Reducing Transportation Impacts through Fuel Improvements in Metro Vancouver

Hasti Hosseinizand

University of British Columbia Sustainable Region Scholars Program

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1 Introduction and Background

Metro Vancouver's regional inventories of criteria air contaminant and greenhouse gas emissions have consistently identified fossil fuel internal combustion engines in on-road vehicles and non-road equipment as a dominant emissions source in our region. Two key regional approaches to reducing emissions from on-road vehicles and non-road equipment are:

- replacement of older high emitting vehicles with newer fossil fuel burning vehicles that have higher efficiency engines and advanced emissions controls, and
- replacement of internal combustion engines through electrification of vehicles.

However, both of these approaches rely on incremental changes over long periods of time, meaning that short term emissions benefits may be small. A third emissions reduction option, with the potential for more immediate impacts, is the improvement of the fuels burned in existing internal combustion engines.

A variety of research evidence indicates that fuel composition can have a significant influence on air pollutant emissions from both gasoline and diesel internal combustion engines. Air pollutant emissions are affected by fuel composition in different ways:

- Emission levels are correlated with levels of fuel impurities such as sulfur and benzene.
- Controlling fuel compositional parameters in narrow ranges will result in improved engine efficiency and consequently lower emissions levels.
- Fuel contamination will degrade engine components such as fuel injectors and combustion cylinders, and emissions control devices such as catalytic converters (Row and Doukas 2008).

Emissions reductions may be realized by modifying the composition of conventional gasoline or diesel fuels, or by developing and expanding the use of alternative or renewable fuels such as biodiesel. This has the potential to not only reduce air pollutant emissions, but also decrease fossil fuels dependency and greenhouse gas emissions (Hajbabaei et al. 2013).

The objective of this study is to review the literature on improved fuels for transportation, and their impact on transportation emissions, as well as explore policy and regulation that could be used to motivate a transition to improved fuels. The focus is on fuels that could replace conventional gasoline and diesel, with particular emphasis on on-road vehicle applications.

2 Air Pollutant Emissions from Internal Combustion Engines

Internal combustion engines produce a wide range of air pollutant species, the most significant of which are carbon monoxide, nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds (VOC), and sulfur oxides (SOx). The following sections provide a brief discussion of each pollutant.

2.1 Carbon monoxide

The incomplete combustion of fuel causes carbon monoxide (CO) production, which has no color, taste, and odor. Because of its strong affinity for hemoglobin, it reduces the ability of blood to transport oxygen. In people with cardiovascular disease, Long-term exposure to low concentrations may have adverse effects (Metro Vancouver's report, 2015). CO can also enhance photochemical smog and ground-level ozone formation.

CO emission in diesel engines is highly dependent on physicochemical properties of the fuel (Patil 2015). The parameters which affect CO production are fuel/air equivalence ratio, fuel type, combustion chamber design, atomization of fuel, injection pressure, and injection timing (Sajjad et al. 2014, Hwang et al. 2014 , Row and Doukas 2008) .

2.2 Nitrogen oxides (NOx)

Nitric oxide (NO) and nitrogen dioxide (NO2) that are produced by the high temperature combustion of fossil fuels are called NOX. At the beginning of the combustion, nitric oxide dominates the emissions, but it rapidly converts to NO2 through chemical reactions. Nitrogen oxides could cause acute and chronic respiratory disease and acid rain. It also plays a major role in ozone formation, and as a precursor to secondary particulate formation (PM2.5) (Metro Vancouver's report, 2015).

Internal combustion engines generate NOx via two different mechanisms: oxidation of atmospheric nitrogen at high temperature via the Zeldovich mechanism (Sajjad et al. 2014), and oxidation of nitrogen bound in the fuel. NOx formation depends on oxygen availability, in-cylinder temperature and residence time (Hwang et al. 2014). In diesel engines, 70-90% of total NOx emitted is composed of NO (Patil 2015).

2.3 Particulate matter (PM)

Particulate matter (PM) refers to solid or semi-volatile particles small enough to remain suspended in the ambient air. It can range in size from 10 micrometers (µm) down to less than

1 nanometer (nm), and can vary widely in shape, surface area and composition. Particulate emissions from internal combustion engines are predominantly fine particles smaller than 2.5 micrometers, often referred to as $PM_{2.5}$. Both chronic and acute human diseases can be caused by Fine particulate matter (Metro Vancouver's report, 2015).

The fine particles produced in internal combustion engines are typically classified into three modes: nucleation mode (< 50 nm), accumulation mode (50-1000 nm) and coarse mode (>1000 nm). Nucleation mode particles mainly consist of volatile organic and sulfur compounds. Most of the soot which consists of solid carbonous agglomerates with semi-volatile components absorbed on their surface is in accumulation mode. Accumulation mode makes up most of the total PM mass concentration (Sajjad et al. 2014, Du et al. 2014, Moon et al. 2010).

Mass concentration of PM in diesel engine exhaust can be reduced by means of modern engine and emissions control technologies, such as diesel particulate filters (DPF) and variable geometry turbochargers (VGT). Although these technologies decrease particles mass, they tend to increase particles' numbers.

2.4 Volatile Organic Compounds (VOCs)

Volatile Organic Compounds (VOC) refers to a class of organic chemicals that can vaporize into the atmosphere at normal ambient temperatures and pressures. VOC emissions from internal combustion engines include both unburned hydrocarbons from fuel (Sajjad et al. 2014, Hwang et al. 2014), as well as gaseous products of incomplete combustion. VOC can be found in urban smog and are precursors of other contaminants present in smog such as ozone and fine particulates. Some VOC (e.g. benzene) can pose a human health risk due to chronic toxicity and carcinogenicity (Row and Doukas 2008).

2.5 Sulfur oxides (Sox)

Sulphur dioxide (SO2), which is a colorless gas with a strong odor can react in the air to form sulphuric acid and sulphate particles. Even short exposure to high concentrations of SO2 and its by-products can cause respiratory disease in humans. Chronic respiratory diseases could be the result of long-term exposure to sulfur oxides. Sulfur oxides can also contribute to the formation of acid rain. If sulfur oxides including SO2 combines with other air contaminants, it could form fine particulates (PM2.5) (Metro Vancouver's report, 2015).

Choice of fuel is important to decrease Sulfur oxide emissions because sulfur emissions are highly dependent on the fuel sulfur content. Therefore, an effective way to reduce Sox emissions is to use low-sulfur fuel.

3 Alternative fuels

During the last decades, there has been a worldwide tendency towards alternative fuels for transportation due to variability in the price of fossil fuels, energy security concerns, and concerns related to greenhouse gas and air pollutant emissions. Fuels produced from biomass such as ethanol and biodiesel, and designer fuels produced from syngas via the Fischer-Tropsch (F-T) process are examples of potential alternative fuels (Sajjad et al. 2014, Gill et al. 2011). Bio-ethanol is the main alternative fuel to fossil gasoline for spark-ignition engines. For diesel engines, biodiesel produced by esterification of plant and animal feedstocks is the most common alternative to fossil diesel, through synthetic diesels produced from either coal or natural gas feedstocks are also of interest.

3.1 Fischer-Tropsch liquid fuels:

The raw material of Fischer-Tropsch (F-T) liquid fuel production can be natural gas, coal, or residual biomass; and the final liquid fuel in each case will be GTL, CTL, and BTL, respectively. GTL fuel is already produced commercially and in some European countries, diesel fuel is blended with GTL as a transportation fuel (Sajjad et al. 2014, Gill et al. 2011). CTL fuels have been produced commercially in South Africa since the 1950s.

The F-T process is a combination of several chemical reactions in the presence of a catalyst. The main steps of F-T process are as below (Sajjad et al. 2014, Gill et al. 2011):

1. Formation of synthetic gas (syngas): In this step, carbon monoxide (CO) and hydrogen (H2) are produced from the decomposition of natural gas, coal, or biomass. Syngas can be produced via steam reforming, auto-thermal reforming (ATR), or gasification (Sajjad et al. 2014, Gill et al. 2011). Syngas is the major intermediate for the industrial production of a wide range of chemicals, including ammonia, methanol, dimethyl ether (DME), acetic acid, and F-T liquid fuels.
2. Catalytic synthesis (conversion of syngas): The final product in this step is highly dependent on the type of reaction, selected catalyst, and operating conditions of the process. The syngas from the previous step is processed in a reactor in the presence of a catalyst. The final product of this step is a mixture of long-chain waxy hydrocarbons and a significant amount of water as a by-product (Sajjad et al. 2014, Gill et al. 2011).
3. Post-processing (Cracking): The hydrocarbon products of catalytic synthesis are processed through refinery cracking operations in the presence of zeolite catalysts and hydrogen to yield shorter hydrocarbons. Finally, after distillation, various fuel products ranging from kerosene to diesel naphtha and lube oils are produced (Sajjad et al. 2014, Gill et al. 2011).

3.2 Biodiesel

Biodiesel is a liquid fuel produced from biogenic sources that can be used in diesel engines without major modifications. The first step of biodiesel production is feedstock selection. Generally, there are four main categories of feedstock for biodiesel production (Atabani et al. 2012):

1. Edible vegetable oil: rapeseed, soybean, peanut, sunflower, palm, and coconut oil.
2. Non-edible vegetable oil: jatropha, Karanja, and sea mango
3. Waste or recycled oil
4. Animal fats: tallow, yellow grease, chicken fat, and by-products from fish oil

The second step of biodiesel production is oil extraction. The main product of oil extraction is crude oil. Three main methods for oil extraction are 1- mechanical extraction, 2- solvent extraction, and 3- enzymatic extraction (Atabani et al. 2012).

After oil extraction, the quality of viscous, low volatility, polyunsaturated oil should be improved. There are four methods to convert oil to the final fuel: 1- pyrolysis, 2- dilution and hydrocarbon blending, 3- micro-emulsion, and 4- transesterification. Because of low cost and simplicity, transesterification is counted as the best method for biodiesel production. In transesterification which consists of a series of reversible reactions, triglycerides are converted to glycerol as a byproduct and biodiesel as the main product. Methanol and ethanol are two alcohols which are mainly used in transesterification process owing to their low cost (Atabani et al. 2012).

3.3 Other oxygenated fuels

3.3.1 Ethanol

Ethanol is a renewable, bio-based resource and highly oxygenated (34.7% by mass) alternative fuel. Ethanol is produced from fermentation of biological feedstock like sugarcane, corn, and molasses. Ethanol and gasoline are completely miscible and they can be blended in a wide range of ethanol concentration (Chauhan et al. 2016).

Ethanol is is most commonly blended with fossil gasoline. Auto-ignition temperature and flash point of ethanol are higher than gasoline which makes it a safer fuel for storage and transportation than gasoline. The calorific value of ethanol is less than gasoline. Ethanol has a very low vapor pressure, thus requires caution in its usage (Chauhan et al. 2016).

Ethanol also has the potential to reduce particulate emissions in a diesel engine. Poor ignition characteristics, low cetane number, and limited solubility in diesel fuel are the obstacles in using ethanol in diesel engines. Due to low cetane number and high self- ignition temperature of alcohols, they are not preferred to be used in diesel engines as soul fuel. The blending of alcohols with other diesel fuels is an option to use them in diesel engines (Masimalai 2014). Due to mentioned limitations with ethanol, it is preferred to convert it to DEE for diesel engine application (Patil 2015).

3.3.2 Dimethyl ether (DME)

Dimethyl ether is the simplest ether with about 34.8% (by mass) oxygen content. DME is a gaseous fuel with similar properties to Liquefied petroleum gas (LPG).

Dimethyl ether is produced in a two-step process, where syngas is first produced and then converted to methanol, followed by conversion of methanol to dimethyl ether. Natural gas, coal, and biomass are the feedstock for dimethyl ether production.

There is no C-C bond in its structure and it only has C-H and C-O bonds. It could result in low HC, low CO and smoke-free emissions in diesel engines (Xinling and Zhen 2009).The operation of DME in a diesel engine does not require engine modifications, however, a new storage system and fuel delivery system are required, which is a challenge while using DME as an alternative fuel. The solution may lie with diethyl ether (Semelsberger, Borup, and Greene 2006).

3.3.3 Diethyl ether (DEE)

Diethyl ether is a renewable oxygenated alternative fuel for diesel engines owing to its high ignition quality. DEE can be produced from ethanol, and is commonly used as a solvent. It can be mixed with diesel fuel at any ratio. It has high cetane number (>125), good energy density, high flammability and is volatile. DEE properties are very similar to DME, however, at ambient conditions, DEE is in liquid form, which makes it attractive to be used as an alternative fuel. As DEE is liquid at ambient conditions and it is less flammable than DME, it will have a safer handling than DME and is more desirable as an alternative fuel. However, its storage is challenging because of its tendency to oxidize. Unlike DME, DEE is rarely used in diesel engines and it is mostly applied in gasoline engines (Patil 2015).

4 Diesel fuel

Diesel engines have higher thermal efficiency, power output, and lower greenhouse gas emissions relative to gasoline engines. However, diesel engines exhibit increased emissions of some pollutants such as NOx and PM relative to gasoline engines. Therefore, new technologies such as electronically controlled high-pressure injection systems and a cooled exhaust gas recirculation (EGR) systems have been developed to reduce emissions from diesel engines (Du et al. 2014, Abu-Jrai et al. 2006, Xinling and Zhen 2009, Kitano, Sakata, and Clark 2005).

4.1 Diesel fuel key properties

The following fuel quality parameters for diesel fuel may impact diesel engine performance, efficiency and emissions:

- **Cetane number -** An indicator of the ignition quality of diesel fuel. It shows the ability of fuel to auto-ignite immediately after injection. A higher cetane number demonstrates shorter time between fuel injection in chamber and ignition, i.e. shorter ignition delay. Shorter ignition delay allows more time for combustion which in turn leads to a complete combustion. Low cetane number causes startup problems, poor fuel economy, unstable engine operation, noise and exhaust smoke (Sajjad et al. 2014, Atabani et al. 2012, Row and Doukas 2008).
- **Lubricity -** The parameter that indicates fuel lubricity is wear scar. It shows the wear that is expected in engine parts when using the test fuel. Larger wear scar shows poorer lubricity of fuel because lubricity minimizes the damage caused by friction. As sulfur is a natural lubricant, care must be taken while using sulfur-free or ultra-low sulfur fuels. To make up the lubricity of fuel due to lack of sulfur, additives can be applied (Row and Doukas 2008). Lubricity by its own does not have a direct relationship with emissions. However low lubricity results in engine components' wear, which will, in turn, leads to increase in emissions (Sajjad et al. 2014, Atabani et al. 2012).
- **Viscosity -** shows the ability of fuel to flow, so it has a strong impact on fuel injection and spray atomization. This parameter is more significant at low temperatures when viscosity increases and as a result fluidity of the fuel is affected. The molecular mass and chemical structure of the fuel has a strong impact on viscosity. For example, biodiesel is more viscous than conventional diesel fuel because of its large chemical structure. Therefore, care must be taken when using biodiesel at low ambient temperatures, at which fuel is likely to solidify. GTL fuel has shown lower viscosity than diesel fuel which is advantageous for fuel injection system and decreases required power to pump the fuel (Sajjad et al. 2014, Atabani et al. 2012).

- **Density -** Fuels with higher density has higher energy concentration. Denser fluid leads to higher viscosity and this will affect injection and pump efficiency, poor combustion, and increased emission. Based on EN ISO 3675/12185[1] and ASTM D1298[2] the density is measured at the temperature of 15 or 20 ° C (Sajjad et al. 2014, Atabani et al. 2012).
- **Calorific value/heating value/ heat of combustion -** This parameter indicates the amount of heat released when a unit value of fuel is combusted. The moisture content of fuel has a major impact on calorific value. Higher heating value is always preferred for a fuel (Sajjad et al. 2014, Atabani et al. 2012).
- **Flash point -** indicates the temperature at which fuel ignites while exposure to a flame or spark. Flash point is inversely related to volatility. Higher flash point is desired because it will cause safer and easier handling and storage of fuel and prevents from unexpected ignition during combustion. While the flash point of conventional diesel fuel is 55-65 °C, GTL and biodiesel have flash points of 80 °C and 150 °C respectively, leading to safer storage and handling (Sajjad et al. 2014, Atabani et al. 2012).
- **Cloud point (CP), Pour point (PP), and cold filter plugging point (CFPP) -** The physical characteristics of diesel fuels at low temperature are of important because at low temperature fuels are more likely to partially or fully solidify, leading to fuel system blockages, which in turn lead to fuel starvation, starting problems and engine damage due to inadequate lubrication. Cloud point, pour point, and cold filter plugging point are three parameters which indicate fuel quality at low temperature. The temperature at which first wax crystals appear when fuel is cooled is called CP. When the amount of wax out of solution is enough to gel the fuel, the temperature is called PP. In other words, PP is the lowest temperature at which fuel can flow. Standard ASTM D2500[3] is used to measure CP and PP. Generally, GTL and BD have slightly higher CP and PP in comparison to conventional diesel fuel. The temperature at which filter plugging starts due to crystallization and gel formation of fuel components is called CFPP. CFPP is approximately halfway between CP and PP. CFPP is measured using ASTM D6371[4] (Sajjad et al. 2014, Atabani et al. 2012).

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[1] EN ISO 3675: Crude petroleum and liquid petroleum products -Laboratory determination of density -Hydrometer method (http://www.iso.org/iso/catalogue_detail.htm?csnumber=26326)

[2] ASTM D1298: Standard Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method (https://www.astm.org/Standards/D1298.htm)

[3] ASTM D2500, Standard test method for cloud point of petroleum products and liquid fuels (https://www.astm.org/Standards/D2500.htm)

[4] ASTM D6371, Standard test method for cold filter plugging point of diesel and heating fuels (https://www.astm.org/Standards/D6371.htm)

- **Acid value -** demonstrates the amount of free fatty acids (FFA) available in the fuel. Higher amounts of FFA present in the sample will result in an increased acid value. The probability of fuel supply system corrosion and engine degradation increases when the acid value of the fuel is high. The acid value is measured based on standards ASTM D3242[5] and ASTM D974[6] for diesel fuel and GTL, respectively. The acid value of GTL is significantly lower than diesel fuel and biodiesel, so it is more engine friendly (Sajjad et al. 2014, Atabani et al. 2012).
- **Iodine number (IN) -**indicates the unsaturation in fatty acids in the form of double bonds that react with iodine. Higher iodine number shows more C=C bonds available in the fuel. Standard EN14111[7] is used to measure IN. The amount of IN in GTL is lower than biodiesel (Sajjad et al. 2014).
- **Carbon residue -** Carbon residue of a fuel shows the tendency of the fuel to form carbon deposit after combustion. Higher carbon residue indicates poor combustion. Standard ASTM D524[8] and ASTM D4530[9] are used to measure carbon residue of GTL and diesel fuel. GTL shows less carbon residue than diesel fuel which is an advantage (Sajjad et al. 2014, Atabani et al. 2012).
- **Sulfur Content -** The presence of sulfur in fuel has adverse effects on engine performance and the environment. The reaction of sulfur with water during combustion will form sulfuric acid and other corrosive compounds which degrade the engine components. Moreover, corrosive compounds could cause acid rain when mixing with atmospheric air. Standards

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[5] ASTM D3242, Standard test method for acidity in aviation turbine fuel (https://www.astm.org/Standards/D3242.htm)

[6] ASTM D974, Standard Test Method for Acid and Base Number by Color-Indicator Titration (https://www.astm.org/Standards/D974.htm)

[7] EN14111, Natural gas- Guidelines to traceability in analysis (https://www.iso.org/obp/ui/#iso:std:iso:14111:ed-1:v1:en)

[8] ASTM D524, Standard Test Method for Ramsbottom Carbon Residue of Petroleum Products (https://www.astm.org/Standards/D524.htm)

[9] ASTM D4530, Standard Test Method for Determination of Carbon Residue (Micro Method), (https://www.astm.org/Standards/D4530.htm)

ASTM D5453[10] and ASTM D2622[11] are used to determine sulfur content in fuel. GTL fuel shows close to zero sulfur content which makes it desirable for combustion (Sajjad et al. 2014).

- **Copper strip corrosion -** This parameter shows the corrosive nature of the fuel when is in contact with copper, brass, or bronze. Standard ASTM D 130[12] is used to determine this parameter. For this test, copper strip is heated up to 50 C in a fuel bath for 3 hours and the degree of corrosion is measured based on standards. GTL and diesel fuel have similar copper strip corrosion values (Sajjad et al. 2014, Atabani et al. 2012).
- **Distillation properties -** Distillation properties show the temperature range over which a fuel volatilizes. It is determined using ASTM D975[13]. Because of difficulty to obtain the end point in the distillation process, 90% (T90) or 95% (T95) distillation point of a fuel is commonly used. A fuel with lower T90 value indicates that it evaporates easily, which improves atomization of fuel and accelerate air/fuel mixing. Low distillation property reduces smoke and PM emissions. GTL has low distillation properties (Sajjad et al. 2014).
- **Ash content -** Ash is the unburnt matter after combustion which consists of inorganic contaminants like catalyst residues, abrasive solids, and soluble metal elements in fuel. High ash content causes plugging in fuel injection system, combustion deposits, and injection system wear. ASTM D482[14] is used to determine ash content of diesel fuel. GTL has shown significant lower ash content than diesel fuel (Sajjad et al. 2014).

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[10] ASTM D5453, Standard Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence, (https://www.astm.org/Standards/D5453.htm)

[11] ASTM D2622, Standard Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry (https://www.astm.org/Standards/D2622.htm)

[12] ASTM D 130, Standard Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test, (https://www.astm.org/Standards/D130.htm)

[13] ASTM D975, Standard Specification for Diesel Fuel Oils (https://www.astm.org/Standards/D975.htm)

[14] ASTM D482, Standard Test Method for Ash from Petroleum Products (https://www.astm.org/Standards/D482.htm)

4.2 Effect of single fuel parameters on diesel engine emissions

Emissions from engines are highly dependent on fuel composition. Changing one fuel parameter affects other fuel properties because fuel properties are correlated. Therefore, studies that try to change one fuel parameter while keeping other parameters constant are of great value, since the effect of fuel parameters are separated.

In this section, some studies that have examined the effects of single diesel fuel properties on exhaust emissions (PM, NOx, HC, and CO) for light-duty vehicles/engines are reviewed. The key fuel parameters that many researchers have focused on are density, aromatics content, cetane number, distillation range, and sulfur content.

The US Environment Protection Agency (EPA) (US EPA 2001) has previously reviewed some key studies about fuel properties on diesel engine emissions. Some of the studies addressed by EPA are discussed here. The European Program on Emissions, Fuels and Engines (EPEFE) (Hublin et al. 1996), Lange (Lange et al. 1993a), and Bertolie (Bertoli, Giacomo, and M.V. 1993, US EPA, 2001) studies tested light-duty vehicles or trucks made in the 1990s. These vehicles/engines encompassed a combination of the following technologies:

- Electronically or mechanically controlled fuel injection system
- Naturally aspirated (NA) or turbocharged (TC) engines, some with intercooler
- Direct injection (DI) or pre or swirl chambers indirect injection (IDI) combustion chambers
- Exhaust Gas Recirculation (EGR) - electronically and mechanically controlled
- Oxidation Catalysts

In EPEFE, Lange, and Bertolie studies, the test cycles used in the light-duty studies included the European MVEG test cycles (ECE15+EUDC)[15], the European ECE R49, and the U.S. FTP[16].

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[15] Emission test cycles are procedures including specific conditions of engine operating temperature, speed, and load. Emission test cycles allow comparable measurements of exhaust emissions for different engines and vehicles. Different international governments have issued their own test cycles.

European MVEG (Motor Vehicle Emission Group) test cycles (ECE15+EUDC) or New European Driving Cycle (NEDC) is a driving cycle to measure emissions of passenger cars. This driving cycle consists of four repeated ECE-15 urban driving cycles (UDC) and one Extra Urban driving cycle (EUDC). The detailed test procedure for the measurement of CO2 and air pollutants are mentioned in The United Nations Economic Commission for Europe (UNECE) R101 (http://www.unece.org/trans/main/wp29/wp29regs101-120.html) and UNECE R83 (http://www.unece.org/trans/main/wp29/wp29regs81-100.html), respectively.

[16] The U.S. FTP (Federal Test Procedure) is a test cycle defined by US Environmental Protection Agency (EPA) to measure regulatory emissions of passenger cars. The details of this driving cycle can be found (https://www3.epa.gov/otaq/sftp.htm)

4.2.1 The European Program on Emissions, Fuels, and Engine Technologies (EPEFE)

This program was conducted by the European automobile and petroleum industries between 1993 and 1995 (Hublin et al. 1996). The goal of the study was to investigate the effect of density, poly-aromatics, cetane number, and T95 on PM, NOx, HC, and CO emissions. The tests were performed on a fleet of 19 vehicles (17 passenger cars, 2 light duty trucks), all fitted with oxidation catalysts. All testing was done with the MVEG test cycle (ECE15+EUDC).

Eleven fuels were categorized in three matrices to examine the effect of one specified fuel parameter in each matrix:

- Matrix 1**:** Fuels 1,2,3,4,5, to investigate the effect of polyaromatics (1 to 8%) and effect of density (828 to 855 g/cm3)

- Matrix 2:
  - (a) Fuels 1,7,10, 11, to investigate the effect of cetane number (50 to 58) at low polyaromatics (1%) and low density (828 g/cm3)
  - (b) Fuels 4,8,9, to investigate the effect of cetane number (50 to 58) at high polyaromatics (8%) and high density (855 g/cm3)
  - Matrix 3:
  - (a) Fuels 1,7,10, 11, to investigate the effect of T95 (325 to345 C) at low polyaromatics (1%) and low density (828 g/cm3)
  - (b) Fuels 4, 6, to investigate the effect of T95 (345 to 370 C), at high density (855 g/cm3) and high polyaromatics (8%)

Table 1 shows the detailed characteristics of eleven test fuels.

Table 1. Fuel properties in EPEFE study

EPD-X-94	1	2	3	4	5	6	7	8	9	10	11
Density (kg/m3)	829.2	828.8	857.0	855.1	828.8	855.5	826.9	855.1	855.4	826.6	827.0
Polyaromatics (%wt.)	1.0	7.7	1.1	7.4	7.1	7.6	1.0	7.3	8.0	1.1	0.9
T95 (0C)	344	349	348	344	346	371	326	345	344	347	329
Cetane number	51	50.2	50	50.3	50.6	50.2	49.5	54.8	59.1	58	57.1
Sulfur (ppm)	404	416	415	442	402	440	432	420	424	469	447

Individual vehicles in EPEFE showed different responses to variation in fuel properties, so emission results were averaged across all vehicles. The observed emission changes are summarized in Table 2.

Table 2. EPEFE averaged percentage changes in emission over combined ECE15+EUDC cycles

Emission effects due to parameters	PM	NOx	HC	CO
Density (827 to 855 g/cm^3)	+19%	-2%	+18%	+17%
Poly-aromatics (1 to 8% m/m)	+5%	+3%	-5.5%	-4%
Cetane (50 to 58)	+5%	+1%	-26%	-25%
T95 (325 to 370 ◦C)	+7%	-5%	-3%	+2%

4.2.2 Lange study

Lange et al. studied the effect of fuel parameter changes (sulfur, mono- and polyaromatics content, density, cetane number, and distillation properties) on PM and NOx emissions in a Mercedes-Benz 250 D (2.5 liters) engine typical of the 1991-1993 model years (Lange et al. 1993b). This passenger vehicle had a 5 cylinder naturally aspirated IDI (indirect injection) engine, and it was equipped with an EGR and an oxidation catalyst. Twelve tested fuels were designed in three matrices over the ECE15+EUDC cycle.

- Set 1**:** fuels 1-5, to investigate the effect of sulfur from other properties
- Set 2: fuels 6-9, to investigate the effect of fuel density from aromatics i.e., fuel pairs 6 and 9 or 7 and 8 were similar in density, but significantly different total aromatics content. There was no control on the variation in cetane number and distillation in this fuel set.
- Set 3: fuels 10-12, to investigate the effect of polyaromatics and distillation properties.

Table 3 shows the detailed properties of tested fuels.

Table 3. Fuel properties in Lange study

	Unit	Set 1					Set 2				Set 3		
Fuels		1	2	3	4	5	6	7	8	9	10	11	12
Density	g/ml	0.826	0.826	0.826	0.826	0.826	0.837	0.807	0.814	0.834	0.844	0.838	0.842
Distilation T90	0C	323	324	325	326	326	326	346	269	345	339	350	344
Cetane no.		56.4	56.4	56.5	56.4	56.1	50.0	70	54	59	48	51	50
Sulfur content	ppm m	<10	220	450	960	1800	500	<10	10	45	680	450	430
Polyaromatics	m %	0.07	0.66	1.29	3.25	3.13	3.3	<0.05	0.1	<0.1	5.7	3.0	3.0

The results of Lange et al's study did not show a significant change in NOx emission by changing fuel characteristics. Regarding PM emissions, it was found that sulfur content, density, and polyaromatics content affect PM emissions significantly. Table 4 shows the observed results in Lange et al study.

Table 4. Averaged percentage changes in PM emission over combined ECE+EUDC cycles in Lang et al. study

Emission effects due to parameters	PM emissions
Density (814 to 834 g/cm3)	+15%
Poly aromatics (3.3 to 5.7 % m/m)	+15%
Cetane (54 to 70)	0
T 90 (269 to 350 ◦C)	N/A (not applicable)
Sulfur level (960 to 1800 ppm)	+15%

4.2.3 Bertoli study

Bertoli et al. studied the effect of density and the sum of di- and tri-aromatics content on PM, NOx, HC, and CO emissions in a matrix of 14 fuels on a passenger vehicle (Bertoli, Giacomo, and Prati 1993). The tests were performed on a direct injection 2.5-liter displacement engine over a cycle representative of the ECE 15 cycle.

Table 5 shows the detailed tested fuel parameters.

Table 5. Fuel properties in Bertoli study

Fuel	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Density (g/ml)	0.829	0.836	0.806	0.827	0.820	0.811	0.821	0.829	0.827	0.841	0.814	0.817	0.814	0.818
Sulfur (ppm)	1300	9420	50	445	2	1	542	1050	1200	2320	2	1	1	1
Cetane no.	57.1	54	52.7	57	59	62.3	56.8	57.4	52.6	47	61	60.1	58.7	56
Aromatics [m%]														
mono-	10.7	14.54	5.67	18.10	14.80	6.1	4.1	4.1	7.8	9.8	5.1	4.9	4.2	3.9
di-	5.5	6.6	1.04	5.60	2.00	0.5	2.4	6.6	6.9	10.7	1	0.1	0.4	0.2
tri-	0.7	1.0	0	0.50	0.10	0	1.0	3.0	0.1	0.1	0	0	0	0
total	16.9	22.1	6.7	24.2	16.90	6.6	7.5	13.7	14.8	20.6	6.1	5.0	4.6	4.1
S-arom	0.9	5.0	0.3	0.3	0	0	0.3	0.7	1.3	1.4	0	0	0	0

Similar to Lange et al results, Bertoli et al. observed that density and di-tri aromatics correlated well with PM emissions. They found no correlation between T95 and emissions of any pollutant among their tested fuels; this result was in contrary with EPEFE results. They also found that an increase in cetane number resulted in reduced emissions of NOx, HC, and CO. The summary of their results is listed in Table 6.

Table 6. Averaged percentage changes in emission over combined ECE15 cycle in Bertoli et al. study

Emission effects due to parameters	PM	NOx	HC	CO
Cetane number (47.5 to 62.5)	No Correlation	-28%	-66%	-37.5%
Di and tri aromatics (0 to 9 % wt)	+60%	Not reported	Not Reported	Not Reported

4.2.4 JOULE 3 program

Thirteen fuels produced by an oil refinery in Finland under a research program funded by the EU were tested to observe the effect of fuel aromatic content on emissions (Zannis et al. 2008a). The tests were performed in 2 single cylinder diesel engines, one direct injection (Lister LV1) and the other one indirect injection (Ricardo E-6).

The test fuels were classified in different sets as below:

- Set 1: To investigate the effect of total aromatics, D1 (total aromatics: 1%), D3, D5, D4, D8, D9, D0 (total aromatics: 26.8%)
- Set 2: To investigate the effect of monoaromatics, D1 (monoaromatic content<1%), D3, D5, D6, D8, D9, D10 (monoaromatic content :12.2% wt)
- Set 3: To investigate the effect of aromatic structure, D4 (has di-aromatics) and D5 (has monoaromatics), both has same aromatic content, both has no tri-aromatics.

The detailed properties of tested fuels are shown in Table 7.

Table 7. Chemical composition and properties of conventional diesel fuels of JOULE 3 program

Reference Fuel	D0	D1	D3	D4	D5	D6	D8	D9	D10	D12
Blending Information	Road vehicle diesel	Base Fuel	Base+ diesel	Base+naphthenics	Base+diesel	Base+diesel	Base+diesel	Base+diesel	Base+diesel	Base+diesel+napthenics
Monoaromatics (%wt.)	22.2	<1.0	23	<1.0	4.4	6.1	7.5	9.4	12.2	10.1
Diaromatics (%wt.)	4.2	<0.1	0.4	5.4	0.6	1.0	1.3	1.6	1.8	4.2
Triaromaics (%wt.)	0.34	<0.02	0.03	<0.02	0.06	0.09	1.1	0.13	0.14	0.13
Total aromatics(%wt.)	26.8	<1.0	2.6	5.7	5.0	7.1	8.8	11.0	14.0	14.3
Cetane no.	52.5	64.05	64.5	60.8	62.25	62.05	61.1	60.25	59.95	57.95
Density, 15 ^{0}C (kg/m^{3})	833.7	779.6	785.8	789.1	792	798.2	804.4	810.5	816.4	815.2

The results of Joule 3 study are shown in Table 8.

Table 8. Averaged percentage changes in emission over combined ECE15 cycle in Joule 3 program

Emission effects due to parameters	soot	NO	CO	HC
Total aromatics (%wt) (<1% to 26.8%)	+46%	+50%	+7% (reason: high C/H ratio)	+50%
Mono aromatics (%wt) (<1% to 12.2%)	+50%	+25%	+6%	+45%

4.2.5 Bielaczyc study

This study was carried out in the laboratories of the BOSMAL Automotive R&D center in co-operation to institute of Internal Combustion Engines at Poznan University of Technology (Bielaczyc, Kozak, and Merkisz 2003). The effect of cetane number and sulfur content of the fuels were studied on emissions in a direct injection (DI) common rail, turbocharged passenger car, equipped with an oxidation catalyst and electronically controlled exhaust gas recirculation. The engine was 4 cylinder and with 2 L displacement volume. The tests were carried out under Urban driving cycle and extra-urban driving cycle (UDC, EUDC).

Eight tested fuels were classified into two matrices to investigate the effect of one specified parameter in each category. The matrices are as below:

- Matrix 1: 4 fuels. To investigate the effect of sulfur content (<5, 50, 350, 2000 ppm)
- Matrix 2: 4 Fuels, to investigate the effect of cetane number (45,50, 55,63)

The detailed properties of tested fuels are listed in Table 9 and Table 10.

Table 9. Properties of fuels with different sulfur content in Bielaczyc study

Fuel code	TF-1S	TF-2S	TF-3S	TF-4S
Sulfur, ppm	2000	350	50	<5
Cetane no.	52	52	52	52
Density at 15 ^{0}C, g/ml	0.815	0.815	0.815	0.815
Aromatics, % (v/v)	5.1	5.1	5.1	5.1

Table 10. Properties of fuels with different cetane number in Bielaczyc study

Fuel code	TF-1C	TF-2C	TF-3C	TF-4C
Sulfur, ppm	300	300	200	100
Cetane no.	45	50	55	63
Density at 15 ^{0}C, g/ml	0.8084	0.8282	0.8244	0.8270

The results of this study are summarized in Table 11.

Table 11. Averaged percentage changes in emission over combined ECE15 cycle in Bielaczyc study

Emission effects due to parameters	PM	NOx	HC	CO
Sulfur content (% in comparison to sulfur free)	Sulfur free< moderate sulfur (+40%)<high sulfur (2000 ppm) (+60%)	No	No	Sulfur free< moderate sulfur (+20-30%)<high sulfur (2000 ppm) (+50%)
Cetane (45 to 63)	No	-6%	-25%	-26%

4.2.6 CRC study

Coordinating Research Council (CRC) (Hochhauser 2008) prepared a report including a review of the literature investigating the impact of fuel parameters on engine emissions.

CRC review results indicated that reducing density caused a reduction in HC, CO, and PM. Reducing polyaromatic hydrocarbon resulted in decreasing in NOx and PM and rising HC, and CO. Increasing cetane number decreased CO and HC emissions while increasing PM. The most obvious effect of reducing sulfur was on decreasing the sulfate portion of particulate matter.

Moreover, decreasing the sulfur content reduced the number of PM especially in the nanometer range. In light duty diesel vehicles, reducing volatility (T90, or T95) resulted in a slight decrease in PM, no change in HC and CO, and mixed effects on NOx. Emissions.

4.2.7 Summary

Five studies (Hublin, Lange, Bertolie, Joule3, and CRC) found that an increase in aromatic content (poly, mono, or di) resulted in higher PM emissions. A similar trend was found between density and PM emission in Hublin, CRC, and Lange studies. Although the impact of aromatics on PM emissions has been consistent across different studies, the magnitude of aromatic effect on PM emission depends on engine design and technologies.

Hublin, Zannis, and CRC studies showed that increasing aromatic content will result in a rise in NOx emissions. A consistent effect of cetane number on NOx, HC, and CO was found by CRC, Hublin, Bertoli, and Bielaczyc, they showed increasing cetane number will lead to a decrease in NOx, HC, and CO emissions. Also, the effect of decreasing sulfur on improving PM emissions was found by CRC, Lange, and Bielaczyc.

In contrast to the above results, was no correlation between some fuel parameters and emissions. Engine design, vehicle technologies, engine operating conditions, and the test cycles have significant roles in the effect of fuel parameters on emissions. As a result, in some cases it is not possibleto isolate the effect of fuel parameters on emissions, without further testing.

A summary of the magnitude and directional changes of emissions from changing fuel properties in is presented in Table 12 to Table 15.

Table 12. Effect of density on engine emissions

Reference	Density range (g/cm^3)	CO	HC	PM	NOx
(Hublin et al. 1996)	827 to 855	+17%	+18%	+19%	-2%
(Lange et al. 1993a)	814 to 834	---------	------	+15%	------

Table 13. Effect of cetane number on engine emissions

Reference	Cetane range	CO	HC	PM	NOx
(Hublin et al. 1996)	50 to 58	-25%	-26%	+5%	+1%
(Lange et al. 1993a)	54 to 70	---------	------	0	------
(Bertoli, Giacomo, and M.V. 1993)	47.5 to 62.5	-37.5%	-66%	----------	-28%
Bielaczyc (2003)	45 to 63	-26%	-25%	-------	-6%

Table 14. Effect of polyaromatics on engine emissions

Reference	Polyaromatic range (%m/m)	CO	HC	PM	NOx
(Hublin et al. 1996)	1 to 8%	-4%	-5.5%	+5%	+3%
(Lange et al. 1993a)	3.5 to 5.7%	---------	------	+15%	------
(Bertoli, Giacomo, and M.V. 1993)	0 to 9% (Di and Tri)	----------	----------	+60%	-----------
(Zannis et al. 2008b)	1 to 26.8% (Total)	+7%	+50%	----------	+50%

Table 15. Effect of sulfur contents on engine emissions

Reference	sulfur range (ppm)	CO	HC	PM	NOx
(Lange et al. 1993a)	960 to 1800	--------	-----------	+15%	-------
(Bielaczyc et al. 2003)	<5 to 50, 350	---------	------	+40%	------
(Bielaczyc et al. 2003)	<5 to 2000	----------	----------	+60%	-----------

The following table represents a summary of knowledge of the impact of diesel fuel property changes on exhaust emissions in light-duty diesel engines.

Table 16. Summary of changing diesel fuel properties on emissions

Note: 0 means no effect/data are lacking to define the effect/data exists but effect is mixed

Emission/parameter	Density↓	Cetane↑	Aromatics↓	Sulfur↓	Volatility↓
HC	↓	↓	0	0	0
CO	↓	↓	0	0	0
NOx	0	↓	↓	0	0
PM	↓	0	↓	↓	↓

4.3 Effect of alternative fuels on diesel engine air pollutant emissions

As discussed in section 3, there are many alternative fuels that can be used in a blend with conventional diesel fuel or in pure form with no or slight modifications to diesel engines. GTL fuels may offer lower emissions of CO, HC, NOx, and PM, and smoke due to their unique characteristics. The interest in biodiesel as an alternative fuel is due to its potential to decrease greenhouse gas emissions, its biodegradability, and its potential to decrease PM emission in diesel engines (Hassaneen et al. 2012).Ethanol and other oxygenate fuels are other examples of renewable alternative fuels that can be used in diesel engines.

There have many efforts to observe the effect of applying different mixtures of alternative fuels on diesel engine emissions. A full list of studies that have been reviewed in this report can be found in Appendix. However, a summary of exhaust emission results of most important studies is listed in

Table *17*.Almost all the authors reported emission improvements while using GTL and its blends with diesel fuel or biodiesel for parameters such PM, NOx, HC, and CO. . GTL diesel typically has high H/C ratio, low aromatic content, low sulfur content, and high cetane number, which lead to reductions of CO and HC in comparison to conventional diesel fuel. The results show that by increasing GTL ratio in the diesel-GTL blend the magnitude of emission reductions increases. By adding biodiesel to GTL, the amount of emission reductions is further increased.

Owing to higher cetane number and lower aromatic content of GTL fuel in comparison to fossil diesel fuel, the combustion temperature is maintained which provides significant NOx reduction relative to biodiesel and diesel. When the ratio of GTL in GTL-diesel blend is increased NOx reductions will also increase. The addition of biodiesel to GTL fuel causes an increase in NOx emissions and a decrement in HC, CO, and PM emissions in comparison to pure GTL. Regarding

PM and smoke, lower emission for GTL relative to diesel fuel were reported. These reductions are likely due to the lower sulfur and aromatic content of GTL fuel relative to fossil diesel fuel.

Table 17. Summary of alternative fuels effect on diesel engine emissions

Reference	Fuel	Cetane no	Sulfur (mg/kg)	Aromatic (%wt)	Oxygen (%wt)	PM	NOx	HC	CO
(Abu-Jrai et al. 2009)	ULSD to GTL	53.9 to 79	46 to <10	24.4 to 0.3 (Total)	-----	------	-75%	------	+25%
(Abu-Jrai et al. 2006)	ULSD to GTL	53.9 to 79	46 to 0.05	24.4 to 0.3 (Total)	-----	-------	-22%	------	--------
(Wu et al. 2007)	DF to GTL	51.7 to 75	0.0403 to 0.0003	27.7 to 1.4 (Total)	------	-27.6%	-12.1%	-20%	-38%
(Wang et al. 2009)	DF to GTL	53.4 to 74.7	50 to <1	17.4 to <0.1	-----	-33%	-13%	- 31-55%	-38%
(Kitano et al. 2005)	DF to GTL	53.4 to 71.5	33 to <1	18.9 to <0.1 (Vol)	-------	-50-70%	-45%	-50%	-60-75%
(Ushakov et al. 2013)	Marine gas oil to GTL	51.9 to 76.6	500 to <5	------	0 to 0.27	-16%	-19%	+10%	-25%
(Hassaneen et al. 2012)	DF to GTL & RME	53.6 to 65.1 & <55	41 to >10 & >10	--------	0 to 0.8 & 11	GTL -32% RME -65%	RME +40%	RME -50%	GTL -26% RME -70%
(Moon et al. 2010)	DF to GTL & GTL+BD40	54 to 84 & 70	3 to <1 & <1	1.7 to <0.1 &-- (poly, % wt)	-------	--------	GTL<<DF &++BD (increase)	GTL<<DF &++BD (decrease) GTL+BD40: -45%	GTL<<DF &++BD (decrease) GTL+BD40: -35%
(Yehliu, Boehman, and Armas 2010)	ULSD to GTL & B100	47.3 to 80.8 & 47.7	15 to <2 & 2-5	------	0 to 0 & 10.79	GTL: -30% B100: +80%	GTL: -33% B100: -6%	GTL: -75% B100: -10%	GTL: -63% B100: -7%
(Mori, Sorimachi,	DF to BD100	-----	------	-----	-------	------	+36.5%	-74.7%	-21%

and Eguchi 2015)									
(Hwang et al. 2014)	DF to BD	50.88 to 51.34	3.93 to 1	-----	-----	-----	-----	-61%	-63%
(Armas, Garcia-Contreras, and Ramos 2013)	DF to GTL & BD	54.2 to 89.2 & 65.6	-----	------	0.66 to 0 & 11.03	GTL: -60% BD: -70%	BD: -12.5%	GTL: -33% BD: -46%	GTL: -52% BD: -14%
(Xinling and Zhen 2009)	DF to GTL & DME	51.7 to 75 & 55-66	0.04 to 0 &0	27.7 to 1.4 &0	0 to 0 & 34.8	GTL: -85.3%	GTL: -15.6% DME:-48.2%	GTL: -15.7% DME:-40.1%	GTL: -21.2 %
(Valentino, Iannuzzi, and Corcione 2013)	DF to Butanol 100	52 to 22	-------	-------	0 to 21.6	------	------	--------	-33%

Regarding emissions test results for biodiesel, the majority of studies reported reductions of HC, CO, and PM when using biodiesel rather than fossil diesel fuel. Biodiesel has higher oxygen content than conventional diesel fuel, which makes biodiesel a fuel with high combustion quality. Biodiesel is free of sulfur and aromatics, so blending biodiesel with diesel fuel reduces PM emissions from the engine. Biodiesel typically has a slightly higher cetane number than diesel fuel which causes a reduction in ignition delay. Moreover, biodiesel has superior lubricity properties, which decreases engine wear and tear and increases engine efficiency. Besides all the advantages, biodiesel produces relatively higher NOx emissions than diesel fuel. The reason for high NOx emissions of biodiesel is attributed to its high oxygen content (Hassaneen et al. 2012, Atabani et al. 2012).

Regarding emissions test results for DEE or DME, the results of studies showed that adding DEE or DME to diesel fuel resulted in a reduction in CO and NOx. DME and DEE have high cetane number and oxygen content, so they decrease combustion temperature and reaction time, which in turn reduces NOx emissions. Many researchers have reported that it is possible to have a smokeless combustion with an oxygen content of more than 30% by mass (Patil 2015).

Results of using methanol in a blend with diesel fuel showed a reduction in NOx emissions due to the high oxygen content of methanol which will result in decreasing combustion temperature (Masimalai 2014).

Coordinating Research Council (CRC, Hochhauser 2008) prepared a report including a review of the literature on fuel effects on vehicle emissions. The results in CRC report showed that using biodiesel decreased HC, CO, and PM emissions. However, biodiesel resulted in NOx increase. The effect of biodiesel on decreasing PM, HC, and CO was stronger than increasing NOx. In particulate matter, the soot component decrease was responsible for the overall reduction. Regarding the use of other oxygenates in diesel vehicles, no clear results have been found in CRC study. It is expected that all oxygenates show similar emission behavior due to their high oxygen content, however, HC, CO, and NOx emissions showed mixed results. The only conclusion that was valid in all studies was that using oxygenates decreases PM. Further studies are needed on oxygenate fuels. FT diesel fuels showed similar results in all studies addressed by CRC report; using FT fuel caused a decrease in all emissions of CO, HC, NOx, and PM.

The following table represents a summary of knowledge of the impact of alternative fuel on exhaust emissions in light-duty diesel engines.

Table 18. Summary of effect of using alternative fuels on emissions

Emission/parameter	FT fuel	Biodiesel
HC	↓	↓
CO	↓	↓
NOx	↓	↑
PM	↓	↓

5 Gasoline fuel

5.1 Gasoline key properties

- **Oxygen-** Presence of oxygen molecule in gasoline reduces unburned hydrocarbon emissions as wells as carbon monoxide. methyl tert-butyl ether (MTBE) with a chemical formula of $C_5H_{12}O$ or ethanol with a chemical formula of C_2H_5OH are two oxygenates that are added to gasoline to enhance the exhaust emissions (Yacobucci 2006). Moreover, addition of these oxygenates improves octane rating. Nowadays, MTBE is less desirable than ethanol because it was found as polluting underground supplies in the US (Gray and Handwerk 2001).
- **Toxic compounds in gasoline-** Lead is one of the toxic metals that has been added to gasoline for a long time as Tetraethyl lead (TEL) to increase gasoline octane rating (Yacobucci 2006). Lead exhaust emissions from internal combustion engines is a toxic air pollutant and is a serious threat to human health (Gray and Handwerk 2001). Manganese is an another metal that its high level of inhalation could be toxic to human. Similar to lead, manganese compounds like Methylcyclopentadienyl manganese tricarbonyl (MM*T)* have been added to gasoline to increase octane rating (Gray and Handwerk 2001).

  Since the benzene (aromatic compound) present in the gasoline is a carcinogenic, its amount in gasoline should be controlled. The combustion of benzene results in formation of toxic compounds that are harmful to human health,
  like aldehydes, butadiene, and polycyclic aromatic hydrocarbons (PAHs) (Gray and Handwerk 2001).

Olefins are reactive hydrocarbons that can react with nitrogen oxides in the presence of sunlight and form photochemical smog. As a result, the amount of olefin compound in the gasoline should be limited (Gray and Handwerk 2001).

- **Oxidation Stability-** It is likely that oxidation process occurs when gasoline is stored in tanks. As a result of the oxidation degradation, gum (sticky resins) could be formed which can precipitate out of gasoline and lead to fouling of engine compartments, which will in turn reduces engine efficiency. To increase gasoline oxidation stability, different anti-oxidation additives are added to gasoline (Jones and Pujado 2006).
- **Gasoline Sulfur Content-** Gasoline is normally presents in gasoline and it should be removed, otherwise will cause problems. The sulfur compounds in the gasoline converts to sulfur oxide emissions through combustion. Sulfur oxide emissions are harmful environmental pollutants and could react with water vapor to form an acidic corrosive gas that can hurt engine system. Many jurisdictions limit the sulfur content of gasoline to maximum 10 ppm (will be further discussed in section 6) (Yacobucci 2006).

- **Reid Vapor Pressure (RVP)-** Reid Vapor Pressure is a physical property used to present the volatility of gasoline. It is the vapor pressure at 37.8 °C (100 °F) of gasoline and is determined by standard method ASTM D323[17]. Reid Vapor Pressure is an important parameter because can impact the starting and warm-up of spark ignition internal combustion engines. To control the evaporative emissions from gasoline engines, there are many regulations that limit RVP (Liptak 1999). The gasoline should be volatile enough to guarantee easy starting and at the same time the volatility should meet standards to limit air pollutant emissions.
- **Volatility-** The vapor pressure of gasoline is a key property for the level of emissions of volatile compounds. Volatility shows how easily a fuel evaporates. Volatility is an extremely important property because combustion takes place in the gas environment, where gasoline must vaporize to initiate the combustion. A fuel's volatility can be expressed by distillation curves, vapor pressure, or vaporization enthalpy. Gasoline contains hundreds of compounds and each of them has different boiling points. The volatility of gasoline is determined based on Reid vapor pressure (fuel's vapor pressure at 37.8° C) and distillation curves (Mohd Yusoff et al. 2015).
- **Octane Rating-** Octane number indicates the fuel resistance to self-ignition or the indicator of gasoline's anti-knocking strength. Research octane number (RON) correlates

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[17] ASTM D323: Standard Test Method for Vapor Pressure of Petroleum Products (Reid Method) (http://www.astm.org/Standards/D323.htm)

with commercial automotive spark-ignition engine anti-knock performance under mild conditions operation, while motor octane number (MON) represents operations under severe conditions. Antiknock index (AKI) is defined as the mean of MON and RON. Fuel with high octane number prevents from premature ignition that causes knocking and will, in turn, can damage the engine (Mohd Yusoff et al. 2015).

5.2 Effect of fuel parameters on gasoline engine air pollutant emissions

5.2.1 CRC study

Coordinating Research Council (CRC) (Hochhauser 2008) prepared a report that included a review of the literature investigating the impact of fuel parameters on engine emissions. . A summary of their results for light duty diesel vehicles from reviewing many studies is presented here. CRC results showed that decreasing sulfur in gasoline resulted in decreased HC, CO, NOx, and toxic emissions like benzene, and 1,3 butadiene. Decreasing aromatic content in CRC study caused a reduction in HC, CO, and toxic emissions like benzene, however, it caused an increase in NOx emissions. Benzene and non-benzene aromatics in gasoline both contribute to exhaust benzene emissions. However, the contribution of benzene to benzene emissions is almost 10 times higher than the contribution of non-benzene compounds. Therefore, decreasing benzene content in gasoline resulted in a reduction of toxic emissions of benzene. Decreasing olefin content led to a decrease in NOx and toxic emissions like 1,3 butadiene and an increase in HC emissions. Decreasing Reid Vapor Pressure (RVP) showed a decrease in HC and CO emissions. Decreasing volatility (T50 and T90) resulted in a reduction of HC, CO, and toxic emissions and increase in NOx emissions. The addition of oxygenates to gasoline decreased HC, CO, and overall toxic emissions and increased NOx emissions. Although blending oxygenates with gasoline decrease the total toxic emissions, aldehyde emissions may increase depending on the type of oxygenate that is used. For example, MTBE increases formaldehyde and ethanol increases acetaldehyde.

5.2.2 EPA study

The US EPA (US EPA, 2013) tested the effect of gasoline fuel properties on regulated and air toxic exhaust emissions from Tier 2 LDVs, with 27 different fuel formulations tested. The study tested the addition of ethanol at four levels of 0, 10, 15, and 20% (vol), and generally the results revealed that increasing the ratio of ethanol in the blend increases Nox, HC, and CO emissions. The study also tested the effect of volatility by using RVP, T50, and T90 and concluded that increasing the volatility increases the level of emissions. Moreover, the results showed that by increasing the aromatic contents, NOx, HC, and CO emissions are increased.

5.2.3 Other studies

CONCAWE (Goodfellow et al. 1996) has performed a study to observe the effect of gasoline quality on emissions of advanced gasoline vehicles in the market in 2002. Three direction injection (DI) cars and one advanced multipoint injection (MPI) car were covered in this study. The tests were performed under a composite test cycle. Experiments consisted of eight fuels with different volatility (E70 in the range of 22-38%), final boiling point (in the range of 176-197 C), aromatic content (in the range of 26-38%), olefin content (in the range of 5-14 %), and sulfur content (in the range of 40-50 ppm). The vehicle specifications are listed in Table 19.

Table 19. Vehicles specifications in CONCAWE study (Goodfellow et al. 1996)

	Car A	Car B	Car C	Car D
Displacement (cm^3)	1998	1796	1997	1598
Max Power (kw @ rpm)	103@5500	85@5500	107@6000	81@5800
Inertia class (kg)	1250	1360	1470	1360
No of Cylinder	4	4	4	4
Valves per cylinder	4	4	4	4
Max torque (Nm @ rpm)	200@4250	175@3750	193@4100	155@4400
Compression ration	10.0:1	10.5:1	11.4:1	12.0:1
Combustion/injection/control system	Stoichiometric DI	MPI Variable valve actuation	Lean DI	Lean DI
Catalyst system	TWC	TWC	TWC+ NOx trap	TWC+ NOx trap
Emissions Compliance	Euro-3	Euro-4	Euro-3	Euro-4

In another study conducted by EPEFE (Stradling et al. 2004), the effect of aromatics, and volatility (E100) was evaluated in sixteen European gasoline vehicles from seven different manufacturers. Fuel injection system in vehicles was either MPI or single point injection (SPI), some engines were equipped with EGR. The tests were performed under a composite test cycle. Nine fuel with varying aromatics (three different level of 20, 35, 1nd 50% V/V) and volatility (three different levels of E100: 35, 50, and 65% V/V) were studied.

Two main programs that have studied the effect of sulfur content in gasoline on emissions are EPEFE and CONCAWE. The EPEFE program (Petit et al. 1996) was joint by European automotive (ACEA) and the oil (EUROPIA) industries. In this program, the effect of sulfur content in four different fuels was studied on the emissions of 16 vehicles from seven different manufacturers.

The tests were performed under a composite test cycle. The sulfur levels tested were 18, 95, 182, and 382 ppm, while other fuel parameters were held constant.

The CONCAWE study (Rickeard et al. 2003) aimed to understand the effect of sulfur in gasoline on emissions from advanced gasoline vehicles technologies in the market in 2002. The specifications of four vehicles used in this study are shown in Table 20. The tests were performed under combined NEDC. The sulfur content was changed at four levels (4, 9, 48, and 148 ppm) in 4 different fuels, and other parameters were kept constant.

Table 20. Characteristics of test vehicles in CONCAWE study (Rickeard et al. 2003)

	Car A	Car B	Car C	Car D
Displacement (cm^3)	1998	1796	1997	1598
Max Power (kw @ rpm)	103@5500	85@5500	107@6000	81@5800
Inertia class (kg)	1250	1360	1470	1360
No of Cylinder	4	4	4	4
Valves per cylinder	4	4	4	4
Max torque (Nm @ rpm)	200@4250	175@3750	193@4100	155@4400
Compression ration	10.0:1	10.5:1	11.4:1	12.0:1
Combustion/injection/control system	Stoichiometric DI	MPI Variable valve actuation	Lean DI	Lean DI
Catalyst system	TWC	TWC	TWC+ NOx trap	TWC+ NOx trap
Emissions Compliance	Euro-3	Euro-4	Euro-3	Euro-4

Alcohols are preferred alternative fuels for gasoline engine because they do not need major engine modifications. Many researchers have evaluated the impact of blending ethanol with gasoline on spark ignition engine performance and emissions.

Singh et al. (Singh et al. 2016a) studied the effect of blending ethanol (5, 10, and 20%) with gasoline in a 4 cylinder, MPFI gasoline engine. The detailed specifications of the engine are listed in Table 21, and fuel properties are listed in Table 22.

Table 21. Engine specifications in Singh et al.'s study (Singh et al. 2016a)

Engine Type	Gasoline Engine
Fuel system	Multi-point fuel injection
Engine size	1196 cc
No. of cylinders * valve/cylinder	4*4
Compression ratio	9.9

Maximum torque	101 Nm @3000 RPM
Maximum power	54 kW @6000 RPM

Table 22. Fuel properties in Singh et al.’s study (Singh et al. 2016a)

S.No	Properties		Gasoline (G)	E5	E10	E20
1	Density @ 15 ^{0}C, kg/m3	-	747.7	749.7	751.0	755.5
2	Distillation					
	• Recovery up to 70 ^{0}C (%vol.)		29.5	37.6	47.6	44.4
	• Recovery up to 100 ^{0}C (%vol.)		50.2	52.8	56.1	67.1
	• Recovery upto 150 ^{0}C (%vol.)	Min	88.0	88.6	89.6	90.2
	• Final boiling point, ^{0}C	Max	178.8	178.8	180.2	175.5
	• Residue, (%vol)	Max	1	1	1	1
3	Existent gum, g/m3	Max	8.0	10.0	12.0	28.0
4	Reid Vapour Pressure at 38 ^{0}C, kPa	Max	53.6	59.5	61.4	59.9
5	Vapor lock index					
	• Summer	Max				
	• Other months	Max	742.5	858.2	947.2	909.8
6	Copper strip corrosion (for 3 hr @ 50 C)	Max	1a	1a	1a	1a
7	Oxidation stability, minutes	Min	>360	>360	>360	>360

8	Research Octane Number (RON)	Min	91.3	92.9	94.6	98.4
9	Motor Octane Number (MON)	Min	81.6	82.2	83.5	85.3
10	Benzene content, % volume	Max	.56	.52	.50	.42
11	Olefin content, % volume	Max	9.0	8.8	8.5	7.0
12	Aromatic content, % vol	Max	33.0	30.1	27.0	25.8
13	Ethanol content, % volume	Max	0	5	10	20
14	Sulphur content, total, % mass	Max	0.001	0.001	0.001	0.001
15	Lead content, g/l	Max	0.00001	0.00001	0.00001	0.00001
16	Calorific Value, kJ/kg	-	43000	42200	41400	39800

In another study, Shanmugam et al. (Shanmugam et al. 2009) studied emissions from combustion of E10 compared to pure gasoline in three gasoline engines. Engine specifications are listed in Table 23. Properties of E10 is listed in Table 24.

Table 23. Engine specifications in Shanmugam et al.'s study (Shanmugam et al. 2009)

Engine Parameters	#1	#2	#3
No. of cylinders	4		
Bore * stroke (mm)	75*79		75*67.5
Capacity (cc)	1396 (1.4 L)		1193 (1.2 L)
Cylinder/engine arrangement	Inlet/transverse		
Valve configuration	2V SOHC		
Compression ratio	10:1		
P max (kW @ rpm)	62.5 @ 5500	51.5 @ 4800	48 @ 5000
Max engine speed (rpm)	6200	5300	5300
Max torque (N.m @ rpm)	120 @ 3500	124 @ 2600	102 @ 2600
Emission compliance	Bharath stage 3		
EMS	MPFI-Sequential Injection		

Table 24. Properties of 10% ethanol blended fuel in Shanmugam et al.'s study (Shanmugam et al. 2009)

Parameters	Unit	Value
Density at 15 ^{0}C	Kg/m3	760.9
Initial boiling point	^{0}C	45
Recovery up to 70 ^{0}C	% vol.	43
Recovery up to 100 ^{0}C	% vol.	55
Recovery up to 150 ^{0}C	% vol.	88
Final boiling point	^{0}C	177
Residue	% vol.	1

RON		97
Reid vapor pressure	kPa	50
Ethanol content	% vol.	10
Oxygen content	% mass	3.5

Kumar and Babu (Kumar, Khatri, and Babu 2008) also studied the emissions of combustion E10, E30, and E70 compared to pure gasoline in a 500 cc, water cooled single cylinder SI engine. However, fuel properties were not mentioned.

5.2.4 Summary of gasoline engine studies

Goodfellow et al. and Stradling et al. found that an increase in volatility and a decrease in aromatic content resulted in reduced HC emissions (Goodfellow et al. 1996, Stradling et al. 2004). However, the magnitude of aromatic and volatility effect on HC emission depends on engine design and technologies. There was no correlation between volatility and aromatic content and other emissions. There was no clear and general relation between olefin content and emissions. As discussed earlier in this section, the results of CRC study were differed from these results.

The effect of sulfur content on HC, CO, and NOx emissions were clear in CRC, Petit at al. and Rickeard et al. study. Decreasing sulfur content improved toxics, CO, HC, and NOx emissions in gasoline engines (Petit et al. 1996 , Rickeard et al. 2003).

Singh et al., Shanmugam et al., and Kumar et al. reported that addition of ethanol to gasoline decreases CO and HC emissions, with a penalty of increasing NOx emissions (Kumar et al. 2008, Shanmugam et al. 2009, Singh et al. 2016a). The high octane number and oxygen content of ethanol improve combustion efficiency which in turn decreases CO and HC emissions, with the penalty of increasing NOx emissions. These results were similar to CRC study. However, the EPA study results on ethanol were completely different from other studies, showing increasing emissions of all pollutants as ethanol levels were increased.

As explained in Section 4.2.7, different engine design, vehicle technologies, engine operating conditions, and the test cycles between studies make it difficult to observe correlations between changes some fuel parameters and engine emissions.

A summary of the magnitude and directional changes of emissions from changing fuel properties in is presented in Table 25 to Table 28.

Table 25. Effect of volatility on gasoline engine emissions

Reference	Volatility range (%v/v)	CO	HC	NOx	PM
(Stradling et al. 2004)	E70: 22 to 38	+4%	-10%	----	-----
(Goodfellow et al. 1996)	E100: 35 to 50	-9%	Up to -42%	Up to +20%	-------
(Goodfellow et al. 1996)	E100: 50 to 65	+7%	Up to -1.4%	-----	-----

Table 26. Effect of Aromatic content on gasoline engine emissions

Reference	Aromatic range (%v/v)	CO	HC	NOx	PM
(Stradling et al. 2004)	38 to 26	-----	-5%	-24%	-----
(Goodfellow et al. 1996)	50 to 20	-18%	Up to -30%	Up to +15%	-------

Table 27. Effect of sulfur on gasoline engine emissions

Reference	sulfur range (ppm)	CO	HC	NOx	PM
(Petit et al. 1996)	382 to 18	-10%	-10%	-10%	------
(Rickeard et al. 2003)	148 to 4	NS	NS	NS	-----

Table 28. Effect of ethanol on gasoline engine emissions

Reference	Ethanol content	CO	HC	NOx	PM
(Singh et al. 2016a)	E5	-12%	-8%	+4%	-----
(Singh et al. 2016b)	E10	-50%	-30%	+78%	-----
(Singh et al. 2016b)	E20	-65%	-38%	+109%	-----
(Shanmugam et al. 2009)	E10	-13%	-19%	+16%	-----
(Kumar et al. 2008)	E10	-74%	-----	+16%	------
(Kumar et al. 2008)	E30	+28%	-----	+67%	-----
(Kumar et al. 2008)	E70	+28%	+60%	-----	------

The following table represents a summary of knowledge of the impact of fuel property changes on exhaust emissions in gasoline engines.

Table 29. Summary of changing gasoline fuel properties on emissions

Note: 0 means no effect/data are lacking to define the effect/data exists but effect is mixed

Emission/parameter	Aromatics↓	Benzene↓	Olefins↓	Sulfur↓	Oxygenates↑	RVP↓	Volatility↓
HC	↓	0	0	↓	↓	↓	↓
CO	↓	0	0	↓	↓	↓	↓
NOx	↑	0	↓	↓	↑	0	↑
Toxics	↓	↓	↓	↓	0	0	↓

6 International standards

The following section provides an overview of standards and regulations for fuel quality in Canada and relevant jurisdictions around the work. Standards for gasoline and diesel fuels are listed in Table 30 and Table 31 , respectively.

6.1 Canadian standards and regulations

6.1.1 Federal

Standards for fuel composition and quality in Canada are developed by the Canadian General Standards Board (CGSB). CGSB is a federal government organization that creates standards in support of the economic, regulatory, health, safety and environmental interests of government, industry, and consumers. The goal of setting the standards is to ensure that fuels meet specific standards that guarantee the efficient operation of the engine (Row and Doukas 2008).

CGSB standards for gasoline and diesel are CAN/CGSB 3.5[18], and CAN/CGSB 3.517[19], respectively. These standards in Canada are voluntary unless specified as mandatory in legislation.

The parameters included in these standards are commercial and can be regulated provincially and federally, where the most restrictive regulations generally apply. The stipulation for enforcement in federal level in Canada is on *Canadian Environmental Protection Act, 1999*[20] (CEPA 1999). CEPA 1999 specifies the minimum and maximum limits for fuel characteristics.

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[18] *Automotive Gasoline* (CAN/CGSB-3.5-2011): http://www.scc.ca/en/standardsdb/standards/26260

[19] Automotive Low-Sulfur Diesel Fuel (CAN/CGSB-3.517):

2015 version http://ccinfoweb2.ccohs.ca/legislation/documents/stds/cgsb/galsd15e.pdf

[20] *Canadian Environmental Protection Act, 1999:* www.ec.gc.ca/lcpe-cepa/default.asp?lang=En&n=26A03BFA-1

This section presents the Canadian standards and regulations developed under CGSB and CEPA 1999 for gasoline and diesel in two different sections.

6.1.1.1 Gasoline

The CGSB standard for *Automotive Gasoline* (CAN/CGSB-3.5-2011) applies to four grades of gasoline to be used in spark-ignition engines under a range of environmental conditions. The gasoline fuels under this standard may contain limited concentrations of alcohols or aliphatic ethers. However, no lead or phosphorous compounds may be added (Row and Doukas 2008).

The fuel parameters that are regulated under CEPA 1999, are benzene with the limit of less than 1% by volume, lead with the limit of less than 5 mg/L, phosphorous with the limit of less than 1.3 mg/L, renewable fuel with the minimum and maximum limits of 5 and 10% by volume, and sulfur with the limit of 30 ppm pool annual average until December 31, 2016. Starting from January 1, 2017 the pool average should not exceed 10 mg/kg. The main renewable fuel which is used in Canada is ethanol (Row and Doukas 2008).

6.1.1.2 Diesel

The CGSB standard for Automotive Low-Sulfur Diesel Fuel (CAN/CGSB-3.517) applies to two types of diesel fuel intended to use in diesel engines. The only parameter that is regulated federally in Canada is sulfur with the maximum level of 15 ppm (Row and Doukas 2008).

6.1.1.3 Fuel quality monitoring and enforcement

The responsibility of fuel quality enforcement at the federal level is specified in Environment Canada's Compliance and Enforcement Policy for CEPA 1999. At the federal level, most regimes adhere to mandatory self-monitoring. Every fuel producer/importer should submit a report to the Minister, and the report should include the volume of fuel produced in the batch, date of fuel production, and fuel specifications. The copy of each report should be kept for 5 years after submission (Row and Doukas 2008).

6.1.2 Provincial

All the provinces in Canada try to only meet the mandatory parameters of federal fuel regulation, with the exception of Manitoba which requires sellers of gasoline and diesel to adhere to the established industry voluntary standard (Row and Doukas 2008).

6.2 US standards and regulations

6.2.1 Federal

In the US, ASTM International has the responsibility to set specifications and standards for fuels. In fact, ASTM specifies the accepted range for different fuel parameters. After the standard is agreed by ASTM, the federal government through the U.S. Environmental Protection Agency (EPA) also sets standards. EPA derives its authority from the Clean Air Act (CAA)[21]. When state legislatures adopt that standard by reference, the standard becomes law in a particular state. The states then set regulations to enforce and monitor the fuel parameters. Specifications and requirements that EPA sets replace state requirements, except in the case of California, that has the authority from CAA to set its own fuel requirements. The reason is that California has started to set environmental regulation before the federal government and has a longer history in this aspect (Row and Doukas 2008, Kavanagh 2014).

6.2.1.1 Gasoline

ASTM D48-14[22] Standard Specification for Automotive Spark-Ignition Engine Fuel covers characteristics of automotive fuels for use in ground vehicles equipped with spark-ignition engines over a wide range of operating conditions. The eight parameters that are regulated in federal level are sulfur, benzene, vapor pressure, Oxygen content, lead, phosphorous, T50 and T90 distillation temperatures (Row and Doukas 2008, Kavanagh 2014).

6.2.1.2 Diesel

ASTM D 975-15[23] is the Standard Specification for Diesel Fuel Oils in the US. The only diesel parameters that have been regulated federally in the US are sulfur, cetane number, and aromatic content (Row and Doukas 2008, Kavanagh 2014).

6.2.1.3 Fuel quality monitoring and enforcement

The responsibility of monitoring and enforcement of fuel quality in the US is on both federal government and states (many of them not all). The high penalty and random inspections in the US decrease the instances of noncomplying fuel. EPA also uses other tools to guarantee the fuel quality in the US, these tools are as below:

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[21] Clean Air Act (CAA): https://www.epa.gov/laws-regulations/summary-clean-air-act

[22] ASTM D48-14 : Standard Specification for Automotive Spark-Ignition Engine Fuel (https://www.astm.org/Standards/D4814.htm)

[23] ASTM D 975-15: Standard Specification for Diesel Fuel Oils (https://www.astm.org/Standards/D975.htm)

- Recordkeeping: All the parties must keep the required records by EPA for the period that EPA requests.

- Reporting: All the parties must submit the report including required information on a regular basis.

- Registration: Any regulated fuel producer and importer must register in EPA.

- Sampling/Testing: each batch of fuel must be tested by refiner or importer.

- Labeling: Fuel pumps must be labeled based on EPA regulations.

The number of fuel samples per day, week, month or year by EPA are variable. EPA takes 10,000 to 30,000 gasoline samples per year. Samples for federal testing are taken from truck loading terminals and retail outlets and fleet operator facilities. Samples are also taken at refineries. The samples are then tested by ASTM methods. Generally, all noncompliant samples are sent to the laboratory. Notices of violation are issued for noncompliant samples (Row and Doukas 2008, Kavanagh 2014).

6.2.2 California

California is the most stringent state in the US to regulated fuel standards. The California standards are more stringent than federal ones, so California standards are discussed in detail below. The California Air Resources Board (CARB) has the responsibility to improve air quality through stringent fuel standards (Row and Doukas 2008).

6.2.2.1 Gasoline

This section focuses on reformulated gasoline (RFG) requirements in California. Based on EPA definition, RFG is the formulated gasoline to reduce emissions of ozone-forming and toxic air pollutants. RFG should have higher levels of oxygenates and lower levels of benzene, olefins, and aromatics to guarantee less evaporation in summer months than conventional gasoline. After regulating RFG by the federal government in the US, California created its own RFG standards in 1995 called CaRFG[24]. The parameters that are regulated for RFG in California are Reid vapor pressure, T50 and T90 distillation temperatures, total aromatics, olefins, oxygen, benzene, and Sulphur contents (Row and Doukas 2008).

6.2.2.2 Diesel

California Diesel samples are tested on three different fuel parameters: sulfur, aromatic hydrocarbon content, and polynuclear aromatic hydrocarbon content (Row and Doukas 2008).

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[24] CaRFG: http://www.arb.ca.gov/fuels/gasoline/carfg3/carfg3.htm

6.2.2.3 Fuel quality monitoring and enforcement

The CARB, responsible organization for fuel monitoring in California, conduct surprise inspections of producing, marketing and storing facilities of diesel and gasoline fuel. The collected samples are analyzed on the same day of sample collection in a mobile fuel laboratory. If the fuel quality does not meet the regulations, further investigation is conducted. In 2007, fewer than 1% of gasoline samples were noncompliant with standards, and most of them were from seasonal RVP requirement non-compliance due to the changeover of fuels between seasons. For diesel fuel, less than 1% of fuels sampled were not compliant with requirements (Row and Doukas 2008).

6.3 EU standards and regulations

The responsibility of setting mandatory fuel requirements in EU is on Fuel Quality Directive or FQD (Directive 98/70/EC[25] as amended). Enforcement of fuel quality is the responsibility of member states. All the 31 member states should respect the standards. However, in EU the standards are established by the European Committee for Standardization (CEN). Quality standards (referred to as ENs) are technical specifications and are not compulsory. This is why the list of parameters in European standards for fuels are longer than those mentioned by the directive (Row and Doukas 2008, Kavanagh 2014).

6.3.1 Gasoline

Gasoline quality properties are established by the most recent version of gasoline standard EN 228:2012[26], "Automotive fuels – Unleaded petrol – Requirements and test methods."
The fuel parameters that are regulated for gasoline in EU are lead, aromatic content, Reid vapor pressure, sulfur, olefin content, benzene, bio-components and oxygen, RON, MON, manganese, distillation properties E100 and E150 (Row and Doukas 2008, Kavanagh 2014).

6.3.2 Diesel

Diesel quality properties are established by the most recent version of diesel standard EN 590:2013[27] "Automotive fuels – Diesel – Requirements and test methods." The fuel parameters that are regulated for diesel in EU are density, poly-aromatics, cetane, sulfur, biodiesel (FAME), distillation temperature T95 (Row and Doukas 2008, Kavanagh 2014).

6.3.3 Fuel quality monitoring and enforcement

In EU, based on Directive 98/70/EC, member states must establish their own fuel quality monitoring system (FQMS) at the national level and report the results to the European

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[25] Directive 98/70/EC: http://ec.europa.eu/clima/policies/transport/fuel/documentation_en.htm

[26] EN 228:2012: https://www.document-center.com/standards/show/BS-EN-228

[27] EN 590:2013: https://www.document-center.com/standards/show/EN-590

commission yearly. Not implementing the required monitoring by the member states has serious consequences, and may lead to financial penalties imposed by the commission.

All the member states should submit a report on national fuel quality to the European commission each year by June 30. The report should include the compilation of the collected samples and the analysis of the results, detailed quantities of gasoline and diesel sold in the country, and the details of the national fuel quality monitoring system. After organizing the submitted reports, European commission publishes the EU monitoring report (Row and Doukas 2008, Kavanagh 2014).

The detailed features of monitoring procedure are as follows:

- The fuel properties in the Directive 98/70/EC should be tested. However, other parameters based on member states' decision can be tested.
- 100-200 samples per year depending on the size of the country should be collected.
- Samples should be taken from strategic locations throughout the country, especially at the sale stations.

6.4 Australia standards and regulations

The Australian Department of the Environment administers the Fuel Quality Standards Act 2000[28] (the Act), which provides the legislative basis for national fuel quality and fuel quality information standards for Australia. Some of the fuel requirements are established nationwide and some are established at the state level. If the state requirements are more stringent than the national ones, the more stringent standard is applied (Row and Doukas 2008, Kavanagh 2014).

6.4.1 Gasoline

Gasoline in Australia is regulated under Fuel Quality Standards Act 2000 (the Act), the parameters that are regulated for gasoline are: RON, MON, sulfur, lead, benzene, aromatic content, olefin content, final boiling point (FBP), oxygen content, ethanol, Tetr butyl alcohol, ether, phosphorous, oxidation stability, existent gum, copper corrosion (Row and Doukas 2008, Kavanagh 2014).

6.4.2 Diesel

Diesel quality is regulated under Fuel Standard (Automotive Diesel) Determination 2001[29] in Australia. The fuel specifications that are regulated are: cetane number and cetane index, sulfur, poly-aromatics, density, viscosity, distillation temperature T95, flash point, carbon

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[28] Fuel Quality Standards Act 2000: https://www.legislation.gov.au/Details/C2004C01151

[29] Fuel Standard (Automotive Diesel) Determination 2001: https://www.legislation.gov.au/Details/F2006C00554

residue, water and sediment, ash, lubricity, copper corrosion, oxidation stability, conductivity, color, FAME (Row and Doukas 2008, Kavanagh 2014).

6.4.3 Fuel quality monitoring and enforcement

The Australian Department of the Environment undertakes fuels testing across all areas of the national fuel supply chain. The sampling takes place at hundreds of sites each year primarily at distribution terminals and points of sale (gas stations). Fuel monitoring in Australia includes record keeping, reporting, industry self-monitoring, information sharing with consumers and other groups, and certification. In the case of non-compliance, companies may face the Severe consequence. In Australia, penalties for noncompliance are as high as $550,000.00 under the Fuel Quality Standards Act. Compliance levels are quite high in Australia. In 2011-2012 and 2012-2013 periods, approximately 1.3% or 67 out of 5,275 samples taken did not meet the regulations (Row and Doukas 2008, Kavanagh 2014).

6.5 Japan standards and regulations

In Japan, the mandatory standards for fuels are set by the Central Environment Council (CEC) under the Ministry of Environment. The voluntary standards, on the other hand, are established under the Ministry of Economy, Trade, and Industry (METI) and are called Japanese Industrial Standards (JIS) (Row and Doukas 2008, Kavanagh 2014).

6.5.1 Gasoline

The gasoline standards in Japan are JIS K 2202:2012[30], which was revised in March 2012 to allow for up to 10 vol% ethanol for E10 grades. There are currently two grades of gasoline in Japan: regular and premium. From the 18 parameters mentioned in JIS standard, only 8 are mandatory by CEC, including sulfur, benzene, oxygen, methanol, ethers (5 or more C atoms), existent gum, color, ethanol. Lead and kerosene limits are not included in JIS, but are mandatory in the CEC gasoline standard, so CEC mandates 10 parameters in overall. Lead is specified as “undetectable,” while kerosene has a limit of 4 vol% max in the CEC gasoline standard (Row and Doukas 2008, Kavanagh 2014).

6.5.2 Diesel

The standard that is in use for diesel in Japan is JIS K 2204[31]. Japan has five diesel grades: Class Special 1, Class 1, Class 2, Class 3 and Class Special 3. They are applied in a different season and ambient temperatures. Out of the 10 parameters listed in JIS K 2204 standard, CEC regulates only three of them: cetane index, sulfur, and T90. CEC regulates another six parameters that are

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[30] JIS K 2202:2012: http://www.webstore.jsa.or.jp/webstore/Com/FlowControl.jsp?lang=en&bunsyoId=JIS+K+2202%3A2012&dantaiCd=JIS&status=1&pageNo=0

[31] JIS K 2204 http://www.webstore.jsa.or.jp/webstore/Com/FlowControl.jsp?lang=en&bunsyoId=JIS+K+2204%3A2007&dantaiCd=JIS&status=1&pageNo=0

currently not included in JIS K 2204, including Oxidation stability, total acid number, acidity, methanol, triglycerides, FAME content (Row and Doukas 2008, Kavanagh 2014).

6.5.3 Fuel quality monitoring and enforcement

Companies are not allowed to sell their fuel not complying with the national quality specifications in Japan. The National Petroleum Association (NPA), which is an industry body consisting of oil companies in Japan has the responsibility of fuel inspection. METI enforces the law on companies that do not comply with the fuel standards. Mandatory checks by the NPA occurs every 10 days for all companies at their service stations. In these checks, samples from regular gasoline, premium gasoline, automotive diesel, and kerosene are collected by NPA, randomly. Also if the company meets the required conditions, the "Quality Control Plan Authorization System" can be applied; in this system, an annual one-time quality analysis happens instead of the 10-day quality checks. The collected samples are analyzed at NPA's regional test centers. If the samples do not meet the standards, NPA reports to METI so that suitable measure are taken. Results are not published in detail publicly, but a minimum fine of ¥1 million (US$10,000) or 1 year of imprisonment is given to companies that do not meet the law. In addition, the business will shut down for a period of 6 months, or business registration can be revoked (Row and Doukas 2008, Kavanagh 2014).

6.6 South Korea standards and regulations

There are two laws in South Korea that regulate fuel quality: Clean Air Quality Preservation Act[32] by the Ministry of Environment (MOE) and the Petroleum Product Quality Standards in the Petroleum and Alternative Fuel Business Act by the Ministry of Trade, Industry and Energy (MOTIE). Fuel quality is monitored and enforced by a government organization called the Korea Petroleum Quality and Distribution Authority, known as K Petro. In the past, South Korea's fuel specifications have largely been based on EU and California ARB regulations (Row and Doukas 2008, Kavanagh 2014).

6.6.1 Gasoline

Gasoline is regulated under "Petroleum and Alternative Fuels Business Act". South Korea currently has two grades of gasoline: regular and premium. From all the parameters that are regulated under the Petroleum and Alternative Fuels Business Act, the following parameters are regulated under the Clean Air Quality Preservation Act: Aromatics, benzene, lead, phosphorous, oxygen, olefins, sulfur, RVP, and T90 (Row and Doukas 2008, Kavanagh 2014).

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[32] Clean Air Quality Preservation Act http://projects.wri.org/sd-pams-database/south-korea/air-quality-preservation-act

6.6.2 Diesel

Similar to gasoline, diesel fuel in South Korea is regulated under “Petroleum and Alternative Fuels Business Act”. The following parameters are regulated by the Clean Air Preservation Act: Cetane Index, density, sulfur, polyaromatics, total aromatics, and carbon residue, lubricity (Row and Doukas 2008, Kavanagh 2014).

6.6.3 Fuel quality monitoring and enforcement

K Petro is the government’s organization that ensures the fuel quality and manages the distribution of petroleum products and illegal products. Regular and irregular quality inspection across all stages, including production, imports, transportation, storage, pipeline, service stations, etc are performed by K Petro (Row and Doukas 2008, Kavanagh 2014).

The two types of inspection are as follows:

- Regular inspection by law
    - refinery: 1 time per month
    - imports: whenever petroleum products are imported
    - storage tanks and pipelines: 1 time per quarter
- Irregular inspection by law: all stages

Currently, only 1-2% of the fuels sampled could not meet the required specifications. The detail of laboratory results is not accessible by public. Warnings are first issued to companies whose samples do not meet fuel quality specifications. And after some repeated warnings, revocation and suspension of businesses and severe fines are permitted (Row and Doukas 2008, Kavanagh 2014).

Table 30. International Gasoline standards

Country/Region	**Canada**	**Australia**	**EU**			**Japan**		**South Korea**	**U.S.**	**California**
Spec Name	CGSB 3.5	Fuel Quality Standards Act 2000	Dir. 98/70/EC as amended	EN 228:2012	EN 228:2012	JIS K 2202:2012	JIS K 2202:2012	Petroleum and Alternative Fuels Business Act	ASTM D 4814-14	RFG phase 3
Source	Canadian General Standards Board	Department of Environment	Dir. 98/70/EC as amended	EN 228:2012	EN 228:2012	Japanese Standards Association	Japanese Standards Association	Korea Petroleum Quality & Distribution Authority	ASTM International	
Grade		ULP / PULP[33]	Petrol	Unleaded Petrol	Unleaded Petrol E10	Regular / Premium	Regular (E) / Premium (E)	Regular / Premium	Unleaded	
Year of implementation		Nov 2007 / Jan 2008	May-09	Apr-13	Apr-13	Mar-12	Mar-12	Jan-09	May-14	
Property										
RON, min		91 / 95	95	95	95	89 / 96	89 / 96	91 / 94		
MON, min	82	81 / 85	85	85	85					
Antiknock index (MON+RON)/2, calculated, min	87-93									
Sulfur, ppm, max	30 (current pool average) 80: cap limit 10 (effective from January 1, 2017)	150 / 50	10	10	10	10	10	10	80	15
Lead, g/l, max	undetectable	0.005	0.005	0.005	0.005			0.013	0.013	
Manganese, g/l, max	0.018		2	2	2					
Benzene, vol%, max	1	1	1	1	1	1	1	0.7		0.7
Aromatics, vol%, max		42% pool average over 6 months with a cap of 45%	35	35	35			24		22

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[33] PULP: Premium unleaded petrol, ULP: Regular unleaded petrol

Country/Region	Canada	Australia	EU			Japan		South Korea	U.S.	California
Olefins, vol%, max		18	18	18	18			16		4
RVP @ 37.8°C (100°F), kPa, min-max	38-107		60 max	45-60 (class A) - 70-100 (class F1)	45-60 (class A) - 70-100 (class F1)	44-65 (s) / 44-93 (w)	44 (s) / 55 (w)	44-82	103 max	44.1-49.6
VLI, calculated, max				1050 (class C1) - 1250 (class F1)	1064 (class C1) - 1264 (class F1)					
Density @ 15°C (60°F), kg/m3, min-max				720-775	720-775	783 max	783 max			
Distillation									DI=569 - 597	
T10, °C, max						70	70	70	70(7)	
T50, °C, min-max						75-110	70-105 (s) / 65-105 (w)	125 max	77-121	95
T90, °C, min-max	185-190					180 max	180 max	170 max	190 max	146.1
E70, vol%, min-max				20-48 (class A) - 22-50 (class F1)	22-50 (class A) - 24-52 (class F1)					
E100, vol%, min-max			46 min	46-71	46-72					
E150, vol%, min			75	75	75					
FBP, °C, max		210		210	210	220	220	225	225	
Residue, vol%, max				2	2	2	2	2	2	
Oxygen, wt%, min-max		2.7 wt% max (no ethanol) 3.9 wt% max (with ethanol)	3.7 max	2.7 max	3.7 max	1.3 max	1.3-3.7	2.3 max		1.8-2.2
Oxygenates										
Methanol, vol%, max			3	3	3			0.1 wt%		
Ethanol, vol%, max	5-10	10	10	5	10	3	10			
Isopropyl alcohol, vol%, max			12		12					
Isobutyl alcohol, vol%, max			15		15					

Country/Region	Canada	Australia	EU			Japan		South Korea	U.S.	California
Tert-butyl alcohol, vol%, max		0.5	15		15					
Ethers (5 or more C atoms), vol%, max		1 vol% DIPE; 1 vol% MTBE	22		22	7	7			
Others, vol%, max			15		15					
Phosphorus, g/l, max	0.0013	0.0013		0(13)	0(13)			0.0013	0.0013	
Oxidation stability .min	N0.1 (max)	360		360	360	240	240	480	240	
Water and sediment, vol%, max								0.01		
Existent gum (solvent washed), mg/100ml, max	5	5		5	5	5	5	5	5	
Existent gum (solvent unwashed), mg/100ml, max						20	20			
Corrosion										
Copper corrosion, 3hr @ 50°C, merit (class), max	No. 1	1		1	1	1	1	1	1	
Silver corrosion, merit (class), max									1	
Color						Orange	Orange	Yellow / Green		
Appearance				Clear & bright	Clear & bright					
Dye content, g/100 l, max				Allowed	Allowed					
Use of additives				Allowed	Allowed					

Table 31. International diesel standards

Country/Region	Canada	Australia	EU		Japan	South Korea	U.S.	California
Spec Name	CGSB 3.517	Fuel Standard (Automotive Diesel) Determination 2001	Dir. 98/70/EC as amended(1)	EN 590:2013	JIS K 2204:2007	Petroleum and Alternative Fuels Business Act	ASTM D 975-14	
Source	Canadian General Standards Board	Department of the Environment	Dir. 98/70/EC as amended	EN 590:2013	Japanese Standards Association	Korea Petroleum Quality & Distribution Authority	ASTM International	
Grade		-	Diesel	Diesel	Class Special 1 / Class 1 / Class 2 / Class 3 / Class Special 3	Automotive Diesel	No.1-D S15 / No.2-D S15	
Year of implementation		Mar-09	May-09	Jul-13	Jan-07	Jan-09	Feb-14	
Property								
Cetane number, min	40	51.0	51	51 (temperate) / 47-49 (arctic & severe winter)	50 / 50 / 45 / 45 / 45	52	40	48
Cetane index, min	40	46		46 (temperate) / 43-46 (arctic & severe winter)	50 / 50 / 45 / 45 / 45	52	40	48
Sulfur, ppm, max	15	10	10	10	10	10	15	15
Polyaromatics, wt%, max		11	8	8		5		3.5
Total aromatics, vol%, max						30	35	10
Density @ 15°C (60°F), kg/m3, min-max		820-850	845 max	820-845 (temperate) / 800-840 (arctic & severe winter)	860 max	815-835		
Viscosity @ 40°C, cST, min-max	1.7-4.1	2-4.5		2.000-4.500 (temperate) / 1.200-4.000 (arctic & severe winter)	2.7 / 2.7 / 2.5 / 2(2) / 1.7 (min)	1.9-5.5	1.3-2.4 / 1.9-4.1	2-4.1
Distillation								
T90, °C, min-max	360				360 / 360 / 350 / 330/ 330 (max)	360 max	288 max / 282-338	228-321
T95, °C, max		360	360	360				
E180, vol%, max				10				
E250, vol%, max				<65				
E340, vol%, min				95				
E350, vol%, min				85				

Country/Region	Canada	Australia	EU		Japan	South Korea	U.S.	California
Flash Point,°C, min	40	61.5		above 55.0	50 / 50 / 50 / 45 / 45	40	38 / 52	54.4
Carbon residue 10%, wt%, max	0.2	0.2		0.3	0.1	0.15	0.15 / 0.35	
Cold Filter Plugging Point (CFPP),°C, max				+5 (class A temperate) to -44 (class 4 arctic & severe winter)	- / -1/ -5 / -12 / -19	-18(2)		
Pour Point (PP),°C, max					5 / -2.5 / -7.5 / -20 / -30	-23.0 (w)(4)/ 0.0 (s)		
Cloud Point (CP),°C, max				-10 to -34				
Water and sediment, vol%, max	0.05	0.05				0.02	0.05	
Water, vol%, max		200 ppm		200 mg/kg				
Ash, wt%, max		100 ppm		0.01		0.02	0.01	
Total contamination, ppm, max				24				
Lubricity, HFRR wear scar diam @ 60°C, micron, max		460		460		400	520	520
Copper corrosion, 3hr @ 50°C, merit (class), max	No.1	1		1			3	
Copper corrosion, 3hr @ 100°C, merit (class), max						1		
Oxidation stability, mg/100ml, max		2.5		25g/m3				
Conductivity @ ambient temp, pS/m, min	25	50					25	
Color, max		2						
Dye content, g/100 l, max				Allowed				
Use of additives				Allowed				
FAME content, vol%, max		5	7	7		5	5	
Metal content (Zn, Cu, Mn, Ca, Na, other), g/l, max								

7 Comparison of fuel quality standards and monitoring and enforcement procedure in different jurisdictions

In comparison with other jurisdictions, Canada generally has fewer and less stringent mandatory fuel requirements and monitoring and enforcement procedures. As mentioned earlier, Canada has some compulsory national fuel requirements (sulfur, benzene content) and other fuel standards are voluntary unless regulated by the province like Manitoba. The details of major differences of gasoline in Canada with other jurisdictions are listed in Table 32.

Internationally, the sulphur content in gasoline is moving towards 10 ppm. Canada's regulation until December 31, 2016 requires gasoline sulfur levels to a yearly pool average of 30 ppm and maximum of 80 ppm. This regulation was less stringent than other jurisdictions and was improved. Starting from January 1, 2017 the gasoline pool average in Canada should not exceed 10 ppm[34]. Phosphorous, corrosion, lead, benzene, manganese, ethanol, oxidation stability and existent gum in Canada are aligned with other jurisdictions.

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[34] http://laws-lois.justice.gc.ca/PDF/SOR-99-236.pdf

Table 32. Comparison of gasoline standards in Canada with international standards (EU, US, California, Australia, Japan, South Korea)

Parameter	Current limit	Comment
Sulfur	Max 30 ppm pool average, Max 80 ppm cap limit Future limit (starting from January 1. 2017): 10 ppm	-By the upcoming sulfur standard (effective from January 1, 2017) Canada's sulfur standard will be similar to other leading jurisdictions like EU, Japan, and South Korea (10 ppm). The limit for California is 15 ppm. The present limit of US is 80 ppm but U.S. will reduce this limit to 10 ppm starting Jan. 1, 2017. Australia with the limit of 150/50 ppm for pulp/ all grades is lagging behind other jurisdictions. -The sulfur reduction will result is a reduction of HC, CO, NOx, and toxic emissions.
Aromatics	No limit	-Except Japan and US, other jurisdictions have a limit for aromatic content. The limit for EU, South Korea, and California are max 35, 24, and 22 % (vol) aromatic content. -Reduced aromatic content could significantly decrease toxic air pollutants, especially benzene. Reduction could also decrease HC and CO emissions.
Octane	Min 82 (MON)	-US and California do not have limit for octane. -The limit for Australia is 81/85 (MON), for EU 85 (MON), Japan 89/96 (RON), and South Korea 91/94 (MON)
Olefin	No Limit	-Similar to Canada, US and Japan do not have a limit for olefin -EU: max 18% (vol) -Australia: max 18% (vol) -South Korea: max 16% (vol) -California: max 4% (vol) -olefin reduction could result in NOx and toxic emission reduction
Oxygen	No limit	-Similar to Canada, US and California do not have a limit for oxygen -Australia: 2.7% (wt) max -EU: 3.7% (wt) max -Japan: 1.3% (wt) max -South Korea: 2.3% (wt) max
RVP	@ 37.8°C 38-107 kPa	-reduction of RVP could result in decreased HC and CO -EU: max 60 kPa -Japan: 44-65, 44-93 kPa -South Korea: 44-82 KPa US: max 103 KPa California: 44.1-49.6 KPa
Volatility, T90	185-190 °C	-Decreasing Volatility could result in reduction of HC, CO, and toxic emissions -EU and Australia do not have limit -Japan: max 180 °C -South Korea: max 170 °C -US: max 190 °C -California: max 146.1 °C

The details of major differences of diesel in Canada with other jurisdictions are listed in **Error! Not a valid bookmark self-reference.**. Other diesel parameters that are not mentioned in the table are aligned with other jurisdictions.

Table 33. Comparison of diesel standards in Canada with international standards (EU, US, California, Australia, Japan, South Korea)

Parameter	Current limit	Comment
Polyaromatics	No Limit	-Decreasing polyaromatics could reduce NOx and PM emissions. Similar to Canada, US and Japan do not have limits -Australia: max 11% (wt) -EU: max 8% (wt) -South Korea: max 5% (wt) -California: max 3.5% (wt)
Cetane number	Min 40	-Increasing cetane number could reduce HC, CO, and NOx emissions - The minimum limit of cetane number in Canada is lower than all jurisdictions except the US. - Australia: min 51 -EU: min 51 -South Korea: min 52 -California: min 48 -Japan: min 50 US: min 40
Sulfur	Max 15 ppm	-Decreasing sulfur content will reduce PM emissions. - the limit of Canada is similar to US and California - The limit of Canada is less stringent than Australia, EU, Japan, and South Korea (max 10 ppm)
Denisty	No Limit	-Decreasing density could reduce HC, CO, and PM emissions. -Similar to Canada, US and California do not have limits. -Australia: 820-850 kg/m3 (@ 15 C) -EU: max 845 kg/m3 (@ 15 C) -Japan: max 860 kg/m3 (@ 15 C) South Korea: 815-835 kg/m3 (@ 15 C)
Volatility	T90: max 360 ◦C	-Reducing volatility could decrease PM emissions. -Canada limit for T90 is less stringent than US and California -Australia (T95): max 360 C -EU (T95): max 360 C -Japan (T90): max 360 C -South Korea (T90): max 360 C -US (T90): max 228 C -California (T90): 228-321 C

Beside the fuel standards, processes used to monitor fuel quality and enforce the standards are of great importance. Fuel standards and regulations cannot by themselves guarantee good fuel quality at filling stations. It is the monitoring and enforcement policies that guarantee the compliance with the regulations, especially if these policies include penalties for not meeting the regulations.Table 34 shows a comparison of fuel quality monitoring and enforcement programs in different jurisdictions.

Comparing all the fuel quality monitoring programs, it appears that monitoring and enforcement are more stringent in other jurisdictions in comparison to Canada. In Canada, the basis of fuel quality monitoring is self-reporting, while in all other jurisdictions listed in the table, fuel testing is undertaken by a governmental organization. Mandatory penalties and fines are the common approaches used by all other jurisdiction to enforce fuel regulations. However, in Canada, there is no penalty in noncompliance situations.

Table 34. Comparison of Fuel Quality Monitoring Programs and Enforcement Schemes

Jurisdiction	Fuel quality monitoring	Enforcement Scheme	Noncompliance rates
Canada	-Mandatory self-reporting at federal level -All fuel producers and importers should submit a report to the Minster, including volume of fuel produced in the batch, date of fuel production, and fuel specifications	NO	No Data
US	-By law: sampling/testing, recordkeeping, auditing, certification, registration, surveys, attest, labeling -Sampling of fuels is undertaken by US EPA, from importers, refineries, distributors, and service stations.	Yes, federal and state: Administrative prosecution and penalties, injunctions.	Very few instances of noncompliance. Public information of noncompliance is not available.
California	-By law: CARB is responsible for surprise inspection of production, marketing and storage facilities of fuel, same day analysis	Yes, penalties.	In 2007: less than 1% of gasoline and diesel samples were noncompliant with standards.
EU	By law: the EU regulation should be performed by the Member States. MS are responsible for fuel monitoring and annual report preparation to European Commission.	Yes, Member States assign entities which undertake testing of fuels at service stations. The Member States may impose fines on fuel distributors.	Noncompliance rate is 1.5% to 2% on average in all MS.
Australia	By law: Sampling program; record keeping/reporting; industry self-monitoring; information sharing with consumer and other groups; certification. The Australian Department of the Environment undertakes fuels testing across all areas of the national fuel supply chain. Samples may be taken	Yes: Severe fines may be levied for off-spec/noncompliant fuel; injunctions.	In 2011-12 and 2012-13: Approximately 1.3%

Jurisdiction	Fuel quality monitoring	Enforcement Scheme	Noncompliance rates
	from importers, refineries, distributors and service stations.		
Japan	By law: Sampling/testing every 10 days by industry only at the service stations; reporting to the government's Ministry of Economy, Trade, and Industry (METI)	-Yes: minimum ¥1 million (US$10,000) or 1 year of imprisonment; business shut down for 6 months or business registration revoked. -Result are not available to public in details	The government reports no cases of noncompliance.
South Korea	By law: Sampling program by the government's Korea Petroleum Quality & Distribution Authority (K Petro) at all stages: refineries, terminal, fueling stations, etc. Two types of inspection: Regular and irregular.	Yes: warnings, business permit revocations, suspension of business, severe fines.	On average, 1-2% of samples collected do not comply.

8 References

Abu-Jrai, A. et al. 2006. “Effect of Gas-to-Liquid Diesel Fuels on Combustion Characteristics, Engine Emissions, and Exhaust Gas Fuel Reforming. Comparative Study.” *Energy and Fuels* 20(6):2377–84.

Abu-Jrai, A. et al. 2009. “Performance, Combustion and Emissions of a Diesel Engine Operated with Reformed EGR. Comparison of Diesel and GTL Fuelling.” *Fuel* 88(6):1031–41. Retrieved (http://dx.doi.org/10.1016/j.fuel.2008.12.001).

Armas, Octavio, Reyes Garcia-Contreras, and Angel Ramos. 2013. “Impact of Alternative Fuels on Performance and Pollutant Emissions of a Light Duty Engine Tested under the New European Driving Cycle.” *Applied Energy* 107:183–90. Retrieved (http://dx.doi.org/10.1016/j.apenergy.2013.01.064).

Atabani, A. E. et al. 2012. “A Comprehensive Review on Biodiesel as an Alternative Energy Resource and Its Characteristics.” *Renewable and Sustainable Energy Reviews* 16(4):2070–93. Retrieved (http://dx.doi.org/10.1016/j.rser.2012.01.003).

Bertoli, C., N. Del Giacomo, and Prati M.V. 1993. “The Influence of Fuel Composition on Particulate Emissions of DI Diesel Engines.” (412).

Bielaczyc, P., M. Kozak, and J. Merkisz. 2003. “Effect of Fuel Properties on Exhaust Emissions from the Latest Light-Duty DI Diesel Engine.” *JSAE*.

Chauhan, Bhupendra Singh, Ram Kripal Singh, H. M. Cho, and H. C. Lim. 2016. “Practice of Diesel Fuel Blends Using Alternative Fuels: A Review.” *Renewable and Sustainable Energy Reviews* 59:1358–68. Retrieved (http://www.sciencedirect.com/science/article/pii/S1364032116000927).

Du, Jiakun et al. 2014. “Experimental Study on Combustion and Particle Size Distribution of a Common Rail Diesel Engine Fueled with GTL/diesel Blends.” *Applied Thermal Engineering* 70(1):430–40. Retrieved (http://dx.doi.org/10.1016/j.applthermaleng.2014.05.037).

Gill, S. S., A. Tsolakis, K. D. Dearn, and J. Rodríguez-Fernández. 2011. “Combustion Characteristics and Emissions of Fischer-Tropsch Diesel Fuels in IC Engines.” *Progress in Energy and Combustion Science* 37(4):503–23. Retrieved (http://dx.doi.org/10.1016/j.pecs.2010.09.001).

Goodfellow, C. L., Gorse R.A., M. J. Hawkins, and J. .. McArragher. 1996. “European Programme on Emissions, Fuels and Engine Technologies (EPEFE) - Gasoline Aromatics/E100 Study.” *SAE International* 10.4271/96(online).

Gray, J. .. and G. .. Handwerk. 2001. *Petroleum Refining Technology and Economics*. 4th editio. Marcel Dekker Inc.

Hajbabaei, Maryam, Kent C. Johnson, Robert Okamoto, and Thomas D. Durbin. 2013. “Evaluation of the Impacts of Biofuels on Emissions for a California Certified Diesel Fuel from Heavy-Duty Engines.” *SAE Int J. Fuels Lubr* 6(2):393–406. Retrieved (http://www.sae.org/technical/papers/2013-01-1138).

Hassaneen, Ahmed, Axel Munack, Yvonne Ruschel, Olaf Schroeder, and Jurgen Krahl. 2012. “Fuel Economy and Emission Characteristics of Gas-to-Liquid (GTL) and Rapeseed Methyl Ester (RME) as Alternative Fuels for Diesel Engines.” *Fuel* 97:125–30. Retrieved (http://dx.doi.org/10.1016/j.fuel.2012.01.077).

Hewu, Wang, Han Hao, Xihao Li, Ke Zhang, and Minggao Ouyang. 2009. “Performance of Euro III Common Rail Heavy Duty Diesel Engine Fueled with Gas to Liquid.” *Applied Energy* 86(10):2257–61. Retrieved (http://dx.doi.org/10.1016/j.apenergy.2009.02.004).

Hochhauser, Albert. 2008. *REVIEW OF PRIOR STUDIES OF FUEL EFFECTS ON VEHICLE EMISSIONS*.

Hublin, M., P. .. Gadd, D. .. Hall, and K. .. Schindler. 1996. “European Programmes on Emissions, Fuels and Engine Technologies (EPEFE) - Light Duty Diesel Study.” (412).

Hwang, Joonsik, Donghui Qi, Yongjin Jung, and Choongsik Bae. 2014. “Effect of Injection Parameters on the Combustion and Emission Characteristics in a Common-Rail Direct Injection Diesel Engine Fueled with Waste Cooking Oil Biodiesel.” *Renewable Energy* 63:9–17.

Iorio, Silvana Di et al. 2014. “Engine Performance and Emissions of a Small Diesel Engine Fueled with Various Diesel / RME Blends.” (x).

Jones, David and Peter Pujado. 2006. *Handbook of Petroleum Processing*.

Kavanagh, Tanya. 2014. *International Fuel Quality Standards and Their Implications for Australian Standards*.

Kitano, Koji, Ichiro Sakata, and Richard Clark. 2005. “Effects of GTL Fuel Properties on DI Diesel Combustion.” *SAE transactions* 114(4):1415–25.

Krahl, Jürgen et al. 2009. “Comparison of Exhaust Emissions and Their Mutagenicity from the Combustion of Biodiesel, Vegetable Oil, Gas-to-Liquid and Petrodiesel Fuels.” *Fuel* 88(6):1064–69. Retrieved (http://dx.doi.org/10.1016/j.fuel.2008.11.015).

Kumar, Alok, D. .. Khatri, and MKG Babu. 2008. “Experimental Investigations on the Performance, Combustion and Emission Characteristics of Alcohol Blended Gasoline in a Fuel Injected Spark Ignition Engine.” *Fuel* 470–75.

Lange, W. .., A. Muller, J. S. McArragher, and V. Schafer. 1994. “The Effect of Gasoline Composition on Exhaust Emissions from Modern BMW Vehicles.” *SAE* (412).

Lange, W. W. et al. 1993a. “The Influence of Fuel Properties on Exhaust Emissions from Advanced Mercedes Benz Diesel Engines.” (412).

Lange, W. W. et al. 1993b. “The Influence of Fuel Properties on Exhaust Emissions from Advanced Mercedes Benz Diesel Engines.” (412). Retrieved (http://dx.doi.org/10.4271/932685).

Lapuerta, Magin, Octavio Armas, J. J. Hernandez, and Athanasios Tsolakis. 2010. “Potential for Reducing Emissions in a Diesel Engine by Fuelling with Conventional Biodiesel and Fischer-Tropsch Diesel.” *Fuel* 89(10):3106–13.

Liptak, Bela G. 1999. *Process Measurement and Analysis*.

Liu, Haifeng, Zunqing Zheng, and Mingfa Yao. 2015. “Effects of Fuel Physical and Chemical Properties on Combustion and Emissions on Both Metal and Optical Diesel Engines and on a Partially Premixed Burner.” *Sae*.

Masimalai, Senthil Kumar. 2014. “Influence of Methanol Induction on Performance , Emission and Combustion Behavior of a Methanol - Diesel Dual Fuel Engine.” *SAE International*.

MetroVancouver Air Quality and Climate Change Devision annual report,2015, "2014 Lower Fraser Valley Air Quality Monitoring Report"

Mohd Yusoff, Ashraf, N. W. M. Zulkifli, B. M. Masum, and H. H. Masjuki. 2015. “Feasibility of Bioethanol and Biobutanol as Transportation Fuel in Spark-Ignition Engine: A Review.” *RSC*

Advances 100184–211. Retrieved (http://dx.doi.org/10.1039/C5RA12735A).

Moon, Gunfeel, Yonggyu Lee, Kyonam Choi, and Dongsoo Jeong. 2010. “Emission Characteristics of Diesel, Gas to Liquid, and Biodiesel-Blended Fuels in a Diesel Engine for Passenger Cars.” *Fuel* 89(12):3840–46. Retrieved (http://dx.doi.org/10.1016/j.fuel.2010.07.009).

Mori, Kazutoshi, Koji Sorimachi, and Kunihisa Eguchi. 2015. “Study for Effects of Bio-Diesel Fuel and Engine Oil on Exhaust Emission and PN of Diesel Engine.”

Nithyanandan, Karthik, Han Wu, Ming Huo, and Chia-Fon Lee. 2014. “A Preliminary Investigation of the Performance and Emissions of a Port-Fuel Injected SI Engine Fueled with Acetone-Butanol-Ethanol (ABE) and Gasoline.” *SAE Technical Papers* 1. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-84899573289&partnerID=tZOtx3y1).

Patil, K. R. 2015. “Effect of Oxygenate and Cetane Improver on Performance and Emissions of Diesel Engine Fuelled with Diethyl Ether- Diesel Blends.”

Petit, A., J. G. Jeffrey, F. .. Palmer, and R. Steinbrink. 1996. “European Programme on Emissions, Fuels and Engine Technologies (EPEFE) - Gasoline Aromatics/E100 Study.” *SAE International* 10.4271/96(online).

Rickeard, D. J. et al. 2003. *Fuel Effects on Emissions From Modern Gasoline Vehicles Part 2 - Aromatics , Olefins and Volatility Effects*.

Row, Jesse and Alex Doukas. 2008. *Fuel Quality in Canada: Impact on Tailpipe Emissions*.

Sajjad, H. et al. 2014. “Engine Combustion, Performance and Emission Characteristics of Gas to Liquid (GTL) Fuels and Its Blends with Diesel and Bio-Diesel.” *Renewable and Sustainable Energy Reviews* 30:961–86. Retrieved (http://dx.doi.org/10.1016/j.rser.2013.11.039).

Semelsberger, Troy A., Rodney L. Borup, and Howard L. Greene. 2006. “Dimethyl Ether (DME) as an Alternative Fuel.” *Journal of Power Sources* 156(2):497–511.

Shanmugam, R. Muthu, N. Saravanan, L. Srinivasan, Viswanatha Hosur, and S. Sridhar. 2009. “An Experimental Investigation on 1 . 4L MPFI Gasoline Engine to Study Its Performance , Emission and Compatibility with E10 Fuel.” *SAE*.

Singh, Punit Kumar, A. S. Ramadhas, Reji Mathai, and Ajay Kumar Sehgal. 2016a. “Investigation on Combustion, Performance and Emissions of Automotive Engine Fueled with Ethanol Blended Gasoline.” *SAE International Journal of Fuels and Lubricants* 9(1):2016–01 – 0886. Retrieved (http://papers.sae.org/2016-01-0886/).

Singh, Punit Kumar, A. S. Ramadhas, Reji Mathai, and Ajay Kumar Sehgal. 2016b. “Investigation on Combustion, Performance and Emissions of Automotive Engine Fueled with Ethanol Blended Gasoline.” *SAE International Journal of Fuels and Lubricants* 9(1):2016–01 – 0886.

US EPA, July 2001. "Strategies and issues in correlating diesel fuel properties with emissions". Staff discussion document.

US EPA, April 2013. "Assessing the effect of five gasoline propertie on exhaust emission from light-duty vehicles certified to Tier 2 standards". Final report on program design and data cpllection.

Stradling, R. J. et al. 2004. *Fuel Effects on Emissions From Modern Gasoline Vehicles Part 2 - Aromatics , Olefins and Volatility Effects*.

Ushakov, Sergey, Nadine G. M. Halvorsen, Harald Valland, Dag H. Williksen, and Vilmar Æsøy. 2013. “Emission Characteristics of GTL Fuel as an Alternative to Conventional Marine Gas

Oil." *Transportation Research Part D: Transport and Environment* 18(1):31–38. Retrieved (http://dx.doi.org/10.1016/j.trd.2012.08.007).

Valentino, Gerardo and Stefano Iannuzzi. 2015. "Effect of Different Fuels Properties on Emissions and Performance of a Light Duty Four-Cylinder Diesel Engine Under Premixed Combustion."

Valentino, Gerardo, Stefano Iannuzzi, and Felice Esposito Corcione. 2013. "Experimental Investigation on the Combustion and Emissions of a Light Duty Diesel Engine Fuelled with Butanol-Diesel Blend." *Sae*. Retrieved (http://www.sae.org/technical/papers/2013-01-0915).

Wang, Hewu, Han Hao, Xihao Li, Ke Zhang, and Minggao Ouyang. 2009. "Performance of Euro III Common Rail Heavy Duty Diesel Engine Fueled with Gas to Liquid." *Applied Energy* 86(10):2257–61. Retrieved (http://dx.doi.org/10.1016/j.apenergy.2009.02.004).

Wu, Tao, Zhen Huang, Wu-gao Zhang, Jun-Hua Fang, and Qi Yin. 2007. "Physical and Chemical Properties of GTL - Diesel Fuel Blends and Their Effects on Performance and Emissions of a Multicylinder DI Compression Ignition Engine." *Energy and Fuels* 21(4):1908–14.

Xinling, Li and Huang Zhen. 2009. "Emission Reduction Potential of Using Gas-to-Liquid and Dimethyl Ether Fuels on a Turbocharged Diesel Engine." *Science of the Total Environment* 407(7):2234–44. Retrieved (http://dx.doi.org/10.1016/j.scitotenv.2008.11.043).

Yacobucci, Brent D. 2006. *Boutique Fuels and Reformulated Gasoline: Harmonization of Fuel Standards*.

Yehliu, Kuen, Andre L. Boehman, and Octavio Armas. 2010. "Emissions from Different Alternative Diesel Fuels Operating with Single and Split Fuel Injection." *Fuel* 89(2):423–37. Retrieved (http://dx.doi.org/10.1016/j.fuel.2009.08.025).

Zannis, T. C., D. T. Hountalas, R. G. Papagiannakis, and Y. A. Levendis. 2008a. "Effect of Fuel Chemical Structure and Properties on Diesel Engine Performance and Pollutant Emissions: Review of the Results of Four European Research Programs." *SAE International Journal of Fuels and Lubricants* 1(1):384–419. Retrieved (http://saefuel.saejournals.org/content/1/1/384.short).

Zannis, T. C., D. T. Hountalas, R. G. Papagiannakis, and Y. A. Levendis. 2008b. "Effect of Fuel Chemical Structure and Properties on Diesel Engine Performance and Pollutant Emissions: Review of the Results of Four European Research Programs." *SAE International Journal of Fuels and Lubricants* 1(1):384–419.

9 Appendix

Table 35. Studies on the effect of FT fuels and their blends on emissions of diesel engine

Study	**Engine**	**Fuel type**	**Fuel characteristics**	**CO**	**HC**	**NOx**	**PM**	Smoke/soot	CO2
(Du et al. 2014)	4 cylinder, 4 stroke (S), light-duty, turbocharged, intercooled diesel engine, common-rail direct injection (CRDI) engine,3 L, CR:17 -NO exhaust gas recirculation (EGR). -transient test cycle	GTL/diesel blends G0 G10 G20 G30 G60 G100	***Cetane number:** G0 (52), G10 (53.6), G20 (55.2), G30 (56.8), G60 (61.9), G100 (75) ***Total aromatics (%vol):** G0 (11.7), G10 (10.72), G20 (9.74), G30 (8.74), G60 (5.67), G100 (1.4) ***Sulfur (% wt):** G0,(0.0030) G10 (0.0027), G20 (0.0025), G30 (0.0022), G60 (0.0014), G100 (0.0003) ***Oxygen (% wt):** G0 (0.74), G10 (0.67), G20 (0.6), G30 (0.53), G60 (0.31), G100 (0) *** Density (kg/m3 @ 15 C):** G0 (832), G10 (827), G20 (822), G30 (817), G60 (803), G100 (783) ***T90 (C):**	NO DATA	NO DATA	NO DATA	@GTL ratio↑ accumulation (50-1000 nm) particles↑, nucleation mode (<50 nm) ↓, total particle number conc ↑ ***Reason:** ↓sulfur in GTL prevents from nucleation mode,↑cetane number, GTL composed of n-alkanes, ignition delay ↓, % of pre-mixture ↓, so carbonaceous particles↑ because of more in-cylinder fuel rich zones	NO DATA	NO DATA

			G0 (316), G10 (314), G20 (313), G30 (312), G60 (310), G100 (307)						
(Hassaneen et al. 2012)	Diesel engine 6-cylinder, 6.37L, 4S CR: 17.4, DI (direct ignition), NA(naturally aspirated), RP: 205 KW RS: 2300rpm Common Rail -ECE 13-mode test	-GTL(BTL) -German RME (Rapeseed methyl ester) -Diesel fuel (DF)	***Total Sulfur(mg/kg):** RME>10, GTL>10, DF 41 ***Cetane Number:** RME<55, GTL 65.1, DF 53.6 ***Oxygen (%wt):** RME 11, GTL 0, diesel 0 ***Density (kg/m3 @ 15 C):** RME 883, GTL 780.1, Diesel 825.1	-All fuels: CO<EURO5 (1.5g/kWh) RME 70%↓<GTL 26% ↓<DF	-All fuels: HC<EUR5. -RME 50%↓<GTL up to 30%↓<DF	-All fuels: NOx>EURO5 (2 g/kWh) GTL=DF<<RME 40% ↑ ***Reason** for ↑NOx of RME: oxygen content	-Only RME< Euro5(0.02 g/kWh) RME: 10-30nm GTL, DF: 30-200nm RME 65%↓ <GTL 32%↓<DF ***Reason**: RME forms smaller particles, so mass of RME↓, biodiesel produces ultrafine particles!!	NO DATA	GTL:5% ↓ than DF and RME
(Moon et al. 2010)	CRDi diesel engine, 4-cylinder, 2LCR:17.7 ,TC,IC, Common Rail direct injection, turbocharged intercooled. -EGR: yes - steady state Engine -without any after-treatment systems	-DF -GTL fuel. - D+BD20 (80% diesel+20% biodiesel by vol); - G +BD20); -G+BD40	***Cetane NO:** DF 54, D+BD (20) 55, GTL 84, G+BD (20) 76, G+BD (40) 70 ***Poly aromatics (%wt):** DF 1.7, D+BD (20) -, GTL<0.1, G+BD (20)-, G+BD (40) – ***Sulfur (mg/kg):** DF 3, D+BD (20) 1, GTL<1, G+BD (20) <1, G+BD (40) <1 ***Density (kg/m3 @ 15 C):** DF 829.4, D+BD (20) 831, GTL 776.6, G+BD (20) 798.7, G+BD (40) 819.7	-Significantly CO↓for GTL than DF. ***Reason:** GTL has higher cetane number. ++ BD in GTL blends ↓↓ CO. ***Reason:** BD decreases cetane, however, increases Oxygen GTL<<DF ++BD to GTL<<GTL G+BD40 (35%↓)<G+BD20=GTL (25%↓)<D+BD20 (22%↓)<DF	-Significant HC↓ for GTL than DF. ***Reason:** GTL has higher cetane number. ++ BD in GTL blends further ↓↓ HC ***Reason:** BD decreases cetane however increases Oxygen GTL<DF ++BD to GTL<GTL G+BD40 (45%↓)<	NOx↓ for GTL than DF under all conditions. ***Reason:** higher cetane number -With ++ biodiesel concentration in blends NOx ↑↑ ***Reason:** Higher oxygen content (GTL<DF) ++BD to GTL>GTL D+BD20 (10%↑)>G+BD40 (8%↑)>GTL (5%↑)>G+BD20 (2%↑)> DF	**With EGR:** -Nucleation mode: PM↑ for GTL than DF -Accumulation mode: Significant PM↓ for GTL than DF **Without EGR:** -Nucleation mode: about30%,18%,27% , and 40% ↓in D+BD20, GTL, G+BD20, and G+BD40 respectively than DF -Accumulation mode: About 36%, 29%,43%, and 52%↓for D+BD20, GTL,G+BD20, and G+BD40, respectively than DF.	NO DATA	NO DATA

					G+BD20 (30%↓)< GTL (28%↓)< D+BD20 (20%↓)< DF				
(Abu-Jrai et al. 2009)	Lister-Petter TR1 Engine, single Cylinder, 0.773 L DI (direct injection), NA EGR-REGR - engine operation conditions chosen are part of the 13-Mode European Stationary Cycle.	ULSD (Ultra low sulfur diesel) and GTL	***Cetane number:** ULSD 53.9, GTL 79 ***Sulphur (mg/kg):** ULSD 46, GTL<10 ***Aromatics(%wt**) ULSD 24.4, GTL 0.3 ***Density (kg/m3 @ 15 C):** ULSD 827.1, GTL 784.6 ***90% distillation (C):** ULSD 329, GTL 342.1	CO: GTL up to 25%↑> ULSD	NO DATA	(GTL↓ up to 75%<ULSD)	NO DATA	GTL↓ up to 60%<ULSD	NO DATA
(Xinling and Zhen 2009)	Medium-duty Diesel Engine 6-cylinder, 8.27L, 4S CR:18.1, DI, TC, IC (internal combustion) RP: 184KW RS: 2200rpm Common Rail, turbocharged - 10-mode steady cycle	-GTL -Di methyl ether (DME) -DF	***Cetane NO:** DF 51.7, GTL 75, DME 55-66 ***Oxygen content:** DF 0, GTL 0, DME 34.8 ***Sulfur content (%wt)** DF 0.04, GTL 0, DME 0 ***Aromatics:** DF 27.7, GTL 1.4, DME 0 ***Density (gc/m3 @ 15 C):** DF 0.84, GTL 0.779, DME 0.668	GTL: lowest CO GTL: 21.2%↓	DME 40.1%↓<GTL 15.7%↓<DF	DME 48.2%↓<GTL 15.6%↓<DF	Number: GTL 85.3%↓<DME=Diesel ***Reason** of DME=Diesel: accumulation particle number↓, because of Oxygen and no c-c bond, and nucleation↑ and condensation of semi-volatile compounds↑ Mass conc of GTL 43.9%↓	DME 48.2%↓<GTL 22.1% ↓<DF	NO DATA

(Abu-Jrai et al. 2006)	Lister-Petter TR1 Engine 1-Cylnider ,0.7L, CR: 15.5, DI, NA, RP: 8.6KW RS: 2500RPM, air cooled EGR	-GTL -ULSD -GD50: ULSD-GTL blend (50/50 vol %)	***Cetane number:** ULSD 53.9, GTL 79 ***Sulfur(mg/kg):** ULSD 46, GTL 0.05 ***Aromatics (%wt):** ULSD 24.4, GTL 0.3 ***Density (kg/m3 @ 15 C):** ULSD 827.1, GTL 784.6 ***90% distillation (C):** ULSD 329, GTL 342.1	NO DATA	NO DATA	GTL 22%↓<GD50 (16%↓) <DF	NO DATA	DF<GD50<GTL	NO DATA
(Wu et al. 2007)	Diesel engine 6-cylinder, 8.27L, 4S CR:18, DI, TC,IC RP: 184 KW RS: 2200rpm Common Rail, turbocharged - ECE R49 13-mode cycles.	-diesel -GTL(G100) -GTL blends: G10 (10%GTL+ 90% DF), G20, G30, G50, G70	***Cetane NO:** DF 51.7, GTL 75 ***Sulfur(%wt):** DF 0.0403, GTL 0.0003 ***Total aromatics (%wt):** DF 27.7, GTL 1.4 ***Poly aromatics(%wt):** DF 6.2, GTL 0.4 ***Density (kg/m3 @ 15 C):** DF 839.2, GTL 779 ***90% distillation (C):** DF 330.8, GTL 310.1	++ GTL% in blends ↓CO G100<G50<G30 <G20<G10<DF -G100 up to 38%↓CO< DF.	++GTL% in blends↓ emissions. G100<G50< G30 <G20<G10< DF -G100 up to 20%↓<DF.	++GTL% in blends ↓NOx. G100<G50<G30 <G20<G10<DF G30: Up to 4.3%↓ G70: up to 9%↓ G100: up to 12.1%↓	G100 ↓PM 27.6%<DF G100<G50<G30<G20<G10<DF	GTL<soot DF. -G30, G70 and G100 up to ↓9.7%,12.8%,15.6% respectively< DF ++GTL% in blends ↓soot. G100<G50<G30< G20<G10<DF	NO DATA
(Krahl et al. 2009)	Mercedes-Benz, Euro 3 engine, 6-cylinder, 6.37L, CR: 17.4, TC, IC, RS: 2300RPM, RP: 205KW,	-diesel (DF) (meeting EU standard EN590) -GTL -RME (rapeseed methyl ester)	***Sulfur content (mg/kg):** DF<1, GTL<0.5, RSO 2.6 ****Cetane NO:** DF 53.2, GTL57.6, RSO 42.6 ***Monoaromatics (%vol):**	-All fuels< Euro 3 limits. RME 54%↓<RSO 18%↓<DF<GTL 3.6%↑	All fuels< Euro 3	Except GTL and DF other fuels **>**Euro 3 limit. GTL 14%↓<DF<RME 16%↑<RSO 29%↑	All fuels <Euro 3 RME 57%↓<GTL 31%↓<DF<RSO 29%↑	No DATA	NO DATA

	turbocharged, intercooler - 13-mode European Stationary Cycle	-RSO (rapeseed oil)	DF 16, GTL- ***Diaromatics (%vol):** DF 4.3, GTL- ***Polyaromatics (%vol):** DF 0.1, GTL- ***Density (kg/m3 @ 15 C):** DF 833.8, GTL 795, RSO 919.6						
(Lapuerta et al. 2010)	Nissan diesel engine 4-cylinder, 2L, 4S, CR: 18. DI, TC, IC RP: 82KW RS:4000rpm Common Rail, turbocharger, intercooled EGR	-diesel fuel(DF) -GTL, -soybean biodiesel (BSOY) -GTL, -Biodiesel blend (G30B70)	***O %(wt):** DF 13.87 ,GTL 15.29 ,BSOY 11.84, G30B70 (12.69) ***Sulphur content (ppm wt):** DF 34 ,GTL 0 ,BSOY 0, G30B70 (0) ***Lubricity:** DF 259, GTL 560, BSOY 233, G30B70 (156) ***Cetane number:** DF 52, GTL 79, BSOY 53, G30B70 – ***Density (kg/m3 @ 15 C):** DF 834, GTL 783, BSOY 886, G30B70 (856)	CO↓ for GTL than other fuels. -not significant	-GTL: lowest emission. -biodiesel 74%↓<GTL 47%↓<DF	-Biodiesel< slightly DF --not significant	-GTL and BSOY: lowest emission – -G30B70< only DF Particle number: Biodiesel up to 66%↓<blend up to 54%↓<GTL up to 36%↓<DF	++bio-diesel in GTL blends ↓smoke. Biodiesel and blend 50%↓<GTL 16%↓<DF	NO DATA
(Hewu et al. 2009)	Cummins Euro III diesel engine, 6-cylinder, 5.9L CR:17.5,TC,IC RP:136KW, RS:2500rpm - European Steady-State test Cycle (ESC)	GTL fuel, diesel fuel (DF)	***Cetane number**: GTL74.7, Diesel 53.4 ***Sulfur (mg/kg):** GTL <1, Diesel 50 ***Aromatics (%):** GTL <0.1, Diesel 17.4 ***Density (kg/m3 @ 15 C):**	CO for GTL 38% ↓<DF	Total HC for GTL ↓< DF in a range of 31–55%.	13% NOx ↓ GTL< DF	Up to 33%↓ observed with GTL< DF.	NO DATA	NO DATA

			GTL777.3, Diesel 824.1						
(Yehliu et al. 2010)	Light-duty Diesel Engine, DI 4-cylinder, 2.5L, 4S CR: 17.5 , DI,TC RP: 103 kW RS: 4000 rpm Common Rail, single split injection, EGR - steady-state testing -no diesel particulate filter (DPF)	-Ultra Low Sulfur diesel fuel (BP15), -Soybean Methyl Ester (B100) -GTL fuel	***Oxygen content (%O):** BP15 (0), B100 (10.79), GTL (0) ***Sulfur (ppm wt):** BP15 (15), B100 (2-5), GTL<2 ***Derived cetane number:** BP15 (47.3), B100 (47.7), GTL (80.8) ***Density (g/cm3 @ 15 C):** BP15 (0.837), B100 (0.8843), GTL<0.8	GTL 63%↓<B100 (7%↓)<BP15	GTL 75%↓<B100 (10%)↓<BP 15	GTL 33%↓<B100 (6%)↓<BP15	GTL 30%↓<BP15<B100 (80%)↑	NO DATA	NO DATA
(Hajbabaei et al. 2013)	**ENGINE 1:** Cumminus ISM 370 engine, DC electric heavy duty engine, 2006 model year, 10.8 L, EGR, RP: 385hp, RS: 1800 rpm **ENGINE 2:** 2007, Detroit diesel MBE 4000, DC electric heavy duty, 12.8 L, EGR, diesel particulate filter (DPF), RP: 3450-450 hp, RS: 1900 rpm - lightly loaded Urban Dynamometer	-Baseline: CARB-certified diesel -Blends with soy-based biodiesel, animal-based biodiesel, -renewable diesel (BTL), GTL	***Aromatics (vol%):** CARB 18.7, renewable 0.4, GTL 0.5, soy--, animal-- ***Cetane number:** CARB 55.8, renewable 72.3, GTL>74.8, soy 47.7, animal 57.9 ***Sulfur (ppm):** CARB 4.7, renewable 0.3, GTL 0.9, soy 0.7, animal 2 ***Carbon (%wt):** CARB 86.1, renewable 84.83, GTL 84.6, soy 76.72, animal 75.89 ***Oxygen (% wt):**	-Only for engine 1: % B, R, GTL↑: CO ↓ ENGINE1 results: B5: 4%↓ B20: 7-10%↓ B100:20-27%↓ R20:4-16%↓ R100:12-33%↓ GTL 20: 6%↓ GTL 100: 14%↓ -Engine 2: no significant results R100<B100<R20<GTL100<B20<GTL20<B5	-Only for engine 1: % B, R, GTL↑: THC ↓ ENGINE1 results: B5: 3%↓ B20: 11-16%↓ B100: 55-73%↓ R20: 3%↓ R100:12%↓ GTL 20: 5%↓ GTL 100: 28%↓ -Engine 2: no significant results	NO DATA	-Only for engine 1: % B, R, GTL↑: PM ↓ ENGINE1 results: B5: 9%↓ B20: 10-26%↓ B100:31-69%↓ R20:4%↓ R100: 28-34%↓ GTL 20: 8%↓ GTL 100: 29%↓ -Engine 2: no significant results ***Reason** of ↓ PM for renewable: ↓density and aromatic, ↑ paraffinic nature, ↑ cetane number, ↑ boiling point	NO DATA	-%B↑: CO2 ↑ -R/GTL ↑: CO2 ↓ -ENGINE 1 results: B100: 0.7-4.2% ↑ R100: 3.3-3.4% ↓ GTL 50: 1.9% ↓ GTL 100: 3.5% ↓ -ENGINE 2 results: B100: 1.6-5%↑ *Reason: CO2 emission~ C/energy of fuel (lb carbon/million Btu),

	Driving Schedule (UDDS), standard Federal Testing Procedure (FTP) for heavy-duty engines, 40 miles per hour (mph) CARB heavy heavy-duty diesel truck (HHDDT) Cruise, and a 50 mph CARB HHDDT Cruise.		CARB 0.23, renewable 0.03, GTL--, soy 11.31, animal 11.89 ***API gravity (@ 60 F):** CARB 39.3, renewable 51.3, GTL 48.4, soy 28.5, animal 28.5 ***90%distillation (F):** CARB 612, renewable 547, GTL 648, soy --, animal ---						Biodiesel has ↓ HV, for the same work: Carbon consumption ↑, CO2 emission ↑
(Kitano et al. 2005)	Diesel Engine , 4-Cylinder ,2L, CR:16:1, TC,IC Common rail -- steady operating conditions, EC driving cycle - four Urban Driving Cycles (UDC) and one Extra Urban Driving Cycle (EUDC)	EURO 4 DF and GTL fuels : J series (higher CN), N-series(Lower CN)	***Cetane number:** J1 (85), J2 (85), J3 (85), N1 (71.5), N2 (71.5), N3 (71.5), Diesel (53.4) ***Aromatics (% vol)** J1 (<0.1), J2(<0.1), J3(<0.1), N1(<0.1), N2(<0.1), N3(<0.1), Diesel (18.9) ***Sulfur (mass ppm):** J1 (<1), J2(<1), J3(<1), N1(<1), N2(<1), N3(<1), Diesel (33) ***density (15 C, g/ml):** J1 (0.782), J2(0.773), J3(0.786), N1(0.757), N2(0.751), N3(0.764), Diesel (0.840)	GTL 60-75%↓< DF	GTL (J)75% ↓<GTL (N) 50%↓<DF	GTL 45% ↓<< DF	GTL (N2) 50-70% ↓<DF	GTL 45% ↓<< DF	NO DATA

(Armas et al. 2013)	4 cylinder, 4 S, turbocharged inter cooled, 2L Nissan diesel engine, common rail injection, EGR, Oxidation catalyst (DOC), DPF, RP: 110 kW, RS: 4000 rpm - New European Driving Cycle (NEDC).	Diesel GTL Animal based biodiesel	***Oxygen content (%w/w):** Diesel 0.66, GTL 0, biodiesel 11.03 ***Cetane number:** Diesel 54.2, GTL 89.2, biodiesel 65.6 ***density (15 C, g/ml):** Diesel 845, GTL 774, biodiesel 877	CO: GTL 52%↓< biodiesel 14% ↓<diesel *Reason: same as THC (CO and THC are due to incomplete combustion)	THC: Biodiesel 46%↓<GTL 33%↓< diesel *Reason: Biodiesel (aromatics ↓, oxygen↑), GTL (poly aromatics↓, volatility↑ so better vaporization)	Biodiesel 12.5%↓< diesel -GTL=diesel	Biodiesel 70%↓< GTL 60%↓<diesel	Biodiesel <GTL <diesel *reason: biodiesel has oxygen, biodiesel and GTL have no aromatics	NO DATA
(Ushakov et al. 2013)	4 S, turbocharged. Intercooled, DI, heavy duty diesel engine - 4-mode steady E2 cycle simulating constant-speed main propulsion application and E3 cycle for propeller-law-operated engines	Low sulfur MGO (marine gas oil) GTL	***Cetane number:** MGO 51.9, GTL 76.6 ***Oxygen content (%wt):** MGO 0, GTL 0.27 **Sulfur content (ppm):** MGO 500, GTL<5 **H/C ratio (molar):** MGO 1.88, GTL 2.10 ***Density (g/cm3):** MGO 0.849, GTL 0.779	GTL 25%↓ *Reason: oxygen and complete combustion	THC 10% ↑ *Reason: in CO2 section	GTL 19% ↓ NOx *Reason: temperature ↓, cetane number ↑	GTL 16% ↓ of mass of PM GTL 21% ↑ of number of PM *Reason of number: nano-particles↑, higher contribution of HC to PM	GTL 30%↓ smoke *Reason: aromatics ↓↓	GTL 4% ↓ CO2 *Reason: H/C ratio ↑ CO2 emission ~ fuel consumption ~ density and heating value GTL: density ↓, HV=same, so for equal energy volumetric fuel consumption ↑, so wall-wetting ↑, so HC ↑

Table 36. Studies on the effect of oxygenate fuels and their blends on emissions of diesel engine

Study	Engine	Fuel type	Fuel characteristics	CO	HC	NOx	PM	Smoke/soot	CO2
(Patil 2015)	Kirloskar TV1 model diesel engine, single cylinder, 4S, Water cooled, DI, NA, 0.661 L, CR: 18, RP: 3.7 KW, RS: 1500 rpm,	-Diesel and Diethyl ether blends DE2D (2% ether), DE5D, DE8D, DE10D, DE15D, DE20D and DE25D	***Cetane number:** D100 (52), DE100 (125), DE5D (55.65), DE8D (57.84), DE10D (59.3), DE15D (62.95), DE20D (66.6), DE25D (70.25) ***oxygen content (%wt):** D100 (0), DE100 (21.6), DE5D (0.927), DE8D (1.49), DE10D (1.86), DE15D (2.82), DE20D (3.79), DE25D (4.78) ***density (15 C, kg/m3):** D100 (836), DE100 (713), DE5D (829), DE8D (826), DE10D (823), DE15D (817), DE20D (811), DE25D (805)	++DEE in the blend: ↓ CO (reason: higher oxygen, higher Cetane) DE20D (60%↓)<D100	++DEE in the blend: ↑ HC (contrary to other emissions, reason: higher heat of evaporation for DEE, slower evaporation, slower and poorer fuel-air mixing) DE20D (50%↑)> D100	++DEE in the blend: ↓ NOx (reason: higher oxygen, higher cetane, shorter combustion time) DE20D (60%↓)< D100	NO DATA	++DEE in the blend: ↓ smoke opacity (reason: higher oxygen) DE20D (20%↓)<D100	NO DATA
(Mori et al. 2015)	L4 DI TCI diesel engine, 2.9 L, RP: 96 KW, RS: 3200 rpm, CR: 17.5, with cooler, after treatments (DOC, DPF)	-Diesel -Biodiesel -blends: BD20, BD 50, BD 100	***density (15 C, kg/m3):** DF 0.817, BDF20 (0.826), BDF50 (0.849), BDF100 (0.885)	++BD: CO↓ -BD100: CO↓ 21% (reason: oxygenated compounds)	++BD: HC↓ -BD100: HC↓ 74.7% (reason: oxygenated compounds)	++BD: NOx↑ -BD100: NOx↑ 36.5% (reason: high density of BD containing oxygenated compounds, combustion temp↑)	++ BD: particles in accumulation range ↓	++BD: smoke↓ -BD100: smoke↓ 74% (reason: oxygenated compounds)	++BD: CO2↑ -BD100: CO2↑ 5.8% (reason: fuel consumption ↑)

(Masimalai 2014)	Single cylinder diesel engine, 4S, water cooled, CI, CR: 15, RP:3.68KW, RS: 1500 rpm	Diesel (pilot fuel-high cetane no) and methanol (primary fuel, high octane no), Energy share of methanol (%): 0-70	***Cetane number:** Diesel 45-55, methanol 3-5 ***Oxygen content (% wt):** Diesel 0, methanol 50 ***density (kg/m3):** Diesel 840, methanol 790	@ 44% methanol energy share: CO 22%↑ -++ methanol: CO↑	@ 44% methanol energy share: HC 40%↑ -++ methanol: HC↑	@ 44% methanol energy share: NOx 8%↓ -++ methanol: NOx↓	NO DATA	@ 44% methanol energy share: smoke 53%↓ -++ methanol: smoke↓	NO DATA
(Iorio et al. 2014)	3 cylinder, 2 valves, diesel engine, 1 L, CR: 17.5, RP: 15KW, RS: 3600 rpm, direct injection with CR, NA	-Diesel -rapeseed methyl ester (RME) -blends: 20% and 50% of biodiesel	***Cetane number:** Diesel 51.8, B20 (52.8), B50 (54.4), B100 (57) ***Oxygen (%wt):** Diesel (0.9), B20 (2.9), B50 (5.9), B100 (10.80) ***density (15 C, kg/m3):** Diesel 834.4, B20 (844.9), B50 (860.6), B100 (886.8) ***90 % Distillation temp (C):** Diesel 334.9, B20 (335.2), B50 (335.7), B100 (336.5)	Co ↓ up to B20: 37%↓ B50: 64% ↓ B100: 82%↓ **Reason:** Oxygen in biodiesel↑, enhance complete combustion	HC ↓ up to B20: 36%↓ B50: 20% ↓ B100: 40%↓ **Reason of ↓** unburned hydrocarbons**:** absence of aromatics, distillation curve (diesel has ↑ final distillation point, the final fraction of diesel may not completely vaporize and burn, HC↑), C↓, O ↑	High speeds (not a general trend): NOx ↓ up to B20: 7.7%↓ B50: 5.7% ↓ B100: 17%↓ **Reason:** 1-O↑: NOx ↑ 2-combustion temp↑: NOx↑ Here: 2nd and NOx↓ NOx is formed by **oxidation** of atmospheric nitrogen at sufficiently high t**emperatures**.	PM ↓ up to B20: 34%↓ B50: 63% ↓ B100: 89%↓ **Reason:** O↑ (a complete combustion) and aromatic (soot precursor) ↓ in biodiesel, C↓, C-C bonds ↓ -Particle No and size ↓ Reason: same	NO DATA	NO DATA
(Hwang et al. 2014)	Single cylinder, direct injection diesel engine, common rail injection, 0.98 L, CR: 17.4	Diesel and biodiesel from waste cooking oil	***Cetane number:** Diesel 50.88, biodiesel 51.34 ***sulfur content (mg/kg):** Diesel 3.93, biodiesel 1 ***density (15 C, kg/m3):**	CO: 63% ↓ Same reasons as above	HC: 61%↓ Same reasons as above	NOx: 36% ↑ Same reasons as above	NO DATA	Smoke: 66.7% ↓ Same reasons as above	NO DATA

			Diesel 820, biodiesel 878						
(Valentino et al. 2013)	Turbocharged, water cooled, DI diesel engine, common rail injection, 1.2 L, CR: 16.8 - New European Driving Cycle (NEDC)	Diesel, and butanol-diesel blend (B20)	***Cetane number:** Diesel 52, Butanol 100 (<22), B20 (<46) ***Oxygen content (%wt):** Diesel (-), Butanol 100 (21.6), B 20 (4.2) ***density (15 C, kg/m3):** Diesel 840, Butanol 810 , B20 (834)	CO: 33%↓	HC: not significant	NOx: not significant	NO DATA	Smoke: up to 40%↓ **Reason:** 1-cetane number of butanol ↓, ignition delay ↑, time for mixing ↑ 2-volatility of B20 ↑, dispersion of fuel vapor in combustion chamber, better mixing preparation	NO DATA
(Liu, Zheng, and Yao 2015)	**-METAL ENGINE:** single cylinder diesel engine, 1 L, EGR -**OPTICAL ENGINE**: Single cylinder, 4S, CR:15, 0.664 L	-Diesel fuel Blends: -REF 20: (20%vol cetane and iso- cetane) to study the effect of aromatics and sulfur -Heptane 20: (20% heptane), physical properties (boiling point, viscosity) -DMF 20: (20% DMF), cetane↓, Oxygen↑	***Cetane number:** Diesel 56, Ref 20 (56), Heptane 20 (56), Butanol 20 (50), DMF 20 (45) ***Oxygen: content(%wt):** Diesel (0), Ref 20 (0), Heptane 20 (0), Butanol 20 (4.3), DMF 20 (3.6) ***Aromatic content (%wt):** Diesel (11.9), Ref 20 (9.52), Heptane 20 (9.52), Butanol 20 (9.52), DMF 20 (9.52) ***Sulfur content (% wt):** Diesel (0.0045), Ref 20 (0.0036), Heptane 20	No difference -fuel properties have no effect on CO	No difference -fuel properties have no effect on THC	-fuel properties have no effect on diesel, Ref 20, heptane 20, butanol 20: all the same -NOx DMF 20>other fuels	NO DATA	-Ref 20, heptane 20 were the same as diesel: fuel properties (sulfur and aromatics) had no effect on soot emission -DMF 20< Butanol 20 -Oxygen and cetane have effect on Soot emission O in DMF20< O in butanol 20 However:	NO DATA

		-Butanol 20: (butanol 20%), cetane↓, Oxygen↑	(0.0036), Butanol 20 (0.0036), DMF 20 (0.0036) ***density (20 C, g/cm3):** Diesel (0.826), Ref 20 (0.839), Heptane 20 (0.798), Butanol 20 (0.814), DMF 20 (0.839)					Cetane in DMF 20< cetane in butanol 20: the reason for lower soot (improved premixed conditions)	
(Valentino and Iannuzzi 2015)	Turbocharged water cooled, 4 cylinders, DI diesel engine, common rail injection, EGR, 1.2 L, CR: 16.8 - New European Driving Cycle (NEDC)	-Diesel (European low sulfur <10 ppm) -RME biodiesel, B100 -Blends: B30 B60 G30 G60 (gasoline with octane 95) BU 30 (butanol)	***Cetane number:** Diesel (52), B30 (52.1), B60 (52.2), B100 (52.3), G30 (41.3), G60 (30.6), BU30 (43.9) ***Oxygen content (% wt):** Diesel --, B30 (3.2), B60 (6.3), B100(10.5), G30--, G60---, BU30 (6.5) ****density (15 C, kg/m3):** Diesel 840, B30 (853), B60 (866), B100(883), G30 (810), G60 (780), BU30 (828)	NO DATA	NO DATA	No significant difference in NOx emission, so Oxygen availability of biodiesel may not cause NOx ↑.	NO DATA	Diesel>…>G60 ++gasoline or ++ butanol: smoke ↓ G60: 96%↓ G30:92%↓ BU30:84%↓ B60:77%↓ B100:75%↓ B30:58%↓ ***Reason**: -G60 has ↓↓ cetane and ↑↑ ignition delay -BU 30: oxygen availability, positive effect on soot	NO DATA

Table 37. Studies on the effect of changing gasoline properties on emissions of gasoline engine

Study	Engine	Fuel type	Fuel characteristics	CO	HC	NOx	PM	CO2
(Stradling et al. 2004)	-Test cycles: ECE, EUDC, combined NEDC **Car A:** Displacement (cm3): 1998, Max power (kW @rpm): 103 @5500, Inertia class (kg): 1250, 4 cylinder, 4 valves per cylinder, Max torque (Nm@ rpm): 200@4250, CR 10:1, Combustion/injection/control system: stoichiometric DI, catalytic system: TWC, Emission compliance: Euro-3 **Car B:** Displacement (cm3): 1796, Max power (kW @rpm): 85 @5500, Inertia class (kg): 1360, 4 cylinder, 4 valves per cylinder, Max torque (Nm@ rpm): 175@3750, CR 10.5:1, Combustion/injection/control system: MPI variable valve actuation, catalytic system: TWC, Emission compliance: Euro-4 **Car C:** Displacement (cm3): 1997, Max power (kW @rpm): 107 @6000, Inertia class (kg): 1470,	-8 fuels with different E70/E100 (volatility) 22-38% , final boiling point (FBP) 176-197 C, Aromatics 26-38% , and Olefin 5-14% -Sulfur: 40-50 ppm	***FBP (C):** F1 (174), F2 (180), F3 (174), F4 (177), F5 (195), F6 (202), F7 (195), F8(196) ***E 70 C (%v/v):** F1 (19.1), F2 (33.4), F3 (39.2), F4 (20.5), F5 (41.2), F6 (24.5), F7 (22.8), F8(39) ***E 100 C (%v/v):** F1 (48.2), F2 (61.9), F3 (62.9), F4 (46.7), F5 (62.2), F6 (48), F7 (47.4), F8(62.5) ***Olefins (%v/v):** F1 (5.5), F2 (3), F3 (12.7), F4 (14.1), F5 (4.9), F6 (5.3), F7 (13), F8(14.2) ***Aromatics (%v/v):** F1 (25), F2 (37.8), F3 (27.7), F4 (39.9), F5 (28.6), F6 (38.5), F7 (24.1), F8(35.9)	**E 70: (Car C)** 22→38: +4% **FBP: (Car B, C)** 176→197: +20% **Aromatics:** not significant **Olefins:** not significant	**E 70:** 22→38: -10% **FBP:** 176→197: -9% **Aromatics:** 26→38: +5% **Olefins:** not significant	**E 70:** (Car A) 22→38: +21% **FBP:** (Car A) 176→197: +21% **Aromatics:**(Car D) 26→38: +24% **Olefins:** not significant	-Not regulated for spark ignition engines **FBP:** 176→197: +81% **Olefins:** 5→14: +24%	-Not regulated **Aromatics:** 26→38: +2%

	4 cylinder, 4 valves per cylinder, Max torque (Nm@ rpm): 193@4100, CR 11.4:1, Combustion/injection/control system: Lean DI, catalytic system: TWC+ Nox trap, Emission compliance: Euro-3 **Car D:** Displacement (cm3): 1598, Max power (kW @rpm): 81 @5800, Inertia class (kg): 1360, 4 cylinder, 4 valves per cylinder, Max torque (Nm@ rpm): 155@4400, CR 12:1, Combustion/injection/control system: Lean DI, catalytic system: TWC+ Nox trap, Emission compliance: Euro-4							
(Goodfellow et al. 1996)	-Details on engine in reference -16 vehicles from 7 different manufacturer -Engine capacity: 1.4, 1.6, 1.8, 2, 2.4, 2.5, 2.9 -Fuel injection: MPI or SPI -some engines with EGR, some without -Air injection: some yes some no -New MVEG test cycle	-9 fuels with different aromatic (20,35,50% V/V), and Mid range volatility (E100, 35, 50, 65% v/v) -Bezene: 2% v/v -Sulfur up to 100 ppm *aromatics↓: CO↓, HC ↓, CO2↓, NOx↑ *Volatility↑:	***Aromatics (%v/v):** F1 (24.1), F2 (37), F3 (51.1), F4 (19.5), F5 (35.2), F6 (48.3), F7 (20.3), F8(34.1), F9 (34.8) ***E100(%v/v):** F1 (40.7), F2 (36.3), F3 (36.5), F4 (51.4), F5 (51), F6 (50.3), F7 (64.5), F8(61.8), F9 (59.9)	-composite cycle **-Aromatic: 50→20:** -18% (not dependent on E 100) **-E100: 35 →50:** -9% (not dependent on aromatics) **-E100: 50→65:** +7%	-composite cycle **-Aromatic: 50→20:** E100=35: -30% (max) E100=50: -11% E100=65: -10% (dependent on E 100) **-E100: 35 →50:** Aromatics=20: -25% Aromatics=35: -35%	**-Aromatic: 50→20:** E100=35: +15% (max) E100=50: +8% E100=65: +3% (dependent on E 100) **-E100: 35 →50:** Aromatics=20: +7% Aromatics=35: +13% Aromatics=50: +20% (max)	No Data	**-Aromatic: 50→20:** E100=35: -5% (max) E100=50: -5% E100=65: -5% (not dependent on E 100)

		HC ↓, NOx↑, CO2 (-), CO ??		(not dependent on aromatics)	Aromatics=50: -42% (max) (dependent on aromatics) **-E100:** **50 →65:** Aromatics=20: -0.6% Aromatics=35: -1% Aromatics=50: -1.4% (max) (dependent on aromatics)	(dependent on aromatics)		
(Petit et al. 1996)	-Modified European driving cycle -Details on engine in reference -16 vehicles from 7 different manufacturer -Engine capacity: 1.4, 1.6, 1.8, 2, 2.4, 2.5, 2.9 -Fuel injection: MPI or SPI -some engines with EGR, some without -Air injection: some yes some no	-4 fuels with different sulfur content -base fuel: 18 ppm sulfur, All other properties constant (aromatic, E100, Olefin,…)	**-Aromatics (% vol):** 19.5 -E 100 (% vol): 51.4 **-Olefin (% vol):** 4.4 **-MTBE (% vol):** 9.5 **-Benzene (% vol):** 2.5 -RON: 97.7 -**Sulfur(ppm):** 18,95, 182, 382	Composite cycle **-Sulfur: 382→18** ppm: -10%	Composite cycle **-Sulfur: 382→18** ppm: -10%	Composite cycle **-Sulfur: 382→18** ppm: -10%	NO DATA	NO DATA
(Singh et al. 2016a)	Gasoline engine, Multi point fuel injection, engine size 1196 cc, 4 cylinder, 4 valves per cylinder, CR: 9.9, Max torque: 101 Nm @ 3000 rpm, Max power: 54 kW @6000 rpm	Three fuels, E 5, E10, E20, effect of ethanol *Oxygen in blend↑: combustion efficiency↑, NOx↑, CO2↑, CO↑, HC↑	***RON:** gasoline (91.3), E5 (92.9), E10 (94.6), E20 (98.4) ***Benzene content (% vol):** gasoline (0.56), E5 (0.52), E10 (0.50), E20 (0.42) ***Olefin content (% vol):** gasoline (9), E5 (8.8), E10 (8.5), E20 (7)	@ rated power conditions (6000 rpm) -E5: -12% -E 10: -50% -E20: -65% *Reason: more complete combustion,	@ rated power conditions (6000 rpm) -E5: -8% -E 10: -30% -E20: -38% *Reason: more complete combustion, because of oxygen+ ethanol	@ rated power conditions (6000 rpm) -E5: +4% -E 10: +78% -E20: +109% (double)	NO DATA	@ rated power conditions (6000 rpm) -E5: +1% -E 10: +10% -E20: +14%

			***Aromatic content (% vol):** gasoline (33), E5 (30.1), E10 (27), E20 (25.8) ***Sulfur Content (% mass):** 0.001 (all)	because of oxygen	molecules are polar and cannot be absorbed easily by un-polar molecules in lubricating oil layer			
(Shanmugam et al. 2009)	-3 gasoline engines -4 cylinder, capacity: (two 1.4 L and one 1.2 L), CR: 10:1, P max (kW @ rpm): 62.5@500, 51.5@4800, 48@5000, Max engine speed (rpm): 6200, 5300, 5300 -BS3 drive cycle	E10 compared to neat gasoline	* E10 properties: RON:(97), Reid vapor pressure (50 kPa), Oxygen content(% mass): 3.5	-13%	-19%	+16%	NO DATA	-2%
(Kumar et al. 2008)	500 cc, water cooled single cylinder SI engine,	E10, E30, and E70 compared to gasoline	NO DATA	@ highest speed (2500 rpm) E 10 (-74%), E30 (+28%), E70 (+28%)	@ highest speed (2500 rpm) E 10(-), E30 (-), E70 (+60%)	@ highest speed (2500 rpm) E 10 (+67%), E30 (-), E70 (-)	NO DATA	NO DATA
(Rickeard et al. 2003)	4 vehicles Cycles: ECE, EUDC, combined NEDC -Displacement: Car A 1998, Car B 1796, Car C 1997, Car D 1598, -Max power (kW @rpm): 103 @5500, 85@5500, 107@6000, 81@5800 -All 4 cylinder, all 4 valves per cylinder, CR: 10, 10.5, 11.4, 12 -combustion/injection control system:	Sulfur effects (4-148 ppm) Compared to fuel 1 with 4 ppm sulfur	***Sulfur (ppm)** Fuel 1: 4, fuel2:9, fuel3:48, fuel 4: 148 ***Base fuel (fuel 1 with min sulfur)** RON: 94.9, E100 (%v/v): 58.8, Olefin (% v/v): 3.5, Aromatics (% v/v): 29.7, Benzene (%v/v): 0.2	Combined NEDC -no significant effect of sulfur content	Combined NEDC -no significant effect of sulfur content	Combined NEDC -no significant effect of sulfur content	NO DATA	NO DATA

	stoichiometric DI, MPI, Lean DI, LEAN DI							
(Nithyanandan et al. 2014)	Without catalytic converter -single cylinder engine, displacement 575 cc, CR: 9.6, the number of valves 4, port fuel injection	Different ratio of ABE (Acetone-butanol-ethanol mixture) with gasoline neat gasoline, ABE 20%, ABE 40%	No DATA	ABE 20↑ ABE 40 ↓ -CO and HC have mixed effects -a small amount of ABE fuel: slightly helps the air/fuel mixing and oxidation process. However ABE 40: latent heat of vap↑, and degrades combustion quality	ABE 20: -50% ABE 40: --	Not significant	NO DATA	NO DATA
(Lange et al. 1994)		-13 fuels B1: base fuel -B4-B7: variation in group of oxygenate B4: 15% cyclohexane B5:15% isoparaffin B6: 15% MTBE B7: 15% alcohol -B8 and B9: lower aromatic		-emissions compared to B1 -B6: -8% -B7: -15% -B8:-20% -B9:-17% -B10:-24% -effect of sulfur: not significant	-emissions compared to B1 -B4, B5: -- -B6, B7: -12% (MTBE, alcohol) -B8: -15% (low aromatic+ isoparaffin) -B9:-- (Low aromatic+olefin) (less volatile than others)	-emissions compared to B1 -B4: -5% -B5:-8% -B6:-28% -B7: -16% -B8: -48% -B9: -13% -B10:-41% -effect of sulfur" 100 to 10 ppm: -17%		

		content from 45% to 25%, and to understand the effect of olefin and paraffinic fuels -B8: isoparaffin -B9: olefin -B10: low aromatic (25%), and MTBE+ isoparaffin -B14 to B16: effect of sulfur (10-100 ppm) -C1: similar to B1 with different benzene -C2: similar to B10 with different benzene			-B10: -30% (low aromatic+isoparaffin+MTBE) -effect of sulfur: not significant **Generally:** Low aromatic and isoparaffin+MTBE and high volatility best reduction in HC, CO, NOx			