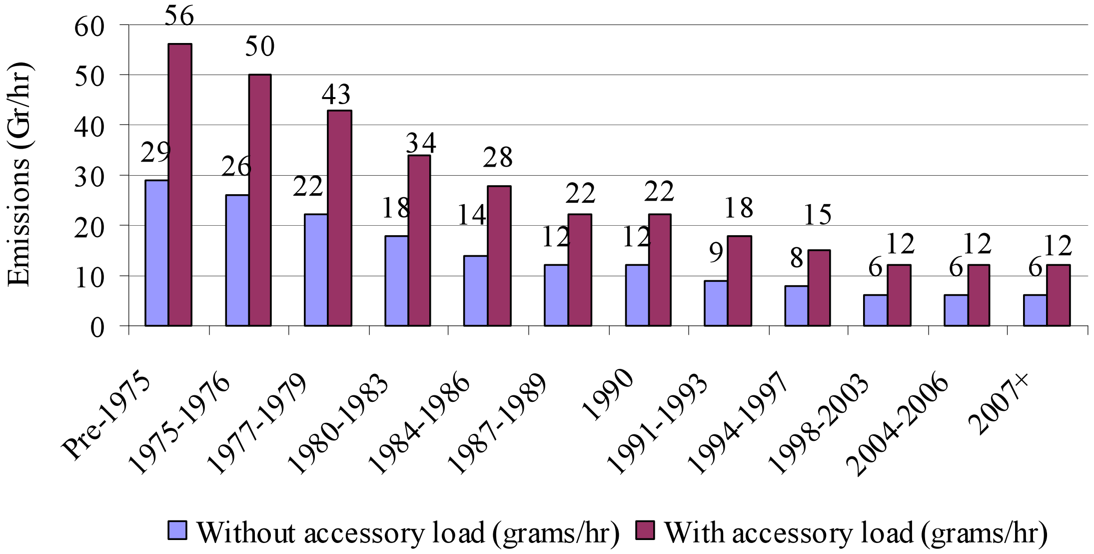

**Figure 2.12: Comparison of Idle HC Emissions with and without accessory load (EMFAC, 2002)**

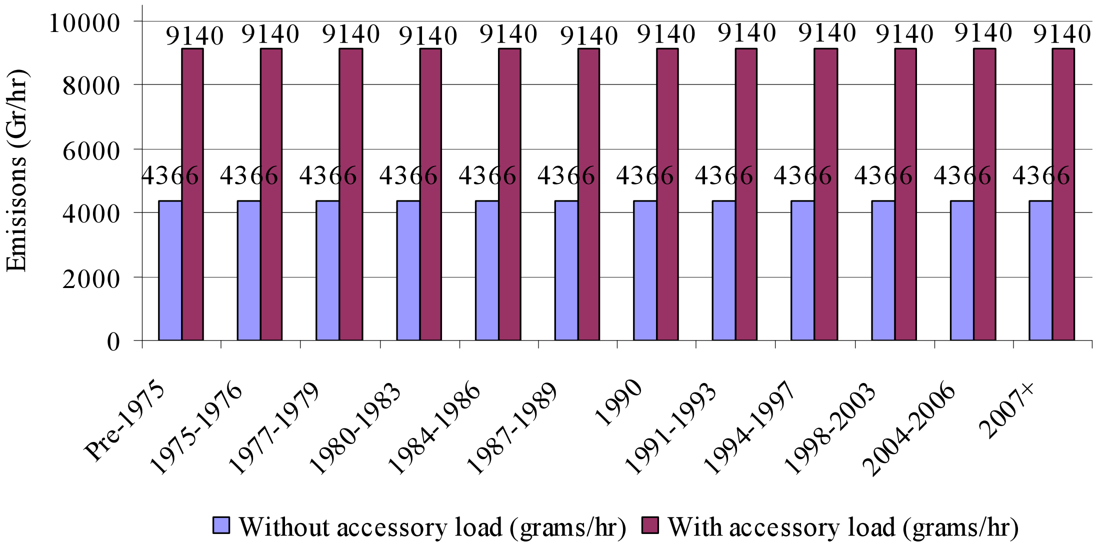

**Figure 2.13: Comparison of Idle $CO_2$ Emissions with and without accessory load (EMFAC, 2002)**

### 2.5.8. Idling Emission Unit Costs

One of the most challenging issues surrounding the cost of emissions is estimating the unit cost of emissions. The idling emission unit cost rates used in this research are shown in Table 2.7 (based on Table 3.6 and Appendix A, Table A-2). As seen in Table 2.7, the unit cost of emissions is significantly different across different emissions types. Therefore, these unit cost rates have to be used with prudence, as some indications amid others, because they're based on a certain range of values from different authors, who have not necessarily used the same estimation mode (confer Section 2.8).

Table 2.7: Average Emissions Unit Cost Rates

(Based on Table 3.6 and Appendix A, Table A-2)

| Emissions | CAD$/Gram of emissions |
|---|---|
| **$CO_2$** | 0.0000417 |
| **NOx** | 0.017 |
| **HC** | 0.000928 |
| **CO** | 0.000127 |
| **PM** | 0.24 |

Table 2.8, Table 2.9, Figure 2.14 and Figure 2.15 illustrate the evolution of each emission unit type costs between 1975 and present, without accessory load and with accessory load. Monetary values are assigned to each emission according to the degree of damage caused on human health and the environment. PM emissions costs have continuously decreased since 1975, but remain significant because of their high unit cost value. PM emissions reduction is partly due to the particulate filters imposed on vehicles' engine. On the contrary, NOx emissions costs have considerably increased since 1975, especially since 1990, due to a fairly high unit cost value as well as the increasing use of diesel engines that generate many nitrogen oxides. CO and HC costs have been minimal between 1975 and the present. $CO_2$ emissions from diesel engines have an impact on the environment but have lower unit cost values than PM and NOx. PM and NOx emissions stay quite high because of their volume produced in the air.

**Table 2.8 Idling Emissions Unit Costs without Accessory Load**

| Model-Year Group | PM ($CAD/ Gram) | NOx ($CAD/ Gram) | CO ($CAD/ Gram) | HC ($CAD/ Gram) | $CO_2$ ($CAD/ Gram) |
|---|---|---|---|---|---|
| **Pre-1975** | 1.6152 | 0.4930 | 0.0051 | 0.0269 | 0.1821 |
| **1975-1976** | 1.3728 | 0.4930 | 0.0047 | 0.0241 | 0.1821 |
| **1977-1979** | 1.1232 | 0.4930 | 0.0044 | 0.0204 | 0.1821 |
| **1980-1983** | 0.8472 | 0.4930 | 0.0039 | 0.0167 | 0.1821 |
| **1984-1986** | 0.6360 | 0.4930 | 0.0036 | 0.0130 | 0.1821 |
| **1987-1989** | 0.4800 | 0.4930 | 0.0032 | 0.0111 | 0.1821 |
| **1990** | 0.4800 | 1.4280 | 0.0032 | 0.0111 | 0.1821 |
| **1991-1993** | 0.3600 | 1.4280 | 0.0029 | 0.0084 | 0.1821 |
| **1994-1997** | 0.2712 | 1.4280 | 0.0025 | 0.0074 | 0.1821 |
| **1998-2003** | 0.2040 | 1.4280 | 0.0023 | 0.0056 | 0.1821 |
| **2004-2006** | 0.2040 | 1.4280 | 0.0023 | 0.0056 | 0.1821 |
| **2007+** | 0.0216 | 1.4280 | 0.0023 | 0.0056 | 0.1821 |

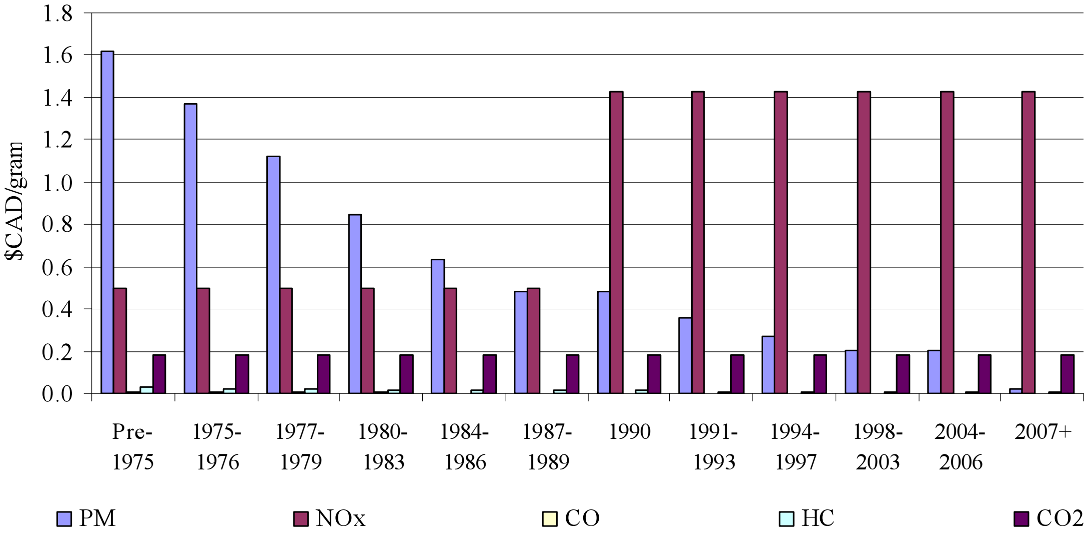

**Figure 2.14: Idling Emissions Unit Costs without Accessory Load**

Table 2.9: Idling Emissions Unit Costs with Accessory Load

| Model-Year Group | PM ($CAD/ Gram) | NOx ($CAD/ Gram) | CO ($CAD/ Gram) | HC ($CAD/ Gram) | $CO_2$ ($CAD/ Gram) |
|---|---|---|---|---|---|
| **Pre-1975** | 5.2608 | 0.9690 | 0.0245 | 0.0520 | 0.3811 |
| **1975-1976** | 4.4736 | 0.9690 | 0.0231 | 0.0464 | 0.3811 |
| **1977-1979** | 3.6576 | 0.9690 | 0.0215 | 0.0399 | 0.3811 |
| **1980-1983** | 2.7576 | 0.9690 | 0.0193 | 0.0316 | 0.3811 |
| **1984-1986** | 2.0712 | 0.9690 | 0.0174 | 0.0260 | 0.3811 |
| **1987-1989** | 1.5624 | 0.9690 | 0.0156 | 0.0204 | 0.3811 |
| **1990.0000** | 1.5624 | 2.8050 | 0.0156 | 0.0204 | 0.3811 |
| **1991-1993** | 1.1736 | 2.8050 | 0.0141 | 0.0167 | 0.3811 |
| **1994-1997** | 0.8856 | 2.8050 | 0.0127 | 0.0139 | 0.3811 |
| **1998-2003** | 0.6648 | 2.8050 | 0.0114 | 0.0111 | 0.3811 |
| **2004-2006** | 0.6648 | 2.8050 | 0.0114 | 0.0111 | 0.3811 |
| **2007+** | 0.0672 | 2.8050 | 0.0114 | 0.0111 | 0.3811 |

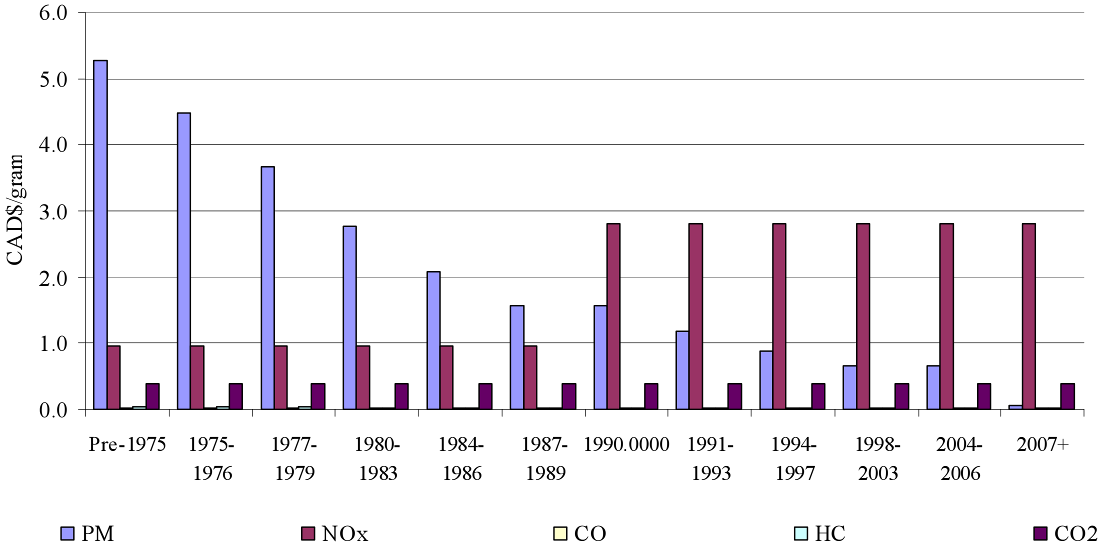

Figure 2.15: Idling Emissions Unit Costs with Accessory Load

## 2.6. TRANSPORT EMISSIONS IN CANADA

Transport is a large and diverse sector accounting for 26 percent of Canada's total GHG emissions in 2001 (Nix 2003). Transport includes emissions from the fuel combustion for the transport of passengers and freight subcategories, including road transport, as seen in the following Table 2.10.

From 1990 to 2001, GHG emissions from transport, driven primarily by energy used for freight transport, increased by 22.4 percent, or 34.2 million tonnes (Environment Canada 2001). Overall, transport was the second leading emissions-producing sector in 2001, contributing 187 mega tonnes and accounting for over 31 percent of Canada's emissions growth from 1990 and 2001. Table 2.10 and Figure 2.16 through Figure 2.18 illustrate shipping activity, GHG emissions, and GHG intensity by transport sector from 1990 to 2000, respectively (Environment Canada 2001).

**Table 2.10: Freight Transportation in Canada and GHG Emissions – 1990-2000 (Greenhouse Gas Report; Environment Canada, 2001)**

| Transportation Sectors | 1990 | 2000 |
|---|---|---|
| **Road Transportation** | | |
| Shipping Activity (billion t-km) | 74.7 | 165.1 |
| GHG Emissions (Mt of $CO_2$ eq) | 27.7 | 43.1 |
| Emissions Intensity (GHG per g of $CO_2$ eq) | 370.4 | 264.7 |
| **Railway Transportation** | | |
| Shipping Activity (billion t-km) | 235.9 | 320.5 |
| GHG Emissions (Mt of $CO_2$ eq) | 6.9 | 6.5 |
| Emissions Intensity (GHG per g of $CO_2$ eq) | 29.2 | 20.2 |
| **Maritime Transportation** | | |
| Shipping Activity (billion t-km) | 53.4 | 38.7 |
| GHG Emissions (Mt of $CO_2$ eq) | 5.0 | 5.1 |
| Emissions Intensity (GHG per g of $CO_2$ eq) | 94.6 | 132.0 |

Figure 2.16 illustrates shipping activity across the three modes of freight transportation between 1990 and 2000. As seen in Figure 2.16, railway shipping activity

has increased by 36 percent since 1990, while road shipping activity has increased by 120 percent between 1990 and 2000. On the contrary, maritime activity decreased by 27 percent from 1990 to 2000. Just-in-time delivery, growing trade with the United States, and rationalisation of Canadian transportation since 1995, are primary reasons for the significant increase of road transport activity. Therefore, as seen in Figure 2.17, GHG emissions resulting from road shipping activity have increased, by 58 percent, compared to railway maritime emissions which have remained relatively the same since 1995.

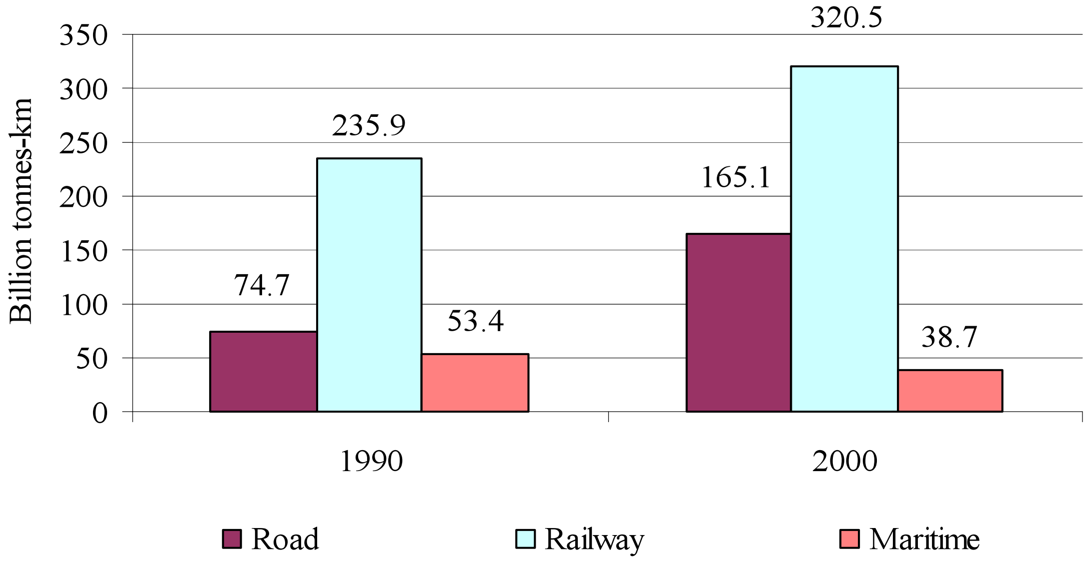

**Figure 2.16: Shipping Activity in Canada by Transport Mode in 1990-2000 (Greenhouse Gas Report; Environment Canada, 2001)**

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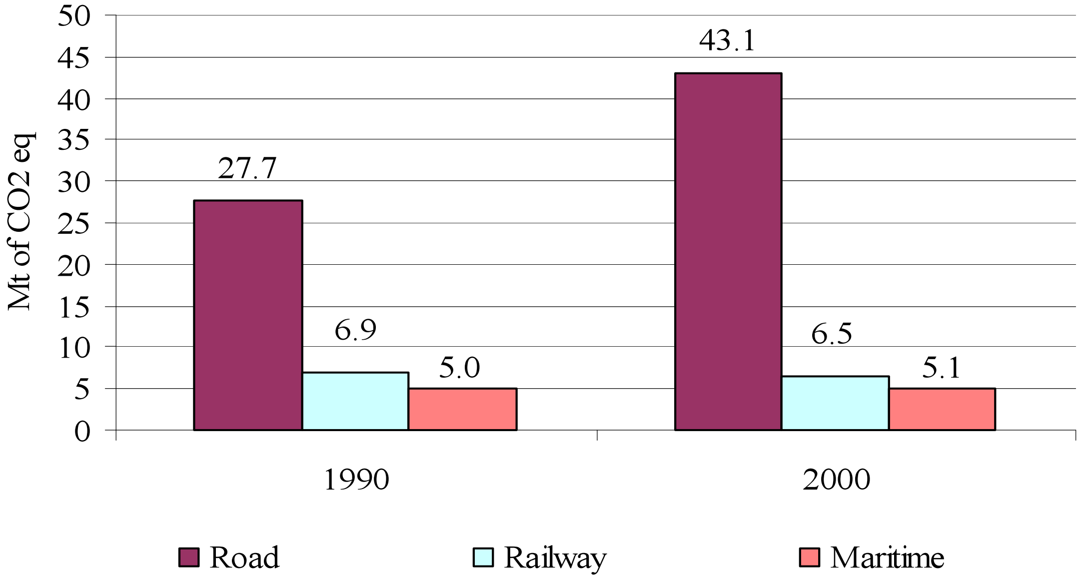

**Figure 2.17: GHG Emissions in Canada by Transport Mode in 1990-2000 (Greenhouse Gas Report; Environment Canada, 2001)**

Figure 2.18 illustrates the evolution of emissions intensity in terms of GHG per gram of $CO_2$ equivalent (GHG emissions divided by shipping activity). Thanks to technology advances in diesel engine efficiency, emissions intensity resulting from road and railway transportation has decreased between 1990 and 2000 (28.5 and 30.8 percent respectively), while emissions intensity from maritime transportation has increased, by 39.5 percent. However, in 2000 road emission intensity was still much higher relative to the railway and maritime emission intensities, due to the high amount of GHG produced (Figure 2.17) compared to the number of kilometres travelled (Figure 2.16).

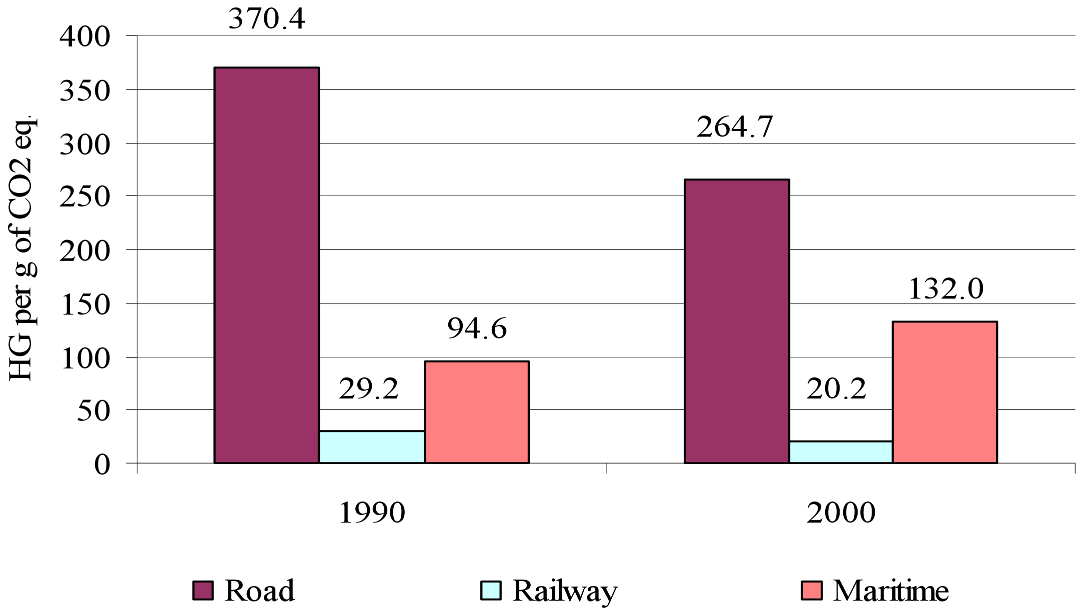

**Figure 2.18: Canada Emissions Intensity in Canada by Transport Mode In 1990-2000 (Greenhouse Gas Report; Environment Canada, 2001)**

Table 2.11, Figure 2.19, and Figure 2.20 show the spectrum of GHG emissions by vehicle type in Canada. In 2001, emissions from heavy-duty diesel vehicles contributed nearly 38 t to Canada's total GHG emissions (an increase of 54 percent since 1990 emissions). While there are difficulties in obtaining accurate and complete data for specific freight transport modes, the trends in data for trucks haulers in Canada show conclusively that freight hauling by truck increased substantially and that this activity is the primary task performed by heavy-duty diesel vehicles, which has been constantly increasing over the past two decades.

**Table 2.11: GHG Emissions from Canadian Transport, 1990-2001 in Kilo tonnes of $CO_2$ equivalent (Environment Canada, 2001)**

| | 1990 | 1995 | 2000 | 2001 |
|---|---|---|---|---|
| **Transportation (Total)** | **153,186** | **168,965** | **190,329** | **187,430** |
| **Domestic Aviation** | **10,738** | **10,860** | **13,723** | **12,121** |
| **Road Transportation** | **106,860** | **118,700** | **131,460** | **133,519** |
| Gasoline Automobile | 53,740 | 51,313 | 48,254 | 48,519 |
| Diesel Automobiles | 672 | 594 | 605 | 596 |
| Light Duty Gasoline Trucks | 21,754 | 28,489 | 37,564 | 39,426 |
| Light Duty Diesel Trucks | 591 | 416 | 645 | 643 |
| Heavy Duty Gasoline Trucks | 3,139 | 4,757 | 4,374 | 4,125 |
| Heavy duty Diesel Trucks | 24,524 | 30,815 | 38,676 | 38,606 |
| Motorcycles | 230 | 214 | 239 | 242 |
| Propane and Natural Gas | 2,210 | 2,100 | 1,104 | 1,140 |
| **Railway** | **7,111** | **6,430** | **6,668** | **6,554** |
| **Domestic Marine** | **5,049** | **4,375** | **5,107** | **5,513** |
| ***Others*** | ***23,528*** | ***28,600*** | ***33,370*** | ***29,722*** |
| Off Road | 16,528 | 16,528 | 22,094 | 19,466 |
| Pipelines | 6,900 | 12,008 | 11,276 | 10,256 |

Figure 2.19 shows that the primary contribution of GHG emissions is from the road transportation sector. In addition, road transport emissions increased by 25 percent between 1990 and 2001. This confirms the fact that, compared with all forms of transportation, road transportation remains the most significant producer of GHG emissions in Canada.

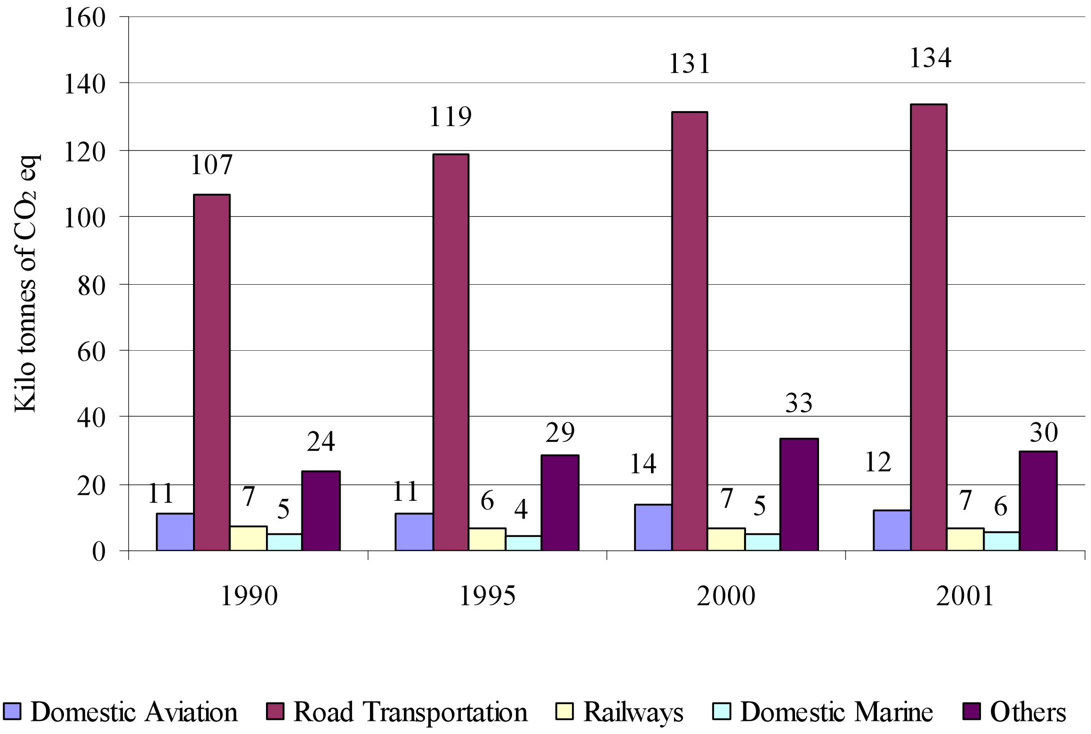

**Figure 2.19: GHG Emissions from Canadian Transport (Environment Canada, 2001)**

As seen in Figure 2.20, within each road transport mode, gasoline automobiles are the highest producer of GHG emissions (average of 50.5 percent); followed by heavy duty diesel trucks and light duty gasoline trucks (average of 33.5 and 32 percent approximately), followed by heavy duty gasoline trucks, diesel automobiles, light duty diesel trucks, motorcycles, and propane and natural gas vehicles. Gasoline automobiles showed a small decrease of 9.3 percent between 1990 and 2001. Light duty gasoline trucks and heavy duty diesel trucks showed an increase in emission by 77 percent and 56 percent, respectively, between 1990 and 2001.

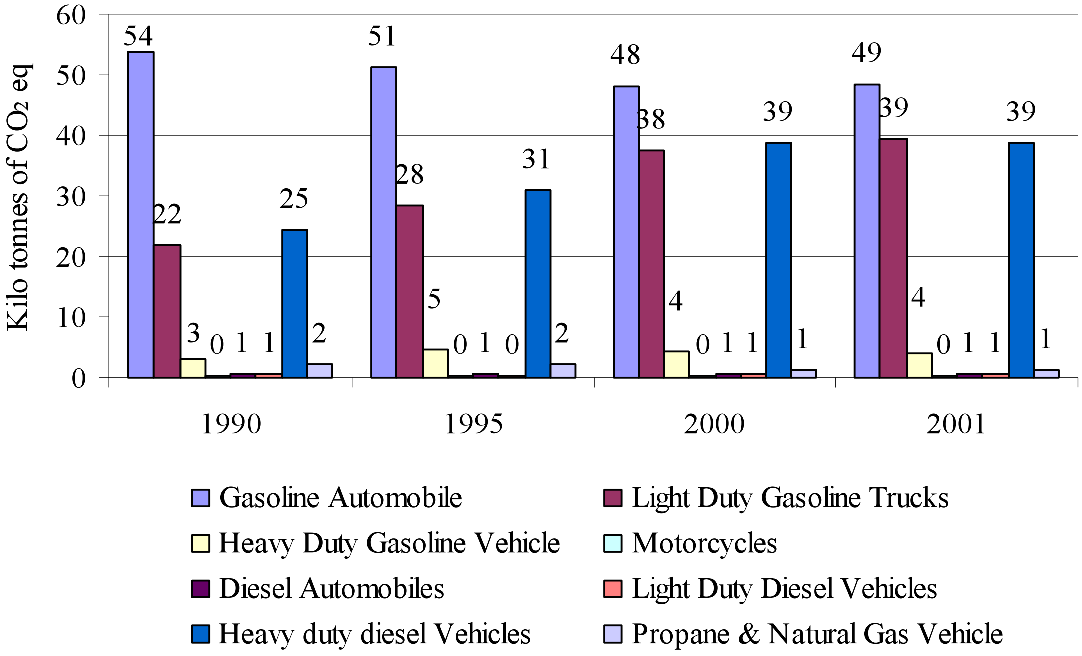

**Figure 2.20: GHG Emissions across Canadian Road Transportation Modes (Environment Canada, 2001)**

## 2.7. METHODOLOGIES FOR EVALUATING EMISSIONS QUANTITIES

Based on the literature review, four different emissions quantities calculation methods are summarized in this chapter:

- Environment Canada methodology;
- U.S. Environment Protection Agency (USEPA) MOBILE 6 model for heavy-duty engine emission factors;
- Australian life cycle analysis, and;
- UC Berkeley fuel-based inventory for heavy-duty diesel truck emissions.

### 2.7.1. Environment Canada Emissions Methodology

To estimate emissions from fuel combustion across transportation sectors, including heavy-duty diesel vehicles, the following emissions costing methodology has been adopted by Environment Canada:

*Quantity of Fuel Combusted x Emission Factor per physical unit of Fuel = Emissions*

*2*

Using Environment Canada method of calculating emissions, the appropriate quantity of each fuel combusted is multiplied by a fuel and technology-specific emissions factor, expressed in grams of pollutant per unit of fuel consumed (litre). Table 2.12 summarizes emissions factors for carbon dioxide, methane and nitrous dioxide for heavy duty diesel vehicles (Environment Canada 2000).

**Table 2.12: Combustion Emission Rate by Vehicle Emissions Control Type (Environment Canada, 2000)**

| Use | $CO_2$ | $CH_4$ | $N_2O$ |
|---|---|---|---|
| | Grams of emission per litre of fuel burned | | |
| **Advance Control** | 2730 | 0.12 | 0.08 |
| **Moderate Control** | 2730 | 0.13 | 0.08 |
| **Uncontrolled** | 2730 | 0.15 | 0.08 |

The results summarized in Table 2.12 have been calculated using parameters such as emissions factors, identical to those used by the USEPA in its MOBILE model. The level of control (advanced, moderate, or uncontrolled) is related to the degree of technology within the engine, electronics, and exhaust systems as illustrated in Figure 2.21.

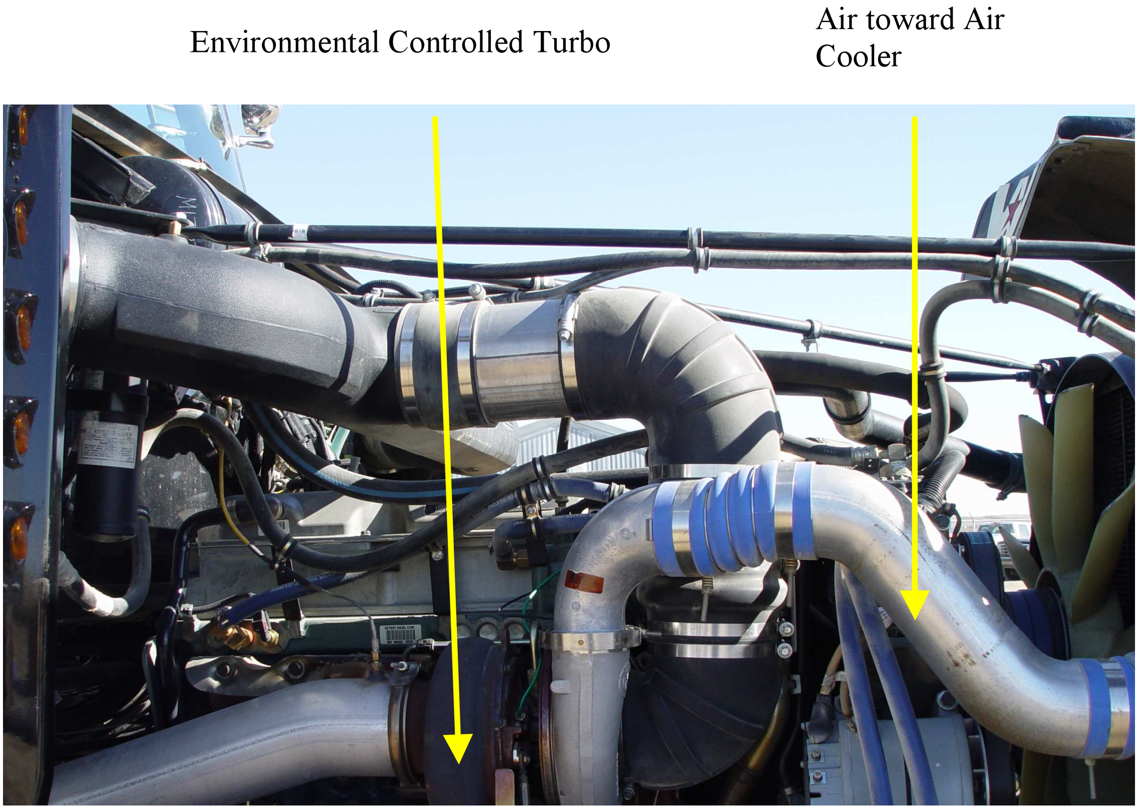

**Figure 2.21: Typical Environmental Controlled Detroit Diesel Engine from Heavy Duty Vehicle Engine (Picture in Lloyd Minster, September 2003)**

### 2.7.2. US EPA MOBILE 6: Update Heavy-Duty Engine Emission Factors

MOBILE is a computer based emissions model created by the US Environment Protection Agency (EPA) that estimates emissions rates (in grams per mile traveled) from the fleet of motor vehicles in a given community (Arbor 1998). It includes parameters, such as vehicle mix, speed, temperature, emissions control programs, that account for the mass of pollutants emitted from each class of on-road sources.

$$\text{Emission Factor (g/mi)} = \text{Work-Specific Emission Level (g/bhp-hr)} \times \text{Conversion Factor (bhp-hr/mi)} \qquad 3$$

As seen in Equation 3, the USEPA MOBILE 6 conversion factors estimate the heavy-duty engine emission factors, including diesel engines, with the updated methodology MOBILE6, to determine the emission factor by multiplying a work-specific emission level, in units of grams per brake horsepower-hour (g/bhp-hr), or grams per kilowatt-hour (g/kW-hr), by a conversion factor which converts work units into mileage units, brake horsepower-hour per mile (bhp-hr/mi).

However, since emissions standards for both gasoline and diesel vehicles are expressed in terms of grams per brake-horsepower, conversion factors in terms of brake horsepower-hour per mile (bhp-hr/mi) were used to convert the emissions certification data from engine testing to in-use grams per mile. The conversion factors used in MOBILE6 are calculated from the following expression where BSFC is brake-specific fuel consumption:

*Conversion factor (bhp-hf/mi) = Fuel density (pounds/gallon) / BSCF (lb/bhp-hr) x*
*Fuel economy (mi/gal) 4*

The Environment Protection Agency defines heavy-duty vehicles as those vehicles exceeding 8,500 pounds (3,800 kilograms) gross vehicle weight. Heavy-duty diesel vehicles are divided into 8 categories, as summarized in the following Table 2.13.

**Table 2.13: Environment Protection Agency Heavy Vehicle by Weight Classes (EPA, 1999)**

| Heavy –Duty Diesel Vehicles | Description | Gross Vehicle Weight (lb) |
|---|---|---|
| Class 2B | Light-heavy duty diesel truck | 8,501 – 10,000 |
| Class 3 | Light-heavy duty diesel truck | 10,001 – 14,000 |
| Class 4 | Light-heavy duty diesel truck | 14,001 – 16,000 |
| Class 5 | Light-heavy duty diesel truck | 16,001 – 19,500 |
| Class 6 | Medium heavy-duty truck | 19,501 – 26,000 |
| Class 7 | Medium heavy-duty truck | 26,001 – 33,000 |
| Class 8A | Heavy heavy-duty truck | 33,001 – 60,000 |
| Class 8B | Heavy heavy-duty truck | More than 60,000 |

To calculate the average brake specific fuel consumption (BSFC) for each vehicle class summarized in Table 2.13, data engine specific BSFC were requested from engine manufacturers, based upon the engine horsepower, engine specifications, and engineering knowledge of the various engine families. Engine family data for different years were obtained from USEPA and used to weight the BSFC. Sales data are first categorized into weight classes using manufacturers' suggestions, engine horsepower, and actual vehicle populations for each model. Engine family BSFC were then weighted by sales fractions in each category listed in Table 2.13.

Fuel economy was calculated using the 1992 Truck Inventory and Use Survey (TIUS) Micro data. Details of those calculations are concentrated in the report *Update of Heavy-Duty Engine Emission Conversion Factors—Analysis of Fuel Economy, Non-Engine Fuel Economy Improvements and Fuel Densities, March 1998, from L. Browning*. As for fuel densities, they are determined from National Institute for Petroleum and Energy Research (NIPER) publications for both gasoline and diesel.

When the data for fuel economy and fuel densities are calculated, the engine conversion factor can be estimated. Once the engine conversion factor is known, emissions levels can be calculated removing the engine from the test vehicle's chassis (frame), mounting it on a test stand, and operating the engine on a testing apparatus known as an engine dynamometer. Emission levels produced on the engine dynamometer are then measured in grams per brake-horsepower-hour (g/bhp-hr) (Arbor 1998).

In response to the need to further reduce air pollution at the national level, the EPA is finalizing a new set of combined emission standards for nitrogen oxides (NOx) and non-methane hydrocarbons (NMHC), hereafter referred to as HC from heavy duty engines. Table 2.14, Table 2.15, and Table 2.16 summarize the emissions standards for heavy-duty diesel vehicles respectively since the mid-1980s, including the proposed new standards, in the USA, European Union and Australia (Worldwide diesel emissions standards 2002).

Table 2.14 and Figure 2.22 summarized emissions standards for the United States. Diesel engines produce high quantities of CO and NOx, compared to HC and PM. Moreover, between 1985 and 2004, CO and HC emissions standards barely decreased in emissions unit rate when NOx and PM emissions standards decreased by approximately 76.6 percent and 83.3 percent, respectively. These significant changes might be due to the fact that NOx and PM emissions have a more critical impact on the human health, with higher damage costs (average of $17,433/Mt and $241,184/Mt respectively), compare to CO and HC emissions (average of $127/Mt and $928/Mt respectively).

**Table 2.14 EPA Emission Standards for Heavy-Duty Diesel Engine operating in USA (EPA, 1999)**

| Model year | Pollutant (grams/brake horsepower-hour) | | | |
|---|---|---|---|---|
| | Hydrocarbons (HC) | Carbon Monoxide (CO) | Nitrogen Oxides (NOx) | Particulates Matter (PM) |
| 1985-1987 | 1.3 | 15.5 | 10.7 | None |
| 1988-1989 | 1.3 | 15.5 | 10.7 | 0.60 |
| 1990 | 1.3 | 15.5 | 6.0 | 0.60 |
| 1991-1992 | 1.3 | 15.5 | 5.0 | 0.25 |
| 1993 | 1.3 | 15.5 | 5.0 | 0.25 |
| 1994-1995 | 1.3 | 15.5 | 5.0 | 0.1 |
| 1996-1997 | 1.3 | 15.5 | 5.0 | 0.1 |
| 1998-2003 | 1.3 | 15.5 | 4.0 | 0.1 |
| 2004 | 2.5 (HC +NOx) | 15.5 | 2.5 (HC +NOx) | 0.1 |

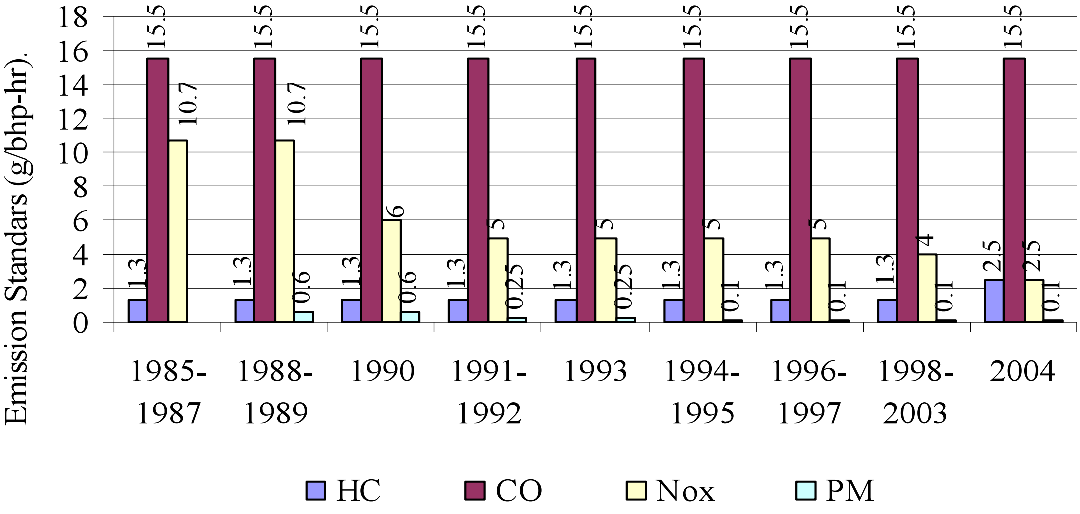

**Figure 2.22: EPA Emission Standards for Heavy Duty Diesel Engines by Emission Type (EPA, 1999)**

As well, to compare with the US data, Table 2.15 and Figure 2.23 show that, among European emissions standards, there is a relative order of magnitude of emissions across the emissions types, for the same reasons as the US. However, all European emissions standards decrease in the 1992-2008 time period, by 66.6 percent for CO emissions, 58.2 percent for HC, 75 percent for NOx, and 27.6 percent for PM. The Australian emissions standards are summarized in Table 2.16, based on a combination of the US and the European Union standards.

**Table 2.15: Emission Standards for Heavy-Duty Diesel Engine in European Union (EPA, 1999)**

| Emissions Standards | Dates and Category | CO (g/kW) | HC (g/kW) | NOx (g/kW) | PM (g/kW) |
|---|---|---|---|---|---|
| Euro I | 1992, under 85 kW | 4.5 | 1.10 | 8.0 | 0.61 |
| | 1992, more than 85 kW | 4.5 | 1.10 | 8.0 | 0.36 |
| Euro II | 1996 | 4.0 | 1.10 | 7.0 | 0.25 |
| | 1998 | 4.0 | 1.10 | 7.0 | 0.15 |
| Euro III | 1999 | 1.5 | 0.25 | 2.0 | 0.02 |
| | 2000 | 2.1 | 0.66 | 5.0 | 0.10 |
| Euro IV | 2005 | 1.5 | 0.46 | 3.5 | 0.02 |
| EuroV | 2008 | 1.5 | 0.46 | 2.0 | 0.02 |

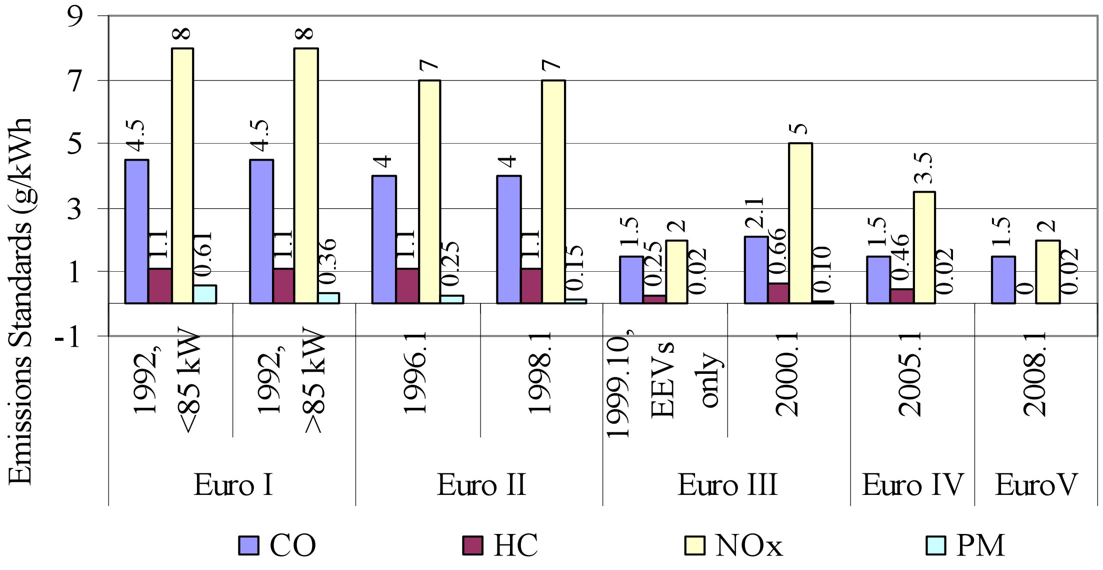

**Figure 2.23: Emission Standards for Heavy-Duty Diesel Engines in European Union (EPA, 1999)**

**Table 2.16: Australia Emission Standards for Truck Emissions (EPA, 1999)**

| ADR Categories | | | 2002/3 Diesel | 2003/4 Petrol | 2004/5 Petrol | 2006/7 Diesel |
|---|---|---|---|---|---|---|
| **Vehicle Description** | **GVM[1]** | **Category** | | | | |
| Light | ≤3.5t | NA | Euro 2 | Euro 2 | Euro 3 | Euro 4 |
| Medium | 3.5≤ 12t | NB | Euro3 or US 98**a** | US 96 | US 98**a** | Euro 4 or US 2004 |
| Heavy | More than 12t | NC | Euro3 or US 98**a** | | | Euro 4 or US 2004 |

[1] Gross Vehicle Mass

**a** – US EPA model year 2000 and later certificate or equivalent testing required (to ensure that no emissions defeat devices are used).

### 2.7.3. Australian Emissions Calculation Method: Life Cycle Analysis

The emissions of most interest in relation to Australian diesel powered vehicles are NOx, HC, and PM. NOx are a precursor to the formation of photochemical smog. There is also evidence that NOx reacts with other pollutants to form particles (Beer et al. 2000).

In a report published by the Australian Greenhouse Office in March 2000, a life cycle analysis has been applied to the emissions from the use of different transport fuels, both combustion and evaporative emissions being included, as well as the full life cycle of the fuel (pre-combustion and fossil combustion). However, this thesis research considered only direct emissions from vehicles (tailpipe emissions).

The first step of this analysis estimated the GHG and air quality emissions from each fuel expressed as the mass of emissions per unit of energy –kilograms/mega joules. In fact, the quantity of pollutants emitted by a vehicle depends not only on its mass, but also on operating field state conditions, fuel type (gasoline, diesel, alcohol, etc.), fuel formulation (oxygenated gasoline, low sulphur diesel), engine type and age, pollution control devices, driver behaviour, and level of maintenance. The fuel combustion is also estimated, characterizing the fuel in terms of its energy per unit of volume in units of mega joules/litre, as well as the performance characterizing the fuel in terms of the per-kilometre emissions. The Australian Greenhouse Office method examines the units associated with the quantities:

*(grams/kilometre) = (grams/mega joule) x (mega joules/kilogram) x (kilograms/litre) x (litres/kilometre)* *5*

The first term (grams/kilometre) is the performance measure of emissions per distance travelled. Emissions per distance traveled are determined by the product of engine emissions (grams/mega joules), the fuel combustion characteristics (mega joules/kilograms), the fuel density (kilograms/litre) and the vehicle fuel economy (litres/kilometre). Fuel is presented in terms of emissions per tonne-km in the case of trucks. There are also some generalizations concerning the emissions from diesel vehicles resulting from different fuels (Beer et al. 2000). These include: the less volatile and more aromatic the fuel, the higher the exhaust particles emissions; oxygenated fuel produces fewer particles due to more complete combustion, providing that other fuel-related qualities, e.g. cetane number, remain constant; and significant evaporative emissions may result from use of volatile fuels such as liquefied petroleum gas (LPG) or ethanol.

The Australian Greenhouse Office uses a $CO_2$ emissions factor of 69.7 grams/mega joule for diesel fuel (of energy density 38.6 mega joule/litre) through Workbook 3.1 on Transport of the Australian Greenhouse Inventory methodology (National Greenhouse Gas Inventory Committee 2000), whereas, for other emissions, the default emission factors are given in g/km in Table 2.17and Figure 2.24. As seen on Figure 2.24, heavy diesel trucks produce the highest amount of NOx, which is due to their combustion type.

**Table 2.17: Emissions Rates across Diesel Vehicle Type and Emission Type (National Greenhouse Gas Inventory Committee; Australia, 2000)**

| Vehicle | $CH_4$ (g/km) | $N_2O$ (g/km) | NOx (g/km) | CO (g/km) | NMVOC (g/km) |
|---|---|---|---|---|---|
| Light trucks | 0.01 | 0.014 | 1.18 | 1.11 | 0.53 |
| Medium trucks | 0.02 | 0.017 | 3.1 | 1.82 | 0.99 |
| Heavy trucks | 0.07 | 0.025 | 15.29 | 7.86 | 3.78 |
| Buses | 0.03 | 0.025 | 4.9 | 2.88 | 1.56 |

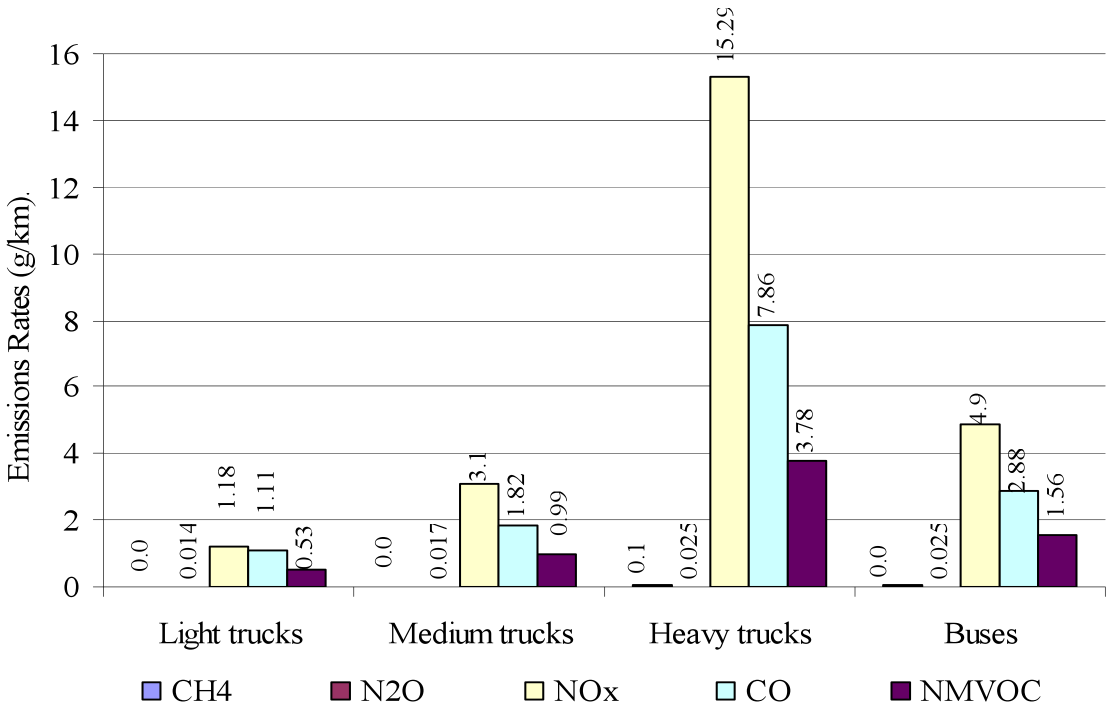

**Figure 2.24: Australian Emissions Rates across Vehicle Type and Emission Type (National Greenhouse Gas Inventory Committee; Australia, 2000)**

### 2.7.4. UC Berkeley Fuel-Based Inventory for Heavy-Duty Diesel Trucks Emissions

A fuel-based method for estimating heavy-duty diesel truck emissions has been described by the department of Civil Engineering of Berkeley, University of California (Dreher and Harley 1998). The vehicle emissions rates were measured by the amount of diesel fuel consumed, within the San Francisco Bay Area during summer 1996. Heavy-duty diesel trucks (i.e., diesel powered trucks with gross weight exceeding 3,860 kg) were found to be a primary source of particulate matter (PM) and nitrogen oxide (NOx) emissions. Motor vehicle emissions are currently estimated using the travel-based MOBILE emissions factors model developed in the U.S Department of the Environment. In this approach, estimates of vehicle travel have been combined with emissions factors expressed on a mass per unit distance travel basis to obtain a motor vehicle emission inventory.

Traditionally, vehicle activity has been estimated using travel demand models. Spatial and temporal vehicle activity has been predicted using socioeconomic data such as population, employment, automobile ownership, and income, combined with knowledge of travel time between points, available modes of transportation, and a description of the roadway network. Heavy-duty vehicle travel represents only a small fraction of total vehicle travel, so little effort has been made to describe truck travel explicitly within travel demand models. Heavy vehicles also do not follow the same spatial and temporal patterns as light-duty vehicle travel.

Alternative measurements of vehicle kilometres of travel (VKT) for trucks may be used to estimate truck activity. However, truck VKT may be used in conjunction with state-wide fuel sales to estimate total heavy-duty truck activity, using the amount of fuel consumed as a measure of activity. Accurate diesel fuel sales data are available at the state level, and truck VKT is reported at the county level. Heavy-duty diesel truck emissions are regulated per unit of brake work output by the engine. A potentially large source of uncertainty in using MOBILE model to estimate heavy-duty truck emissions is needed to convert from gram per brake horse power hour units (as measured in the laboratory during engine dynamometer tests) to mass emission rates per unit distance traveled. Since heavy-duty trucks encompass a wide range of diesel engine sizes and gross vehicle weights, emissions factors normalized to work output vary less than they would on a distance traveled basis. Furthermore, performance maps for heavy-duty diesel engines indicate that brake-specific fuel consumption (BSFC) varies only from

220 to 260 g/kW-h for this engine. Therefore, work output by the engine can be directly related to fuel input, and heavy-duty diesel engines are effectively regulated and designed to meet emission targets on a per unit of fuel burned basis.

A fuel-based emission inventory for heavy-duty diesel trucks combines vehicle data (volume of diesel fuel consumed) with emissions factors normalized to fuel consumption (mass of pollutant emitted per unit volume of fuel burned) to estimate emissions within a region of interest.

At the state level, precise fuel consumption data are available through tax records. Spatial and temporal use of diesel fuel was estimated using the following equation:

$$A_{i,j,k,l} = (D/365)\, f v_i\, mj\, dk\, h_{k,l} \qquad 6$$

Where $A_{i,j,k,l}$ is the amount of fuel burned in air area $i$ during month $j$, day of week $k$, and hour $l$; $D$ is the annual state-wide volume of diesel fuel used by on-road vehicles; f is the fraction of on-road diesel fuel used for heavy-duty trucks; $v_i$ is the fraction of state-wide fuel use in air basin $i$; $mj$ is the ratio of daily fuel sales in month $j$ to annual average daily sales; $dk$ is the ratio of fuel used on day $k$ to the average weekly value; and $h_{k,l}$ is the fraction of total fuel used on day $k$ that occurs during hour $l$. Methods for estimating the parameters described in equation 6 are explained below.

In the UC Berkeley model, emissions factors obtained from engine dynamometer tests are reported in grams of pollutant emitted per unit of brake work performed by the engine. These emissions factors can be normalized to fuel consumption as follows:

$$EIp = Sp/BSFC \qquad 7$$

Where $EIp$ is the emission index for specified pollutant $p$, in units of mass of pollutant emitted per unit mass of fuel burned; $Sp$ is the brake specific pollutant emission factor obtained from the dynamometer test, expressed in g/kW-h units; and

*BSCF* is the brake-specific brake consumption of the engine being tested, also in g/kW-h. Emissions factors for heavy-duty diesel trucks also can be calculated from measurements of exhaust pollutant concentrations. Heavy-duty diesel trucks emit only small amounts of hydrocarbons. Therefore, by carbon balance, the mass of diesel fuel burned can be determined directly from exhaust emissions of $CO_2$ and CO. An emission index *EIp* for pollutant *p* can be calculated using:

$$EIp = \Delta(P)/\left(\Delta(CO_2) + \Delta(CO)\ w_c\right. \qquad 8$$

Where $\Delta(P)$ is the exhaust concentration of pollutant $P$ corrected for background levels and expressed in $\mu mm^{-3}$; $\Delta(CO_2)$ and $\Delta(CO)$ are the exhaust concentration of $CO_2$ and CO less background, expressed in $\mu m\ C\ m^{-3}$; and $w_c$ is the weight fraction of carbon in diesel fuel. Exhaust PM and NOx emissions are estimated by multiplying vehicle activity, as measured by the volume of fuel used, by emission factors expressed per unit volume of fuel burned.

With the UC Berkeley approach, heavy-duty diesel trucks of the San Francisco Bay Area have been estimated at the upper bound to emit $110 \times 10^3$ kg/day of NOx, and $3.7 \times 10^3$ kg/day of fine particles on weekdays. Emissions were observed to decline by 70-80 percent on weekends. This fuel-based method provides a useful, independent check on traditional travel-based emissions inventory models.

## 2.8. ROAD TRANSPORT HOLISTIC FINANCIAL VALUATION

Finances related to transportation costs can be categorized in three main categories:

- User;
- Agency, and;
- Social / Environmental.

Road users and agency costs and benefits have commonly been quantified in transportation activities (Bein 1997). Societal costs and benefits, such as environmental costs and benefits, have usually been judged too negligible to be quantified. However, over recent years and with the introduction of the Kyoto Protocol, societal costs and benefits are being integrated in road asset management decisions. From a holistic social perspective, any reduction in cost can be deemed as a benefit to society, due to the inherent nature for market pricing adjustments to take place.

### 2.8.1. Agency Costs

Road agency costs are those costs directly related to the capital, preservation and operation of the infrastructure. Road agency costs include:

- Roadway land value that represents the amount of land devoted to road transport infrastructure;
- Roadway capital and operations costs, including infrastructure construction, maintenance, preservation, operating, materials supply resources, and;
- Traffic operations costs that are law enforcement, emergency services, lightings, *et cetera.*

### 2.8.2. Road User Costs

Road user costs are those costs directly incurred by road users. Road user costs include:

- Vehicle operating costs (purchase, insurance, fuel, taxes, tolls, tires, maintenance, parking fees);
- Travel time costs, and;
- Safety and health costs, including crash damages, personal security, and public health.

### 2.8.3. Societal and Environmental Costs

Societal costs are those costs directly related to transport activities but incurred by society. Many transport social costs are called non-monetary, including accidents, social impacts and environmental degradations. Even if it is difficult to estimate these costs, they exist and, even using the lowest reasonable cost-estimates, they are significant, but often under priced. Environmental impacts, and particularly air pollution costs, are very difficult to quantify and tend to be described as intangibles, including:

- Air pollution and greenhouse gas emissions, affecting people and nature health;
- Noise, measured by sounds and vibrations;
- Natural resources consumption, such as petroleum consumption;
- Land use impact, referring to effects of transportation activities and facilities on land use patterns, as well as transport infrastructure materials supply such as gravel pits and quarries;
- Water pollution, involving surface changes and groundwater flows;
- Waste disposal, concerning harmful abandoned vehicles and materials, and;
- Safety to society as a whole.

### 2.8.4. Definition of Costs Categories

Cost may involve money, time, land, or loss of an opportunity to enjoy a benefit. In the case of air pollution and therefore, gas emissions, costs can be translated into harmful to health, or quantity of fuel consumed. Considering the relation between costs and benefits, these tend to be a mirror image relationship. For instance, some costs are reduction of benefits and benefits are reduction of costs (Bein 1997).

As summarized in Section 1.0, air pollution emissions are external, variable, non-market, and may be direct or indirect. An externality is an effect that impacts third parties without compensation or invitation. External costs represent a failure of the market to capture all costs (including non-monetary costs) of production and consumption. Transportation externalities are produced directly by road construction, maintenance and use of road materials, and indirectly during the production and disposal of fuel, vehicles, road materials and machinery. These impacts that are embodied in the direct and indirect activities include the use of energy and resources, and the production of pollution. Non-market costs are costs involving goods that are not directly bought and sold, such as aesthetics, health, and comfort. Because non-market goods and services don't usually have market transactions in which one could see the price the market puts on them, non-market monetized values are also termed shadow prices.

Although uncertain, low estimates of indirect and non-market costs such as air pollution can lead to increased social and environmental damages. For instance, low estimates of pollution costs reduce the justification for control measures, resulting in more emissions. If cost categories are excluded from quantitative analysis, they can be described qualitatively; however, the risks of these qualitative measures are often left out of the final analysis used in decisions.

### 2.8.5. Quantification Techniques for Valuing Emissions

Techniques used to monetize environmental costs such as air pollution, to enable them to be reported in financial statements, are based on the level of damage they produce. Two techniques typically used for evaluating air pollution costs are:

- *Damage cost valuation*, which involves estimating the actual value of the harm caused by air polluting emissions, and;

- *Control cost valuation,* which simply examines the cost of the measure necessary to reduce the effect of pollutant emissions.

### 2.8.6. Damage Cost Emissions Valuation

To estimate the costs of pollutants in terms of emissions, it is important to know the emissions rates of a truck according to its size, mass, engine power, type of fuel used, distances traveled, speed, *etc*. The emissions factors can be expressed in several different units, i.e. grams of pollutant per unit of fuel consumed (grams/litre), grams per unit of distance traveled (grams/kilometre or grams/vehicle-kilometre), or grams per mega joule (grams/MJ) which is the energy consumed. Once the emissions factors have been identified, each pollutant has to be valued, i.e. an emissions unit cost must be given, in terms of $/km or $/kg (or tonne) of pollutant emitted.

Air emissions are one of the most often cited external costs of road transport. Although tailpipe emissions rates measured by standard tests have decreased significantly, actual reductions are believed to be smaller. Researchers estimate that actual CO and HC emissions are four to five times higher, and NOx emissions are about twice as high as tailpipe tests standards indicate (Bein 1997). In addition, increased vehicle travel has offset much of the reduction in emissions rates realized by recent technological developments. As a result, vehicle emissions continue to be a major environment problem. In addition, vehicle tire and brake lining wear produce about the same quantity of small particulates as tailpipe emissions, and road dust produces even more.

Emission damage costs refer to damage caused by motor vehicle emissions, specifically human health, environmental damage, and avoidance action, resulting from various air emissions. They often are costs imposed on society per tonne of gas emitted. Values ($/tonne) can be derived by identifying groups in society who are at risk, estimating the response of these groups to certain levels of air pollution, estimating the values of these responses using data, such as medical expenses. For instance, the cost of each pollutant can be based on reported willingness to pay to avoid the negative consequences (health effects, degraded environment, etc.), or willingness to accept compensation for the damage caused (Fanhauser 1995). It can be calculated via a dose-response model where human mortality is a function of air pollution, these values having to be used in caution .

### 2.8.7. Emission Unit Cost Estimates

Quantifying air pollution costs requires information about vehicle emissions rates, the impacts these pollutants have on human mortality, morbidity, crop damage, wildlife, aesthetic and climate, and placing values on these impacts. Indeed, agencies worldwide have diverse costing methods to describe the harmful effects that each pollutant has on human health and the environment itself; they use shadow prices, human health costs of motor vehicle air pollution, as well as the monetization of the energy production external costs (Bein 1997).

Table A-2 from Appendix A illustrates emission unit cost estimates assembled from some chosen global agency sources. The range of emission costs varies considerably according to the country of the analysis performed, the type of emission, and the costs, which are expressed in this research in CAD$ per tonne. In order to reflect as precisely as possible the values of year 2004 , an inflation rate of two percent has therefore been assumed and used to convert all data in 2004 CAD$. Figure 2.25 to Figure 2.29 display the unit emission cost low and high values from the agencies worldwide by emission type, plus the calculated overall average.

It is crucial to remember that the values shown in Figure 2.25 to Figure 2.29 represent only one part of the total worldwide research made on the subject, the objective in this thesis being to find data available in terms of cost per mass of emission. Moreover, the air pollution and climate change impacts in terms of monetary quantifications were not easy to find and they had to be assumed most of the time

Therefore, according to Fankauser, Nordhaus (1991) is supposed to be the pioneer in providing an estimate of pollution damage, especially from GHG emissions, in economic costs. However it seems that he only included agriculture and sea level rise factors in his analyses. Improvement of these estimates came with Cline and Titus (1992). Based on Nordhaus model, Cline provided an updated alternative including some features in the cost estimates, such as no regret option and risk aversion, and by using a another discount rate. The disount rate might be one of the main causes of such diversity within the sources value.

However, these three authors concentrated their studies only on the United States, whereas Fanhauser (1995) analysed the effects of climate change on six different regions, including the United States, the European Union, China, the countries of the ex USSR, the OECD nations, and the world as a whole.

Regarding the TBP TCRP Report 78 (2002), were used 1991 US$ data from Delucchi and based on health visibility and crops damage from all motor-vehicles direct emissions, in all areas of the US. The values of Delucchi were then summarized and simplified in this report, the revised value roughly approximating the low and high costs of emissions. Delucchi has then improved his own data (TCRP 2002).

Pratt values (2002) were not finalized, as she explained in her analysis, and some further refinements were expected. She considered herself her analysis as a starting point of view for integrating transportation related environmental externalities. As well, because of the lack of research and data developed on emissions costs estimates in Australia, she used overseas studies, from the EU and the US, where the local conditions are different from her country. Therefore she considered the determination of the emissions costs in her analysis very uncertain, with some inconsistencies.

Another approach is this from the European Commission ExternE (1998), which monetizes the average energy production external costs for fourteen European countries. Then Heaney (1999) estimates air pollution unit costs in rural Ireland.

All this collection of analyses show that quantifying emissions in monetary terms is very difficult, and vary according to the features involved in the estimates, the country, or the discount rate used. The analyses can be considered as neither accurate or complete, and considerable error can be expected (Fankauser 1995). That's why economic valuation of non market goods such as air pollution is very controversial. However, using this data was crucial in this research in order to demonstrate the importance of the emissions impacts on the environment and human health.

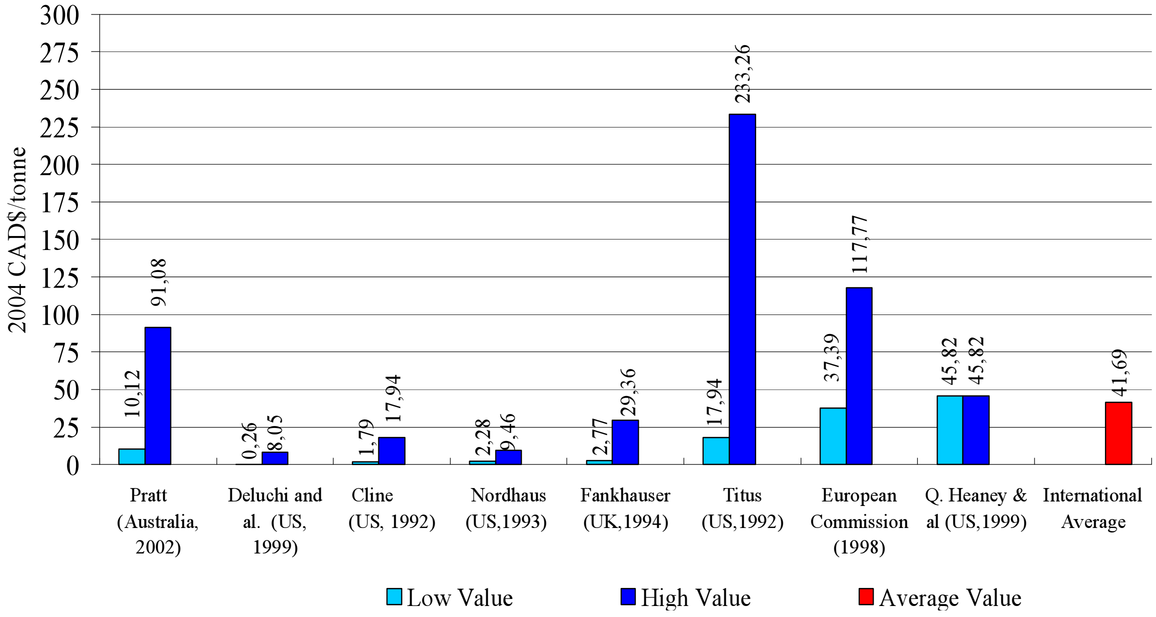

**Figure 2.25: Published $CO_2$ Unit Emission Costs from Agencies Worldwide**

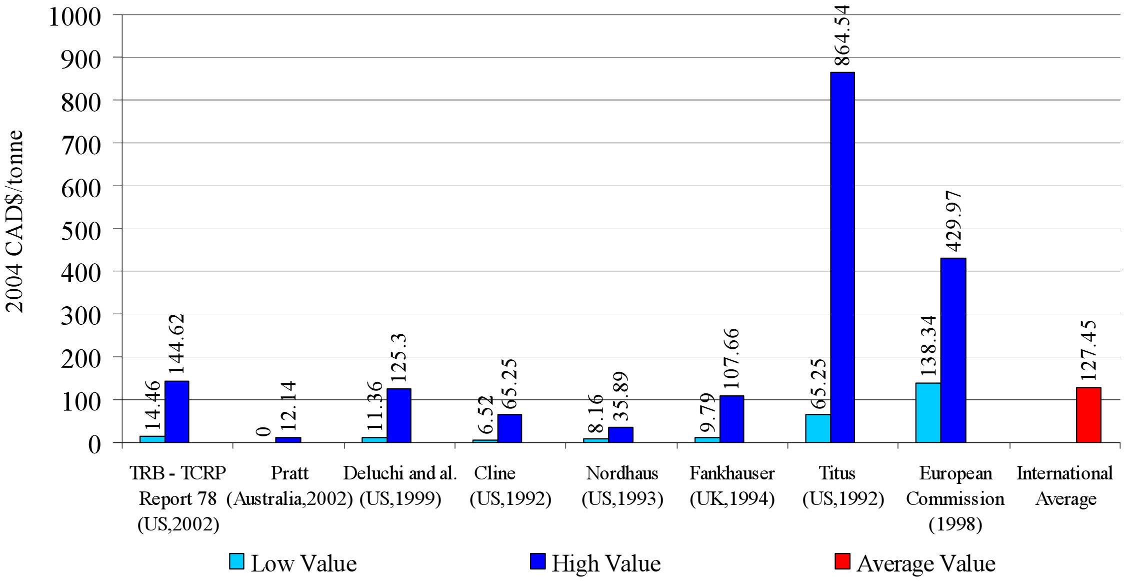

**Figure 2.26: Published CO Unit Emission Costs from Agencies Worldwide**

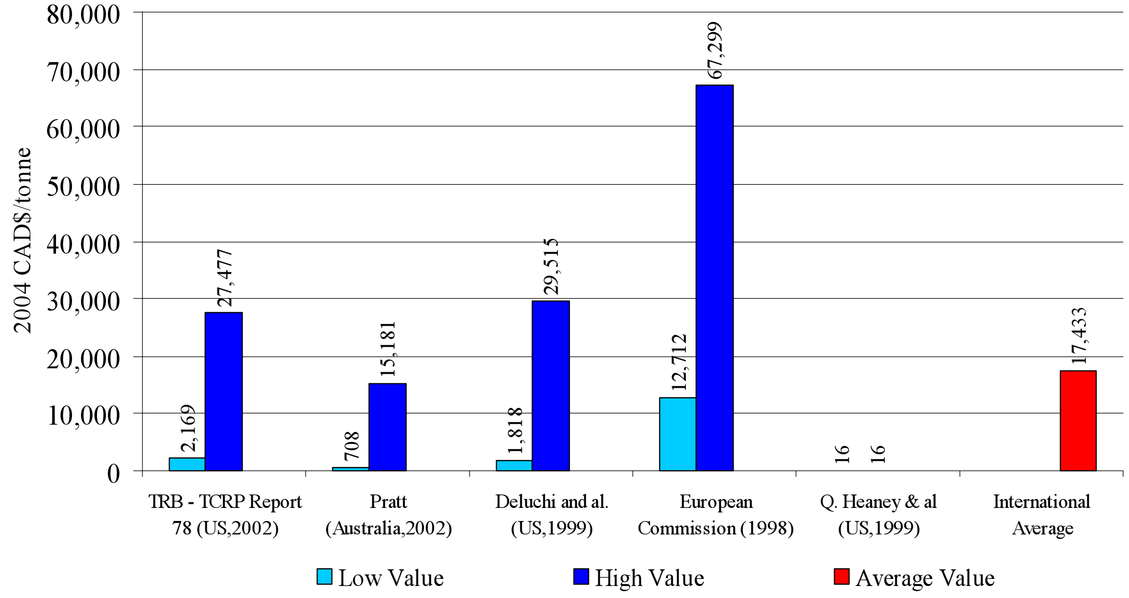

**Figure 2.27: Published NOx Unit Emission Costs from Agencies Worldwide**

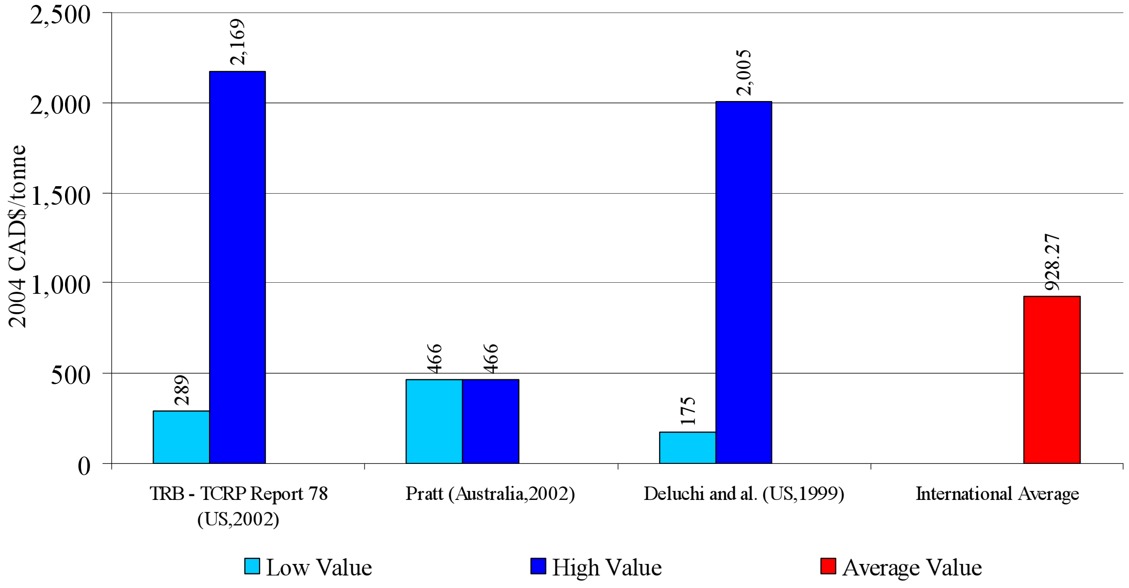

**Figure 2.28: Published HC Unit Emission Costs from Agencies Worldwide**

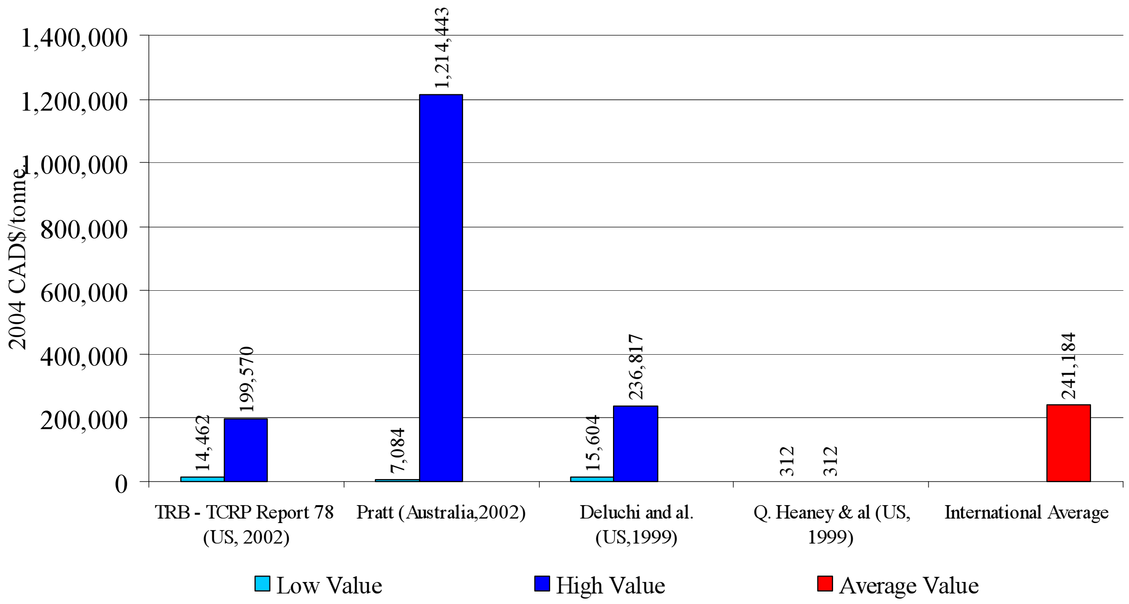

**Figure 2.29: Published PM Unit Emission Costs from Agencies Worldwide**

The lowest value, the highest value, and the calculated average of each emission published results have been summarized in Chapter 3.0. They were used in this thesis as the model assumptions.

In summary, on 16 December 2002, Canada was the 99th country to ratify the Kyoto Protocol in order to reduce total greenhouse gas (GHG) emissions to fifteen percent below 1990 levels within the time frame of 2008-2012. Transportation emissions are particularly concerned by these Kyoto targets.

Indeed, in 2001, transportation accounted for approximately 26 percent of GHG generated in Canada, 71 percent of this amount is due to road transportation, and 32 percent of the 71 percent is associated with heavy diesel trucks. Between 1990 and 2000, road transport activity has more than doubled, while railway shipping and maritime activity have remained stable. Just-in-time delivery, growing trade with the United States, and rationalisation of Canadian transportation since 1995, are primary reasons for the significant increase of road transport activity and the overall number of km travelled, especially by heavy diesel trucks.

Moreover, in 2000, road emissions intensity was still higher relative to the railway and maritime emission intensities, due to the high amount of GHG produced compared to the number of kilometres travelled. The primary reason for this includes the overall increased t-km traveled by trucks over the past two decades, and the growing number of internal combustion engines used by diesel trucks, suspected of causing significant air pollution and global climate changes.

However, over the past decade, technologies in commercial vehicle engine and chassis designs have improved fuel efficiency and have reduced emissions by 80 percent since the 1970’s. One of the reasons for the improved efficiency is that most domestic freight is transported by trucks with six axles or more: an eight-axle B-train operating at 62,500 kilograms uses 36 percent less fuel hauled per t-km than does a five-axle semi-trailer operating at 31,000 kilograms gross vehicle weight. Therefore, in order to reduce the emissions and make the Canadian transportation strategies become sustainable to meet the Kyoto targets, increasing the size and weights of trucks to reduce the number of kilometres travelled, and thus, the amount of fuel used, should be seriously considered.

Although Kyoto Protocol focuses only on greenhouse gas emission, such as carbon dioxide ($CO_2$), heavy diesel vehicles produce other emissions that seriously harm human health: carbon oxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and particulate matter (PM). Damage resulting from these emissions are divided in three categories: air pollution damage for CO, NOx and HC, fine particle damage for PM, and global warming for $CO_2$.

The heavy diesel truck emissions volumes are impacted by different characteristics that influence the diesel engine’s combustion efficiency. The air-fuel ratio has a significant effect on the decreasing emission rate of HC and PM in the combustion chamber, while the rate of air-fuel mixing increases NOx emissions; PM emissions decrease. Fuel injection and combustion timing effects tend to increase $NO_x$ emissions. On the other hand, earlier injection tends to reduce PM and light-load truck HC emissions. As well, emission volumes vary with the activity type and the vehicle performance. They include fuel type; vehicle configuration, weights and dimensions; field operations; vehicle engine and drive train characteristics; road roughness; road stiffness; vehicle rolling resistance; and idling emissions.

To understand how emissions volumes can be calculated, four different emissions quantities calculation methods have been studied in this chapter: the Environment Canada methodology, which uses an emission factor for its calculations; the U.S. Environment Protection Agency (USEPA) MOBILE 6 model, based on an conversion emission factor; the Australian life cycle analysis, using a simple equation to determine the performance measure of emissions per distance travelled ; and the UC Berkeley fuel-based inventory for heavy-duty diesel truck emissions, using official fuel consumption data. The Australian life cycle analysis was chosen in this research to help quantify the emissions.

Finally, costs involved by air pollution emissions can be translated into harmful health, or quantity of fuel consumed, and are considered external, variable, non-market, and may be direct or indirect. In order to enable the emissions costs to be reported in financial statements, two techniques are typically used for evaluating air pollution costs. There are damage cost valuation, which involves estimating the actual value of the harm caused by air polluting emissions; and control cost valuation, examining the cost of the measure necessary to reduce the effect of pollutant emissions.

Agencies worldwide have diverse costing methods to describe the harmful effects that each pollutant has on human health and the environment itself, as presented at the end of this section. All these data have to be used with caution because of their diversity and their different degree of accuracy. They will be further used to be compared with the model results.

# 3.0 EMISSIONS MODEL FORMULATION

## 3.1. INTRODUCTION

Road transportation costs and benefits can be categorized by road users, road agencies, and society. Road user and agency costs and benefits have been commonly quantified in transportation economical evaluation activities. Many societal costs and benefits such as environmental costs have usually been judged too complex or indirect and less important to quantify. However, over recent years, road managers are beginning to include societal factors into their road asset management decisions.

Canadian transport activities significantly influence the use of natural resources, generate approximately 25 percent of all national pollution, and generate significant solid waste. For these reasons, world transportation became aware of the importance of reducing environmental costs in order to protect and sustain the environment. The reduction of greenhouse gas emissions and pollution is a way to reduce environmental costs. As well, improved transport efficiency will prevent and mitigate environmental damage from transportation activities, and provide a more environmentally sustainable transportation system.

This project aims to quantify environmental costs and benefits due to the changes in various commercial vehicle operation policies. An environmental benefit model was developed in this research. The model was used to evaluate the installation of weigh-in motion systems in Canadian weigh stations as well as increased truck size and road structural upgrading projects in short heavy haul roads within the heavy oil industry in typical Western Canadian field state conditions.

Typical ranges of independent variables were encoded in Decision Programming Language (DPL). This Decision Analysis Software was used to determine the expected values and sensitivity of the environmental benefits across various scenarios.

## 3.2. EMISSIONS MODEL FORMULATION

Based on the significant range of emission unit costs as presented in Section 2.8.7, it is clear that there is considerable uncertainty when attempting to model emission quantities as well as associated unit costs of emissions across different agencies. A decision model was therefore developed with the ability to quantify the uncertainty associated with environmental costs and benefits. The model employed in this research was performed using a decision analysis technique, Decision Programming Language (DPL). DPL is a software created by Applied Decision Analysis, that incorporates decision trees and influence diagrams (Clemen 1995). DPL is a powerful analytical software package and has numerous features for analyzing decision models in a variety of ways. This software works with Microsoft Excel spreadsheets, enabling both DPL and the spreadsheets to be connected to each other, in order to achieve probabilistic analyses and to resolve problems confronted with uncertainty.

### 3.2.1. Influence Diagram

Influence diagrams provide a graphical representation of multivariable decision situations. Different decision elements are illustrated in the influence diagram as nodes. These nodes are linked to each other in a specific way to represent the relationship among the elements that influence the decision to be made. Three main types of nodes are used in the influence diagram: decision nodes, chance nodes, and value nodes. A decision node (rectangular shape) indicates the particular problem at hand and draws the different outcomes or alternatives. A chance node (oval shape) is related to probability, variability, or chance, associated with a particular value. The range of values and their respective probabilities are often based on previous knowledge and experience and are considered as independent variables. A value node (curved shape) is used when a specific value for an input is known or computed, and is usually considered as a dependent variable. This is the value that is used to calculate the outcome. Figure 3.1 illustrates a simplified influence diagram of the research model.

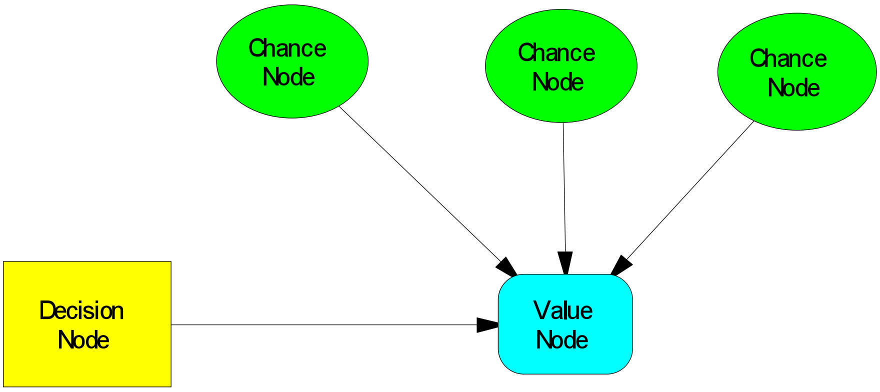

**Figure 3.1: Influence Diagram**

Once the value, chance, and decision nodes have been encoded into DPL, the values are exported into Microsoft Excel to allow calculations to be performed. The results of the specific calculations can then be imported back to DPL for final calculation of an expected value, and probabilistic distribution about the mean value.

## 3.3. EMISSIONS MODEL VARIABLE DESCRIPTION

The emissions model developed in this research was used to quantify the environmental emissions impact from various commercial vehicle operations. Various inputs need to be considered in the model in order to obtain results as accurate as possible. The variables considered in the model are divided into two main groups: independent variables, and dependent variables. Figure 3.2 summarizes these variables.

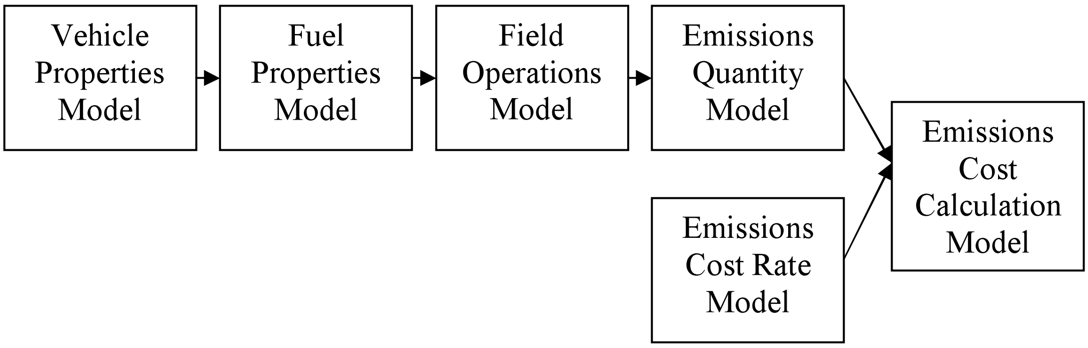

**Figure 3.2: Emissions Model Architecture**

### 3.3.1. Interaction of Independent and Dependent Variables

Figure 3.3 illustrates the different independent and dependent variables (rectangle shape for independent variables, oval shape for dependent variables) of the model. The variables are regrouped in three sub sections: vehicle property, fuel property, and field operations. As well, Figure 3.3 illustrates the interaction across variables within the emissions calculation model. The variables are illustrated in more details in Appendix B.

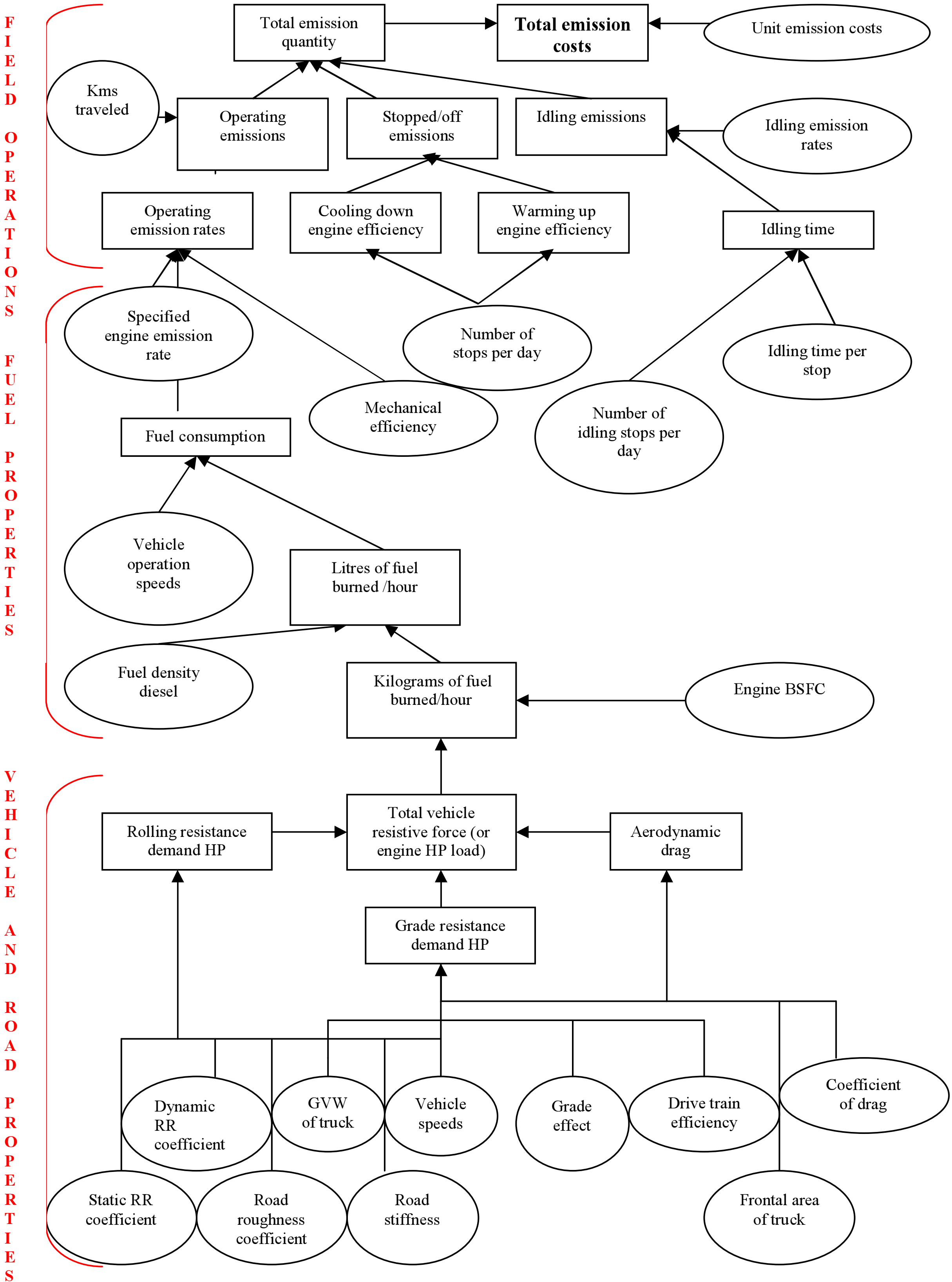

**Figure 3.3 Emissions Model Variables**

### 3.3.2. Vehicle Resistance to Motion

Fuel consumption and therefore, emissions generation, is a function of the resistance to motion. Vehicle resistance to motion can be illustrated by three categories: rolling resistance, grade resistance, and aerodynamic drag.

#### 3.3.2.1. Vehicle Rolling Resistance

Rolling resistance demand horsepower (RHP) is the sum of the forces at the area of contact between a vehicle's tire and road surface acting against the direction of movement, and equal to (Fitch 1994):

$$RHP = (C_8 + C_v\, mph) x C_R x KR\, x\, mph / 375 \qquad 9$$

Where:

- RHP: Rolling resistance horsepower/1000 pounds gross vehicle weight at drive wheels
- $C_8$: Static rolling resistance coefficient: applied at stationary vertical tyre load on the road, calculated in pounds/vehicle ton.
- $C_v$: Dynamic rolling resistance coefficient: applied vertical tyre load on the road when the vehicle is in motion, calculated in pounds/vehicle ton.
- $K_R$: Road roughness coefficient, defined by three categories of roughness: smooth, moderate and rough, according to the road quality.

The standard for pavement roughness measurement is the International Roughness Index (IRI) translated in mm/m or m/km. For example, an IRI value of 0 mm/m indicates absolute smoothness. An IRI value in the order of 10 mm/m represents a rough unpaved road (TAC 1997). In the emissions model developed in this research, IRI values were translated into coefficients of roughness, according to the road quality, as indicated in Table 3.1

- $C_R$: Road rolling resistance in pounds per 1000 lbs GVW, expressed in various percent grades according to road stiffness (MPa), as illustrated in Table 3.2 (Fitch 1994).

**Table 3.1: Road Roughness Emissions Parameters**

| **IRI Value (mm/m)** | 3.5 | 7.0 | 10.0 |
|---|---|---|---|
| **Road Roughness Emissions Coefficient** | 1.0 | 1.2 | 1.5 |

**Table 3.2: Road Rolling Resistance RR and Stiffness Emissions Parameters**

| **Road Surface** | **Road Conditions** | **RR in %** | **Stiffness Conversion (MPa)** |
|---|---|---|---|
| Concrete | Excellent | 1.00 | 5000 |
| Concrete | Good | 1.50 | |
| Concrete | Poor | 2.00 | |
| Hot Mix Asphalt | Good | 1.25 | |
| Hot Mix Asphalt | Fair | 1.75 | 2500 |
| Hot Mix Asphalt | Poor | 2.25 | |
| Cold Mix | Good | 1.50 | |
| Cold Mix | Fair | 2.25 | |
| Cold Mix | Poor | 3.75 | 1000 |
| Cobbles | Ordinary | 5.50 | |
| Cobbles | Poor | 8.50 | |
| Snow | 5 cms | 2.50 | |
| Snow | 10 cms | 3.75 | 250 |
| Dirt | Smooth | 2.50 | |
| Dirt | Sandy | 3.75 | |
| Mud | Mud | 3.75 to 15.00 | |
| Sand | Level soft | 6.00 to 10.00 | |
| Sand | Dune | 16.00 to 30.00 | 0 |

### 3.3.2.2. Grade Resistance

Grade resistance reduces vehicle speed and thus, requires the vehicle to use more power to maintain speed. Grade resistance demand horsepower may be calculated as (Fitch 1994):

$$NHP = (GVW \times Gxx\ mph) / (37{,}500 \times E) \qquad 10$$

Where:

- NHP: Net engine hp at flywheel (vehicle grade resistance hp)

- GVW: Gross vehicle weight (chassis and payload)
- G: Road grade (%)
  mph: miles per hour
- E: Drive train efficiency (% for direct gear drive): including transmission, clutch, driveline and drive axles. It transmits the engine's power to the rear wheels, and varies from 50 to 90 percent in efficiency.

#### 3.3.2.3. Aerodynamic Drag

Aerodynamic drag or air resistance power (hp) demand is equal to: (Fitch 1994)

$$AHP = (FA\ x Cd\ x\ mph^3)/156{,}000 \qquad 11$$

Where:

- AHP: horsepower required to overcome air resistance at sea level
- FA: Frontal area (square-feet)
- $(mph)^3$: (miles per hour) cubed
- Cd: Aerodynamic drag coefficient (between 0.7 and 0.9 for semi-trailers), defined as:

$$Cd = D/Qa \qquad 12$$

Where:

- D: Air drag in pounds
- Q: dynamic pressure = $0.5\ pV^2$
  - p: Air density, averages 1.2 $kg/m^3$ in Western Canada
  - $V^2$: Squared velocity
- a: Frontal area (square-feet)

### 3.3.3. Fuel Quantity

Fuel is usually characterized by its economy (or consumption) as the number of litres of fuel consumed in one kilometre, depending on the following factors:

$$\text{Fuel Economy} = (\text{BSCF} \times \text{Total HP})/\text{Fuel density}/\ \text{Speed (km/hr)} \quad (13)$$

Where:

- Engine BSCF (Brake Specific Fuel Consumption) is the measured fuel flow in kilograms per hour divided by the horsepower: Fuel kilograms per Hour / Brake Horsepower. A heavy diesel vehicle engine of average efficiency generally burns about 0.153 kilograms of fuel per horsepower per hour. The best (lowest) brake number always occurs at peak torque where the engine is the most efficient.

- Fuel density: (kilograms/litre). The greater the fuel density, the greater the mass of fuel that can be stored in a given tank, and the greater the mass of fuel energy that can be delivered to the combustion chamber. For diesel oil, the fuel density is generally equal to 0.839 kilogram/litre.

- Total horsepower (HP) load or brake horsepower (or total resistance) is the maximum power available from an engine as measured by a dynamometer, such as 450, or 500 HP for a heavy truck. This is the sum of rolling resistance demand hp, grade resistance demand hp, and aerodynamic drag, as presented in Section 3.3.2.

### 3.3.4. Emissions Rates

Emissions generated during truck operations are divided in three categories: operating emissions, idling emissions, and warm-up / cool-down cycle emissions. The model described in this research is based on operating emissions calculations of the

Australian life cycle analysis, from the Australian Greenhouse Gas Office, which could easily be implemented in the model of this research. According to the Australian Greenhouse Gas Office, the operating emissions of a vehicle are:

*Operating emissions = Emission rate x Fuel combustion characteristics*
*x Fuel density x Fuel economy* 14

Where:

- Operating emissions are measured in: grams/kilometre
- Specific engine emission rate is measured grams/mega joules. According to EPA standards, diesel engine emissions are (Appendix C):
    $CO_2$: 73.3 grams/mega joule
    CO: 5.77 grams/mega joule
    NOx: 1.49 grams/mega joule
    PM: 0.037 grams /mega joule
    HC: 0.48 grams/mega joule
- Fuel combustion characteristics are measured in mega joules/kilogram. Also called Mass density (concentration mass to volume), it has an average of 42.78 MJ/kg for diesel engines.
- Fuel density: fuel combustion characteristics times fuel density gives the thermal efficiency (or energy content of fuel) which is expressed here by 35.89 MJ/L.

Idling emissions of heavy trucks can also have a significant impact on vehicle generated emissions. Generally, a typical heavy truck would consume around 3.63 litres of fuel per hour of idling (EPA standards). This translates to between 20 and 40 litres of fuel wastage per day per truck.

Warm-up / cool-down cycle emissions have also to be considered when quantifying heavy vehicle emissions. Truck stops per day are important because diesel engines need to cool down before shutting down, and to warm up after starting up (average of 5 min and 15 min, respectively). Cooling down and warming up actions are related to the engine efficiency in terms of the amount of emissions produced during warm up and cool down cycles. To compute these emissions, the base idling emissions rate average across various diesel engines was used and multiplied by an efficiency-related factor, as assumed in Table 3.3. Engine efficiency was assumed to range from 50 to 100 percent (in terms of thermal energy of diesel fuel converted into mechanical work).

**Table 3.3: Engine Idling Efficiency Factors (Expert Judgments)**

| % Engine Efficiency | Model Emissions Factors |
|---|---|
| 100 | 1.0 |
| 75 | 1.5 |
| 50 | 2.0 |

### 3.3.5. Emissions Characteristics

Based on the EPA standards (1999) and the CSIRO Atmospheric Research Report to the Australian Greenhouse Office (2000), Table 3.4, Table 3.5, and Appendix C summarize the engine emissions rates used for this research and represent the engine operating emissions rates used to calculate the vehicle operating emissions in grams per kilometre traveled. A probability of one was used to simplify the calculations. However, in reality, these engine emissions rates may vary from these standards. Table 3.5 represents the engine emissions rates in terms of idling, cooling down and warming up, in grams per hour. A normal distribution of 0.25 for low, 0.5 for base, and 0.25 for high, was used to describe engine efficiency and is based on Table 3.3: Engine Idling Efficiency Factors. Further details of engine emissions rates are shown in Appendix C.

**Table 3.4: Engine Operating Emissions Characteristics**

| Emissions Rate (grams/mega joules) | Values Bases | Probabilities Bases |
|---|---|---|
| Carbon Dioxide CO2 | 73.3 | 1 |
| Carbon Oxide CO | 5.77 | 1 |
| Nitrogen Oxides NOx | 1.49 | 1 |
| Hydrocarbons HC | 0.48 | 1 |
| Particulate Matter PM | 0.03 | 1 |

**Table 3.5: Engine Idling Emissions Rates (Experts Judgment)**

| Emissions | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| **Carbon Dioxide ($CO_2$)** | | | | | | |
| Idling (g/hr) | 4366 | 5846 | 9140 | 0.25 | 0.50 | 0.25 |
| Cooling down (g/hr) | 731 | 974 | 1462 | 0.25 | 0.50 | 0.25 |
| Warming up (g/hr) | 2192 | 2923 | 4385 | 0.25 | 0.50 | 0.25 |
| **Carbon Monoxide (CO)** | | | | | | |
| Idling (g/hr) | 18 | 41 | 90 | 0.25 | 0.50 | 0.25 |
| Cooling down (g/hr) | 5 | 7 | 10 | 0.25 | 0.50 | 0.25 |
| Warming up (g/hr) | 15 | 21 | 31 | 0.25 | 0.50 | 0.25 |
| **Nitrogen Oxides (NOx)** | | | | | | |
| Idling (g/hr) | 84 | 109 | 165 | 0.25 | 0.50 | 0.25 |
| Cooling down (g/hr) | 14 | 18 | 27 | 0.25 | 0.50 | 0.25 |
| Warming up (g/hr) | 41 | 55 | 82 | 0.25 | 0.50 | 0.25 |
| **Hydrocarbons (HC)** | | | | | | |
| Idling (g/hr) | 6.00 | 8.00 | 12.00 | 0.25 | 0.50 | 0.25 |
| Cooling down (g/hr) | 1.00 | 1.33 | 2.00 | 0.25 | 0.50 | 0.25 |
| Warming up (g/hr) | 3.00 | 4.00 | 6.00 | 0.25 | 0.50 | 0.25 |
| **Particulate Matter (PM)** | | | | | | |
| Idling (g/hr) | 0.85 | 1.45 | 2.77 | 0.25 | 0.50 | 0.25 |
| Cooling down (g/hr) | 0.18 | 0.24 | 0.36 | 0.25 | 0.50 | 0.25 |
| Warming up (g/hr) | 0.54 | 0.72 | 1.08 | 0.25 | 0.50 | 0.25 |

### 3.3.6. Emissions Costs

Emissions costs are the product of the emission unit rates (grams/km), the number of kilometres traveled, and the emission unit costs (CAD$/metric tonne produced), as shown in the following equation:

$$\text{Emission costs} = (\text{Emission rate} \times VKT) \times \text{Unit emission cost} \qquad 15$$

Where:

- Emissions costs: total annual costs of each gas emission in terms of CAD$
- Operating emission rate: quantity of each pollutant emitted in grams/kilometre
- VKT: vehicle kilometre traveled
- Unit emission cost: CAD$ per metric tonne of gas emitted /1,000,000 (need for $ per gram). Data were collected from agencies worldwide for each emission, and an assumed value for the low, average and high costs collected was considered and encoded with a probability. Table 3.6 and Figure 3.4 through Figure 3.8 illustrate these ranges of costs used in the model, based on Figure 2.25 through Figure 2.29 in Section 2.0, the average costs being calculated from all the values collected from agencies worldwide (Confer Appendix A, Table A-2).

**Table 3.6: Emission Unit Costs from Agencies Worldwide**

| **Emission Type** | **Values (CAD$/metric tonne)** | | |
|---|---|---|---|
| | **Low**<br>**0.25** | **Average**<br>**0.5** | **High**<br>**0.25** |
| **$CO_2$** | 0.26 | 41.69 | 233.26 |
| **NOx** | 16.49 | 17,433 | 67,299 |
| **HC** | 175.28 | 928.27 | 2,169.23 |
| **CO** | 6.52 | 127.45 | 864.54 |
| **PM** | 311.57 | 241,184 | 1,214,443 |

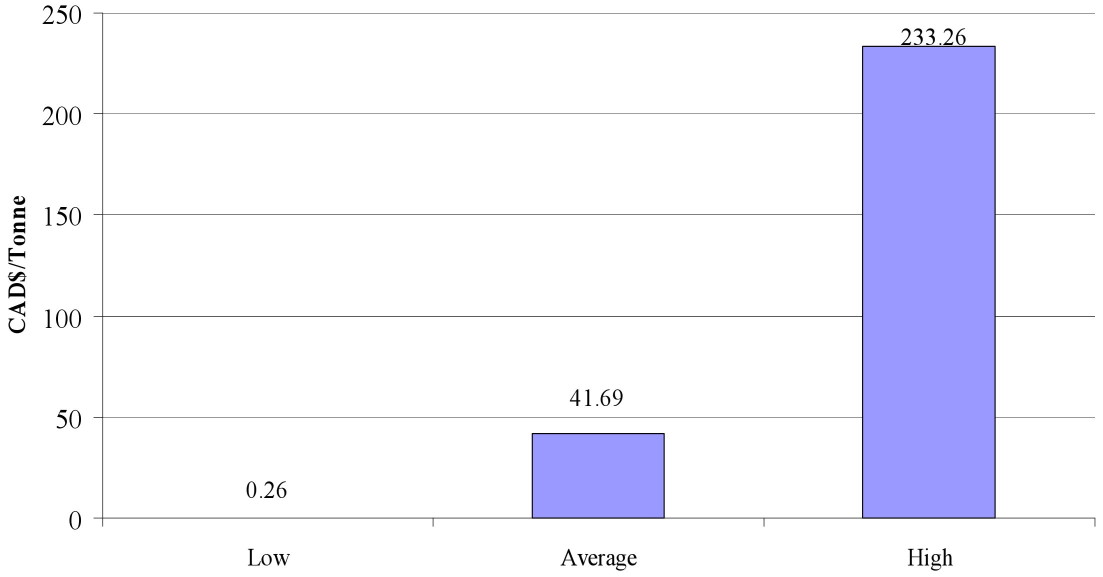

Figure 3.4: Range of $CO_2$ Unit Costs from Agencies Worldwide

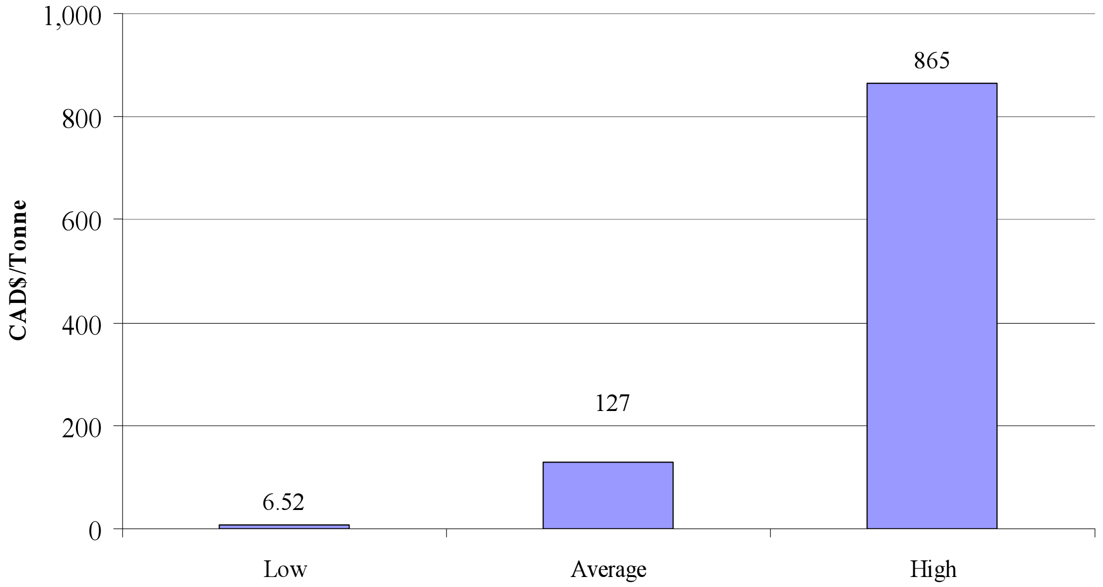

Figure 3.5: Range of CO Unit Costs from Agencies Worldwide

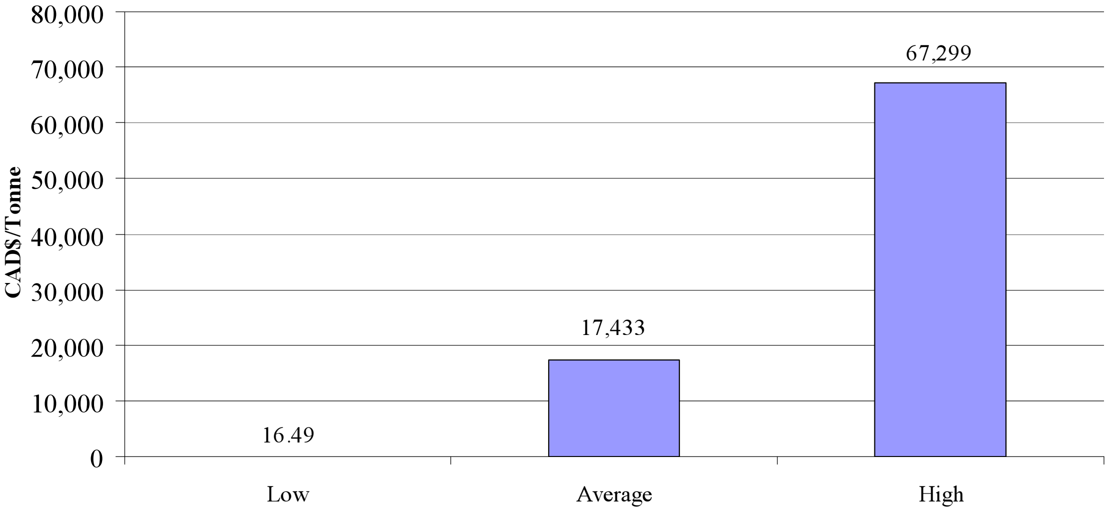

Figure 3.6: Range of NOx Unit Costs from Agencies Worldwide

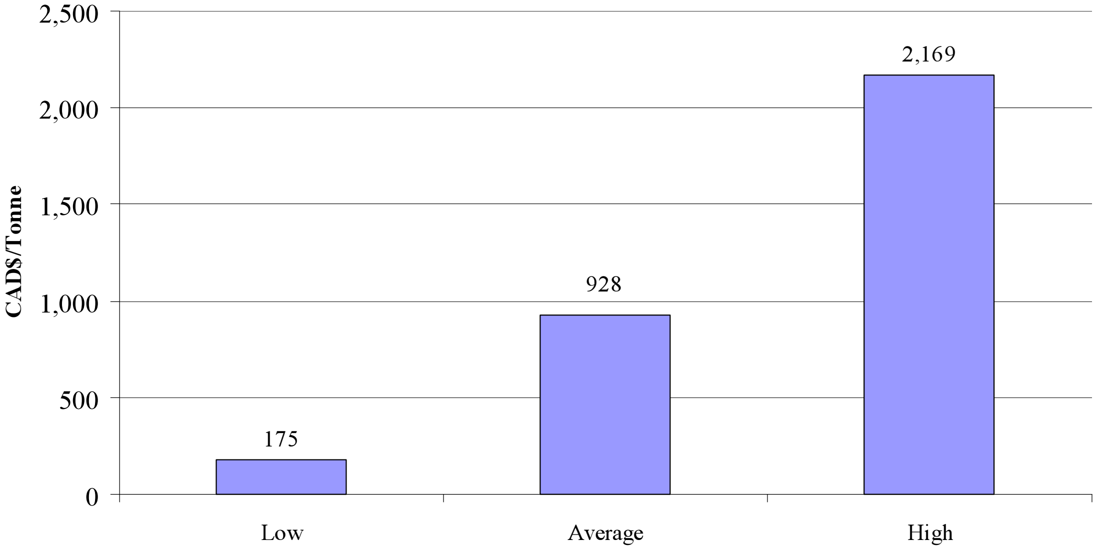

Figure 3.7: Range of HC Unit Costs from Agencies Worldwide

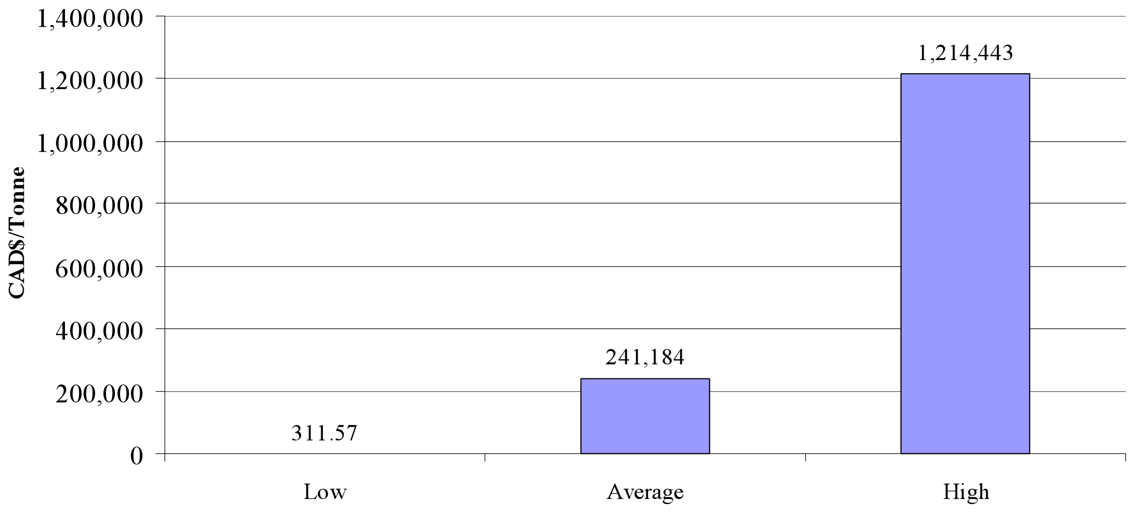

**Figure 3.8: Range of PM Unit Costs from Agencies Worldwide**

The difference in ranges across these different emissions unit costs are due to the important variation of the values collected within the published results, as shown in Table A-2.

### 3.4. FORMULATION OF EMISSIONS MODEL

Due the inherent uncertainty in quantifying vehicle emissions, costing, and modeling, probabilistic distributions were assigned to each independent variable. Most of the variables were encoded with a normal distribution: 0.25 for low, 0.5 for average, and 0.25 for high. Some variable probabilistic distribution was based on the findings of the literature review and was then directly assigned a probability of one. However, because the emissions model is flexible and user-definable, some variables have been encoded with different probabilities based on expert judgment, such as road stiffness and WIM idling times, or on research experiments performed to characterize specific emissions factors. Table 3.7 summarizes probabilistic distributions assigned for each variable of the model, in case the variables are sensitive to change. The values of each variable vary according to the case study and thus, are independently illustrated in Chapters 4.0 and 5.0.

## Table 3.7 Assumed Independent Variables Probabilistic Distribution (Experts Judgment and Literature Review)

| Variable Name | Probabilities<br>Low | Most Likely | High |
|---|---|---|---|
| **Field Operations** | | | |
| Cooling down engine efficiency | 0.25 | 0.50 | 0.25 |
| Warming up engine efficiency | 0.25 | 0.50 | 0.25 |
| Number of shut down per day | 0.25 | 0.50 | 0.25 |
| Number of stops loading/unloading per day | 0.25 | 0.50 | 0.25 |
| Idling time per stop when loading | 0.15 | 0.60 | 0.25 |
| Idling time per stop when unloading | 0.15 | 0.60 | 0.25 |
| Idling time with weigh-in-motion system[1] | 0.15 | 0.60 | 0.25 |
| Idling time without weigh-in-motion system[1] | 0.80 | 0.15 | 0.05 |
| **Fuel Properties** | | | |
| Engine BSFC | 0.25 | 0.50 | 0.25 |
| Idling emissions rates | 0.25 | 0.50 | 0.25 |
| Fuel density | | 1.00 | |
| Thermal efficiency | | 1.00 | |
| Specific emissions rates | | 1.00 | |
| **Vehicle Properties** | | | |
| Vehicle speeds | 0.25 | 0.50 | 0.25 |
| Static rolling resistance coefficient | 0.25 | 0.50 | 0.25 |
| Dynamic rolling resistance coefficient | 0.25 | 0.50 | 0.25 |
| Road roughness | 0.25 | 0.50 | 0.25 |
| Road stiffness | 0.25 | 0.50 | 0.25 |
| Drive train efficiency | 0.25 | 0.50 | 0.25 |
| Road Grade | 0.25 | 0.50 | 0.25 |
| Coefficient of drag | 0.25 | 0.50 | 0.25 |

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[1] Only in the case study of Chapter 5.2

# 4.0 MODEL VALIDATION

## 4.1. INTRODUCTION

In order to validate the emissions model developed in this research, a case study was performed using the emissions model to quantify the emissions produced from long distance heavy truck haul in Canada. The $CO_2$ emissions quantities calculated by the model developed in this research were then compared with published results.

## 4.2. MODEL INPUTS

The primary parameters considered in the validation of the model were related to:

- Truck fleet operational characteristics;
- Road characteristics, and;
- Engine characteristics.

### 4.2.1. Truck Fleet Operational Characteristics

In the validation modeling, it was assumed that 150,000 partially loaded and unloaded heavy diesel trucks operate 250 days per year on Canadian roads. The average gross vehicle weights of heavy vehicles were assumed to range from:

- 32,500 kgs (70,540 lbs, 5 axles);
- 43,500 kgs (95,700 lbs, 6 axles), and;
- 50,000 kgs (110,230 lbs, 8 axles).

In this case study, each vehicle was assumed to drive approximately 1000 kilometres in a ten hour-day, at varied speeds of 70 km/h, 80 km/h, and

90 km/h (45 mph; 50 mph; and 55 mph). It was assumed each truck stopped once a day for loading (0.25 to 1 hour) and once for unloading (0.20 to 0.50 hours). Idling time was modeled to help quantify idling emissions. Also, it was assumed that, under routine operational conditions, vehicle stop and shut down occurs two to five times per day, which involves increased engine emissions during cooling down and warming up cycles. Based on section 3.0, Table 4.1 summarizes average values and estimated probabilities related to truck characteristics.

**Table 4.1: Truck Characteristics Independent Variables Parameters (Experts Judgment)**

| Variables | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| Average GVW (kgs) | 32,000 | 43,500 | 50,000 | 0.60 | 0.15 | 0.25 |
| Vehicle frontal area ($m^2$) | 8.00 | 9.50 | 11.00 | 0.25 | 0.50 | 0.25 |
| Average operating speed (km/h) | 70 | 90 | 110 | 0.25 | 0.50 | 0.25 |
| Drive train efficiency (%) | 50 | 75 | 90 | 0.25 | 0.50 | 0.25 |
| Coefficient of drag | 0.70 | 0.80 | 0.90 | 0.25 | 0.50 | 0.25 |
| Idling time when loading (hr) | 0.25 | 0.50 | 1.00 | 0.15 | 0.60 | 0.25 |
| Idling time when unloading (hr) | 0.20 | 0.25 | 0.50 | 0.15 | 0.60 | 0.25 |
| Number of loading/unloading stops per day | | 2.00 | | | 1.00 | |
| Number of shut down cycle per day | 2 | 3 | 5 | 0.25 | 0.50 | 0.25 |

### 4.2.2. Road Characteristics

Road quality has an impact on tire-road interaction and therefore, the rolling resistance of the vehicle, which in turn influences fuel consumed and pollutants emitted. In this model, five components of the road were assumed to play a role on fuel consumption and emissions: road stiffness, dynamic rolling resistance, static rolling resistance, road roughness, and road grades. Table 4.2 summarizes the values and probabilities used in this case study for the five road variables.

**Table 4.2: Road Characteristics Independent Variables (Experts Judgment)**

| Variables | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| Static rolling resistance coef.[2] | 4.00 | 6.00 | 8.00 | 0.25 | 0.50 | 0.25 |
| Dynamic rolling resistance coef[2]. | 0.06 | 0.07 | 0.08 | 0.25 | 0.50 | 0.25 |
| Road stiffness (MPa)[3] | 1500 | 2500 | 5000 | 0.25 | 0.25 | 0.50 |
| Road roughness IRI- mm/m[4] | 3.50 | 7.00 | 10.00 | 0.50 | 0.25 | 0.25 |
| Grade (%)[3] | -1.50 | 1.00 | 1.50 | 0.25 | 0.50 | 0.25 |

### 4.2.3. Engine Characteristics

As presented in Section 3.0, emissions are related to the engine efficiency. The values of brake specific fuel consumption (BSFC), fuel density, engine efficiency, and thermal efficiency, were based on a literature review in the mechanical engineering area, as well as on Caterpillar and Cummins web pages (www.caterpillar.com; www.cummins.com). In addition, standard operating and idling emissions rates of engines documented from US EPA were used to calculate the final emissions rates. Table 4.3 summarizes the engine characteristics considered in the model developed in this research.

**Table 4.3: Engine Characteristics Independent Variables (Experts Judgment)**

| Variables | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| BSFC (kg/hp-hr) | 0.150 | 0.153 | 0.155 | 0.25 | 0.50 | 0.25 |
| Fuel density (kg/l) | | 0.839 | | | 1.00 | |
| Thermal efficiency (MJ/l) | | 35.89 | | | 1.00 | |
| Operating emissions rates (g/MJ) | | Varies according to the emission type, as summarized in Tables 3.4 and 3.5. | | | 1.00 | |
| Idling emissions rates (g/hour) | | | | 0.25 | 0.50 | 0.25 |
| Cooling down efficiency (g/hr) | | | | 0.25 | 0.50 | 0.25 |
| Warming up efficiency (g/hr) | | | | 0.25 | 0.50 | 0.25 |

From the truck characteristics summarized in Table 4.1 through Table 4.3, only the variables found sensitive in the deterministic sensitivity analysis performed in Section 4.3 were assigned probabilities.

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[2] Motor Truck Engineering Handbook; 1994.; coefficients expressed in pounds per vehicle ton

[3] Experts Judgments

[4] Pavement Design and Management Guide

## 4.3. DETERMINISTIC MODEL VARIABLE SENSITIVITY ANALYSIS

A deterministic sensitivity analysis was performed across all independent variables in order to determine which variables were the most sensitive to field state conditions in this model. Based on the results of the sensitivity analysis, Table 4.4 shows the typical ranges of values applied to each variable. Figure 4.1 illustrates the variables that produce sensitivity in terms of annual mega tonnes of $CO_2$ emitted in Canada. The results of the sensitivity analysis show that two of the independent variables have a significant impact on the outcome of the model, especially in the case of short heavy haul applications. As seen in Figure 4.1, the variables that produced the most significant change in emissions are road grade and road stiffness.

Moreover, because the variable related to idling time at weigh stations has less significant effect compared to road grade and road stiffness, this is not represented in Figure 4.1. However, idling time at weigh stations is also recognized as sensitive because of its direct impact on the weigh-in-motion systems case study, and was assigned probabilities in the weigh-in-motion model (Section 5.2). In the case of the model validation, only the ranges of the two primary variables were assigned probabilities in the DPL model to more accurately evaluate Canadian heavy trucks emissions and to compare the results with the published results shown in Appendix A.

In Figure 4.1, the expected value of the sensitivity analysis, determined in terms of emissions released, indicates the sensitivity of each variable in descending order or sensitivity. Each variable is represented with a maximum value/expected result and a minimum value/expected result. It should be noted that the amount of emissions released are expressed in terms of negative numbers, which was the single technique to represent the results in the DPL model.

### Table 4.4: Sensitivity Analysis Independent Variables

| Variable Name | Description | Low | Most likely | High |
|---|---|---|---|---|
| **Field Operations** | | 0.25 | 0.5 | 0.25 |
| Cooling down engine efficiency | Grams of $CO_2$ emitted when the engine is cooling down for 5 min before turning off | 730.75 | 974.3 | 1461.5 |
| Warming up engine efficiency | Grams of $CO_2$ emitted when the engine is warming up for 15 min before turning off | 2192.2 | 2923 | 4384.5 |
| Number of stops per day | Vehicle's stops per day | 2 | 3 | 5 |
| Number of stops loading/unloading | Number of stops when loading and unloading a vehicle | 1 | 2 | 10 |
| Time per stop when loading/unloading | Calculated in hours | 0.2 | 0.33 | 1 |
| Number of weigh stations a day[5] | | 2 | 3 | 5 |
| Idling time without weigh-in-motion system[5] | Calculated in hours | 0.083 | 0.167 | 0.5 |
| Idling time with weigh-in-motion system[5] | Calculated in hours | 0 | 0.083 | 0.1 |
| **Fuel Properties** | | | | |
| Engine BSFC | Fuel flow in the engine (kg - hour/brake horsepower) | 0.150 | 0.153 | 0.156 |
| Idling emissions rates | Grams of $CO_2$ emitted per hour | 4366 | 5846 | 9140 |
| **Vehicle Properties** | | | | |
| Frontal area | Translated in square meters | 8 | 9.5 | 11 |
| Vehicle speeds | Translated into assumed mph for the calculation in the model | 45 | 50 | 65 |
| Static rolling resistance coefficient | Applied tyre load on the road when no motion (lbs/vehicle tonne) | 4 | 6 | 8 |
| Dynamic rolling resistance coefficient | Applied tyre load on the road when motion (lbs/vehicle tonne) | 0.06 | 0.07 | 0.08 |
| Drive train efficiency | The more power the engine must transmit to the rear wheel, the less efficient (%) | 90 | 75 | 50 |
| Coefficient of drag | Define the air resistance | 0.7 | 0.8 | 0.9 |
| **Road Properties** | | | | |
| Road roughness | Translate the quality of road (mm of roughness per m) into a coefficient | 1 | 1.2 | 1.5 |
| Road stiffness | Road rolling resistance expressed here in % to express the number of MPa. | 1.5 | 1 | 3.75 |
| Road Grade | Grade (%) | - 1.5 | 0.5 | 1.5 |

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[5] Only in the case study of Chapter 5.2

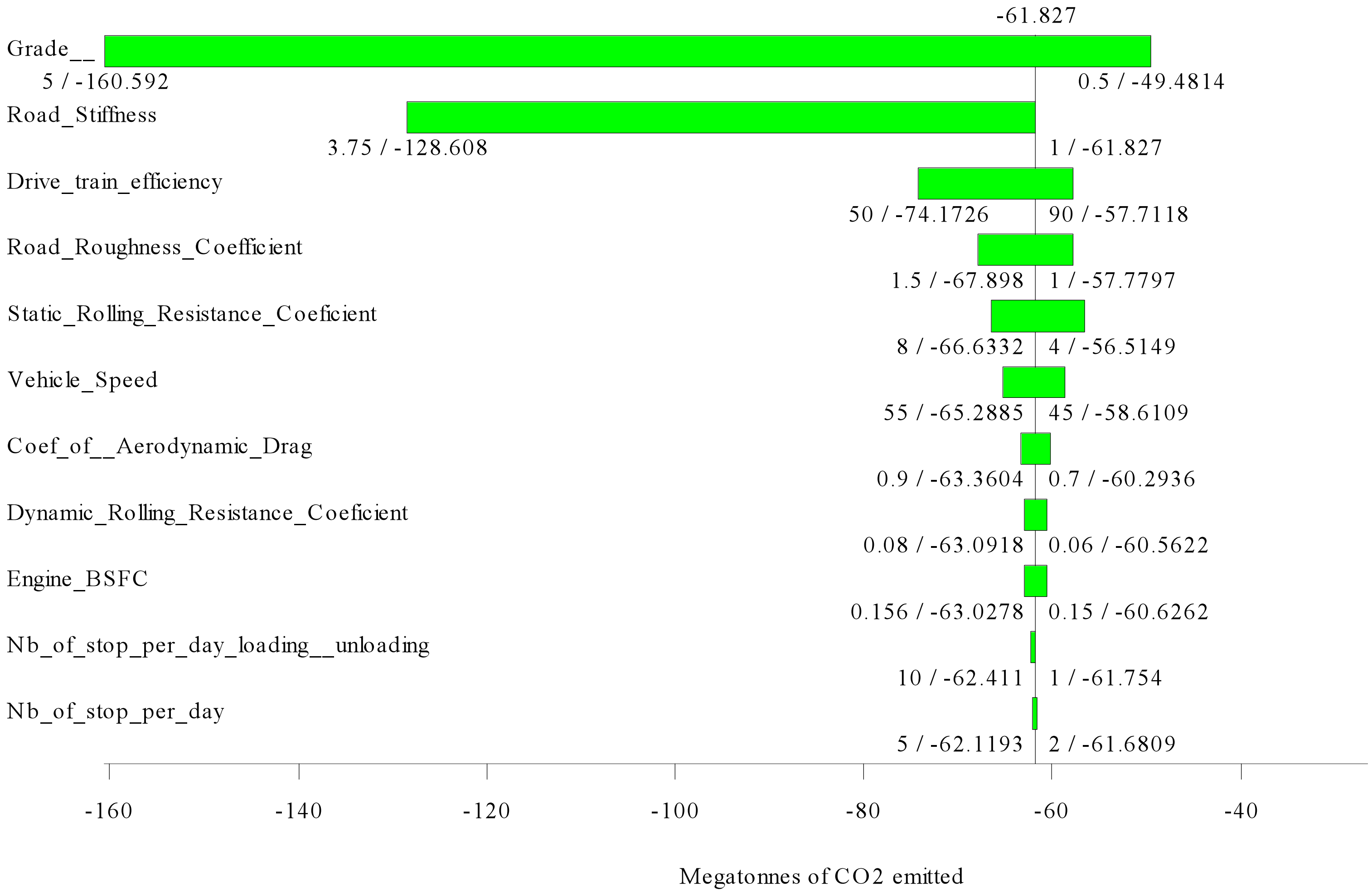

**Figure 4.1: Sensitivity of Canada $CO_2$ across Ranges in Independent Variables (DPL Influence Diagram)**

## 4.4. MODEL VALIDATION

Published results were used to compare the model results with those based on Canadian, Australian and American researches, as summarized in Table 4.5.

**Table 4.5: Sources and Origins of Published Results**

| Sources | Origin |
|---|---|
| Transport Canada | Canada |
| Victoria Transport Policy Institute | Canada |
| Pratt, Australian Transportation Research Forum | Australia |
| CSIRO, Australian Greenhouse Office | Australia |
| www.afcde.doe.gov, US Department of Energy | United States |
| Transportation Research Board | United States |
| Ramamurthy et al, Environmental Science and Technology | United States |
| Yanowitz et al, Environmental Science and Technology | United States |

Based on the sensitivity analysis presented in Figure 4.1, the variables road grade and road stiffness were assigned probabilities due to their sensitivity relative to other variables. Then, a model was created in order to validate outputs compared to published results, in terms of quantity of emissions produced annually in Canada by the assumed 150,000 heavy diesel trucks presented in Section 4.2. Two examples were used to illustrate this comparison. The first example shows the average total amount of $CO_2$ annually produced in Canada; the second example is related to average operating $CO_2$, CO, NOx, HC and PM emissions from heavy diesel vehicles.

Figure 4.2 illustrates results of the first example with the average total $CO_2$ emissions produced annually from heavy diesel trucks in Canada. The average expected value of annual $CO_2$ emissions is 69.4 mega tonnes. The model results can be compared to the published data summarized in Table 2.10: Freight Transportation in Canada and GHG Emissions – 1990-2000 that illustrates 43.1 mega tonnes of GHG emissions in $CO_2$ equivalent for freight transportation in 2000 (Nix 2003).

Figure 4.3 illustrates the comparison of $CO_2$ emissions of model with published $CO_2$ emissions (Nix 2003). The model predictions (69.4 mega tonnes) generate a value higher than the literature emissions (43.1 mega tonnes) by 61 percent. However, given the inherent variability of emissions related variables, the model predicted results appear to be reasonable when compared to the published results.

Figure 4.4 illustrates the second example with the average operating $CO_2$ emissions (grams/kilometre) from the same three types of heavy vehicles in Canada, as calculated by the emissions model generated in this research work. The average $CO_2$ emissions, or model expected value, equal 1,916 g/km and are comparable with the data from Table A-1, Appendix A, as shown in Figure 4.5.

Table A-1 and Figure 4.5 illustrate the rates of $CO_2$ emissions calculated by the model developed in this research, and compared to values published in the literature. $CO_2$ emissions from the literature review ranged from 941 to 1,504 g/km, and averaged 1,275 g/km. The model validation expected value of 1,916 g/km is 50 percent higher than the published average.

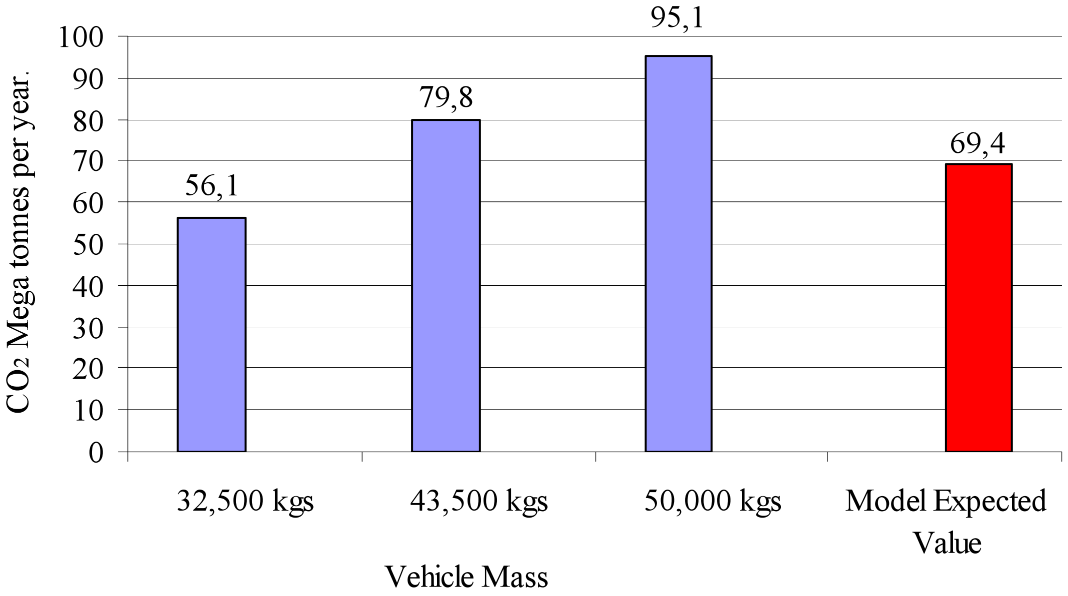

Figure 4.2: Total $CO_2$ Emission from Heavy Diesel Vehicles in Canada as a function of Road Grade and Stiffness

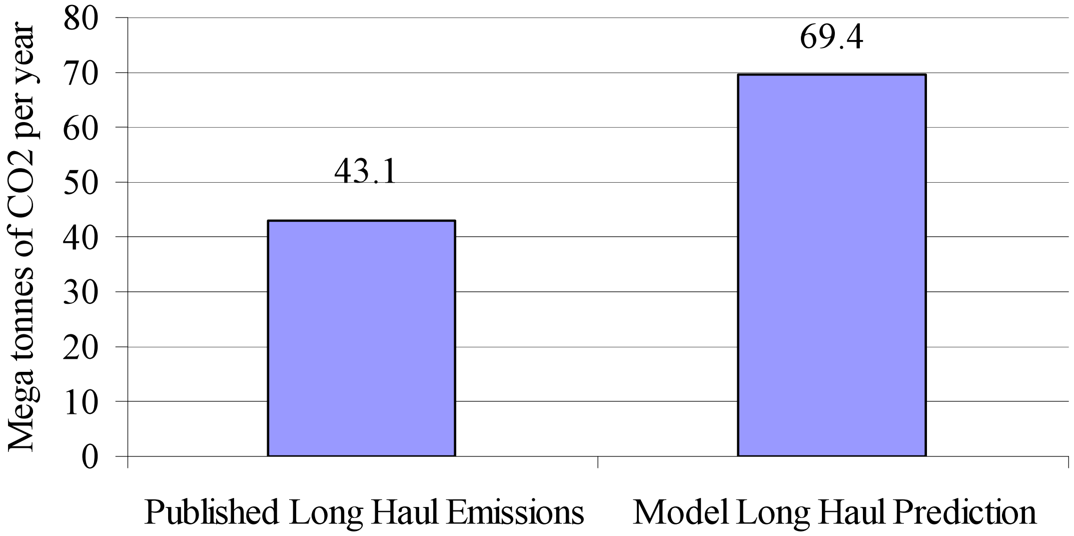

Figure 4.3: Comparison of Probabilistic Model Emissions with Literature Emissions Quantities in Canada

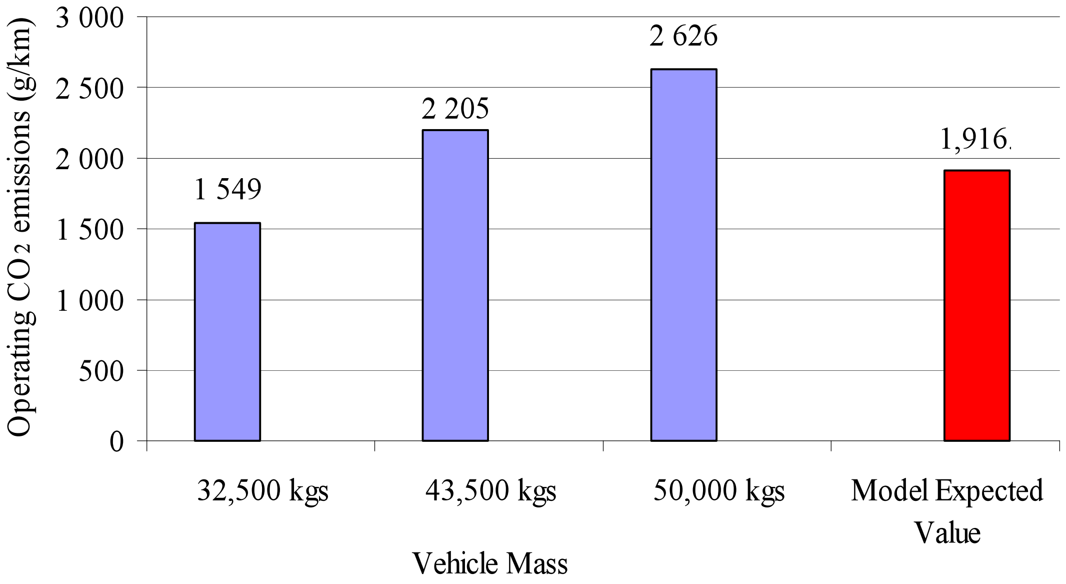

Figure 4.4: $CO_2$ Operating Emission from Heavy Diesel Vehicles as a function of Road Grade and Stiffness

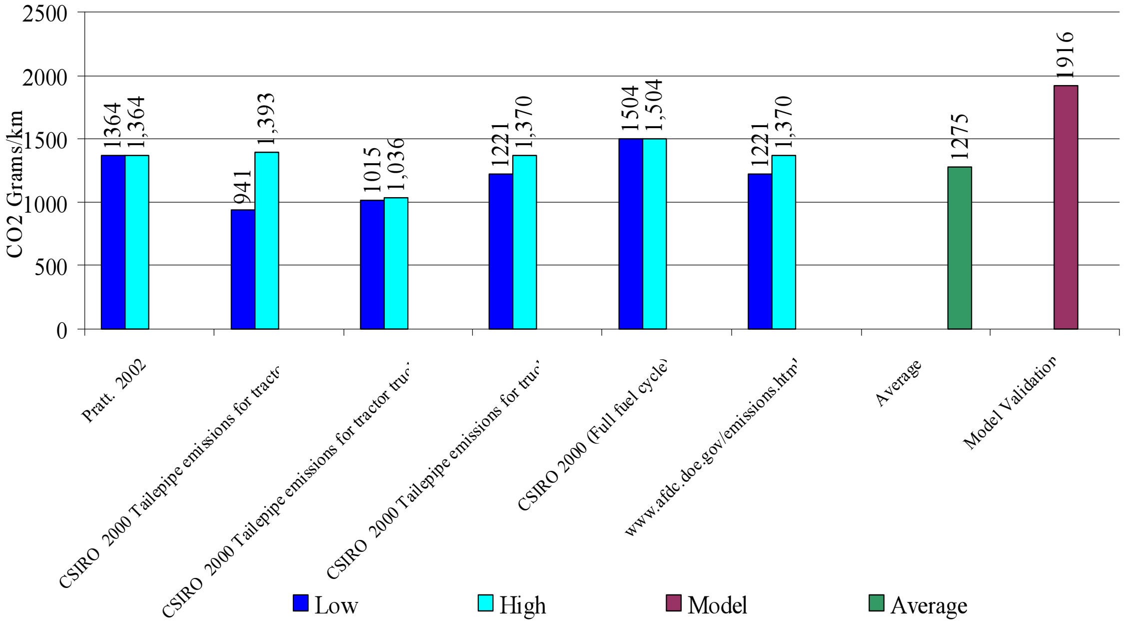

Figure 4.5: Comparison on Published and Model $CO_2$ Emission Rates

Model analysis was performed on operating emissions rates across four other emissions, CO, NOx, HC, and PM. Model results details are summarized in Appendix D, and are illustrated in Figure 4.6 through Figure 4.9. For each gas emission, the average rate calculated by the international studies from the literature review was used to compare with the average rate, or model expected value, calculated in the model prediction. The model results are generally higher than the published results. However, because the model results illustrate extreme cases, in terms of high road grade and stiffness, they stay in the same magnitude of values as the published results.

Figure 4.6 illustrates the rates of CO emissions calculated by the model developed in this research, and compares the values to published CO emissions in the literature. CO emissions from the literature review range from 1.06 to 86.2 g/km, and average 21.3 g/km. The model validation rate of 150.8 g/km is higher by 609 percent than the published average.

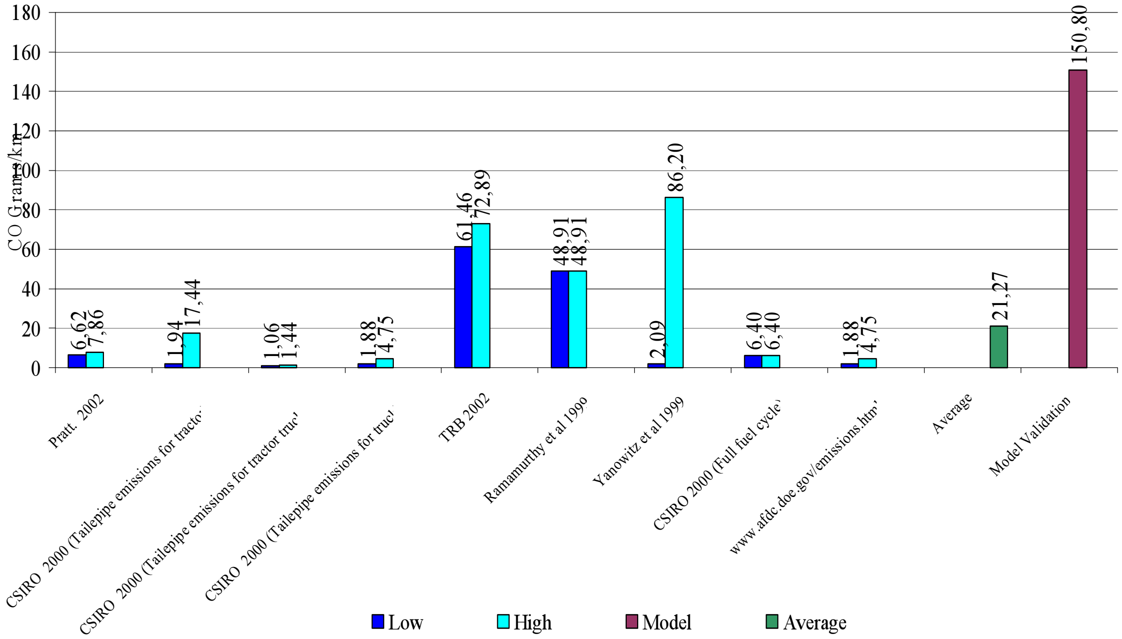

**Figure 4.6: Comparison on Published and Model CO Emission Rates**

Figure 4.7 displays emission rates for NOx. NOx emissions published results range from 0.14 to 42.32 g/km, and average 14.07 g/km. The model validation rate of 38.95 g/km is 176.8 percent higher than the published average.

Figure 4.8 illustrates the emission rates for HC. HC emissions published results range from 0.18 to 57.7 g/km, or average 7.87 g/km. The model validation rate of 12.54 g/km is 59 percent higher than the published average.

Figure 4.9 illustrates the emission rates for PM. PM emissions published results range from 0.19 to 7.43 g/km, and average 1.29 g/km. The model validation rate of 0.96 g/km is 25.6 percent lower than the published average.

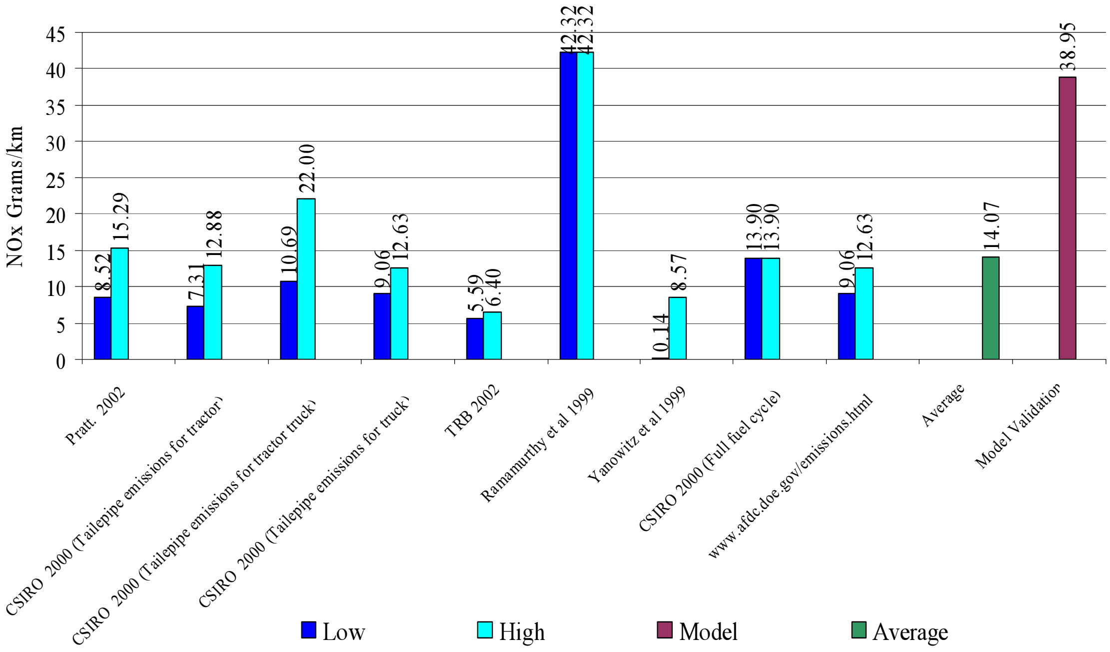

**Figure 4.7: Comparison on Published and Model NOx Emission Rates**

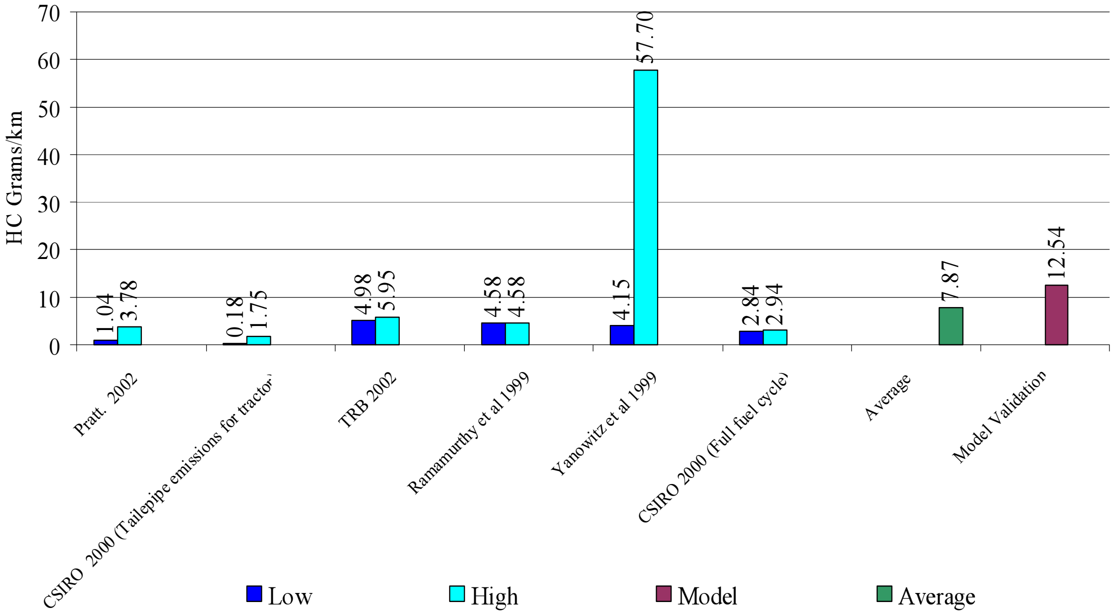

Figure 4.8: Comparison on Published and Model HC Emission Rates

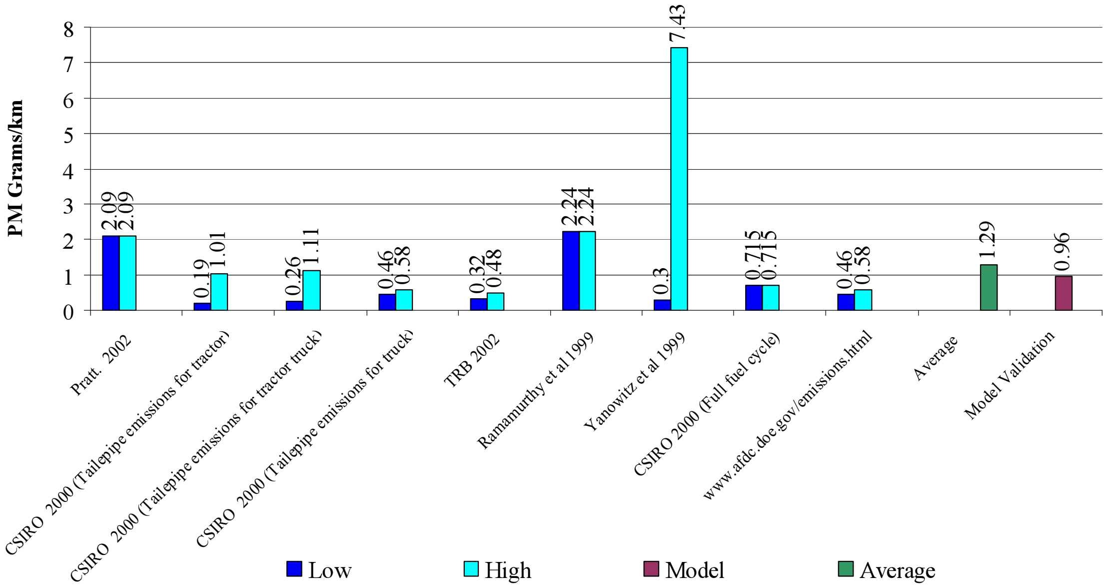

Figure 4.9: Comparison on Published and Model PM Emission Rates

In summary, with the exception of PM emissions results, the model emissions results were higher than the published results. The main cause may be the use of EPA specified engine emission rates (in grams per mega joules) in the DPL calculations. This is especially true for the CO specified emission rate, which is four times higher than the NOx rate, twelve times higher than the HC rate, and one hundred twenty two times higher than the PM rate, as shown in Appendix C-1. These EPA emissions rates were used in the calculations because they were easily available but they should be used with caution. Moreover, knowing that the difference within the published results ranges was high as well, and that these published results show an important uncertainty in their calculation, the model results could be supposed within acceptable tolerances and therefore, validate the relative accuracy of the model when compared to published results. Figure 4.10 and Figure 4.11 illustrate the comparison between the model results and the published averages.

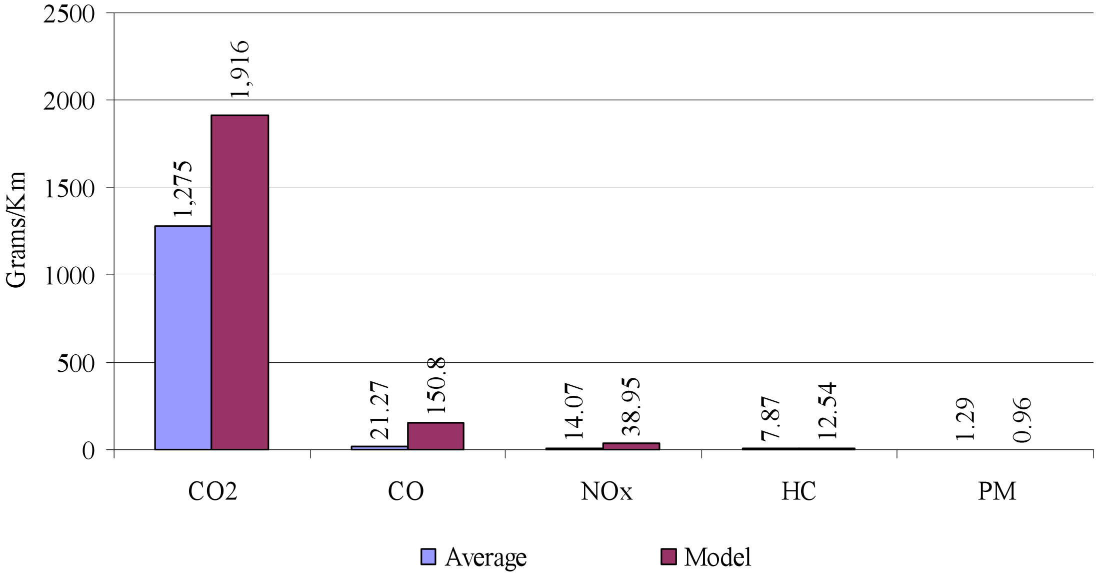

**Figure 4.10: Average Published Emissions versus Model Emissions Projections**

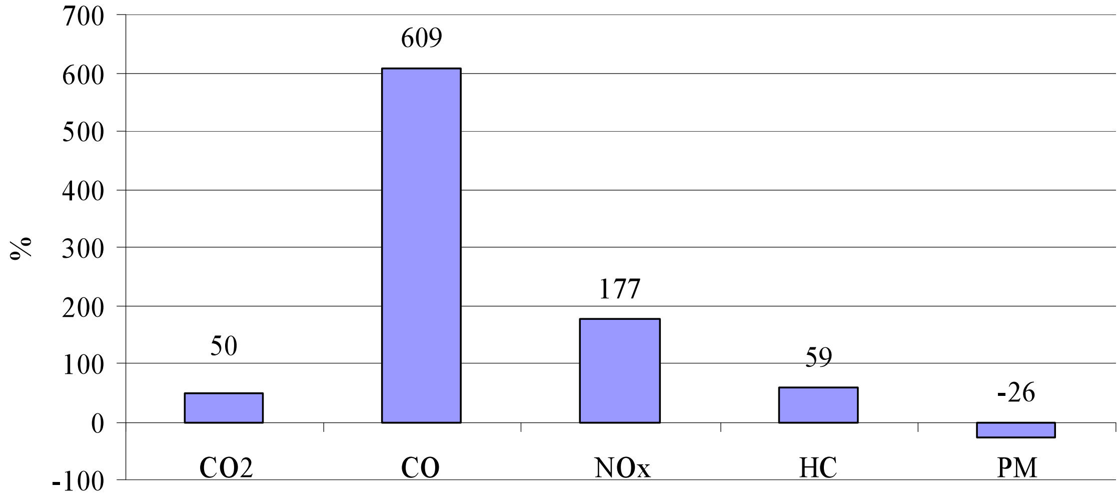

**Figure 4.11: Percent Difference between Predicted Average Model Emissions Results and Average Published Emissions.**

# 5.0 EMISSIONS MODEL APPLIED CASE STUDIES

## 5.1. INTRODUCTION

Two case studies were evaluated to demonstrate the potential application of the emissions model developed in this research. The first case evaluates the effect of weigh-in-motion systems (WIM) used at weigh stations to pre sort trucks entering weigh stations. The second case study, which applies the emissions model developed in this research, evaluates the effect of increased allowable heavy vehicle weights as well as haul road upgrades within short heavy haul in Western Canada. The main objective of both cases is to demonstrate explicitly the fuel consumption and related emissions reductions resulting from innovative road transport policies.

## 5.2. EMISSIONS REDUCTION OF WEIGH-IN-MOTION PRE-CLEARANCED SYSTEMS

In North America and Europe, commercial truck transport activities are increasing due to economic growth, transportation rationalisation, and growing international trade. As a result, there is an increasing need for road authorities to regulate commercial vehicle traffic operating on public roads, particularly by regulating weight limits in order to preserve the infrastructure, sustain safety, and respect commercial vehicle weights and dimensions policies of neighbouring jurisdictions.

Increasing truck traffic as well as overweight trucks on highways has diverse negative impacts:

- Infrastructure impacts translated into pavement, bridges and geometric damage;
- Safety impacts, and;
- Environmental impacts (emissions).

Because the performance of the highway infrastructure can be significantly influenced by the commercial truckload spectra being imposed on them, there is a need to regulate the sizes and weights of heavy vehicles (Fekpe 1997). Enforcement regulations need to be compatible with the existing infrastructure capacity, in order to maintain their structural and functional capacity (Fekpe 1995).

Increasing numbers of trucks and diversity of weights and dimensions policies throughout North America is resulting in enforcement efficiency. According to a study by North Dakota State University in 1996 (Titus 1996), enforcement efforts cost the United States transport industry from \$167 to \$283 million annually for weight regulations, and from \$14 to \$25 million annually in terms of enforcing safety regulations. Manual weight and safety enforcement strategies are time consuming, ineffective, and sometimes adversely affect highway safety. In addition, because of increasing volumes of trucks, there is a need to improve the enforcement efficiency of commercial vehicles subjected to weight and safety inspections in order to decrease the costs imposed on compliant heavy truck operators. Intelligent transportation systems have been developed to help infrastructure managers implement effective weight limit regulations.

Commercial Vehicle Operations (CVO) programs, such as electronic pre-clearance technologies (weigh-in-motion systems, automatic vehicle identification, video capture system, *et cetera*), aim at improving weight regulatory compliance presence and accuracy, as well as fostering associated societal goals, and reducing the industry's costs of compliance.

Weigh-in-motion (WIM) technology provides an efficient and cost effective complement to static weighing. The primary objectives of weigh-in-motion systems are twofold: providing highway designers and agencies with information on traffic volumes types and weights, and thereby facilitating improved pavement design and management. Weigh-in-motion also provides an effective means to pre-sort trucks at weight enforcement facilities (Zhi et al. 1999).

Previous studies indicate that with proper calibration, WIM systems provide accurate data on speed, axle spacing and dynamic weight (Sharma 1990). Today, the implementation of WIM has increased truck productivity by reducing or eliminating the time spent at stations. Moreover, trucks equipped with automatic vehicle identification (AVI) transponders are able to save the largest amount of time (Benekohal 2000). In addition, with WIM, a greater number of trucks can be checked automatically and thus, improve enforcement exposure and the effectiveness of limited enforcement expenditures, helping to minimize road deterioration and risks to public safety and the environment. WIM systems installed at weigh stations are beneficial in that they reduce user-delay costs from \$3 to \$7 million per year (Trischuk 2002). WIM reduces congestion in weigh stations by allowing compliant trucks to bypass the facility, and thereby increase capacity.

The study by North Dakota State University also indicates that technologies and enforcement strategies would greatly reduce the proportion of compliant vehicles subjected to enforcement, and would reduce the weight and safety enforcement costs from \$166 to \$282 million and from \$7.8 to \$13.2 million per year, respectively (Titus 1996).

Moreover, another important contribution of WIM systems is the reduction of emissions. By reducing or eliminating the time trucks spend at weigh stations, WIM systems enable trucks to avoid acceleration/stop/deceleration conditions, as well as to reduce their idling time. Therefore, WIM could result in significant fuel consumption reduction and thus, decrease emissions.

To demonstrate the environmental efficiency of weigh-in-motion systems at weigh stations, inputs related to truck activities at weigh stations were applied to the model. Inputs include truck operations characteristics, engine characteristics and road characteristics, and are illustrated in Chapter 3.0. Detailed calculations of the weigh-in-motion model application are presented in Appendix C.

### 5.2.1. Long Haul Truck Operations Characteristics

To evaluate the effect WIM has on heavy truck emissions at weigh stations, it was assumed that 150,000 heavy diesel trucks operate on the Canadian roads, 250 days per year. It was also assumed that each long haul truck operates 1000 kilometres per day.

Due to operational regulations, trucks are required to report to weigh stations for inspection. Commercial trucks are also limited to 13 hours driving time, 15 hours total operating time per day. Therefore, delay time at enforcement facilities can significantly reduce the effectiveness of commercial trucking in terms of total Mt-Km travelled per day. On average, long haul trucks report to weight enforcement facilities three times per day. The time each truck spends in a weigh station varies from 5 to 30 minutes (0.083 to 0.5 hour), according to the type of inspection being performed. Installing automated pre-clearance systems at weigh stations would enable compliant trucks to bypass the weigh station, reducing or eliminating the stop time. Saving time also means saving fuel by reducing the idle time and thus, reducing emissions.

Table 5.1 summarizes the variables and probabilities included in truck operating characteristics encoded in the weigh-in-motion pre clearance system emissions model application. Only the sensitive variables, the idling time with/without WIM, are assigned probabilities in the model.

**Table 5.1: Long Haul Truck Operational Characteristics Inputs**

| Variables | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| *GVW (kgs)* | *32,000* | *43,500* | *50,000* | *0.65* | *0.10* | *0.25* |
| Speed (km/h) | | 80 | | | 1 | |
| Vehicle frontal area ($m^2$) | | 9.5 | | | 1 | |
| Drive train efficiency (%) | | 75 | | | 1 | |
| Coefficient of drag | | 0.8 | | | 1 | |
| Number of weigh stations a day | | 3 | | | 1 | |
| **Idling time without WIM (hr)** | **0.083** | **0.167** | **0.5** | **0.15** | **0.6** | **0.25** |
| **Idling time with WIM (hr)** | **0** | **0.083** | **0.334** | **0.8** | **0.15** | **0.05** |
| Idling time when loading (hr) | | 0.5 | | | 1 | |
| Idling time when unloading (hr) | | 0.25 | | | 1 | |
| Number of idling stops a day | | 2 | | | 1 | |
| Number of stops off a day | | 3 | | | 1 | |

### 5.2.2. Long Haul Road Characteristics

Table 5.2 illustrates the road characteristics employed in the weigh-in-motion pre clearance case study. Only the sensitive variables, road grade and road stiffness, are assigned probabilities in the model, in accordance with the sensitivity analysis performed in Section 4.3. However, it is interesting to note that weigh stations are typically on the primary road system and therefore, road stiffness is typically assumed to be very good for primary highways.

**Table 5.2: Long Haul Road Characteristics Inputs**

| Variables | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| Static rolling resistance coef.[6] | | 6 | | | 1 | |
| Dynamic rolling resistance coef[6] | | 0.07 | | | 1 | |
| **Road stiffness (MPa)[7]** | **1000** | **2500** | **5000** | **0.15** | **0.25** | **0.6** |
| Road roughness (IRI)[7] | | 3.5 | | | 1 | |
| **Grade coefficient (%)[6]** | **0.5** | **1** | **1.5** | **0.25** | **0.5** | **0.25** |

### 5.2.3. Long Haul Truck Engine Characteristics

As well, Table 5.3 summarizes the values and probabilities assigned to truck engine characteristics used in the case study, as presented in Section 3.0. In the case of the engine characteristics, no variable has been found sensitive enough to be assigned probabilities. Moreover, they were all based on expert judgment.

**Table 5.3: Long Haul Engine Characteristics Inputs**

| Variables | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| Fuel density (kg/l) | | 0.839 | | | 1 | |
| Thermal efficiency (MJ/l) | | 35.89 | | | 1 | |
| BSFC (kg/hp-hr) | | 0.153 | | | 1 | |
| Operating emissions rates (g/MJ) | | Vary according to the emission type, as summarized in Tables 3.4 and 3.5. | | | 1 | |
| Idling emissions rates (g/hr) | | | | | 1 | |
| Cooling down efficiency (g/hr) | | | | | 1 | |
| Warming up efficiency (g/hr) | | | | | 1 | |

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[6] Motor Truck Engineering Handbook; 1994.

[7] Expert Judgments based on falling weight deflection measurements.

### 5.2.4. Long Haul Model Analysis in Canada

The inputs summarized in Table 5.1 through Table 5.3 were applied to the emissions model developed in this research. The emission predictions across the independent variables are shown in Figure 5.1 and are expressed in Mega tonnes of $CO_2$ emitted per year in Canada. The model results indicate that less $CO_2$ is emitted with the use of WIM. The results represent an annual reduction in emissions of 228,000 tonnes, or 0.22 percent of reduction compared to no use of WIM.

**Figure 5.1: CO2 Emissions resulting from Implementation of WIM Pre-Sorting in Canada (DPL Model Calculations)**

Based on the values and probabilities assumed for idle time with and without WIM as illustrated in Table 5.1, calculations indicate that each vehicle would save approximately 41 minutes per day with WIM systems pre-clearance in weigh stations, or close to 5 percent of their allowed driving time (13 hours a day). This would improve the daily efficiency of the commercial vehicle in a t-km basis. (confer Appendix E, Table E-2 for details).

Table 5.4 summarizes the economic benefits of WIM systems at weigh stations in Canada. Savings are presented in terms of the amount of $CO_2$ emissions with and without WIM, as well as the savings in terms of reduced emissions and fuel. Fuel and emissions cost savings are based on low, base, and high values collected from the significant range of agencies worldwide-published results (Appendix A, Table A-2). Diesel fuel price was assumed to range from $0.65 to $1.00 per litre. Appendix E contains detailed costs calculation.

**Table 5.4: Canadian Long Haul Emissions Model Results**

| Variables | Low | Average | High |
|---|---|---|---|
| Canada $CO_2$ Emissions-No WIM (t/year) | | 103.21 | |
| Canada $CO_2$ Emissions (t/year)- WIM | | 102.99 | |
| Net Emissions Avoided (t/year) | | **228,000** | |
| ‘000$ of $CO_2$ saved per year | **59** | 9,505 | **53,183** |
| Fuel savings (‘000litres/year) | **90,551** | 141,574 | **189,565** |
| Fuel savings (‘000$/year) - $0.65/litre | **58,858** | 92,023 | 123,217 |
| Fuel savings (‘000$/year) - $0.8/litre | 72,441 | 113,259 | 151,652 |
| Fuel savings (‘000$/year) - $1/litre | 90,551 | 141,574 | **189,565** |

Consequently, using WIM to pre-sort trucks at weigh stations would reduce Canadian $CO_2$ emissions by an average of 228 kilo tonnes per year, or 0.22 percent reduction of the 43.1 Mega tonnes of $CO_2$ emitted annually by Canada road freight transportation (confer Table 2.10). This is equivalent to an annual saving between $60,000 and $53 million, given the wide range of values (confer Table A-2). WIM pre-sorting would save between 59 and 190 million litres of fuel per year in Canada, resulting in between $59 and $190 million fuel cost savings per year, assuming a range of fuel cost of $0.65/ litre to $1/litre. Therefore these savings can be more important if one litre of fuel costs more that $1.

Moreover, Table 3.6 shows that one tonne of $CO_2$ costs between $0.26 and $233.26, due to the significant range of published unit rates of emissions costs collected from the global agencies. Therefore, in 2000, Canada road freight transportation, which emitted 43.1 Mega tonnes of $CO_2$, generated in between \$11.2 million and \$10,053 million of $CO_2$. Knowing that using WIM to pre-sort trucks at weigh stations would reduce Canadian road freight transportation $CO_2$ emissions by an average of 228 kilo tonnes per year, it would save annually between \$59,000 and \$53 million, or a reduction 0.53 percent.

Finally, in 1990, total Canada $CO_2$ emissions were to 472,000 kilo tonnes (Environment Canada 2001). Therefore, reducing the overall $CO_2$ emissions by 15 percent below 1990 level, as submitted by the Kyoto Protocol, would mean reducing emissions by 70,800 kilo tonnes. Using WIM, $CO_2$ emissions would be reduced by 228 kilo tonnes, which equal 0.32 percent of the 1990 total Kyoto targets for overall Canada $CO_2$ emissions.

Canada's road freight transportation $CO_2$ emissions were 146,000 kilo tonnes in 1990 (Environment Canada 2001). Therefore, reducing $CO_2$ emissions from transportation sector by 15 percent below 1990 levels, as targeted by the Kyoto Protocol, would mean reducing $CO_2$ emissions by 21,900 kilo tonnes. Therefore, using WIM would reduce $CO_2$ emissions by 228 kilo tonnes, which equal 1.04 percent of the 1990 Kyoto targets for the Canada road freight transportation $CO_2$ emissions. These results may be minor but it is one solution among many others to meet the Kyoto protocol targets.

### 5.2.5. Long Haul Model Analysis in the USA

Figure 5.2 and Table 5.5 illustrate the benefits of using WIM at weigh stations in USA. About 1.9 million trucks operating at 27,000 kgs (60,000 lbs) to 36,500 kgs (80,000 lbs) operate annually in the USA. The costs are indicated in CAD\$ and are based on the significant emissions unit rates range of emissions unit costs collected from agencies worldwide, as summarized in Table 3.6.

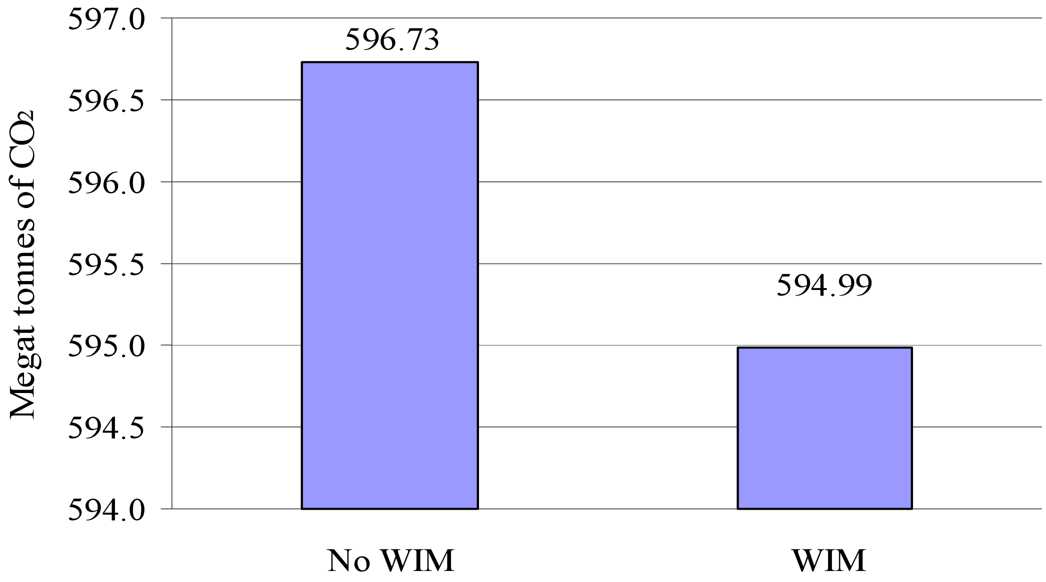

**Figure 5.2: $CO_2$ Emissions resulting from Implementation of WIM Pre-Sorting at US weigh-stations (DPL Model Calculations)**

**Table 5.5: US Weigh Station Model Results**

| Values | Low | Average | High |
|---|---|---|---|
| USA $CO_2$ emissions-No WIM (t/year) | | 596.73 | |
| USA $CO_2$ emissions-WIM (t/year) | | 594.99 | |
| Net Emissions Avoided (t/year) | | **1,737,000** | |
| ‘000$ of $CO_2$ saved per year | **450** | 61,889 | **341,494** |
| Fuel savings (‘000 litres/year) | **689,859** | 1,078,568 | **1,513,517** |
| Fuel savings (‘000$/year) – $0.65/litre | **448,409** | 701,069 | 983,786 |
| Fuel savings (‘000$/year) - $0.8/litre | 551,887 | 862,855 | 1,210,814 |
| Fuel savings (‘000$/year) - $1/litre | 689,859 | 1,078,568 | **1,513,517** |

Deploying WIM systems at US weigh stations would reduce road freight transportation $CO_2$ emissions by an average of 1,737 kilo tonnes per year (0.29 percent), or between $450,000 and $341 million in reduced emission costs per year. As well, it would save between 690 and 1,513 million litres of fuel per year, resulting in between $448 and $1,513 million per year across CVO in the United States, according to the range in unit price of fuel assumed in the model.

It is interesting to note that the amount of emissions saved with WIM at US weigh stations (1,737 kilo tonnes) are eight times as high as the amount of emissions saved with WIM applications in Canada (228 kilo tonnes), as shown in Table 5.4. Figure 5.3 illustrates the annual US $CO_2$ savings in terms of damage value, and shows that the potential savings experienced by deploying WIM at US weigh stations are about eight times higher than Canadian savings. The results concur with the US also having about eight times the truck traffic as Canada (US Department of Transportation 2002)

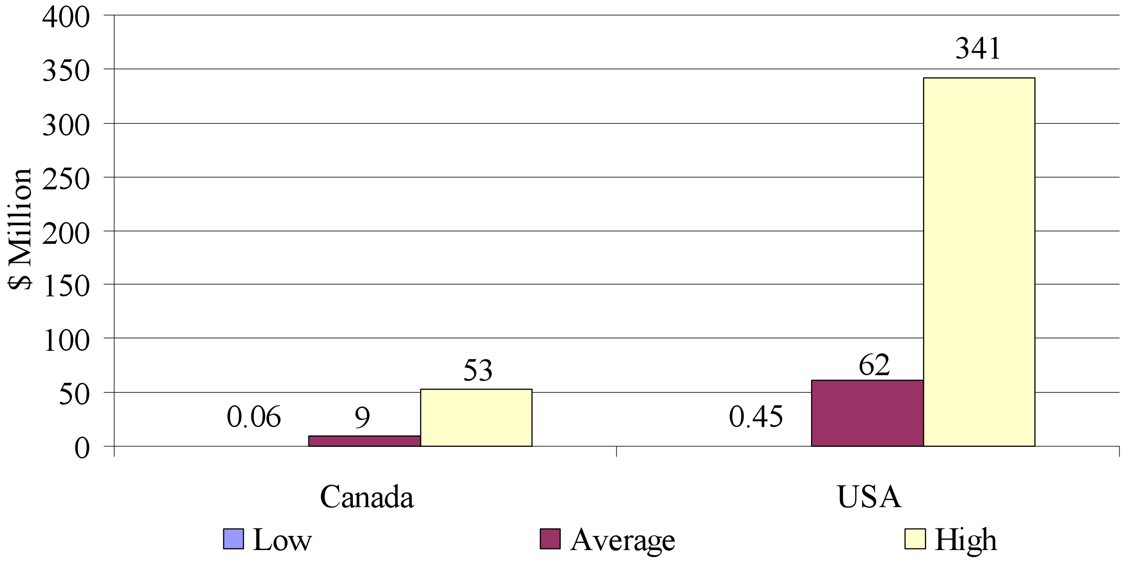

**Figure 5.3: Annual $CO_2$ Savings in Canada and U.S.**

As well, Figure 5.4 illustrates the average annual fuel costs savings comparison ($0.8/litre) and again, shows that the USA fuel savings as approximately eight times as high as Canadian savings.

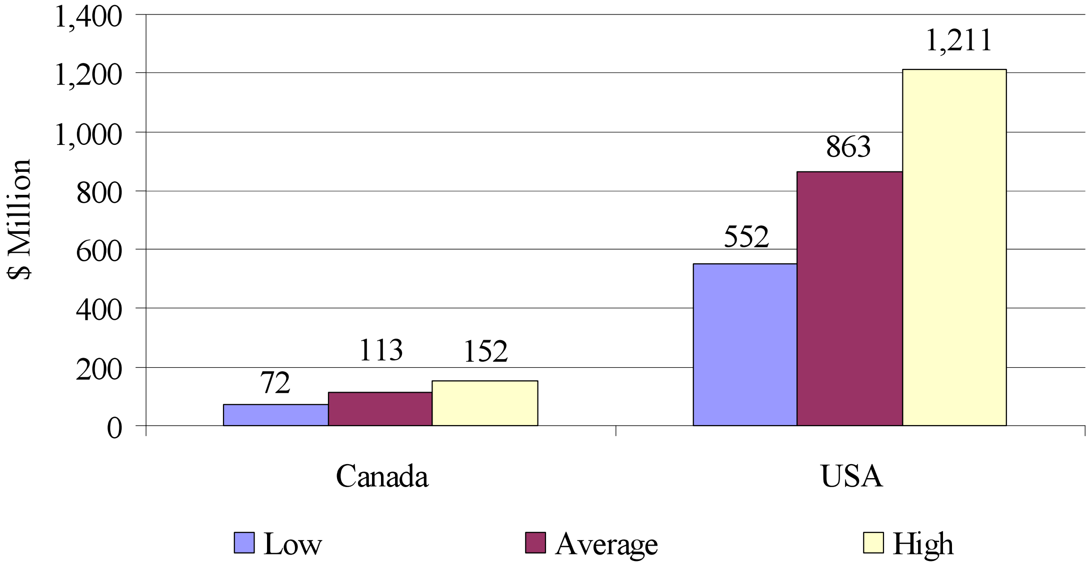

**Figure 5.4: Average Annual Fuel Savings in Canada and U.S.**

## 5.3. SHORT HEAVY HAUL CASE STUDY

One of the primary economic activities in Western Canada is the heavy oil industry. Because the viscosity and density of heavy crude is such that it can not be moved by pipeline, it has to be transported by truck. Therefore, heavy oil production in Western Canada is dependent on efficient road transport.

As a result, the heavy oil industry relies on the road network to provide local access to well sites and to transport oil and water. However, the region's road network is very challenging due to rolling topography, soil type and ground water conditions. In addition, given the nature of heavy oil production, continuous operation is required, regardless of weather conditions. Therefore, the municipal road network serving the heavy oil industry can be easily damaged by heavy trucks during adverse weather conditions. Accelerated road damage can result in a significant reduction in safety and efficiency.

Table 5.6 summarizes the evolution of oilfield production of the Rural Municipality (RM) of Britannia between 2000 and 2002 (Reiter 2003). The RM of Britannia is located in Northwest Saskatchewan, to the East of the Saskatchewan and Alberta border, adjacent to the city of Llyodminster. As seen in Table 5.6, fluid hauled within the RM of Britannia from 2000 to 2002 increased by 22,255 truckloads within the boundaries of the RM of Britannia alone, or close to 20 percent. It is obvious that the increased number of truckloads combined with the poor quality of roads would result in a significant increase in gas emissions. Moreover, within Saskatchewan, GHG emissions increased by a total of 18 percent from 1990 to 2001 in transportation sector, resulting in an increase of 1,060 Mt or 75.7 percent of GHG emissions for heavy-duty diesel vehicles (Environment Canada 2001).

**Table 5.6: Oilfield Production – RM of Britannia (Reiter, 2003)**

| Year | Oil Volume ($m^3$) | Water Volume ($m^3$) | $20m^3$ Truck Loads | % Annual Increase |
|---|---|---|---|---|
| 2000 | 929,250 | 1,378,128 | 115,369 | - |
| 2001 | 1,463,597 | 1,083,049 | 127,333 | 10.5 |
| 2002 | 1,139,669 | 1,612,827 | 137,624 | 20.0 |

The 137,624 tractor/trailer loads referenced in Table 5.6 assume an average of 20 $m^3$ of fluid hauled per truck. The number of truckloads referenced in Table 5.6 only includes trucks hauling crude oil and water, and does not include drilling rigs, service rigs, welding trucks, trucks hauling production sand, or other types of specialty service trucks. Such extreme heavy truck traffic makes it evident that additional maintenance and financing mechanisms will be needed for the municipality to manage and preserve the road infrastructure under the increasing demands of the heavy oil industry in the region. As well, properly maintained road infrastructure will directly reduce vehicle operating costs for heavy oil producers, including environmental costs induced from gas emissions.

One solution would be increasing the allowable loads from the typical $20m^3$ loads, which would decrease the number of trucks; the number of trips; the number of kilometres traveled and thus, will reduce fuel consumption and therefore emissions. In any case, the number of tonnes of heavy crude hauled annually will stay the same. However, in order to accommodate the increased loadings, structural improvements and vertical grade realignment will have to be performed on much of the municipal road infrastructure.

### 5.3.1. Short Heavy Oil Field Haul Model Inputs

The vehicle emissions model developed in this research is based on three main model inputs groups: truck operational characteristics, road characteristics, and engine characteristics. As seen in Sections 5.2.1 through 5.2.3, the sensitive variables, road grade and road stiffness for the RM of Britannia case study, will be assigned probabilities in the model, in accordance with the sensitivity analysis performed in Chapter 4.3. Moreover, truck size being one of the main factors in reducing emissions, three possible vehicle weight limits were undertaken as the decision key in the model application, with:

- 45.5 tonne GVW truck (20 t payload, 6-axle semi);
- 62.5 tonne GVW truck (40 t payload, 8-axle B-train), and;
- 100 tonne GVW truck (80 t payload, hypothetical truck).

#### 5.3.1.1. Short Heavy Oil Field Truck Operational Characteristics

To model the effect of increased heavy truck weights and dimensions, some assumptions were made for existing and potential future truck operations activities within heavy oil field operations, as summarized in Table 5.7 (confer Appendix F).

**Table 5.7: Truck Operations Characteristics**

| Truck Size | 20 $m^3$ fleet | 40 $m^3$ fleet | 80 $m^3$ fleet |
|---|---|---|---|
| Average GVW | 35,500 kgs | 42,500 kgs | 60,000 kgs |
| Loads per day | 551 | 276 | 138 |
| Trucks per day | 56 | 28 | 14 |
| Truck-kms per day | 400 | 400 | 400 |
| Fleet-kms per day | 22,400 | 11,200 | 5,600 |
| Fleet-kms per year | 5,600,000 | 2,800,000 | 1,400,000 |

Values and probabilities assigned to the independent variables outlining the characteristics of typical oil field trucks are based on expert judgments and are summarized in Table 5.8.

**Table 5.8: Truck Characteristics Distributions**

| Variables | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| Vehicle frontal area ($m^2$) | | 9.5 | | | 1 | |
| Average operating speed (km/h) | | 80 | | | 1 | |
| Drive train efficiency (%) | | 75 | | | 1 | |
| Coefficient of drag | | 0.8 | | | 1 | |
| Idling time when loading (hr) | | 0.5 | | | 1 | |
| Idling time when unloading (hr) | | 0.25 | | | 1 | |
| Number of Idling stops a day | | 10 | | | 1 | |
| Number of stops off a day | | 3 | | | 1 | |

#### 5.3.1.2. Road Characteristics

Roads within the RM of Britannia are typically in poor structural condition, principally built of gravel or thin oilfield sand surfacing. As a result, trucks are subject to higher rolling resistance, roughness and low structural stiffness. As well, substantial grades in the area also reduce the operational efficiency of the vehicles. Based on measurements in the field, Table 5.9 summarizes the values and probabilities used to quantify the road characteristics in the heavy oil haul case study.

**Table 5.9: Road Characteristics Inputs**

| Variables | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| Static rolling resistance coefficient.[8] | | 6 | | | 1 | |
| Dynamic rolling resistance coefficient[8]. | | 0.07 | | | 1 | |
| **Road stiffness (MPa)** | **250** | **1000** | **2500** | **0.25** | **0.5** | **0.25** |
| Road roughness (IRI mm/m)[9] | | 7 | | | 1 | |
| **Grade (%)[8]** | **1** | **2** | **5** | **0.25** | **0.5** | **0.25** |

#### 5.3.1.3. Engine Characteristics

Table 5.10 summarizes the values and probabilities assigned to truck engine independent characteristics considered in the emissions model.

**Table 5.10: Engine Characteristics Inputs**

| Variables | Values | | | Probabilities | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| Fuel density (kg/l) | | 0.839 | | | 1 | |
| Thermal efficiency (MJ/l) | | 35.89 | | | 1 | |
| BSFC (kg/hp-hr) | | 0.153 | | | 1 | |
| Operating emissions rates (g/MJ) | | Vary according to the emission type, as summarized in Tables 3.4 and 3.5. | | | 1 | |
| Idling emissions rates (g/hour) | | | | | 1 | |
| Cooling down efficiency (g/hr) | | | | | 1 | |
| Warming up efficiency (g/hr) | | | | | 1 | |

### 5.3.2. Heavy Oil Field Emission Model Analyses

A model applied to the inputs, based on the sensitivity performed in Chapter 4.3, established the road stiffness and the grade effect as the two only independent variables to cause significant impact on emissions and fuel consumption in short heavy haul analyses**.** The results are shown in the following tables and figures, according to the

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[8] Motor Truck Engineering Handbook; 1994.

[9] Pavement Design and Management Guide

emission type and the chosen alternative, including the size of truck and the road upgrade type. The road upgrade levels are defined as follows.

- As is: the roads show poor structural conditions, are supposed to be built of gravel or thin oilfield sand surface, and present substantial grades. The road stiffness equals 250 MP, and average grades of 5 percent.
- Strengthened Road: the roads have been reinforced in terms of structural quality with concrete or hot mix asphalt. The road stiffness is then equal to 5000 MP, but the average grades do not change and stay at 5 percent.
- Grade Realignment: the roads stay in poor structural conditions, the road stiffness stays at 250 MP, but the average grades have been improved to make the grades less steep at 0.5 to 2 percent.
- Complete Upgrade: the roads have been reinforced with concrete or hot mix asphalt, and the grades have been realigned. Road stiffness then equals 5000 MP, and the average grades of 0.5 to 2 percent.

#### 5.3.2.1. Heavy Oil Haul Emission Results

Table 5.11 and Figure 5.5 through Figure 5.9 show a first general view of each emission released per year, according to the truck size and the road upgrade level. All emissions decrease proportionally as the truck size increases and the road upgrade is complete.

**Table 5.11: Annual Emissions by Truck Size and Road Upgrade Level**

| | Truck size | Emissions (Tonnes) | | | |
|---|---|---|---|---|---|
| | | As Is | Strengthened Road | Grade Realignment | Complete Upgrade |
| **$CO_2$** | $20m^3$ | 29,751 | 20,484 | 16,009 | 6,742 |
| | $40m^3$ | 19,423 | 13,879 | 9,584 | 4,039 |
| | $80m^3$ | 16,707 | 12,793 | 6,899 | 2,985 |
| **CO** | $20m^3$ | 2,341 | 1,611 | 1,259 | 530 |
| | $40m^3$ | 1,528 | 1,091 | 753 | 317 |
| | $80m^3$ | 1,314 | 1,007 | 542 | 234 |
| **NOx** | $20m^3$ | 605 | 416 | 325 | 137 |
| | $40m^3$ | 395 | 282 | 195 | 82 |
| | $80m^3$ | 339 | 260 | 140 | 61 |
| **HC** | $20m^3$ | 195 | 134 | 105 | 44 |
| | $40m^3$ | 127 | 91 | 63 | 26 |
| | $80m^3$ | 109 | 84 | 45 | 19 |
| **PM** | $20m^3$ | 12.20 | 8.38 | 6.55 | 2.76 |
| | $40m^3$ | 7.95 | 5.68 | 3.92 | 1.65 |
| | $80m^3$ | 6.83 | 5.23 | 2.82 | 1.22 |

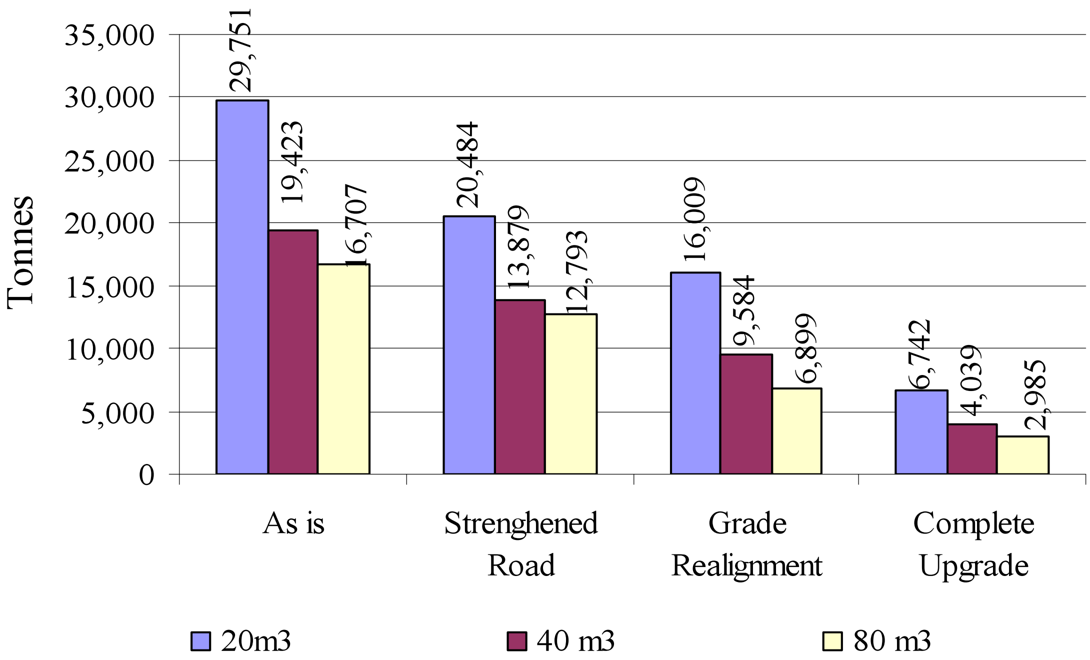

**Figure 5.5: Annual $CO_2$ Emissions by Truck Size and Road Upgrade Level**

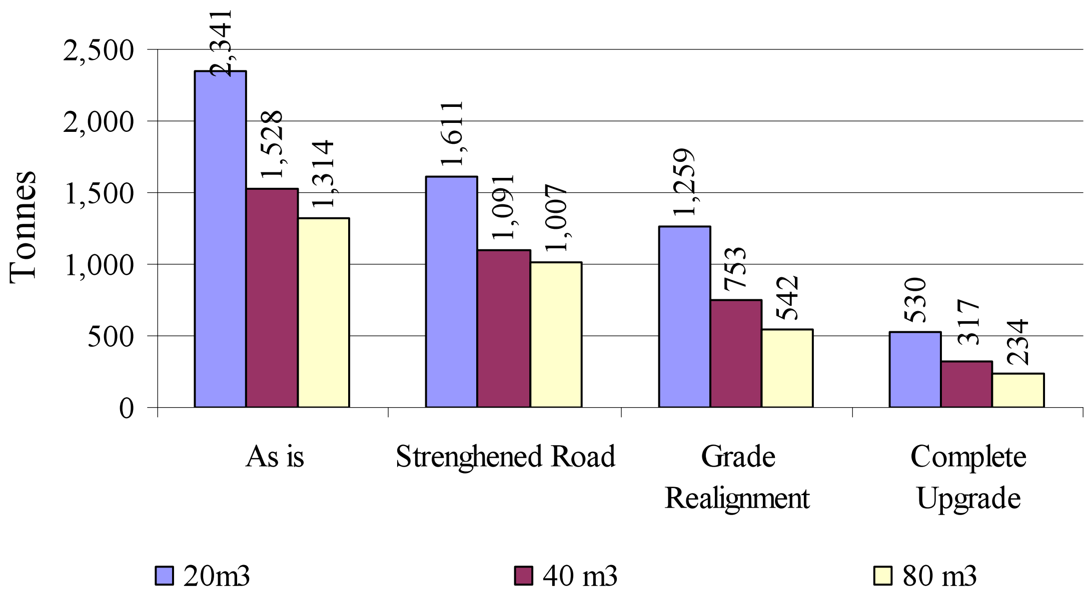

Figure 5.6: Annual CO Emissions by Truck Size and Road Upgrade Level

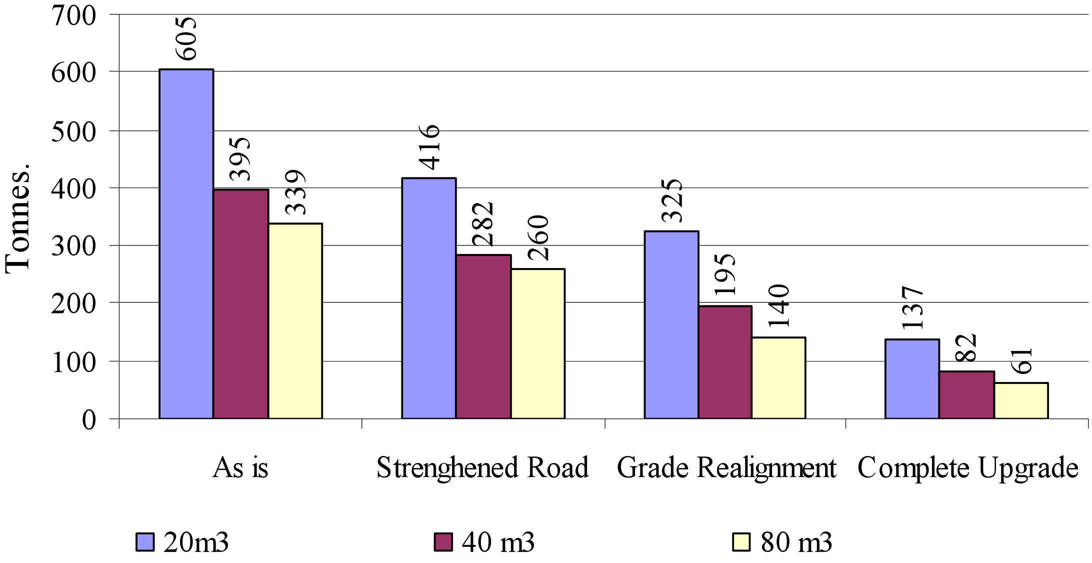

Figure 5.7: Annual NOx Emissions by Truck Size and Road Upgrade Level

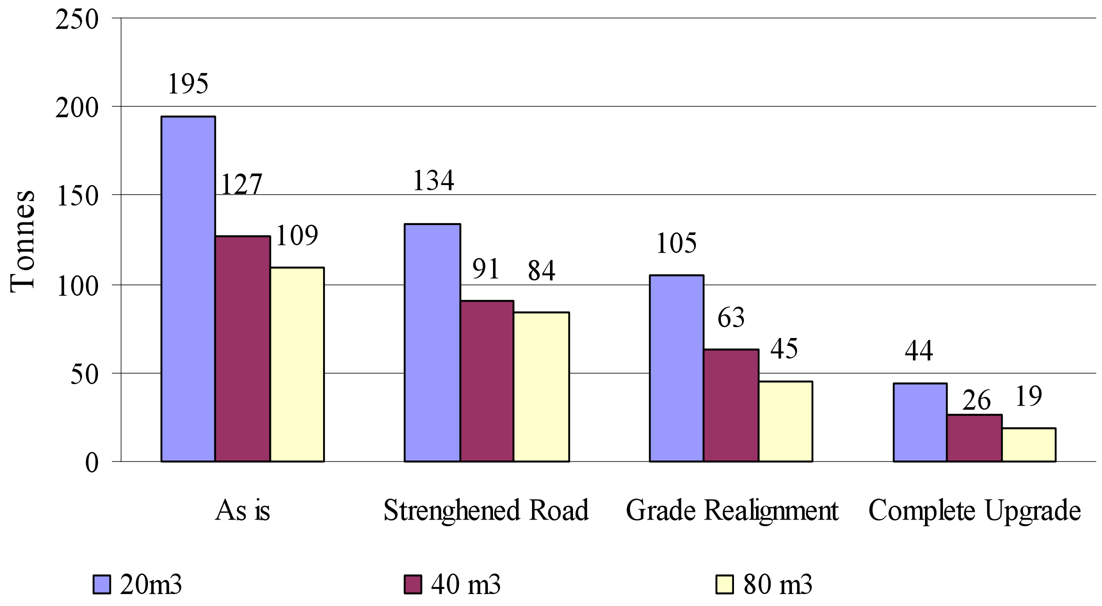

Figure 5.8: Annual HC Emissions by Truck Size and Road Upgrade Level

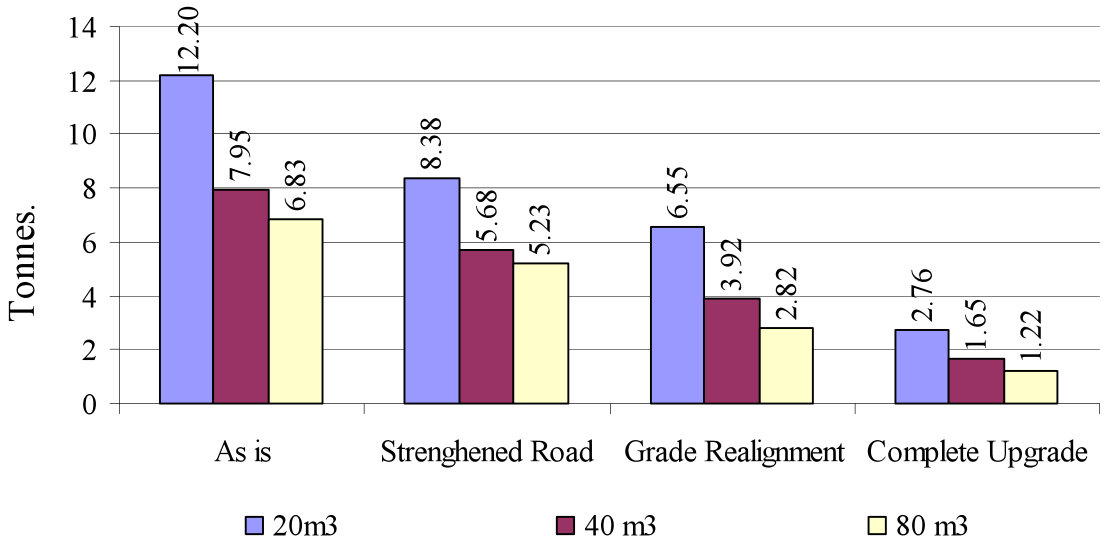

Figure 5.9: Annual PM Emissions by Truck Size and Road Upgrade Level

Table 5.12 and Figure 5.10 summarise emission reductions in terms of percentage according to the truck size increase. These reductions are the same for each emission type, $CO_2$, CO, NOx, HC, and PM. As seen in Table 5.12 and Figure 5.10 the emission reductions are maximal when the truck size is upgraded from 20m$^3$ to 80m$^3$ (44 percent). Then, the reductions are the highest when the road grades are realigned (57 percent for grade realignment, against 56 percent for complete upgrade). In fact, grade realignment and complete upgrade would generate approximately the same emission reduction results, irrespective of truck size. Moreover, the emission reductions from 40m$^3$ to 80m$^3$ are less important than from 20m$^3$ to 40m$^3$, which would mean that there are more benefits by increasing the truck size from 20m$^3$ to 40m$^3$ than from 40m$^3$ to 80m$^3$.

**Table 5.12: Emission Reduction by Truck Size Increase**

| | % Reduction | | | |
|---|---|---|---|---|
| **Truck Size Shift** | **As Is** | **Strengthened Road** | **Grade Realignment** | **Complete Upgrade** |
| **From 20m$^3$ to 40m$^3$** | 35 | 32 | 40 | 40 |
| **From 20m$^3$ to 80m$^3$** | 44 | 38 | 57 | 56 |
| **From 40m$^3$ to 80m$^3$** | 14 | 8 | 28 | 26 |

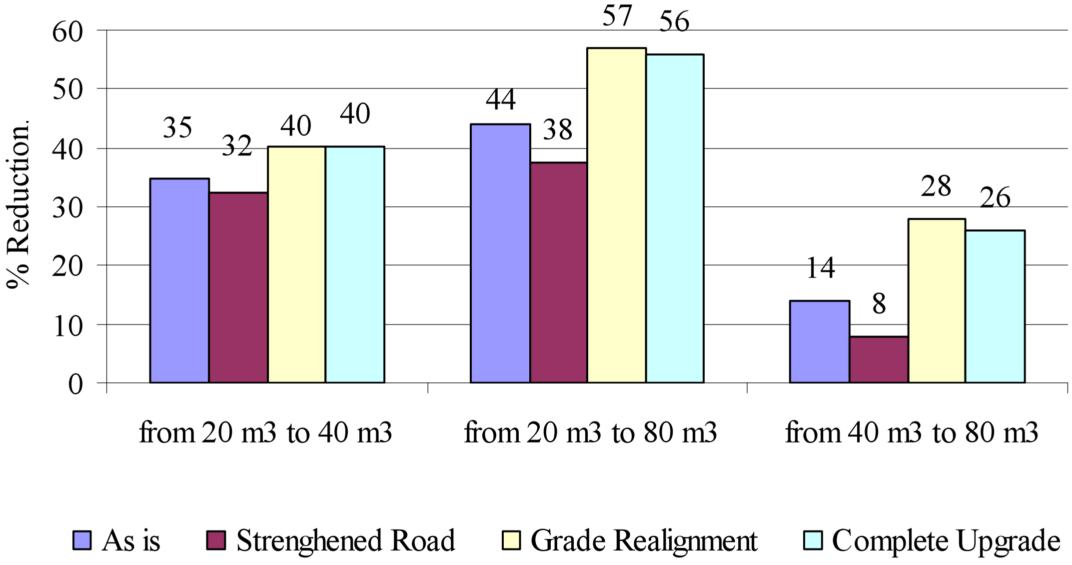

**Figure 5.10: Emission Reductions by Truck Size Increase**

In addition, still for each emission type, the emission reductions by road upgrade indicate in Table 5.13 and Figure 5.11 that the reductions are maximized with an 80m$^3$ truck size on a complete road upgrade, or 82 percent reduction. This would mean that, if roads have a better ride quality, heavier trucks are more efficient, and emit less pollutant. It may also be observed that the emission reductions vary within the truck size type according to the road upgrade level. Indeed, if the road is only strengthened, the emission reductions would decrease as the truck size increases (31 percent reduction for 20m$^3$, 29 percent for 40m$^3$, 23 percent for 80m$^3$). On the contrary, if the road grades are realigned, emission reductions increase as truck size increases (46 percent reduction for 20m$^3$, 51 percent for 40m$^3$, 59 percent for 80m$^3$). Moreover, with a complete upgrade, the emission reductions increase more as the truck size increases (77 percent reduction for 20m$^3$, 79 percent for 40m$^3$, and 82 percent for 80m$^3$). Then, a simple road strengthening is not enough to maximize the emission reductions as the truck size increases. Grade realignment, or even better, a complete upgrade is then required to obtain tangible savings.

**Table 5.13: Emission Reductions by Road Upgrade**

| Truck Size | % Emissions decrease from As is to Strengthened Road | % Emissions decrease from As is to Grade Realignment | % Emissions decrease from As is to Complete Upgrade |
|---|---|---|---|
| **20 m$^3$** | 31 | 46 | 77 |
| **40 m$^3$** | 29 | 51 | 79 |
| **80 m$^3$** | 23 | 59 | 82 |

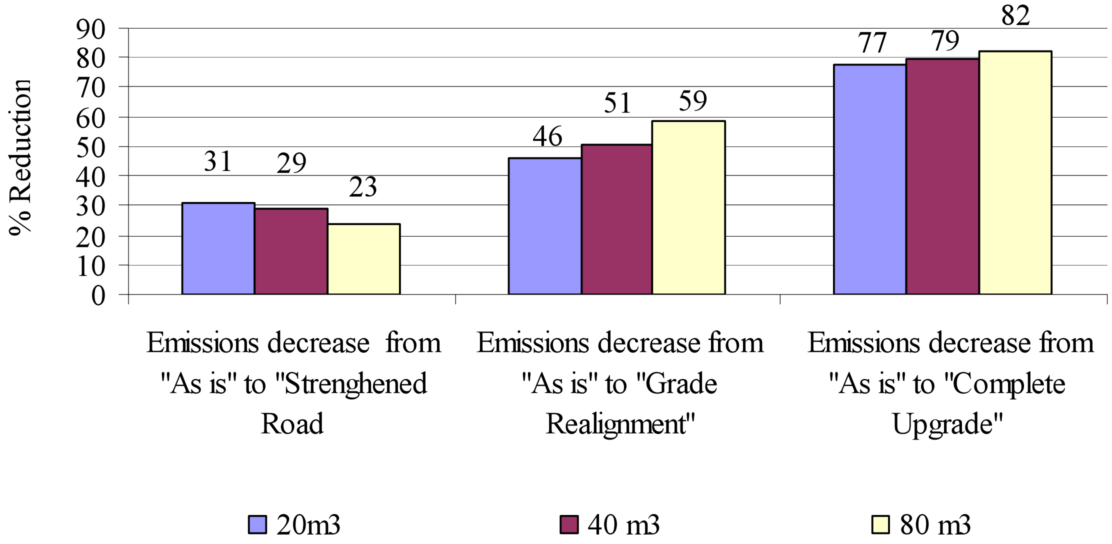

**Figure 5.11: Emission Reductions by Road Upgrade**

Table 5.14 and Figure 5.12 summarize the emission reduction by both truck size and road upgrade. They show that the emission reductions can be optimized when the truck size is increased from 20m$^3$ to 80m$^3$, and when the road receives a complete upgrade, which equals a reduction of 90 percent.

**Table 5.14: Emission Reduction by Truck Size Increase and Road Upgrade**

| | % Reduction | | | |
|---|---|---|---|---|
| **Truck Size Shift** | **As is** | **From As is to Strengthened Road** | **From As is to Grade Realignment** | **From As is to Complete Upgrade** |
| **From 20m$^3$ to 40m$^3$** | 35 | 53 | 68 | 86 |
| **From 20m$^3$ to 80m$^3$** | 44 | 57 | 77 | 90 |
| **From 40m$^3$ to 80m$^3$** | 14 | 34 | 64 | 85 |

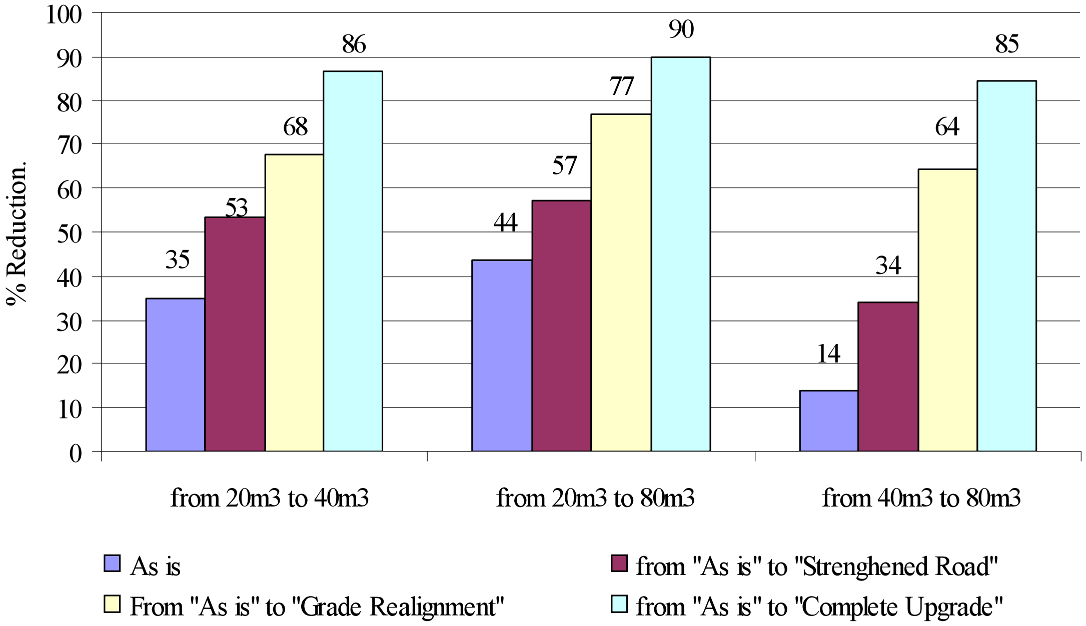

**Figure 5.12: Emission Reduction by Truck Size Increase and Road Upgrade**

Only the $CO_2$ emission reductions by truck size and road upgrade can be related to the Kyoto Protocol targets. The Kyoto Protocol targets mean reducing by 15 percent the overall Canada road freight transportation $CO_2$ emissions under 1990 levels (146,000 kilo tonnes) within the period 2008-2012, which would equal 21,900 kilo tonnes of $CO_2$ reduced emissions. Based on Table 5.11, Table 5.15 illustrates the RM of Britannia $CO_2$ reductions in terms of percentage of the Kyoto Protocol targets for the transportation sector.

**Table 5.15: $CO_2$ Emission Reduction by Truck Size and Road Upgrade in Percentage of Kyoto Protocol Target in RM of Britannia**

| Annual Tonnes of $CO_2$ emissions | | | | | % of Kyoto Protocol Target (21,900 Kt) |
|---|---|---|---|---|---|
| From $20m^3$ on as is road | To $80m^3$ on as is road | To $20m^3$ on upgraded road | To $80m^3$ on upgraded road | Reduction | |
| 29,751 | 16,707 | | | 13,044 | 0.06 |
| 29,751 | | 6,742 | | 23,009 | 0.10 |
| 29,751 | | | 2,985 | 26,766 | 0.12 |

By reducing its annual $CO_2$ emissions, RM of Britannia would contribute between 0.06 and 0.12 percent of the Kyoto Protocol targets for the freight transportation sector, according to the chosen alternative.

These RM of Britannia results are assumed to represent only one percent of the total oil haul. These results can be multiplied by average of 100, (CAPP Statistical Handbook 2004), and show that the whole Canadian oil haul annual $CO_2$ emission reductions would contribute between 6 and 12 percent of the Kyoto Protocol targets for the freight transportation sector in Canada.

### 5.3.2.2. Short Haul Heavy Oil Emission Costs Results for RM of Britannia

Because of the type of data collected in the literature about the mass of emissions produced annually in Canada, the emission reductions costs of $CO_2$ are the only ones that can be compared to Canada emissions costs (references: Table 2.11 and Table 3.6).

Based on the following Table 5.16, if a $20m^3$ truck fleet on a as is road is upgraded to a $80m^3$ truck fleet, there would be some average savings in $CO_2$ costs of \$544,000 (\$1,240,000 - \$696,000), equivalent to 0.03 percent reduction in the Canada road freight transportation $CO_2$ emissions costs.

As seen in Table 5.16, if a $20m^3$ truck fleet on a as is road is changed to a $20m^3$ truck fleet on a complete upgraded road, there would be some average savings in $CO_2$ costs of $959,000 ($1,240,000 - $281,000), equivalent to 0.053 percent reduction in the Canada road freight transportation $CO_2$ emissions costs.

As seen in Table 5.16, if a $20m^3$ truck fleet on a as is road is upgraded to a $80m^3$ truck fleet on a complete upgraded road, there would be some average savings in $CO_2$ costs of $1,116,000 ($1,240,000 - $124,000), equivalent to 0.06 percent reduction in the Canada road freight transportation $CO_2$ emission costs.

Concerning the overall emissions costs as calculated using international published unit rates for emissions, the percentages of reductions are the same as for the emission releases, whatever emission type. Emission reductions costs are optimum as the truck size is upgraded from $20m^3$ to $80m^3$, especially with a complete upgrade of the road, and involve an emission costs reduction up to 90 percent, as summarized in Table 5.12 through Table 5.14; and Figure 5.10 through Figure 5.12.

### Table 5.16: Emissions Cost by Truck Size and Road Upgrade Level

| Emissions | Truck size | '000 CAD$ | As is | Strengthened Road | Grade Realignment | Complete Upgrade |
|---|---|---|---|---|---|---|
| **$CO_2$** | $20m^3$ | Low | 8 | 5 | 4 | 2 |
| | | Average | **1,240** | 854 | 667 | **281** |
| | | High | 6,939 | 4,778 | 3,734 | 1,573 |
| | $40m^3$ | Low | 5 | 4 | 2 | 1 |
| | | Average | 810 | 579 | 400 | 168 |
| | | High | 4,531 | 3,237 | 2,236 | 942 |
| | $80m^3$ | Low | 4 | 3 | 2 | 1 |
| | | Average | **696** | 533 | 288 | **124** |
| | | High | 3,897 | 2,984 | 1,609 | 696 |
| **CO** | $20m^3$ | Low | 153 | 105 | 82 | 35 |
| | | Average | **2,984** | 2,053 | 1,605 | **675** |
| | | High | 20,239 | 13,928 | 10,885 | 4,582 |
| | $40m^3$ | Low | 100 | 71 | 49 | 21 |
| | | Average | 1,947 | 1,390 | 960 | 404 |
| | | High | 13,210 | 9,432 | 6,510 | 2,741 |
| | $80m^3$ | Low | 86 | 66 | 35 | 15 |
| | | Average | **1,675** | 1,283 | 691 | **298** |
| | | High | 11,360 | 8,706 | 4,686 | 3,023 |
| **NOx** | $20m^3$ | Low | 10 | 7 | 5 | 2 |
| | | Average | **10,547** | 7,252 | 5,666 | **2,388** |
| | | High | 40,716 | 27,996 | 21,872 | 9,220 |
| | $40m^3$ | Low | 7 | 5 | 3 | 1 |
| | | Average | 6,886 | 4,916 | 3,399 | 1,430 |
| | | High | 26,583 | 18,978 | 13,123 | 5,519 |
| | $80m^3$ | Low | 6 | 4 | 2 | 1 |
| | | Average | **5,910** | 4,533 | 2,441 | **1,063** |
| | | High | 22,814 | 17,498 | 9,422 | 4,105 |
| **HC** | $20m^3$ | Low | 34.18 | 23.49 | 18.40 | 7.71 |
| | | Average | **181.01** | 124.39 | 97.47 | **40.84** |
| | | High | 423.00 | 290.68 | 227.77 | 95.45 |
| | $40m^3$ | Low | 22.26 | 15.95 | 11.04 | 4.56 |
| | | Average | 117.89 | 84.47 | 58.48 | 24.14 |
| | | High | 275.49 | 197.40 | 136.66 | 54.40 |
| | $80m^3$ | Low | 19.11 | 14.72 | 7.89 | 3.33 |
| | | Average | **101.18** | 77.97 | 41.77 | **17.64** |
| | | High | 236.45 | 182.22 | 97.22 | 41.22 |
| **PM** | $20m^3$ | Low | 4 | 3 | 2 | 1 |
| | | Average | **2,942** | 2,021 | 1,580 | **666** |
| | | High | 14,816 | 10,177 | 7,955 | 3,352 |
| | $40m^3$ | Low | 2 | 2 | 1 | 1 |
| | | Average | 1,917 | 1,370 | 945 | 398 |
| | | High | 9,655 | 6,898 | 4,761 | 2,004 |
| | $80m^3$ | Low | 2 | 2 | 1 | 0 |
| | | Average | **1,647** | 1,261 | 680 | **294** |
| | | High | 8,295 | 6,352 | 3,425 | 1,482 |

#### 5.3.2.3. Short Haul Heavy Oil Fuel Consumption for RM of Britannia

As well, the fuel consumption reduces when the truck size is increased to 80m$^3$ and the roads are upgraded. The maximum fuel consumption reduction is still equal to 90 percent, equivalent to (3,368,000 – 337,000) 3,031,000 litres of fuel saved annually. Table 5.17 and Figure 5.13 illustrate the results.

Again, the percentages of fuel reductions by truck size, road upgrade, and both combined, are the same as the percentages of emissions reductions presented in Table 5.12 through Table 5.14 and Figure 5.10 to Figure 5.12.

**Table 5.17: Fuel Consumption ('000 litres) by Truck Size and Road Upgrade Level**

| Truck Size | As is | Road Upgrade Levels<br>Strengthened Road | Grade Realignment | Complete Upgrade |
|---|---|---|---|---|
| **20m$^3$** | **3,368** | 2,319 | 1,812 | 762 |
| **40m$^3$** | 2,198 | 1,570 | 1,084 | 456 |
| **80m$^3$** | 1,891 | 1,447 | 780 | **337** |

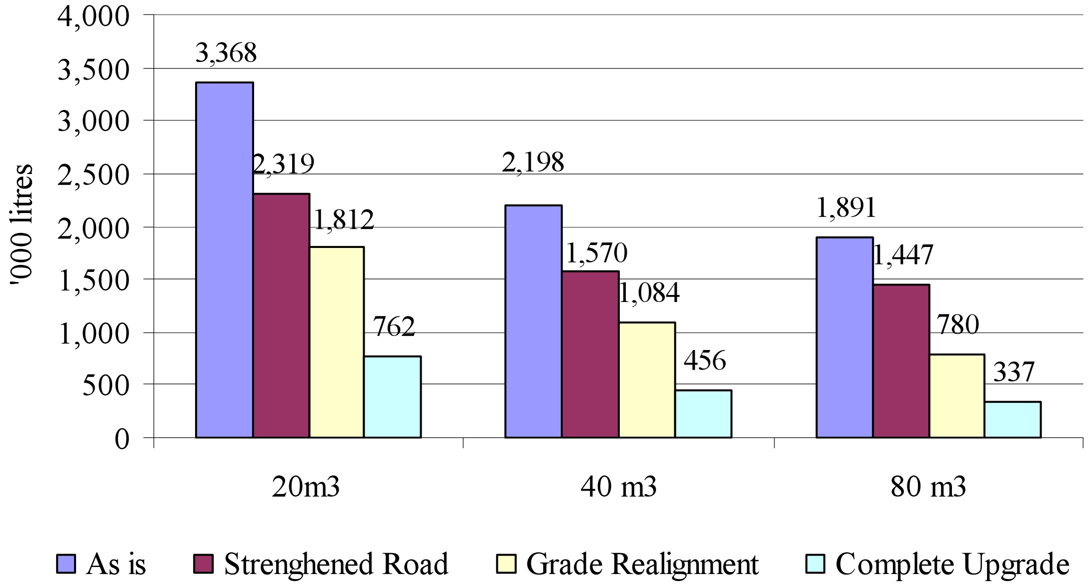

Figure 5.13: Fuel Consumption by Truck Size and Road Upgrade Level

Based on Appendix F, Figure 5.14 shows that, by increasing the truck size, the number of t-km travelled decreases, especially from 20m$^3$ to 80m$^3$, or 75 percent. The reduction of the t-km travelled is important in terms of safety, because less kilometres travelled means lower speeds, as well as less exposure through fewer number of trucks.

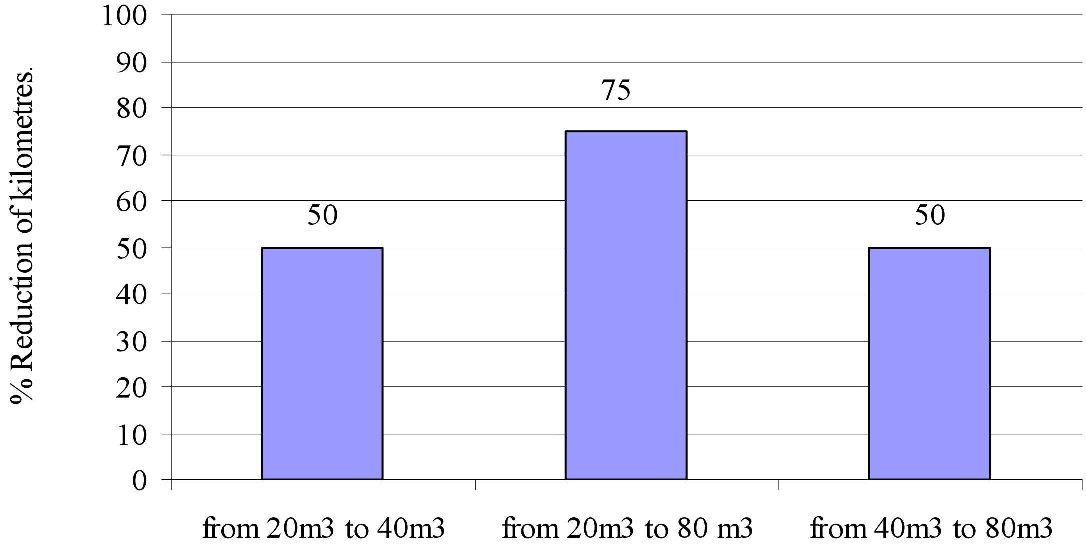

**Figure 5.14: Kilometres Travelled by Truck Size**

These reductions can also be applied to the number of trucks used a day. Indeed, by using 40m$^3$ payload trucks instead of 20m$^3$ payload trucks, the number of trucks will be reduced from 56 to 28 trucks a day, or a reduction of 50 percent. Moreover, if these 20m$^3$ payload trucks are replaced by 80m$^3$ payload trucks, the fleet will equal 14 trucks a day, or a reduction of 75 percent. In any case, the amount of heavy oil hauled annually will stay the same. (Confer Appendix F).

#### 5.3.2.4. Short Haul Heavy Oil Fuel Costs Savings

If the sizes of heavy oil field trucks are increased from 20m$^3$ to 80 m$^3$, and if the road is completely upgraded, fuel cost reductions would be as well maximized (90 percent). Based on Table 5.17, Table 5.18 and Figure 5.15 illustrate the data. The values are based on diesel fuel unit price varying between \$0.65 (low), \$0.80 (average), and

\$1.00 (high) per litre. Therefore, if a 20m$^3$ fleet on a as is road is upgraded to a 80m$^3$, the reduction equals 43.9 percent, or 1,477,000 litres of fuel saved, which is equivalent to an average of \$1,181,894 (\$2,694,538 - \$1,512,644). Then, when a 20m$^3$ fleet on a as is road is upgraded to a 20m$^3$ fleet on a complete upgraded road, the reduction equals 77.4 percent, or 2,606,000 litres of fuel saved, which is equivalent to an average of \$2,084,855 (\$2,694,538 - \$609,683). Finally, when a 20m$^3$ fleet on a as is road is upgraded to a 80m$^3$ fleet on a complete upgraded road, the reduction equals 90 percent, or 3,031,000 litres of fuel saved, which is equivalent to an average of \$2,425,314 (\$2,694,538 - \$269,224). Fuel costs savings are then in between \$1.2 and \$2.4 million per year.

In summary, emissions quantities (Table 5.11), emissions costs (Table 5.16), fuel quantities (Table 5.17), and fuel costs (Table 5.18) show the same annual savings in percentage according to the truck size and the road upgrade. However, in terms of costs savings, the results vary between the emissions savings and the fuel savings, as explained in the following section.

**Table 5.18: Fuel Costs by Truck Size and Road Upgrade**

| Truck Size | $ Values | As is | Strengthened Road | Grade Realignment | Complete Upgrade |
|---|---|---|---|---|---|
| | Low | 2,189,312 | 1,507,083 | 1,177,597 | 495,368 |
| **20m$^3$** | Average | **2,694,538** | 1,854,871 | 1,449,350 | **609,683** |
| | High | 3,368,173 | 2,318,589 | 1,811,688 | 762,104 |
| | Low | 1,428,978 | 1,020,773 | 704,569 | 296,364 |
| **40m$^3$** | Average | 1,758,742 | 1,256,336 | 867,162 | 364,755 |
| | High | 2,198,428 | 1,570,420 | 1,083,952 | 455,944 |
| | Low | 1,229,023 | 940,840 | 506,928 | 218,745 |
| **80m$^3$** | Average | **1,512,644** | 1,157,957 | 623,911 | **269,224** |
| | High | 1,890,805 | 1,447,446 | 779,889 | 336,530 |

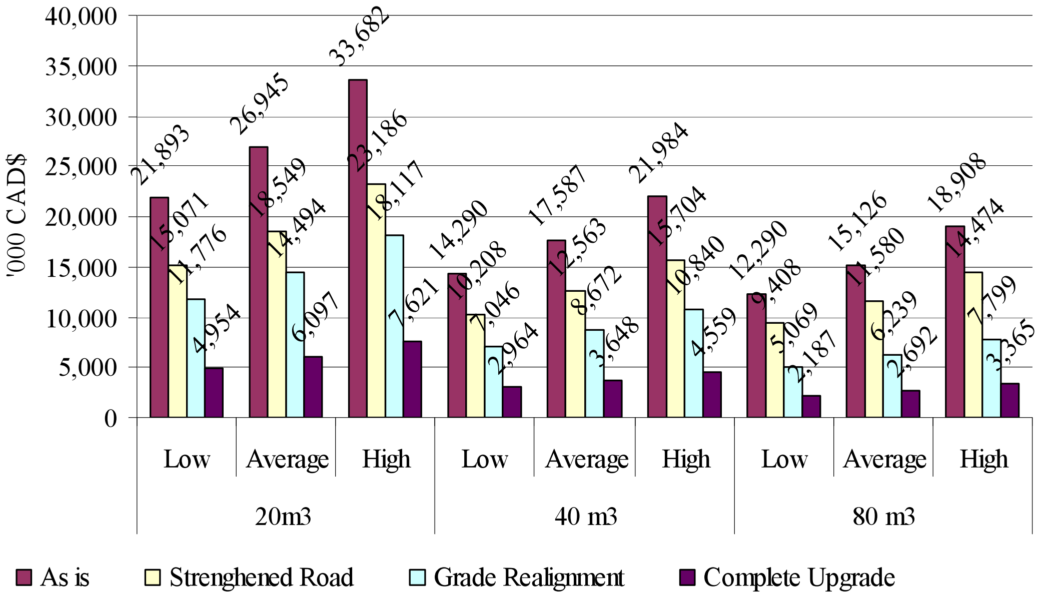

**Figure 5.15: Fuel Costs by Truck Size and Road Upgrade**

### 5.3.2.5. Comparison between Short Haul Heavy Oil Emissions Savings and Fuel Savings

Table 5.19, Table 5.20, Figure 5.16 and Figure 5.17 illustrate the average minimum and maximum savings that can be made from a 20m$^3$ on an as is road alternative to an 80m$^3$ on an upgraded road alternative. These savings are based on emissions and fuel average costs from Table 5.16 and Table 5.18.

**Table 5.19 : Minimum Costs Savings from Increased Truck Size to 20m$^3$ to 80m$^3$ for a Typical Heavy Oil Haul Rural Municipality**

| | Costs ($) | | Minimum Savings |
|---|---|---|---|
| | 20m$^3$ on an *as is* road | 80m$^3$ on an *as is* road | |
| **Fuel** | 2,694,538 | 1,512,644 | 1,181,894 |
| **$CO_2$** | 1,240,000 | 696,000 | 544,000 |
| **CO** | 2,984,000 | 1,675,000 | 1,309,000 |
| **NOx** | 10,547,000 | 5,910,000 | 4,637,000 |
| **HC** | 180,010 | 101,180 | 79,830 |
| **PM** | 2,942,000 | 1,647,000 | 1,295,000 |
| **Total Emissions** | **17,893,010** | **10,029,180** | **7,863,830** |

**Table 5.20: Maximum Costs Savings from Increased Truck Size to 20m$^3$ to 80m$^3$ for a Typical Heavy Oil Haul Rural Municipality**

| | **Costs ($)** | | **Maximum Savings** |
|---|---|---|---|
| | **20m$^3$ on a *as is* road** | **80m$^3$ on an upgraded road** | |
| **Fuel** | 2,694,538 | 269,224 | 2,425,314 |
| **$CO_2$** | 1,240,000 | 124,000 | 1,116,000 |
| **CO** | 2,984,000 | 298,000 | 2,686,000 |
| **NOx** | 10,547,000 | 1,063,000 | 9,484,000 |
| **HC** | 180,010 | 17,640 | 162,370 |
| **PM** | 2,942,000 | 294,200 | 2,647,800 |
| **Total Emissions** | **17,893,010** | **1,796,840** | **16,096,170** |

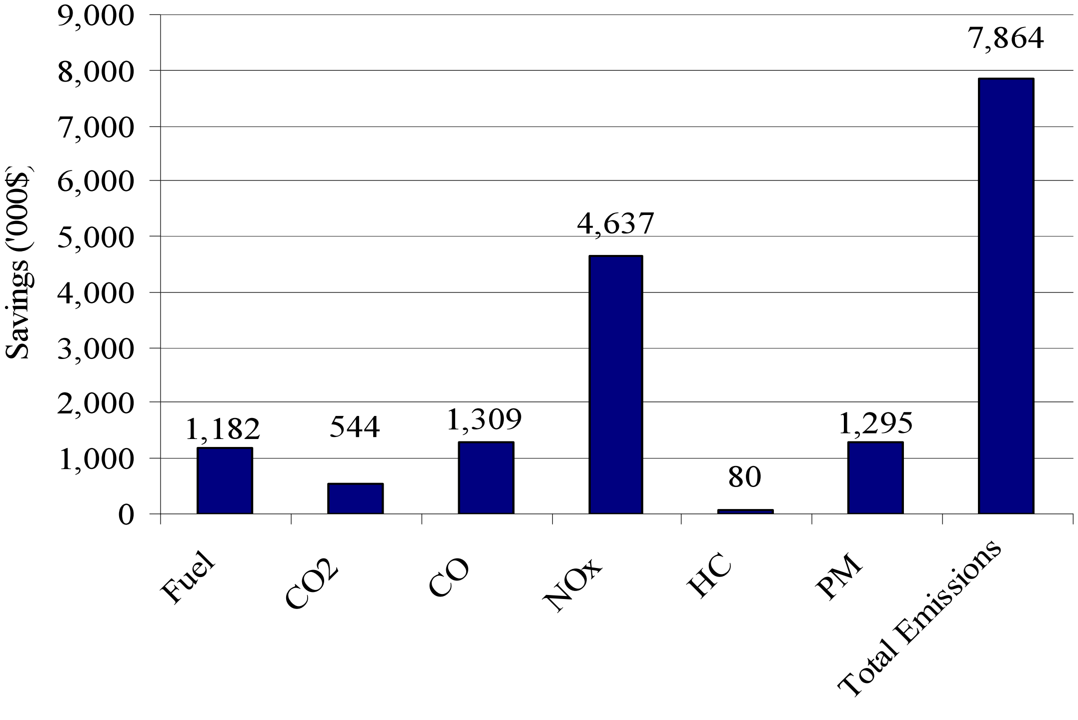

**Figure 5.16: Minimum Costs Savings from Increased Truck Size to 20m$^3$ to 80m$^3$ for a Typical Heavy Oil Haul Rural Municipality**

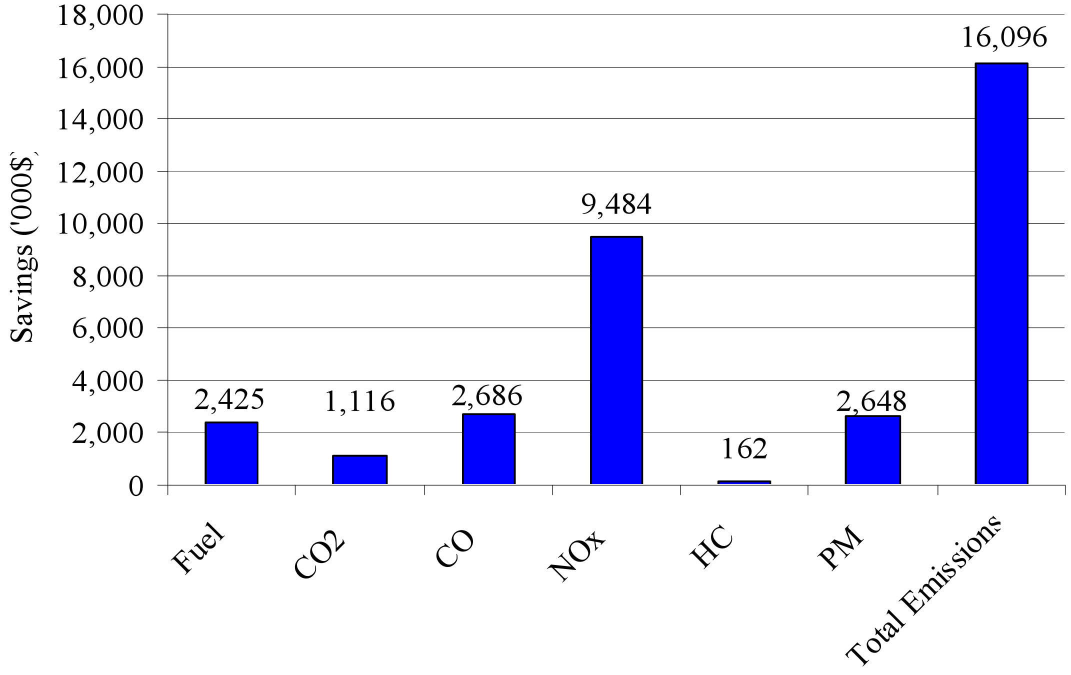

**Figure 5.17 : Maximum Costs Savings from Increased Truck Size to 20m$^3$ to 80m$^3$ for a Typical Heavy Oil Haul Rural Municipality**

In both cases, emissions costs savings are significantly greater than fuel cost savings. This difference is partly due to the fact that one litre of fuel does not produce one tonne of emissions, which also varies according to the emissions type. For example, based on EPA standards for idling emissions (confer Appendices C and F), one hour of idling would equal 3.63 litres of fuel, and between 4.36 kgs and 9.14 kgs of $CO_2$ emitted. Therefore one litre of fuel could produce between 1.2 kgs and 2.5 kgs of $CO_2$ These differences in $ savings are presented in Table 5.21 and Figure 5.18. Indeed the RM's total emissions costs savings would be approximately $8 million to $16 million, while the overall fuel costs savings would be approximately $1.2 to $2.5 million, approximately 15 percent of emissions savings.

Table 5.21: RM of Britannia Range of Annual Costs Savings

| | **Minimum $ Savings** | **Maximum $ Savings** |
|---|---|---|
| **Fuel** | 1,181,894 | 2,425,314 |
| **CO2** | 544,000 | 1,116,000 |
| **CO** | 1,309,000 | 2,686,000 |
| **NOx** | 4,637,000 | 9,484,000 |
| **HC** | 79,830 | 162,370 |
| **PM** | 1,295,000 | 2,647,800 |
| **Total Emissions** | **7,863,830** | **16,096,170** |

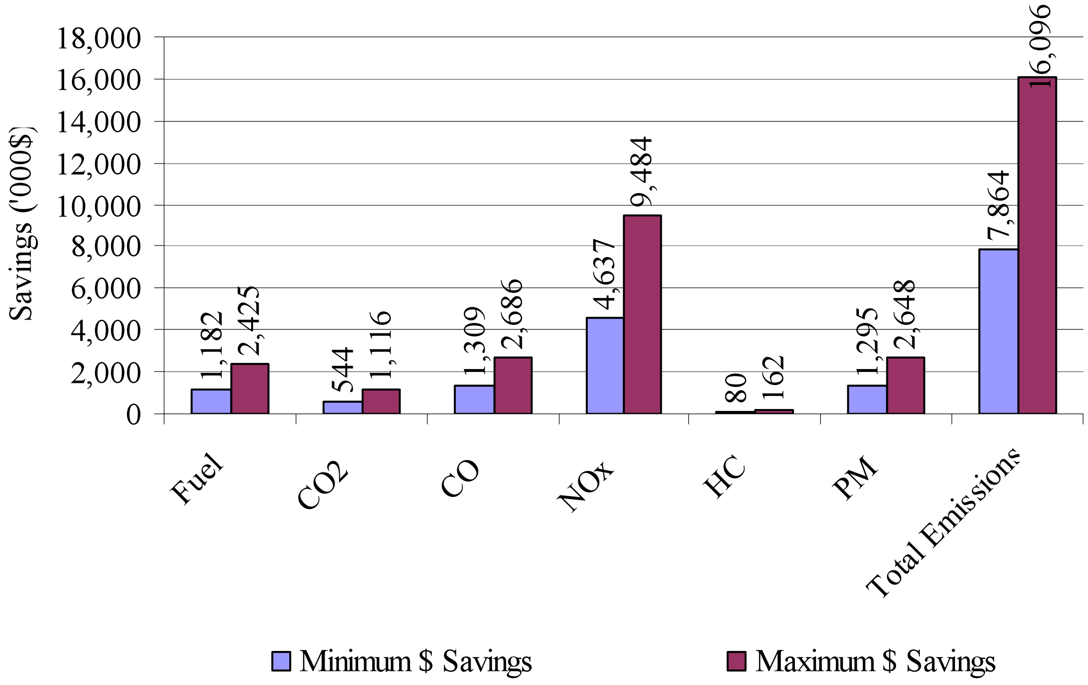

Figure 5.18: RM of Britannia Range of Emissions Cost Savings

### 5.3.3. Short Haul Heavy Oil Savings across Western Canada

To include all the RM's and counties within Western Canada and encompass all savings in heavy oil industry, emission and fuel costs savings results from the RM of Britannia were multiplied by 50, assuming RM of Britannia accounts for two percent of heavy oil field production in Western Canada, and based on 2004 CAPP data about Canadian crude oil production (CAPP Statistical Handbook 2004)

Based on Table 5.15, Table 5.22 illustrates the $CO_2$ emission reduction within the overall RM's and counties in Western Canada in terms of percentage of the Kyoto Protocol targets for transportation sector. The Kyoto Protocol targets represent a reduction of 15 percent of the Canadian road freight transportation $CO_2$ emissions related to 1990 levels (146,000 kilo tonnes) within the period 2008-2012. This translates to 21,900-kilo tonnes of $CO_2$ emissions to be reduced in Canada.

**Table 5.22: $CO_2$ Emission Reduction by Truck Size and Road Upgrade in Percentage of Kyoto Protocol Target**

| Tonnes of $CO_2$ emissions | | | | | % of Kyoto |
|---|---|---|---|---|---|
| From $20m^3$ on as is road | To $80m^3$ on as is road | To $20m^3$ on upgraded road | To $80m^3$ on upgraded road | Reduction | Protocol Target (21,900 Kt) |
| 1,487,550 | 835,350 | | | 652,200 | 2.9 |
| 1,487,550 | | 337,100 | | 1,150,450 | 5.3 |
| 1,487,550 | | | 149,250 | 1,338,300 | 6.1 |

Therefore, by reducing their $CO_2$ emissions with improved road upgrades and larger more efficient vehicles operating in the heavy oil sector , reduction in emissions across all RM's and counties in Western Canada would be approximately 2.9 to 6.1 percent of the Kyoto Protocol targets for the transportation sector, according to the chosen alternative. Concerning the emissions and fuel costs savings, the results, which were all multiplied by 50, are illustrated in Table 5.23 and Figure 5.19 and are based on Table 5.21.

Table 5.23: Western Canada Heavy Oil Emission Savings

| | Emissions Savings $20m^3$ to $40m^3$ Truck with no Road Upgrades | Emissions Savings $20m^3$ to $40m^3$ Truck with Road Upgrades |
|---|---|---|
| **Fuel** | 59,094,700 | 121,265,700 |
| **CO2** | 27,200,000 | 55,800,000 |
| **CO** | 65,450,000 | 134,300,000 |
| **NOx** | 231,850,000 | 474,200,000 |
| **HC** | 3,991,500 | 8,118,500 |
| **PM** | 64,750,000 | 132,390,000 |
| **Total Emissions** | **393,191,500** | **804,808,500** |

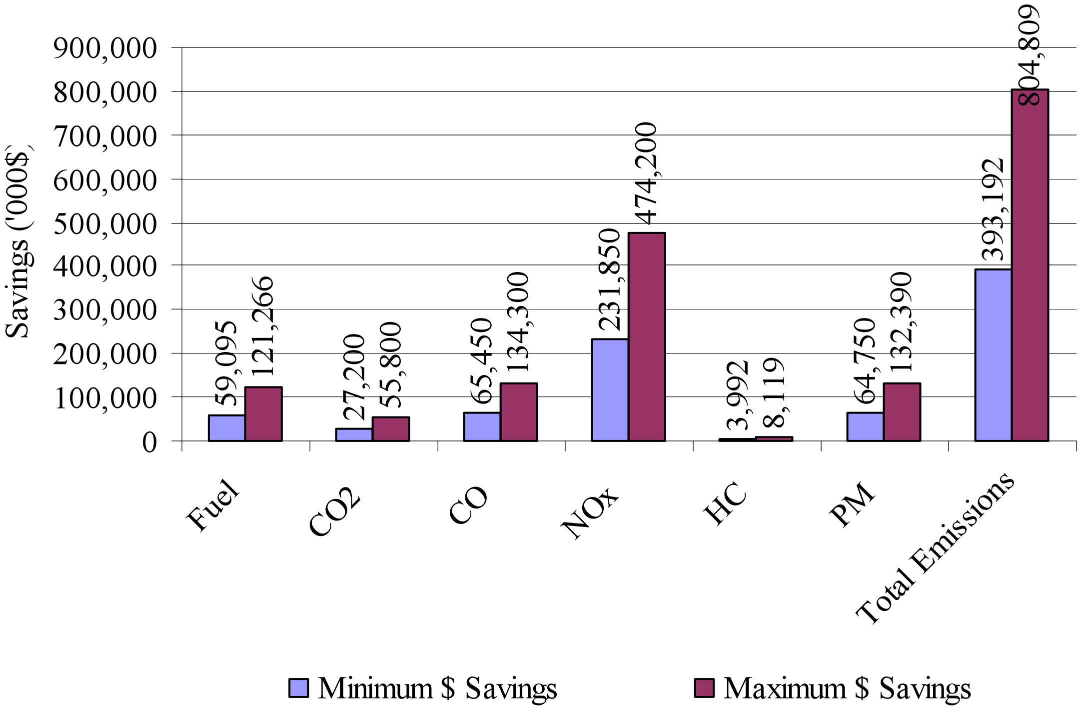

Figure 5.19: Western Canada Reduced Emission Savings across Heavy Oil

Across heavy oil production in Western Canada, the emissions savings would range from \$393 million and \$805 million, while the overall user cost fuel savings would range from \$59 million and \$121 million.

This chapter calculated benefits to road users in terms of reduced fuel consumption and clearly illustrates the relative importance of reduced emissions costs in road transport calculations. This chapter illustrates how the mechanistic emissions model developed in this research can be applied to diverse commercial transport applications. In both cases, the model illustrates the significant cost of heavy vehicle emissions related to road transport. If published emissions quantities and unit costs of emissions are correct, this model accurately predicts emissions quantities and costs associated with heavy truck transport, both in long haul and short heavy haul applications.

# 6.0 SUMMARY, CONCLUSION AND RECOMMENDATIONS

Air pollution from road transportation has a significant impact on human health and the environment. As a result, world transportation agencies are now considering environmental costs in addition to conventional agency and road user costs, in order to preserve the environment, and optimize the holistic social utility of transport.

The objective of this research is to develop a fundamentals based fuel consumption and emissions model. The model was built with the ability to quantify the fuel users and environmental costs and benefits resulting from alternative truck transport strategies and road structural upgrades, including weigh-in-motion systems and increases in allowable heavy vehicle weights.

Within the model, independent variables were identified and categorized in three main groups, vehicle properties, fuel properties, and field operations. Values, including emissions costs, and probabilities were assigned to quantify all the independent variables, using data from the worldwide literature review.

A sensitivity analysis was then performed across all independent variables by field application in order to determine which independent variables would affect the results. The analysis indicates that idle time was sensitive to change in the case of the weigh-in-motion case study, while road grades and road stiffness were sensitive to change in the case of the short heavy haul case study.

The validation of the model was performed by comparing the model results with published results. The model predictions, quantified in terms of annual $CO_2$ emitted in Canada, were higher than those reported the literature by approximately 52 percent.

A second comparison was performed in terms of emission unit rates, or grams/kilometre, for $CO_2$, CO, NOx, HC, and PM emissions. Again, the model predictions were, apart from PM emissions, found to be higher than the published results. Indeed, $CO_2$ emission results from the model predictions were higher by 50 percent than the average published results; CO emission results were higher by 609 percent than the average published results; NOx emission results were higher by 177 percent than the average published results; HC emission results were higher by 59 percent than the average published results; and PM emission results were lower by 26.5 percent than the average published results. However, the difference of values between the model results and the literature results was in the same range as the difference of values within the literature results themselves. Therefore, the model results were realistic enough to validate the model.

The model was then applied to two field case studies: 1) using weigh-in-motion to pre sort trucks at weigh stations in Canada and the US; and 2) short heavy oil field haul within heavy oil production.

First, the model showed that using WIM systems to pre-sort trucks at weigh stations would reduce Canadian road freight $CO_2$ emissions by an average of 228 kilo tonnes per year, which would represent 1.04 percent of the 1990 Kyoto Protocol targets in the road freight transportation sector (21,900 kilo tonnes), or between $60,000 and $53 million per year. Therefore, using WIM systems in Canada would reduce the overall Canada road freight transportation $CO_2$ emission costs (between $11.8 million and $10 trillion in 2000) by 0.53 percent. Concerning fuel, it would save from 90 to 190 million litres per year in Canada, resulting in between $59 and $190 million of annual direct operating cost savings.

If WIM systems were used in the United States, it would save between 690 and 1,513 million litres of fuel, or between CAD $448 million and CAD $1.5 trillion, and would reduce the emissions by 1.7 million tonnes (- 0.29 percent), or between CAD $450,000 and CAD $342 million.

The second case study that applied the emission model developed in this research evaluated the impact of truck size and road upgrades within a typical heavy oil producing rural municipality. Results indicate that by increasing allowable heavy vehicle weights and dimensions while upgrading roads, in terms of strengthening and grade realignment, the fuel consumption, the emissions, and the related costs would be proportionally reduced by an average of 68 percent per year.

More particularly, by increasing allowable vehicle weights and dimensions only, the reductions would range from 14 percent minimum, when the truck size is upgraded from $40m^3$ to $80m^3$, to 56 percent maximum, when the truck size is upgraded from $20m^3$ to $80\ m^3$. By upgrading the roads, the reductions would range from 23 percent to 82 percent, respectively. Finally, by combining vehicles size increase and road upgrades, the reductions would then range from 14 percent to 90 percent, the best reduction being when the truck size is upgraded from $20m^3$ to $80m^3$ and the road completely upgraded. However, the emission reductions from a $40m^3$ to $80m^3$ were found to be less important than from $20m^3$ to $40m^3$, which would mean that there are more benefits to increasing the size from $20m^3$ to $40m^3$ than from $40m^3$ to $80m^3$.

In addition, the $CO_2$ emission reductions within a typical rural municipality would vary between 13 and 27-kilo tonnes per year, according to the selected alternative, which would represent between 0.06 and 0.12 percent of the 1990 Kyoto Protocol targets for the Canadian road freight transportation $CO_2$ emission reductions. These $CO_2$ emission reductions were multiplied by 50 to encompass all RM's and counties in Western Canada in heavy oil industry (CAPP Statistical Handbook, 2004). The reductions would vary between 652 and 1.4 million tonnes per year, representing between 2.9 and 6.1 percent of the 1990 Kyoto Protocol targets for the Canadian road freight transportation $CO_2$ emission reductions.

The reductions in $CO_2$ in a typical heavy oil producing rural municipality would also involve $CO_2$ costs savings, representing between $544,000 and $ 1.1 million per year, according to the alternative selected. Taking the five emissions types together ($CO_2$, CO, NOx, HC, and PM), it would represent between $8 million and $16 million saved per year, and between $1.2 million and $2.4 million of fuel costs savings per year.

Based on these results, total environmental emissions savings within the entire heavy oil field of Western Canada would range between \$393 million and \$805 million, while fuel savings would range between \$59 million and \$121 million. These \$ savings must be used with vigilance because they're based on unit cost rates from the literature review, which is not exhaustive. However, it provides an interesting view of the importance of savings resulting from alternative alternate truck transport strategies.

In conclusion, this research model developed a mechanistic evaluation of transportation emissions in terms of user fuel costs and emissions savings. The model was developed based on fundamental engineering principles, as well as providing an analysis framework that is relatively simple, flexible, and user-friendly to be applicable to diverse sustainable transportation strategies.

Future applications of this model will include the ability to assess the environmental benefits of intermodal cargo transports: loading truck trailer containers onto rail cars would be efficient to reduce emissions and their related costs, by limiting the number of trucks on roads. The model could also be used to evaluate the environmental benefits of implementing various traffic control systems that avoid idling time caused by intersections and therefore, would reduce fuel consumption, emissions released, and associated costs. In this case, it is recommended to expand the model by performing other analyses across particular engineering design systems, such as the implications of emissions of a complete road upgrade or WIM implementations in terms of construction cost.

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# APPENDIX A: EMISSIONS FACTORS AND COSTS

## Summary of Agency Worldwide data

## Table A.1: Emissions Rates for Heavy Trucks

| Sources for emissions rates | Calculation factors | low-high | $CO_2$ | Nox | HC | CO | PM |
|---|---|---|---|---|---|---|---|
| **Pratt. 2002** | g/km | low | 1363.91-e | 8.52 | 1.04 | 6.62 | 2.09 |
| | | high | 1363.91-e | 15.29 | 3.78 | 7.86 | 2.09 |
| **CSIRO Atmospheric Research Report to the Australian Greenhouse Office - March 2000<br>Tailpipe emissions** | g/km for tractor diesel | average | 1155 | 10.49 | 0.8 | 4.57 | 0.46 |
| | | low | 941 | 7.31 | 0.18 | 1.94 | 0.19 |
| | | high | 1393 | 12.88 | 1.75 | 17.44 | 1.01 |
| | g/km for tractor truck | average | 1036 | 15.73 | | 1.31 | 0.6 |
| | | low | 1015 | 10.69 | | 1.06 | 0.26 |
| | | high | 1058 | 22 | | 1.44 | 1.11 |
| | g/km for Truck | average | 1296 | 11.02 | | 2.65 | 0.51 |
| | | low | 1221 | 9.06 | | 1.88 | 0.46 |
| | | high | 1370 | 12.63 | | 4.75 | 0.58 |
| **CSIRO Atmospheric Research Report to the Australian Greenhouse Office - March 2000<br>Full fuel cycle** | g/km | Precom | 208 | 1.01 | 2.12 | 3.42 | 0.165 |
| | | Foss.comb | 1296 | 12.89 | 0.82 | 2.98 | 0.55 |
| | | Total | 1504 | 13.9 | 2.94 | 6.4 | 0.715 |
| **TRB - TCRP Report 78 (2002)** | g/km | low | | 5.59 | 4.98 | 61.46 | 0.32 |
| | | high | | 6.4 | 5.95 | 72.89 | 0.48 |
| **Ramamurthy et al (1999)** | g/km | average | | 42.32 | 4.58 | 48.91 | 2.24 |
| **Yanowitz et al. (1999)** | g/km | low | | 0.14 | 4.15 | 2.09 | 0.3 |
| | | average | | 1.71 | 23.39 | 18.23 | 1.95 |
| | | high | | 8.57 | 57.7 | 86.2 | 7.43 |
| www.afdc.doe.gov/emissions.html | g/km | low | 1221 | 9.06 | | 1.88 | 0.46 |
| | | average | 1296 | 11.02 | | 2.65 | 0.51 |
| | | high | 1370 | 12.63 | | 4.75 | 0.58 |

## Table A.2: Emissions Costs

| Sources for cost rates | Calculation factors | low-high | $CO_2$ | Nox | VOCs | CO | PM |
|---|---|---|---|---|---|---|---|
| **TRB - TCRP Report 78 (2002)** | 2004 CAD $/tonne | low | | 2,169.23 | 289.23 | 14.46 | 14,461.56 |
| | | high | | 27,476.96 | 2,169.23 | 144.62 | 199,569.53 |
| **Pratt 2002** | 2004 CAD $/tonne | low | 10.12 | 708.42 | 465.54 | 0.00 | 7,084.25 |
| | | high | 91.08 | 15,180.53 | 465.54 | 12.14 | 1,214,442.69 |
| **Deluchi et al. - 1999** | 2004 CAD$/tonne | low | 0.26 | 1,817.90 | 175.28 | 11.36 | 15,603.91 |
| | | high | 8.05 | 29,515.15 | 2,004.80 | 125.30 | 236,817.31 |
| **Cline (1992)** | 2004 CAD$/tonne | low | 1.79 | | | 6.52 | |
| | | high | 17.94 | | | 65.25 | |
| **Nordhaus (1993)** | | low | 2.28 | | | 8.16 | |
| | | high | 9.46 | | | 35.89 | |
| **Fankhauser (1994)** | | low | 2.77 | | | 9.79 | |
| | | high | 29.36 | | | 107.66 | |
| **Titus (1992)** | | low | 17.94 | | | 65.25 | |
| | | high | 233.26 | | | 864.54 | |
| **European Commission - 1998** | 2004 CAD$/tonne | low | 37.39 | 12,712.12 | | 138.34 | |
| | | high | 117.77 | 67,299.47 | | 429.97 | |
| **Heaney et al. (1999)** | 2004 CAD$/tonne | average | 45.82 | 16.49 | | 0.00 | 311.57 |

# APPENDIX B: DPL WORKSHEET VARIABLES

## Table B.1: DPL Worksheet Variables

| |
|---|
| 1000LB GVW |
| SPEED (KM-HR) |
| FRONTAL AREA ( SQ-FT2) |
| AERODYNAMIC DRAG (FOR TOTAL LBS) |
| DRIVE TRAIN EFFICIENCY |
| GRADE EFFECT % |
| GRADE RESISTANCE HP PER 1000LB |
| STATIC RR COEF |
| DYNAMIC RR COEF |
| ROAD RR % |
| ROAD ROUGHNESS COEFFICIENT |
| ROLLING RESISTANCE HP PER 1000LB |
| TOTAL RESISTIVE FORCE HP |
| ENGINE BSFC (KG OF FUEL/HR/HP) @1700 RPM |
| KG FUEL BURNED/HR |
| FUEL DENSITY (OR KG/L) |
| L FUEL BURNED/HR |
| FUEL CONSUMPTION (L/KM) |
| SPECIFIED ENGINE EMISSION RATE |
| THERMAL EFFICIENCY (MJ/L) |
| EMISSION RATES (G/KM) |
| KMS TRAVELED |
| OPERATING EMISSIONS (G/DAY) |
| NUMBER OF WEIGHT STATIONS PER DAY |
| TIME PER STOP IN WEIGHT STATION |
| TOTAL TIME IN WEIGHT STATIONS |
| NUMBER OF STOP LOADING/UNLOADING PER DAY |
| TIME PER STOP IN LOADING/UNLOADING |
| TOTAL TIME LOADING/UNLOADING |
| TOTAL DELAY TIME IN IDLING |
| IDLING EMISSION RATE (G/HR) |
| IDLING EMISSIONS (G/ DAY) |
| NUMBER OF STOP OFF PER DAY |
| COOLING DOWN ENGINE EFFICIENCY (G EMISSIONS/5MIN) |
| COOLING DOWN EFFICIENCY PER DAY |
| WARMING UP ENGINE EFFICIENCY (G EMISSIONS/15 MIN) |
| WARMING UP EFFICIENCY PER DAY |
| STOPPED OFF EMISSIONS (G/DAY) |
| TOTAL EMISSIONS (TONNE/TRUCK-DAY) |
| TOTAL EMISSIONS CANADA (MT/YEAR) |

# APPENDIX C: ENGINE EMISSIONS CHARACTERISTICS
## Detailed Calculations

## C-1 OPERATING EMISSIONS RATES

According to US EPA Standards, emissions rates, expressed in grams per brake horsepower an hour, are:

CO: 15.5g/bhp-hr
NOx: 4g/bhp-hr
HC: 1.3g/bhp-hr
PM: 0.10g/bhp-hr

Need to convert the emissions rates in grams per mega joules:

$CO_2$: 73.3g/Mj[10]
CO: 5.77g/Mj
NOx: 1.49g/Mj
HC: 0.48g/Mj
PM: 0.037g/Mj

## C-2 IDLING EMISSIONS RATES

According to California Emissions Inventory Model, EMFAC2002, the idling emissions for the model –year group 2004-2006 are as followed.

**Table C.1: Idling Emissions**

| Emissions | $CO_2$ | CO | NOx | HC | PM |
|---|---|---|---|---|---|
| **Low rate (g/hr)** | 4366 | 18 | 84 | 6 | 0.85 |
| **Average rate (g/hr)** | 5846 | 41 | 109 | 8 | 1.45 |
| **High rate (g/hr)** | 9140 | 90 | 165 | 12 | 2.77 |

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[10] CSIRO Atmospheric Research Report to the Australian Greenhouse Office; Life-cycle Emissions, an Analysis of Alternative Fuels For Heavy Vehicles; March 2000.

## C-3 ENGINE EFFICIENCY CALCULATIONS

Cooling down activity: 5 minutes per stop, or 1/12 hour.
Warming up activity: 15 minutes per stop, or 1/4 hour
Use of idling emissions average rates from the primary table as a computation base.

**Table C.2: Assumed Engine efficiency factors**

| % Engine Efficiency | Factors |
|---|---|
| 50 | 1 |
| 35 | 1.5 |
| 25 | 2 |
| 10 | 3 |

**Cooling down engine efficiency calculations**

Example of $CO_2$: if an engine is 25% efficient, is rate of $CO_2$ will be:

$$(5846/12)\text{x } 3=1461.5 \text{ g/hr}$$

where:

5846: average idling rate in g/hour for CO2
/12: equivalent at 1/12 hour or 5minutes
3: efficiency factor, related in this case to 25% efficiency.

**Table C.3: Assumed Cooling Down Engine Efficiency Inputs**

| Emissions g/hr | Idling rate | Efficiency | | | Probability | | |
|---|---|---|---|---|---|---|---|
| | | 25% | 50% | 75% | | | |
| **$CO_2$** | 5846 | 1461.5 | 974.3 | 730.75 | 0.25 | 0.5 | 0.25 |
| **CO** | 41 | 10.25 | 6.83 | 5.125 | 0.25 | 0.5 | 0.25 |
| **NOx** | 109 | 27.25 | 18.17 | 13.62 | 0.25 | 0.5 | 0.25 |
| **HC** | 8 | 2 | 1.33 | 1 | 0.25 | 0.5 | 0.25 |
| **PM** | 1.45 | 0.362 | 0.242 | 0.181 | 0.25 | 0.5 | 0.25 |

**Warming up engine efficiency calculations**

Example of $CO_2$: if an engine is 25% efficient, its rate of $CO_2$ will be:

(5846/4)x 3=4384.5 g/hr

where:

5846: average idling rate in g/hour for $CO_2$
/4: equivalent at 1/4 hour or 15minutes
3: efficiency factor, related in this case to 25% efficiency.

**Table C.4: Assumed Warming up Engine Efficiency Inputs**

| **Emissions g/hr** | **Idling rate** | **Efficiency** | | | **Probability** | | |
|---|---|---|---|---|---|---|---|
| | | **25%** | **50%** | **75%** | | | |
| **$CO_2$** | 5846 | 4385.5 | 2923 | 2192.2 | 0.25 | 0.5 | 0.25 |
| **CO** | 41 | 30.75 | 20.5 | 15.4 | 0.25 | 0.5 | 0.25 |
| **NOx** | 109 | 81.75 | 54.5 | 40.87 | 0.25 | 0.5 | 0.25 |
| **HC** | 8 | 6 | 4 | 3 | 0.25 | 0.5 | 0.25 |
| **PM** | 1.45 | 1.087 | 0.725 | 0.544 | 0.25 | 0.5 | 0.25 |

# APPENDIX D: DETERMINISTIC AND PROBABILISTIC MODELING IN TERMS OF OPERATING EMISSIONS

## Details for each emission

## EMISSIONS IN GRAMS PER KILOMETRE

### 1 – Carbon Dioxide $CO_2$

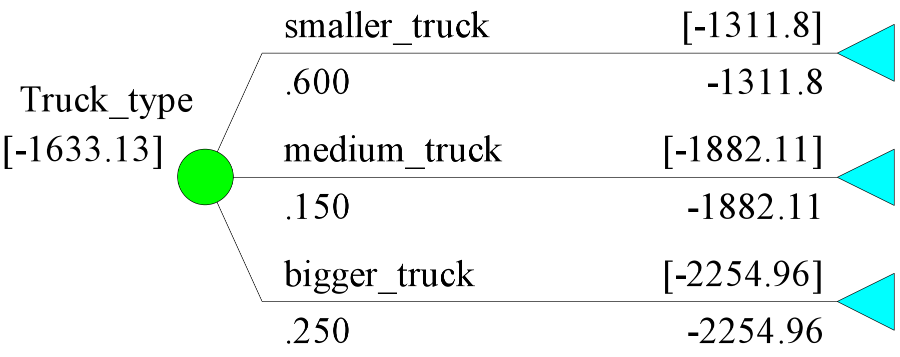

Figure D.1: $CO_2$ Deterministic Decision Tree

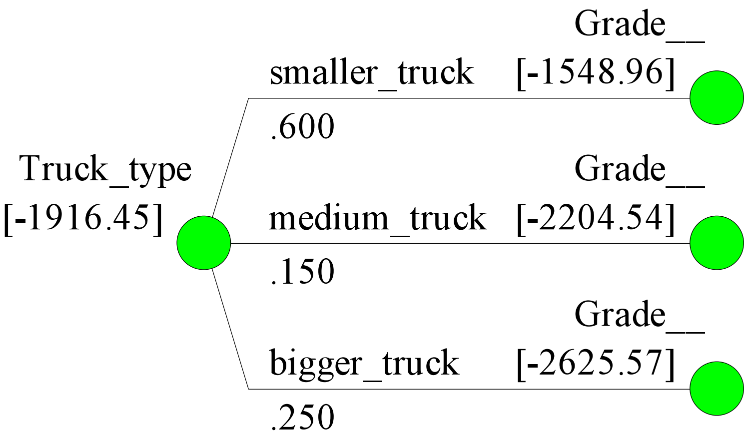

Figure D. 2: $CO_2$ Probabilistic Decision Tree

## 2 – Carbon Oxide CO

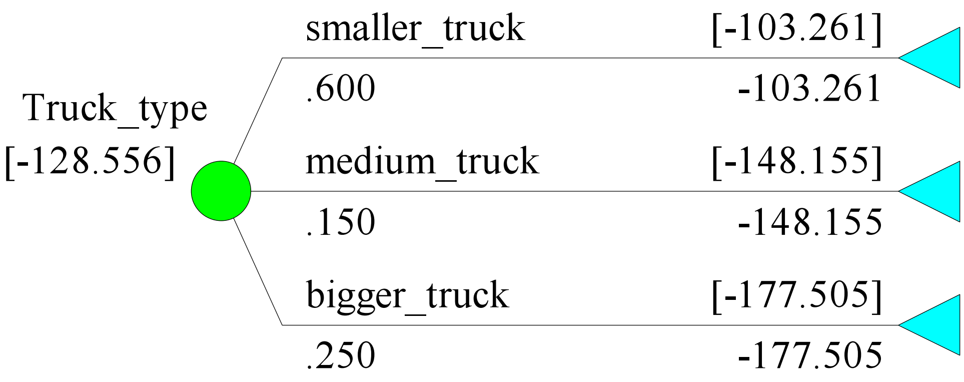

**Figure D.3: CO Deterministic Decision Tree**

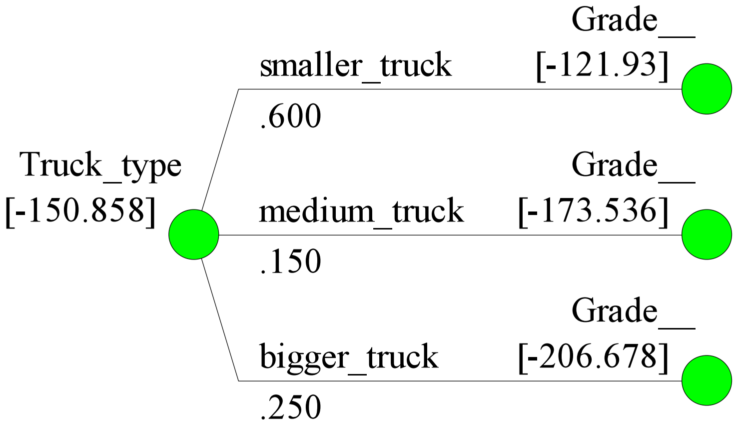

**Figure D.4: CO Probabilistic Decision Tree**

### 3 – Nitrogen Oxides NOx

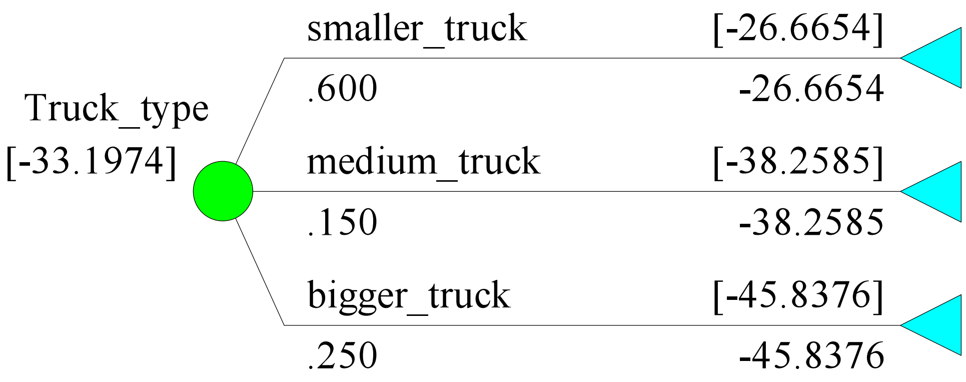

**Figure D.5: NOx Deterministic Decision Tree**

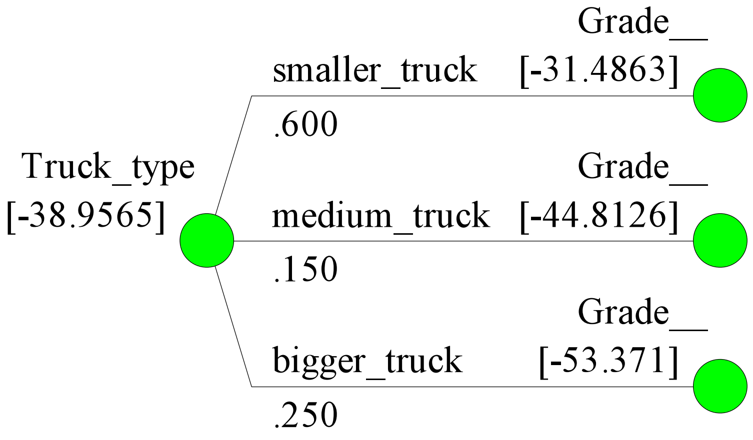

**Figure D.6: NOx Probabilistic Decision Tree**

### 4 – Hydrocarbons HC

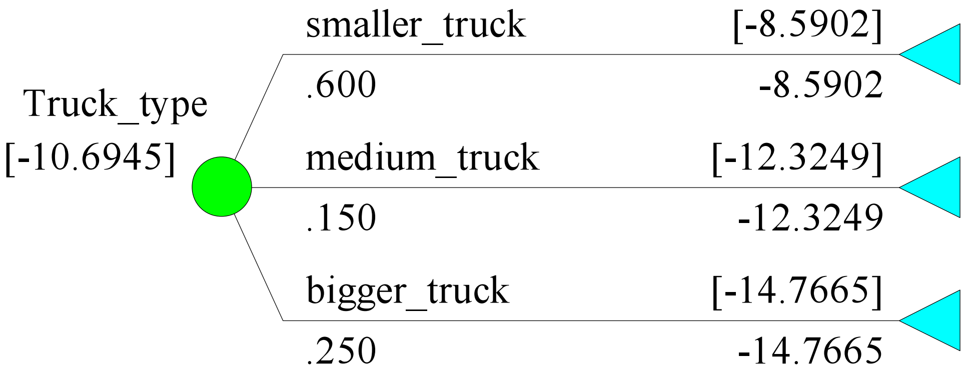

**Figure D.7: HC Deterministic Decision Tree**

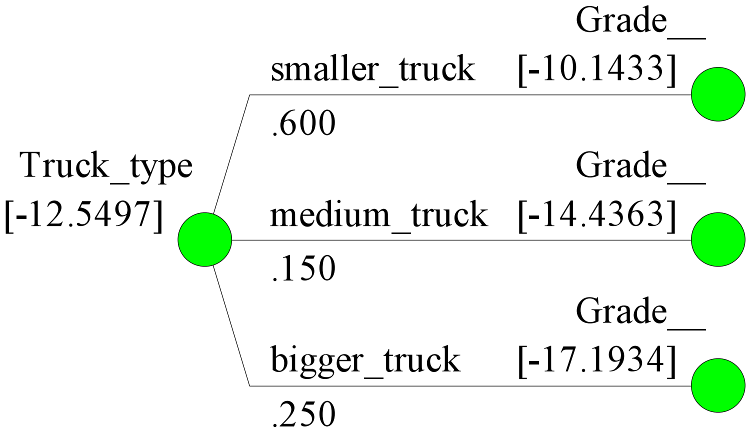

**Figure D.8: HC Probabilistic Decision Tree**

### 5 – Particulate Matter PM

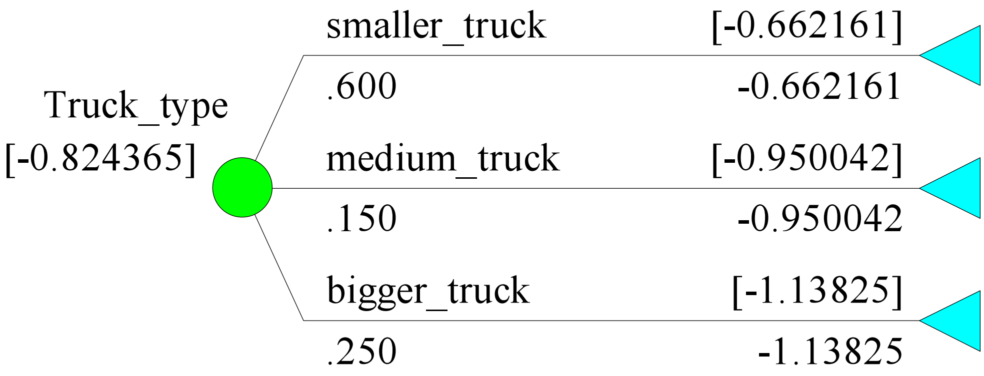

**Figure D.9: PM Deterministic Decision Tree**

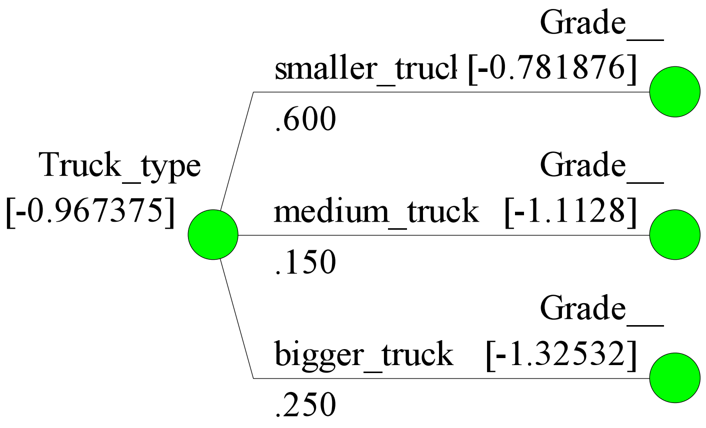

**Figure D.10: PM Probabilistic Decision Tree**

# APPENDIX E: WIM EMISSIONS
## Detailed calculations

**Table E.1: $CO_2$ Costs from Agencies Worldwide:**

|  | Values (CAD$/metric tonne) |  |  |
|---|---|---|---|
| **Emissions** | **Low** | **Base** | **High** |
| **$CO_2$** | 0.259 | 41.69 | 233.26 |

**Table E.2: Idling Time Data**

| Variables | Values |  |  | Probabilities |  |  |
|---|---|---|---|---|---|---|
|  | Low | Base | High | Low | Base | High |
| Number of weigh stations a day |  | 3 |  |  | 1 |  |
| Idling time without WIM (hour) | 0.083 | 0.167 | 0.5 | 0.15 | 0.6 | 0.25 |
| Idling time with WIM (hour) | 0 | 0.083 | 0.334 | 0.8 | 0.15 | 0.05 |

- Average idling time per truck a day without WIM in weigh station:
  ((0.083x0.15) + (0.167x0.6) + (0.5x0.25))x 3 = 0.7 hour or **42 min**.

- Average idling time per truck a day with WIM in weigh station:
  ((0x0.8) + (0.083x0.15) + (0.334x0.5))x 3 = 0.087 hour or **1 min**.

Therefore, using WIM pre-clearance systems in weigh stations would save (42-1)= 41 minutes per truck a day.

## A – CANADA

Litres of fuel savings:
One hour of idling = 3.63 litres of fuel consumed
One hour of idling = average of 5,846 grams of $CO_2$ emitted
Then, 228,000 tonnes of $CO_2$ saved =

Low: (228,000x 3.63)/(**9140**/1000,000)= **90,551,422** litres of fuel saved.
Average: (228,000x 3.63)/(**5846**/1000,000)= **141,753,730** litres of fuel saved.
High: (228,000x 3.63)/(**4366**/1000,000)= **189,564,820** litres of fuel saved.

**Table E.3: Fuel Price:**

| | Values (CAD$/litre) | | |
|---|---|---|---|
| | **Low** | **Base** | **High** |
| **Fuel** | 0.65 | 0.8 | 1 |

**Table E.4: Canada WIM Results**

| Values | Low | Average | High |
|---|---|---|---|
| Canada $CO_2$ Emissions-No WIM (Mt/year) | | 103.21 | |
| Canada $CO_2$ Emissions (Mt/year)- WIM | | 102.99 | |
| Net Emissions Avoided (Tonnes/year) | | **228,000** | |
| '000$ of $CO_2$ saved per year | **59** | 9,505 | **53,183** |
| Fuel savings ('000litres/year) | **90,551** | 141,574 | **189,565** |
| Fuel savings ('000$/year) - low | **58,858** | 92,023 | 123,217 |
| Fuel savings ('000$/year) - average | 72,441 | **113,259** | 151,652 |
| Fuel savings ('000$/year) - high | 90,551 | 141,574 | **189,565** |

## B – UNITED STATES

Litres of fuel savings:
One hour of idling = 3.63 litres of fuel consumed
One hour of idling = average of 5,846 grams of $CO_2$ emitted
Then, 1,737,000 tonnes of $CO_2$ saved =
Low: (1,737,000 x 3.63)/(**9140**/1000,000)= **689,858,860** litres of fuel saved.
Average: (1,737,000 x 3.63)/(**5846**/1000,000)= **1,078,568,300** litres of fuel saved.
High: (1,737,000 x 3.63)/(**4166**/1000,000)= **1,513,516,600** litres of fuel saved

**Table E.5: Fuel Price:**

| | Values (CAD$/litre) | | |
|---|---|---|---|
| | **Low** | **Base** | **High** |
| **Fuel** | 0.65 | 0.8 | 1 |

**Table E.6: USA WIM Results**

| Values | Low | Average | High |
|---|---|---|---|
| USA $CO_2$ emissions-No WIM (Mt/year) | | 784.43 | |
| USA $CO_2$ emissions-WIM (Mt/year) | | 782.69 | |
| Net Emissions Avoided (Tonnes/year) | | **1,737,000** | |
| ‘000$ of $CO_2$ saved per year | **452** | 72,416 | **405,173** |
| Fuel savings (‘000 litres/year) | **689,859** | 1,078,568 | **1,513,517** |
| Low Fuel savings (‘000$/year) | **448,409** | 701,069 | 983,786 |
| Average Fuel savings (‘000$/year) | 551,887 | 862,855 | 1,210,814 |
| High Fuel savings (‘000$/year) | 689,859 | 1,078,568 | **1,513,517** |

# APPENDIX F: TRUCK ACTIVITIES
## Detailed calculations

## F1 - Data collected for 20m$^3$ payload trucks

Activity of RM of Britannia in 2002: 137,624 truckloads with 20m$^3$ trucks (Gross weight of 45.5 metric tons or 100,309 lbs).

- 1 truck = 10 loads per day

- Work time = 250 days per year

*Results:* 137,624 / 250 = **551 loads per day**
551 / 10 = **56 trucks used per day**

## F2 - Assumptions for 40m$^3$ and 80m$^3$ payload trucks

- If we use 40 m$^3$ payload trucks (Gross weight of 62.5 metric tons or 137,788 lbs each), instead of 20m$^3$ payload trucks, we need:

*Results:* (1,139,669[a] + 1,612,827[b]) / 40 = 68,813 loads per year
68,813 / 250 = **276 loads per day**
276 / 10 = **28 trucks used per day**

- If we use 80m$^3$ payload trucks (Gross weight of 100 metric tons or 220,460 lbs each), we need:

*Results*: (1,139,669[a] + 1,612,827[b]) / 80 = 34,407 loads per year
34,407 / 250 = **138 loads per day**
138 / 10 = **14 trucks used per day**

## F3 - Assumptions for annual kms traveled

- In RM of Britannia, one 20m$^3$ truck drives about 20 kms one way haul.

*Results*: (20x2)x10 loads = 400kms per truck-day

400x 56 trucks-day = **22,400 total kms per day for a 20m$^3$ trucks fleet**

or 22,400x250 = 5,600,000 kms per year for a 20m$^3$ trucks fleet

- As well, one 40m$^3$ truck drives 400 kms per day

*Results*: 400 x 28 trucks-day = **11,200 total kms per day for a 40m$^3$ trucks fleet**

(or 11,200x250 = 2,800,000 kms per year for a 40m$^3$ trucks fleet)

- Finally, if 70m$^3$ trucks are used, they will also drive 400 kms per day

*Results*: 400x 14 trucks-day = **5,600 total kms per day for a 80m$^3$ trucks fleet**

or 6,400 x 250 = 1,400,000 kms per year for a 80m$^3$ trucks fleet

## F4 - Average loading/unloading weight of each truck type

1. 20m$^3$ truck
    - GVW: 45,500 kgs
    - Payload: 20m$^3$ = 20,000 kgs
    - Average weight :(45,500 + (45,500-20,000))/2 = **35,500 kgs** (or 78,264 lbs)
2. 40m$^3$ trucks
    - GVW: 62,500 kgs
    - Payload: 40m$^3$ = 40,000 kgs
    - Average weight :(62,500 + (62,500-40,000))/2 = **42,500 kgs** (or 93,695 lbs)
3. 80m$^3$ truck
    - GVW: 100,000 kgs
    - Payload: 80m$^3$ = 80,000 kgs
    - Average weight :(100,000 + (100,000-80,000))/2 = **60,000 kgs** (or 132,276 lbs)

# APPENDIX G: ABBREVIATIONS

Bhp: Brake horsepower

BSFC: Brake Specific Fuel Consumption

$CH_4$: Methane

CO: Carbon Oxide

$CO_2$: Carbon Dioxide

$CO_2$ eq: Carbon Dioxide equivalent

CVO: Commercial Vehicle Operations

DPL: Decision Programming Analysis

EMFAC2002: Emissions Factors 2002

GHG: Greenhouse Gas

GVW: Gross Vehicle Weight

GWP: Global Warming Potential

HC: Hydrocarbons

IRI: International Roughness Index

KW-h: Kilo watt per hour

Km: kilometresz

LPG: Liquefied Petroleum Gas

MJ: Mega Joule

MOBILE: Mobile Source Emissions Factor Model

NIPER: National Institute for Petroleum and Energy Research

NMHC: Non Methane Hydrocarbons

NMVOC: Non Methane Volatile Organic Compound

| | |
|---|---|
| NOx: | Nitrogen Oxide |
| NO2: | Nitrogen Dioxide |
| PM: | Particulate Matter |
| RM: | Rural Municipality |
| SOF: | Soluble Organic Fraction |
| $SO_2$: | Sulphur Dioxide |
| t-km: | tonne per kilometre |
| TIUS: | Truck Inventory and Use Survey |
| USEPA: | United States Environmental Protection Agency |
| VKT: | Vehicle-Kilometre travelled |
| VOC: | Volatile Organic Compound |
| WIM: | Weigh-in Motion |