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ALTERNATIVE FUEL EFFECTS ON VEHICLE EMISSIONS AND INDOOR AIR QUALITY

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Masters of Science

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ABSTRACT

There are two main reasons for using alternative fuels in the transportation sector. One is to reduce the dependence on petroleum oil. The other to reduce emissions produced by on-road vehicles. This thesis is concerned with the emissions effects of using alternative fuels to replace conventional gasoline and diesel in transportation. Each chapter in the thesis is based on a stand alone paper. One study is a literature survey on the effects of alternative fuels on road vehicle emissions. The next study describes the emissions results of a propane to natural gas fuel conversion of forklifts. The final study characterizes the effect of the conversion project with a model relating indoor vehicle use to indoor air quality. The major conclusion of this thesis is that, if proper care is taken in vehicle technology, alternative fuels can be used to reduce vehicle emission and to help improve air quality.

"To laugh often and much,
to win the respect of intelligent people
and the affection of children,
to earn the appreciation of honest critics
and endure the betrayal of false friends,
to appreciate beauty, to find the best in others,
to leave the world a bit better,
whether by a healthy child,
a garden patch, or a redeemed social condition;
to know even one life has breathed easier because you have lived.
This is to have succeeded!"

- Ralph Waldo Emerson

- *DEDICATION* -

It has been said there are two lasting bequests we can give our children: One is roots. The other is wings. I thank my mother and father for giving me both. I dedicate this work to their love and support and to my baby brother Gurpreet, for being my friend before, now, and forever.

PREAMBLE

Alternative fuels have been touted as a solution for air quality and as a way to replace the use of limited petroleum supply. As implied by the name, "alternative fuels" are considered as such because many are a non-petroleum resource. They are typically simpler in composition than gasoline and diesel and as a result expected to be "cleaner". This MSc thesis is a study on the effect of alternative fuel use on motor vehicle emissions. As part of the research, the impact of changing emissions on overall air quality is assessed. The objective is to show the relationship between fuel and vehicle emissions and whether some of the more currently viable alternative fuels are capable of reducing emissions and in turn improving air quality.

There are several complications in demonstrating a relationship between fuel and vehicle emissions. Vehicle emissions are not solely dependent on fuel choice. Many factors and parameters together help determine what exits the tailpipe of a vehicle. Such things as fuel composition, fuel delivery and control systems, engine design, age and maintenance of the vehicle, exhaust after-treatment as well as the types of loads put on the vehicle all affect emissions to some extent.

The thesis attempts to show the relationship between alternative fuels and motor vehicle emissions through three independent yet complimenting studies. The work includes surveying published literature, conducting our own emissions tests with an indoor fleet of forklifts converted from propane to natural gas, and modeling the air quality implications of the emissions reduction achieved through the conversion project.

ACKNOWLEDGMENTS

I would like to take this opportunity to acknowledge everyone who has made the completion of this thesis possible. I extend my appreciation to Dr. Dave Checkel for giving me the opportunity to do my research under his supervision and for his many contributions and insights. I would also like to thank and recognize NSERC for the financial support in completing this degree. I am deeply indebted to the assistance from Doris, Linda and Helen in the Mechanical Engineering office and all of the other instructors within the department that I may have had the opportunity to become in contact with. A special thanks goes out to all the friends I have come to know during the completion of this degree, the ones still here and those that have already left. I leave here taking with me a lot of great memories that I will never forget. See you in the real world.

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NOMENCLATURE

a	air exchange rate (1/hr)
C	indoor pollutant concentration (ppm)
C_o	outdoor pollutant concentration (ppm)
k	net rate of removal processes other than air exchange (1/hr)
P	fraction of the outdoor pollutant level that penetrates the building shell (-)
S	indoor pollutant source strength (g/hr)
V	building volume (m^3)
t	time (hr)

ABBREVIATIONS

A/F or AFR	- Air to Fuel Ratio (mass basis)
ACGIH	- American Conference of Governmental Industrial Hygienists
AF	- Alternative Fuel
AFV	- Alternative Fuel Vehicle
ARB	- Air Resources Board
ASHRAE	- American Society of Heating, Refrigerating and Air-Conditioning Engineers
CAAA	- Clean Air Act Amendment
CARB	- California Air Resources Board
CBD	- Central Business District
CNG	- Compressed Natural Gas
CO	- Carbon Monoxide
CO_2	- Carbon Dioxide
E85	- Ethanol-85
E95	- Ethanol-95
ECT	- Engine Coolant Temperature
EE/FSU	- Eastern Europe/Former Soviet Union
EGO	- Exhaust Gas Oxygen
EGR	- Exhaust Gas Recirculation
EPA	- Environmental Protection Agency
FFV	- Flexible Fuel Vehicle
FID	- Flame Ionization Detector
FLT	- Forklift Truck
FTP	- Federal Test Program
GC	- Gas Chromatography
HC	- Hydrocarbons
HDV	- Heavy-Duty Vehicle
HVAC	- Heating, Ventilation and Air Conditioning
IAQ	- Indoor Air Quality
ICE	- Internal Combustion Engine
IEO99	- International Energy Outlook 1999
LDT	- Light-Duty Truck
LDV	- Light-Duty Vehicle
LEV	- Low Emission Vehicle
LHV	- Lower Heating Value
LNG	- Liquified Natural Gas
LPG	- Liquid Petroleum Gas/Propane
M100	- Methanol-100
M85	- Methanol-85
MAP	- Manifold Air Pressure
MON	- Motor Octane Number
MTBE	- Methyl Tertiary Butyl Ether
N_2O	- Nitrous Oxide

NDIR	- Non-Dispersive Infrared
NGV	- Natural Gas for Vehicles
NMHC	- Non-Methane Hydrocarbon
NMOG	- Mon-Methane Organic Gas
NO	- Nitric Oxide
NO_2	- Nitrogen Dioxide
NO_X	- Nitrogen Oxides
NYBUS	- New York Bus Test Cycle
OEL	- Occupational Exposure Limit
OEM	- Original Equipment Manufacturer
OPEC	- Organization of the Petroleum Exporting Countries
PM	- Particulate Matter
RFG	- Reformulated Gasoline
RON	- Research Octane Number
RVP	- Reid Vapor Pressure
SO_2	- Sulfur Dioxide
STEL	- Short Term Exposure Level
THC	- Total Hydrocarbons
TLV	- Threshold Limit Value
TWA	- Time-Weighted Average
ULEV	- Ultra Low Emission Vehicle
VOC	- Volatile Organic Compounds
ZEV	- Zero Emission Vehicle

CHAPTER 1

INTRODUCTION

CHAPTER 1: INTRODUCTION

Motor vehicles have come to be the major attributable source of air pollutant emissions in most urban areas [1,2,3]. The increasing size of urban areas, increasing vehicle populations and increased driving distances have led to serious pollution levels in many cities. The overall emissions of air pollutants can lead to smog and general public health problems. The term smog was invented in early Britain to describe the dirty soot filled air caused by the burning of sulphurous coal. The term is now associated more with the Los Angeles style "haze" and is typically preceded with the word "photochemical". The additional term is due to the photochemical process of HC and NO_X in the presence of sunlight to produces toxic compounds. Health concerns are not only an issue in urban areas with road vehicles but the same health problems are encountered with indoor vehicle operation in warehouses and factories. Alternative vehicle fuels have been touted as a solution which offers reduced emissions and cleaner air. This thesis examines that claim.

1.1 MOTOR VEHICLE EMISSIONS

Motor vehicles using gasoline and diesel emit large quantities of carbon monoxide (CO), unburnt hydrocarbons (HC), nitrogen oxides (NO_X), and toxic substances such as benzene, formaldehyde, acetaldehyde, lead, and particulates [2]. The impact of automobile emissions on urban air pollution has aroused public attention and research interest over several decades [2,4]. The United States is the foremost petroleum oil consumer in the world, and its pollution problems appeared many years ago. Due to its early struggle with air quality, the state of California not only began their emissions reduction programs earlier, but on a larger scale, including the approving of many acts, amendments, standards, and regulations. Technology forcing standards are being implemented by the Air Resources Board (ARB) in order to lower vehicle pollution levels. However, despite significant reductions in air pollution achieved throughout California over the past two decades, air pollutant levels in many areas of the state continue to exceed National Ambient Air Quality Standards [3].

The contribution of vehicle emissions to air pollution can be significant. In 1990, the U.S. Environmental Protection Agency (EPA) estimated that transportation sources were responsible for 63% of the CO, 38% of the NO_X, and 34% or higher of the HC's (national contribution of transportation emissions in the U.S.)[2]. In Europe, road transportation is blamed for roughly 50~70% of the NO_X, and around 50% of volatile organic compounds (VOC) [2]. Other sources report the contribution of automobiles to CO air pollution being 50% during wintertime in the Pacific Northwest, USA; about 68.5% in Guangzhan, Peoples Republic of China; and as high as 98% in Tehran, Iran [4].

Emission standards have been introduced in an attempt to control the huge contribution of emissions to the atmosphere. Tailpipe emission standards specify the maximum amount of pollutants allowed in exhaust gases discharged from engines. Over the years there have been many changes to the emissions standards and test procedures. Today, emissions from internal combustion engines are regulated in many countries throughout the world. However, regulatory authorities in different countries have not been consistent in adopting emissions test procedures and many types of vehicle and engine test cycles are in use.

Though the g/km emissions have been reduced considerably with the advanced technologies of vehicles and fuels, the large vehicle number (at 1994, roughly over 140,000,000 vehicles in the USA are powered by internal combustion engines fueled with gasoline and diesel [6]), and travel distances have kept increasing over the past forty years. Predictions show that conventional fueled vehicle fleet emissions will be reduced to the lowest technologically feasible level. Additionally, the continued growth in vehicle miles traveled will counteract reductions in vehicle emissions and air quality will again begin to deteriorate [3,7].

Air pollution is not only considered a nuisance, but is also a threat to public health [1]. Vehicle emissions are a concern indoors as well as outdoors. Running vehicles inside buildings leads to direct health problems of exposed workers due to low ventilation and high concentrations of CO, NO_X and unburnt toxics in exhaust (and soot of diesels). Poisonings can occur quickly, even in the presence of what many would consider "adequate ventilation" and in areas that many would define as relatively open spaces, such as parking garages [8].

Health impacts of poor air quality range from irritation of eyes, nose and respiratory tracts to some more serious problems such as impaired lung function, decreased resistance to infection, increased incidence and severity of lung cancer, reproductive problems, birth defects, and premature death mainly due to respiratory and heart conditions [1,9]. Prior use of equipment without incidence has sometimes given users a false sense of safety; such users have been poisoned on subsequent occasions [8]. In total, air pollution has human health impacts, increases the cost of living and hurts the economy and environment. Table1.1 shows how various substances present in vehicle exhaust can effect humans.

Table 1.1: ACGIH Exposure Limits for Commonly Found Exhaust Species and Their Known Effects on Humans [9]

SPECIES	15 min - STEL* PPM	8 hr - TWA** PPM	CRITICAL EFFECTS
CO	400	50	Anoxia; Cardiovascular system; Central nervous system; reproductive
CO_2	30000	5000	Asphyxiation
NO		25	Anoxia; Irritation; Cyanosis
NO_2	5	3	Irritation; Pulmanory edema
N_2O		50	Reproductive; Blood; Neuropathy; Asphyxiation
Formaldehyde	2	1	Irritation; Cancer (nasal)
Acetaldehyde	150	100	Irritation
Acrolien	0.3	0.1	Irritation; Pulmanory edema
Benzene		10	Cancer
Styrene	100	50	Neurotoxicity; Irritation; Central nervous system
Toluene	150	100	Central nervous system
Xylenes	150	100	Irritation
1,3 Butadiene		10	Cancer
Methane			Asphyxiant
Propane			Asphyxiant
Ozone		0.05-0.1	Pulmanory function; irritation; headache
SO_2	1		Irritation

*Short Term Exposure Limit **Time Weighted Average

Many programs to reduce transportation emissions are being introduced. The goal is to reduce impacts on health and the environment, protect the atmosphere for future generations and improve visibility for safety, aesthetics, business development and tourism [1]. Alternative fuels are acclaimed for lower emissions so the question is whether converting a significant fraction of vehicles to alternatives will help reach such goals.

1.2 WORLD FUEL CONSUMPTION

The role of alternative fuels for the future is being shaped not only by ecological reasons but by huge energy consumption rates. Most of the consumption is by the industrialized nations as seen in Table 1.2.

Table 1.2: 1996 Consumption Data (10^{18} Joules) [10]

	Industrialized	**EE/FSU**	**Developing**	**World**
Oil	**90.4**	12.7	50.7	**153.8**
Natural Gas	**46.4**	22.9	17.4	86.7
Coal	37.8	13.7	**46.3**	97.8
Nuclear	**20.9**	2.95	1.58	25.4
Other	**18.1**	3.06	11.2	32.4
Total	213.6	55.3	127.2	**396.1**

Note: Industrialized – North America, Western Europe, Japan, Australasia
EE/FSU – Eastern Europe and Former Soviet Union
Developing – Developing Asia, Middle East, Africa, Central and South America.

The total world energy use has been increasing steadily with little or no sign of slowing down. Energy use has risen by about 105.5 x 10^{18} Joules from 1982 to 1996, as shown in Figure 1.1.

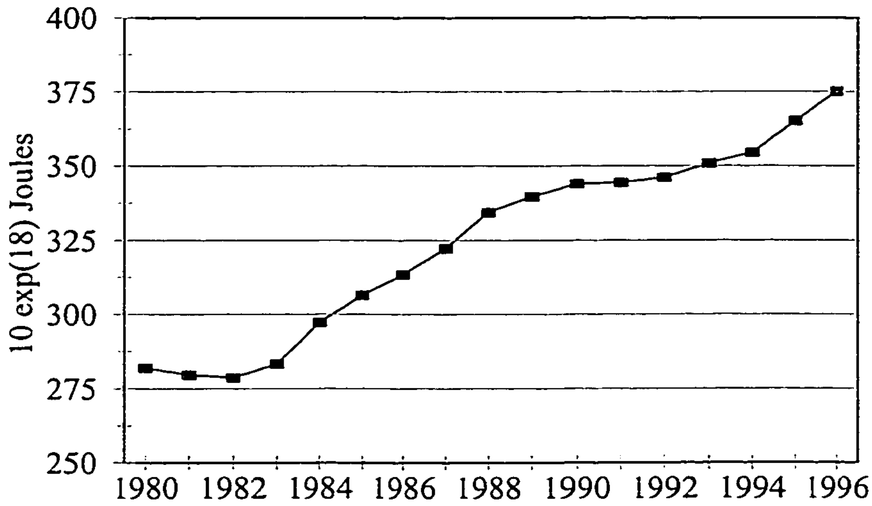

Figure 1.1: Historic Trend of World Energy Consumption [10]

One of the major areas of energy consumption is petroleum oil. The U.S. Department of Energy projections indicate that the world oil consumption will rise to nearly 110 million barrels per day by 2020 [10]. Figure 1.2 shows the rise in petroleum consumption over the past two decades. Over 40% of the total primary energy supply in 24 industrialized nations is petroleum oil. More than half of this oil is used by the transportation sector. Currently the U.S. consumes about 17.7 million barrels of oil per day and the transportation sector accounts for about 67% of that [11,12].

The most recent US geological survey assessment of worldwide oil resources estimated recoverable oil resources in the range of 2.1 to 2.8 trillion barrels. Currently, cumulative production and estimates on proven reserves are both approximately 800 billion barrels [10].

At a frozen rate equal to today's consumption/demand, these estimated recoverable reserves would be consumed in approximately 80 to 105 years.

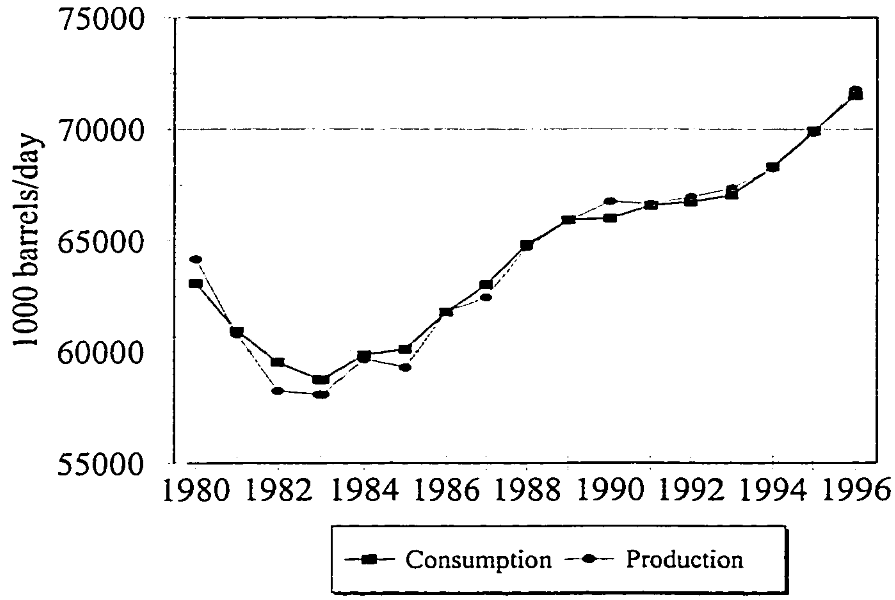

Figure 1.2: Historic Trend in World Petroleum Consumption and Production [10]

Projections of future consumption rates show an even faster depletion of reserves due to demand growth of developing nations. Economic growth and energy demand is linked, but the strength of that link varies among regions and stages of economic development [10]. In industrialized countries, history shows the link to be relatively weak. That is, energy demand growth lags behind economic growth. For every percent increase in economic activity, energy demand increases only about half a percent. In developing countries, demand and economic growth have tended to be more closely correlated, with energy demand growth tending to track the rate of economic expansion. The process of economic development is energy intensive and rising living standards enable broad access to electricity and motorized means of transportation. The accompanying widespread development of infrastructure causes growth in energy-intensive industries such as steel and cement. As economies continue to develop, however, the rate of energy use tends to fall relative to economic expansion. Consumer demands tend to evolve toward increased use of services that are not energy intensive [10].

A nation's transportation system is generally an excellent indicator of its level of economic development [10]. The developing countries are expected to have huge economic growth within the next few decades in order to join the ranks of the industrialized nations. In 1996 the world population of vehicles was 675 million and is expected to reach 1.1 billion by the year 2020 [10]. The most important factor influencing future size of the world's vehicle fleet is the degree to which developing Asia and Central and South America do in fact undergo rapid motorization. These two regions account for 52% of the projected increase in the world vehicle population over the next 20 years [10].

Table 1.3: Expected Percentage Annual Economic Growth from 1995 to 2020 [10]

	1995-2020 Projections		
	Low	Expected	High
Industrialized Countries	1.3	2.3	3.2
EE/FSU	1.4	2.9	5.7
Developing Countries	3.1	4.8	6.3

At present, transportation energy accounts for 48% of world oil demand. Projections indicate a growth in transportation fuel use of 77% or 27 million barrels per day by 2020. Much of this rise is due to the developing countries that are expected to account for 55% of the growth in transportation energy demand [10].

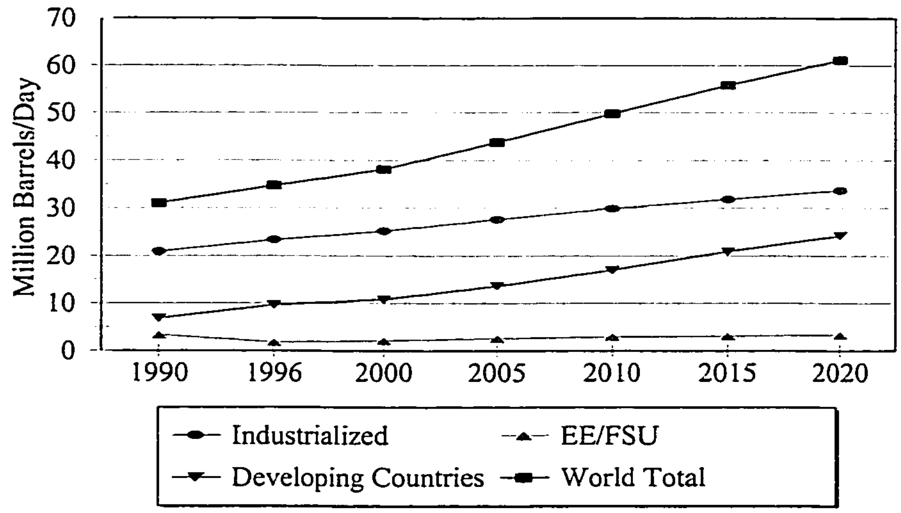

Figure 1.3: World Total Energy Consumption for Transportation by Region (gasoline, diesel, jet fuel)[10]

Projections indicate transportation and economic growth will increase petroleum consumption. Alternative fuels are being considered as an energy source which can help reduce the strain on petroleum reserves. Oil reserve depletion being a major motivator, fuels being labeled as "alternatives" to gasoline are usually those based on a non-petroleum resource. Despite the interest in alternative fuels to replace oil, much more research and market development is required.

The alternative fuels market is a very small market in the transportation sector and offers much less choice and sophistication of vehicles. As an example, Table 1.4 shows the representation of alternative fuels vehicles in the U.S. Compared to the total vehicle population in the U.S., approximately 208 million vehicles in 1997[10], alternative fuels represent a very small presence (less than 1%). Vehicles are available as an original equipment manufacturer (OEM) vehicle, one specifically designed by the manufacturer to run on an alternative fuel, or a converted vehicle, a vehicle with an aftermarket fuel system for operation with an alternative fuel. A more detailed discussion on vehicle conversions is given in Appendix H.

Table 1.4: Estimated Number of Alternative Fuel Vehicles In Use in the United States by Fuel [13]

FUEL	1992	1993	1994	1995	1996	1997	Avg. Annual Growth Rate (%)
LPG	221,000	269,000	264,000	259,000	256,000	273,000	4.3
CNG	23,191	32,714	41,227	50,218	62,805	81,747	28.7
LNG	90	299	484	603	715	955	60.4
M85	4850	10,263	15,484	18,319	19,636	19,787	32.5
M100	404	414	415	386	155	130	-20.3
E85	172	441	605	1527	3575	5859	102.5
E95	38	27	33	136	341	341	55.1
ELEC.	1607	1690	2224	2860	3306	3925	19.6
TOTAL ALT	**251,352**	**314,848**	**324,472**	**333,049**	**356,533**	**385,744**	**8.9**

1.3 RESPONSIVE SOLUTIONS

While replacing petroleum oil is one reason for using alternative fuels, this study focuses on the vehicle emissions aspects of alternative fuels. Therefore, the following discussion on alternative fuels is done so with vehicle emissions in mind.

1.3.1 VEHICLE TECHNOLOGY

There is widespread agreement that both vehicle technology and fuel technology combine to determine vehicle emission levels. In order to comply with progressively more stringent standards, advanced engine technologies have been developed and incorporated into new vehicles.

Emission control technologies can significantly reduce the emissions level from vehicles when properly maintained [14,15]. Missing or dysfunctional emissions equipment has serious implications on emission levels. For example: a disconnected air pump can increase HC emissions 200% and CO emission by 800%; a disconnected exhaust gas recirculation system (EGR) can increase NO_X emission 175%; a missing or damaged catalytic converter can increase HC emissions 475% and CO emissions by 425%; and a disabled oxygen sensor can increase HC emission 445% and CO emission 1242% [14,15].

The g/km emission limits for certification of modern vehicles are stringent, e.g. with 96% reductions mandated in comparison to estimated pre-control levels for CO and HC [16]. Emission levels of vehicles are strongly dependent on the technology level of engine/emission control systems. The most important ones are: engine configuration (mainly modifications or redesign of the combustion chamber, air intake manifold and piston); advanced fuel injection system (e.g. port fuel injection closed-loop feedback system); advanced combustion control system (mainly maintaining stoichiometric air/fuel ratio); advanced after-treatment system (e.g. EGR, 3-way catalyst); advanced onboard electronic control.

Today's gasoline vehicle is very sophisticated in terms of technology. Alternative fuels technology in comparison is at it's infancy with advancements still to come. There is uncertainty associated with predicting the specific technology that automobile manufactures will apply to future vehicles to comply with the more stringent standards. However, it is certain that more new and advanced technology will be used for low emission (LEV), ultra low emission (ULEV), and zero emission motor vehicles (ZEV).

1.3.2 ALTERNATIVE FUELS

Alternative fuels are substantially non-petroleum and yield energy security and environmental benefits [19]. In response to occurrences of increasingly severe ambient ozone levels regional environmental managers are examining the possibility of cleaner fuels for automobiles[17]. The issue of environmental protection, especially the improvement of air quality, is one of the powerful driving forces for alternative fuel use in the transportation sector. Use of alternative fuels is considered to be an effective measure to meet strict emissions regulations of PM and NO_X [17]. There is a concerted effort by local and federal governments to promote alternative fuels through various rebates, tax breaks, low-interest loans and other subsidies [18]. For example, the USA has passed several energy acts to promote the production and use of alternative fueled vehicles and alternative fuels. These Acts include the 1980 Energy Security Act, The Alternative Motor Fuels Act of 1988 and the Energy Policy Act of 1992[19].

Changing from conventional fueled vehicles to alternative fueled vehicles is very complex and the introduction of this change needs cooperation from many areas to address the many issues and aspects. There are four main factors, which are used by the automotive industry, government and public to value or assess the success of new alternatives. They are: availability, performance, environmental "friendliness" and cost-effectiveness. As an example, liquid petroleum gas (LPG) or propane, has been used as an engine fuel for over 50 years. Low pollution characteristics have been recognized particularly by users of propane fuel forklift trucks and other industrial vehicles that operate indoors [20]. It is also very economical and readily available.

Given the push of depleting oil reserves and environmental concern, much research has gone on in the field of alternative fuels. This has produced a vast array of information available dating back several decades. In these studies researchers have looked at solar power, electric power, biomass as well as the more popular liquid and gaseous fuels such as reformulated gasolines and diesels, propane, butane, liquefied or compressed natural gas, alcohols and hydrogen. Currently the most viable, accepted and researched alternative fuels are reformulated gasoline (RFG), reformulated diesel, compressed natural gas (CNG), liquid petroleum gas (LPG), Methanol-85 (M85)and Methanol-100 (M100). Two of the more popular fuels that are not discussed in this thesis are Ethanol and electric vehicles. Ethanol's main benefit is that it is made from renewable agricultural sources such as sugar cane or corn. However, even if all of the U.S. corn crop was converted to ethanol, it would satisfy only 11% of the current transportation needs and would be more expensive than petroleum-based fuel [12]. Electricity is also a very good alternative when considering local air pollution. But at present the cost of electric vehicles and limited driving-range prevents their widespread use so they are not discussed.

1.4 THESIS SCOPE AND OBJECTIVES

Both government and automotive industry have increased their efforts to develop and use advanced technologies, which have made the effective use of some alternative motor fuels possible. But there is continuing concern over the potential impact of alternative fuels on air pollution, and the actual air quality benefits of using alternative fuels. As viable candidates to replace conventional fuels, they must demonstrate their impact on air quality is better than conventional fuels or at least equivalent. Recent years in the USA, there have been some large projects/programs for demonstrating effects of alternative fuels. Some of these have lasted several years, such as: "United States Postal Service Alternative Fuel Vehicle Environmental Assessment", "Alternative Fuels for Vehicles Fleet Demonstration Program "(in New York State), and "Texas Alternative Fuel Fleet Program" [21,22,23,24]. In addition there have been many smaller or medium sized research projects, which have provided valuable data and information.

Currently, the following four alternative motor fuels have been used at relatively large scale and are treated in this thesis as the main "clean" burning motor fuels: RFG, CNG, LPG,and M85.

So if fuels such as these have been researched for decades can one say that one fuel is better than all the rest? Or rank them from best to worst in terms of emissions? To do so is not as straight forward as it may first appear. Several reasons are apparent within the literature:

- Differences in vehicles and vehicle technologies.
- Alternative fuels technology is not as sophisticated as gasoline systems.
- Papers may be promoting specific technology and not reporting proper emissions testing.
- Differences in test conditions i.e. test cycle.
- No inclusion of comparable baseline data for conventional fuel.

When predicting the emissions effects of future vehicles running on alternative fuels it is important to be aware of all of the above in past studies. A careful review of currently available studies has been conducted to compare and assess currently viable alternative fuels. Chapter 2 is based on a stand alone paper presenting this literature review. The study has been conducted so as to minimize the problems mentioned above. Not all the papers and studies provide quality information so comparisons are made by creating a smaller subset of comparable papers.

The literature review helped shape an experimental investigation with two alternative fuels: LPG and CNG. A conversion project involving a fleet of forklifts was done. This involved seven forklift trucks being converted from LPG-powered, carbureted, two-way catalytic converter systems to CNG powered, fuel-injected, closed-loop controlled, three-way catalytic converter systems. Chapter 3 is based on a stand alone paper on the emissions testing and results. The study considers emission effects of fuel control and delivery system, emissions treatment as well as fuel characteristics. Other factors studied were the effects of vehicle age and vehicle maintenance.

The conversion project was taken one step further to assess the effects of the fuels and systems conversion on indoor air quality (IAQ). The interaction of pollutant species and indoor concentrations has been well researched from such constant emission sources such as surfaces, gas-fired ranges and heaters. Very little has been done however in the area of vehicle emissions modeling and IAQ. Chapter 4 is based on a stand alone paper on the mass-balance modeling of IAQ in a warehouse due to indoor forklift operation. Comparisons are made between an LPG and CNG system. Chapter 5 is the summary and conclusions chapter and presents the overall findings of the thesis.

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CHAPTER 2

EMISSIONS EFFECTS OF ALTERNATIVE FUELS IN LIGHT-DUTY AND HEAVY-DUTY VEHICLES

CHAPTER 2: EMISSIONS EFFECTS OF ALTERNATIVE FUELS IN LIGHT-DUTY AND HEAVY-DUTY VEHICLES

2.1 INTRODUCTION

With approximately 95% of transportation energy originating from petroleum-based fuels, concerns over supply stability, natural resource depletion and ecological degradation have motivated industry, government, and the public to consider alternative transportation fuels. This work does not address supply stability and resource depletion issues, but instead concentrates on the third key driver for alternative fuel use: tailpipe emission effects of using alternative fuels.

Many researchers have recognized the need to study alternative automotive fuels and have studied the effects of various alternative fuels on a wide range of vehicle types. This has produced a vast array of published literature dealing with the capability of vehicles to run on alternative fuels, on development of alternative fuel system components and on the emissions when running with alternative fuels. Unfortunately, despite the ease of finding published reports, it is not easy to decide what environmental benefits might result from using such alternatives.

The perceived health, environmental and economic impacts of these emissions have led to a series of progressively tighter motor vehicle emissions standards over the past three decades. Emission standards of various countries are included in Appendix A. In meeting these standards, much progress has been made and continues to be made in reducing overall emissions. For example, the EPA reported on "continued progress" in reducing air pollutants between 1984-93. These reductions included [1]:

- 37% drop in CO
- 12% drop in NO_2
- 20% drop in particulates (1988-93)
- 12% drop in smog
- 89% decrease in lead
- 26% drop in sulphur dioxide

Much of this progress is attributed to cleaner-running engines, better engine controls and tailpipe exhaust treatment. However, contributions to this progress have also been made through better fuel quality and composition changes. Some of the fuel changes include [1]:

- Lead removed from gasoline

- Gasoline Reid vapor pressure reduced in the May-Sept. summer driving season
- Oxygenates added to gasoline to reduce CO emissions in certain winter climates
- 85% sulphur reduction in Diesel fuel for highway vehicles to reduce particulates (soot and smoke)

Further reductions in fuel sulphur content and further controls on hydrocarbon and oxygenate composition are forecast for the near future.

Despite the significant gains in vehicle emissions, air quality problems persist in many large urban areas. Further progress in lowering emissions would be welcome. "Clean" alternative fuels are often cited as one method of making a step change to lower vehicle emissions.

- Is this the case?
- If so, which fuel(s) is (are) the best?
- How much advantage would each fuel provide?

When searching published literature for the answers to these questions, it quickly becomes clear that there are no simple answers. There are a great many studies describing vehicle emissions with alternative fuels. However, the degree of advantage (or disadvantage) varies between studies.

There are several reasons for large variations between studies:

Reasons related to the vehicles

- Research has been done with many different vehicles and fuel systems. Fuel systems for alternatives are generally not as sophisticated as the baseline gasoline systems and this leads to some variability of results.
- The continual evolution of "baseline" vehicle technology and "baseline" fuel formulation is another complication in evaluating the emissions impact of alternative fuels. For example, conversion of a simple 1970's vehicle to a carbureted natural gas fuel system may achieve simultaneous reductions of hydrocarbons, carbon monoxide and nitrogen oxides compared with the gasoline version. The same relative result is not so easily obtained with the more sophisticated, low-emission base vehicles of the present or future.

Reasons related to the testing and reporting

- Many papers focus on a specific vehicle / emissions technology and simply give emissions results with / without the use of that technology and do not compare to a conventional fueled baseline vehicle.
- Many of the tests reported in published literature use very simple test conditions such as idle / fast idle tests or steady speed tests. Some avoid cold start conditions. While such tests produce relative results, it is not clear whether the differences would stand up over a range of operating conditions. Some of the more commonly used test cycles are explained in further detail in Appendix B.
- Some published reports do not adequately describe the test conditions, making it difficult to accept or deny the claimed results.

Given the uncertainty created by these problems, it is difficult to use the mass of available literature to predict the emissions effect of any future shift to alternative fuels.

The objective of this chapter is to provide the best possible answer on emissions effects of alternative fuels by conducting a critical literature review. The literature has been searched to provide a limited subset of papers which report emissions results based on adequate tests with representative vehicles. The chosen papers cover both light-duty (LDV) and heavy-duty vehicles (HDV), using as baseline, conventional gasoline for LDV and diesel for HDV. Alternative fuels considered include reformulated gasoline (RFG), compressed natural gas (CNG), liquid petroleum gas (LPG), methanol-85 (M85) and methanol-100 (M100).

2.2 PROPERTIES AND ATTRIBUTES OF RFG, LPG, CNG, M85, M100 AS ALTERNATIVE FUELS

2.2.1 REFORMULATED GASOLINE – RFG

With the high cost of dedicated alternative-fueled vehicles, the lack of alternative fuel infrastructure and the low cost of petroleum-based fuel, it would make sense to improve air quality by modifying gasoline to reduce emissions. Gasoline is often assumed to be similar to iso-octane but actually contains over 500 hydrocarbons, mostly in the C_3 to C_{12} range. Conventional gasoline is only required to meet certain performance-based property tests and has minimal composition control. "Reformulated" gasoline or RFG has both a narrower range of permissible properties and has specific composition requirements. One key aspect is the addition of oxygenates: fuel compounds such as alcohols and ethers that contain oxygen as well as hydrogen and carbon. Adding oxygenates can provide antiknock benefits and reduce volatility, aromatic content, and the reactivity of emissions. The result is that reformulated gasoline can run in virtually all vehicles including dedicated and bifuel vehicles and can potentially reduce vehicle emissions. Dedicated vehicles are design specifically to run on one specific fuel while bifuel or flexible fuel vehicles (FFV) are capable of running on both a conventional fuel or an alternative fuel. Bifuel operation should not be confused with dual-fuel operation which allows for the use of conventional fuel and alternative fuel at the same time.

In the United States, RFG has been mandated for some of the worst ozone non-attainment areas over the past several years. Many studies and programs demonstrated good results in the reduction of emission levels. The main reason for RFG ability to reduce emissions lies in the fuel properties, which are shown in Table 2.1. The table describes fuel property data of the two typical gasoline fuels available in the United States, (a) RF-A: Auto/Oil industry average gasoline, (b) a reformulated gasoline meeting California's Phase-II gasoline specification. The significant differences between reformulated gasoline and conventional gasoline are: sulfur wt %, MTBE vol %, and Oxygen wt % [2]. These differences are expected to give RFG lower emission levels at comparative test conditions (Federal Test Program (FTP) was used as the test procedure).

Table 2.1: Fuel Property Data for Reformulated Gasoline [2]

	Unit	RF-A	CARB Phase II
Specific Gravity		0.749	0.740
Sulfur	wt %	0.0285	0.0042
Lead	g/gal	< 0.001	ND
Phosphorus	g/gal	<0.0001	ND
Benzene	vol %	1.07	0.70
MTBE	vol %	-	11.0
Aromatics	vol %	33.4	22.6
Olefins	vol %	8.3	4.0
Saturates	vol %	58.3	62.0
RON*		92.0	92.1
MON		83.7	85.0
Carbon	wt %	86.74	85.68
Hydrogen	wt%	13.22	12.32
Oxygen	wt%	-	2.00
RVP**	psi	8.85	6.80

*RON/MON - Research Octane Number and Motor Octane Number ** RVP - Reid Vapor Pressure

2.2.2 COMPRESSED NATURAL GAS – CNG

Natural Gas has considerable potential as a clean fuel for motor vehicles. Because there is plentiful supply, natural gas seems to be the most viable alternative fuel in the immediate future. It is estimated that reserves of conventional natural gas is 145.5 $x10^{12}$ m^3 [3]. Currently more compressed natural gas is used in motor vehicles than liquefied natural gas (LNG) due to the cryogenic storage requirement of LNG. In this literature only CNG will be discussed.

The composition of CNG varies throughout the world. It is mainly dependent on original gas composition and processing. A typical composition would include at least 90% methane followed by around 2% ethane and the balance composed of small percentages of propane, butane, nitrogen, carbon dioxide and traces of other gases [4]. However, typical utility-supplied natural gas can vary considerably in composition, even on a day-to-day basis [5]. Table 2.2 shows the various components of natural gas.

Table 2.2: Typical Composition of Natural Gas [4]

Category	Component	Formula	Amount
Paraffin	Methane	CH_4	70 ~98 %
	Ethane	C_2H_6	1 ~ 10 %
	Propane	C_3H_8	Trace ~5 %
	Butane	C_4H_{10}	Trace ~ 2 %
	Pentane	C_5H_{12}	Trace ~ 1 %
	Hexane	C_6H_{14}	Trace ~ 0.5 %
	Heptane and higher	C_7 +	None ~ Trace
Aromatic	Benzene	C_6H_6	Traces
Non-hydrocarbon	Nitrogen	NO_X	Trace ~ 15 %
	Carbon Dioxide	CO_2	Trace ~ 1 %
	Hydrogen sulfide	H_2S	Trace
	Helium	He	Trace ~ 5 %
	other Sulfur&Nitrogen comp.		Trace
	Water	H_2O	Trace ~ 5 %

The variable composition and properties of natural gas lead to some difficulties in assessing real world emissions. For certification purposes, a specific natural gas composition has been specified as given in Table 2.3. Typical properties as a motor fuel are provided in Table 2.4.

Table 2.3: EPA and CARB Certification CNG Composition (Mole %) [6]

Component	CARB	EPA
Methane	90.0 ± 1.0	> 89
Ethane	4.0 ± 0.5	Max 4.5
C3 and higher	2.0 ± 0.3	Max 2.5
C6 and higher	< 0.2	Max 0.2
Oxygen	< 0.6	Max 0.6
Inert Gases (CO_2 + N_2)	3.5 ± 0.5	Max 4.0
Odorant	detectable	<1/5 flam. limit in air

Table 2.4: Fuel Properties of Natural Gas [(1)] [7]

Specific Gravity	15°C, 1 bar	0.79×10^{-3}
Boiling Point	°C	- 162
LHV*	MJ/kg MJ /L	45.9 8.0 [(2)]
LHV stoichiometric mixture	MJ /kg	2.75
Octane Number		Research 130, Motor 120
Stoichiometric A /F ratio		15.7
Vapor Flamability limits	% vol.	5.3-15
Molecular Weight	kg/kmol	18.7

* LHV - Lower Heating Value (1) Average composition; (2) In storage conditions (15 °C, 220 bar)

As shown in Tables 2.2 - 2.4, the primary constituent of natural gas is methane [6]. As a gas under normal conditions, it mixes readily with air in any proportion and is flammable over a fairly wide range of air fuel ratios, (5-15%), permitting lean-burn engine technology. With a research octane number of 130 (the highest of any commonly used fuel), it can be used with engine compression ratios as high as 15:1, (compared to ~10:1 for gasoline), thus optimizing engine efficiency [7].

2.2.3 *METHANOL - M85 & M100*

Methanol has many desirable combustion and emission characteristics. It is a relatively simple, single-compound fuel, i.e. CH_3OH. Table 2.5 compares the composition of methanol to traditional petroleum based fuels. The high octane number (expressing antiknock performance), high latent heat of vaporization (which can make the fuel-air charge mixture cooler and thereby increase charge density), and excellent lean combustion properties make methanol a good fuel for spark-ignition (SI) Otto-cycle engines [8]. The high fuel/air ratio and latent heat properties combine to provide a low flame temperature compared with conventional gasoline and diesel, and thus offer NO_X emission advantages. Methanol contains no heavy hydrocarbons and no carbon-carbon bonds giving it low particulate emissions as well [9].

One of the disadvantages of methanol is the low energy density, which means that a large amount of fuel is required to achieve the same power output. Range of a vehicle powered by methanol is about 50 to 60 percent of the range from an equal volume of gasoline. The low vapor pressure and high latent heat of vaporization of methanol can also cause cold start difficulties for engines at low ambient temperatures [10]. A low cetane number can make it difficult to use in compression ignition diesel engines [11], although ignition additives and ignitor technology have provided satisfactory operation. Toxicity of methanol has also become an issue when used in areas which have traditionally used diesel fuel.

Table 2.5: Physical Properties of Methanol, Gasoline, and Diesel Fuel [10]

Property	Methanol	Gasoline	Diesel
Formula	CH_3OH	C_6 -C_{14}	C_{12}-C_{20}
Specific gravity at 16°C	0.796	0.70-0.78	0.80-0.88
Density at 20°C (kg/L)	0.791	0.70-0.78	0.80-0.88
Initial boiling point range, °C	64	27-49	190-210
Vapor pressure at 38°C, kPa	31.9	48.2-103	negligible
Flash point minimum, °C	11	- 43	38
Auto-ignition temperature °C	464	232-482	204-260
Flamability limits, vol % in air			
Lower	6.7	1.4	
Higher	36.0	7.5	
Heating value at 20°C, kJ/L			
Lower	15,760	32,160 (avg)	36,090 (avg)
Higher	17,900	34,780	---
Stoichiometric mass, air-fuel ratio	6.45	14.4-15.0	15.0 (avg)
Energy, kJ/m^3 of standard			
stoichiometric mixture at 20°C	3450	3500	3610
Latent heat of vaporization at 20°C			
kJ/kg	220	350	230-470
Octane number			
Research	106	91-98	x
Motor	92	82-92	x
Cetane	?	x	45-55
Sulfur content, wt %	0	0.020-0.045	0.20-0.25

M85 is a mixture of 85% Methanol and 15% Gasoline. The blend is used to partially alleviate some of the problems associated with using pure Methanol (M100), particularly difficult cold starts at temperatures below approximately 15°C and also safety concerns which include in-tank flamability, lack of flame luminosity and minimal odor or taste.

2.2.4 LIQUIFIED PETROLEUM GAS – LPG

LPG is considered to be a viable alternative fuel to conventional gasoline or diesel. LPG is mainly comprised of propane (over 90%) with the balance composed of butanes and propylene. Produced as a by product of both natural gas processing and crude oil refining, LPG is the third most widely used vehicle fuel, well behind gasoline and diesel. There are about 3.8 million LPG vehicles operating in the world [12]. The fuel is typically stored and handled as a liquid under pressures of around 1.03 MPa (150 psi) but flashes to vapor easily when released at atmospheric pressure. LPG vapors are much heavier than air and will collect at ground level when released.

Table 2.6: CARB Certification LPG Composition (Mole %) [6]

Component	CARB
Propane	93.5 ± 1.0
Butane (C_4H_{10})	1.9 ± 0.3
Propene (C_3H_6)	3.8 ± 0.5

2.3 EMISSIONS CONSIDERED

This thesis concerns itself with specific pollutants from vehicles which are included in the current emission standards of agencies such as the Environmental Protection Agency (EPA) of the United States, the California Air Resources Board (CARB) and the European Community. The pollutants produced by fuel combustion can be categorized into four classes according to the nature of the compounds and the effect when it is released into the atmosphere. These four classes would be:

<u>Regulated Emissions</u>

Total Hydrocarbons (THC), Nonmethane Organic Gases (NMOG), Non methane Hydrocarbon (NMHC), Carbon Monoxide (CO), Nitrogen Oxides (NO_X).

Air Toxins

Benzene, 1,3-Butadiene, Formaldehyde, Acetaldehyde, etc.

Ozone Precursors

$C_2 \sim C_{12}$ Hydrocarbons: Alkanes, Alkenes, Alkynes , Aromatics. Oxygenated Organic Compounds: Aldehydes, Ethers, Ketones, Methanol, and Ethanol. Methyl Nitride; Nitrous Acid; Nitrogen Oxides (NO_X).

Greenhouse Gases

Carbon Dioxide (CO_2); Methane; Nitrous Oxide.

The compounds specified as regulated emissions, air toxins and ozone precursors are the main cause of local and regional air quality problems; the greenhouse gases may contribute to changes of world climate. Due to high cost and experimental constraints, most projects or programs do not measure all the pollutants of the four classes.

This work concentrates on the Regulated Emissions class, i.e. the pollutants which are strictly controlled by emission standards published by EPA (Environment Protection Agency), CARB (California Air Resources Board), and European Community. These compounds (THC, NMHC, CO, NO_X, and particulate matter (PM)) are the most widely measured and reported. Toxic compounds are also included when the data are available.

2.4 VARIABLES AFFECTING VEHICLE EMISSIONS TEST RESULTS

Many factors affect emissions from vehicles. This makes it difficult to compare emissions results from different papers unless the tests and treatment of data were carefully controlled to make the tests truly comparable. Some of the important parameters are discussed below.

2.4.1 TEST CYCLE

Most light duty vehicle (LDV) test cycles specify a series of vehicle operations during which emissions are collected and analyzed in a specific manner. The emissions results are presented as a g/mile or g/km value based on the mass being emitted over the specified test duration and the distance thus traveled. Tests for heavy duty vehicles (HDVs) generally concentrate on the engine since the weight and configuration of vehicles may vary widely. Engine operating conditions are specified and accumulated emissions results are presented on a power-specific basis (g/bhp-hr or g/kWh) based on the mass emitted. In general, the LDV and HDV emissions numbers for different test cycles are not comparable due to differences in the speed, power and other operating conditions between cycles.

A paper by Rijkeboer et al [13] presented test results for four fuels: LPG, CNG, Baseline Gasoline and Diesel. The four fuels are tested over five different test cycles, the Urban Drive Schedule, European-Cold Start, European-Hot Start, US-Federal Test Program, and Traffic Jam. The findings of the paper are presented in Figure 2.1 as a percentage difference comparing CO, NO_2, Particulates and Toxic emissions. From the figure, it is seen that one may claim superiority of one fuel over another depending on which test was conducted.

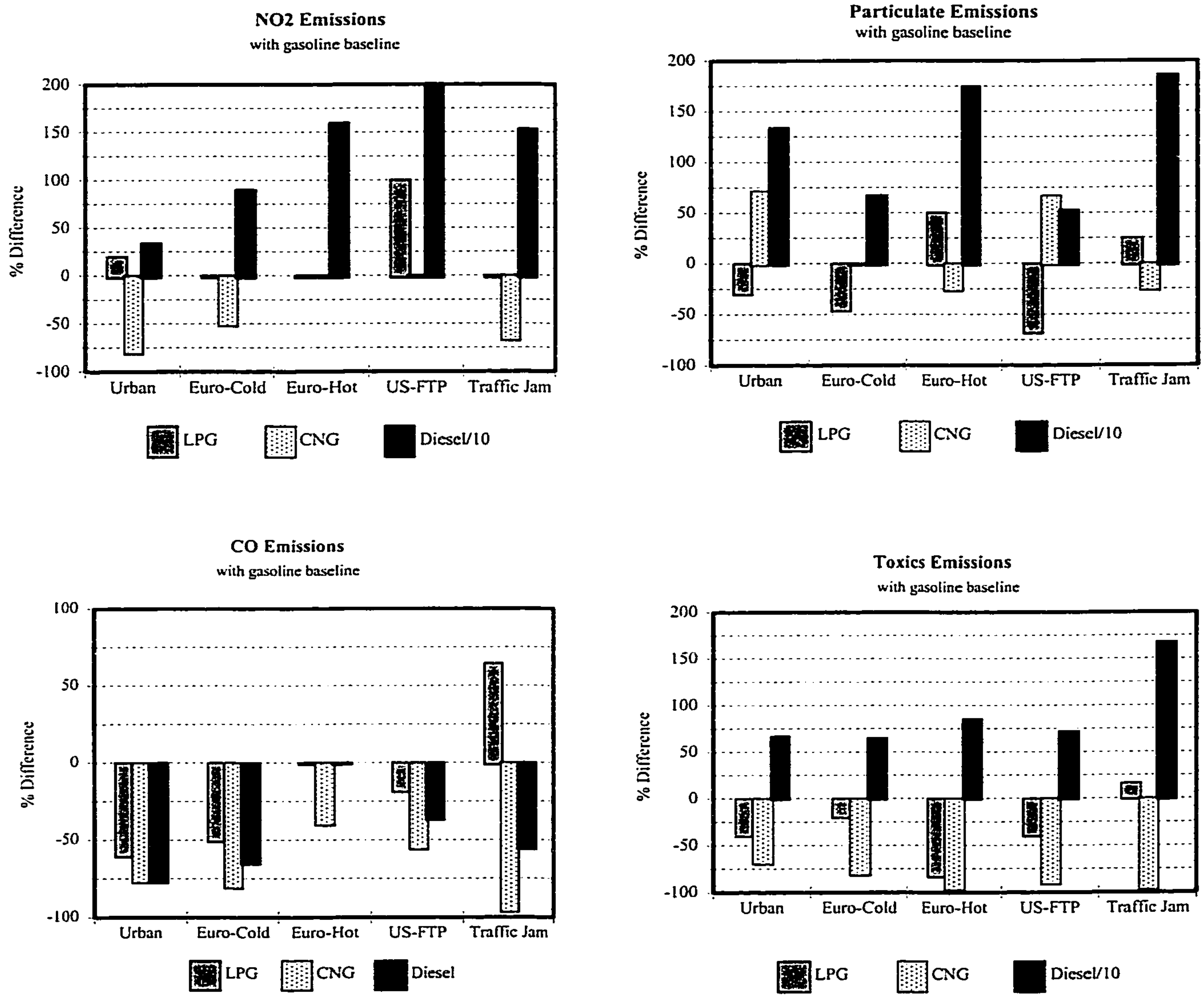

Figure 2.1: Relative Emissions for Different Test Cycles with Industry Average Gasoline as Baseline [13]

2.4.2 *FLEET YEARS/TECHNOLOGY*

Emissions standards have changed over the years and vehicle technologies have improved to meet the required levels of emissions control. The emissions from different fleet years is an important point since the majority of vehicles on the road at any given time are not new. A paper by Burns et al [14] describes the average emissions with different fleet years for RFG and Gasoline. Figure 2.2 shows a fuels comparison where the newer part of the vehicle fleet benefitted more than older vehicles, presumably due to better catalytic converters, fuel metering techniques etc.

Figure 2.2: Reformulated and Baseline Gasoline Emissions for Different Fleet Years [14]

Similarly, Howes and Rideout [15] tested four same-model vehicles, (1992 GM 2500 LDT 5.7 L V8), each equipped with a different natural gas conversion system. Each of the four conversion kits featured adaptive/block learn capabilities as well as close loop operation. Two of the kits had integral spark control, one was manifold absolute pressure (MAP) based while the fourth was not equipped with spark control. As shown in Figure 2.3, there was a tremendous difference in emissions with the different conversion technologies. The vehicles all provided a large NMHC and CO_2 benefit as would be expected with natural gas. However, the different technologies strongly affected the results for the species more important to local air quality (CO, NO_X and HCHO). It is worth noting that vehicle technology has more effect on species like CO and NO_X which are strongly affected by engine operating conditions like air to fuel ratio, compression ratio, and speed and load, while species like CO_2, and HCHO are more dependent on fuel composition.

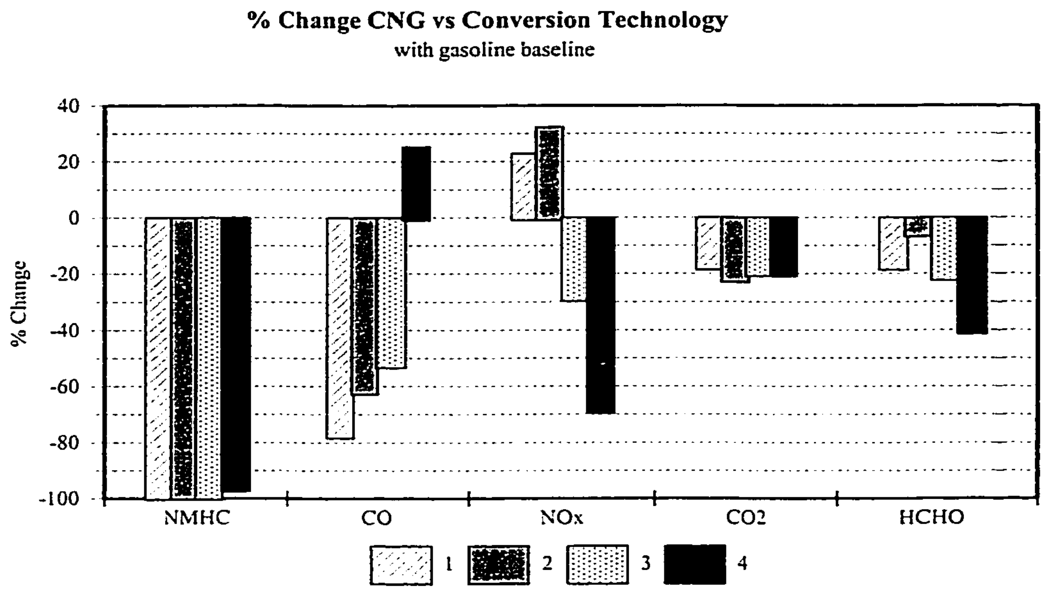

Figure 2.3: Emissions on CNG Relative to Gasoline for Four Different Conversion Technologies [15]
Note: Numbers 1-4 represent 4 different conversion systems

An additional paper by Bass, Bailey and Jaeger [16] assesses three different LPG conversion kits. Kit 1 was described as an adaptive digital processor, kit 2 was an automated fuel control processor, and kit 3 was a feedback control system. Results were presented as emission variation compared with the baseline gasoline system. Between the three kits, HC emissions ranged from +54% to -43%, CO emissions from + 89% to -65%, and NO_X emissions from +286% to 36%.

These examples emphasize the effect of vehicle technology on vehicle emissions. Simply using a given fuel is not likely to produce lower emissions, especially if the baseline is a current (or future) vehicle that is able to meet low emissions standards.

2.4.3 VEHICLE AGE AND MILEAGE

Another source of uncertainty in alternative fuel effects on emissions is vehicle age and mileage. The mileage affects both overall condition of the vehicle and specific emissions control devices. For example, most detailed studies of emissions try to account for the degradation effect on catalytic converters by aging them to 50,000 km where it is assumed catalyst degradation has stabilized.

Howes and Rideout [15] conducted tests on CNG fueled LDTs once before and once after 50,000 km had been accumulated by normal road operation. Figure 2.4 shows the emissions for the four conversions systems after accumulating 50,000 km. The different systems responded differently to the mileage effects. Some actually show better emissions reductions for certain species (possibly due to improved tuning), but most did not maintain the same emissions performance after 50,000 km of operation.

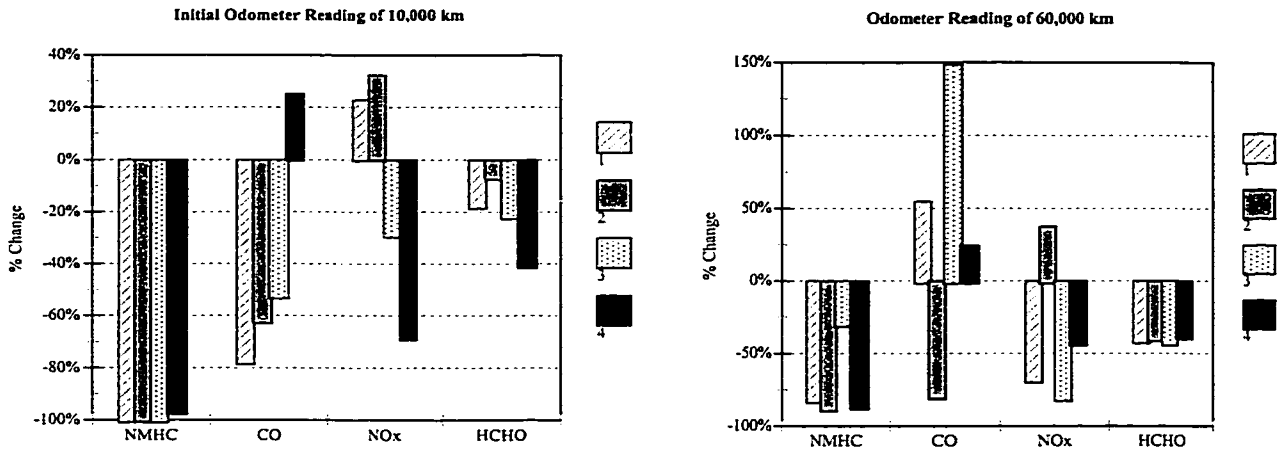

Figure 2.4: Effect of Mileage Accumulation on Relative Emissions Index for Four Different CNG Conversion Systems,(Emissions Shown as % Change Relative to Gasoline Baseline: Low Mileage and After 60,000 km) [15]
Note: Numbers 1-4 represent 4 different conversion systems.
Note: Note that scale changes in 60,000 km figure.

2.4.4 VEHICLE MAINTENANCE

The general tendency for emissions performance to degrade with mileage and age leads to the question of vehicle maintenance. The maintenance state of the vehicle has a definite impact on the actual emissions, both under test conditions and in real world driving. Carlson et al [17] illustrate the effect of vehicle maintenance, showing that most older vehicles have deteriorated significantly from their original design standards. Figure 2.5 shows the test results for 13 vehicles from the 1975-1980 model year vehicles tested before maintenance (as received) and after tune-up (baseline) with any needed correction of original equipment emission system defects. Note the results of this paper are shown here to illustrate the effects poor vehicle maintenance may have on emissions and that these vehicles are not representative of the present fleet.

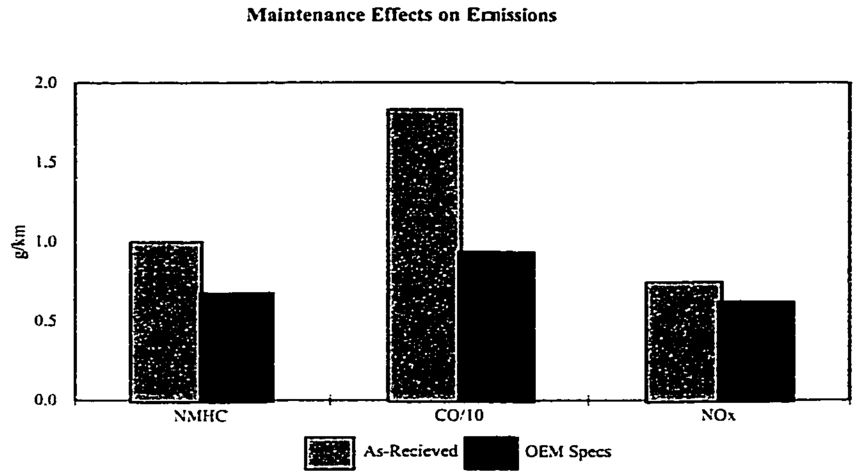

Figure 2.5: Maintenance Effects on Vehicle Emissions [17]

The absolute emissions differences between well and badly maintained vehicles of any age are considerably larger than observable effects of emission control technology and vehicle age [18]. A study looked at real world automobile CO and HC emissions based on remote sensing data collected from 22 locations around the world [18]. Results showed deterioration of mean emissions as a function of vehicle age is mainly controlled by vehicle maintenance. Also, the fraction of vehicles with high emission rates increases with age because of progressive lack of maintenance, more unrepaired failures, and tampering. The paper also concluded that emissions control technology is an effective factor to control exhaust emissions but is most effective when combined with proper vehicle maintenance [18].

2.4.5 LOW AMBIENT TEMPERATURE

The temperature at which a vehicle is operated or tested also has a definite effect on the emissions produced. In particular, fuels respond differently to low temperature operation depending on the fuel properties. Low ambient temperatures increase friction, increase cylinder leakage, prolong catalyst warm-up time and decrease fuel volatility. All of these factors can give rise to increased exhaust emissions. As an example, Laurikko and Nylund [19] conducted FTP75 cold start testing on gasoline LDVs at +20°C, -7°C and -20°C. Figure 2.6 shows dramatically higher emissions at the lower temperatures for both vehicles tested.

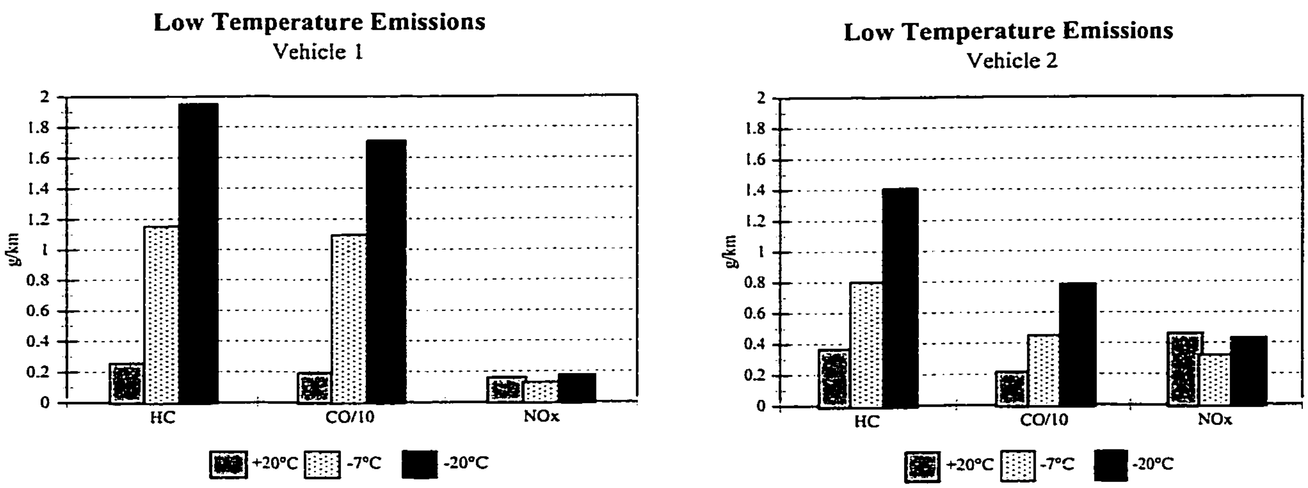

Figure 2.6: Effect of Low Temperature on Emissions for a Gasoline Vehicle [19]

As an additional example, Figure 2.7 shows the low temperature effects on emissions of four CNG vehicles compared with the baseline gasoline vehicle. (The results are presented as percentage emissions change and the four columns represent different conversion systems).

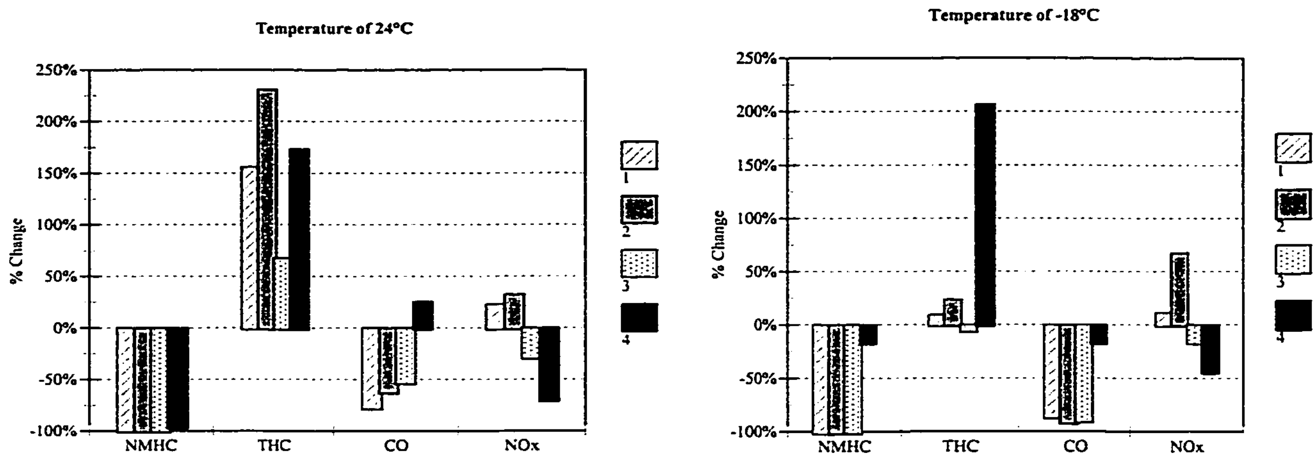

Figure 2.7: **Temperature Effects on Relative Emissions Indices for CNG with 4 Different Conversion Technologies: 24°C and -18°C (Gasoline Baseline)**[15]

2.5 EMISSIONS CHANGES WITH ALTERNATIVE FUELS FOR LIGHT-DUTY VEHICLES

2.5.1 DESCRIPTION OF LDV PAPERS SELECTED

A wide range of papers was surveyed to locate comparable emissions results for the different alternative fuels mentioned, as well as gasoline which would be the common baseline fuel for light-duty vehicles. Although papers from many sources were collected, the majority of studies quoted in this review are SAE papers. To make a good comparison between fuels, there must be a common reference point. The selected papers use vehicles classified as light-duty vehicles (LDV) or as light-duty trucks (LDT). For relevance to future emissions, only papers on new or standard technology are considered. This means three way catalyst, fuel injection, exhaust gas recirculation with feedback computer control, and in proper working condition. Another important criterion is the test cycle used. Studies which include testing with the US-FTP cycle (Federal Test Procedure) were preferred since this is the most relevant cycle for North American LDV's and is also the most common test cycle in available papers. The FTP test cycle stipulates exhaust gas sampling from engine start, thus including cold start characteristics of fuels. Some cycles which are considered equivalent to the US-FTP test cycle include the US-FTP75, EUDC (with cold start) (Extra-Urban Driving Cycle) and UDDS (Urban Dynamometer Drive Schedule) cycle. Many otherwise informative papers were not used because they do not provide adequate test cycle description, use non-standard test cycles, use older technology vehicles or do not control other parameters which could affect emissions.

Even with these limitations on which studies to consider, there are many sources for scatter in the data. Since a reliable baseline is of primary importance, only papers which include a baseline test on the gasoline counterpart of the vehicle were used. This allows treating the emissions change as a relative emission index rather than an absolute change in emissions. For papers dealing with dedicated alternative fueled vehicles only studies which provided emissions data on a comparative gasoline production vehicle of the same make and model were used.

The relative emissions indices are presented as a percentage change which is calculated:

Relative Emissions Index = 100% * (A – B) / B

where: A = emission rate of pollutant from Alternative fueled vehicle.

B = emission rate of pollutant from Baseline fueled vehicle.

2.5.2 LDV EMISSIONS COMPARISON

<u>Reformulated Gasoline (RFG) for LDVs</u>

There are many published papers supplying data on relative emission levels of conventional gasoline and RFG. These papers generally provide a consistent picture.

Considering Table 2.7, it can be seen that THC, NMHC and CO emissions are generally lower with reformulated gasoline than with conventional gasoline in nearly every study. However the magnitude of the differences is variable. THC emission reductions range from 10% to 35% reduction. The NMHC changes range from 0% to -27%; and the CO emission changes range from 0% to -43%. The differences in the magnitude of emission reduction are apparently tied to specifics of vehicle technologies, (e.g. vehicle model, emission control systems, etc.). NO_x emission changes did not show a consistent trend for the different studies but NO_x emission is reduced in most cases when reformulated gasoline is used in place of conventional gasoline.

These studies show that, under comparable conditions, using reformulated gasoline to displace conventional gasoline will generally reduce all emissions except for aldehydes.

Furthermore, reformulated gasoline is cited as a more cost-effective fuel for obtaining emission reductions than CNG, LPG, and M85 [18].

Table 2.7: Relative Emission Index for RFG in LDV's, (Gasoline Baseline)

THC	NMHC	CO	NO_X	CO_2	1	2	3	4	REF	# of Vehicles
-23%	-24%	-25%	-12%	-	-45%	-32%	16%	-14%	14	13
-14%	-10%	3%	3.5%	-	-36%	-83%	21%	-63%	20	1
-27%	-24%	-21%	-12%	0%	-47%	-30%	14%	-22%	21	3
-25%	-25%	-29%	-18%	-	-51%	-44%	12%	6%	22	6
-	-2%	-43%	-41%	-	-30%	-60%	13%	25%	23	1

Note: (1-4) are toxic compounds: 1 – Benzene, 2 – 1,3 Butadiene, 3 – Formaldehyde, 4 - Acetaldehyde

Compressed Natural Gas - CNG for LDVs

Because conventional gasoline is still the dominant fuel for light-duty vehicles, it is used as the baseline of comparison for CNG vehicles. Results drawn from published studies are represented in Table 2.8a and 2.8b. Compared to emissions from conventional gasoline vehicles, the THC emission from CNG vehicles were consistently higher. According to the above studies, the differences range from +18% to +340%. This is due to the main constituent of natural gas being methane which is very difficult to oxidize in the catalytic converter. The NMHC emission however, which greatly affect the ozone formation potential, is consistently lower than those from conventional gasoline, percent changes range from –14% to –97%. The highest reductions are reached by dedicated Natural Gas vehicles.

CO and NO_X emission percent changes from these published papers varied widely. In most cases CO and NO_X emissions from CNG light-duty vehicles were lower than that from conventional gasoline vehicles.

Table 2.8a: Relative Emission Index for CNG in LDV's, (Gasoline Baseline)

THC	NMHC	CO	NO_X	REF.	# of Vehicles
340%	-	-30%	-40%	6	4
-	-14%	69%	32%	23	1
18%	-80%	-64%	-81%	24	3
83%	-90%	-58%	-50%	21	3
140%	-	-60%	-13%	13	2
-	-72%	-21%	39%	25	88
157%	-99%	-42%	-11%	15	4
-	-80%	274%	160%	26	1
177%	-53%	42%	13%	27	13
-	-83%	-66%	-31%	28,29	37
453%	-84%	218%	150%	49	20

Table 2.8b: Relative Emission Index for Toxic Emissions on CNG (LDV, Gasoline Baseline)

1	2	3	4	REF.	# of Vehicles
>-99%	>-99%	-41%	-83%	21	3
-86%	-99%	-47%	-99%	23	1
-96%	-95%	48%	-62%	28,29	37

Note: (1-4) are toxic compounds: 1 – Benzene, 2 – 1,3 Butadiene, 3 – Formaldehyde, 4 - Acetaldehyde

<u>Liquified Petroleum Gas - LPG for LDVs</u>

At present, almost all LPG vehicles initially start out as gasoline vehicles. Emissions characteristics of LPG vehicles are dependent on how well the LPG system is integrated with the existing vehicle emission control system. Usually properly integrated LPG vehicles have lower carbon monoxide emissions, but hydrocarbon and oxides of nitrogen are not always down, it seems there is a trade between THC and NO_X emissions: the reduction of NO_X emission often means an increase of THC emission.

Table 2.9: Relative Emission Index for LDV's on LPG, (Gasoline Baseline)

THC	NMHC	CO	NO_x	CO_2	1	2	3	4	REF.	# of Vehicles
-35%	-	-71%	210%	- 15%	-99%	>-99%	-81%	-83%	16	1
-20%	-	-19%	40%	-	-	-	-	-	13	5
26%	-	-36%	53%	-	-	-	-	-	2	2
83%	178%	-67%	77%	-14%	-	-	-	-	29	3

Note: (1-4) are toxic compounds: 1 – Benzene, 2 – 1,3 Butadiene, 3 – Formaldehyde, 4 - Acetaldehyde

Methanol - M85 for LDVs

There were 9 published reports on M85 vehicle emissions which met the standard required for inclusion in this literature review. The results from this range of studies were not uniformly consistent. For example, all studies which reported THC emissions showed a decrease. However, some found a significant increase in NMHC emissions for the same cases. CO and NO_X emissions trends were variable with a tendency to be in opposite directions: if CO decreased, NO_X increased and vice versa. In most cases, there was a substantial increase in formaldehyde emissions compared with the gasoline baseline. However, all studies showed a substantial reduction in non-aldehyde toxic compounds.

Table 2.10a: Relative Emission Index for LDV's on M85, (Gasoline Baseline)

THC	NMHC	CO	NO_x	HCHO	Ref.	# of Vehicles
-31%	55%	-13%	-11%	965%	22	6
-16%	-	8%	-5%	-7%	2	5
-	55%	81%	-20%	-	23	1
-25%	-	0%	18%	468%	30	1
-32%	45%	-2%	11%	333%	31	1
-	67%	67%	-43%	168%	26	2
-61%	-	-55%	11%	360%	32	3
-	-23%	-17%	34%	593%	28,33	87
-	-57%	-44%	87%	-	34	1

Table 2.10b: Relative Emission Index of Toxic Emissions on M85, (LDV's, Gasoline baseline)

1	2	3	4	REF.	# of Vehicles
-72%	-80%	965%	19%	22	6
-55%	-99%	467%	-99%	23	1
-67%	-85%	593%	-44%	28	87

Note: (1-4) are toxic compounds: 1 – Benzene, 2 – 1,3 Butadiene, 3 – Formaldehyde, 4 - Acetaldehyde

2.5.3 LOW AMBIENT TEMPERATURE EFFECTS ON EMISSIONS OF ALTERNATIVE FUELED LDVS

As mentioned previously, low ambient temperatures have a profound effect on exhaust emissions and fuel consumption i.e. they both go up as ambient temperature gets cooler. Different emissions tests give different emissions rates due to effects of atmospheric temperature, pressure, humidity and background air purity. However, temperature is the parameter with the most profound effect on vehicle emissions. As a result, comparing the different fuels based on tests at standard test cycle temperatures in the range of 20°C to 30°C does not give complete understanding of the fuels behavior in the real world. There are several papers which consider low ambient temperature effects going back to the early 80's but most deal with only gasoline. Howes and Rideout [15] deal with low temperature effects on CNG with respect to gasoline and Gabele [30] compares temperature effects on M85.

The CNG study tested 4 different fuel delivery systems, some of which were only prototypes at the time of testing. Tests were conducted at 24°C and at -18°C. The results are presented in Table 2.11 as relative emission index compared with the gasoline baseline tested at the same temperature.

Table 2.11: Change in Emission Levels for CNG Conversions at Low Temperature (Gasoline Baseline)

NMHC		THC		CO		NO_X		HCHO		REF.
24°C	-18°C	24°C	-18°C	24°C	-18°C	24°C	-18°C	24°C	-18°C	
>-99%	>-99%	156%	9%	-78%	-86%	23%	11%	-18%	-18%	15 (1)
>-99%	>-99%	231%	24%	-63%	-92%	32%	68%	-7%	-10%	15 (2)
>-99%	>-99%	68%	-6%	-53%	-90%	-29%	-16%	-22%	-24%	15 (3)
-97%	-15%	174%	207%	25%	-17%	-69%	-45%	-41%	-30%	15 (4)

Note: Numbers in parentheses represent 4 different conversion systems.

The table shows that temperature does not affect CNG's ability to reduce NMHC emissions. Also, with cooler temperatures the THC emissions from the CNG vehicles are not as high as the gasoline emissions. CO emissions appear to be unaffected with only slightly better CO reduction capabilities at the lower ambient temperatures. NO_X

emissions seem to behave more variably from system to system. For the toxic emissions formaldehyde seems unaffected by the cooler temperatures.

The temperature effect on emissions of an M85 FFV were studied using both higher and lower temperatures, (32°C, 24°C and 4°C), Table 2.12. In this study, the vehicle running on M85 produced a similar THC advantage to gasoline at all temperatures. CO emissions are similar to gasoline with slight reductions at high and low temperatures. NO_X emissions are higher at all temperatures and appear to increase sharply at low temperature, possibly because of more aggressive spark advance at conditions where emission testing is not normally carried out. However these results are only for one vehicle and, as previous comparisons have shown, it is difficult to extrapolate to future fleets based on a single instance.

No published data sources were found which provided full LPG and RFG tests at low ambient temperatures. Further study is required on these fuels.

Table 2.12: Change of M85 Relative Emission Index at Different Temperatures (Gasoline Baseline)

THC			CO			NO_X			REF.
32°C	24°C	4°C	32°C	24°C	4°C	32°C	24°C	4°C	
-53%	-66%	-62%	-14%	0%	-3%	19%	18%	40%	30

2.5.4 MILEAGE DEGRADATION EFFECTS ON EMISSIONS OF ALTERNATIVE FUELED LDVS

Another concern with a transition to alternative fuels is the durability of alternative fuel systems with mileage accumulation. A good deal of information is available on emissions degradation rates of conventional gasoline fueled vehicles. However, there is only limited published data for mileage effects on the alternative fueled vehicles, partially because most AFVs are prototypes or aftermarket conversions.

Howes and Rideout [15] looked at emissions changes after accumulating 50,000 km (10,000 km to 60,000 km) on four different CNG conversion systems, some of which were prototypes, (Table 2.13). These vehicles tend to show significant changes in emissions after mileage accumulation. While CNG-fueled vehicles retain their NMHC and formaldehyde advantages over gasoline, the trends of NO_X and CO are variable, indicating less consistent control of air-fuel ratio as the vehicles aged.

Table 2.13: Mileage Effects on Relative Emissions Index for CNG Conversions (Baseline Gasoline)

NMHC		CO		NO_X		HCHO		REF.
10K	60K	10K	60K	10K	60K	10K	60K	
>-99%	-82%	-78%	55%	23%	-68%	-18%	-42%	15(1)
>-99%	-88%	-63%	-79%	32%	38%	-7%	-40%	15(2)
>-99%	-30%	-53%	148%	-29%	-81%	-22%	-43%	15(3)
-97%	-99%	25%	24%	-69%	-43%	-41%	-38%	15(4)

Note: Numbers in parentheses represent 4 different conversion systems.

McCabe et al [35] provide degradation effects on FFV vehicles operating on M85. These data, Table 2.14, indicate that the FFV's initial advantage in THC and CO emissions (compared to gasoline) degraded to become a disadvantage after 160,000 km (6000 km to 160,000 km). Since the vehicles also had a disadvantage in NO_X and formaldehyde emissions, mileage accumulation had essentially canceled any emissions advantage of M85 use.

Table 2.14: Mileage Degradation Effects on M85

THC		CO		NO_X		HCHO		REF.
6K	**160K**	**6K**	**160K**	**6K**	**160K**	**6K**	**160K**	
-28%	29%	-20%	36%	180%	9%	250%	233%	35

2.6 HEAVY-DUTY VEHICLES AND ALTERNATIVE FUELS

2.6.1 DESCRIPTION OF SELECTED HDV PAPERS

As with light-duty vehicles, many papers have been published dealing with emissions of alternative fueled heavy-duty vehicles. However, the only papers selected for inclusion in this study are those which provide comparable data for both the alternative fueled vehicle and a conventional fueled baseline vehicle. Since the great majority of HDV's are diesel-powered, this meant having a diesel baseline. More flexibility on accepting different test cycles was required with HDVs than LDVs since there have been more recent changes in HDV test cycles and a greater variety of test cycles are in use. Fortunately, most heavy-duty cycles are more comparable than LDV cycles since they all produce emissions values with units of power-specific emission rates (grams per hp.hr).

2.6.2 *HDV EMISSIONS COMPARISON*

The main emissions concerns from heavy-duty diesel vehicles are particulate matter (PM) and NO_X. NMHC, THC and CO are all low because of the inherently lean mixtures used in diesel engines. However, heavy-duty alternative fuel vehicles operating on non-diesel cycles might produce substantially greater amounts of THC, NMHC and CO, raising those emissions to levels of concern.

Compressed Natural Gas - CNG

Because of its widespread availability and comparatively low price, natural gas has frequently been considered for heavy-duty vehicle use. Table 2.15 lists the comparable results found in a number of studies meeting the basic criteria. In most cases, THC emission from CNG fueled vehicles are higher than those from conventional diesel vehicles. Since the majority of this increase is non-reactive methane, this is not a concern for ozone and smog potential. However, most HDV studies did not present NMHC data. The CO emissions on CNG vary relative to conventional diesel. However, they are lower in a majority of cases. The advantage of reduced CO is not large since CO is not typically considered to be a problem for the baseline diesels. CNG produced the greatest advantage in the areas where diesel vehicles have the most problems: NO_X and PM. The NO_X emissions from CNG fueled vehicles were consistently reduced by a substantial amount compared to their diesel counterparts. Particulate emissions from CNG vehicles were also consistently and substantially lower (by 80-99%) than their diesel counterparts. This suggests that CNG replacement for similar-vintage diesel engines would produce substantial emissions reductions. (Note however, that the diesel baseline is improving to meet future NO_X and PM standards and that changes in diesel fuel formulation will produce lower baseline PM emissions even in current vehicles.

Table 2.15: Relative Emission Index for HDV's on CNG, (Diesel Baseline)

THC	CO	NO_X	PM	Test Cycle	REF.	# of Vehicles
-42%	-90%	-57%	-99%	-	36	3
756%	-37%	-6%	-	CBD	37	52
265%	-94%	-36%	-97%	CBD	38	8
321%	-84%	-26%	-93%	NYBUS	2	36
450%	-87%	-76%	-96%	Transient (US)	5	2
-83%	-93%	-99%	-94%	ECE-R49	40	1
216%	200%	-72%	-81%	Real Bus	41	1
-	-75%	-56%	-90%	Real Bus	11	?
554%	-94%	-55%	-99%	Transient (US)	10	?
281%	-94%	-36%	-98%	CBD	42	8
1083%	43%	6.0%	-77%	CBD	43	1
658%	-93%	-52%	-99%	CBD	44	15
530%	17%	-54%	-98%	CBD	28	60

Methanol - M100

Traditionally, methanol presented some problems for compression ignition engines due to its corrosive nature, low lubricity and low cetane number. However, with an abundance of supply in the 1980's and 1990's, technologies evolved to solve these problems and compression ignition M100 engines were developed. With applications focused on urban vehicles, emissions have been a priority. Table 2.16 lists the emissions changes presented in a number of papers describing emissions of HDVs running on methanol.

THC and CO emission changes were highly variable with both increases and decreases. This is indicative of variable effects combined with a low value for the baseline diesel engine. There is also some concern that largely mechanical fuel systems were not as well optimized for M100 engines as for the baseline diesels, leading to inconsistent emissions results on M100. However, consistent reductions were seen for NO_X and PM emissions. The low flame temperature of methanol is expected to give reduced NO_X and most studies showed a NO_X reduction of 30-65%. Methanol's simple fuel structure (with no carbon-carbon bonds) is expected to reduce PM emissions and most studies showed more than 80% PM reduction. Overall, these NO_X and PM reductions are almost as good as those shown for CNG. One side effect however of using alcohol fuel is the appearance of formaldehyde (HCHO in Table 2.16).

Table 2.16: Relative Emission Index for HDV's on M100, (Diesel Baseline)

THC**	CO	NO_X	PM	HCHO	Test Cycle	REF.	# of Vehicles
-89%	-99%	-33%	-81%	-	Holster*	39	3
335%	-15%	-43%	-85%	-	CBD	42	4
525%	52%	-54%	-79%	-	CBD	45	46
230%	-15%	-43%	-71%	2053%	CBD	46	2
324%	-47%	-24%	-87%	915%	CBD	47	6
-37%	-24%	-41%	-84%	412%	Transient	46	2
-5.4%	-33%	1.3%	-22%	-8.3%	Transient	48	4
-22%	-45%	-62%	-80%	1996%	NYBUS	46	2
-100%	12%	-37%	-80%	1492%	NYBUS comp.	46	2
30%	11%	-6.3%	-	-	13 MODE	48	4
679%	69%	-64%	-80%	-	CBD	44	10
13%	-22%	-48%	-84%	-	CBD	34	1

*similar to CBD cycle. **THC is usually OMHCE for methanol fuel emissions.

Liquefied Petroleum Gas - LPG

Because almost all LPG vehicles start out as spark ignition (gasoline) vehicles, there are few compression ignition engines using LPG. The one paper which shows the use of LPG in a heavy-duty engine reports marked reductions in the NMHC, CO, NO_X and PM as shown in Table 2.17.

Table 2.17: Relative Emission Index for HDV's on LPG, (Diesel Baseline)

NMHC	CO	NOx	PM	Test Cycle	REF.	# of Vehicles
-38%	-95%	-55%	-94%	Real Bus	11	?

2.7 SUMMARY AND CONCLUSIONS

In summary, alternative fuels can provide substantial emissions reduction benefits over conventional gasoline and diesel. The greatest emission reductions are attained by dedicated vehicles. However, bi-fuel vehicles and conversions can also offer emissions reductions with the potential for greater market penetration.

Fuel characteristics of different fuels affect the production of specific emissions such as THC, CO, NO_X and Toxics differently. Additionally, reported vehicle emissions depend not only on fuel characteristics but also on vehicle characteristics like fuel and emissions systems technology, age, condition, bi-fuel or dedicated function, test cycle etc.

Using RFG to displace conventional gasoline showed the benefits which could be directly expected from the composition changes: reduced CO, THC, and aromatic compound emissions. The emissions reductions tend to be modest but can be applied to an entire fleet since no vehicle changes are required. Further, emissions of NO_X tend to be lower as well. However, these reductions were partially countered by increased formaldehyde emissions.

Using natural gas (CNG) increased total hydrocarbon emissions dramatically but also decreased non-methane hydrocarbons dramatically. As expected from the composition of natural gas, toxic compounds (aromatics and aldehydes) were greatly reduced compared to gasoline. Light-duty vehicle studies typically report a reduction in CO and NO_X emissions for conversion vehicles. Dedicated CNG vehicles specifically optimized for natural gas demonstrate the lowest emissions to date. For heavy-duty vehicles, using CNG significantly and consistently reduced particulate matter. In most cases CO and NO_X emission were also reduced compared with the diesel baseline.

Light-duty vehicles using LPG are able to reduce the THC and CO values compared with the gasoline baseline. However, NO_X was usually found to increase greatly in the LDV studies, possibly due to more aggressive spark timing. LPG-fueled vehicles showed great reduction in toxic emissions compared with conventional gasoline vehicles. As a heavy-duty engine fuel, LPG has found little use and so emissions data is sparse. However, the information available shows dramatic improvements are possible.

Light-duty vehicles using M85 showed variable amounts of decrease in THC, and approximately the same CO and NO_X emissions as gasoline, accompanied by a huge increase in formaldehyde emissions. Except for increased formaldehyde emissions, the changes with M85 were moderate.

Using M100 in heavy-duty vehicles produced variable emissions trends concerning THC and CO. However, M100 offered large and consistent emissions benefits for NO_X and PM which are the more serious problems for the baseline diesel vehicles.

Based on data from the selected papers, it can be seen that alternative fuels can reduce vehicle emissions compared to vehicles using conventional fuels. In recent years, advanced technologies have greatly reduced emission levels of traditional gasoline and diesel vehicles and the alternatives must be optimized to a similar degree to show any advantage. At the present time, most AFV's are conversions, bi-fuel vehicles or flexible fuel vehicles (FFV) and they have not been optimized to the same degree as traditional-fueled vehicles. However, vehicles which are dedicated alternative fuel vehicles employing sophisticated technology produce a significant benefit over conventional gasoline and diesel.

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CHAPTER 3

TAILPIPE EMISSIONS COMPARISON BETWEEN LPG AND CNG FORKLIFTS

CHAPTER 3: TAILPIPE EMISSIONS COMPARISON BETWEEN LPG AND CNG FORKLIFTS

3.1 INTRODUCTION

Forklift trucks play a major and vital role in materials handling in all sorts of industry. Applications range from outdoor construction sites to indoor food handling. As a result forklifts are available in various configurations ranging in size, lift capacity, lift height and power source. Application is the main factor in defining these parameters. The study considers only the issue of power source for forklift trucks from an emissions stand point.

The operation of forklift units indoors can lead to the build up of elevated concentrations of various exhaust components. The severity of the problem depends on vehicle emission rates, building size and building ventilation rates. Exhaust build-up is greatest in areas which lack adequate ventilation. This can occur for an entire building, for example when doors are closed in cold weather, or for particular locations, for example closed spaces such as coolers or truck boxes. Results are exposure of plant workers and forklift operators to high pollutant levels, possibly exceeding regulated occupational exposure levels. The human health effects and occupational exposure levels (OELs) of exhaust species are described in Appendix C and D respectively. Possible solutions are to increase building or local ventilation rates, decrease indoor vehicle operations or improve/reduce vehicle emission rates.

In the past, those forklifts used in indoor settings tended to be liquid petroleum gas (LPG) powered or battery powered. However, new pressures in lift truck selection include tougher regulations on lift truck odour and emissions [1]. This has prompted industry and researchers to look for solutions. One such solution is compressed natural gas (CNG) as a new fuel option.

Not only is the type of fuel burned important to exhaust pollutants but vehicle emission rates are strongly correlated to the sophistication of the vehicle's fuel control and emission control system as well. A local brewery in Edmonton, Alberta, Canada operates a fleet of forklift trucks for its indoor operations. Until recently the mixed-age fleet were all carbureted units fueled with propane. The LPG-powered forklift units used a typical carbureted fuel system designed to operate lean of stoichiometric. Two-way catalytic converters were used to oxidize carbon monoxide (CO) and unburnt hydrocarbons (HC) in the exhaust. The gas carburetor systems had a tendency to drift in terms of their state of tune. Lean operation resulted in the units running poorly and were re-tuned. Hence, the tendency was to drift to the rich side of stoichiometric where they would run better but result in high emission rates.

Prompted partially by health concerns within the plant, a project was undertaken to convert the forklifts to fuel injected, closed-loop controlled, CNG systems with three-way catalytic converters. The CNG fuel system is shown below in Figure 3.1. One key component of this conversion project involved an extensive study of vehicle emissions before and after the conversion. This chapter presents the emission test results.

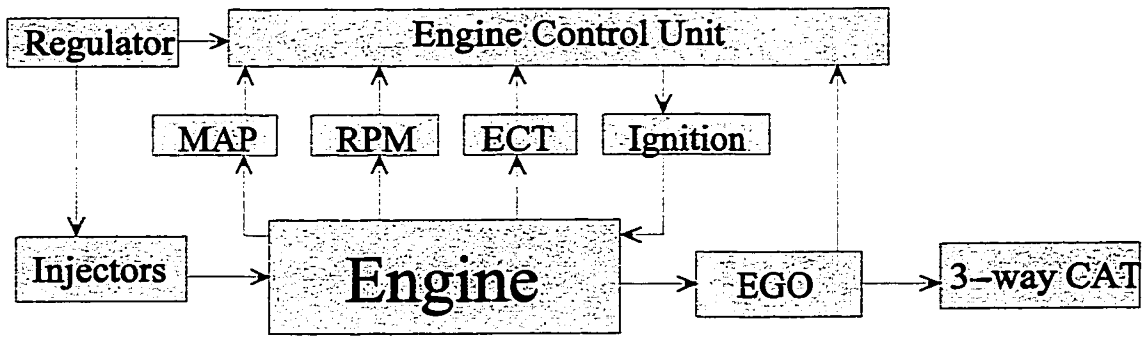

Figure 3.1: CNG Fuel System.

The main motivation for the project was to improve indoor air quality by reducing pollutant emissions from the lift trucks. The emissions test program, in addition to documenting emissions changes, was also geared toward gaining a better understanding regarding conversion systems. Other areas of interest were the interaction of vehicle age and conversion system response, performance comparison of two-way and three-way catalysts, system response to malfunctions, and emissions performance under various states of tune.

The following sections detail the literature, the tests, the analysis procedures, and the results.

3.2 LITERATURE ON FORKLIFT FUEL CHOICE AND EXHAUST EMISSIONS

The studies and papers discussed here are very specific to forklift units. There are many papers on the topic of forklift trucks and in general they address a wide range of issues such as emissions, indoor air quality, new forklift truck (FLT) technologies, hybrids, choice of fuels, battery power, A/C power and hydrogen fuel. This study only considers papers on fuel choice which limits the number of papers considerably. The main reasons for discussing power source are better air quality and reduced fuel cost. For forklifts the main fuel choices are Diesel, gasoline, LPG, CNG or battery power.

Several papers and studies discuss the use of FLTs indoors. When forklifts are operated indoors without proper fresh air ventilation, harmful levels of exhaust gases may be found in the building. A manufacturer offering technical tips states the safest way to prevent a CO threat is to tune the forklift regularly, maintain it properly, and add an exhaust purifier[2]. Simple maintenance items such as improperly gapped spark plugs or a dirty air filter can cause CO emission problems[2].

Diesel and gasoline fuels are generally avoided in the indoor application. Propane and battery power have generally been the accepted choice for forklift trucks operated indoors.

Situations arise however where battery power may have insufficient energy for a forklift duty cycle.

LPG is considered clean and a better alternative to gasoline, based on the following claims[3]:

- LPG produces much lower exhaust emissions than gasoline;
- reduces engine maintenance;
- lowers engine repair cost;
- offers faster cold starting;
- is non-polluting if spilled;
- provides overall lower cost of operation.

The article by Schneider [3] also states that every gasoline-powered lift truck used indoors needs an air-handling system capable of exhausting and replacing 230 m^3/min (8000 cfm) of air while a LPG truck requires 140 m^3/min (5000 cfm). However, the basis for these values is not given or explained.

CNG has also been cited for it's advantages and disadvantages compared to LPG. Interest in CNG is both from the point of view of lowering emissions and in fuel economy. CNG conversion costs between $1800 and $2000 per forklift truck, in many cases using the existing LPG carburetor [1]. The literature deems the advantages of CNG to include [1]:

- wide availability,

- extremely low emissions,
- extended engine life,
- longer oil life,
- safer operation and refueling,
- lower operating costs,
- quick and relatively easy conversion,
- lower risk of accidental combustion,
- cleaner combustion,
- eliminating in-ground fuel tanks,
- smoother cold starts with higher octane fuel,
- safer fuel because CNG quickly dissipates in air,
- and common conversion components that cover almost all lift trucks.

Disadvantages of CNG include such things as an expensive on-site refueling system, moisture in gas supply adding to the cost, CNG conversions cost more than LPG conversions, special high pressure tanks must be tested and re-certified every 5 years, a tank of CNG has a shorter run time than propane or gasoline, and one may need a larger area for compressors and above ground storage tanks[1].

The two principle culprits in ICE exhaust are cited as CO and HC's ignoring NO_X. Although NO_X poses a greater health hazard, with a 15 minute short-term exposure limit (STELs) set as low as 5 ppm and an 8 hour time-weighted average (TWA) at 3 ppm [4], the focus is primarily on HC and CO. One reason for this is CO levels are simply more easily measured than NO_X levels. Additionally, several studies on vehicle emissions report controlling CO levels help control all pollutant levels [5,6,7].

With LPG forklift trucks lean tune calibration and oxidizing catalysts are commonly used. However, benefits of low CO emissions and clean operation are only available if the engines are properly maintained. The key word in engine tuning for LPG is "optimum". The forklifts can be tuned lean enough to reach a point with virtually no CO. However, this typically results in bad forklift performance so it is then recommended to try to tune so as not to exceed Occupational Health and Safety Association (OSHA) standards for CO emissions. Another way to reduce emissions is replace a standard LPG system with an electronically controlled system. An oxygen sensor continuously monitors the exhaust and feeds information to an electronic air/fuel mixture control[1]. This costs about $300 more than a standard LPG conversion.

Operators of LPG forklifts must not be lulled into the belief that the fuel works magic under any condition. In most indoor cases with good air handling that changes air often, trucks using LPG are not a problem. They do however become a problem on congested docks, inside trailers and railcars. Emissions from forklifts cause all of the problems of operating an automobile in a closed garage.

The debate on superiority as a cleaner fuel between CNG and LPG is ongoing. Tests have proven with a well tuned forklift engine and properly calibrated fuel system, either LPG or CNG will produce low emissions without sacrificing good performance [8]. However, the reverse is also true. Both LPG and CNG can produce very high levels of CO and other emissions if the engines are not correctly tuned. The debate cannot be resolved easily due to the fact most papers on forklift truck emissions take a relatively simple approach to the problem of characterizing emissions. Most of the discussions are based on simple mixer carburetor systems which do not provide stable performance or emission characteristics. However, the papers do provide enough insight to show current research and advancements in FLTs to help reinforce this investigation. Also, there are no test programs suitable for forklifts, except in the case for Diesels using diesel engine tests, and no detailed emissions test results on LPG and CNG lift trucks have been reported. Therefore it was necessary to develop a test program which enables and allows to run tests which include new performance and long term stability. The development of the test program is described in detail in Appendix E.

3.3 TEST METHODS AND MEASUREMENT

3.3.1 MULTI-MODE TEST PROGRAM

One main requirement for the test was for it to be well representative of the forklifts actual duty cycle. The tests were to be done without interference with normal operations and have minimal test setup and run time. The result was a specially developed multi-mode, steady-state test schedule. The test was done stationary but loaded in the range of conditions to give realistic emissions. Testing mimicked the loads seen during typical duties which include idle, drive (no load), lift and lower load, drive (carry load), and push pallets. Each of the forklifts operate on eight different operating modes defined by specifying the engine speed and manifold vacuum. With the forklift stationary and the drive wheels chocked, various combinations of hydraulic and drive system loads were used to run the engine at the desired speed/vacuum point for each test mode.

The eight test modes were chosen to represent a common operating point based on analysis of engine data records from in-service operation. To do this, several forklifts were equipped with non-functioning engine control computers which continuously monitored engine speed, manifold vacuum, coolant temperature and other parameters (107 columns of data in all). The data stream was transmitted to a base station as the forklifts worked through their normal shifts. Subsequent analysis of the forklift data showed a relatively consistent operating pattern of engine speed and manifold pressure for different units and different plant duties. A set of 8 speed/load test modes were chosen which represent the majority of engine operating time and energy consumption. For each test mode, a weighting factor is assigned based on the number of seconds the forklift engine operates in that mode in a typical hour. Test results in each mode are converted to grams/second of fuel use or pollutant production. Then, a composite result for each test is calculated based on a weighted sum of the results in all modes. Since the composite test result is averaged over several operating modes, the effects of anomalous results due to measurement noise or machine variability at any particular operating mode are minimized [9]. Table 3.1 shows the speed, manifold pressure and time weighting factor for each of the 8 Modes.

Table 3.1: RPM, MAP and Weighting for Modes of the 8-Mode Test [9].

MODE	A	B	C	E	F	G	H	J
RPM	IDLE	1200	1200	1500	1500	1600	1500	1900
MAP (kPa)	IDLE	50	70	50	65	80	IDLE	70-80
WEIGHT (sec)	1224	576	360	216	432	216	432	144

Each forklift was tested on propane fuel before conversion. Since the propane "mixer" system has no feedback control and tends to drift with time, tests on propane involve the units in various states of tune. Where possible, each forklift was tested "as-is"; that is in the condition it came off of the plant floor. It was then tuned according to the manufacturer's procedure giving an "OEM" or Original Equipment Manufacturer setting and re-tested.

As part of the conversion process, the original catalytic converters, (oxidizing or two-way converters) were replaced with new three-way catalytic converters capable of reducing NO_X as well as oxidizing CO and hydrocarbons. Where possible, these converters were installed and tested on propane before the CNG conversion was completed. Once the CNG conversion was installed and tested, post-conversion tests were run with CNG fuel. Each forklift was tested in the normal, closed-loop operation state. In addition, maintenance faults were simulated by unplugging coolant temperature sensors or exhaust gas oxygen sensors to push the system into open-loop operation.

Upon completion of the first four CNG conversions, the forklifts were operated for an additional 5 months with three running on propane and four on CNG. This gave comparative data on loss-of-tune, system degradation and catalyst degradation for both propane and CNG systems. At the end of this period, all seven units were tested "as-is" and, if necessary, tuned or repaired to the original equipment manufacturer (OEM) condition and re-tested. Then, the final units were converted to CNG and checked by post-conversion tests.

3.3.2 TEST MEASUREMENTS AND INSTRUMENTS

Figure 3.2 shows schematically the forklift test setup and instrumentation. The majority of the measurement instruments and calibration gases were from the Engine Laboratory in the Department of Mechanical Engineering at the University of Alberta. During each test, engine speed, temperatures, fuel consumption, air consumption, and emissions measurements were continuously recorded by the computer at one second intervals. Additional measurements including 5-Gas analyzer output, Gas Chromatograph analyses, and miscellaneous other items were recorded by hand during specific test modes.

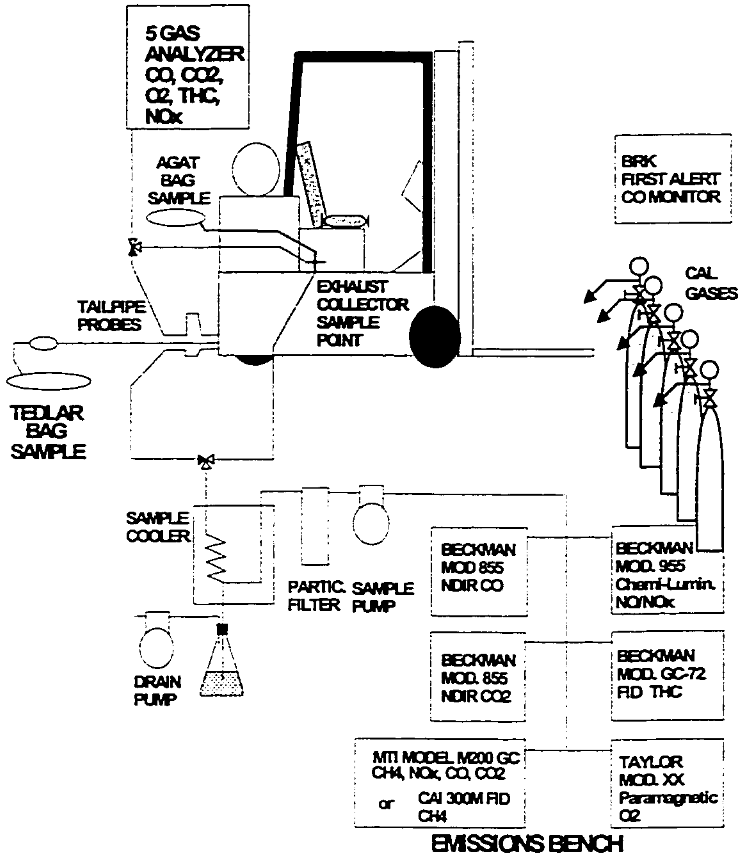

Figure 3.2: Schematic of Emissions Sampling and Analysis Equipment [9]

3.4 CNG CONVERSION RESULTS

The main purpose of the forklift fuel system conversions was to improve indoor air quality by reducing vehicle emissions inside the plant. To test whether this purpose was accomplished, emissions testing was done on the entire fleet and involved:

- tests of LPG and CNG fuel systems on each vehicle,
- comparison of the various forklift vintages,
- replacement of 2-way catalytic converters with 3-way catalytic converters,

- tests of LPG systems in various states of tune,
- tests of CNG systems operating with various malfunctions.

The following subsections report the findings of the conversion study from an emissions viewpoint. The forklift fleet consists of seven units representing 3 separate age groups: "OLD" (units 6, 9 and 10), "MIDDLE AGED" (units 2D and 2E), and "NEW" (units 13 and 44). The reported emissions measurements are presented in grams/hour for an average forklift, i.e. averaged over the fleet of similar vehicles/tests. In terms of health, the most important pollutants are NO_X, which is an eye and lung irritant, and CO which de-activates blood hemoglobin leading to headaches, fatigue and nausea. Test data validation and complete emissions test results are shown in Appendix F and G respectively.

3.4.1 CNG AND LPG FORKLIFT EMISSIONS COMPARED IN NORMAL OPERATION

Data in Figure 3.3 and Table3. 2 show the overall effect of converting existing forklift trucks from LPG-carbureted/two-way catalytic converter systems to CNG-closed-loop/three-way catalytic converter systems. The LPG systems were tuned to OEM specifications immediately before the test. The closed loop CNG system provided dramatically less toxic emissions: 77% less NO_X and 76% less CO.

The high emission rates on LPG are attributed to lack of any NO_X emission controls and to poor calibration stability of the LPG carburetor system. The LPG systems were intended to run lean to produce low CO and HC emissions. This lean operation optimized the effectiveness of their two-way catalysts but also led to high engine-out NO_X emissions with no after-treatment.

Regarding CO emissions, the newest LPG-powered forklift units, when tuned to lean OEM specifications, produced emissions comparable to the CNG conversions. However, the propane carburetor systems did not maintain a constant fuel/air ratio over the engine operating range and their operating point tended to drift with time, leading to much higher emissions. Forklifts with older LPG fuel systems tended to produce much higher emissions than the newest ones and drift out of tune faster. With the conversion to a feedback-controlled CNG fuel injection systems, the emissions of both old and new forklifts were reduced to essentially the same low levels.

Forklifts running on CNG generated 46% more THC (total hydrocarbons) emissions than those running on LPG. However, the majority of the THC from CNG systems was non-toxic methane while the THC from LPG systems was mostly higher hydrocarbons and aldehydes. This means the CNG-fueled systems actually produced less hydrocarbon odor and toxicity than the LPG systems. As shown in Figure 3.3 and Table 3.2, the NMHC (non-methane hydrocarbons) were reduced by 92% from 6 g/hr to 0.5 g/hr.

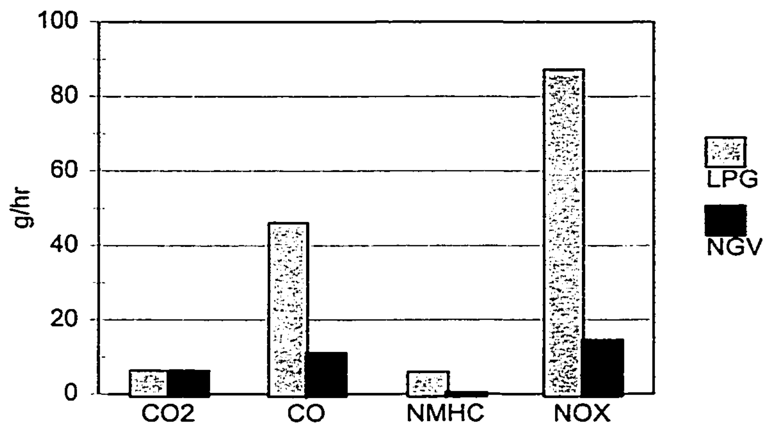

Figure 3.3: Comparison of Closed Loop CNG Emissions with LPG OEM Emissions[9]
(OEM=Best Case for LPG)(*CO_2 values in kg/hr, other emissions in g/hr).

Table 3.2: Comparison of Closed Loop CNG Emissions with LPG OEM Emissions[9]
(OEM=Best Case for LPG).

	LPG				CNG			
UNIT	CO_2	CO	NMHC	NO_X	CO_2	CO	NMHC	NO_X
6	5.4	6.2	4.3	45.9	6.9	8.8	0	12.7
9	6.6	101.1	10.6	45.7	7.1	14.6	0.8	5.1
10	7.6	25.3	6.6	64.8	6.9	8.8	2.4	18.5
2D	5.8	134.9	6.4	170.1	6	7.4	0	15.7
2E					5.8	18.5	0.2	37.7
13	6.3	4.5	5.2	174.7	6.3	8.7	0.3	5.7
44	6.3	5.1	2.9	22.5	5.9	11.4	0	7.1
AVG	**6.3**	**46.2**	**6**	**87.3**	**6.4**	**11.2**	**0.5**	**14.6**

*CO_2 values in kg/hr, other emissions in g/hr.
* CH_4 emissions are available in Appendix G

The CO_2 emissions on CNG were equal to or slightly higher than comparable emissions on LPG, (6.4 kg/hr compared with 6.3 kg/hr). The CNG fuel has the advantage of a lower Carbon/Hydrogen ratio than LPG. However, this is offset because the CNG/three-way catalyst systems run stoichiometric mixtures to get good tailpipe emissions. This results in slightly higher fuel consumption than the LPG systems which are typically tuned to operate lean to attain higher efficiency. The result is approximately equal CO_2 emissions.

This basic comparison shows a strong emissions benefit for CNG when both systems are presented in their "best" state of tune. Noticeable differences are seen in the CO and NO_X which are the most important pollutants for worker safety and indoor air quality issues.

The above results show the LPG systems in their "just-tuned" state. However, being carbureted systems with no feedback control, these LPG units tended to drift from their state of tune even during the short period of time for an 8-mode emissions test. A more realistic comparison of the CNG and LPG systems was obtained by comparing the CNG results with LPG systems in their "As-Is" state of tune when received from the plant floor. The tendency for LPG units to run much richer than their recommended state of tune provided dramatic emissions results as shown in Figure 3.4 and Table 3.3.

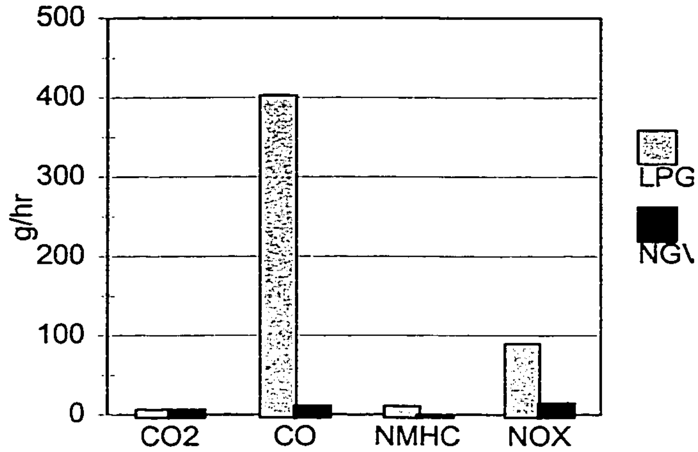

Figure 3.4: Comparison of Closed Loop CNG Emissions with LPG As-Is Emissions[9]
(*CO_2 values in kg/hr, other emissions in g/hr).
(Note change of vertical scale to 5x the scale in Figure 3.3)

Table 3.3: Comparison of Closed Loop CNG Emissions with LPG As-Is Emissions
(Blank rows indicate no As-Is tests available on LPG)

	LPG				CNG			
UNIT	CO_2	CO	NMHC	NO_X	CO_2	CO	NMHC	NO_X
6	6.8	903.5	20.5	96.3	6.9	8.8	0	12.7
9					7.1	14.6	0.8	5.1
10					6.9	8.8	2.4	18.5
2D	6.1	339.3	15.3	61.5	6.0	7.4	0	15.7
2E					5.8	18.5	0.2	37.7
13	6.3	69.8	4.8	160.6	6.3	8.7	0.3	5.7
44	6.6	297.9	2.7	40.2	5.9	11.4	0	7.1
AVG	**6.5**	**402.6**	**10.8**	**89.7**	**6.4**	**11.2**	**0.5**	**14.6**

*CO_2 values in kg/hr, other emissions in g/hr.
* CH_4 emissions are available in Appendix G

The LPG As-Is emissions are the most realistic capture of emissions from LPG forklifts as they actually run on the plant floor. Table 3.3 indicates the majority of the LPG units produced much higher CO emissions after a period of operation than shortly after being tuned. The As-Is CO emissions averaged 403 g/hr compared with 46 g/hr after tuning. This tendency to drift rich is not too surprising in that the units which drift towards the lean operation would become too lean and tend to run poorly. As a result they receive maintenance attention and re-tuning. On the other hand, units which drift towards the rich side tend to run well and do not necessarily receive any maintenance attention. The average NO_X emission rate appears similar in service at 90 g/hr compared with 87 g/hr just after tuning.

The resulting comparison between As-Is LPG units and Closed-Loop CNG units showed the CNG systems produced 97% less CO and 84% less NO_X. In addition, the CNG systems produced less THC, (41% less, even including methane), and marginally less CO_2, (6.4 kg/hr compared with 6.5 kg/hr for LPG).

These tables provide additional insight regarding individual unit responses to the LPG and CNG fuel systems. The seven units represent 3 separate age groups: "OLD" (units 6, 9 and 10), "MIDDLE AGED" (units 2D & 2E), and "NEW" (units 13 & 44). Older forklifts running on LPG appeared to produce substantially higher emissions than the newer units, presumably due to some combination of worn regulators, worn mixers, plugged lines, etc. Newer units, when freshly tuned to OEM settings were actually competitive with the CNG system in terms of CO but had higher NO_X emission rates. However, the conversion to a feedback-controlled CNG fuel injection system benefitted all age groups, bringing them down to a common, low emission rate.

3.4.2 EFFECT OF FUEL SYSTEM AND CATALYST MALFUNCTIONS ON CNG FORKLIFT EMISSIONS

The CNG fuel injection system uses several engine sensors to help adjust, maintain and control the Air/Fuel ratio at the desired point for good engine-out emissions and high catalyst effectiveness. These sensors are proven very reliable in automotive systems but are still susceptible to failure. Some basic sensors, such as the engine speed/position sensor, are so critical that any failure would shut down the engine. (Fortunately, the experience with millions of cars shows these sensors almost never fail.) However, the two engine sensors which can fail and still allow continued operation (with possibly degraded performance) are the exhaust gas oxygen (EGO) sensor and the engine coolant temperature (ECT) sensor. This section describes the emissions response of CNG forklifts running with failed sensors.

It is worth noting that the engine control computer detects failed or disconnected sensors and signals a maintenance requirement by making the fuel gauge twitch periodically. Hence, unlike a carbureted system which drifts out of tune and runs on, the fuel injected systems should not operate with failed sensors for any long period.

3.4.2.1 Exhaust Gas Oxygen (EGO) Sensor Malfunction

The EGO sensor is critical as it is the feedback sensor which provides for continual adjustment of air/fuel ratio in Closed Loop operation. In the event of an EGO sensor malfunction or disconnection, the CNG fuel injection system goes into open loop operation and begins to twitch the fuel gauge to alert the operator of a malfunction. As it operates

Open Loop, the engine control computer uses the last fuel map stored in memory and multiplies by a factor less than one to bias towards slightly lean operation. This would be expected to result in less carbon monoxide and more oxides of nitrogen than normal as well as giving a slight power reduction due to the leaner mixtures.

Figure 3.5 and Table 3.4 show the measured effect of the lean-burn open-loop strategy on tailpipe emissions for CNG-fueled forklifts operating with the EGO sensor disconnected. As expected, lean-burn operation gave reduced CO emission, down from 11.2 g/hr to 4.7 g/hr, and increased NO_X emission, up from 14.6 to 33.5 g/hr. While the increased NO_X emission is undesirable, it is worth noting that it was still considerably lower than the 89.7 g/hr produced by the LPG-fueled forklifts.

In lean-burn conditions, the THC emission rate rose from 10.5 g/hr to 12.6 g/hr, (still mostly methane). With lean burn, the fuel economy on CNG was improved compared with the normal, stoichiometric operation. This showed up as reduced CO_2 emissions, down from 6.4 g/hr to 5.7 g/hr.

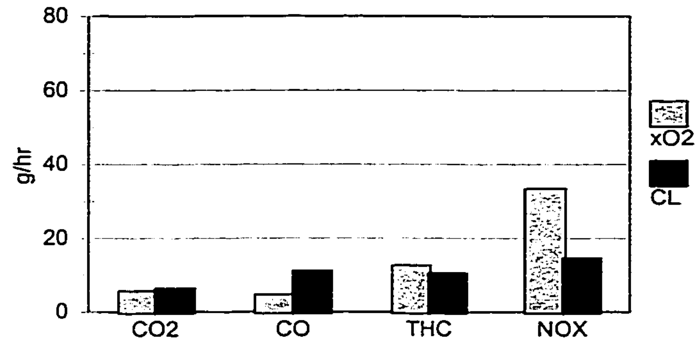

Figure 3.5:Comparison of Open Loop CNG Emissions with Closed Loop Emissions[9]
(*CO_2 values in kg/hr, other emissions in g/hr).
(xO2 = Open Loop due to O2 sensor failure, CL=Closed Loop (normal) operation).

Table 3.4: Comparison of Open Loop CNG Emissions with Closed Loop Emissions[9]

	Open Loop (xO2)				Closed Loop (Normal)			
UNIT	CO_2	CO	THC	NO_X	CO_2	CO	THC	NO_X
6	5.9	5.3	31.4	8.9	6.9	8.8	17.7	12.7
9					7.1	14.6	8.2	5.1
10					6.9	8.8	13.6	18.5
2D	6.0	5.9	6.8	17.9	6.0	7.4	5.7	15.7
2E	5.5	5.2	12.3	82.9	5.8	18.5	14.3	37.7
13	5.6	4.1	5.4	25.0	6.3	8.7	5.4	5.7
44	5.4	3.0	7.3	32.6	5.9	11.4	8.7	7.1
AVG	**5.7**	**4.7**	**12.6**	**33.5**	**6.4**	**11.2**	**10.5**	**14.6**

*CO_2 values in kg/hr, other emissions in g/hr.
* CH_4 emissions are available in Appendix G

3.4.2.2 Temperature Sensor Malfunction

The CNG system uses an ECT (engine coolant temperature) sensor to help set fueling strategy. In the event this sensor fails, an approximate temperature is assumed by the engine controller. Test results presented in Figure 3.6 and Table 3.5 show disconnecting the ECT sensor affects the closed loop emissions performance but the differences are relatively small.

With the ECT disabled, CO emissions rose from 11 to 17 g/hr and NO_X emissions rose from 15 to 20.5 g/hr. THC and CO_2 emissions were almost unchanged.

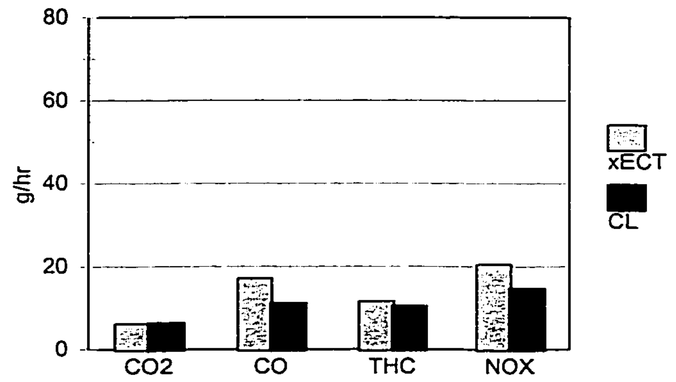

Figure 3.6: Comparison of Emissions for CNG Systems with ECT Sensor Disabled[9]
(*CO_2 values in kg/hr, other emissions in g/hr).
(xECT = operation with Engine Coolant Temperature sensor disconnected)

Table 3.5: Comparison of Emissions for CNG Systems with ECT Sensor Disabled

	ECT Sensor Disabled				Normal Closed Loop Operation			
UNIT	CO_2	CO	THC	NO_X	CO_2	CO	THC	NO_X
6	7.1	9.3	19.4	10.5	6.9	8.8	17.7	12.7
9	6.2	6.9	8.8	14.6	7.1	14.6	8.2	5.1
10	6.8	34.9	21.5	35.8	6.9	8.8	13.6	18.5
2D	6.3	9.9	1.7	17.2	6.0	7.4	5.7	15.7
2E	4.9	43.1	15.6	50.8	5.8	18.5	14.3	37.7
13	6.0	6.0	5.6	8.3	6.3	8.7	5.4	5.7
44	6.2	9.8	8.1	6.4	5.9	11.4	8.7	7.1
AVG	**6.2**	**17.1**	**11.5**	**20.5**	**6.4**	**11.2**	**10.5**	**14.6**

*CO_2 values in kg/hr, other emissions in g/hr.
* CH_4 emissions are available in Appendix G

3.4.2.3 Catalyst Ineffective/Disconnected

Catalytic converters degrade with time and can degrade rapidly if they are overheated. Overheating of catalysts can occur due to poor fuel control or engine misfiring. To measure the impact of catalyst degradation or damage, the worst case scenario would be a totally ineffective catalyst, that is, tailpipe emissions would be the same as engine-out emissions.

Figure 3.7 and Table 3.6 compare the engine-out emissions produced by running an average LPG unit or CNG unit with no exhaust treatment. Based on engine-out emissions, the CNG-fueled systems have a substantial advantage in CO and NO_X emissions, 57% and 27% lower respectively. Emissions of NMHC are also much lower, by 92%.

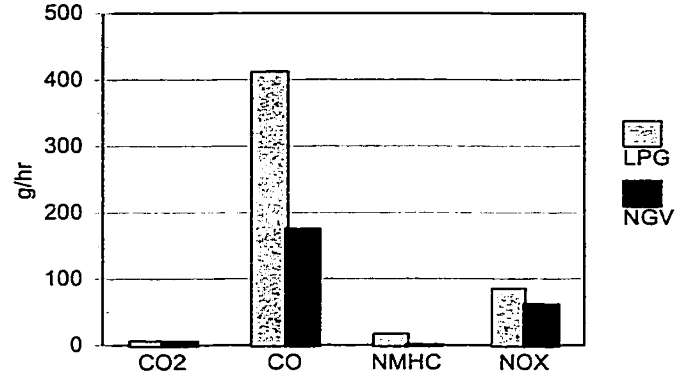

Figure 3.7: Engine-out Emissions of LPG As-Is and CNG Closed Loop[9]
(Note: Figure Vertical Scale raised to 500 g/hr)
(*CO_2 values in kg/hr, other emissions in g/hr).

Table 3.6: Engine-out Emissions of LPG As-Is and CNG Closed Loop[9]

	LPG				CNG			
UNIT	CO_2	CO	NMHC	NO_X	CO_2	CO	NMHC	NO_X
6	6.9	983.3	27.6	95.9	6.5	167.1	0	64.7
9					6.9	229.5	2.9	49.4
10					6.7	165.6	4.3	66.0
2D	6.1	309.2	22.4	86.1	5.6	186.7	0.7	49.1
2E					5.7	131.8	0.6	101.7
13	6.3	57.4	12.2	106.2	5.9	205.5	0.6	44.7
44	6.5	299.6	7.1	54.7	5.5	145.3	0	61.6
AVG	6.5	412.4	17.3	85.7	6.1	175.9	1.3	62.5

*CO_2 values in kg/hr, other emissions in g/hr.
* CH_4 emissions are available in Appendix G

3.5 TWO-WAY AND THREE-WAY CATALYTIC CONVERTER

3.5.1 CATALYTIC CONVERTER EFFECTIVENESS

Two-way catalytic converters for spark ignition engines are used to oxidize CO and HC's in the exhaust stream and are not capable of reducing NO_X. Sufficient oxygen is required to oxidize the CO and HC, which is normally supplied by the engine running lean of stoichiometric, but could also be supplied by an air pump which puts extra air into the exhaust stream. The two-way catalysts on the LPG forklifts were conventional oxidizing platinum catalyst. However, a three-way catalytic converter simultaneously removes CO, HC and NO_X pollutants from the exhaust. The NO reduction and CO and HC oxidation is done with one catalytic reactor and typically requires the engine to operate very near stoichiometric so as to provide sufficient CO and HC to react with the NO_X. The mixture "window" for high conversion efficiencies for all three pollutants is very narrow. Maintaining such a tight fuels control is typically beyond the control capabilities of a carburetor and requires a more sophisticated feedback-controlled carburetor or fuel-injection system. The three-way catalytic converters installed on the forklifts are typical of current automobile converters using a platinum-rhodium catalyst.

New three-way catalytic converters were initially installed on some of the LPG-powered forklifts. These forklifts were tested initially and after a period of normal plant operation on LPG to determine engine-out and tailpipe emissions. The ratio of downstream/upstream emission rate (averaged over the multi-mode test procedure) gave a measure of the effectiveness of the catalytic converter.

Catalyst effectiveness is affected by both the catalyst chemical activity and the equivalence ratio. Interpreting catalyst effectiveness is further complicated since they are based on the composite results of multi-mode testing. It is possible for a unit to run rich in one mode and lean in another, resulting in trade-offs between high and low effectiveness for CO, THC and NO_X.

Table 3.7 shows the measured effectiveness of the original two-way catalytic converters for the three main pollutants: 37% effective on CO, 26% effective on THC and -4% effective on NO_X. The effectiveness on CO and THC was lower than would be expected from a properly functioning catalyst. However, this was biased by several rich-running modes which produced high emission levels with insufficient oxygen to let the catalyst work. The negative effectiveness on NO_X indicates that an additional 4% NO_X was formed in the catalytic converter.

Table 3.7: Upstream and Downstream Emissions Comparison on LPG - Existing 2-way Converters[9]

	UPSTREAM				DOWNSTREAM			
UNIT	CO_2	CO	THC	NO_X	CO_2	CO	THC	NO_X
6	6.4	28.6	35.8	84.2	6.3	8.3	25.6	85.7
10	7.1	65.8	18.5	69.0	7.3	40.9	11.8	73.1
2D	6.1	77.1	18.9	102.3	6.3	58.4	16.5	107.6
AVG	**6.5**	**57.2**	**24.4**	**85.2**	**6.6**	**35.9**	**18.0**	**88.8**

*CO_2 values in kg/hr, other emissions in g/hr.
* CH_4 emissions are available in Appendix G

Table 3.8 shows the difference that a new three-way catalyst makes to the LPG system. The new three-way catalysts were much more effective than the old two-way catalysts at treating the exhaust which was produced. They oxidized 52% of the CO, 65% of the THC and simultaneously reduced 31% of the NO_X.

Table 3.8: Upstream and Downstream Emissions Comparison on LPG - New 3-way Converters[9]

	UPSTREAM				DOWNSTREAM			
UNIT	CO_2	CO	THC	NO_X	CO_2	CO	THC	NO_X
6	5.4	85.7	27.1	94.5	5.4	6.2	7.5	45.9
10	7.5	82.2	19.9	67.1	7.6	25.3	6.6	64.8
2D	5.8	180.9	21.0	121.6	5.8	134.9	9.8	85.1
AVG	**6.2**	**116.3**	**22.7**	**94.4**	**6.3**	**55.5**	**8**	**65.3**

*CO_2 values in kg/hr, other emissions in g/hr.
* CH_4 emissions are available in Appendix G

Table 3.9 presents the results of testing three-way catalytic converters on CNG-fueled engines. The overall results are impressive with the catalyst oxidizing 94% of CO and 55% of THC while simultaneously reducing NO_X by 77%. Achieving high levels of CO oxidation and NO_X reduction simultaneous requires very tight control of the Air/Fuel ratio (as can be expected from a feedback-controlled fuel injection system). These results show it was achieved. The relatively lower conversion efficiency of THC would be because the THC is mostly methane, which is harder to oxidize than the higher hydrocarbons.

Table 3.9: Upstream and Downstream Emissions Comparison on CNG - New 3-way Converters[9]

	UPSTREAM				DOWNSTREAM			
UNIT	CO_2	CO	THC	NO_X	CO_2	CO	THC	NO_X
2D	5.6	186.7	17.3	49.1	6.0	7.4	5.7	15.7
2E	5.7	131.8	21.0	101.7	5.8	18.5	14.3	37.7
6	6.5	167.1	41.3	64.7	6.9	8.8	17.7	12.7
9	6.9	229.5	23.8	49.4	7.1	14.6	8.2	5.1
10	6.7	165.6	36.6	66.0	6.9	8.8	13.6	18.5
13	5.9	205.5	10.1	44.7	6.3	8.7	5.4	5.7
44	5.5	145.3	12.1	61.6	5.9	11.4	8.7	7.1
AVG	**6.1**	**175.9**	**23.2**	**62.5**	**6.4**	**11.2**	**10.5**	**14.6**

*CO_2 values in kg/hr, other emissions in g/hr.
* CH_4 emissions are available in Appendix G

3.5.2 THREE-WAY CATALYTIC CONVERTER DEGRADATION WITH TIME

New catalysts are expected to lose some activity and then reach a stable activity level after some hours of use. Four units were converted, tested and then retested after intervals of two and six months to provided some initial measure of degradation on the three-way catalysts.

Table 3.10 shows the effectiveness measurements on the three-way catalytic converters including the time of each test. Catalyst effectiveness is calculated as:

Catalyst Effectiveness = (Upstream - Downstream) / (Upstream) x 100%

Table 3.10: Catalyst Effectiveness Degradation[9]

UNIT	AGE	CO	THC	NO_X
9	New	94%	72%	96%
9	2 Months	93%	54%	89%
9	6 Months	93%	70%	83%
10	New	95%	74%	65%
10	2 Months	95%	65%	94%
10	6 Months	94%	42%	56%
13	New	98%	64%	97%
13	2 Months	98%	36%	90%
13	6 Months	92%	41%	81%
2E	New	88%	33%	63%
2E	2 Months	91%	24%	56%
2E	6 Months	82%	34%	68%

3.6 FUEL SYSTEM / EMISSIONS DEGRADATION WITH TIME

As already mentioned, the LPG units used a carbureted fuel system and their emissions deteriorated dramatically over time. For comparison, the variation of CNG system emissions is also documented over time. To avoid conflicting with changes to the catalytic converter effectiveness, only the engine-out emissions are considered as shown in Table 3.11. The first CNG-system test for each unit was done shortly after conversion. The first test is used as the benchmark and the fractional change in emissions (%increase or %decrease) is presented for each subsequent test (2 months and 6 months). Initially, the units had been recently converted while later they were "As-Is" off the plant floor.

Table 3.11: CNG Conversion Kit Emissions Response with Time[9]

(Number in table is %Change in Engine-out Emission Rate after conversion)

UNIT	DATE	CO_2	CO	THC	NO_X
9	New	-	-	-	-
9	2 Month	0%	-14%	-14%	-17%
9	6 Month	0%	-47%	-9%	-20%
10	New	-	-	-	-
10	2 Month	-1%	-21%	2%	74%
10	6 Month	-4%	-47%	18%	56%
13	New	-	-	-	-
13	2 Month	7%	-44%	-23%	37%
13	6 Month	2%	-61%	-35%	17%
2E	New	-	-	-	-
2E	2 Month	-9%	-28%	-42%	136%
2E	6 Month	-18%	-8%	-36%	72%

The results show no dramatic trend of conversion system degradation. Overall, the CO emissions reduced with time on all units while the THC and NO_X emissions either increased or decreased. The largest changes are an increase in NO_X emissions on Unit 2E. However, there were some ignition system problems with Unit 2E that were eventually diagnosed and solved after the 6 month tests. This might help explain the shift in NO_X emissions which are particularly sensitive to ignition timing.

For comparison, Table 3.12 shows the time response of two LPG/carbureted units over the same 6 month time span. Again, the results are shown as a percentage difference from the initial testing of the same pair of units. Initially, the LPG units had been recently tuned to OEM specs while after 6 months testing is done with the units "As-Is". The table shows the tendency of the LPG forklift units to run richer in operation, thus raising CO and THC while reducing NO_X.

Table 3.12: LPG Carburetor System Emissions Response with Time[9]
(Number in table is %Change in Engine-out Emission Rate after conversion)

UNIT	DATE	CO_2	CO	THC	NO_X
6	Initial	-	-	-	-
6	6 Month	3%	6260%	78%	-63%
2D	Initial	-	-	-	-
2D	6 Month	-13%	1105%	101%	-56%

3.7 SUMMARY AND CONCLUSIONS

The main incentive for the forklift conversion project involved improving indoor air quality by emissions reductions. The emissions tests also provided an opportunity to study and answer many other questions relating to vehicle conversions and emissions. In this case, the original forklifts used carbureted LPG systems and two-way catalytic converters. The CNG conversion system used an automotive-style fuel injection system and three-way catalytic converter. Testing involved a multi-mode test procedure which was repeated on each unit before conversion, after conversion, and after various amounts of operating time on each fuel.

The major finding of the project was that the CNG-converted forklifts, with a more sophisticated fuel and emissions system, produced much lower emissions than they did when operating on LPG.

The major emission concerns are NO_X and CO emissions because engines produce both of these pollutants in substantial quantities and both are toxic to people at relatively low levels.

When comparing the more advanced CNG system forklifts with the same units running on carbureted LPG systems, the CNG-fueled forklifts:

- produce significantly lower engine-out emissions,
- have higher catalytic converter effectiveness,
- have better calibration stability, and
- have better maintenance fault tolerance.

Tests show the newest LPG-fueled units could approach the CO emission rates of CNG-fueled units when the LPG-fueled units had just been tuned to a lean operating point. However, their NO_X emission rates were much higher at that same operating point. After tuning, due to the open-loop mixer-style fuel system, the LPG-fueled units tend to drift to a richer setting, resulting in much higher emissions of both CO and NO_X for LPG-fueled units under actual operating situations.

The CNG conversions gain several advantages from their fuel injection system. Their emission rates remain stable over time because of continuous self-calibration while the propane system emissions tend to worsen with time, (at a higher rate for older propane units). The CNG conversions achieve a high catalyst effectiveness of the three-way catalytic converters which the carbureted propane units could not match due to less precise mixture control. Even with maintenance faults, the CNG-converted forklifts could perform better than normal LPG forklift emission rates (while notifying the user of a maintenance requirement).

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CHAPTER 4

THE EFFECTS OF INDOOR VEHICLE EMISSIONS ON BUILDING AIR QUALITY

CHAPTER 4: THE EFFECTS OF INDOOR VEHICLE EMISSIONS ON BUILDING AIR QUALITY

4.1 INTRODUCTION

Vehicle emissions are known to contribute significantly to air pollution, both outdoors as well as indoors. It has been demonstrated in medical findings that poor air quality can lead to adverse health conditions [1]. Studies have linked poor air quality to physical symptoms such as eye, nose and throat irritation; dryness of mucous membranes and skin; mental fatigue and headaches. The effects of poor air quality can take on an even more serious note in workplaces more hazardous pollutants have been linked to cancer, interference with the nervous and/or respiratory system and even death [1,2]. Alternative fuels are offered as a solution by way of reduced and "cleaner" emissions resulting for better air quality.

Poor air quality is the result of improper ventilation in an area where pollutant buildup can occur. Sources for pollutant emissions can be as simple as paint fumes, cleaners, photocopy machines or small appliances. In many situations short term exposure cases may be handled through opening a window or door. However, in cases where constant exposure is expected, proper ventilation and air quality must be dealt with more carefully. The options are either to provide better ventilation through the heating, ventilation and air conditioning (HVAC) system or to eliminate or reduce the pollutant source emissions.

As detailed in Chapter 3, workplace air quality concerns led to a project to reduce vehicle emissions at a brewery in Edmonton, Canada. The brewery operated a fleet of propane - powered (LPG) forklift trucks in an indoor environment. Continuous use of the multiple units raised concerns of exhaust buildup within the facility and when units were operated in truck trailers and other tight enclosures. Air quality is not only a concern to the forklift operator but also for the other employees who worked in and around the area. The project involved the conversion of LPG forklift trucks to compressed natural gas (CNG) power. The LPG forklifts were carbureted units using two-way catalytic converters. The trucks were converted to fuel injected, closed-loop-controlled, natural gas systems with three-way catalytic converters. Emissions rates were measured through emissions testing before and after conversion. The objective of this chapter is to quantify the effect of changing fuels, fuel delivery system, and emissions treatment system on indoor air quality. A mass-balanced mathematical model was derived which uses pollutant emissions and building data to predict indoor pollutant concentrations in an industrial building.

4.2 LITERATURE ON INDOOR VEHICLE EMISSIONS AND AIR QUALITY MODELING

In most of the available literature, vehicle exhaust emissions and indoor air quality were treated as separate topics of discussion. The few studies which looked at both did so experimentally i.e. monitored various exhaust components in indoor air in conjunction with internal combustion engine use [3-8]. Mathematical modeling of indoor environment concentrations has been well investigated involving a wide array of emissions sources. The modeling studies generally concluded that relatively simple models could be used to predict indoor air concentrations as a function of emission processes and building ventilation. These studies were however generally limited to devices producing lower and more regular emission rates than forklift trucks.

Literature on forklift trucks generally makes some reference to the problems associated with using lift trucks indoors. Most papers discuss the various fuel options and the advantages and disadvantages of each. A few studies report emissions tests and provide the exhaust composition for the test modes they used. These test modes were typically chosen arbitrarily in the absence of a set standard for forklift truck testing. No study was found in the literature which directly assessed indoor air quality in conjunction with forklift use. There exists however enough support in the literature on pollutant emission modeling from which to develop an understanding and apply the fundamentals to a particular application.

For more than two decades models have been proposed to predict indoor air quality [9]. Most research of emission sources and air quality are done with such things as gas heaters, petroleum lamps, small utility internal combustion engines, or solvents evaporating from surfaces; i.e. relatively constant emission sources.

There are two types of models discussed in the literature: empirical and mathematical. Empirical models are equations derived by arbitrarily fitting experimental data. The form of the equation and parameter values are selected to best fit the data. These models may not be applicable to situations other than those in which the data set was collected and as a result typically appear simpler than other models. However, they can be quite accurate for the specific case.

Most studies use a mass-balance mathematical modeling technique. Mathematical mass-balance models begin with a theoretical equation describing the generation and loss of pollutants within the volume. Experimental data may be used to fine tune the value of model parameters. This type of model is more flexible in general application as well as offering a greater understanding of the physical/chemical processes. The level of validity that these models can achieve is dependant on the complexity with which the physical/chemical processes are defined and the precision with which the input factors are defined or known. However, the key to predicting indoor air pollutant concentrations depends on the accuracy of the source models incorporated into the models [10,11].

As mentioned, many studies were conducted on space heaters or ranges [9,12-17]. A chamber study by Moschadreas et al [17] compared indoor air quality simulations with a mathematical mass-balance model and reported that predicted and measured values agreed very well, if the input values are well known. In the chamber study, the model predicted NO_2 concentrations within 5% throughout the duration of the experiment. A study predicting indoor air quality (IAQ) in public lounges due to multiple smokers also reported excellent agreement (0-12% error) with the respirable suspended particles (RSP) and CO concentrations [18]. A case study investigating an actual renovation project, in which CO fumes emitted from a gas-driven concrete saw/cutter caused CO related symptoms in the operator and nearby workers, used such a mass-balance model to estimate indoor CO levels [19]. Sensitivity of the model was assessed and errors in the initial indoor concentration and volume were reported to have little effect on the model output[17].

Two studies were found which specifically discuss forklifts and indoor air quality concerns similar to this work. A paper by Lee [20] discusses regulation changes which might allow diesel powered forklift trucks indoors if air quality remains within safe levels. The initial scope of that study involved emissions testing of different diesel engines as well as different diesel fuel blends. The emissions data collected were to be used for modeling indoor air concentrations. However, this step was not completed at the time of publishing of the paper and no further developments have been reported. The second study, presented by Gas Research Institute, involved case studies of four companies that independently chose CNG-powered forklifts to improve air quality [21]. The companies originally used LPG-powered lift trucks but found CO levels and odor would build up, especially during winter months when doors and windows are kept closed. Details however are not given on the test cycle, emissions testing, methodology, or forklift technology on the LPG trucks or once converted to CNG. On average the studies claim percent reductions with CNG versus LPG to be: 90% CO, 70% THC, 50% NO_X, and 10% CO_2. No indoor air modeling or monitoring was reported.

There are many other papers discussing indoor air quality modeling using a range of approaches. Most of the studies reviewed use a well mixed volume assumption. Non-uniform mixing is another major area of research as discussed in a literature review paper by Mage and Ott [22]. They review seven papers which deal with non-uniform mixing using a mixing factor and another eight papers which use computational fluid dynamic models and other techniques to map spatial variation of concentration without a mixing factor. Some papers use a multi-room type system with the mass-balance equations [11,14]. However, as a first approximation, a well mixed single compartment volume is typically assumed yielding satisfactory results. A well mixed volume is chosen mainly because both the air and people within a space are moving. Over a period of time people within the space are exposed to the average pollutant level in the space. The toxicity is low enough that the average becomes important rather than the peak levels.

Generally, the papers on indoor vehicle emissions and air quality are quite informative but difficult to directly apply to any other particular situation.

4.3 MATHEMATICAL MASS-BALANCE MODEL

The model developed for this study is based on a single order mass balance differential equation. The indoor space is assumed to be a well mixed volume. The model requires initial concentration, ventilation air exchange rates, penetration factor, emission rate, volume, and absorption factors as inputs. The outdoor concentrations, penetration factors, air exchange rate and source strengths are assumed to be constant over time. The solution of the differential equation gives the concentration of the pollutant in a time interval. Because the model simulates a single well mixed volume, only a single differential equation required solving for each pollutant. This was done analytically and MATLAB was used to generate plots of pollutant concentrations within the volume over time.

The mathematical model is based on the following mass-balance equation:

$$dC = PaC_o dt + S / Vdt - (a + k)Cdt \tag{4.1}$$

C: spatial average indoor pollutant concentration, (ppm);

C_o: outdoor pollutant concentration, (ppm);

P: fraction of the outdoor pollutant level that penetrates the building shell, (-);

a: air exchange rate, (1/ hr);

S: indoor pollutant source strength, (g/hr);

V: building volume, (m^3);

k: net rate of removal processes other than air exchange, (-).

All papers using a mathematical modeling technique use this mass-balance equation in some form. The solution gives the spatial average concentration of a pollutant in an enclosed space of a given volume. The analytical solution is shown in Appendix I.

The spatial average concentration as a function of time is shown below for $t < t_{shutoff}$ and $t \geq t_{shutoff}$ where the variable $t_{shutoff}$ represents the time the forklift unit is shut off i.e. the source term becomes zero: S= 0 g/h.

$$C(t) = \frac{PaC_o + S/V}{(a+k)}[1 - e^{-(a+k)t}] \qquad \text{for } t < t_{shutoff} \qquad (4.2)$$

and for $t \geq t_{shutoff}$.

$$C(t) = \frac{S/V}{(a+k)}[1 - e^{(a+k)t_{shutoff}}]e^{-(a+k)(t-t_{shutoff})} + \frac{PaC_o}{(a+k)}[1 - e^{-(a+k)t}] \qquad (4.3)$$

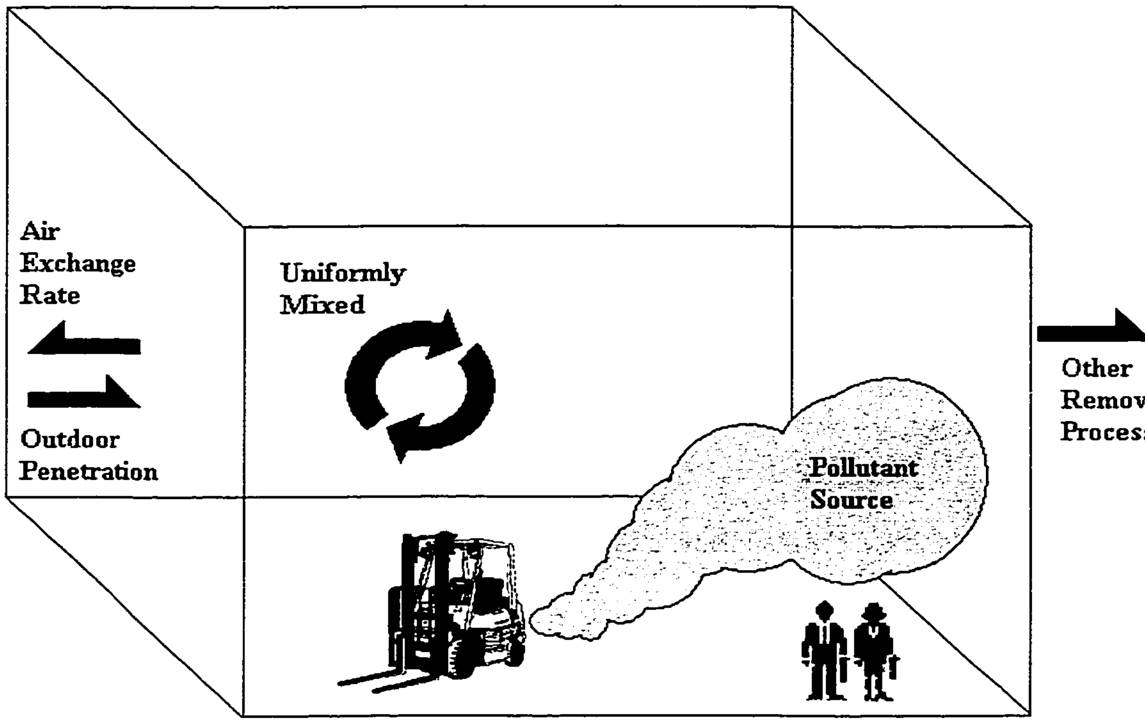

Figure 4.1: Schematic of a Well Mixed Volume with an Emission Source and Key Parameters.

The air exchange rate was varied between 1 and 5 air changes per hour. This range was chosen as a typical range for today's buildings. ASHRAE [20] recommends air exchange limits for road tunnels, tollbooths, parking garages, bus garages, bus terminals and rapid transit, and no recommended limits are given for continuous vehicle operation within an enclosure. The limits in ASHRAE are developed based on the assumptions of intermittent use i.e. vehicles passing through, conventional fuels, and road vehicles. A note on alternative fuels (CNG, LPG, LNG, Methanol, Ethanol, Hydrogen) in ASHRAE says the same requirements may not be valid as those for gasoline and diesel. Also stated is that tests and operating experience indicate that when the level of CO is properly diluted, the other dangerous and objectionable exhaust by-products are also diluted to acceptable levels [3,23,24]. This is based on the assumption that CO is the most harmful pollutant (based on mass and toxicity). This may not be true however for vehicles with CO control devices which do not control other toxics such as NO_X.

The parameter values used for the model are listed in Table 4.1. For each pollutant the occupational exposure limit (OEL) has been listed (if available), the molar mass, initial and outdoor concentrations, penetration factor, other removal factors and source strengths for the two fuel systems. The penetration factor was taken as P=1 [19] for all species and k=0 for CO_2, CO and THC and is taken as 0.166 for NO_X based on published experimental chamber results [13]. NO_X tends to react in the atmosphere to a greater extent which makes it appear to disappear, however, the rate of disappearance is very small compared to the source strength. Note also that carefully selecting P and k factors for this modeling case may be purely academic, since the source strengths are so high. Ambient outdoor concentrations for the city of Edmonton were taken from an online CASA(Clean Air Strategic Alliance) database [25]. These too are fairly insignificant compared to the potential build up of emissions from the forklifts trucks.

Table 4.1: Model Parameters for the Different Pollutant Species.

	TWA	M	C_{IN}	C_O	P	k	S_{LPG}*[26]	S_{CNG}*[26]
	ppm	kg/kmole	mg/m^3	mg/m^3	-	-	kg/hr	kg/hr
CO_2	5000	44	0	560	1.0	0	6.92	6.47
CO	25	28	0	1.14	1.0	0	545.2	13.2
THC	-	16	0	1.408	1.0	0	25.2	12.2
NO_X	3	46	0	0.137	1.0	0.166	78.8	16.7

*Source strengths for different substances based on a fleet average of 7 forklifts - set as default. Forklifts are taken in the normal state of operation as would be found on the plant floor i.e. LPG trucks are in their "AS-IS" state of tune and CNG trucks are in "Closed-Loop" operation.

A computer program incorporating the above model has been developed using MATLAB. The program simulates a forklift running continuously for 8 hrs and then shut off for 16 hrs to complete a full 24 hr day. Both LPG and CNG forklifts have been modeled using experimentally determined emissions values as described in Chapter 3. All variables and parameters can be adjusted readily within the program. The program models one chemical species. It first requires the user to specify the fuel (LPG or CNG), and then the emissions species to model (CO_2, CO, THC or NO_X). The model calculates a source strength for the species based on the fleet average value from the forklift emissions testing. The source strengths for each fuel and pollutant are listed in Table 4.1. An arbitrary emissions source strength may also be provided.

4.4 MODEL RESULTS

A cautionary note that the results presented and discussed within this section should not be viewed as simply an LPG versus CNG fuels comparison based on their emissions. Fuel properties, characteristics and composition do play a key role in vehicle emissions. However, the level of vehicle technology can play an even stronger part in deciding which and how much emissions are produced.

In this case, the comparison is between a traditional LPG system, (carbureted, two-way catalytic system) and a current technology CNG system (fuel injected, closed-loop controlled, three-way catalytic system). Each of the following figures contain two plots of indoor pollutant levels representing a "LPG" and "CNG" scenario. Figures 4.2 to 4.5 compare THC, CO, CO_2 and NO_X levels for one forklift running in a well mixed 2000 m^3 warehouse over a 24 hour period. Each plot shows the forklift being run continuously for 8 hours with different air exchange rates ranging from 1 to 5 air changes per hour. At the top of each plot the fuel and pollutant source strength are shown.. Also labeled on the plots are the 8 hr time-weighted average (TWA) (labeled "+") occupational exposure limit for that particular pollutant species.

The model results are similar to those presented in literature for smaller combustion appliances. The pollutant concentration rises to a saturation level while the source is emitting. Concentration then decays exponentially once the source is removed; or in this case turned off. Notice in Figure 4.2 the CO levels are extremely high for the LPG units inside the building; even at 5 ACH, the CO concentration rises well above the 8 hr TWA. To meet the 8 h TWA (25 ppm) for CO requires 9.9 ACH while the LPG unit is running and only 0.25 ACH for the CNG unit. This is for source strengths of 545.2 g/hr and 13.2 g/hr for LPG and CNG respectively.

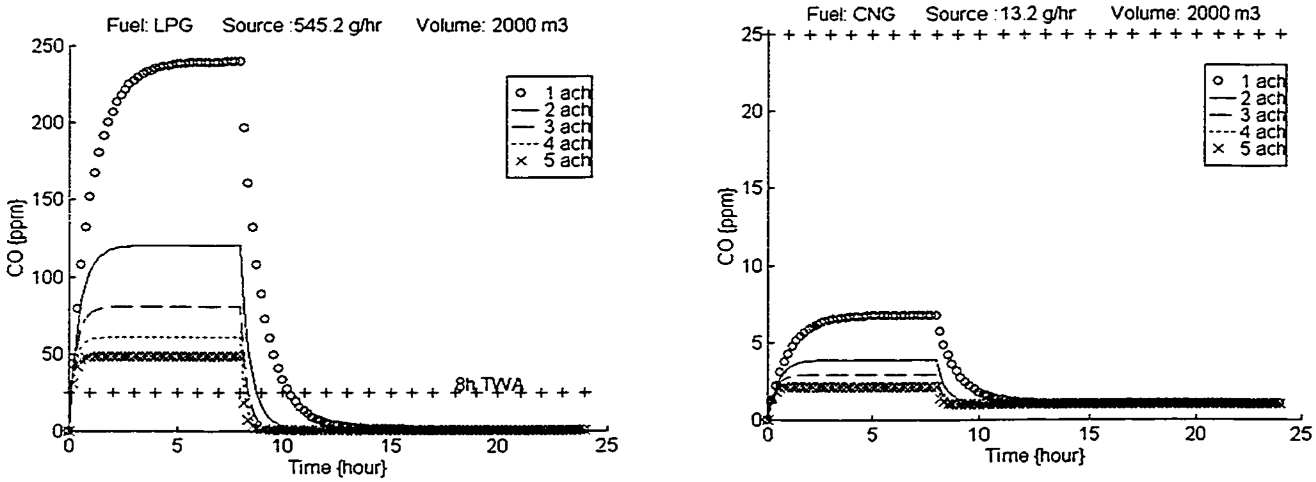

Figure 4.2: Comparison of Indoor CO Levels with a LPG Forklift and CNG Forklift.
(Note change of vertical scale)

Figure 4.3 compares NO_X concentrations for the LPG and CNG forklifts (source strengths of 78.8 g/hr and 16.7 g/hr respectively[26]). NO_X is an irritant at very low levels and occupational standards require individual exposure (average) for an 8 hr work shift not to exceed 3 ppm. The building with the LPG unit operating requires 7.2 ACH to avoid exceeding the limit while only 1.5 ACH is required for the CNG units.

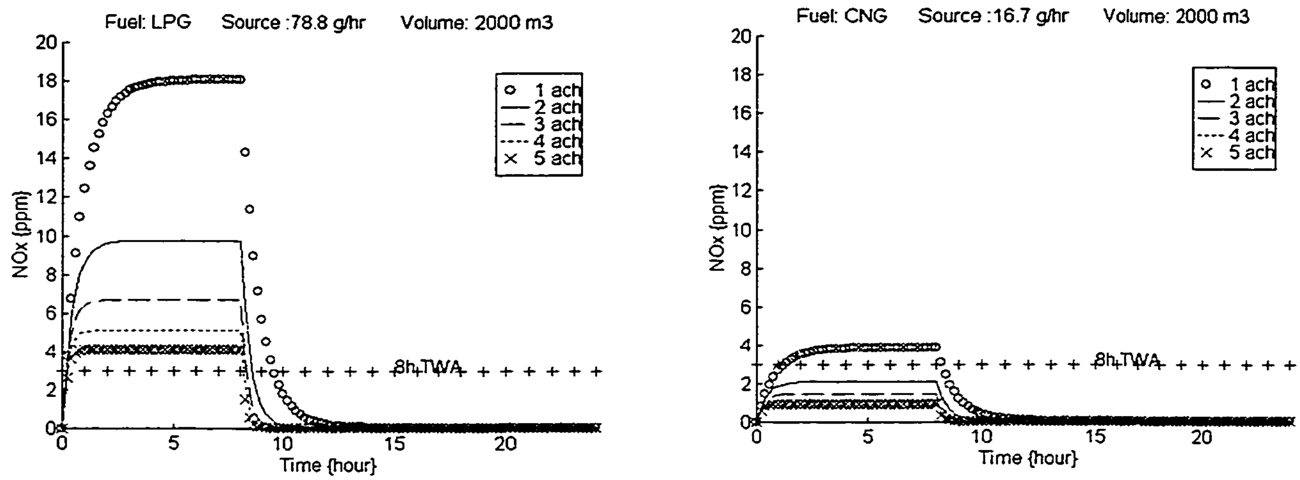

Figure 4.3: Comparison of Indoor NO_X Levels with a LPG Forklift and CNG Forklift.

CO_2 emission rates are very close for the two fuels: 6.92 kg/hr for LPG and 6.47 kg/hr for CNG [26]. It was found that CO_2 concentration is not a problem inside the building. Both require only minimal air exchange (0.39 ACH for LPG and 0.36 ACH for CNG), to meet occupational standards.

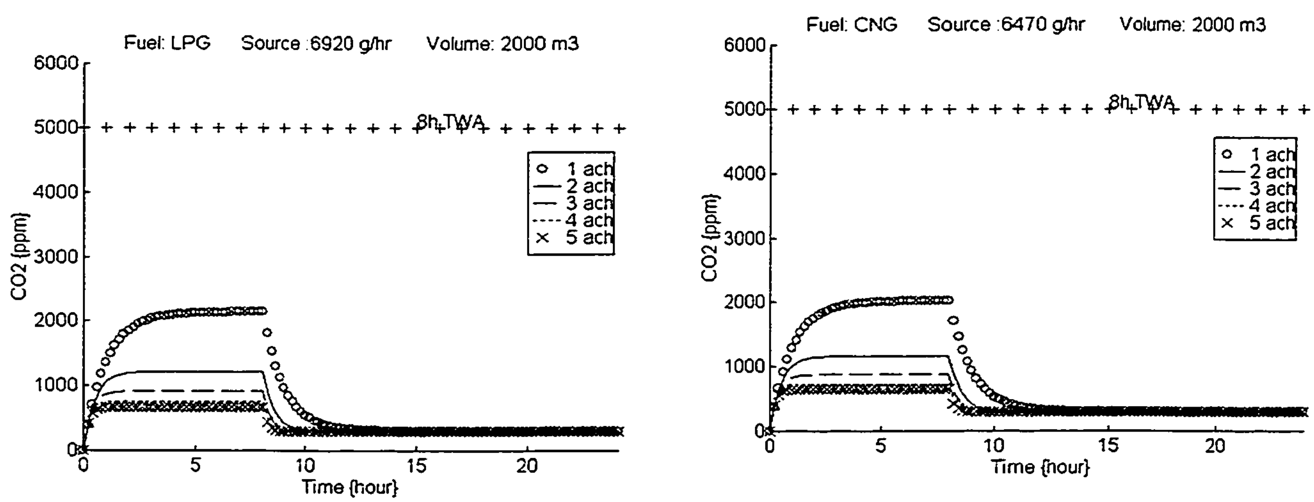

Figure 4.4: Comparison of Indoor CO_2 Levels with a LPG Forklift and CNG Forklift

Propane and methane, the main constituents for LPG and CNG respectively are considered asphyxiants. They do not have OEL's but standards do require the oxygen content to be above 18% by volume at all times. THC emissions strengths are 25.3 g/hr for LPG and 12.2 g/hr for CNG [26]. The THC values are quite low as is shown in the plots of Figure 4.5 and may be handled easily by typical HVAC systems provided the THC emissions do not contain significant amounts of toxic compounds such as benzene and aldehydes. Both LPG and CNG have minimal amounts of higher hydrocarbons and toxic compounds this is not a problem.

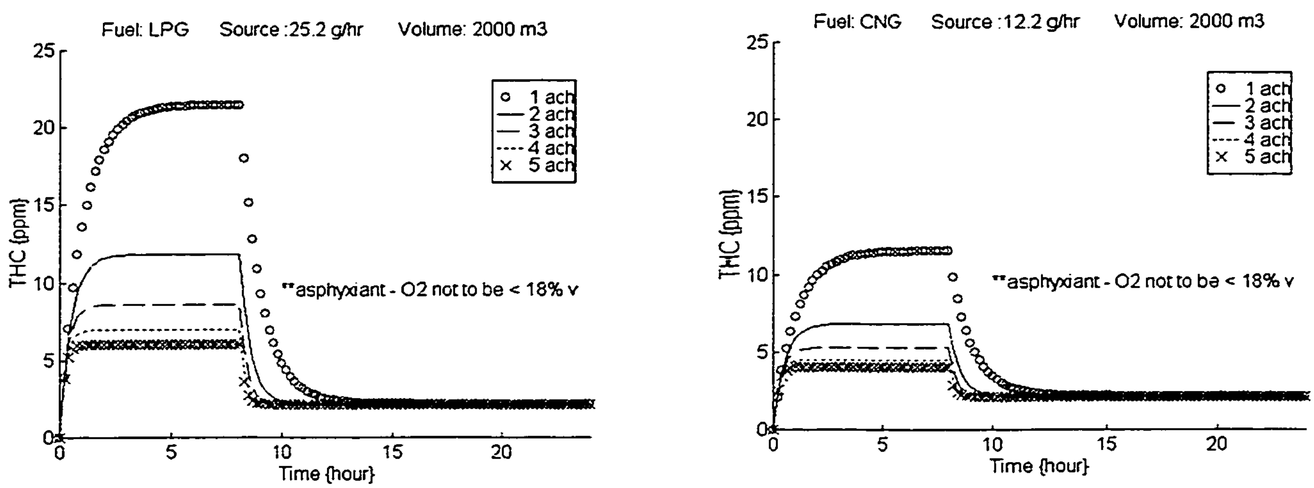

Figure 4.5: Comparison of Indoor THC Levels with a LPG Forklift and CNG Forklift.

4.5 SUMMARY AND CONCLUSIONS

The objective of this chapter was to measure the effect of vehicle emissions on indoor air quality with the use of a mathematical model. Indoor air quality concerns led to an indoor forklift fleet of seven units being converted from a LPG, carbureted, two-way catalytic converter system to a CNG, fuel injection, closed-loop controlled, three-way catalytic converter system. With the support of literature on indoor air quality modeling and pollutant source emissions, a mathematical model was used to predict pollutant concentrations in a 2000 m^3 warehouse. General results of the model were similar to the concentration time contours seen in other models. The model showed that LPG forklift emissions were a problem emitting 545.2 g/hr of CO and 78.8 g/hr of NO_X. CO was the worst problem, requiring ventilation levels of approximately 10 ACH. For the cleaner CNG units emitting 13.2 g/hr of CO and 16.7 g/hr of NO_X, NO_X was the most critical pollutant, but control required only 1.5 ACH. This shows that the use of alternative fuels with proper attention to vehicle technology can reduce emissions sufficiently to substantially improve air quality.

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CHAPTER 5

SUMMARY AND CONCLUSIONS

CHAPTER 5: SUMMARY AND CONCLUSIONS

This MSc thesis was a study on the effect of alternative fuel use on vehicle emissions. As part of the research, the impact of changing emissions on overall air quality has been assessed. The objective was to show the relationship between fuel and vehicle emissions and whether some of the currently available alternative fuels are capable of reducing emissions and in turn improving air quality.

Literature on emissions studies on vehicles operating with alternative fuels stretches back through the 1970's. It was found that many research papers present data on different alternative fuels. The review showed that alternative fuels can provide substantial emissions reduction benefits. The greatest emission reductions are attained by dedicated vehicles using more sophisticated vehicle technology. However, bi-fuel vehicles and conversions using simpler and more cost-effective technology can also offer emissions reductions with a greater potential for market penetration.

Reported vehicle emissions depend not only on fuel characteristics but also on vehicle characteristics like fuel and emissions system technology, age, condition, bi-fuel or dedicated function, test cycle etc. The study found:

- For spark ignition engines, reformulated gasoline (RFG) was found to reduce all emissions compared to industry average gasoline, except formaldehyde.
- For spark ignition engines, the greatest benefits of compressed natural gas (CNG) is seen in its ability to reduce toxic emissions. Vehicles also showed a reduction in CO and NO_X production.
- CNG use in compression ignition engines reduces particulates and NO_X as well as CO.
- For spark ignition engines, propane (LPG) was found to reduce THC and CO emissions with higher NO_X production. LPG also offers comparable toxic emissions reductions as CNG.
- For spark ignition engines, methanol (as M85) showed no change in CO and NO_X and variable response with THC emissions but showed a definite increase in formaldehyde.
- Methanol use in compression ignition engines (as M100) shows benefits in NO_X and particulates with variable THC and CO response.

The numerous studies on vehicle emissions provide a good understanding on the relationship between alternative fuels, level of vehicle technology, and emissions. Based on data from the selected papers, it was found that alternative fuels can reduce vehicle emissions compared to vehicles using conventional fuels. In recent years, advanced technologies have greatly reduced emission levels of traditional gasoline and diesel vehicles and the alternatives must be optimized to a similar degree to show any advantage. At the present time, most AFV's are conversions, bi-fuel vehicles or flexible fuel vehicles (FFV) and they have not been optimized to the same degree as traditional-fueled vehicles. However, vehicles which are dedicated alternative fuel vehicles employing sophisticated technology produce a significant benefit over conventional gasoline and diesel.

A conversion project undertaken to reduce pollutant emissions from forklift trucks gave an opportunity to study technology effects on emissions. The carbureted LPG units (a fleet of 7 units of various age) utilizing a mixer system and two-way catalytic converter were converted to a fuel injected, closed-loop controlled CNG system with three-way catalytic converters. A detailed emission test program documented the effect of these technology changes on emissions and found the advanced CNG system provided huge emissions reductions compared to the original simple LPG system.

When comparing the more advanced CNG system forklifts with the same units running on the simpler carbureted LPG systems, the CNG-fueled forklifts:

- produced significantly lower engine-out emissions,

- had higher catalytic converter effectiveness,
- had better calibration stability, and
- had better maintenance fault tolerance.

The forklift conversion project was prompted by indoor air quality concerns. The emissions performance values gathered from the testing provided useful information to determine what effect the conversion would have on indoor air quality. With the support of literature on air quality modeling and pollutant sources, a model was derived to simulate how a conversion project such as this may impact pollutant levels within a 2000 m^3 warehouse. The model showed that the emissions levels of the lower technology LPG forklifts quickly resulted in air pollutant problems indoors. The lower emission levels of the more advanced CNG forklifts could substantially improve indoor air quality, allowing the building to meet occupational exposure limits with normal building air exchange rates.

In conclusion, alternative vehicle fuels can help reduce harmful emission and improve air quality. The responsibility however cannot be laid simply on the fuel itself and its "cleaner" characteristics. Parameters such as fuel delivery systems, engine design, exhaust treatment and engine control systems all play an integral role in allowing the alternative fuels to perform to their potential. The greatest emissions benefits are attained through the use of advanced fuel and emissions systems on dedicated alternative fueled vehicles.

APPENDIX A

Emission Standards of Various Countries Around the World

APPENDIX A

EMISSION STANDARDS OF VARIOUS COUNTRIES AROUND THE WORLD

Tailpipe emissions standards specify the maximum amount of pollutants allowed in exhaust gasses of a motor vehicle. Emission standards were first initiated in California in the 1950's to control CO and HC emissions. The US federal government became involved with air pollution in 1955. In 1963 the activity was enhanced with the introduction of the Clean Air Act, to stimulate state and local air pollution control efforts. A 1965 amendment to the Clean Air Act authorized national standards for emissions for all motor vehicles sold nationally, beginning with the 1968 model year [1]. Today many countries around the world are concerned with vehicle exhaust pollution and have either developed their own emission standards or have adopted others. This Appendix shows the tailpipe emission standards for Light-Duty (LDV) and Heavy-Duty Vehicles (HDV) for various countries around the world. The countries currently on the forefront of setting emissions standards include the US, European Union, Japan, Korea, and Thailand.

Emissions are measured over an engine or vehicle test cycle. Test cycles are used to create repeatable emissions measurement conditions and simulate real driving conditions. Engine test cycles are typically used for heavy-duty engines, since heavy-duty vehicles can vary widely in size, while vehicle test cycles are used for light-duty vehicles. Regulated emissions include: Total Hydrocarbons (THC), Non-methane Organic Gases (NMOG), Non-methane Hydrocarbons (NMHC), Carbon Monoxide (CO), Nitrogen Oxides (NO_X), and particulate matter (PM).

Emission Standards for the United States of America

Table A1: EPA Tier 1 Emissions Standards for Passenger Cars and LDTs, FTP 75 (g/mi)[1]

Category	50,000 miles/5 years						100,000 miles/10 years[1]					
	THC	NMHC	CO	NO_X[2] diesel	NO_X gasoline	PM	THC	NMHC	CO	NO_X[2] diesel	NO_X gasoline	PM
Passenger cars	0.41	0.25	3.4	1.0	0.4	0.08	-	0.31	4.2	1.25	0.6	0.10
LDT, LVW < 3,750 lbs	-	0.25	3.4	1.0	0.4	0.08	0.8	0.31	4.2	1.25	0.6	0.10
LDT, LVW > 3,750 lbs	-	0.32	4.4	-	0.7	0.08	0.8	0.40	5.5	0.97	0.97	0.10
HLDT, ALVW < 5,750 lbs	0.32	-	4.4	-	0.7	-	0.8	0.46	6.4	0.98	0.98	0.10
HLDT, ALVW > 5,750 lbs	0.39	-	5.0	-	1.1	-	0.8	0.56	7.3	1.53	1.53	0.12

1 - Useful life 120,000 miles/11 years for all HLDT standards and for THC standards for LDT.
2 - NO_X limits for diesels apply to vehicles through 2003 model year.

Abbreviations:

LVW – loaded vehicle weight (curb weight + 300 lbs)
ALVW – Adjusted LVW (the numerical average of the curb weight and the GVWR)
LDT – light-duty truck
HLDT – heavy light-duty truck (i.e., any light-duty truck rated greater than 6000 lbs GVWR)

Table A2: California Emission Standards for Light-Duty Vehicles, FTP 75 (g/mi)[1]

Category	50,000 miles/5 years					100,000 miles/10 years[1]				
	NMOG[a]	CO	NO_X	PM	HCHO	NMOG[a]	CO	NO_X	PM	HCHO
Passenger cars										
Tier 1	0.25	3.4	0.4	0.08	-	0.31	4.2	0.6	-	-
TLEV	0.125	3.4	0.4	-	0.015	0.156	4.2	0.6	0.08	0.018
LEV	0.075	3.4	0.2	-	0.015	0.090	4.2	0.3	0.08	0.018
ULEV	0.040	1.7	0.2	-	0.008	0.055	2.1	0.3	0.04	0.011
LDT1, LVW < 3750 lbs										
Tier 1	0.25	3.4	0.4	0.08	-	0.31	4.2	0.6	-	-
TLEV	0.125	3.4	0.4	-	0.015	0.156	4.2	0.6	0.08	0.018
LEV	0.075	3.4	0.2	-	0.015	0.090	4.2	0.3	0.08	0.018
ULEV	0.040	1.7	0.2	-	0.008	0.055	2.1	0.3	0.04	0.011
LDT2, LVW > 3750 lbs										
Tier 1	0.32	4.4	0.7	0.08	-	0.40	5.5	0.97	-	-
TLEV	0.16	4.4	0.7	-	0.018	0.200	5.5	0.9	0.10	0.023
LEV	0.1	4.4	0.4	-	0.018	0.130	5.5	0.5	0.10	0.023
ULEV	0.050	2.2	0.4	-	0.009	0.070	2.8	0.5	0.05	0.013-

a- NMHC for all Tier 1 standards

Table A3: California Emission Standards for Medium-Duty Vehicles, FTP 75 (g/mi)[1]

Category	50,000 miles/5 years					120,000 miles/11 years				
	CO	NO_X	PM	HCHO	NMOG[a]	CO	NO_X	PM	HCHO	NMOG[a]
MDV1, 0-3750 lbs										
Tier 1	0.25	3.4	0.4	-	-	0.36	5.0	0.55	0.08	-
TLEV	0.125	3.4	0.4	-	0.015	0.180	5.0	0.6	0.08	0.022
ULEV	0.075	1.7	0.2	-	0.008	0.107	2.5	0.3	0.04	0.012
MDV2, 3751-5750 lbs										
Tier 1	0.32	4.4	0.7	-	-	0.46	6.4	0.98	0.10	-
LEV	0.16	4.4	0.4	-	0.018	0.230	6.4	0.6	0.10	0.027
ULEV	0.100	4.4	0.4	-	0.009	0.143	6.4	0.6	0.05	0.013
SULEV	0.50	2.2	0.2	-	0.004	0.072	3.2	0.3	0.05	0.006
MDV3, 5751-8500 lbs										
Tier 1	0.39	5.0	1.1	-	-	0.56	7.3	1.53	0.12	-
LEV	0.195	5.0	0.6	-	0.022	0.280	7.3	0.9	0.12	0.032
ULEV	0.117	5.0	0.6	-	0.011	0.167	7.3	0.9	0.06	0.016
SULEV	0.059	2.5	0.3	-	0.006	0.084	3.7	0.45	0.06	0.008
MDV4, 8501-10,000 lbs										
Tier 1	0.46	5.5	1.3	-	0.028	0.66	8.1	1.81	0.12	-
LEV	0.230	5.5	0.7	-	0.028	0.33	8.1	1.0	0.12	0.040
ULEV	0.138	5.5	0.7	-	0.014	0.197	8.1	1.0	0.06	0.021
SULEV	0.069	2.8	0.35	-	0.007	0.100	4.1	0.5	0.06	0.010
MDV5, 10,001-14,000 lbs										
Tier 1	0.60	7.0	2.0	-	-	0.86	10.3	2.77	0.12	-
LEV	0.300	7.0	1.0	-	0.036	0.430	10.3	1.5	0.12	0.052
ULEV	0.180	7.0	1.0	-	0.018	0.257	10.3	1.5	0.06	0.026
SULEV	0.090	3.5	0.5	-	0.009	0.130	5.2	0.7	0.06	0.013

a- NMHC for all Tier 1 standards.

In October 1997 the EPA adopted a new emission standard for the 2004 model year and later heavy-duty diesel engines used in trucks and buses. Manufacturers are given the opportunityto certify engines to one of two options shown below.

Table A4: Manufacturer Options for Engine Certification[1]

OPTION	NMHC & NO_X	NMHC
1	2.4	n/a
2	2.5	0.5

Table A5: EPA Emission Standards for Heavy-Duty Engines (g/bhp-hr)[1]

YEAR	HC	CO	NO_X	PM
Heavy-Duty Diesel Truck Engines				
1990	1.3	15.5	6.0	0.60
1991	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.10
1998	1.3	15.5	4.0	0.10
Urban Bus Engines				
1991	1.3	15.5	5.0	0.25
1993	1.3	15.5	5.0	0.10
1994	1.3	15.5	5.0	0.07
1996	1.3	15.5	5.0	0.05*
1998	1.3	15.5	4.0	0.05*

* - in-use PM standard 0.07.

Table A6: California Emissions Standards for Heavy-Duty Diesel Engines (g/bhp-hr)[1]

YEAR	NMHC	THC	CO	NO_X	PM
Heavy-Duty Diesel Truck Engines					
1987	-	1.3	15.5	6.0	0.60
1991	1.2	1.3	15.5	5.0	0.25
1994	1.2	1.3	15.5	5.0	0.10
Urban Bus Engines					
1991	1.2	1.3	15.5	5.0	0.10
1994	1.2	1.3	15.5	5.0	0.07
1996	1.2	1.3	15.5	4.0	0.05

Emission Standards for the European Union

Emission test cycle for these regulations is the ECE 15 and EUDC procedure.

Table A7: EU Light-Duty Vehicle Standards for Passenger Vehicles[2]

CATEGORY	YEAR	TEST	UNIT	HC&NO_X	HC	CO	NO_X
All Vehicles	1983-87	ECE-15	g/km	5.0-7.0	-	14.0-27.0	-
Displacement >2 L	1988-89	ECE-15	g/km	-	1.6	6	0.8
Displacement 1.4 to 2 L	1988-89	ECE-15	g/km	-	2	8	1.0
Displacement <1.4 L	1988-89	ECE-15	g/km	-	4	11	1.5

Table A8: EU Emission Standards for Diesel Cars (g/km)[1]

TIER	YEAR	HC & NO_X	NO_X	CO	PM
Euro I	1992	0.97	-	2.72	0.14
Euro II –IDI	1996	0.7	-	1.0	0.08
Euro II – DI	1999	0.9	-	1.0	0.10
Euro III	2000	0.56	0.50	0.64	0.05
Euro IV	2005	0.30	0.25	0.50	0.025

Table A9: EU Emission Standards for Diesel Light-Duty Trucks (g/km)[1]

CLASS	YEAR	HC & NO_X	NO_X	CO	PM
I (<1305 kg)	1994	0.97		2.72	0.14
	2000	0.56	0.50	0.64	0.05
	2005	0.30	0.25	0.50	0.025
II (1305-1760 kg)	1994	1.40		5.17	0.19
	2001	0.72	0.65	0.80	0.07
	2006	0.39	0.33	0.63	0.04
III (>1760 kg)	1994	1.70		6.90	0.25
	2001	0.86	0.78	0.95	0.10
	2006	0.46	0.39	0.74	0.06

The EU light duty vehicle standards are different for diesel and gasoline vehicles. Diesels have lower CO standards, while their NO_X standards are approximately three times higher than those for gasoline vehicles. Gasoline vehicles are exempt from PM standards.

Table A10: EU Emission Standards for HD Diesel Engines (g/kWh; smoke in m^{-1})[1]

TIER	Date & Category	TEST CYCLE	CO	HC	NO_X	PM	SMOKE
EURO I	1992, < 85 kW	ECE R-49	4.5	1.1	8.0	0.612	
	1992, > 85 kW		4.5	1.1	8.0	0.36	
EURO II	1996.10		4.0	1.1	7.0	0.25	
	1998.10		4.0	1.1	7.0	0.15	
EURO III	1999.10 EEVs only	ESC & ELR	1.5	0.25	2.0	0.02	0.15
	2000.10		2.1	0.66	5.0	0.10 0.13*	0.8
EURO IV	2005.10		1.5	0.46	3.5	0.02	0.5
EURO V	2008.10		1.5	0.46	2.0	0.02	0.5

* for engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3000 min^{-1}

In the year 2000 the old steady-state ECE R-49 test cycle is replaced by 2 cycles. A stationary cycle, ESC (European Stationary Cycle), and a transient ETC (European Transient Cycle). Smoke opacity is measured on the ELR (European Load Response) test. Stricter values for extra low emission vehicles known as EEVs (enhanced environmentally friendly vehicles)

Table A11: EU Emission Standards for Diesel and Gasoline Engines (g/kWh)[1]

TIER	Date & Category	TEST CYCLE	CO	NMHC	CH_4[a]	NO_X	PM[b]
EURO III	1999.10 EEVs only	ETC	3.0	0.40	0.65	2.0	0.02
	2000.10		5.45	0.78	1.6	5.0	0.16 0.21[c]
EURO IV	2005.10	ETC	4.0	0.55	1.1	3.5	0.03
EURO V	2008.10		4.0	0.55	1.1	2.0	0.03-

a- for non NG only

b- not applicable on gas engines

c- for engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3000 min^{-1}

Emission Standards in Japan.

The current test method is the 10-15 mode cycle which supercedes the older 10-mode cycle (effective 1991.11.1 for domestic, 1993.4.1 for imports)

Table A12: Japanese Emission Standards for LPG and Gasoline Cars[2]

CATEGORY	DATE	TEST	CO	HC	NO_X
LPG & Gasoline	1978-187	10-Mode	2.7	0.39	0.48

Table A13: Japanese Emission Standards for Diesel Cars (g/km)[1]

Vehicle Weight*	Date	CO		HC		NO_X		PM	
		max	mean	max	mean	max	mean	max	mean
< 1265 kg	1986	2.7	2.1	0.62	0.40	0.98	0.70		
	1990	2.7	2.1	0.62	0.40	0.72	0.50		
	1994	2.7	2.1	0.62	0.40	0.72	0.50	0.34	0.20
	1997	2.7	2.1	0.62	0.40	0.72	0.40		0.08
	2002[a]		0.63		0.12		0.28		0.052
> 1265 kg	1986	2.7	2.1	0.62	0.40	1.26	0.90		
	1992	2.7	2.1	0.62	0.40	0.84	0.60		
	1994	2.7	2.1	0.62	0.40	0.84	0.60	0.34	0.20
	1997	2.7	2.1	0.62	0.40	0.84	0.40		0.08
	2002[a]		0.63		0.12		0.30		0.056

Max – to be met as type approval limit if sales are less than 2000 per vehicle model per year and generally as an individual limit in series production.

Mean – to be met as a type approval limit and as a production average.

*- equivalent inertia weight

a – new short term targets issued by the Central Council for Environmental Pollution Control

The test procedure for heavy-duty vehicles is the 13-mode cycle which replaced the earlier 6-mode cycle.

Table A14: Japanese Emission Standards for Diesel Commercial Vehicles[1]

Vehicle Weight*	Date	Test	Unit	CO		HC		NO_X		PM	
				max	mean	max	mean	max	mean	max	mean
< 1700 kg	1988	10-15 mode	g/km	2.7	2.1	0.62	0.40	1.26	0.90		
	1993			2.7	2.1	0.62	0.40	0.84	0.60	0.34	0.20
	1997			2.7	2.1	0.62	0.40	0.84	0.40		0.08
	2002[a]				0.63		0.12		0.28		0.052
1700-2500 kg	1988	6 mode	ppm	980	790	670	510	500 (DI) 350 (IDI)	380 (DI) 260 (IDI)		
	1993	10-15 mode	g/km	2.7	2.1	0.62	0.40	1.82	1.30	0.43	0.25
	1997/98			2.7	2.1	0.62	0.40	1.82	0.70		0.09
	2003[a]				0.63		0.12		0.49		0.06
2500-12000 kg**	1988/89	6 mode	ppm	980	790	670	510	520 (DI) 350 (IDI)	400 (DI) 260 (IDI)		
	1994	13 mode	g/kWh	9.20	7.40	3.80	2.90	7.80 (DI) 6.80 (IDI)	6.00 (DI) 5.00 (IDI)	0.96	0.70
	1997/98			9.20	7.40	3.80	2.90	7.80 (DI) 6.80 (IDI)	4.50		0.25
> 12000 kg	1994	13 mode	g/kWh	9.20	7.40	3.80	2.90	7.80 (DI) 6.80 (IDI)	6.00 (DI) 5.00 (IDI)	0.96	0.70
	1999			9.20	7.40	3.80	2.90	7.80 (DI) 6.80 (IDI)	4.50		0.25
	2004[a]				2.22	0.87		3.38			0.18

Max – to be met as type approval limit if sales are less than 2000 per vehicle model year and generally as an individual limit in series production.
Mean – to be met as a type approval limit and as a production average.
*- gross vehicle weight
** - 1997: GVW 2500-3500 kg; 1998: GVW 3500-12000 kg.
a- new short term targets issued by the Central Council for Environmental Pollution Control

Emissions Standards for South Korea

Table A15: Korean LPG and Gasoline Emission Standards[2]

Category	Year	Test	Unit	HC	CO	NO_X
Cars < 800cm^3	1987	CVS-75	g/km	2.1	8	1.5
Cars up to 12 passengers or 2500 kg	1987	CVS-75	g/km	0.25	2.1	0.62
LDT upto 2700 kg	1987	CVS-75	g/km	0.5	6.21	1.43

Table A16: Korean Diesel Emission Standards[1]

Category		Test	Unit	Date	HC	CO	NO_X	PM
Diesel Passenger Cars		US FTP 75	g/km	1993.1.1	0.25	2.11	0.62	0.120
				1996.1.1	0.25	2.11	0.62	0.080
				1998.1.1	0.25	1.50	0.62	0.080
				2000.1.1	0.25	1.20	0.62	0.050
Light-Duty Trucks GVW < 3t	1993-97	Japan 6 mode	ppm	1993.1.1	670	980	350 IDI 750 DI	-
		US FTP 75	g/km	1996.1.1	0.50	6.21	1.43	0.310
	1998 and later LW<1.7t	US FTP 75	g/km	1998.1.1	0.25	2.11	1.40	0.140
				2000.1.1	0.25	2.11	1.02	0.110
				2004.1.1	0.21	1.27	0.64	0.080
	1998 and later LW>1.7t	US FTP 75	g/km	1998.1.1	0.50	2.11	1.40	0.250
				2000.1.1	0.50	2.11	1.06	0.140
				2004.1.1	0.33	1.52	0.71	0.080
Heavy-Duty Diesel Engines GVW > 3t		Japan 6 mode	ppm	1993.1.1	670	980	350 IDI 750 DI	-
		ECE R49 (13 mode)	g/kWh	1996.1.1	1.20	4.90	11.0	0.900
				1998.1.1	1.20	4.90	6.0 (9.0)*	0.250 (0.500)*
				2000.1.1	1.20	4.90	6.0	0.250 (0.500)*
				2002.1.1	1.20	4.90	6.0	0.150 (0.100)*

*- applies to buses.
GVW – gross vehicle weight
LW – loaded weight (curb weight + 130 kg)

Emission Standards for Thailand

Table A17: Light-Duty Diesel Fueled Vehicles[1]

Tier	Effective	Reference Std.	Type	Weight (kg)	CO	HC + NO_X	PM g/km
1	29 Jan 1995	ECE R 83	PC <= 6 seats, < 1400cc	-	45 g/test	15 g/test**	-
			PC <= 6 seats, >= 1400cc	-	30 g/test	8 g/test	-
		ECE R 15-04	6 <PC <= 9 seats PC > 2500 kg Truck <= 3500 kg	R<=1020	58 g/test	19 g/test	-
				1020 <R<=1250	67 g/test	20.5 g/test	-
				1250<R<=1470	76 g/test	22 g/test	-
				1470<R<=1700	84 g/test	23.5 g/test	-
				1700<R<=1930	93 g/test	25 g/test	-
				1930<R<+=2150	101 g/test	26.5 g/test	-
				2150<R	110 g/test	28 g/test	-
2	23 Feb 1996	ECE R 83	PC <+ 6 seats	R<=1020	2.72 g/km	0.97 g/km	0.14
		ECE R 15-04	6 < PC<= 9seats PC>2500 kg Truck<=3500 kg	1020 <R<=1250	58 g/test	19 g/test	-
				1250<R<=1470	67 g/test	20.5 g/test	-
				1470<R<=1700	76 g/test	22 g/test	-
				1700<R<=1930	84 g/test	23.5 g/test	-
				1930<R<+=2150	93 g/test	25 g/test	-
				2150<R	101 g/test	26.5 g/test	-
					110 g/test	28 g/test	-
3	1 Jan 1997	ECE R 83-01 (B)	PC <= 6 seats	-	2.72 g/km	0.97 g/km	0.14
		93/59/EEC	6<PC<=9seats PC>2500 kg Truck <=3500 kg	R<=1250	2.72 g/km	0.97 g/km	0.14
				1250<R<=1700	5.17 g/km	1.40 g/km	0.19
				1700<R	6.90 g/km	1.70 g/km	0.25
4	1 Jan 1999* 30 Sep 2001 (DI)*	94/12/EC	PC <= 6 seats	-	1.00 g/km	0.70 g/km	0.08
		93/59/EEC	6<PC<=9seats PC>2500 kg Truck <=3500 kg	R<=1250	2.72 g/km	0.97 g/km	0.14
				1250<R<=1700	5.17 g/km	1.40 g/km	0.19
				1700<R	6.90 g/km	1.70 g/km	0.25
5	1 Oct 1999 (R<=1250 kg)* 1 Oct 2000 (R>1250 kg)* 30 Sep 2001 (DI)*	94 /12/EC	PC <= 6 seats	-	1.00 g/km	0.70 g/km	0.08
		96/69/EC	6<PC<=9seats PC>2500 kg Truck <=3500 kg	R<=1250	1.00 g/km	0.70 g/km	0.08
				1250<R<=1700	1.25 g/km	1.00 g/km	0.12
				1700<R	1.50 g/km	1.20 g/km	0.17

*- proposed **- 6 g/test NO_X

Table A18: Heavy-Duty Diesel Fueled Vehicles (g/kWh)[1]

Tier	Effective	Reference Std.	CO	HC	PM	NO_x
1	-	ECE R 49-01	11.2	2.4	-	14.4
2	12 May 1998	EURO I	4.5	1.1	0.36	8.0
3	1 Jan 1999*	EURO II	4.0	1.1	0.15	7.0

*proposed

REFERENCES

[1] DieselNet, "Vehicle Emission Standards", http:www.dieselnet.com.

[2] N. Ostrouchov, "International New Vehicle Emissions Standards: Internal Report", Transportation Systems Division, Industrial Program Branch, Concervation and Protection, Environment Canada, 1995.

APPENDIX B

Test Cycles in use for Emissions Testing

APPENDIX B

TEST CYCLES IN USE FOR EMISSIONS TESTING

Emission cycles are a sequence of speed and load conditions performed on an engine or chassis dynamometer. Emissions measured on vehicle (chassis) dynamometers are usually expressed in grams of pollutant per unit of distance traveled, e.g. g/km or g/mi. Emissions measured on an engine dynamometer test cycle are expressed in grams of pollutant per unit of mechanical energy delivered by the engine, typically g/kWh or g/bhp-hr. This appendix presents the test cycles currently in use for emissions testing.

Depending on the character of the speed and load changes, cycles can be divide into steady state cycles and transient cycles. Steady state cycles are a sequence of constant engine speed and load modes. Emissions are analyzed for each test mode. Then the overall emission result is calculated as a weighted average from all test modes. In a transient cycle the vehicle (engine) follows a prescribed driving pattern which includes accelerations, decelerations, changes of speed and load, etc. The final test results can be obtained either by analysis of exhaust gas samples collected in plastic bag samples over the duration of the cycle or by electronic integration of a fast response, continuous emissions measurement [1].

Emissions Test Cycles are developed by three leaders in engine emissions: USA, European Union, and Japan. USA has three vehicle test cycles it has developed.

- FTP 72 (also known as the Urban Dynamometer Driving Schedule (UDDS) or LA-4 cycle), shown in Figure B1. The same engine driving cycle is known in Sweden as A10 or CVS (Constant Volume Sampler) cycle and in Australia as the ADR 27 (Australian Design Rules) cycle.
- FTP 75, shown in Figure B2. This cycle is known as the ADR 37 in Australia (Australian Design Rules) cycle.
- FTP Transient shown in Figure B3.

Emission Standards Test Cycles of the United States.

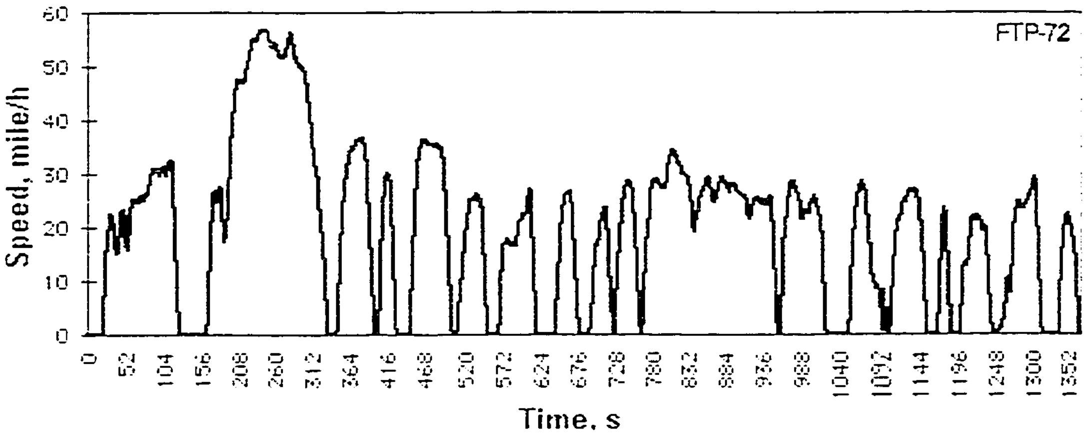

Figure B1: FTP 72 Test Cycle [1]

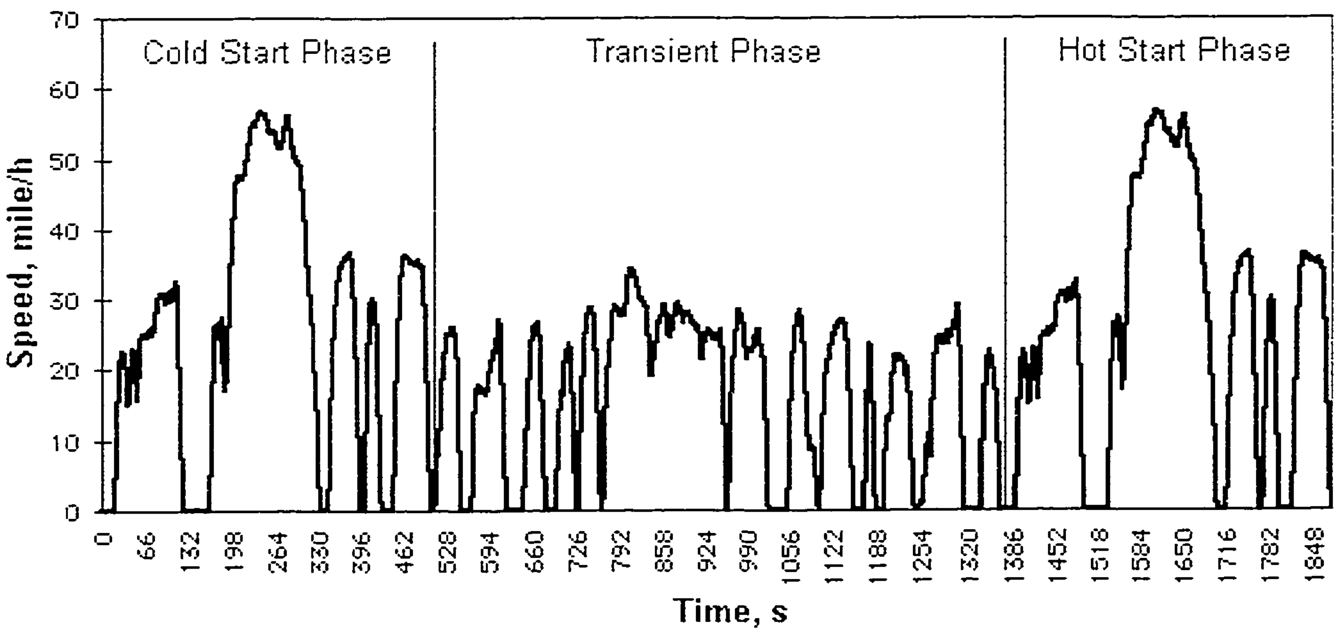

Figure B2: FTP 75 Test Cycle [1]

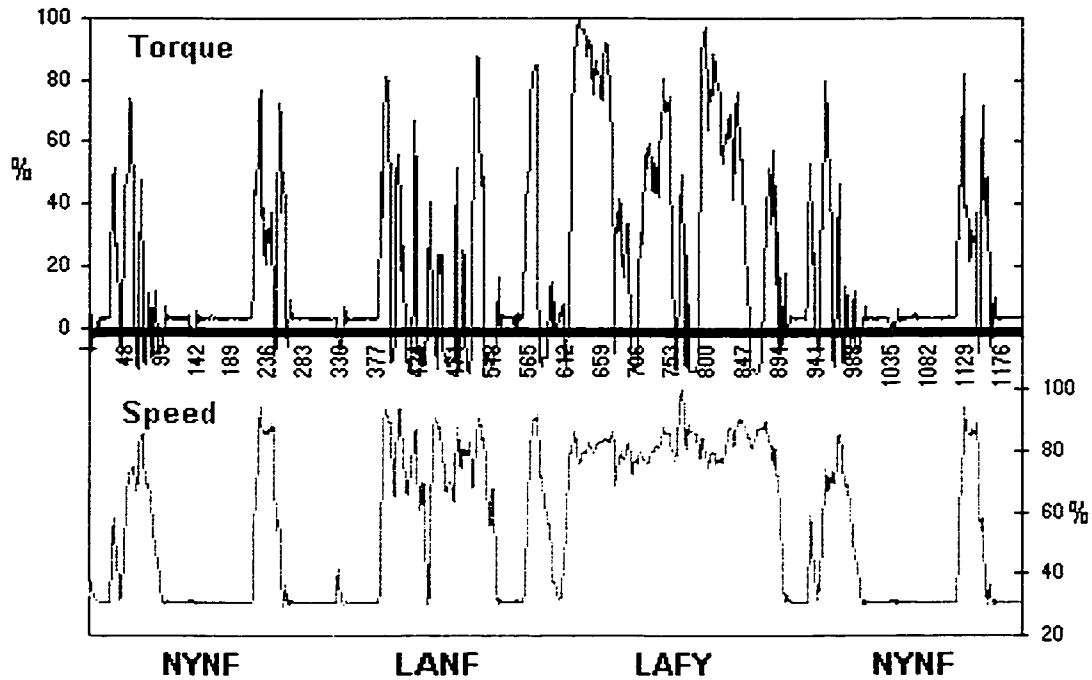

Figure B3: FTP Transient Test Cycle [1]

Emissions Standards in the USA for car and light-duty trucks are one of the most recognized standards when it comes to emissions for vehicles [1]. Currently car and light truck emissions are measured over the Federal Test Procedure (FTP 75) test and expressed in g/mile. In addition to the FTP 75 test, a Supplemental Federal Test Procedure (SFTP), shown in Figure B4, will be phased-in between 2000 and 2004. The SFTP includes additional test cycles to measure emissions during aggressive highway driving (US06 cycle), and also to measure urban driving emissions while the vehicle's air conditioning system is operating (SC03 cycle shown in Figure B5).

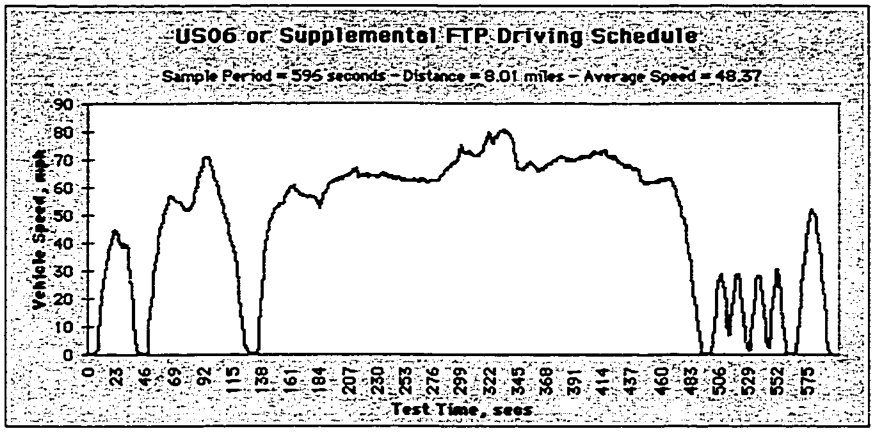

Figure B4: Supplemental Federal Test Procedure (SFTP/US06)

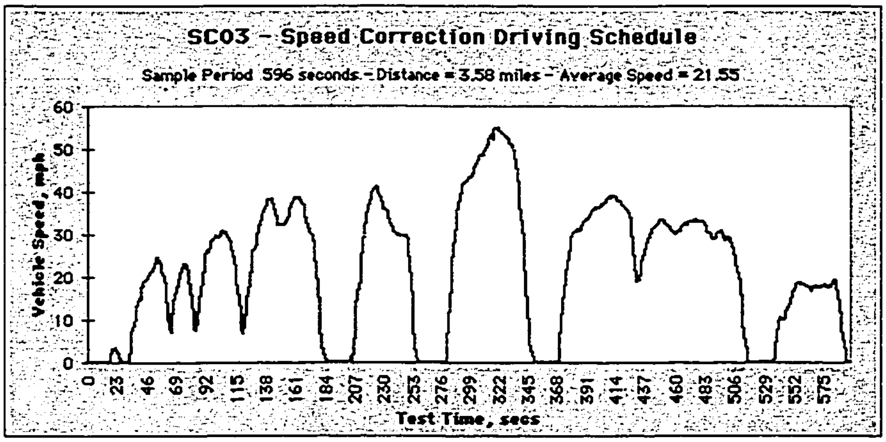

Figure B5: Speed Correction Driving Schedule for Air Conditioning System (SC03)

The Central Business District (CBD) Cycle and New York Test Cycle are chassis dynamometer testing procedures for heavy-duty vehicles. Figure B6 represents the CBD cycle and Figure B7 represents the NY cycle.

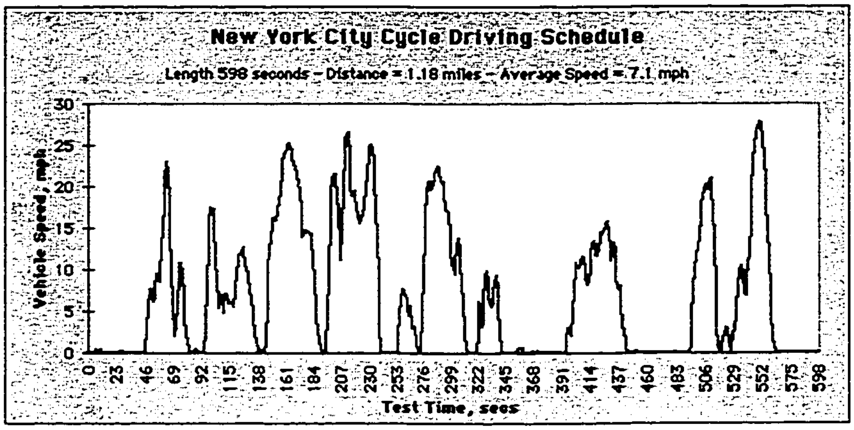

Figure B6: Central Business District Cycle [1]

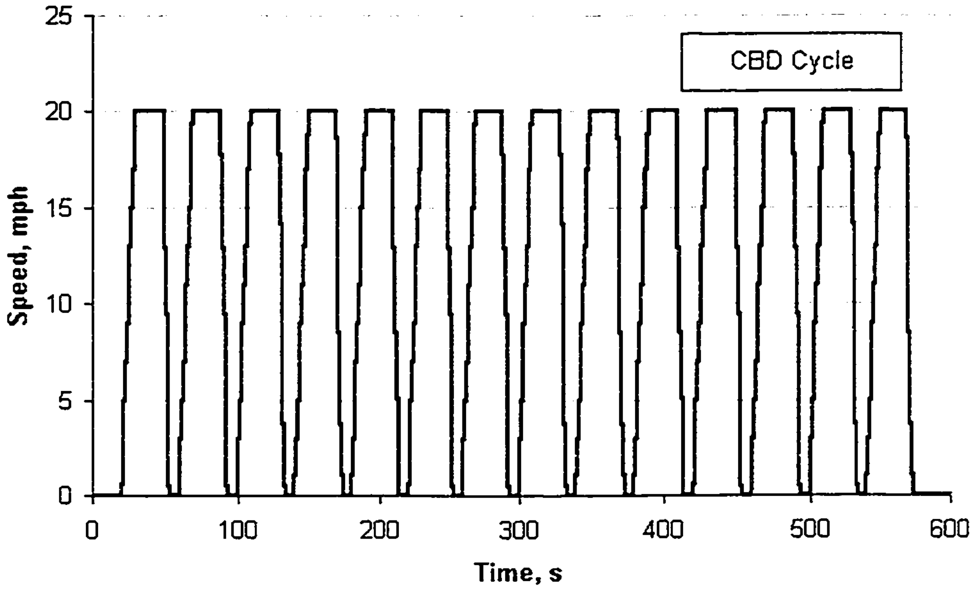

Figure B7: New York Test Cycle [2]

Emission Standards Test Cycles of the European Union.

Europe has 4 test cycles it uses for emissions testing:

ECE15+EUDC - is a combined vehicle test cycle consisting of 4 ECE segments and one Extra-Urban Driving Cycle (EUDC). The ECE is also known as the Urban Driving Cycle (UDC). Figure B8 shows the ECE15 segment of the cycle and Figure B9 shows the EUDC portion.

ECE R-49 - is a 13-mode steady-state engine dynamometer test and is shown in Figure B10.

ESC - the European Stationary Cycle (ESC) is also a 13-mode steady-state procedure that now has replaced the R-49 test cycle. This cycle is shown in Figure B11.

ETC - the European Transient Cycle (ETC) is also known as the FIGE Transient Cycle. This cycle is shown in Figure B12.

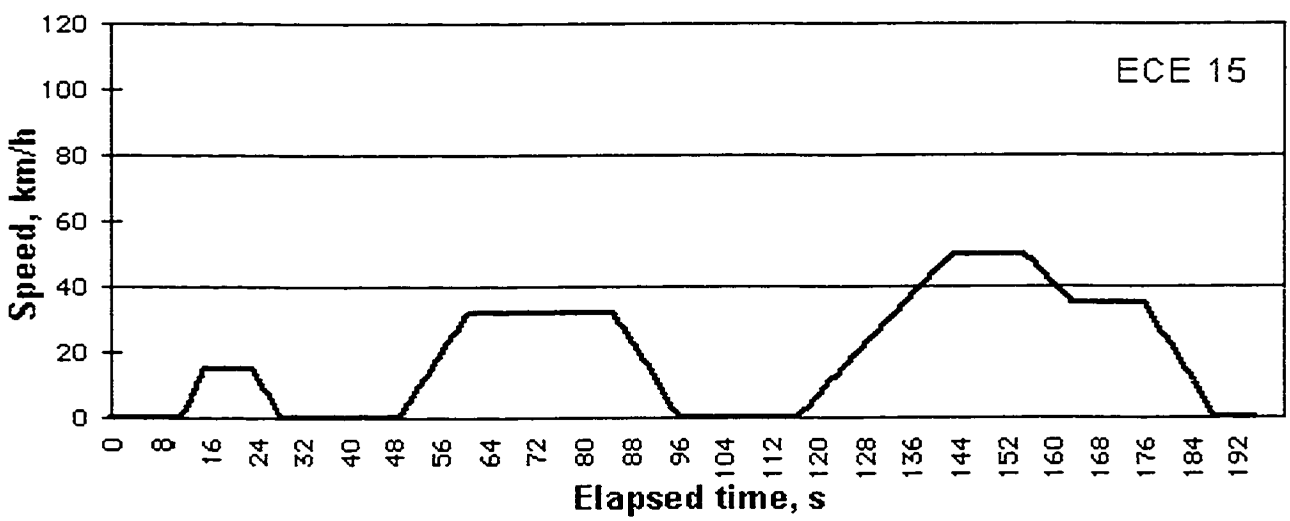

Figure B8: ECE 15 Test Cycle [1]

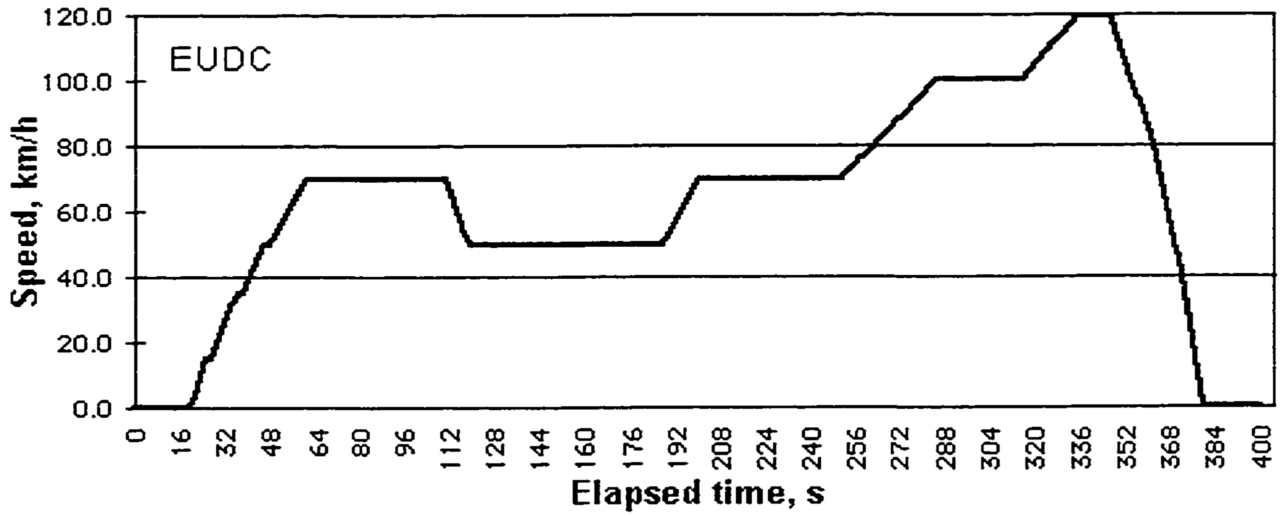

Figure B9: Extra-Urban Drive Cycle (EUDC) [1]

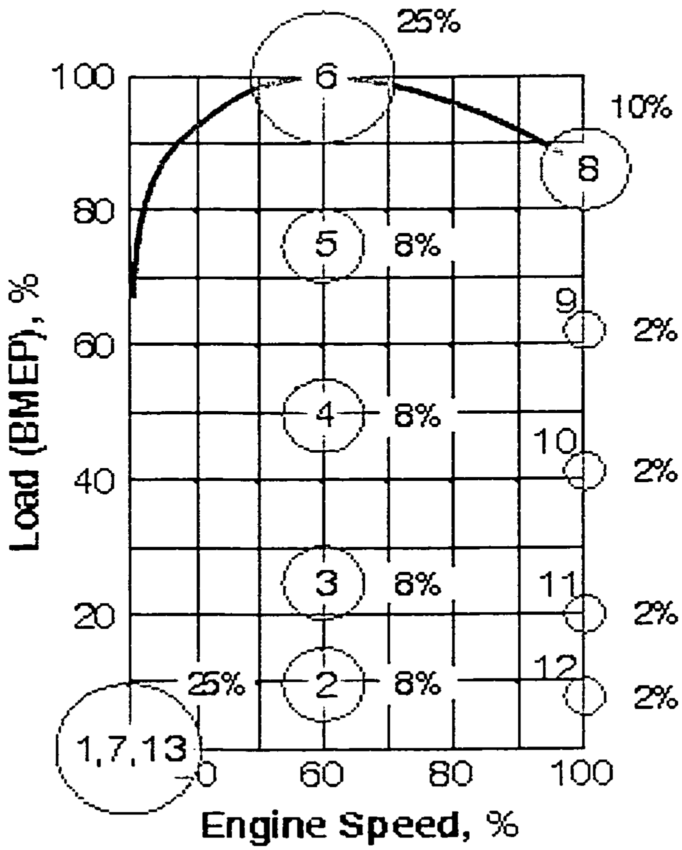

Figure B10: ECE R-49 Test Cycle [1]

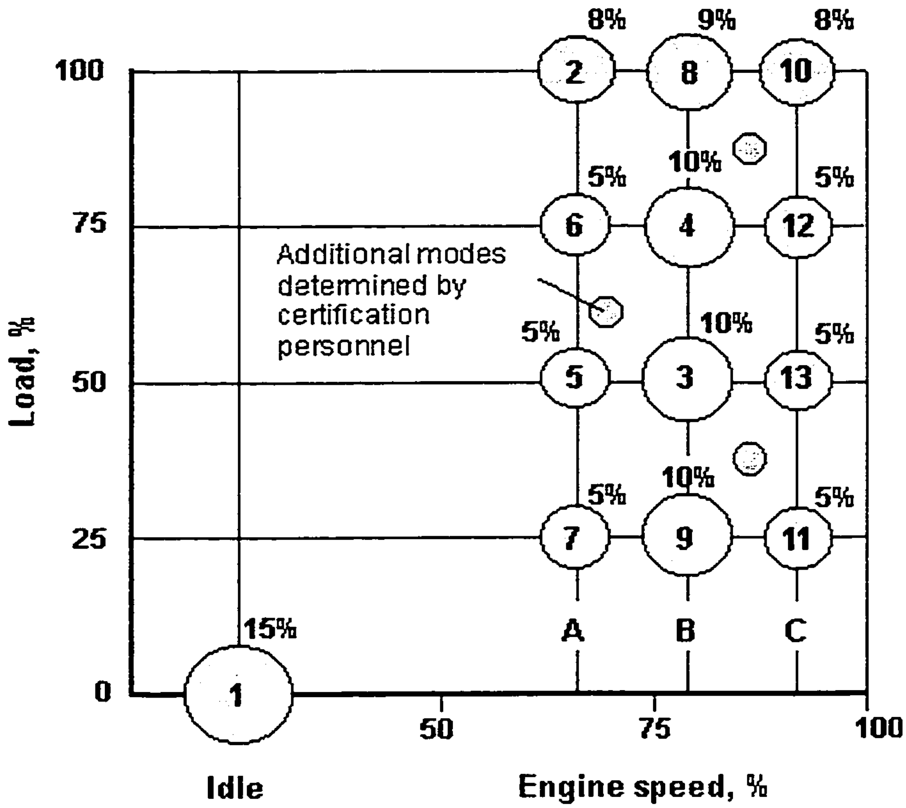

Figure B11: European Stationary Cycle (ESC) [1]

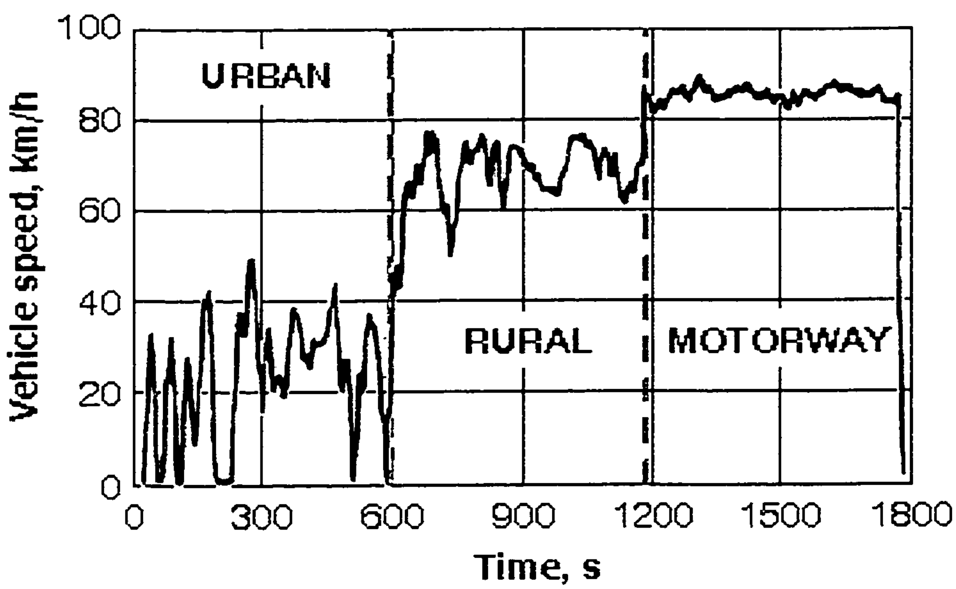

Figure B12: European Transient Cycle (ETC) [1].

Emission Standards Test Cycles of Japan.

Japan has 4 test cycles which have been used for emissions testing of vehicles:

- 10-Mode Cycle - is an urban driving cycle replaced by the 10-15 mode cycle for LDVs, Figure B13 shows the 10-mode cycle.
- 10-15 Mode Cycle - is the urban driving cycle which is currently in use, Figure B14 shows the 15-mode cycle and Figure B15 shows the combined 10-15 mode cycle.
- 6 Mode Cycle - two 6-mode tests were used for HDVs: one for diesel and one for gasoline/LPG vehicles. Details for the 6-mode test are given in Table B1.
- 13 Mode Cycle - replaces the 6-mode for HDVs. Modes are the same for diesel and gasoline but weighting factors are different. Table B2 shows details for the 13-mode test.

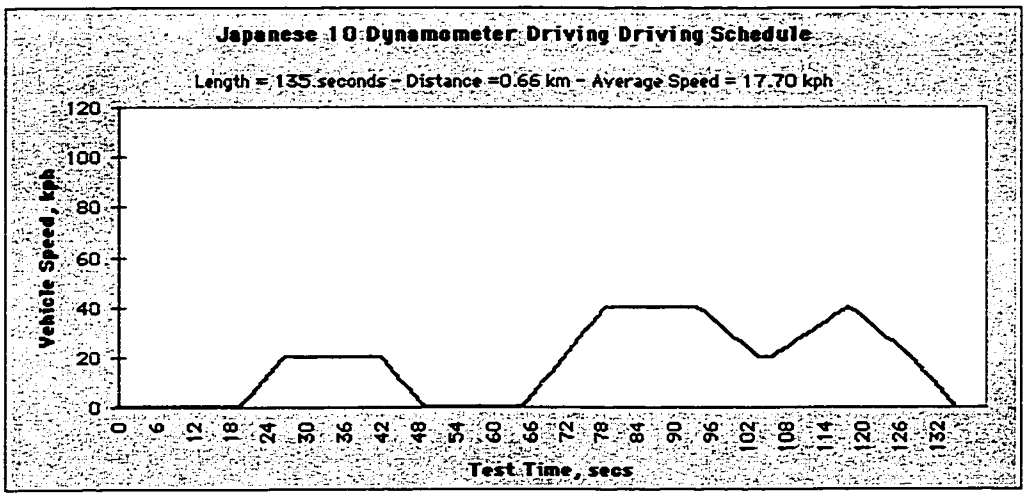

Figure B13: Japanese 10 Mode Test Cycle [2]

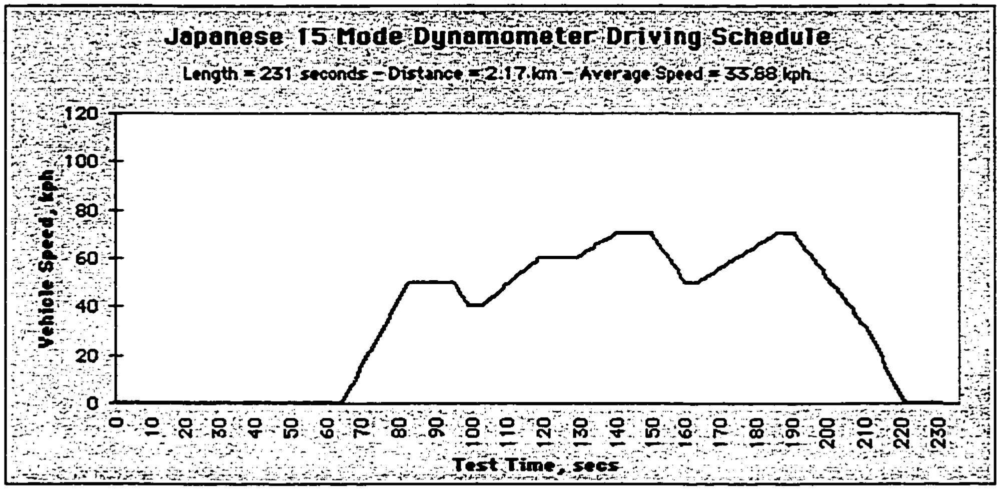

Figure B14: Japanese 15 Mode Test Cycle [2]

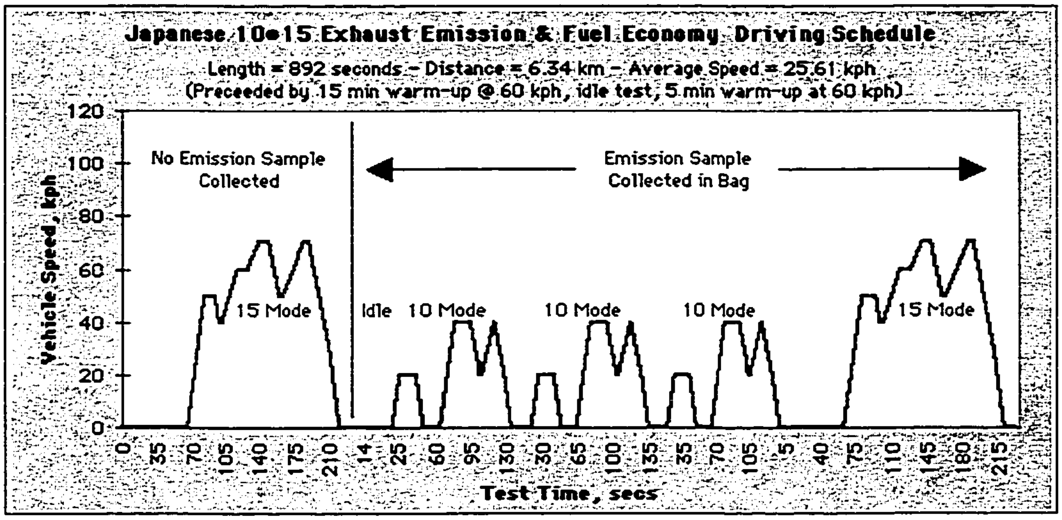

Figure B15: Japanese 10-15 Mode Test Cycle for Emissions and Fuel Economy [2]

Table B1: Japanese 6 Mode Test Cycle [1]

Mode	Speed(% of nominal)	Load (%)	Weighting factor
1	idle	-	0.355
2	40	100	0.071
3	40	25	0.059
4	60	100	0.107
5	60	25	0.122
6	80	75	0.286

Table B2: Japanese 13 mode Test Cycle [1]

Mode	Speed (% of nominal)	Load (%)	Weighting factor
1	idle	-	0.410/2
2	40	20	0.037
3	40	40	0.027
4	idle	-	0.410/2
5	60	20	0.029
6	60	40	0.064
7	80	40	0.041
8	80	60	0.032
9	60	60	0.077
10	60	80	0.055
11	60	95	0.049
12	80	80	0.037
13	60	5	0.142

REFERENCES

[1] DieselNet, http: www.dieselnet.com.

[2] Environmental Protection Agency, http: www.epa.gov/oms/labmthod.htm.

APPENDIX C

Exhaust Speciation and Human Health Effects

APPENDIX C:

EXHAUST SPECIATION AND HUMAN HEALTH EFFECTS

Vehicle exhausts may contain a great many toxic compounds, particularly when the fuel itself contains toxic compounds, (especially gasoline which contains many aromatics, solvents, etc which are individually toxic or carcinogenic). The acute health responses that have been associated with air pollution include changes in respiratory mechanics (lung function), changes in respiratory symptoms such as coughing or asthma attacks, cardiac symptoms such as angina attacks, disabilities, absences from work or school, hospitalization, and premature mortality [1].

In considering exhaust from vehicles, the focus is generally on the following substances.

CO (Carbon Monoxide)

An estimated 10,000 persons in the US seek medical attention each year for CO poisoning of which 1500 die. CO is a colorless, odorless and tasteless gas produced from incomplete combustion. CO acts like an asphyxiant by interfering with the normal uptake of oxygen by the blood and the delivery of the oxygen to body tissues. Hemoglobin in red blood cells has affinity for CO 210 times that of oxygen [2]. Oxygen supply to body tissues is reduced even more because of a shift to the left of the oxyhemoglobin saturation curve as a result of the combination of CO with the hemoglobin. The shift results in the reduction in the ability of the red blood cells to release the remaining oxygen to body tissues. Tissues most sensitive to the lack of oxygen are heart and circulatory system and brain and central nervous system. High levels cause unconsciousness. Death can occur when COHb reaches 60 to 80 % [2]. Toxic effects of CO are due to its combining with the hemoglobin in the blood to form COHb [3]. For low level exposure to CO, such as COHb of 2 to 5 %, the health effects are not well defined. In young and healthy people, decreased oxygen intake ability and work capacity have been noticed at COHb concentrations as low as 5%. Patients suffering from angina have been shown to be affected by COHb levels as low as 2.9%. Neurobehavioral functions have been shown to be affected at COHb levels of 5% [3]. CO leads to decreased alertness, decreased visual acuity, headaches, and nausea. The effects of CO exposure and resulting carboxyhemoglobin formation are essentially identical to those of other factors which reduce oxygen available to body tissues, such as chronic lung disease, disorders reducing blood circulation, and high altitude. In short term COHb reduces the oxygen carrying capacity causing tissue hypoxia [25]. Chronic exposure (like smoking) the body compensates somewhat by increasing the concentration of red blood cells and hemoglobin available. Central nervous system, cardiovascular system and liver are most sensitive. Important factors effecting CO uptake include-time of exposure, up to 16 hrs is required for the blood to reach equilibrium after an increase in CO concentration [4].

CO_2 (Carbon Dioxide)

CO_2 is a simple asphyxiant, but can also cause headaches, dizziness, dyspnea, inconsistent heart rate, coma, and convulsions at levels below full asphyxia [5]. Average concentration in the atmosphere is about 340 ppm but levels vary widely with time and location [6]. An increase in the ambient level of carbon dioxide brings about a rise in the acidity of the blood and an increase in the rate and depth of breathing. Over longer periods, like days, regulation of blood CO_2 level occurs by kidney action and the metabolism of bone calcium leading to some demineralization of the bone. Exposer to levels such as 50,000ppm can cause effects in the central nervous system, like headaches and dizziness and visual distortion. Lowest concentration at which adverse health effects have been observed is 7000 ppm at which level increased blood acidity has been observed after several weeks of continuous exposure [6].

NO_X (Nitrogen Oxides)

NO_X refers to a number of compounds – NO, NO_2, N_2O, OONO, ON(O), N_2O_3, N_2O_4, N_2O_5 [4]. The most well studied is NO_2 now for over 30 years. Epidemiological evidence shows an increased incidence of acute respiratory infections, especially in infants and children, resulting from exposure to NO_2, possibly augmented by NO. These gases tend to combine with moisture to form acids. The exact mechanism of toxicity is the oxidation of fatty acids to produce highly reactive free radicals which can impair chemical and functional properties of membranes and alter structural proteins. Both NO and NO_2 also combine with hemoglobin in the blood forming methemoglobin which reduces oxygen carrying capacity of the blood [4]. They are equally effective in producing methemoglobin and they are about 4 times more effective than CO of the same concentration in reducing oxygen carrying capacity of the blood [4]. NO_2 causes cumulative lung damage, moderate irritation to the eyes and nose, and can cause coughing, frothy sputum, dyspnea, chest pain, pulmonary edema, cyanosis, tahcypnea, tachycardia, and eye irritation [5]. For NO_2, respiratory illness was observed in adults and children chronically exposed to mean levels of near 0.10 ppm [6]. Clinical studies indicate normal and asthmatic subjects can experience detrimental respiratory effects when exposed for brief periods to levels of 0.5 ppm [6].

Aldehydes

Formaldehyde, acetaldehyde, and acrolien are the more prevalent aldehydes in exhaust. They act as eye, nose, throat and skin irritants, can produce nausea, kidney damage, chronic respiratory disease, inhibit the immune system, and have been shown to be mutagenic or carcinogenic or both. Major effect is irritation of the eyes, nose and throat [6]. Significant increase in symptoms of irritation are observed at levels of formaldehyde greater than 1 ppm (periods of 1.5 to 30 minutes). In the best conducted studies formaldehyde irritation does not occur at levels less than 0.6 ppm. Acrolein is one of the most irritating of the aldehydes with most people reporting eye irritation at levels less than 1 mg/m3. Severe irritation results from exposure to 0.8 ppm [6]. Irritation of the upper respiratory tract is the primary symptom of acrolien inhalation, but lung edema can occur after exposure to high concentrations. In addition skin contact causes skin burns and severe injury to the cornea. Acetaldehyde is considerably less irritating where symptoms of irritation are felt at levels of 25 ppm [6].

Aromatics

Benzene, styrene, toluene, and the o-, — and p- xylenes are known to irritate eyes, nose and throat, and cause drowsiness, dizziness, headaches, vomiting, nausea, fatigue, abdominal pain, confusion, insomnia, and euphoria [5]. The xylene isomers are clear, flammable liquids with an aromatic hydrocarbon odor. Some studies also report gastrointestinal disturbances, in addition to kidney, heart, liver, and neurological damage. Styrene monomer is a colorless, oily liquid with an aromatic odor. Styrene is an irritant, a narcotic, and a neuropathic agent and is classified as a possible human carcinogen. The principal effects due to styrene exposure involve the central nervous system. These effects include difficulty in concentrating, feeling of intoxication, liver injury, peripheral nervous system dysfunction, abnormal pulmonary function, chromosomal changes, reproductive effects in addition to the list of subjective complaints give previous. Toluene is a flammable, colorless liquid with an aromatic hydrocarbon odor. Exposure to toluene has been known to cause headaches, nausea, bad taste in mouth, lassitude, temporary amnesia, impaired coordination, and anorexia. In longer term exposures, aromatics may be carcinogenic.

Olefins (alkenes)

1,3 Butadiene has been found to present a more potent cancer risk than benzene and formaldehyde. 1,3 Butadiene is a mild irritant to eyes, nose and throat, causes drowsiness and light headedness [5].

Paraffins

Generally, the saturated paraffin hydrocarbons are considered to be inert. However, all of them are potentially asphyxiants. Methane (CH_4) in particular is an asphyxiant since it can potentially be released in large quantities and mixes well with air. The heavier paraffins tend to form heavier-than-air clouds when released in large quantities. Propane (C_3H_8) can cause dizziness and disorientation.

Others

Ozone is a powerful and irritating pollutant that affects the respiratory system and can cause lung disease. Sulfur dioxide (SO_2) is an eye, nose, throat and skin irritant, and causes bronchoconstriction, coughing, choking, rhinorrhea, mutagen, and is suspect of reproductive effects. It is a colorless, nonflammable gas or liquid with a suffocating odor. Exposure to sulfur dioxide causes both acute and chronic effects. The chronic effects of exposure include permanent pulmonary impairment, which is caused by repeated episodes of bronchoconstriction. Acute effects of SO_2 exposure include upper respiratory tract irritation, rhinorrhea, choking, and coughing. These symptoms are so disagreeable that most persons will not tolerate exposure for longer than 15 minutes. Within 5 to 15 minutes of the onset of exposure persons develop temporary reflex bronchoconstriction and increased airway resistance.

The literature on air pollutant speciation and health is vast. It varies from general, handbook type lists of compounds and effects to highly specialized epidemiological investigations and medical investigations of the effects of specific compounds.

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APPENDIX D

Occupational Exposure Levels of Exhaust Species from Around the World

APPENDIX D

OCCUPATIONAL EXPOSURE LEVELS

There are a many occupational health agencies in the world. Even within each country there may exist several which recommend and enforce workplace and public exposure limits. The methods, measures and permissible levels vary from country to country and even from agency to agency within a country.

OEL's are one of the most efficient instruments of protection of workers' health. They have a long tradition, much longer than any other exposure standard. The first initiatives were taken in Germany more than one century ago. The first proposals for occupational exposure limits were published by Karl Bernhard Lehmann in 1886 [1]. Occupational exposure limits for airborne chemicals are in use around the world. This demonstrates their usefulness, but there are international problems associated with their use [2]. Problems include: many users see limits as a frontier between safe and unsafe, or assume that substances that do not have limits are safer than substances that do. A small risk may be considered acceptable by one person and unacceptable by another, especially if one person is paying for control and another is bearing the risk to health [2]. Ultimately, there is the question of whether <u>any</u> set exposure limit is tolerable if the lowest achievable exposure still corresponds to significant risk [2].

Only a few countries have developed OEL's of their own. Existing experience in the world shows that they may have different names, such as Threshold Limit Value (TLV) in the US ACGIH , which is also used in some other countries, or Maximum Concentration at the Workplace (MAK) in Germany, or Maximum Allowable Concentrations (MAC) in Russian Federation and Poland [3]. Different names of OEL's resulted from their different definitions. Until now, Germany has registered more than 500 chemicals in the national MAK-list, the US TLV-list contains approximately 600 compounds, and even more are found in the list of the USSR. Holland and Sweden started their own national systems towards the end of the seventies. The United Kingdom is at the very beginning of a new system based on a tripartite decision process [1].

Occupational toxicologists, physicians and hygienists have reached a broad agreement on the approaches and the methods to provide the basic scientific information needed to recommend, evaluate, and revise permissible levels for occupational exposure [3]. The development of occupational exposure limits is based on expert evaluation of scientific evidence. The main scientific evidence is the information on exposure-effect and exposure-response relationships. An exposure-effect relationship is defined as the relationship between quantified exposure and quantified severity of health effect, in an individual or a defined group. An exposure-response relationship is the relationship between quantified exposure and the percentage of individuals showing an effect of specified severity [3].

Toxicity, acute, subacute and chronic toxic effects, metabolism and other toxicokinetic criteria, exposure-effect and exposure-response relationship, critical adverse effects have been taken into consideration as the main criteria for health-based OEL value development [3]. Mention should be made that there is a need for harmonization and internationally accepted definitions of OEL's, critical criteria for OEL's value derivation, harmonization of approaches, methodology and health risk assessment procedure which serve as scientific bases for OEL establishment [3].

Things to Know When Applying OEL's

OEL's should be applied by individuals well trained and experienced in occupational health. They can not be applied in cases where exposure duration or work intensity exceeds the prerequisite conditions for setting an OEL. OEL's are set based on various information obtained from experiences in industries and experiments on humans and animals. Data set quality and quantity vary. Types of health effects considered in setting OEL's depend on the substances involved; an explicit health impairment provides the basis for OEL's in certain substances, while non-health effects such as discomfort, irritation or CNS suppressive effects afford the basis in others. Thus they cannot be used as a relative scale of toxicity. Due to variance in individual susceptibilities, discomfort, deterioration of pre-existing ill health or occupational disease may be induced at levels of exposure below OEL's, even though the chances of this should be remote. Because they do not represent a definitive borderline between safe and unsafe it is not correct to conclude that environments above the OEL's are the direct and sole cause of health impairment in workers. The limits cannot be used as reference values in non-occupational environments. They are revised when considered necessary

Regarding carcinogens, the scientific community does not recognize the existence of a threshold dose below which no cancer will occur. A different problem but with an identical practical application, concerns exposure limits for substances which cause sensitivity. The observance of the exposure limits is not sufficient to protect people who are sensitized to the specific substance used at work; however, it is known that the lower the exposure to chemicals with sensitizing capacity, the fewer workers who will develop allergic syndromes. It has already become clear that several key principles concerning the criteria of setting OEL's need to be discussed in detail because already existing national scientific committees have applied different approaches to develop their limit values.

Limits

The indicative criteria which will be taken as a guide in deciding what kind of limit should be set are given:

Occupation Exposure Standard: ability to identify with reasonable certainty, a concentration averaged over a reference period, at which there is no indication that the substance is likely to be injurious to employees if they are exposed by inhalation day after day to that concentration and ; the OES can reasonably be compiled with and; exposure to concentrations greater than the OES for the period of time it might reasonably be expected to take to identify and remedy the cause of excessive exposure, are unlikely to produce serious short- or long-term effects on health.

Maximum Exposure Limit: a substance not able to satisfy the criteria for an OEL's and which has or is liable to have a serious risk to man including acute toxicity and/or potential to cause serious long-term health effects or; socio-economic factors, which indicate that although the substance meets the criteria for an OES a numerically higher value is necessary if certain uses are to be reasonable.

Immediately Dangerous to Life and Health (IDLH): defined as conditions which pose immediate danger to life or health, or conditions that pose a threat of severe exposure. IDLH limits were created mainly to assist in making decisions regarding respirator use. Above the IDLH only supplied air respirators should be used, below the IDLH air purifying respirators may be used.[4]

Time-Weighted Average (TWA): determined by sampling the breathing zone of the worker for 8 hrs. mathematically expressed as TWA = (Ci*ti)/ti where Ci is the average concentration over time period ti, and ti is the period of time during which one sample is taken.[4]

Short Term Exposure Limit (STEL): 15 minute TWA concentration which must not be exceeded even if the 8 h TWA is within standards. TWA-STEL are given for contaminants for which short term hazards are known. For the rest an excursion factor of 3 has been used. STEL should not exceed 3 times the TWA limit.[4]

Ceiling (C): both the TWA and STEL permit limited excursion if, in the end, the average is below the exposure limit. The ceiling value, however, may not be exceeded. [4]

Threshold Limit Value (TLV): The rational for setting the TLVs is given in a publication called "Documentation of the TLVs". They are the airborne concentrations of substances devised by the ACGIH that represents conditions under which it is believed that nearly all workers may be exposed day after day with no adverse effect. TLV's are advisory exposure guidelines, not legal standards, that are based on evidence from industrial experience, animal studies, or human studies when they exist. There are three different types of TLV's - time-weighted average (TLV-TWA), short term exposure limit (TLV-STEL) and , ceiling (TLV-C).

Recommended Exposure Limits (REL): are set by National Institute for Occupational Safety and Health (NIOSH) which is part of the department of Health and Human Services. NIOSH scientists recommend exposure limits to OSHA, based on animal and human studies. These are often more conservative than TLV. NIOSH publishes criteria documents that include the data related to each standard, as well as sampling techniques and control measures.[4]

Permissible Exposure Limit (PEL): OSHA has the power to warn, site, and fine violators. The OSHA Act required OSHA to set standards that will provide safe working conditions, but required it to set its permanent standard by negotiation and consensus. As a result only about 25 permanent standards have been set since 1973. In the meantime they have adopted existing standards of the ACGIH TLV as the interim standard [4]. The permissible exposure limits must be upheld by employers at all times. In some cases the Threshold Limit Value established by ACGIH may be lower than OSHA PEL in which case employers must strive to keep exposures as low as reasonably achievable and follow the TLV's.

The following tables list exposure threshold criteria for a number of substances which are of interest in vehicle exhaust. The values are provided for various countries and for a number of provinces in Canada.

Table D1: Comparison of International OEL's for Specific Substances.

SUBSTANCES	UNIT	AUSTRALIA		BELGIUM		CZECH		DENMARK		FINLAND		FRANCE		GERMANY		HUNGARY	
		TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL
ACETALDEHYDE	ppm	100	150	100	150			25		50	75	100		50			
	mg/m3	180	270	180	270	200	400	45		90	135	180		90			25
ACROLEIN	ppm	0.1	0.3	0.1	0.3			0.1			0.1		0.1	0.1			
	mg/m3	0.25	0.8	0.23	0.69	0.5	1	0.25			0.25		0.25	0.25		0.25	0.5
BENZENE	ppm	10		10				3		3	10	3					
	mg/m3	30		32		10	20	16		15	30	16					5
1,3-BUTADIENE	ppm	10		10				10		50							
	mg/m3	22		22		20	40	22		73							10
CARBON DIOXIDE	ppm	5000	30000	5000	30000			5000		5000				5000			
	mg/m3	9000	54000	9000	54000	9000	45000	9000		9000				9000			9000
CARBON MONOXIDE	ppm	50	400	50	400			35		30	75	50		30			
	mg/m3	55	440	57	458	30	150	40		34	86	55		33		20	40
FORMALDEHYDE	ppm	1	2	1	2				0.3		1		2	0.5			
	mg/m3	1.5	3	1.2	2.5	0.5	1		0.4		1.3		3	0.6			0.6
METHANE	ppm																
	mg/m3																
NITROGEN DIOXIDE	ppm	3	5	3	5			3	5	3	6		3	5			
	mg/m3	6	10	5.6	9.4	10	20	5.6	9.4	6	12		6	9		5	10
NITROGEN MONOXIDE	ppm	25		25				25		25		25					
	mg/m3	30		31		10	20	30		30		30					
PROPANE	ppm							1000		800				1000			
	mg/m3							8000		1100				1800			
STYRENE	ppm	50	100	50	100			25		20		50		20			
	mg/m3	215	425	213	426	200	1000	105		85		215		85			50
SULFUR DIOXIDE	ppm	2	5	2	5			2		2	5	2	5	2			
	mg/m3	5	10	2.5	13	5	10	5		5	13	5	10	5			5
TOLUENE	ppm	100	150	100	150			50		100	150	100	150	100			
	mg/m3	375	560	377	565	200	1000	190		375	565	375	560	380		100	300
XYLENE (all isomers)	ppm	80	150	100	150			50		100	150	100	150	100			
	mg/m3	350	655	434	651	200	1000	217		435	655	435	650	440		100	300

source:[7] except where indicated. a - [6]; b - [5]; c - [4]

SUBSTANCES	UNIT	JAPAN		POLAND		SWEDEN		SWITZERLAND		UNITED KINGDOM		USA: ACGIH		USA: OSHAc		USSR	
		TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL
ACETALDEHYDE	ppm	50a				25	50	50	100	100	150	100	150	200			
	mg/m3	90a		5		45	90	90	180	180	270	180	270	360			5
ACROLEIN	ppm	0.1				0.1	0.3	0.1	0.2	0.1	0.3	0.1	0.3	0.1	0.3	0.1	
	mg/m3	0.23		0.5		0.2	0.7	0.25	0.5	0.25	0.8	0.23	0.69	0.25	0.69		0.2
BENZENE	ppm	10	25			1	5	5			5b	10		1		10	25
	mg/m3	32	80	30		3	16	16				32		3.2		5	15
1,3-BUTADIENE	ppm					10	20	5		10		10					
	mg/m3			100		20	40	11		22		22					100
CARBON DIOXIDE	ppm	5000				5000	10000	5000		5000	15000	5000	30000	5000		5000	
	mg/m3	9000				9000	18000	9000		9000	27000	9000	54000	9000			
CARBON MONOXIDE	ppm	50				35	100	30	60	50	300	50	400	50		50	
	mg/m3	57		30		40	120	33	66	55	330	57	458	55			20
FORMALDEHYDE	ppm	0.5				0.5	1	0.5	1	2	2	1	2	1		0.5	
	mg/m3	0.61		2		0.6	1.2	0.6	1.2	2.5	2.5	1.2	2.5	1.5			0.5
METHANE	ppm							10000									
	mg/m3							6700									
NITROGEN DIOXIDE	ppm					2	5	3	6	3	5	3	5	5			
	mg/m3					4	10	6	12	5	9	5.6	9.4	9			2
NITROGEN MONOXIDE	ppm					25	50	25		25	35	25		25			
	mg/m3					30	60	30		30	45	31		30			5
PROPANE	ppm							1000						1000			
	mg/m3							1800						1800			
STYRENE	ppm	50				25	75	50	100	100	250	50	100			50	
	mg/m3	210		100		110	300	215	430	420	1050	213	426			10	30
SULFUR DIOXIDE	ppm		1					1	2	1	3		1	5			1
	mg/m3		5.5	5				6	12	6	18		5.5	13			0.3
TOLUENE	ppm	50a				50	100	100	500	50b	150	100	150	200		100	
	mg/m3	188a		100		200	400	380	1900	375	560	377	565	750			50
XYLENE (all isomers)	ppm	100				50	100	100	200	100	150	100	150	100		100	
	mg/m3	430		100		200	450	435	870	435	650	434	651	435			5

source:[7] except where indicated. a - [6]; b - [5]; c - [4]

Table D2: **1997 ACGIH TLVs: Threshold Limit Values for Chemical Substances and Physical Agents**

SUBSTANCES	UNIT	ACGIH	
		TLV	STEL
ACETALDEHYDE	ppm		25c
ACROLEIN	ppm		
BENZENE	ppm	0.5	2.5
1,3-BUTADIENE	ppm	2	
CARBON DIOXIDE	ppm	5000	30000
CARBON MONOXIDE	ppm	25	
FORMALDEHYDE	ppm	0.5	
METHANE*	ppm		
NITROGEN DIOXIDE	ppm	3	5
NITROGEN MONOXIDE	ppm	50	
PROPANE*	ppm		
STYRENE	ppm	20	40
SULFUR DIOXIDE	ppm		
TOLUENE	ppm	50	
XYLENE (all isomers)	ppm	100s	150s

c - ceiling value
s - skin
* - asphyxiant: minimal oxygen content should not be less than 18% by volume at any time.

Table D3: Comparison of Canadian Provincial OEL's for Specific Substances.

SUBSTANCES	UNIT	BC[8]		ALBERTA[9]		SASK.[10]		MANITOBA[11]		ONTARIO[12]		QUEBEC	
		TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL
ACETALDEHYDE	ppm		25c	100	150				25c	100	150		
	mg/m3					45c				180	270		
ACROLEIN	ppm	0.1	0.3	0.1	0.3					0.1	0.3		
	mg/m3					0.23	0.7			0.23	0.7		
BENZENE	ppm	0.5	2.5	1	5			0.5	2.5				
	mg/m3												
1,3-BUTADIENE	ppm	2		10	25			2		10			
	mg/m3					4.4	8.8			22			
CARBON DIOXIDE	ppm	5000	15000	5000	15000			5000	30000	5000	30000		
	mg/m3					9000	54000			9000	54000		
CARBON MONOXIDE	ppm	25	100	25	200			25		35	400		
	mg/m3					29	220			40	460		
FORMALDEHYDE	ppm	0.3	1c		2c			0.5		1	2		
	mg/m3					.37c				1.5	3		
METHANE*	ppm												
	mg/m3												
NITROGEN DIOXIDE	ppm		1c	3	5			3	5	3	5		
	mg/m3					5.6	9.4			5.6	9.4		
NITROGEN MONOXIDE	ppm	25	35	25	35			50		25			
	mg/m3					31	47			31			
PROPANE*	ppm												
	mg/m3												
STYRENE	ppm	50	75	50	100			20	40	50	200		
	mg/m3					213	426			213	852		
SULFUR DIOXIDE	ppm	2	5	2	5					2	5		
	mg/m3					5.2	13			5.2	10.4		
TOLUENE	ppm	50	100	100	150			50		100	150		
	mg/m3					188	235			376	564		
XYLENE (all isomers)	ppm	100s	150s	100s	150s			100s	150s	100s	150s		
	mg/m3					434s	651s			435s	650s		

SUBSTANCES	UNIT	NB [11]		NS [11]		PEI [11]		NFLD [11]		NWT [13]		YUKON [14]		FEDERAL [11]	
		TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL	TWA	STEL
ACETALDEHYDE	ppm mg/m3		25c		25c		25c		25c	100 180	150 270	100	150		25c
ACROLEIN	ppm mg/m3									0.1 0.23	0.3 0.69	0.1	0.3		
BENZENE	ppm mg/m3	0.5	2.5	0.5	2.5	0.5	2.5	0.5	2.5	10s 32s	25s 80s	10s	32s	0.5	2.5
1,3-BUTADIENE	ppm mg/m3	2		2		2		2		1000 2212	1250 2765	1000	1250	2	
CARBON DIOXIDE	ppm mg/m3	5000	30000	5000	30000	5000	30000	5000	30000	5000 9000	15000 27000	5000	15000	5000	30000
CARBON MONOXIDE	ppm mg/m3	25		25		25		25		50 57	400 460	50	400	25	
FORMALDEHYDE	ppm mg/m3	0.5		0.5		0.5		0.5		2c 2.4c		2		0.5	
METHANE*	ppm mg/m3														
NITROGEN DIOXIDE	ppm mg/m3	3	5	3	5	3	5	3	5	3 6	5 9.4	5		3	5
NITROGEN MONOXIDE	ppm mg/m3	50		50		50		50		25 31	35 43	25	35	50	
PROPANE*	ppm mg/m3														
STYRENE	ppm mg/m3	20	40	20	40	20	40	20	40	50 213	100 426	100	125	20	40
SULFUR DIOXIDE	ppm mg/m3									2 5	5 13	5	5		
TOLUENE	ppm mg/m3	50		50		50		50		100s 375s	150s 560s	100s	150s	50	
XYLENE (all isomers)	ppm mg/m3	100s	150s	100s	150s	100s	150s	100s	150s	100s 434s	150s 652s	100s	150s	100s	150s

c - ceiling value; s - skin; * - asphyxiant: oxygen content should not be less than 18% by volume at any time.

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APPENDIX E

Development of the Multi-Mode Test Program

APPENDIX E

DEVELOPMENT OF THE MULTI-MODE TEST PROGRAM

Fuel economy and emissions testing only makes sense if it is carried out under realistic conditions. Ideally, the testing is carried out on a standard test schedule that has been designed for the class of vehicle concerned, published by a reputable body, and accepted by everyone involved in testing or using such vehicles. However, there does not appear to be such a standard test program for forklift trucks. A repeatable, meaningful test program needed to be developed for this emissions study. This Appendix describes the steps involved in the development of the multi-mode test cycle.

The fuel economy and emissions test program used for these forklifts was a multi-mode, steady-state test schedule which could be run while the vehicles were sitting stationary and connected to air, fuel and emissions measurement equipment. Each forklift was tested in eight different operating modes defined by specifying the engine speed and manifold vacuum. With the forklift drive wheels chocked, various combinations of hydraulic and drive system loads were used to hold the engine at the desired speed/vacuum point for each test mode.

From a fuel economy and emissions standpoint, the most important operating parameters are engine speed and engine load. The speed is measured by the engine controller's engine speed sensor and the load is related to the manifold absolute pressure, (MAP). MAP is low (about 30-40 kPa) when the engine is idling with the throttle closed. It is high (close to atmospheric pressure) when the engine is running at maximum torque. Figure E1 shows the operating range of a typical engine on a speed/MAP diagram. This diagram shows the full range that the engine can cover. However, it does not indicate whether the engine in a given vehicle actually uses the full range or how much of the time it spends at various points in the range. Ideally the test program should test engine emissions and fuel consumption at a number of points in the operating range that are chosen to represent normal operation. That way the test results can be used to represent actual in-use fuel consumption and emissions performance.

For this study, the test modes were selected based on analyzing engine data records from in-service operation. To do this, several forklifts were equipped with engine control computers which were monitoring engine operation but not actually controlling the engine. These controllers continuously monitored 107 items of measured or calculated data which included engine speed, manifold vacuum, coolant temperature, operating time and other parameters. This stream of engine controller data in ASCII serial format was transmitted by radio and recorded on a computer base station as the forklifts worked through their normal shifts. Subsequent analysis of the forklift operating modes showed a relatively consistent operating pattern of engine speed and manifold pressure for different units and different plant duties.

The engine controller logs provided 107 columns of data, recording engine operating state several times per second. These data files were stored as ********.LOG** files, usually with a file name comprised of a forklift unit number followed by the date and the file extension **.log**. Given the vast number of channels, recorded at several times per second, these **.log** files were huge. They were also in hexadecimal, un-calibrated format and contained periodic interruptions and zero's when the engine controller was interrupted in the process of spewing out the data stream. As a result, they needed some processing just to make them usable.

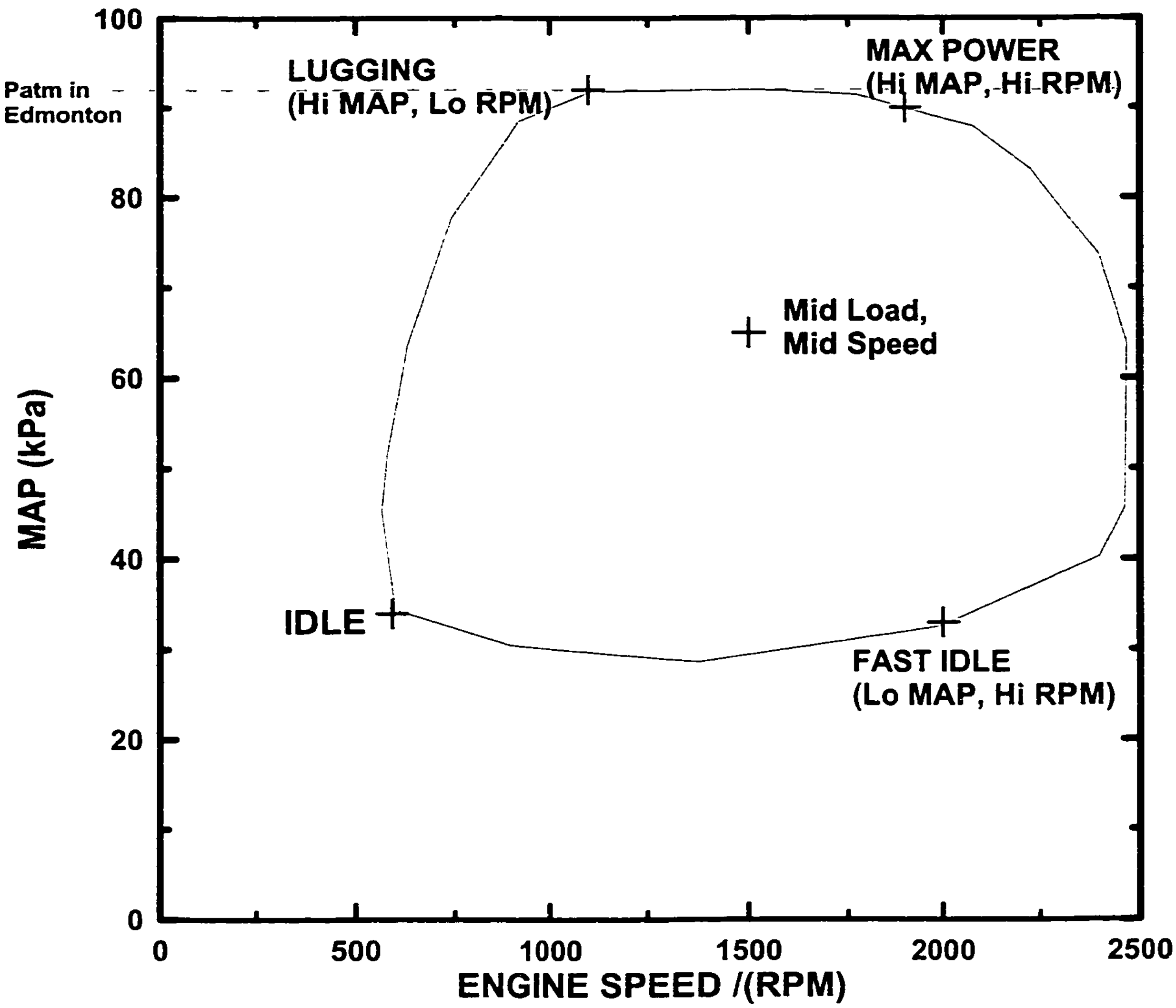


Figure E1: Typical Operating Range Diagram for Spark Ignition Engine

A short Quickbasic program called **ECxBRF.BAS** was written to process engine controller **.log** files and write out a brief version in calibrated engineering units with false values removed. These brief files were given file names like ********.BRF** and contained only 7 data columns:

MAP	**Manifold pressure in kPa**
RPM	**Engine speed in RPM**
O2_Sensor_Volts(A)	**Oxygen Sensor Voltage (instantaneous)**
O2_Sensor_Volts(B)	**Oxygen Sensor Voltage (running average)**
ECT	**Engine Coolant Temperature**
ERT	**Engine Running Time**
FUEL RATE	**Calculated Fuel Flow Rate (for fuel injection)**

Further processing used these **.brf** files to represent the in-use forklift engine operating data.

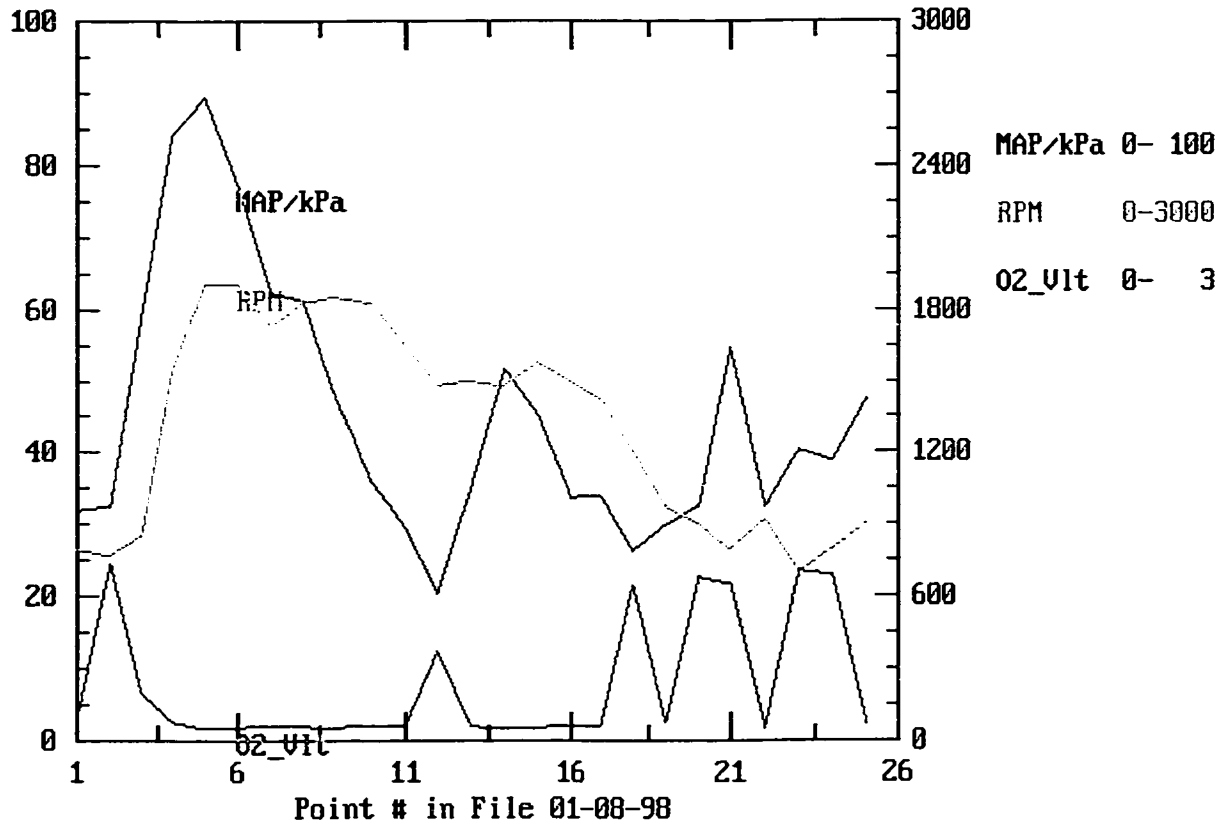


Figure E2: A 25 Second Sample of Forklift Engine Data
Three channels are shown: MAP, RPM and O2 Sensor Voltage

The first step was to examine the data files for general patterns. Figure E2 shows a short slice out of a forklift engine's working day. This diagram was produced by another Quickbasic program called **BRFPLOT.BAS** used to examine data in **.brf** files. The figure shows manifold pressure (MAP), engine speed (RPM), and instantaneous oxygen sensor voltage (O2_Vlt) for a 25 second period. During this period, the MAP abruptly increases from about 32 kPa (idle) to 90 kPa (wide open throttle), then goes through a series of transients as the forklift performs its tasks. Engine speed rises from about 800 rpm to 1800 rpm, then gradually decreases. Oxygen sensor voltage spikes rich (high) or lean (low) depending on the engine fuel control. This is a fairly typical period of forklift operation. Except when idling, the forklifts go through a steady series of accelerations, decelerations, load increases and load decreases. With this forklift operating on propane, the oxygen sensor shows the mixture varying between rich mixtures (high voltage) and lean mixtures (low voltage). Note that this is a propane-powered forklift which is nominally tuned to always provide lean operation. However, it runs rich during several transients in this 25 second period.

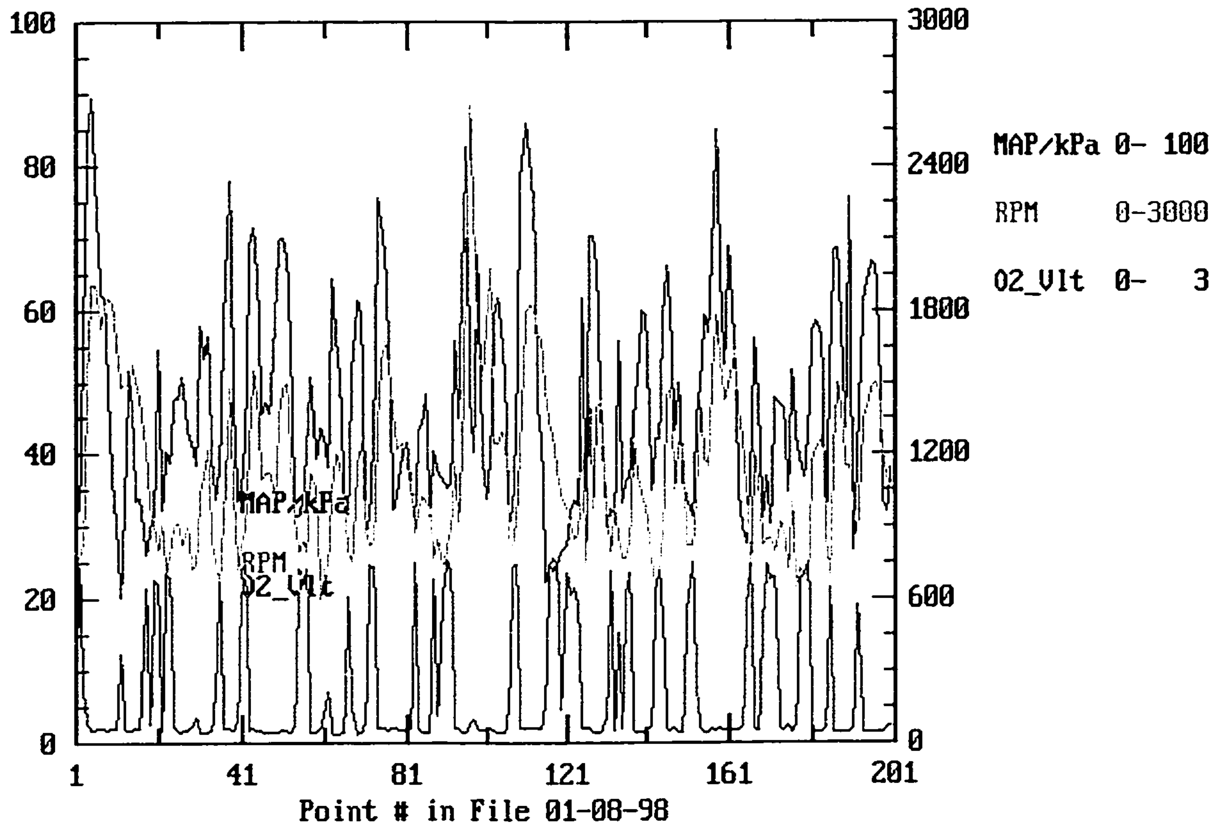


Figure E3: A 200 Second Record of Forklift Operation

Figure E3 shows the same three sensor outputs over a slightly longer period of engine operation. The pattern of engine MAP and speed variations is quite consistent while the forklift works. The oxygen sensor continues to show a series of rich transients with periods of lean operation between them.

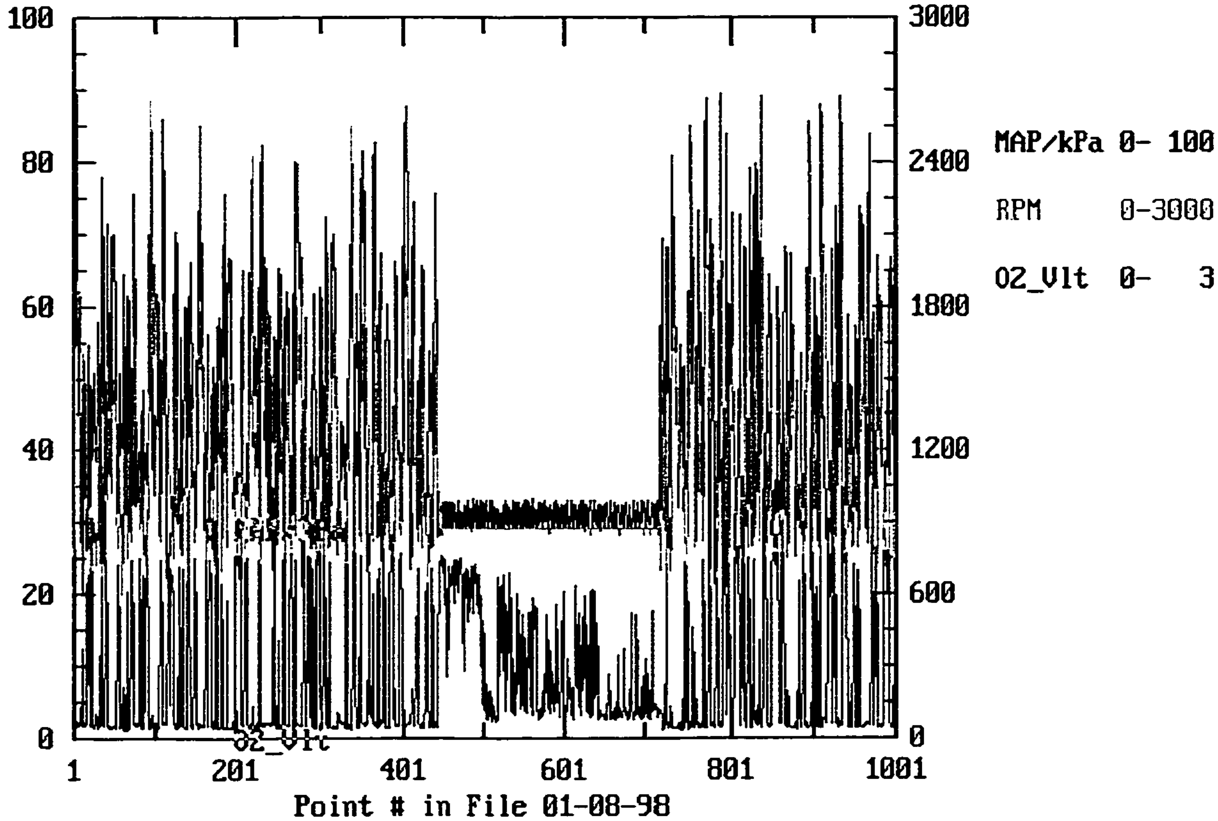


Figure E4: **A 1000 Second Record of Forklift Operation**

Figure E4 shows the same three sensor outputs over a period of 1000 seconds (about 17 minutes). The point is that the patterns continue to repeat themselves except for a prolonged period of idle in the middle. Both engine speed and MAP settled down to approximately steady values. During this idle period, the oxygen sensor indicates that the mixture was first richer than stoichiometric, then oscillated around stoichiometric, and then eventually drifted lean of stoichiometric.

Examining this sort of time series gives some feel for the transient nature of forklift engine operation. Another view of the same set of processes is obtained by cross-plotting the engine speed and manifold pressure.

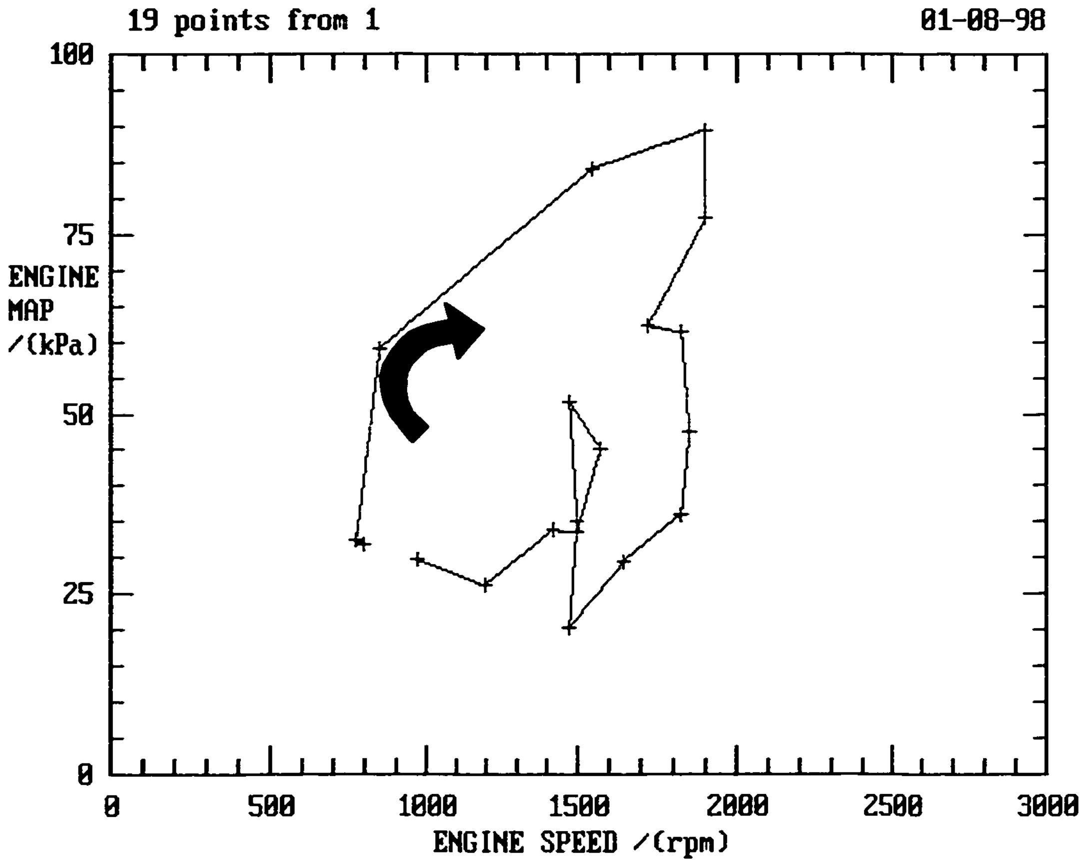


Figure E5: One Engine Acceleration /Work /Deceleration Cycle on a Speed/MAP Diagram

Figure E5 shows the sequence of events as the forklift is actually working. The engine starts at idle (about 34 kPa MAP and 750 rpm). The operator opens the throttle, causing MAP to rise sharply. This gives more torque and the engine reaches peak torque a couple of seconds later as the MAP is around 90 kPa (1 atmosphere in Edmonton). At the same time, the engine RPM has risen from idle to about 1800 rpm. Once the engine is running the desired speed, the operator gradually closes the throttle while keeping speed constant for this lift or driving operation. Thus, MAP drops back to about 35 kPa with the engine running at 1800 rpm. Then, when the driver wants a lower speed, the throttle is closed resulting in a sharp drop in MAP and deceleration of the engine to about 1500 rpm. In this case, the throttle is opened for a few seconds to control speed at 1500 rpm, then closed and the engine decelerates back to idle speed and idle MAP.

Thus, a typical sequence of operations consists of some sort of clockwise loop on the Speed / MAP diagram. If the engine is working hard and continuously, (as when a forklift raises a very heavy load or is used to push a set of heavy pallets), the operation would stabilize at some point in the upper right part of the Speed / MAP diagram. The most common operating

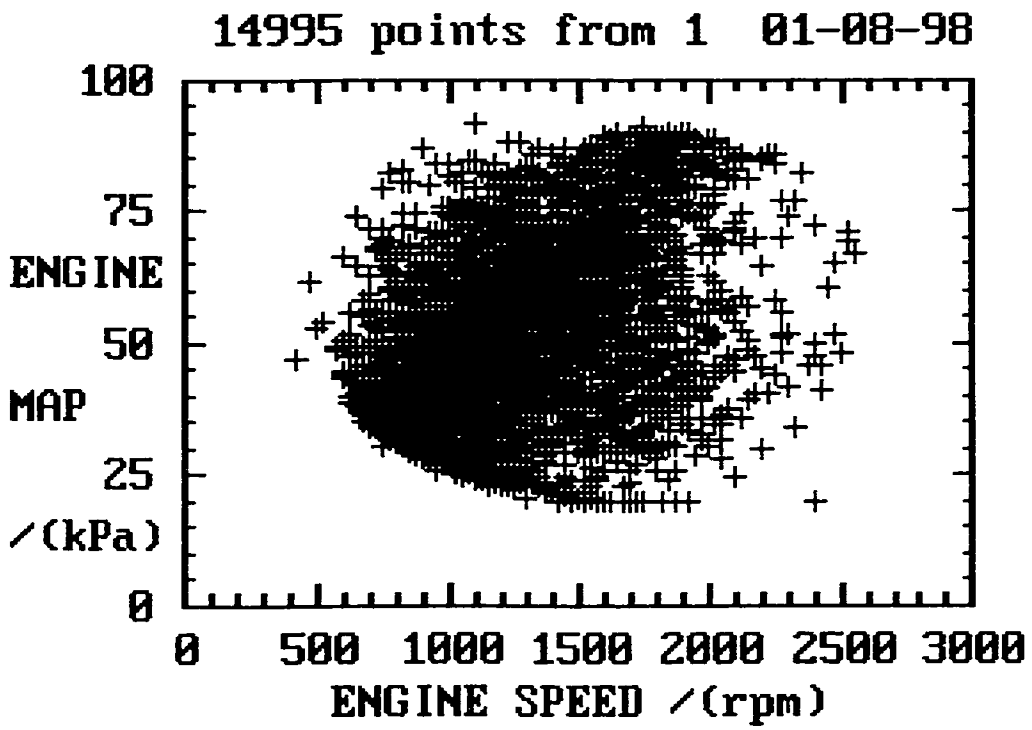


Figure E6: A set of 15,000 Operating Points on a Speed /MAP Diagram

point in terms of time would be Idle in the lower left part of the diagram.

Figure E6 shows the distribution of 15000 data points (about 4 hours) for a working forklift. At this point, the main working area becomes fairly obvious. The mid-speed, variable-load area reaching up and to the right of idle is absolutely black with data points. At the same time, extreme lugging (high MAP, low RPM) has very few points and very high speed (over 2000 rpm) has very few points.

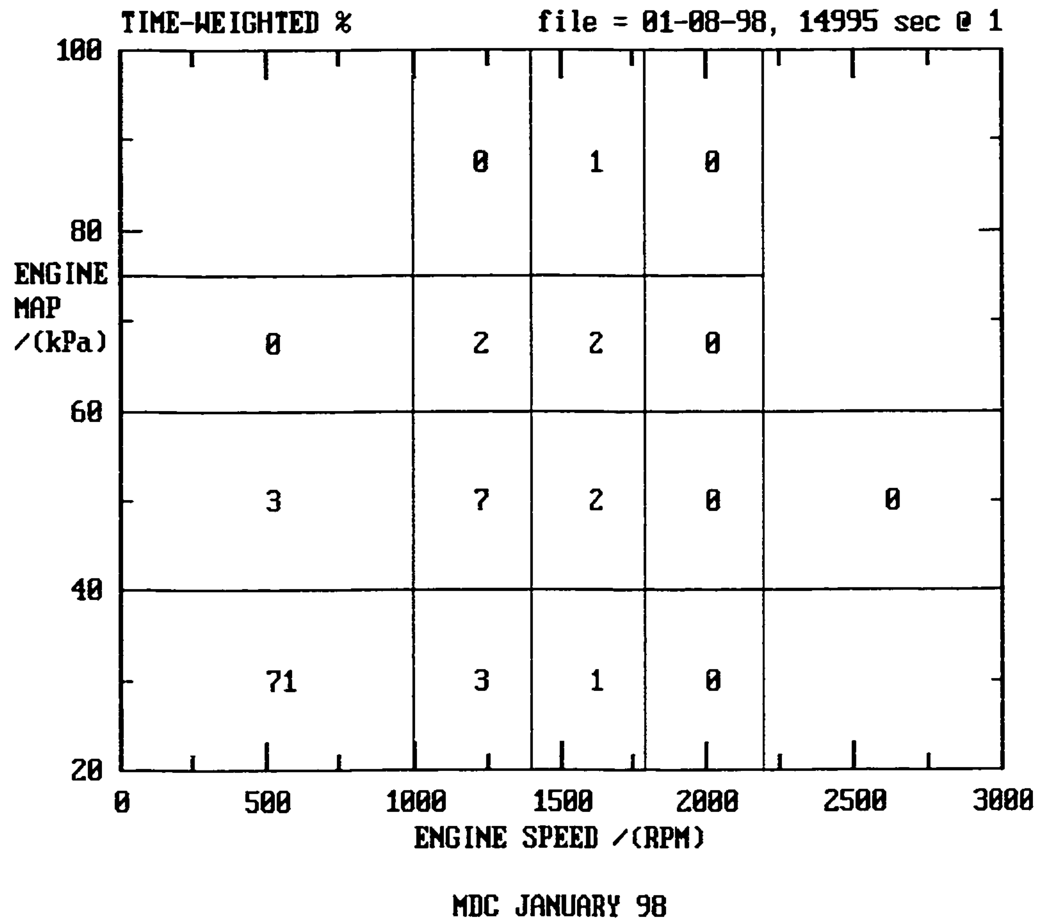


Figure E7: Speed /Map Histogram Based on 15000 Seconds of Forklift Operation.
(0's on the diagram represent zones used <½% of the time. Blank zones were used 0% of the time)

Figure E7 shows the results of taking a histogram of the same speed / MAP data set. This shows that the forklift was actually in the idle mode (<40 kPa MAP, <1000 rpm) for 71% of the time in that particular 4 hour period! This emphasizes that simple scatter plots like Figure E6 can be misleading since they show the range of operation but don't emphasize the amount of repeated time spent at each point in the range.

Considering that fuel consumption and emission rates are proportional to engine power:

Power = Speed * Torque

Torque is not measured directly but it is proportional to

Torque ∝ (MAP - MAP at idle).

Points to the upper right on the Speed / MAP diagram should be weighted more heavily than points to the lower left since they represent higher power and thus higher fuel consumption and pollutant emission rates. To do this systematically, test modes are selected based on an energy-weighted histogram in addition to the simple time-weighted histogram of Figure E7. Each point on the Speed /MAP curve is given an energy score calculated as:

Energy = Speed * (MAP - MAP.at.idle)

(While idle MAP varies depending on idle speed and engine condition, it was arbitrarily set at 38 kPa for analyzing these forklift data files.) The Energy totals in each histogram block are then summed giving another histogram like Figure E8.

This figure shows that the majority of the energy consumed by the forklift is in the few

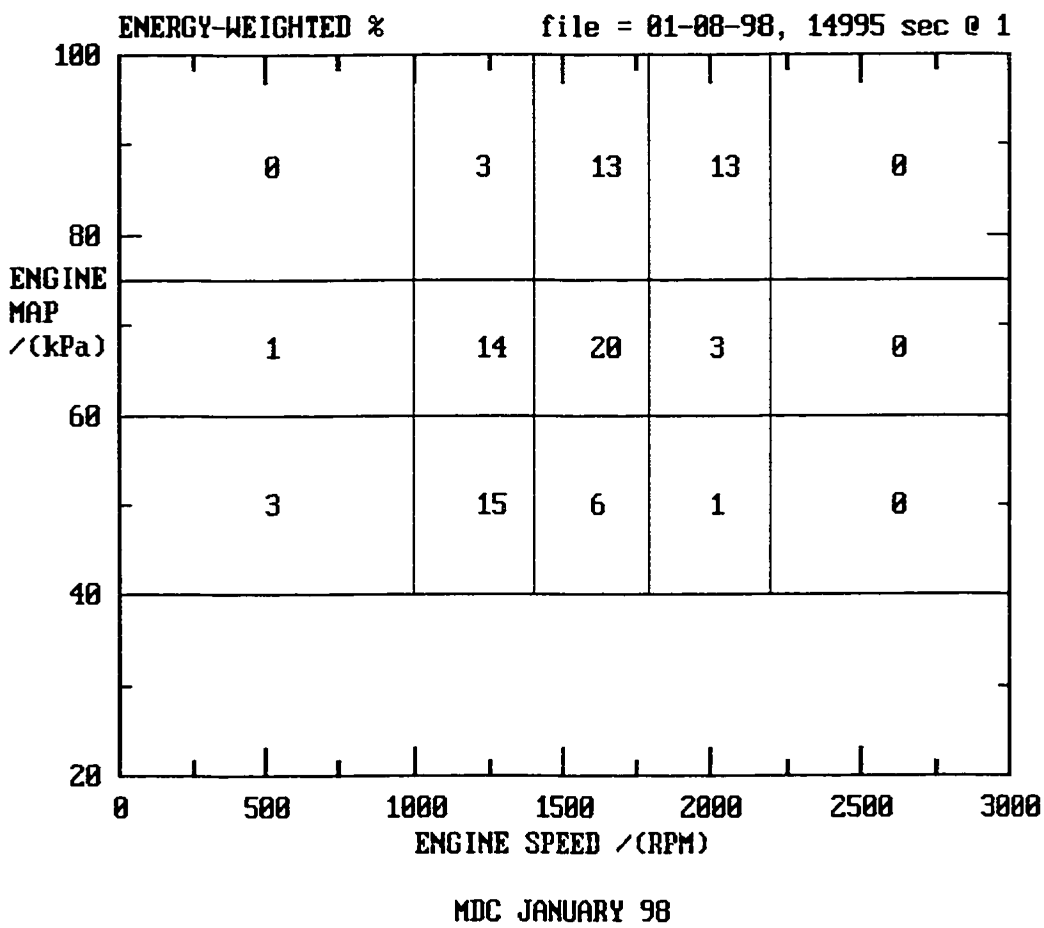


Figure E8: Energy-Weighted Histogram Based on About 4 hours of Forklift Operation

operating modes located up and to the right of idle, ie 1200 rpm and 50-70 kPa MAP, 1500 rpm and 70-90 kPa MAP, plus 2000 RPM and 90 kPa MAP. The forklift engine is running in these histogram blocks for enough time to produce (15% +14% +20% +13% +13% =) 75% of the net output energy. If emissions and fuel consumption rates were fixed, this means that 75% of fuel consumption and emissions would occur in these operating blocks. Thus, any set of test modes should represent these operating blocks. It should also include the idle point since the fuel consumption and emission rates are not actually zero at idle and a lot of time is spent in the idle mode. (Even when the forklift is working steadily, the engine tends to pass through the idle mode (low RPM, low MAP) every few seconds in the sort of on/off duty cycle of a forklift engine.)

This sort of analysis was used with the recorded results of several propane forklifts and one NGV forklift, (the first one converted) to select a common set of test modes for all forklift testing. The result is the set of modes shown in Table E1 and Figure E9.

For each test mode, a weighting factor was assigned based on the number of seconds a forklift engine would operate in that mode over a typical hour. Test results in each mode were converted to grams/second (of fuel use or pollutant production). Then, a composite result for each test was calculated based on a weighted sum of the results in all test modes. This summation method inherently handles the differing power levels and consumption rates for different modes.

It is common practice for technicians who are converting or tuning engines to run their own sort of "multi-mode test" while they make adjustments. This typically consists of making an idle adjustment with the engine in "idle mode" and then setting the "power circuit" with the engine running at a high speed idle condition, say 2000 or 2500 rpm. While this generally produces the desired results, it does not exercise the engine and fuel system over a significant part of the engine operating range. Figures E10 and E11 compare the Speed /MAP diagrams from a pair of tests. The data points in Figure E10 were recorded by the engine controller during an actual multi-mode test as used in this study. Note the high concentration of points in the high-MAP, mid-RPM region which dominates actual forklift operation. The data points in Figure E11 were recorded by the engine controller during an extended technician tune-up. Note the idle point and the scatter of points along the fast idle point (which is not a significant mode during normal operation). The additional cluster of points in Figure E11 shows where the technician actually loaded the engine by locking hydraulics to get a higher load.

During testing, the forklift was run in each test mode for a period of about 2 to 3 minutes while the operator controlled the forklift to match the specified engine speed and MAP values <u>as measured by the engine controller</u> and displayed on a laptop computer. The running time in each mode provided a few seconds for the operator to find a combination throttle and hydraulic controls that loaded the engine to the right conditions, then time for both upstream and downstream emissions tests with a sufficient break to ensure that the exhaust samples were properly analyzed. Fuel consumption and emission rates were based on a 30 second average of the continuously recorded fuel and emission instruments.

Table E1: RPM, MAP and Weighting for all modes of the 8-Mode Test.

MODE	A	B	C	E	F	G	H	J
RPM	IDLE	1200	1200	1500	1500	1600	1500	1900
MAP (kPa)	IDLE	50	70	50	65	80	IDLE	70-80
WEIGHT (sec)	1224	576	360	216	432	216	432	144

(Note that the test modes are number A through J with no mode D and I. We originally picked 10 test modes and, after a few tests, showed that the results were not significantly different if the D and I modes were ignored and their weight was combined with the C and J modes.)

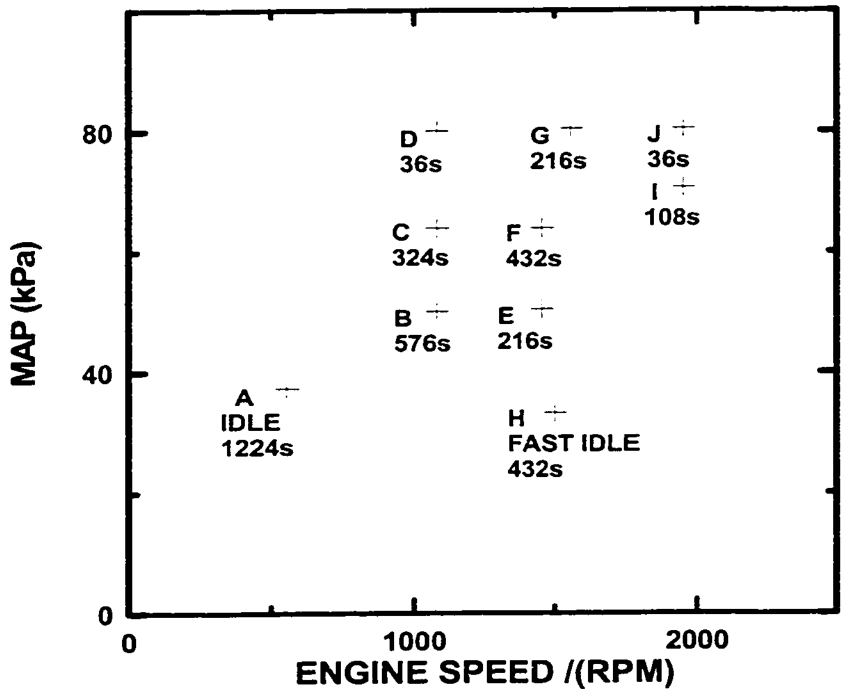


Figure E9: Selected Test Modes and Weight Factors Shown on Speed / MAP Curve
(Modes D and I were combined with Modes C and J after Initial Testing)

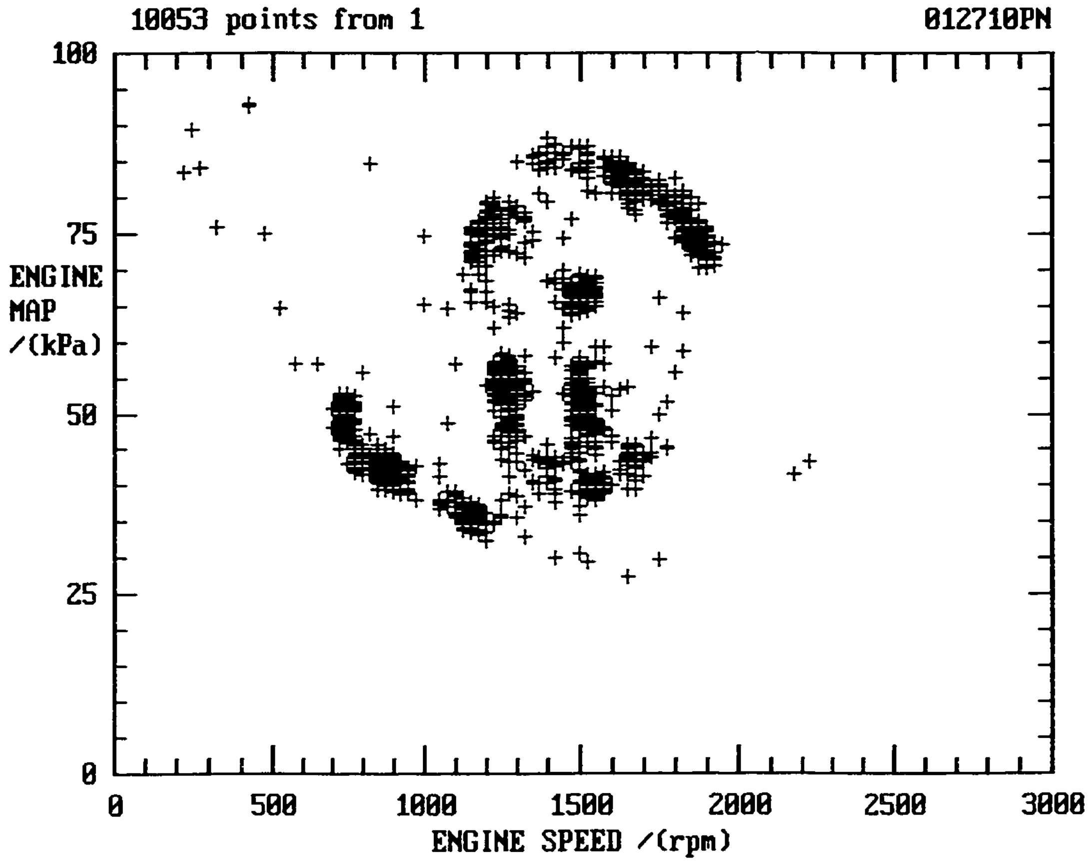


Figure E10: Speed /MAP Diagram Recorded During a Multi-Mode Test in this Study.

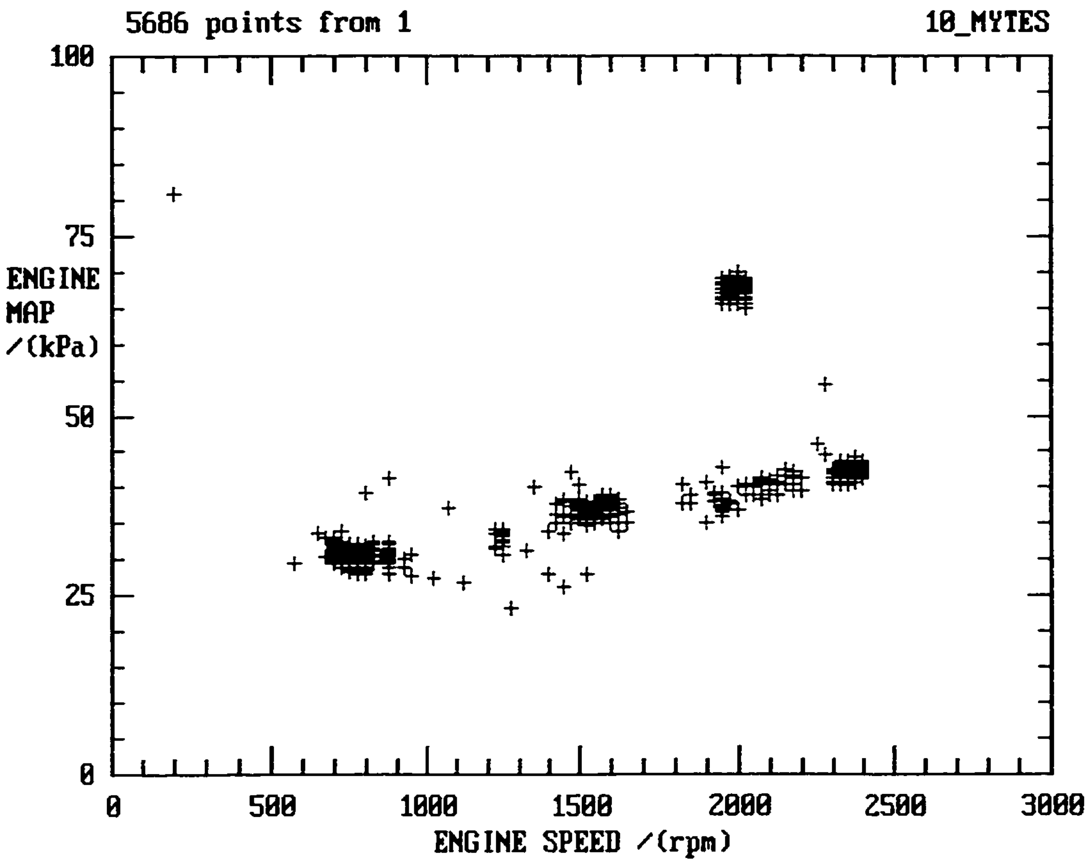


Figure E11: Speed /MAP Points Recorded During a Typical Tuning Session.
Note the majority of the points are along the idle power curve, (low MAP). The one set of higher data points, (2000 rpm, 70 kPa MAP), was obtained by loading the forklift hydraulic system.

APPENDIX F

Test Data Validation

APPENDIX F

TEST DATA VALIDATION

Given the complexity of the tests and the wide range of values being controlled and measured, there was always a danger that calculated results would be biased by a few erroneous readings. A series of preliminary analysis checks was used to detect and correct such readings. The validation program **SHOOTER.BAS** was used to read in each series of test mode files and calculate a number of diagnostic ratios for each mode and for the complete test series:

$$\text{AIR} = \frac{\text{kg/hr Air}}{\text{RPM x MAP}} \tag{F-1}$$

$$\text{FUEL} = \frac{\text{kg/hr Fuel}}{\text{RPM x MAP}} \tag{F-2}$$

$$CO_2\text{-1} = \frac{\text{g/hr } CO_2 + CO(44/28)}{\text{RPM x MAP}} \tag{F-3}$$

$$CO_2\text{-2} = \frac{\text{kg/hr } CO_2}{\text{kg/hr Fuel}} \tag{F-4}$$

$$\text{CARBON} = \frac{\text{g/hr } CO_2/44 + CO/28 + NMHC/16 + CH_4/16}{\begin{array}{c}\text{Fuel x 3 / 44} \quad (\text{LPG-}C_3H_8) \\ \text{or} \\ \text{Fuel /16} \quad (\text{NGV-}CH_4)\end{array}} \tag{F-5}$$

These ratios essentially test a number of measurements simultaneously to show whether they are consistent with one another. For example, the ratio labeled AIR in the above figure is a measure of engine volumetric efficiency, and the ratio labeled CARBON is a fuel/exhaust carbon balance. These ratios were carefully examined to find any significant anomalies in fuel flow, air flow or emission measurements. The most common errors were in engine speed measurement, (a non-critical measurement where the analog voltage converter was affected by different engine ignition systems), and in fuel flow measurement, (sometimes affected when the forklift crept far enough ahead that the fuel line pulled on the scale holding the propane or NGV tank).

Each of the test modes' data is saved as a separate file. A sample data file for a particular mode is shown in Figure F1. This file contains all of the emissions, MAP, RPM, fuel and air flow measurements etc. for a particular mode. The 8 files representing the 8 modes of the test are all converted from a ppm measurement to a more meaningful g/hr value. This results in a final output file as shown in Figure F2. These are the values which are read in by the validation program. The program as mentioned reads in these files to calculate five different diagnostic ratios, equations (F-1) through (F-5). These ratios get written into an Excel spreadsheet for comparison and plotting. Figure F3 shows a sample of a set of diagnostic values for Unit 2D. For anomalous results to be more easily seen the values are plotted. Figure F4 shows a collection of plots.

```
07-10-1998
14:08:07
C:\QB\FORK\FORKDAT\JUL101403.DAT
C:\QB\FORK\FORKDAT\JUL101403.DIR
703,       "Patm, mm Hg"
30,        "Avg Time"
385.8164,  "Exh Temp, øC"
17.29387,  "Wet Bulb, øC"
22.16555,  "Dry Bulb, øC"
.7069206,  "O2, %"
11.14491,  "CO2, %"
243.7067,  "CO, ppm"
1861.867,  "THC, ppm"
1928.382,  "CH4, ppm"
33.66502,  "NOx, ppm"
740.9744,  "Engine Spd, RPM"
4.554419,  "Air Turbine, L/s"
2075.54,   "Scale NGV, g"
41.70065,  "MAP, kPa"
5.036507,  "Air Rate, g/s"
.3175603,  "Fuel Rate NGV, g/s"
```

Figure F1: Sample of Raw Data File for a Single Mode

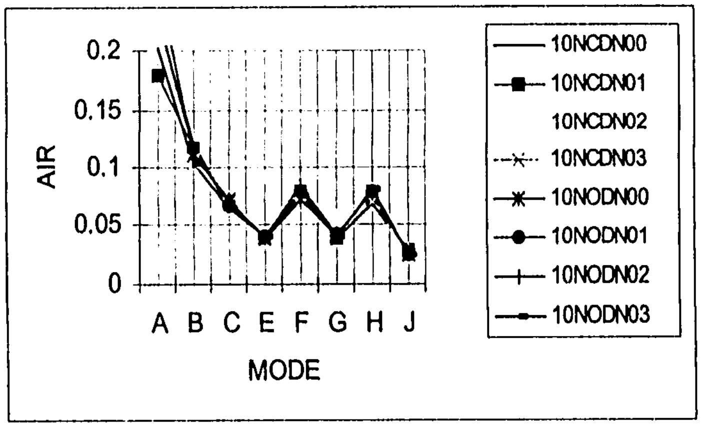
```
File = 06NCDN00.OUT, 07-17-1998 16:52:10
*******************************************************************************************
*******************************************************************************************
**** FORKAN3 ********************** MODE SUMMARY ***************** Checkel 980708 ****
*******************************************************************************************
*******************************************************************************************
       Unit 6, File JL101403, Downstream of Cat, 8 modes, fuel = NGV
                                                                                COMPOSITE
       MODE           A       B       C       E       F       G       H       J       /TOTAL
       RPM            741     1194    1260    1581    1533    1658    1585    2059
       MAP kPa        41.7    53.0    74.1    53.8    64.7    79.1    39.2    77.3
       WGHT sec       1224    576     360     216     432     216     432     144     3600s

       AIR & FUEL             grams/sec                                               kg/h
       AIR            5.0     12.2    17.3    13.8    17.0    23.7    9.1     26.8    42.7
       NGV            0.32    0.66    0.98    0.85    1.02    1.41    0.51    1.57    2.50
       AFR mass       15.9    18.4    17.5    16.2    16.7    16.8    17.9    17.1    17.1
       AFR emis       17.4    17.0    16.9    17.0    17.0    17.1    17.1    16.9
       H/C ratio      3.9     3.9     3.8     3.9     3.9     4.0     4.0     3.9

       MAJOR PRODUCTS         grams/sec                                               kg/h
       N2             3.88    9.35    13.21   10.61   13.07   18.20   6.99    20.52   32.7
       CO2            0.80    1.98    2.81    2.25    2.76    3.82    1.45    4.37    6.9
       H2O            0.63    1.55    2.21    1.78    2.21    3.09    1.20    3.44    5.5

       MINOR PRODUCTS         mgrams/sec                                              g/h
       NO             0.2     6.6     2.5     5.8     2.1     2.8     1.1     1.0     8.3
       NOx            0.3     10.2    3.8     8.9     3.2     4.3     1.6     1.5     12.7
       CO             1.1     2.6     4.1     3.2     3.7     4.2     2.0     3.1     8.8
       NMHC           0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.0
       CH4            5.03    11.53   2.26    4.83    1.46    2.40    2.15    6.82    17.7
```

Figure F2: Sample of Processed Emissions Data File

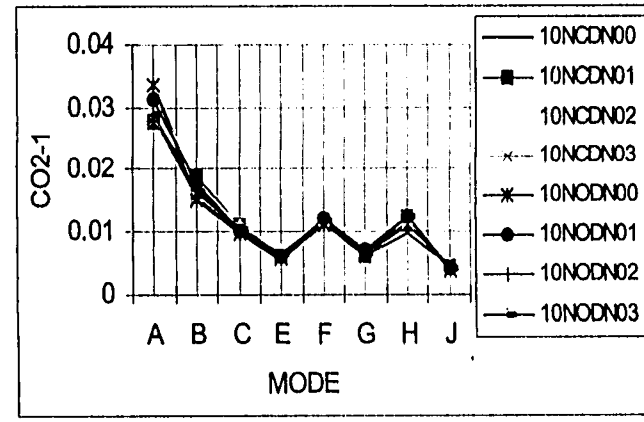
AIR	0.155	0.0845	0.0545	0.0351	0.0663	0.0342	0.0604	0.0234	2D	D	N	C	N
AIR	0.189	0.0803	0.0522	0.0367	0.0604	0.0335	0.0584	0.0222	2D	D	N	C	N
AIR	0.137	0.0851	0.0572	0.0331	0.0663	0.0358	0.0632	0.0248	2D	D	N	O	N
AIR	0.173	0.0867	0.0518	0.0314	0.0577	0.0349	0.0587	0.023	2D	D	N	X	N
CARBON	1.02	1	1	0.996	1.02	0.959	0.966	1.05	2D	D	N	C	N
CARBON	1.01	1.01	0.992	0.996	1.01	0.954	1	1.02	2D	D	N	C	N
CARBON	1.01	1.03	0.997	0.996	1.01	1.03	1	1.01	2D	D	N	O	N
CARBON	1.02	1.01	0.966	0.996	0.971	1.05	0.967	1.04	2D	D	N	X	N
CO2-1	0.0242	0.0136	0.0086	0.0055	0.0105	0.0055	0.0095	0.0037	2D	D	N	C	N
CO2-1	0.0303	0.0131	0.0085	0.0058	0.0096	0.0055	0.0096	0.0036	2D	D	N	C	N
CO2-1	0.0215	0.0139	0.009	0.0054	0.0107	0.0058	0.0102	0.004	2D	D	N	O	N
CO2-1	0.0259	0.0122	0.0078	0.005	0.0085	0.0054	0.0094	0.0036	2D	D	N	X	N
CO2-2	2.8	2.75	2.75	2.73	2.79	2.63	2.65	2.87	2D	D	N	C	N
CO2-2	2.75	2.76	2.71	2.73	2.76	2.61	2.75	2.77	2D	D	N	C	N
CO2-2	2.76	2.81	2.73	2.73	2.78	2.81	2.75	2.76	2D	D	N	O	N
CO2-2	2.77	2.77	2.64	2.73	2.66	2.88	2.66	2.85	2D	D	N	X	N
FUEL	0.0086	0.0049	0.0031	0.002	0.0038	0.0021	0.0036	0.0013	2D	D	N	C	N
FUEL	0.011	0.0047	0.0031	0.0021	0.0035	0.0021	0.0035	0.0013	2D	D	N	C	N
FUEL	0.0078	0.0049	0.0033	0.002	0.0039	0.0021	0.0037	0.0014	2D	D	N	O	N
FUEL	0.0093	0.0044	0.003	0.0018	0.0032	0.0019	0.0036	0.0012	2D	D	N	X	N
	A	B	C	E	F	G	H	J	UNIT	U/D	FUEL	TUNE	CAT

NUMBER OF FILES: 4

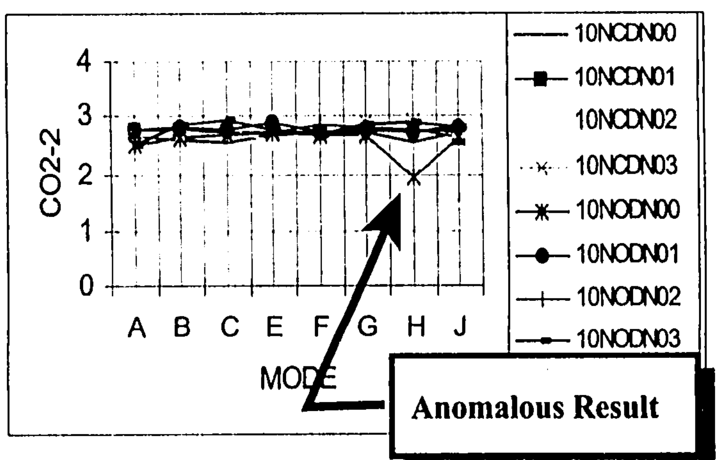
Figure F3: Sample of Excel Spreadsheet Containing Diagnostic Ratios for a Series of Tests



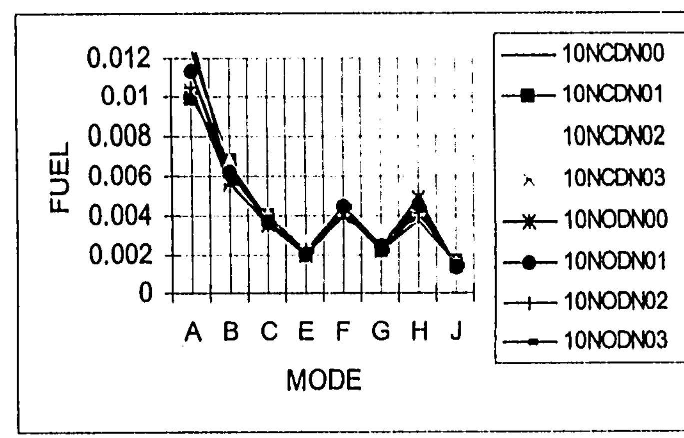
(a)



(b)

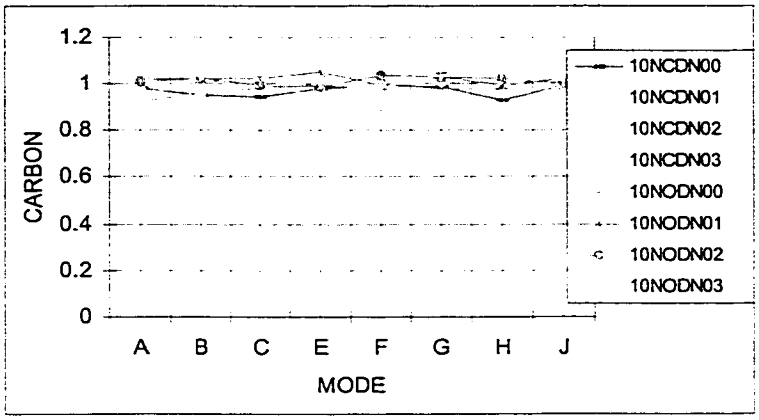


(c)



(d)

Figure F4: Generated Plots of Diagnostic Ratios ((a) through (d), (e) contd. next page)



(e)

After generating these plots, corrections were made to adjust any clearly inaccurate measurements ,as seen in Figure F4 (c). This was sometimes accomplished by re-sampling test modes using the **FORKSHOW.BAS** program and in some cases redundant sources of information were used to replace bad values. For example, if the fuel flow reading was clearly wrong, the Air/Fuel ratio calculated from exhaust gas analysis was divided into the air flow rate to provide a best-available estimate of fuel flow.

APPENDIX G

Composite g/hr Emissions Results - Upstream and Downstream

APPENDIX G

COMPOSITE G/HR EMISSIONS RESULTS - UPSTREAM AND DOWNSTREAM

This appendix presents all of the results from the emissions testing on the Forklift units. Emission results are from tests conducted over the 8-mode test cycle developed specifically for this study as described in Appendix F. Test results are shown for all of the 7 units under their various configurations. The forklift configurations vary through their states of tune, fuel source (LPG or CNG), and the catalytic converter (original 2-way or new 3-way). Values for the pollutants are given in grams per hour (gph) with the exception of CO_2 which are in kilograms per hour (kgph). Table G1 contains the tailpipe emissions i.e. after the catalytic converter. Table G2 contains engine out emissions data i.e. before the catalytic converter.

Table G1: Composite Tailpipe Emissions Results

UNIT	FUEL	TUNE	CATALYST	CO2 kgph	CO gph	NMHC gph	CH4 gph	NOx gph
6	LPG	ASIS	OLD	7.1	127.7	23.7	0	157.4
6	LPG	ASIS	OLD	6.5	1679.3	17.3	44.4	35.2
6	LPG	BEST	OLD	7.5	391.6	1.1	45.7	101.2
6	LPG	OEM	NEW	5.4	6.2	4.3	3.2	45.9
6	LPG	OEM	OLD	6.3	8.3	25.6	0	85.7
6	NGV	CLSD	NEW	6.9	8.8	0	17.7	12.7
6	NGV	xECT	NEW	7.1	9.3	0	19.4	10.5
6	NGV	xO2	NEW	5.9	5.3	0	31.4	8.9
9	LPG	BEST	OLD	6.7	150.6	24.6	0	127.4
9	LPG	OEM	NEW	6.6	101.1	10.6	0	45.7
9	NGV	CLSD	NEW	7.2	10.2	1	6.1	7.9
9	NGV	CLSD	NEW	7.1	16	1.1	6.2	2.4
9	NGV	CLSD	NEW	7	17.5	0.3	10	5
9	NGV	xECT	NEW	6.3	108.8	1.7	13.2	17.4
9	NGV	xECT	NEW	5.8	9.5	0.3	4.1	3.7
9	NGV	xECT	NEW	6.5	4.3	0	13.2	25.5
10	LPG	BEST	NEW	8.4	86.2	20.3	0	2.6
10	LPG	BEST	OLD	7.5	197.5	24.3	0	74.8
10	LPG	OEM	NEW	7.6	25.3	6.6	0	64.8
10	LPG	OEM	OLD	7.3	40.9	11.8	0	73.1
10	NGV	CLSD	NEW	6.9	11.6	0.8	9.2	34.1
10	NGV	CLSD	NEW	7.4	9.3	1.2	7	0.5
10	NGV	CLSD	NEW	6.8	6.1	5.6	18.1	34.1
10	NGV	CLSD	NEW	6.6	8.2	1.9	10.7	5.2
10	NGV	xECT	NEW	7	117.4	2.5	32.6	38.1
10	NGV	xECT	NEW	7.3	12.9	1.1	14.8	34.2
10	NGV	xECT	NEW	6.8	5.9	2.7	13.7	15.3
10	NGV	xECT	NEW	6.1	3.4	0.7	17.8	55.4

UNIT	FUEL	TUNE	CATALYST	CO2 kgph	CO gph	NMHC gph	CH4 gph	NOx gph
13	LPG	ASIS	NEW	6.3	69.8	4.8	0	160.6
13	LPG	BEST	NEW	6.3	1.8	3.6	0	164.2
13	LPG	OEM	NEW	6.3	4.5	5.2	0	174.7
13	NGV	CLSD	NEW	6.1	5.5	0.5	4.1	8.9
13	NGV	CLSD	NEW	6.2	7.8	0.5	4.3	1.1
13	NGV	CLSD	NEW	6.2	17.2	0	5.6	7.8
13	NGV	CLSD	NEW	6.5	4.2	0	6.5	5
13	NGV	xECT	NEW	6	5.6	0.1	3.8	9.8
13	NGV	xECT	NEW	5.9	6.4	0.2	7.1	6.8
13	NGV	xECT	NEW	6.2	42.4	0.9	59.9	18.5
13	NGV	xO2	NEW	5.6	4.1	0	5.4	25
44	LPG	ASIS	NEW	6.6	297.9	2.7	2.8	40.2
44	LPG	OEM	NEW	6.3	5.1	2.9	0.3	22.5
44	NGV	CLSD	NEW	5.9	11.4	0	8.7	7.1
44	NGV	xECT	NEW	6.2	9.8	0	8.1	6.4
44	NGV	xO2	NEW	5.4	3	0	7.3	32.6
2D	LPG	ASIS	NEW	6.7	63.1	10.2	0	65.9
2D	LPG	ASIS	NEW	5.3	896.5	26.3	9.1	27.5
2D	LPG	ASIS	NEW	6.2	58.4	9.3	0	91.2
2D	LPG	ASIS	OLD	6.3	107.6	16.8	0	110.1
2D	LPG	OEM	NEW	5.4	236.9	7.8	6.8	48.2
2D	LPG	OEM	NEW	6.2	32.9	4.9	0	121.9
2D	LPG	OEM	OLD	6.3	58.4	16.5	0	107.6
2D	NGV	CLSD	NEW	5.8	7.6	0	2.2	24.2
2D	NGV	CLSD	NEW	6.2	7.1	0	9.2	7.1
2D	NGV	xECT	NEW	6.3	9.9	0	1.7	17.2
2D	NGV	xO2	NEW	6	5.9	0	6.8	17.9
2E	NGV	CLSD	NEW	6.8	13.1	0.7	6.6	19
2E	NGV	CLSD	NEW	6	22.3	0	29.2	29.1
2E	NGV	CLSD	NEW	4.5	16.1	0	9.2	32.8
2E	NGV	CLSD	NEW	5.8	9.7	0.1	12	67.4
2E	NGV	CLSD	NEW	6	31.5	0	13.7	40
2E	NGV	xECT	NEW	5.8	114.8	0	27.9	43.4
2E	NGV	xECT	NEW	4.3	10.8	0	9	28.4
2E	NGV	xECT	NEW	4.6	3.6	0	10	80.5
2E	NGV	xO2	NEW	5.5	5.2	0	12.3	82.9

Table G2: Composite Engine-Out Emissions Results

UNIT	FUEL	TUNE	CATALYST	CO2 kgph	CO gph	NMHC gph	CH4 gph	NOx gph
6	LPG	ASIS	OLD	7.2	147.5	35.1	0	160.6
6	LPG	ASIS	OLD	6.6	1819	20	43.7	31.2
6	LPG	BEST	OLD	7.5	409.4	1.3	45.1	94.7
6	LPG	OEM	NEW	6.4	28.6	35.8	0	84.2
6	LPG	OEM	OLD	5.4	85.7	17.6	9.5	94.5
6	NGV	CLSD	NEW	6.5	167.1	0	41.3	64.7
6	NGV	xECT	NEW	6.8	174.8	0	43.8	70.4
6	NGV	xO2	NEW	5.8	22.8	0	35.9	11.6
9	LPG	BEST	OLD	6.9	173.9	33.3	0	142.3
9	LPG	OEM	NEW	6.9	265.8	28.8	0	119.1
9	NGV	CLSD	NEW	6.9	152.4	5.2	18.3	45.3
9	NGV	CLSD	NEW	6.9	288.5	1.5	24.3	56.3
9	NGV	CLSD	NEW	6.9	247.5	2	20.2	46.6
9	NGV	xECT	NEW	6.4	421.9	1.2	25	36.7
9	NGV	xECT	NEW	5.5	135.3	3.2	12.6	33
9	NGV	xECT	NEW	6.6	33.1	0.4	15.1	26
10	LPG	BEST	NEW	7.6	351.4	33.5	0	72.8
10	LPG	BEST	OLD	7.1	237.4	26.7	0	68.1
10	LPG	OEM	NEW	7.5	82.2	19.9	0	67.1
10	LPG	OEM	OLD	7.1	65.8	18.5	0	69
10	NGV	CLSD	NEW	6.7	210.9	0.6	48.4	62.7
10	NGV	CLSD	NEW	6.9	188.3	0	20.7	36.9
10	NGV	CLSD	NEW	6.5	105.3	11.7	29.3	77.9
10	NGV	CLSD	NEW	6.7	157.8	5	30.6	86.5
10	NGV	xECT	NEW	6.4	422.4	0.2	52.6	62.4
10	NGV	xECT	NEW	6.7	37.6	0	15.6	30.7
10	NGV	xECT	NEW	6.6	135.1	10.2	32.3	78.2
10	NGV	xECT	NEW	6.1	17.5	4.2	18.8	65.7
13	LPG	ASIS	NEW	6.3	57.4	12.2	0	106.2
13	LPG	BEST	NEW	6.2	26.8	10.1	0	193.3
13	LPG	OEM	NEW	6.3	17.2	10.4	0	189
13	NGV	CLSD	NEW	6.1	109.6	1.2	6.5	46.8
13	NGV	CLSD	NEW	5.8	352.2	0.4	12.8	38
13	NGV	CLSD	NEW	5.7	163.6	0	9.5	42.1
13	NGV	CLSD	NEW	6.2	196.6	0.8	9.3	52
13	NGV	xECT	NEW	5.7	85	0.9	4	25
13	NGV	xECT	NEW	5.7	166.4	1.2	10.5	51.6
13	NGV	xECT	NEW	5.8	245.8	13.3	89.9	48.6
13	NGV	xO2	NEW	5.4	23.8	0	5.7	26.9
44	LPG	ASIS	NEW	6.5	299.6	7.1	2.8	54.7
44	LPG	OEM	NEW	5.8	16.9	11.1	0.7	21.6
44	NGV	CLSD	NEW	5.5	145.3	0	12.1	61.6
44	NGV	xECT	NEW	5.7	152	0	11.6	58.2
44	NGV	xO2	NEW	5.2	11.9	0	7.4	37.5

UNIT	FUEL	TUNE	CATALYST	CO2 kgph	CO gph	NMHC gph	CH4 gph	NOx gph
2D	LPG	ASIS	NEW	6.7	83.2	20.6	0	102
2D	LPG	ASIS	NEW	5.3	929.3	29.3	8.7	45.4
2D	LPG	ASIS	NEW	6	86.8	20.7	0	87.5
2D	LPG	ASIS	OLD	6.3	137.5	19.1	0	109.6
2D	LPG	OEM	NEW	5.2	275	14.9	10.1	86.1
2D	LPG	OEM	NEW	6.4	86.8	16.9	0	157.1
2D	LPG	OEM	OLD	6.1	77.1	18.9	0	102.3
2D	NGV	CLSD	NEW	5.5	182.8	1.3	18.4	63.7
2D	NGV	CLSD	NEW	5.7	190.6	0	14.9	34.4
2D	NGV	xECT	NEW	5.7	178.7	1.1	19.2	64.1
2D	NGV	xO2	NEW	5.7	21.5	0	7.6	17.3
2E	NGV	CLSD	NEW	6.4	153.4	1.5	18.3	60.9
2E	NGV	CLSD	NEW	6.1	134.9	0	34.6	69.5
2E	NGV	CLSD	NEW	4.4	123	0.9	14.7	112.2
2E	NGV	CLSD	NEW	5.7	104.4	0.8	15.1	153.8
2E	NGV	CLSD	NEW	5.8	143.4	0	19.1	112.3
2E	NGV	xECT	NEW	5.6	188.6	0	41.5	61.8
2E	NGV	xECT	NEW	4.1	112.8	0.8	13.2	91.9
2E	NGV	xECT	NEW	4.8	20.2	0.1	11.3	111.6
2E	NGV	xO2	NEW	5.4	14.2	0	12.4	91.3

APPENDIX H

Vehicle Conversion Systems

APPENDIX H

VEHICLE CONVERSION SYSTEMS

A conversion vehicle is one which is originally designed to operate on gasoline or diesel but which has been modified to run on an alternative fuel. Such vehicles can be converted to dedicated, bi-fuel or duel-fuel operation. The conversion of a vehicle to run on an alternative fuel could mean a complete fuel system replacement, including hardware and software components, or adaptation of the existing components. The new system may involve a simple open-loop mixer (or carburetor) as shown in Figure H1 (this was the system originally in place in the LPG forklifts). Fuel systems can also be more sophisticated with closed-loop feedback and fuel injection as shown in Figure H2 (this is the system used in the converted CNG forklifts).

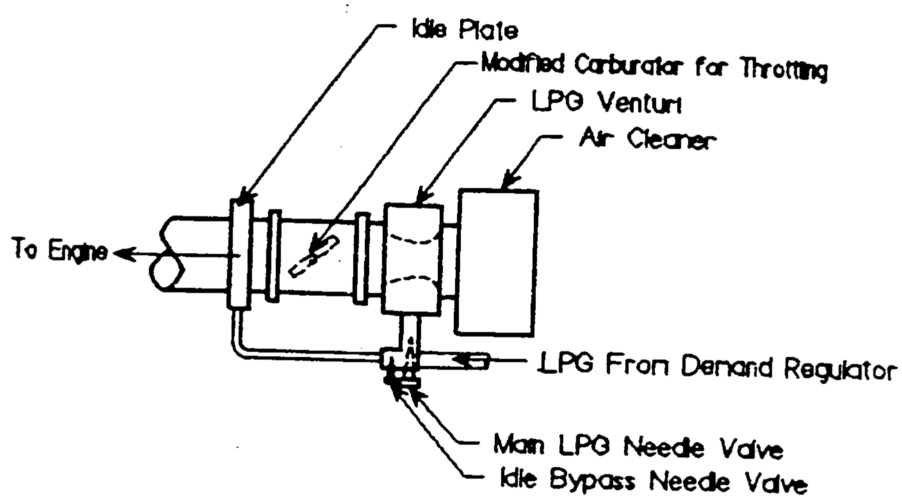


Figure H1: LPG Throttle Venturi Configuration [1]

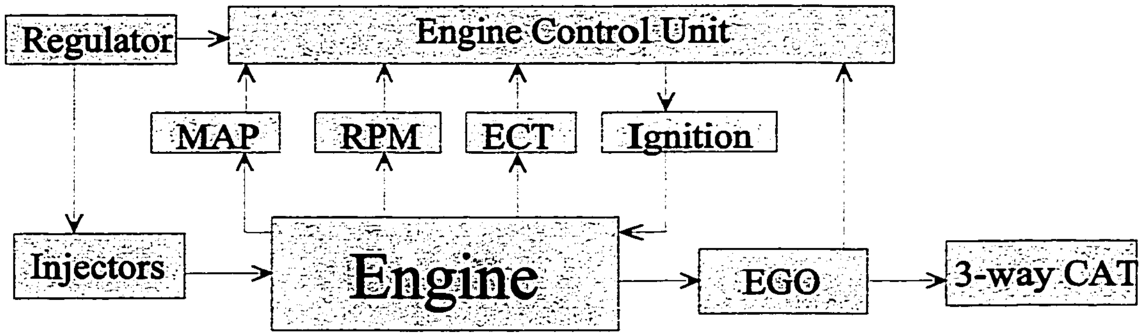


Figure H2: Schematic of Closed-Loop Feedback Fuel Injection CNG Conversion System

Conversion systems vary widely with many choices in the way fuel is administered and controlled. The level of sophistication of the system depends on these choices. Described below are four CNG conversion kits to show how conversions can vary from one system to another. The systems are not critiqued or any one system chosen as being better than another but are simply detailed as to their components and function.

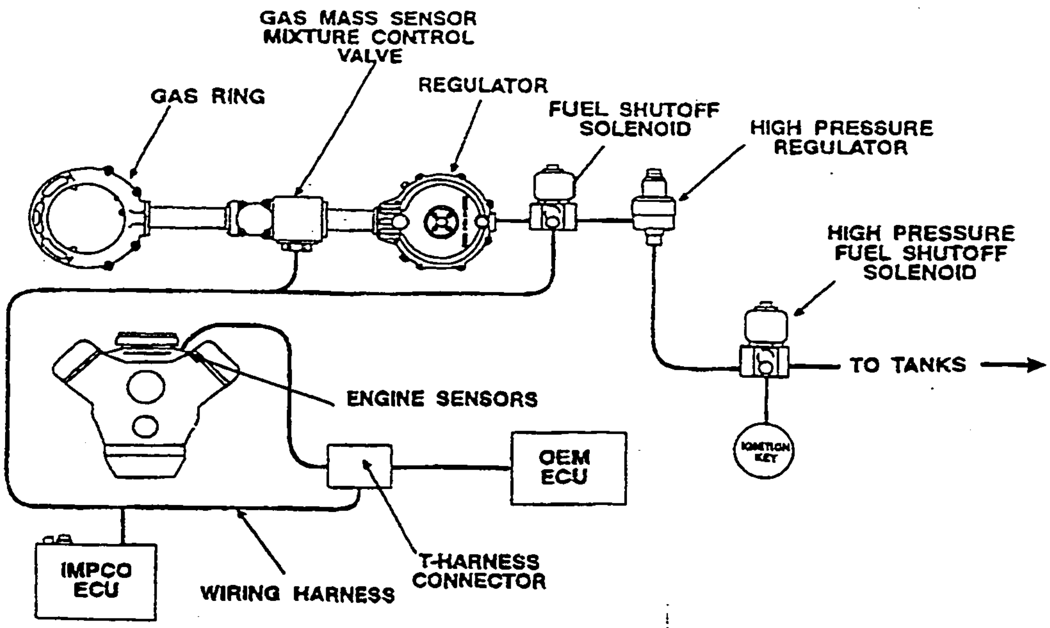


Figure H3: CNG Conversion Kit 1. [2]

The system shown in Figure H3 is considered a more sophisticated system in that it uses more of the vehicle's OEM computer. Manufacturers are expending considerable effort to find technology that uses much of the existing vehicle production hardware to be cost-effective. The system uses two pressure regulators, high and low pressure, to reduce the fuel pressure to usable levels. The gas ring is a continuous flow device placed on the engine throttle body. The amount of fuel required is calculated by using speed density information and exhaust oxygen sensor feedback. Speed density control is an open loop method which calculates the amount of fuel required based on the measured air flow to the engine. The addition of the oxygen sensor in the exhaust allows for continuous monitoring and adjustment of the fuel.

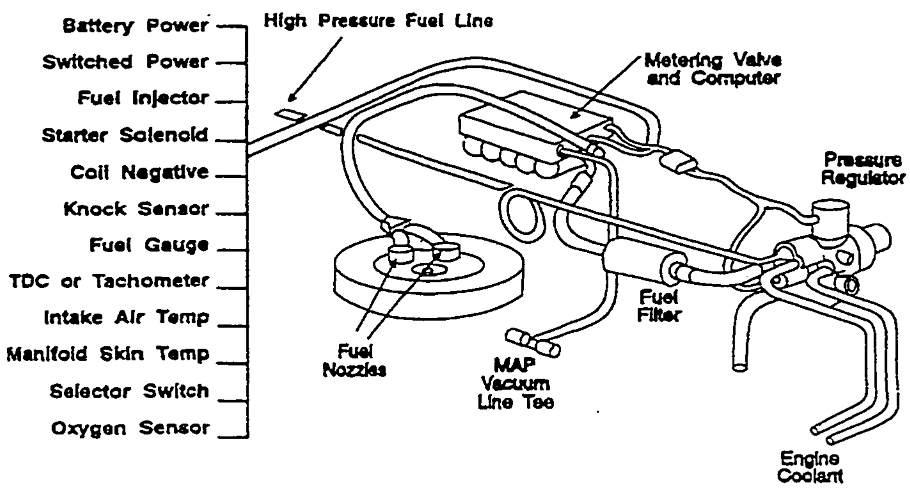


Figure H4: CNG Conversion Kit 2.[2]

The system shown in Figure H4 is also considered a sophisticated system. It uses speed density control as well to measure air and fuel flow and an additional ECU(Electronic Control Unit) to control multiple gas injector valves. This system uses five different gas valves, of varying capacities, to deliver the correct amount of fuel. This system also has control over spark timing.

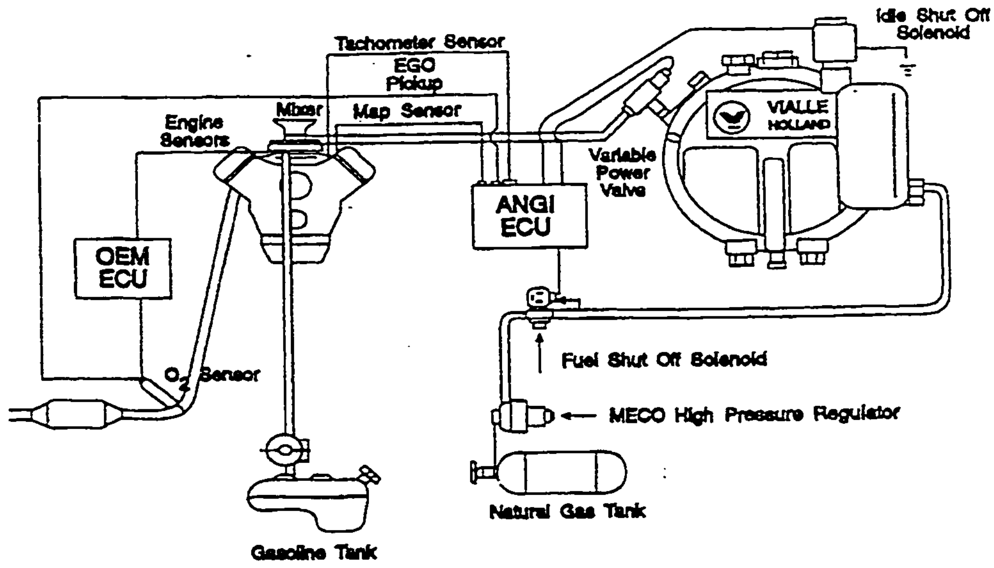


Figure H5: CNG Conversion Kit 3.[2]

Figure H5 shows a system using a conventional mixer. The system uses high and low pressure regulators, a throttle body gas mixing ring, a secondary ECU, and an electronically controlled lean cruise/power valve for fuel control. The system also controls spark timing. The software incorporates two adaptive learn modes to control the cruise/power valve position based on the oxygen sensor signal. The modes are referred to as "tuning" for long term process such as cruise style driving conditions, and "trimming", a short term process which continuously adjusts the cruise/power valve to compensate for short term transients such as power requirements during sudden acceleration.

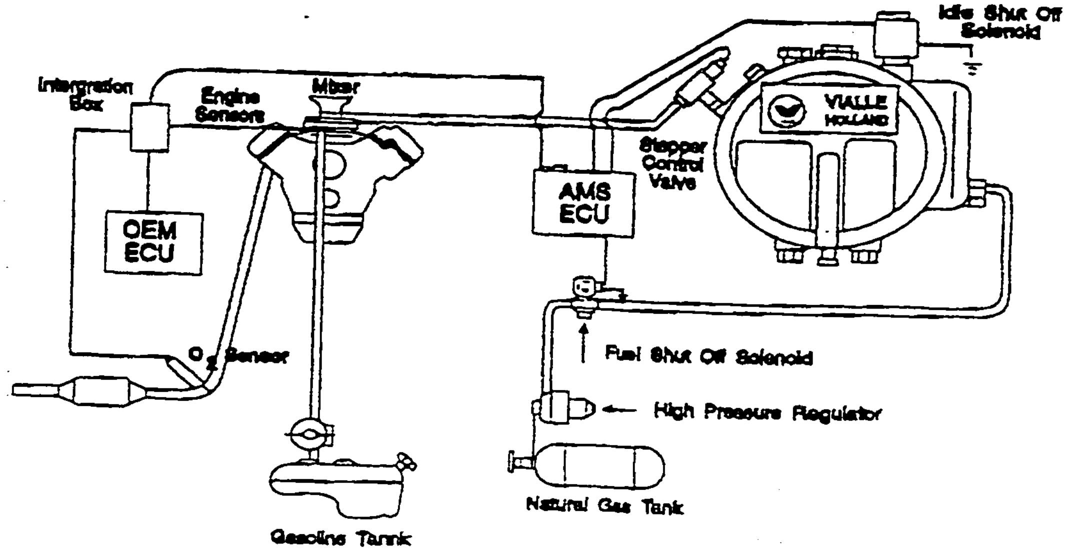


Figure H6: CNG Conversion Kit 4.[2]

Figure H6 shows a system much like that of Kit 3 in Figure H5. This can be adapted to both computer or non-computer controlled engines. Regulated gas is directed towards the stepper motor valve, which limits fuel delivery to the mixer ring based on engine operation and oxygen sensor feedback. This system also incorporates preset compensation values for cold start, idle speed, power enrichment and cruise conditions.

Additionally, conversion systems may incorporate various other components to help optimize the engine for the specific fuel other than the fuel system. For example, special natural gas optimized catalysts could be used for dedicated CNG conversion vehicles. They employment of a turbocharger could offset volumetric losses of using gaseous fuels. Camshaft modifications and compression ratio may also be changed to better take advantage of fuel characteristics. So numerous things can be done to fully optimize a system, however, for manufacturers the cost of doing so for low-volume production may not be feasible.

REFERENCES

[1] John P. Latusek, and Robert W. Burrahm, "Conversion of Two Small Utility Engines to LPG Fuel", SAE Paper 932447, 1993.

[2] John M. Christie, et al, "Evaluation of Aftermarket NGV Hardware", Presented at NGV'94, Toronto, Ontario, October 6, 1994.

APPENDIX I

Mass-Balance Equation - Analytical Solution

APPENDIX I

MASS-BALANCE EQUATION - ANALYTICAL SOLUTION

This appendix shows the analytical solution to the mass-balance differential equation described in Chapter 4. Recalling the equation:

$$dC = PaC_0dt + \frac{S}{V}dt - (a + k)Cdt \qquad \text{(H-1)}$$

where,

- C - indoor pollutant concentration,
- C_0 - outdoor pollutant concentration,
- P - penetration factor for outdoor pollutant,
- a - air exchange rate in air exchanges per hour (ACH),
- S - indoor pollutant source strength,
- V - well mixed volume,
- k - net rate of removal processes other than air exchange and,
- t - time.

The equation (H-1) is solved under the following assumptions:

1. C_0, P, a, S and k are constant over time.
2. Volume is well mixed and therefore C(t) is not spatially dependant.

Analytical Solution:

$$dC = P_a C_o\,dt + S/V\,dt - (a+K)C\,dt$$

$$\frac{dC}{dt} + (a+K)C = P_a C_o + S/V$$

integration factor : $e^{\int (a+K)dt} = e^{(a+K)t}$

$$e^{(a+K)t}\frac{dC}{dt} + (a+K)e^{(a+K)t}C = (P_a C_o + S/V)\,e^{(a+K)t}$$

$$\frac{d\left(e^{(a+K)t}C\right)}{dt} = (P_a C_o + S/V)\,e^{(a+K)t}$$

$t_s \longrightarrow$ time Forklift is shutoff or stopped.

2 Cases : $t < t_s$ and $t \geq t_s$

Case 1 $\Rightarrow$ $t < t_s$

integration $0 \to t$

$$e^{(a+K)t}C(t)\Big|_0^t = \frac{(P_a C_o + S/V)}{(a+K)}e^{(a+K)t} - \frac{(P_a C_o + S/V)}{(a+K)}$$

$$\boxed{C(t) = \frac{(P_a C_o + S/V)}{(a+K)}\left[1 - e^{-(a+K)t}\right] \quad \text{for } t < t_s}$$

Case 2 $\Rightarrow$ $t \geq t_s$

$$e^{(a+k)t} C \Big|_0^t = \frac{(P_a C_o + S/V)}{(a+k)} e^{(a+k)t} \Big|_0^t$$

LHS: $$e^{(a+k)t} C \Big|_0^{t_s} + e^{(a+k)t} C \Big|_{t_s}^{t} = \cancel{e^{(a+k)t_s} C(t_s)} - \cancel{C(0)} + e^{(a+k)t} C(t) - \cancel{e^{(a+k)t_s} C(t_s)}$$

$$= e^{(a+k)t} C(t)$$

RHS: $$\frac{e^{(a+k)t}(P_a C_o + S/V)}{(a+K)} \Bigg|_0^{t_s} + \frac{e^{(a+k)t}(P_a C_o + S/V)}{(a+K)} \Bigg|_{t_s}^{t}$$

$$\frac{(P_a C_o + S/V)}{(a+k)} e^{(a+k)t_s} - \frac{(P_a C_o + S/V)}{(a+k)} + \underbrace{\frac{(P_a C_o + S/V)}{(a+k)} e^{(a+k)t} - \frac{P_a C_o + (S/V)}{(a+k)} e^{(a+k)t_s}}_{S=0}$$

$$\frac{(P_a C_o + S/V)}{(a+k)} e^{(a+k)t_s} - \frac{(P_a C_o + S/V)}{(a+k)} + \frac{P_a C_o}{(a+k)} e^{(a+k)t} - \frac{P_a C_o}{(a+k)} e^{(a+k)t_s}$$

$$\frac{(P_a C_o + S/V)}{(a+k)} \left[e^{(a+k)t_s} - 1 \right] + \frac{P_a C_o}{(a+k)} \left[e^{(a+k)t} - e^{(a+k)t_s} \right] e^{-(a+k)t}$$

$$C(t) = \frac{(P_a C_o + S/V)}{(a+k)} \left[e^{(a+k)t_s} - 1 \right] e^{-(a+k)t} + \frac{P_a C_o}{(a+k)} \left[e^{(a+k)t} - e^{(a+k)t_s} \right] e^{-(a+k)t}$$

for $t \geq t_s$

simplify . . .

$$C(t) = \frac{P_a C_o}{(a+k)} e^{(a+k)t_s} e^{-(a+k)t} + \frac{S/V}{(a+k)} e^{(a+k)t_s} e^{-(a+k)t} - \frac{P_a C_o}{(a+k)} e^{-(a+k)t}$$

$$- \frac{(S/V)}{(a+k)} e^{-(a+k)t} + \frac{P_a C_o}{(a+k)} e^{(a+k)t-(a+k)t} - \frac{P_a C_o}{(a+k)} e^{(a+k)t_s} e^{-(a+k)t}$$

$$= \frac{P_a C_o}{(a+k)} e^{(a+k)(t_s-t)} - \frac{P_a C_o}{(a+k)} e^{-(a+k)t} + \frac{P_a C_o}{(a+k)} - \frac{P_a C_o}{(a+k)} e^{(a+k)(t_s-t)}$$

$$+ \frac{S/V}{(a+k)} e^{(a+k)(t_s-t)} - \frac{S/V}{(a+k)} e^{-(a+k)t}$$

$$= \frac{P_a C_o}{(a+k)} - \frac{P_a C_o}{(a+k)} e^{-(a+k)t} + \frac{S/V}{(a+k)} e^{-(a+k)(t-t_s)} - \frac{S/V}{(a+k)} e^{-(a+k)t}$$

$$= \frac{P_a C_o}{(a+k)} \left[1 - e^{-(a+k)t} \right] + \frac{S/V}{(a+k)} \left[e^{(a+k)t_s} - 1 \right] e^{-(a+k)t}$$

$$\boxed{C(t) = \frac{P_a C_o}{(a+k)} \left[1 - e^{-(a+k)t} \right] + \frac{S/V}{(a+k)} \left[1 - e^{-(a+k)t_s} \right] e^{-(a+k)(t-t_s)}}$$

for $t \geq t_s$.