WORKING PAPER

EMBARQ®

EXHAUST EMISSIONS OF TRANSIT BUSES

Sustainable Urban Transportation Fuels and Vehicles

1. Executive Summary

EMBARQ's Sustainable Urban Transportation Fuels and Vehicles (SUTFV) program aims to take an unbiased approach to analyzing the impacts of different fuels and technologies for bus transit fleets. The program jointly addresses lifecycle costs and emissions of transit buses and is targeted to provide context-specific recommendations for cities in India, Mexico, and Brazil—countries in which EMBARQ works. This report, the first in the SUTFV program, compiles a large data set of in-use transit bus emissions tests for use in a meta-analysis to define ranges of exhaust emissions for fuel and technology combinations. The analysis looks at both local and global emissions to understand their impact on human health and the environment.

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List of Abbreviations

3WC	Three-way catalyst
B100	neat biodiesel (100%)
B20	20% biodiesel, 80% petroleum diesel
B5	5% biodiesel, 95% petroleum diesel
CNG	Compressed natural gas
CO	Carbon monoxide
CO2e	Carbon dioxide equivalent
D	Diesel
D15	Diesel with 15 ppm of sulfur
D150	Diesel with 150 ppm of sulfur
D50	Diesel with 50 ppm of sulfur
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
E	Ethanol
EEV	Enhanced environmentally friendly vehicle
EGR	Exhaust gas recirculation
GHG	Greenhouse gases
HC	Hydrocarbons
ICE	Internal combustion engine
LNG	Liquified natural gas
NMHC	Non-methane hydrocarbons
NREL	National Renewable Energy Laboratory
NOx	Nitrous oxides
O3	Ozone
OC	Oxidation catalyst
PM	Particle matter
SCR	Selective catalyst reduction
THC	Total hydrocarbons
ULSD	Ultra-low sulfur diesel

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Some of the exhaust or tailpipe emissions commonly associated with mobile sources are carbon monoxide (CO), hydro-carbons (HC), nitrogen oxides (NO_x), and particulate matter (PM). These emissions can cause local air pollution and be a determinant in human health problems (U.S. Environmental Protection Agency 2012a). In many countries, these emissions are regulated through emissions standards that spur motor vehicle technology advancements and improved exhaust after-treatments. Exhaust emissions also produce greenhouse gases (GHG), specifically carbon dioxide, which are not reduced by current exhaust after-treatment technologies. Recent GHG emissions regulations in Europe cover only passenger cars and vans, while in 2011, the United States announced the first-ever GHG regulations and fuel economy standards for heavy-duty engines and vehicles (Lindqvist 2012).

The fuels considered in this analysis are diesel with various concentrations of sulfur, biodiesel (100 percent and 20 percent blend with diesel), compressed natural gas (CNG), liquefied natural gas (LNG), and ethanol. The technologies considered are standard internal combustion engines (ICEs) and hybrid ICE-electric, in combination with a variety of exhaust after-treatment technologies. Each of the fuels and technologies has its benefits and costs. A statistical meta-analysis technique for combining the results of 24 independent studies was used to find a range of emissions values for different fuel and technology combinations. The analysis looked at many factors for which data were available, including specific fuel type and relevant technologies, emissions standards, field tests vs. lab tests, drive cycles, CO_2 equivalent emissions, mileage, and altitude.

Overall, the results from the meta-analysis of the compiled studies align with results from studies on individual fuels and technologies. The meta-analysis shows that there is a wide range of emissions values even for the same fuel and technology. Many of the factors explored, such as altitude and drive cycle, do have an impact on emissions. This analysis aids in understanding these variations in order to more accurately evaluate results from further emissions testing. Technologies are often developed to meet emissions standards, and the results of this study imply that emissions standards are generally effective. However, it is demonstrated that not all buses are meeting their expected emissions standards, specifically for NO_x and PM, which also can be associated with wear on the bus.

The analysis also shows that no single fuel is best in all categories of emissions if the appropriate exhaust after-treatment technologies are used, which means that these technologies are key to reducing emissions. The technologies that show the lowest emissions for key pollutants, such as NO_x, PM, and CO_2 equivalence, are compressed natural gas with a three-way catalyst, 100 percent biodiesel, and ultra-low sulfur diesel with selective catalyst reduction. However, because none of the fuels can be classified as the best at reducing all emissions, it is important to consider lifecycle costs and lifecycle emissions for buses in specific locations before making fleet selection decisions. The lifecycle cost and emissions components raise many possible variables, either global or local, which can have an impact on fuel and vehicle recommendations. Understanding how fuels and technologies contribute to exhaust emissions is a first step in understanding the true costs and impacts of urban bus fleets in various urban contexts.

2. INTRODUCTION

Even with the abundance of information available in recent decades regarding alternative fuels and vehicles, it is often unclear which fuel and vehicle types a transit agency should choose for its bus fleet. Existing research on fuels and vehicles often provides in-depth information on transit bus costs or emissions for specific fuels and technologies in specific locations. Many major transit agencies worldwide, especially in the United States and Europe, have done extensive fuel and vehicle testing and cost-efficiency analyses for local and national programs. However, each approach to analysis, as well as the fuels and technologies considered in the tests, can vary significantly. Thus, the results of single studies or a small sampling of studies may not be easily comparable to other agencies' studies or applicable in other locations. In addition, even with the amount of research and data available on transit buses, the full lifecycle costs of vehicles of different fuel types and lifecycle emissions are often not available. Even where the data exist on local pollutant emissions, greenhouse gas emissions, and vehicle costs, these factors are not always considered jointly.

The aim of EMBARQ's Sustainable Urban Transportation Fuels and Vehicles (SUTFV) program is to better understand the full lifecycle costs and emissions of transit buses of different fuel types, as well as the trade-offs between costs and emissions, in order to aid transit agencies' decisions in urban bus fleet procurement. The project will focus on conditions in Mexico, Brazil, and India—countries where EMBARQ currently works—in order to develop local recommendations in various urban contexts.

As part of the SUTFV program, this paper aims to create a better understanding of the exhaust emissions impacts of relevant fuel and technology types by compiling data and research from a variety of transit and government agencies from different countries. Though an effort was made to provide the broadest dataset possible, data were only collected from testing performed on in-use or previously used transit buses. Therefore, these data do not represent all possible conditions for all fuel and technology combinations (particularly emerging technologies and ethanol buses), due to lack of availability of like studies. This report does not consider emissions other than exhaust emissions. For example, upstream emissions from fuel production, vehicle manufacturing, or leakage during vehicle fueling are not included.

Because results of individual bus emissions tests can vary greatly, a small sample size of bus tests, which are typically performed by agencies, may not be representative of a given fuel type generally. The compiled research presented here creates a broader database of emissions testing results from which agencies can make choices. This report is useful in creating a framework for vehicle selection but does not constitute a final recommendation on fuel types for any particular transit agency. Full lifecycle analysis of a transit vehicle in terms of costs and emissions is required.

This paper addresses the following topics:

- significance of regulated and unregulated emissions
- emissions standards
- expected emissions ranges for different fuels and technologies
- effects of specific emissions-reduction technologies on expected emissions
- additional factors that lead to changes in expected emissions

3. BACKGROUND ON EXHAUST EMISSIONS

It is important to understand regulated and unregulated emissions to understand the emissions standards for different transit bus exhaust types. Particulate matter, nitrogen oxides, hydrocarbons, and carbon monoxide, which are addressed in this report, are of primary concern because of the high concentrations of soot, ozone, and smog in many urban areas, as well as their negative health impacts. Volatile organic compounds and black smoke are also significant emissions but are not addressed in the meta-analysis due to lack of data. Tailpipe emissions of transit buses are currently monitored in many countries around the world. National vehicle testing programs and vehicle emissions standards focus on reducing local emissions.

3.1 Significance of Emissions

Air pollution is a major environmental health problem affecting people worldwide. Exposure to air pollutants is largely beyond the control of individuals and requires action by public authorities at the national, regional, and even international levels. According to the World Health Organization (WHO), more than 2 million premature deaths each year can be attributed to the effects of urban outdoor air pollution, at least partly caused by fuel combustion (WHO 2006).

The key pollutants related to transportation exhaust are summarized in Table 1, along with the countries where they are regulated. WHO shows that there are significant health impacts related to nitrogen oxides and sulfur dioxides, while there are specific quantifiable mortality impacts related to PM and ozone (O_3). There is roughly a 6 percent increase in mortality for each 10 $\mu g/m^3$ increase in $PM_{2.5}$ and a 3 to 5 percent increase in mortality for each 60 $\mu g/m^3$ increase in O_3 (WHO 2006). The health and environmental impacts of commonly tested exhaust emissions, which are summarized in Table 1, are further detailed in publications from the WHO and the U.S. Environmental Protection Agency (EPA) (WHO 2006, EPA 2012a).

Table 1 Tailpipe Transportation Emissions for Heavy-Duty Vehicles

Emission types	Local pollutant	GHG pollutant	Regions/countries where regulated
Carbon Monoxide (CO)	x		US, Europe, Brazil, India, Mexico
Carbon Dioxide (CO_2)	x	x	US
Nitrogen Oxides (NO_x)	x	x	US, Europe, Brazil, India, Mexico
Total hydro-carbons (THC)[a]			Europe, Brazil, India
Non-methane hydro-carbons (NMHC)	x		US, Mexico
Particle Matter (PM)[b]	x		US, Europe, Brazil, India, Mexico
Methane (CH_4)		x	Europe
Sulfur dioxide (SO_2)	x		US, Europe, Brazil, India, Mexico through fuel quality standards

Notes:
[a] Total hydrocarbons refers to nonmethane hydrocarbons plus methane.
[b] PM considered in the study includes all particulate sizes, although most particles are under 2.5 nanometer in diameter for both diesel and CNG.

Carbon Monoxide (CO): Carbon monoxide results from incomplete combustion of fuel and is emitted directly from vehicle tailpipes. CO can be a precursor to both CO_2 and ozone, two significant greenhouse gases. Although exposure to CO does not have a cumulative effect on health, instantaneous effects of high concentrations can be dangerous (Nylund et al. 2004, Macias, Martinez, and Unal 2010).

Carbon Dioxide (CO_2): CO_2 is a naturally occurring gas that accounts for approximately 77 percent of global greenhouse gases (Baumert, Herzog, and Pershing 2005). It is also a byproduct of burning fossil fuels and biomass, other industrial processes, and land-use changes. CO_2 from transportation exhaust is not regulated in all countries and for all vehicle types. These regulations are fairly new and are met through fuel efficiency improvements rather than exhaust after-treatment (Lindqvist 2012).

Nitrogen oxides (NO_x): Nitrogen oxides are an important family of air polluting chemical compounds. These highly-reactive gases affect health and lead to increases in global warming. NO_x emissions increase as a result of increasing engine temperature (Macias et al. 2010). Emissions of NO_x from combustion are primarily in the form of nitric oxide (NO) (Nylund et al. 2004). NO can be oxidized into nitrogen dioxide (NO_2) which is a powerful air pollutant by itself and can also react in the atmosphere to form ozone and acid rain. Some emissions reduction technologies can increase the portion of NO_2 in diesel exhaust. Nitrous oxide (N_2O), a significant greenhouse gas, makes up a very small portion of total NO_x emissions for all fuel types (EPA 2012b).

Nonmethane hydrocarbons (NMHC): Nonmethane hydrocarbons in exhaust result from partially burned fuel. There are many potential pollutants resulting from hydrocarbons with different effects (eye, skin and respiratory tract irritation), including acetylaldehyde and formaldehyde. Hydrocarbons can have negative health impacts or contribute to the ground-level ozone or smog (Macias et al. 2010, Nylund et al. 2004).

Methane (CH_4): Methane, in the form of unburned fuel, is a tailpipe emission primarily for natural gas fuels. Although it is not toxic, methane has a global warming potential that is 25 times higher than that of CO_2 (Nylund et al. 2004, Environment Canada 2011a).

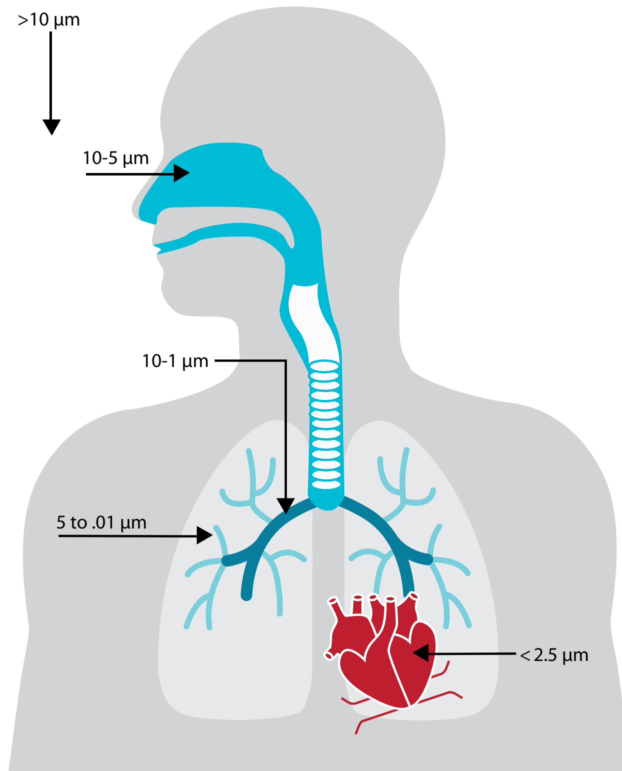
Particulate matter (PM): Particulate matter is a mixture of small particles and droplets, including acids, such as nitrates and sulfates; organic chemicals; metals; soil; or dust. Combustion can produce a large quantity of very fine particles 10 nanometers in diameter or smaller, but it is regulated by measuring the total quantity of all PM particles sizes. The human body cannot protect against exposure to ultrafine particles, which can enter the heart and lungs through inhalation (Figure 1) and have serious health effects, including respiratory diseases and heart and lung conditions (EPA 2012a).

Sulfur Dioxide (SO_2): Mobile-source SO_2 emissions are proportional to sulfur content in fuels (UNEP 2007). SO_2 is linked to many negative health effects, including respiratory system ailments (EPA 2012a).

Other pollutants: Ozone (O_3) is not emitted directly from mobile combustion but is formed in the atmosphere through a complex set of chemical reactions involving hydrocarbons, oxides of nitrogen, and sunlight. Ozone at ground level is a noxious pollutant, but it is not regulated as a tailpipe pollutant. It is the major component of smog, which is responsible for choking, coughing, and stinging eyes (EPA 2012a).

Volatile organic compounds (VOC) can have adverse health effects or contribute to air pollution. Exposure to black smoke exhaust has also been shown to increase the risk of developing lung cancer and therefore mortality risks (De Hartog et al. 2010). Sulfates and nitrates may have some adverse health effects, especially in combination with other emission compounds. However, concentrations of these pollutants emitted from modern vehicles, in combination with low-sulfur fuels and lubricants where available, are low compared with other emission and inhalation sources (Nylund et al. 2004).

Figure 1 Particles Entering the Human Body



This figure shows the particle sizes that can reach the respiratory and circulatory systems. The human body cannot protect against exposure to ultrafine particles.

3.2 Emission Standards

Many national governments use emissions standards and testing to control the amount and types of harmful emissions that are released into the environment as a direct result of fuel combustion. The exhaust emissions considered in this report are based on pollutants regulated by both the European Union emissions standards (Euro) and U.S. EPA standards, which include NO_x, THC or NMHC, PM, and CO. Emissions standards in other countries are often based on these standards. As of 2010, Brazil, Mexico, and India had standards roughly equivalent to Euro III, Euro IV, and Euro III respectively.

To perform emissions testing, the standards require a variety of drive cycles with corresponding emissions limits. An example of these limits for Euro and EPA standards is given in Tables 2 and 3. Both sets of emissions are converted into g/km for comparison. Although there are differences in the thresholds proposed by each agency, there is an overall trend of progressive standards of reducing key pollutants such as NO_x and PM. CO standards in the United States have not changed drastically because heavy-duty diesel vehicles are not a major source of this pollutant (Federal Transit Administration 2006). EPA standards for CO and THC are significantly higher than Euro standards, although NO_x, and PM standards are comparable.

The drive cycles required for emissions testing in different countries can be based on international standards as well as driving conditions in different locations. Euro emissions standards use two specific drive cycles. Since 2000, these cycles have been the European Stationary Cycle (ESC), a sequence of constant speeds and loads, and the European Transient Cycle (ETC), which simulates typical driving patterns. The EPA test is performed with various test cycles, including a transient test cycle, which includes urban and freeway driving conditions, and a steady-state test with a sequence of constant speeds and loads (Dieselnet 2012).

Table 2 Euro Emissions Standards for Transit Vehicles (g/km)

Emission Standards	Date	CO	THC	NO_x	PM
Euro I	1992	8.1	1.98	14.4	0.648
Euro II	1998	7.2	1.98	12.6	0.27
Euro III	2000	3.78	1.188	9	0.18
Euro IV	2005	2.7	0.828	6.3	0.036
Euro V	2008	2.7	0.828	3.6	0.036
EEV		2.7	0.45	3.6	0.036
Euro VI	2013	2.7	0.234	0.72	0.018

Source: Lindqvist 2012.
Notes: 1) Often emissions testing converts results in g/kWh to g/km. The factor of 1.8 km per g/kWh is used in Nylund et al. (2004). See appendix 1 for full sources for conversions. 2) EEV represents a voluntary emission standard between the Euro V and Euro VI standards (Dieselnet 2009).

Table 3 EPA Emissions Standards (g/km)

Emission Standards	CO	THC	NO_x	NMHC	NMHC + NO_x	PM
1994	45.06	3.78	14.54			0.20
1996	45.06	3.78	11.63			0.15
1998	45.06	3.78	11.63			0.15
2004 (1)	45.06	3.78			6.98	0.03
2004 (2)	45.06	3.78		2.91	7.27	0.03
2007	45.06	3.78	3.92	0.41		0.03
2010	45.06	3.78	0.58	0.41		0.03

Source: Transit Cooperative Research Program, 2011.
Notes: EPA converts g/bhp•hr to g/mi using 4.679 bhp•hr per mi. See appendix 1 for full sources for conversions. 2004 (1) and (2) represent two different options for compliance.

Regulation of GHG emissions is more recent in the United States and Europe. The European Union emission standard currently covers only passenger cars and vans, but not heavy-duty vehicles. Because there is currently no after-treatment technology that can reduce CO_2 emissions from road vehicles, CO_2 reductions are achieved through fuel efficiency improvements (Lindqvist 2012). In the United States, the EPA and the National Highway Traffic Safety Administration (NHTSA) are developing the first GHG regulations for heavy-duty engines and vehicles. According to EPA, the regulations will be phased in starting in 2014, and by 2018 the regulations should create an average reduction in GHG emissions per vehicle by 17 percent. The proposed standards are expected to save more than six billion barrels of oil through 2025 and reduce more than 3.1 billion metric tons of CO_2 emissions (EPA 2012c).

4. FUELS AND TECHNOLOGIES

In selecting particular bus technologies, transit agencies must balance fuel and vehicle availability, local conditions, and service needs. Various fuel options have been tested as part of national programs through institute testing and agency pilot programs and locally through agency testing. There are many possible fuels and exhaust after-treatment technology combinations. However, not all of these combinations will be available in the next decade in all countries and at all transit agencies. The fuels addressed in this report are all available, or soon to be available, in Brazil, India, or Mexico.

Table 4 shows the fuels currently being used by agencies in the three target countries of this report. Brazil has a wide variety of fuels available. Cities in Mexico use diesel, hybrids, and CNG. In India, as a result of a Supreme Court order, 13 major cities were required to use CNG vehicles starting in 2001, while diesel fuel is still available for buses in other cities (Roychowdhry 2010).

4.1 Energy Content of Fuels

Interest in using alternative fuels has grown as a way of exploring possible improvements over diesel in air quality and greenhouse gas emissions. More recent concerns with fuels include complying with emissions standards, addressing fuel security, and reducing price volatility. At the same time, diesel remains an important fuel in urban transit because of its high energy density, which means a smaller volume of fuel can transport a bus further. Table 5 shows diesel's high energy content with respect to other fuels which can be used in urban bus fleets. Biodiesel also has a high energy content and has similar fuel efficiency to diesel buses. Many improvements have been made to diesel buses over decades to reduce emissions, as will be discussed in this section. The most recent emissions standards show that buses using any fuel type will comply with the same stringent emissions standards.

Table 4 Fuels Currently Being Used by Transit Agencies in Brazil, India, and Mexico

Target countries	Low-Sulfur Diesel[a]	Diesel	Ethanol	B5	B20	B100	CNG	Hybrid
Brazil	x	x	x	x	x	x		x
India	x	x					x	
Mexico	x	x					x	x

[a] *A Low-Sulfur Diesel: 50 ppm contents of sulfur*

Table 5 Fuels, Energy Content, and Fuel Efficiency

Fuel	Energy content per gallon[a]	Fuel efficiency[b]
Diesel	128,000 - 130,000 Btu	3.2 mpg
Biodiesel	117,000 - 120,000 Btu	3.3 mi/DGE
CNG	33,000 - 38,000 Btu @ 3000 psi 38,000 - 44,000 @ 3600 psi	2.7 mi/DGE
Ethanol (E85)	~ 80,000 Btu	3.2 mi/DGE
Hydrogen	Gas: ~6,500 Btu @ 3,000 psi ~16,000 Btu @ 10,000 psi	2.7 mi/DGE
LNG	~73,500 Btu	2.7 mi/DGE

Sources:
[a] Department of Energy 2012
[b] TCRP 2011

Notes:
DGE: diesel gallon equivalent
psi: pounds per square inch
Btu: British thermal units

4.2 Existing Research on Fuels, Technologies, and Emissions

The following subsections explore the existing literature on fuel types and emissions characteristics of fuels. In addition, they describes exhaust after-treatment technologies and expected emission reductions from each technology. Data from some of the individual studies described here are also included in the meta-analysis in Section 5.

4.2.1 Diesel

Most diesel fuel available is petroleum diesel refined from crude oil (Transit Cooperative Research Program 2011). Because there are concerns that global crude oil resources are being depleted, other sources of diesel are being explored that may have different emissions characteristics. Individual countries offer various grades of diesel that have different sulfur contents. Diesel emissions are affected by the amount of sulfur in the diesel as well as the emission-reduction technologies. CO emissions are low for diesel engines. THC emissions from diesel are generally nonmethane, and less of a concern for global warming. The major concerns for diesel fuel are NO_x and PM emissions (Nylund et al. 2004).

4.2.1.1 Sulfur Content of Diesel Fuel

Reducing sulfur content in fuels not only reduces air pollution related to sulfur, but also allows for the use of exhaust after-treatment technologies. Sulfur in fuel contributes to formation of particulates that clog filters and therefore reduce the effectiveness of emission-reduction technologies like diesel particulate filters. Developing countries commonly have sulfur content levels above 500 parts per million (ppm); sulfur levels below this value allow for the use oxidation catalysts. Below 50 ppm, additional emissions reduction technologies are available (UNEP 2007). Table 6 presents sulfur content levels in Brazil, Mexico, India, the United States, and Europe.

Table 6 Diesel Sulfur Content in Brazil, Mexico, India, the United States, and Europe

Country	2012 (ppm)	Future target (ppm)[a]	Location
Brazil[b]	50	10	Major cities
	500	50	Metropolitan areas
	1800	500	Nationwide
Mexico[b]	15	15	Northern border region and 3 major metro areas
	500	50	Nationwide
India[c]	50		Major cities
	350		Metropolitan areas
	500		Nationwide
U.S.[d]	15		Nationwide
Europe[d]	10		Nationwide

Source:
[a] Brazil 2013, Mexico 2015
[b] UNEP 2012a
[c] UNEP 2012b
[d] UNEP 2012c

4.2.1.2 Diesel Emission-Reduction Technologies

Diesel Oxidation Catalyst (DOC): DOC utilizes a chemical process to break down pollutants from diesel engines in the exhaust stream, turning them into less harmful compounds. This reduces PM, HC, and CO emissions (Translink 2006). DOC can only be used below 500 ppm sulfur content in diesel (UNEP 2007).

Diesel Particulate Filter (DPF): A DPF is a device mounted in the bus exhaust system in the same location and general configuration as other typical exhaust after-treatment devices (e.g. muffler, oxidation catalyst). This helps to meet 2007 EPA standards. Carbon monoxide and hydrocarbons are turned into carbon dioxide and water, respectively. The catalyst also increases the proportion of nitrogen dioxide (NO_2) to nitrogen oxide (NO) in the exhaust. NO is oxidized to NO_2 so as to remove PM from the exhaust. A DPF can reduce the amount of particulate emissions from diesel to comparable levels with CNG (Melendez et al. 2005). A DPF tends to have a greater effect on reducing large particles, greater than 100 nanometers (Nylund et al. 2004). A DPF is only effective with diesel fuel with sulfur content less than 50 ppm (UNEP 2007).

Exhaust Gas Recirculation (EGR): EGR recirculates exhaust gases (mainly containing inert nitrogen, CO_2, and water vapor) into the engine cylinders. This recirculation cools the engine, thereby reducing NO_x emissions and possibly particulate matter (Murtonen and Aakko-Saksa 2009). EGR has been used for more than 25 years on spark-ignition engines (TCRP 2011).

Selective Catalytic Reduction (SCR): SCR combines urea and water to produce ammonia and CO_2, which then combines with NO_x to produce nitrogen and water (Murtonen and Aakko-Saksa 2009). SCR can reduce NO_x emissions by 75 to 90 percent (TCRP 2011). This helps to meet 2010 EPA standards.

4.2.2 Hybrid ICE-Electric

A hybrid-electric vehicle can draw energy from two sources of stored energy: a consumable fuel and a rechargeable energy storage system (Wayne et al. 2004). Exhaust emissions associated with a hybrid are the same as the emissions associated with internal combustion engines, but there can be a reduction in emissions stemming from hybrid systems achieving lower fuel consumption. Reduced fuel consumption is made possible through regenerative braking and reductions in engine transient operation through an improved power management system (World Business Council for Sustainable Development 2004).

4.2.3 Compressed Natural Gas (CNG)

Natural gas is a common fossil energy source with high methane content that is compressed to increase energy density (TCRP 2011). CNG emissions are mainly in the form of methane and NO_x. The air-to-fuel ratio for combustion, such as lean-burn[1] and stoichiometric,[2] can reduce emissions as well (Nylund et al. 2004). Compared to diesel, PM and NO_x emissions are lower for CNG, although the amount of reduction varies by bus (Melendez et al. 2005). CNG generally has low particulate emissions, although the fuel still emits particles that are harmful to health. With higher passenger loads, the amount of PM can increase to levels comparable to diesel (Nylund et al. 2004, Jayaratne et al. 2009). CNG also emits higher quantities of formaldehydes and other nanoparticles with negative health impacts, even with oxidation catalysts.

4.2.3.1 CNG Emission Reduction Technologies

Oxidation Catalysts (OC): OCs are designed to oxidize both CO and HC, resulting in the production of CO_2. Oxidation catalysts can reduce HC, CO, and CH_4 emissions (Nylund et al. 2004, Translink 2006, Johnson Matthey 2011).

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[1] Lean-burn – low fuel to air ratio, can employ higher compression ratios and thus provide better performance, efficient fuel use, and low exhaust hydrocarbon emissions.

[2] Stoichiometric – fuel-to-air ratio allows complete burn of fuel.

Three-way Catalysts (3WC): 3WCs are also known as oxidation-reduction catalysts. They are designed to oxidize both CO and HC and reduce NO_x. This results in the production of CO_2, nitrogen, and water (Johnson Matthey 2011).

4.2.4 Liquefied Natural Gas (LNG)

LNG is cooled natural gas that has a higher energy content than compressed natural gas. CNG and LNG vehicles use the same engines and therefore meet the same emissions standards and use the same emissions reduction technologies (TCRP 2011).

4.2.5 Biodiesel

Biodiesel is commonly made from soybean oil or rapeseed oil, although other sources are available. It is often produced through a process called transesterfication, which combines oils with alcohol and a catalyst to produce biodiesel (TCRP 2011). Biodiesel is naturally lower in sulfur than diesel, which can also reduce PM emissions (Translink 2006).

The difference between emissions for diesel and biodiesel depends on the percent of the blend or the portion of diesel versus biodiesel. For B20 mixes (i.e., 20 percent biodiesel and 80 percent diesel), National Renewable Energy Laboratory shows biodiesel can reduce NO_x emissions between 3 to 6 percent and reduce PM emissions between 15 and 20 percent. Biodiesel can also yield reductions in HC, nonmethane HC, and CO. However, the requirement for all fuel to meet EPA 2010 emission standards has made the differences between diesel and biodiesel almost insignificant (TCRP 2011).

Because diesel and B20 are very similar, many newer bus models can run on both diesel and B20 (TCRP 2011). Because B20 uses the same bus models, these models have many of the same emissions reduction technologies as diesel buses.

4.2.6 Ethanol

Ethanol, or ethyl alcohol, is typically made from corn, sugarcane, or cellulosic feedstock (TCRP 2011). In general, ethanol buses have PM emissions similar to diesel engines with DPF. Ethanol produces lower NO_x emissions compared to diesel, but emits higher amounts of HC and CO than diesel. Newer engine models developed to meet stronger emissions standards can also have low HC and CO values (Motta 1996).

4.2.7 Fuels without Harmful Exhaust Emissions

Other fuels and propulsion technologies, such as hydrogen, hydrogen fuel cells, electricity, and battery electricity, do not produce harmful tailpipe emissions. These are not dealt with in the exhaust emissions portion of this research but will be included in another portion of the project research on lifecycle emissions and lifecycle costs.

5. META-ANALYSIS OF URBAN BUS FLEET EXHAUST EMISSIONS

This meta-analysis presents an overview of exhaust emissions that result from a combination of fuels and technologies. A large dataset with 368 entries was compiled in order to provide the most representative values possible for each combination (study descriptions available in data references). This approach can help increase understanding of the range of possible emissions as there is significant variation between emissions for buses of the same fuel type, technology, and model (San Francisco Municipal Transportation Agency 2002, Jayaratne et al. 2009).

5.1 Methodology

This meta-analysis compares similar transit bus studies to find trends among a larger number of lab and field tests conducted in different locations. The results of each study are not directly comparable due to various testing conditions that are not controlled for, such as the age of the bus, specific terrain, or drive cycle. However, the meta-analysis method allows for generalized results from a variety of buses tested in a variety of conditions and the normalization of data through increasing the sample size for each fuel and technology in the study (Borenstein et al. 2009).

The analysis used both an Interquartile Range (IQR), to find a likely range of emissions and a confidence interval, to find average emissions values.[3] Using these two techniques, the emissions are compared based on the following criteria:

- specific fuel type and relevant technologies: compares emissions from different fuel quality, fuel types, and technologies.
- Euro standard: shows if buses are meeting required standards.[4]
- field tests vs. lab tests: compares tests performed in lab versus field routes.
- drive cycles: compares steady-state, urban, and urban/suburban cycles
- CO_2 equivalent: includes carbon dioxide equivalent in many categories to demonstrate effect on global warming.
- odometer: compares emissions to kilometers on bus odometer.
- altitude: compares emissions to altitude of test.

The following descriptions of factors were considered in the methodology:

Field Tests vs. Lab Tests

Most of the studies collected for this study present emissions results from lab tests. For these tests, the vehicle is driven onto the chassis dynamometer. The bus then follows a specific drive cycle while emissions data are collected. Field tests involve collecting emissions data while a bus is being driven on its regular route in a city. This test does not follow a standard drive cycle and collects data from buses operating under normal conditions. For both types of tests, different loads or weights are often tested, which does have an effect on emissions but is not addressed in this report.

Drive Cycles

Emissions vary based on drive cycles. In general, more aggressive drive cycles result in higher emissions. Drive cycles may represent urban environments only, meaning there are many stops and starts and often large variations in speed. Suburban cycles have fewer stops and starts, and buses are capable of achieving higher operational speeds. Steady-state cycles ramp up to a speed and stay for a given period of time and may repeat the process at different speeds. Because there is a large variety of drive cycles, the cycles were grouped into the environments they represent: urban cycles, urban to suburban, and steady state.

CO_2 Equivalent (CO_2e)

CO_2e combines the amount of a pollutant with its 100-year global warming potential. The difference between natural gas fuels and other fuels regarding GHGs is that the hydrocarbons for natural gas fuels consist of approximately 90 percent methane (See Appendix 2 for calculation). The section, "Significance of Emissions," explains emissions and their relation to global warming potential.

Odometer

Nylund (2004) states that worn-out engines can have higher particulate matter emissions. Therefore, to identify any relationship between the wear on the vehicle and emissions, emissions data were compared to the lifetime mileage.

Altitude

Studies show that emissions of HC, CO, and PM increase at higher altitudes (Yanowitz et al. 2000). McCormick et al. (2000) state that the relationship between altitude and emissions is poorly quantified and that, for buses at high altitude, observed emissions values of HC, CO, and PM may be lower

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[3] The Interquartile Range (IQR) provides a likely range of emissions values for given fuel types. The IQR range represents the middle 50 percent of data points bounded by the upper and lower quartiles (75th and 25th percentiles) (Healey 2005). In developing a confidence interval, we first assume that the data represent a normal distribution (Borenstein et al. 2009). We then determine average values and standard deviations to find the range that includes the desired percent of the emissions values for each type of fuel.
[4] Not enough data to include EPA standards.

than values used in emissions modeling. Also, altitude does not appear to have an effect on NO_x emissions. These two studies do not take into account newer bus emissions standards and technologies. Given the potential variation in emissions at higher altitudes, the study city where each test occurred was recorded along with the altitude, or with altitude estimated as accurately as possible with the given information in reports. This is relevant to this analysis, as Mexico City and other Mexican cities are of high altitude (more than 2,000 meters above sea level). This is less of a concern in Brazil and India, where most major cities are at low altitude (less than 500 meters above sea level). Himalayan India is also of high altitude but contains few urban areas.

5.2 Data Collection

Exhaust emissions data were collected from a total of 24 sources, including reports by cities that conducted emissions testing, government laboratories, institutes with bus testing facilities, or similar reports in peer-reviewed journals. Reports include field or lab tests for 40-foot (12 m) transit buses. Stand-alone engine tests were not included. An initial effort was made to find data on as many types of fuels as may be applicable to Mexico, India, or Brazil. However, only fuels that were currently relevant to these locations were maintained in the final dataset. The studies are also limited to tests performed within the last decade, except for fuels where recent testing data were unavailable.

Table 7 Number of Data Points by Year, Emissions Standard, and Country

Year	Data Points
1994	8
1995	8
1999	15
2001	15
2002	37
2003	58
2004	65
2005	44
2006	30
2007	5
2008	14
2009	60
2010	5

Emissions Standard	Data Points
EPA 1998	7
EPA 2002	4
EPA 2004	9
EPA 2007	6
Euro I	5
Euro II	40
Euro III	25
Euro IV	17
EEV[a]	49

Country	Data Points
US	137
China	4
Europe	99
Canada	73
Australia	12
India	19
Brazil	1

Notes:
[a] EEV represents a voluntary emission standard between the Euro V and Euro VI standards (Dieselnet 2009).

Table 8 Technology Combinations in Dataset

General	Data Points
Oxidation Catalyst (OC)	57
Three-way catalyst (3WC)	40
Diesel particulate filter (DPF)	43
Exhaust gas recirculation (EGR)	23
Selective Catalyst Reduction (SCR)	18

Fuel	Data Points
D + OC	25
CNG + OC	27
CNG + 3WC	40
D + DPF	41
D + EGR	14
D + SCR	11

Combined	Data Points
EGR +OC	8
SCR + DPF	10
DPF + EGR	7

Table 7 shows the number of data points in the dataset for each category, including countries where the test was completed, the year the study was completed (or published if the study year was not available), fuels, and emissions standards. Table 8 shows the combinations of technology that are represented in the dataset. Each data point may represent an individual bus test or an average of three to four tests on one bus, depending on how the study was performed. A large portion of the studies was completed between 2002 and 2006. This is not representative of newer technologies but can account for the lag time in uptake of new technologies. The lag time can be because of reducing the cost of new technologies, incorporating new technologies into bus manufacturing in various countries, and agency fleet renewal cycles. There were also limited data on EPA-certified buses because certification years were not available in the reports. The majority of the data represent the United States, Europe, and Canada, most likely due to limited availability in testing facilities elsewhere.

Fuel Quality

Data were also collected on fuel consumption and fuel quality. Due to a variety of definitions of ultra-low sulfur diesel, low-sulfur diesel, and conventional diesel, the sulfur content of the fuel (parts per million (ppm)) was recorded from the reports. Where these data were not available, estimations were made based on the study year and fuel standards by country or by agency at the time. The fuels were then recategorized based on which common sulfur ppm content values (e.g. 15, 50, 150+ ppm) most closely matched the sulfur content of the fuel (see Table 9). There are also many

Table 9 Number of Data Points by Fuel

Fuel	Data Points
Diesel – 15 ppm	80
Diesel – 50 ppm	29
Diesel – 150 + ppm	62
100% biodiesel	14
20% biodiesel	9
CNG	112
LNG	8
Ethanol	17
Hybrid	25

qualities of CNG, but specific standards have not been developed. Biodiesel has many different pathways. Because of the available reports, the biodiesels represented here are hydrotreated renewable NExBTL diesel (from vegetable oil or animal fat) and rapeseed and soybean methyl esters.

As was available from the reports, data were collected on drive cycle, mileage, location of test (for altitude), field test or lab test, Euro or EPA standard of vehicle, model, and motor type. Bus technologies were also identified to the extent possible, including the presence of particulate filters, catalysts, or exhaust gas recirculation. Emissions data were collected on CO_2, CO, NO_x, THC, CH_4, NMHC, and PM. All units of emissions were converted to grams per kilometer. (See Conversion Factors in Appendix 1.)

5.3 Data Analysis

The following section presents the meta-analysis results. First, the analysis looked at individual emissions (CO, PM, NO_x, THC, and CO_2e) according to the fuel and technology combination. Additional factors such as Euro standards, drive cycles, altitude, and field tests vs. lab tests provided other significant findings through the analysis. Additional graphs are available in the Online Appendix.

5.3.1 Regulated Emissions

Figures 2 and 3 show results from the confidence interval analysis of fuel and technology combinations. The IQR results are available in the Online Appendix. Figure 2 shows the commonly regulated emissions by technology; Euro standards limits are shown to identify which technology types are meeting the standard.

Figure 2a Mean for CO Emissions by Technology (g/km)

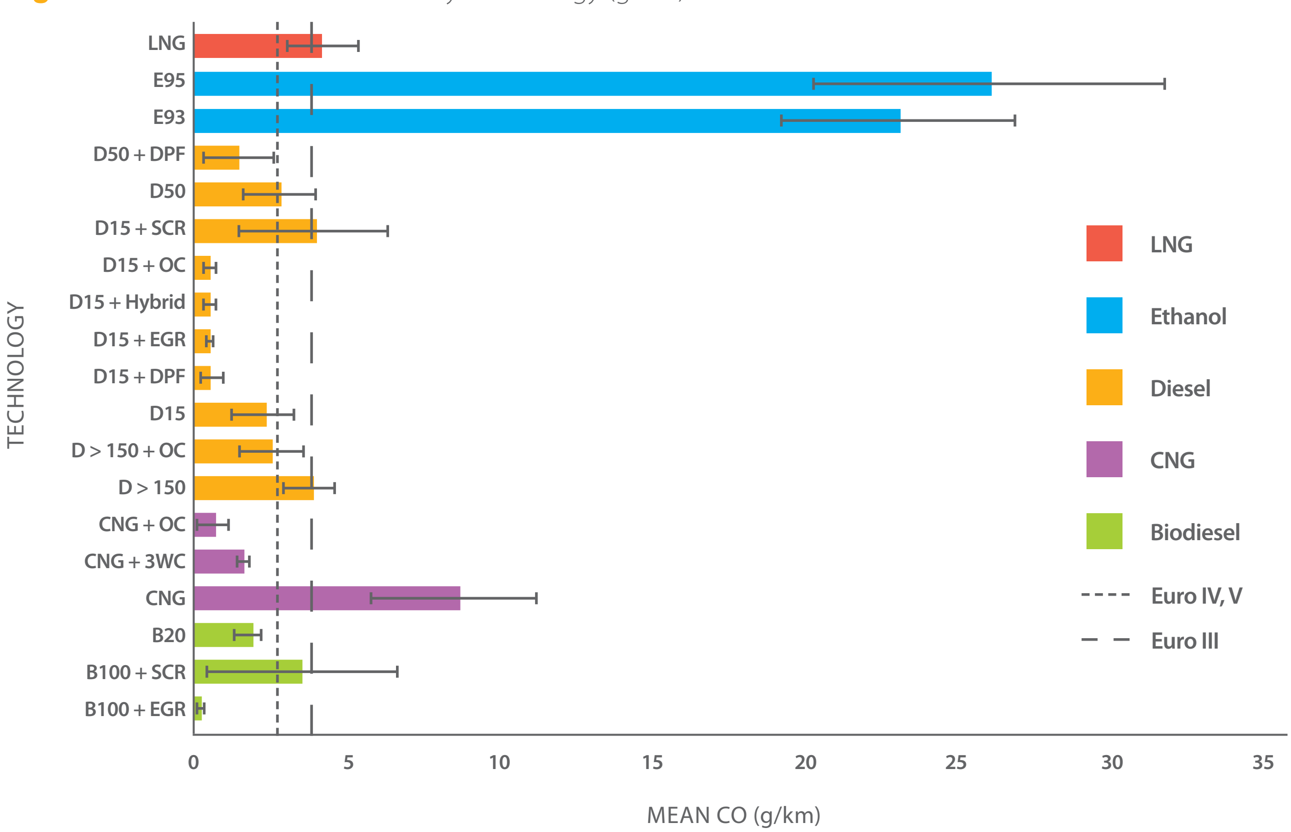


Figure 2b Mean for THC Emissions by Technology (g/km)

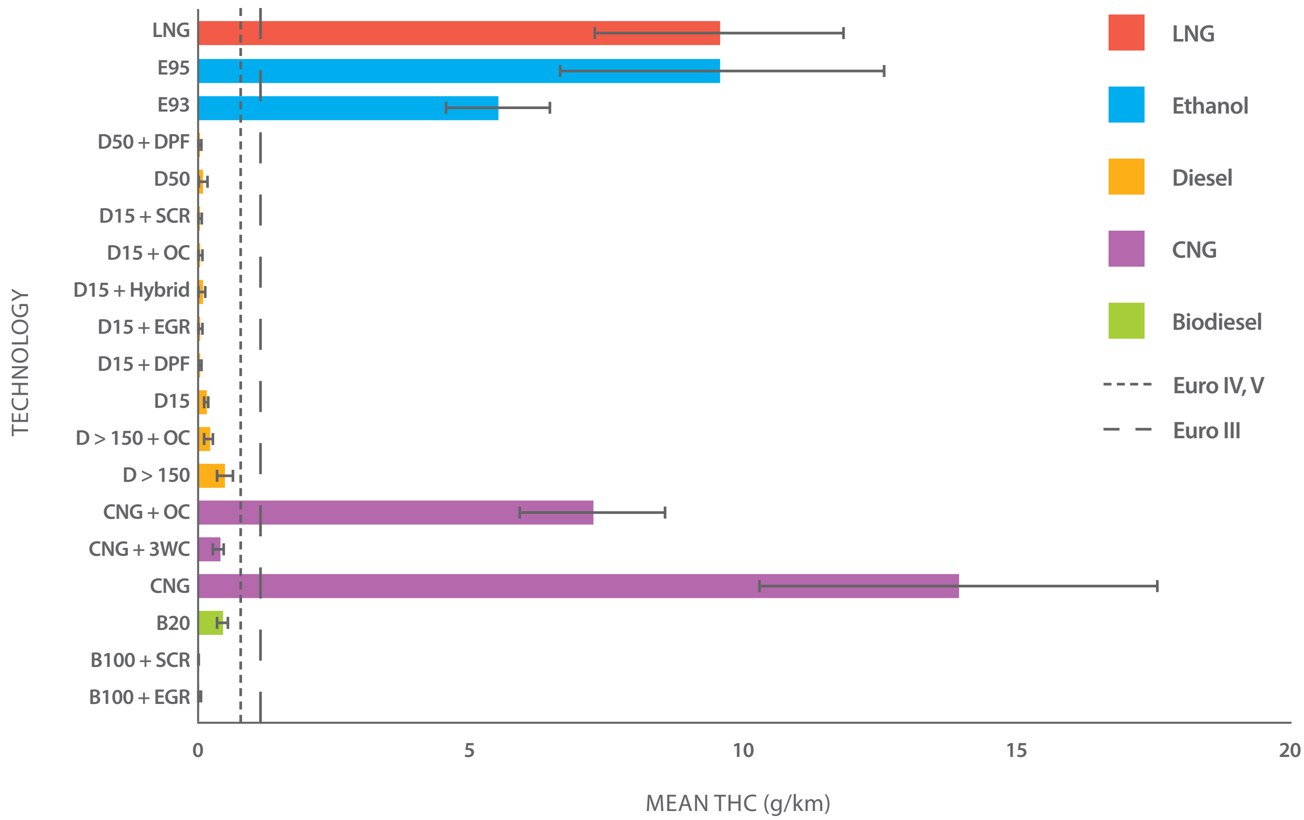


Figure 2c Mean for NO_x Emissions by Technology (g/km)

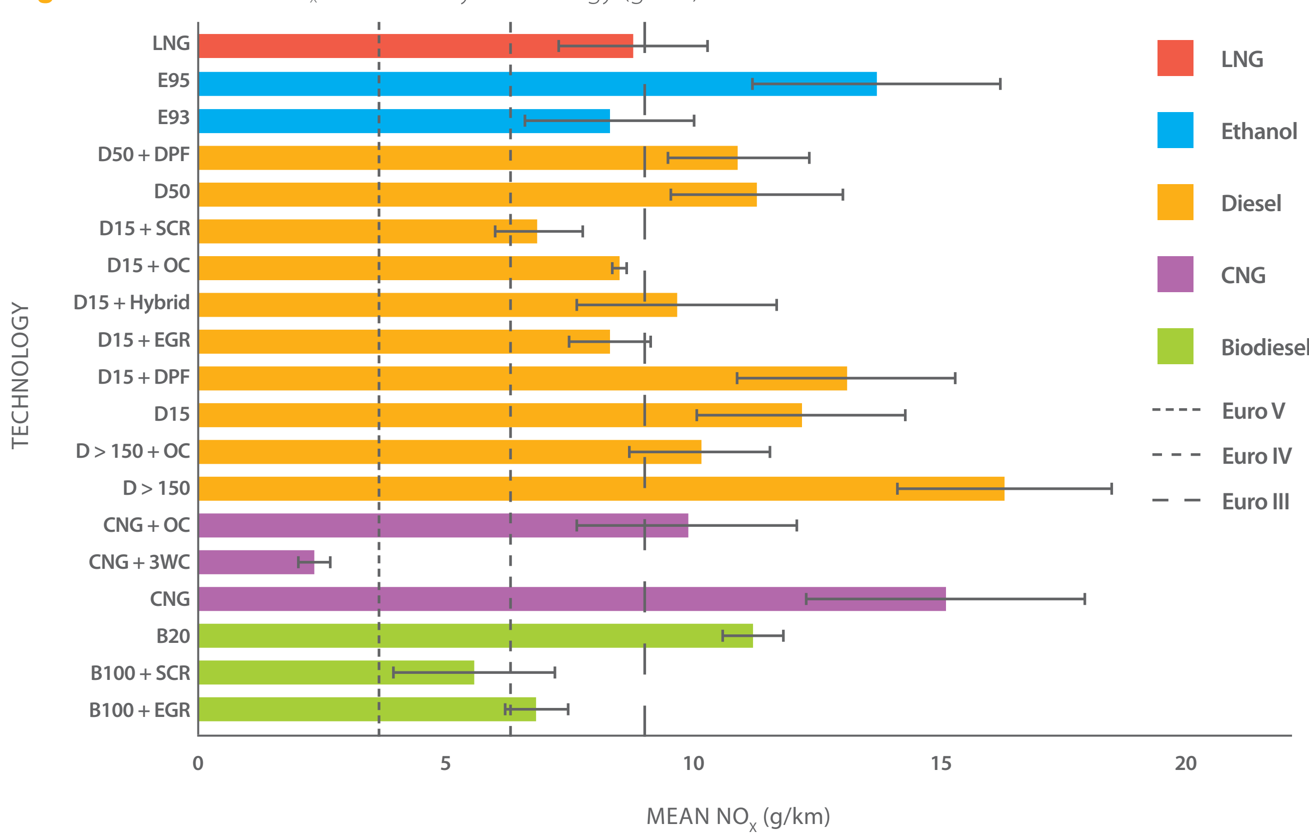


Figure 2d Mean for PM Emissions by Technology (g/km)

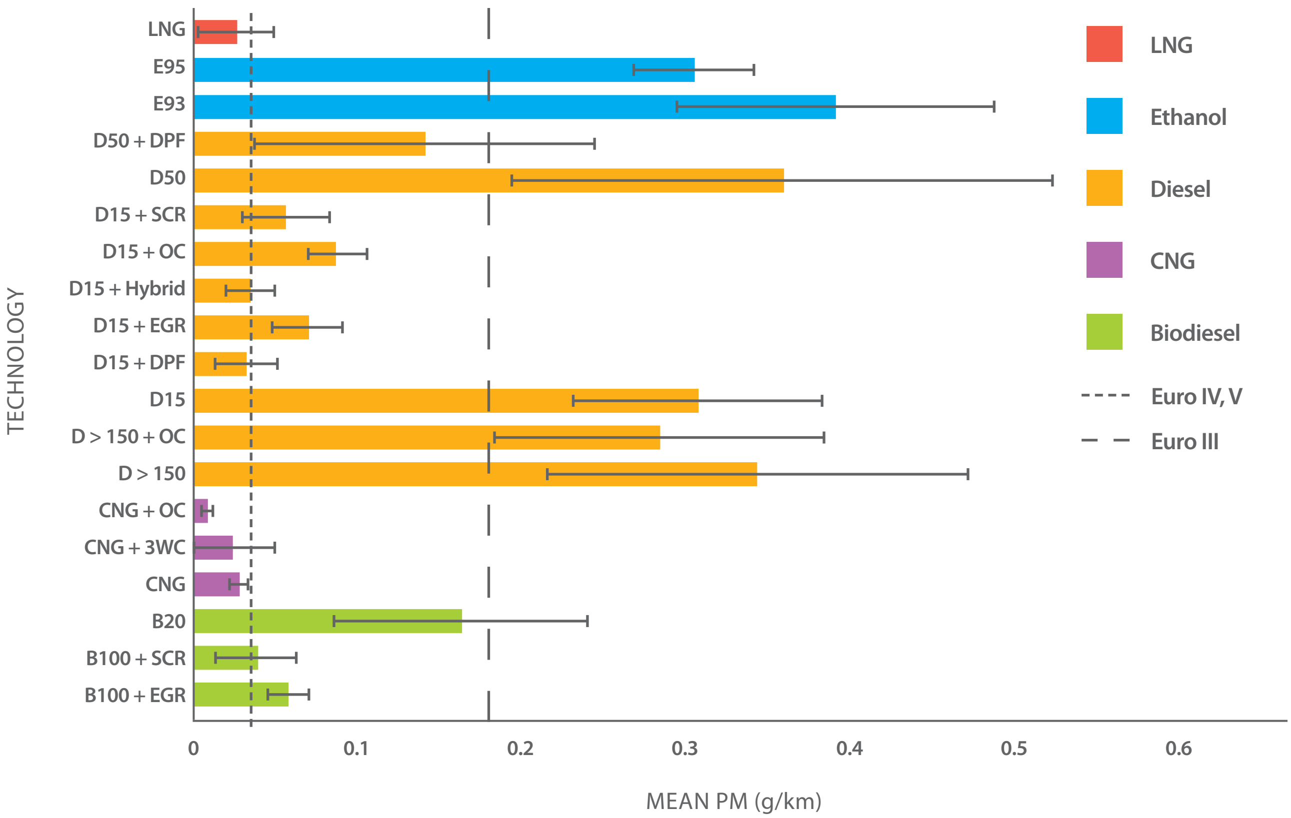
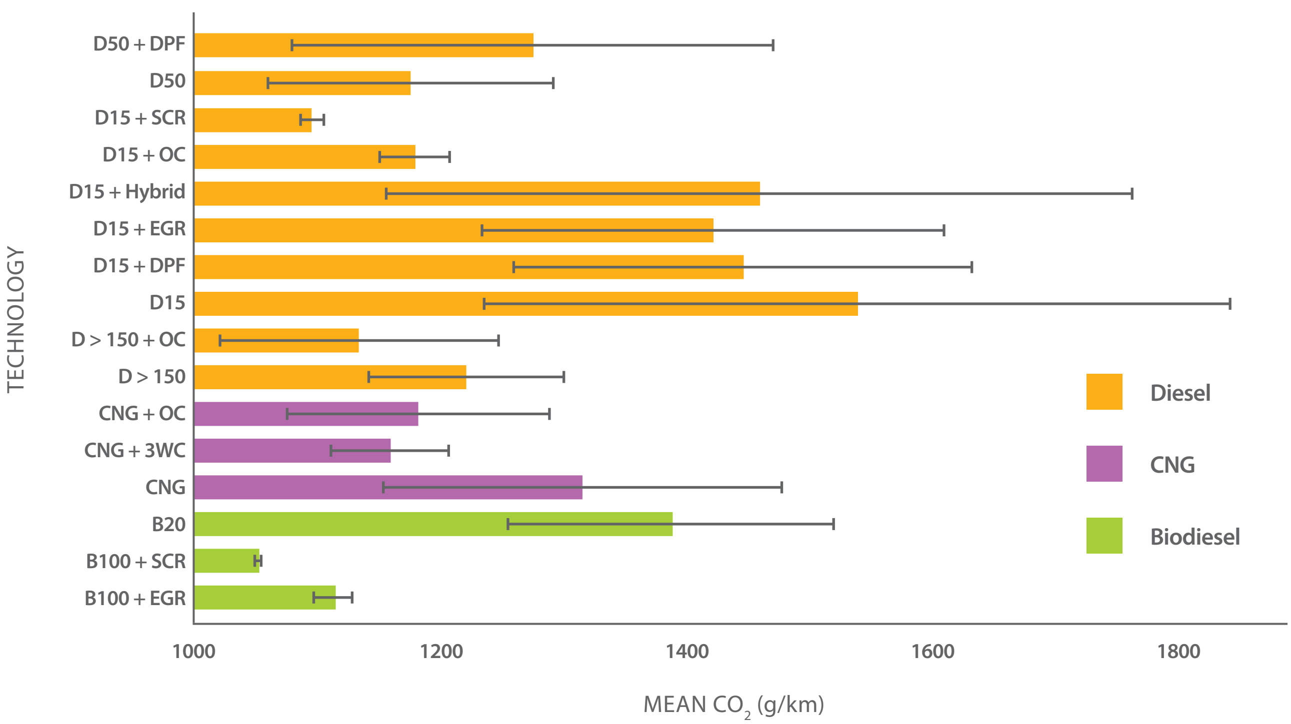


Figure 2e Mean for CO_2 Emissions by Technology (g/km)



A summary of these results is given in Figure 3. In general, emissions reduction technologies are very effective for reducing CO, THC, and PM. The technologies are less effective at reducing NO_x emissions. Fuels without emissions reduction technologies can increase emissions with respect to conventional diesel.

Carbon Monoxide: The lowest CO emissions are from B100 and D15 with EGR, D15 with OC, DPF, or Hybrid, and CNG with OC. This is reasonable considering that oxidation catalysts and diesel particulate filters are meant to reduce CO emissions. Both of the SCR technologies shown have higher CO emissions than similar fuels without SCR. The highest CO emissions are from fuels without emissions reduction technologies: ethanol, LNG and CNG.

Total Hydrocarbons: Due to its composition, diesel has very low values for THC. This is reflected in Figure 2b. THC is important for CNG, LNG, and ethanol. An oxidation catalyst reduces CNG emissions by close to 50 percent, while a 3WC reduces emissions by close to 100 percent. With a 3WC, the THC emissions from a CNG vehicle are comparable to THC emissions from diesel and biodiesel.

Nitrous Oxides: CNG with a 3WC has the lowest NO_x emissions, followed by B100 with EGR and SCR and D15 with EGR and SCR. This confirms an expected result, as 3WC, EGR, and SCR are all meant to reduce NO_x. The NO_x value for E93 is also comparable to D15 with EGR. Figure 2c also shows that oxidations catalysts are also effective at reducing NO_x while DPFs have little effect or increase NO_x. The highest NO_x emitters are D >150, CNG, and E95 without technologies.

Particulate Matter: CNG and LNG are naturally low in particulate emissions. For diesel fuels, the data show that there is a significant reduction in PM as a result of all technologies, especially DPFs. However, other fuels will still have lower quantities of PM. B20 has a 50 percent reduction in PM compared to D15, and CNG with 3WC is 25 percent lower than D15 with DPF.

Carbon Dioxide: The mean and IQR show that there is a wide range of CO_2 emissions. These data also show that technologies used to reduce local pollutants may increase CO_2 emissions. The CO_2 equivalent also shows that technologies may increase overall GHG emissions and that emissions standards do not regulate GHG emissions.

Figure 3a Percent Change in Mean Emissions for Fuels without Exhaust After-Treatment Compared to D >150

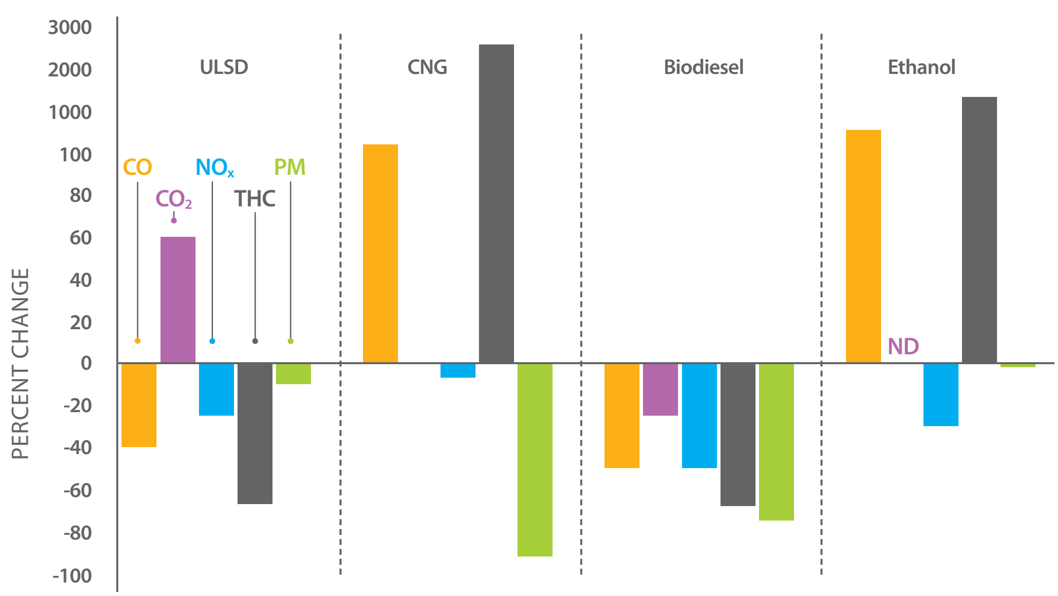


Figure 3b Percent Change in Mean Emissions for ULSD with Technologies Compared to ULSD

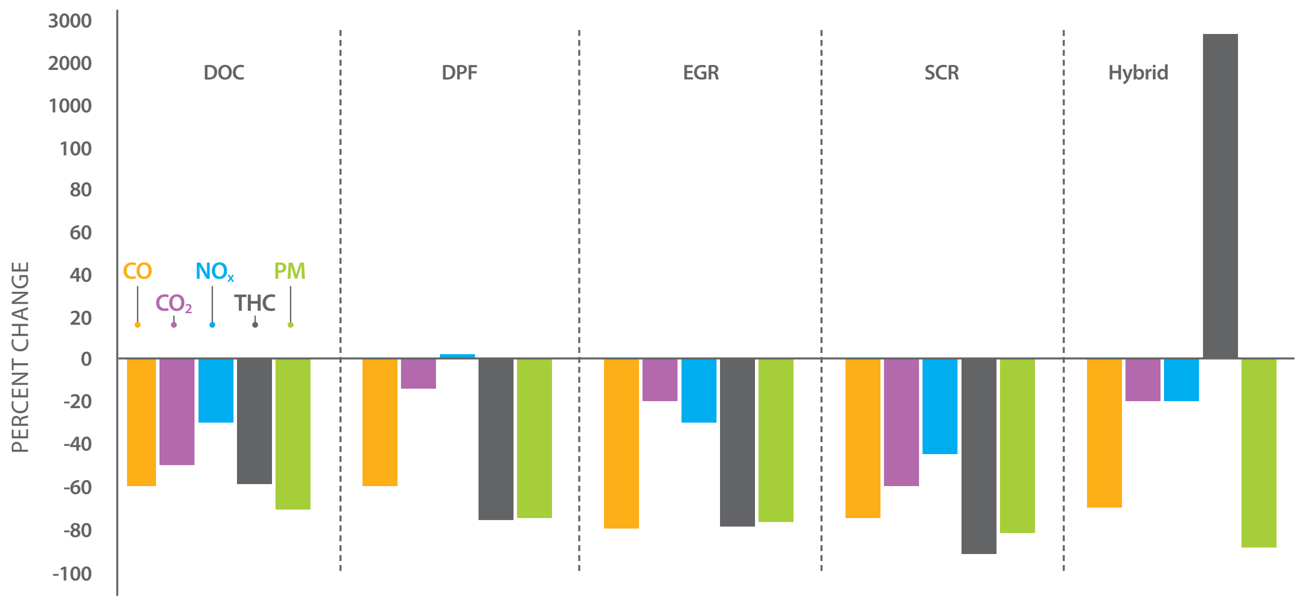
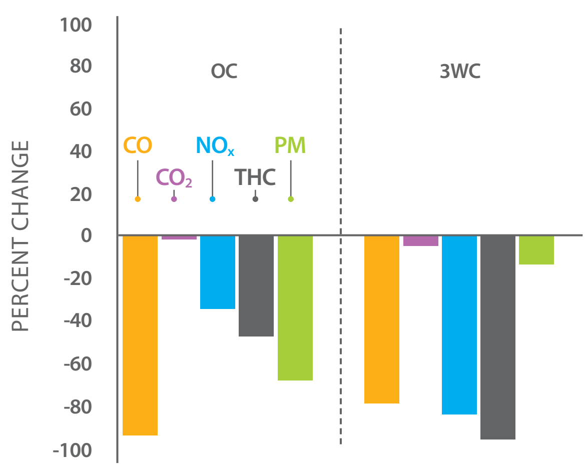


Figure 3c Percent Change in Mean Emissions for CNG with Technologies Compared to CNG

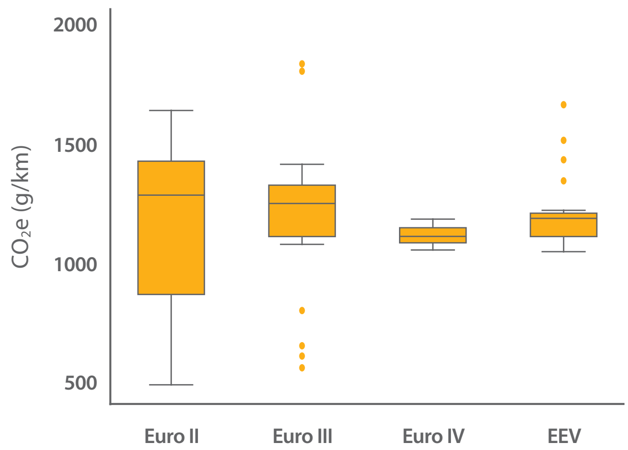


5.3.2. Additional Factors

Euro Standards (see the Online Appendix for graphs): The EPA standard was not analyzed due to lack of data points. The buses are shown to meet the Euro emissions standards for THC, however they are not meeting the Euro standard for CO emissions in all cases. The median emission rate for Euro III and IV-rated vehicles meets the standard, but some values are higher than the standard. In general, buses are not meeting NO_x emissions standards, and not all buses are meeting emissions standards for PM. Figure 4 shows the IQR for CO_2e emissions by Euro standard. Although CO_2 is not regulated by Euro standards, the data show that median CO_2e emissions declined as the standard progressed from Euro II to Euro IV but increased for the EEV interim standard between Euro IV and Euro V. The IQR for CO_2 emissions also decreased as emissions standards progressed.

Field Tests versus Lab Tests: CNG and diesel are the only fuels with significant numbers of lab and field tests to compare. The field tests tend to show larger ranges of emissions than the lab tests, and the median values for NO_x and CO_2 in lab tests are clearly lower than field tests (see the Online Appendix). The varied results in

Figure 4 IQR for CO_2 Equivalent Emissions by Euro Standard



field and lab tests are important to understand when comparing future tests. Comparing one field test to one lab test may show skewed results.

Drive Cycles: For all emissions, the urban cycles show a wider range and higher emissions values than do other drive cycles. Steady-state cycles and urban-to-suburban cycles generally show lower emissions (by at least 30 percent and 20 percent, respectively). There is not a clear trend by individual fuels or technology. When comparing future test data, this respective difference in emissions by drive cycle should be taken into account. (See the Online Appendix for graphs.)

Odometer: Although all emissions were plotted versus mileage, only bus kilometers traveled versus NO_x emissions show that kilometers traveled is a good predictor of increased NO_x emissions. The confidence interval is larger for higher mileage, partly due to fewer high-mileage data points. Plotting CO_2 equivalent versus bus kilometers traveled also shows some correlation, although the relationship is not as strong as with NO_x emissions (Figure 5).

Figure 5 NO_x and CO_2e Emissions Versus Mileage

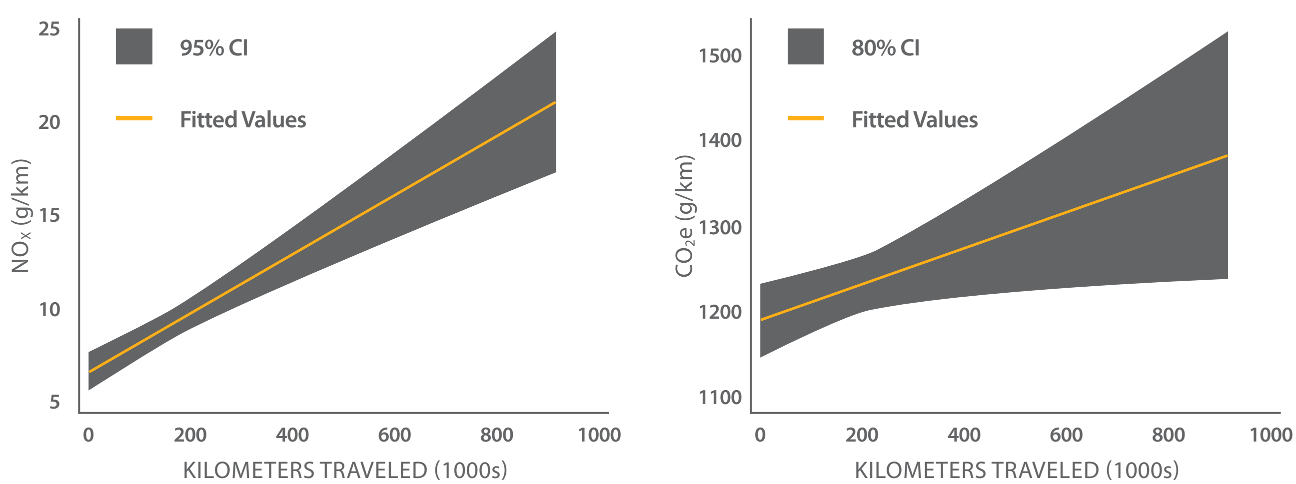
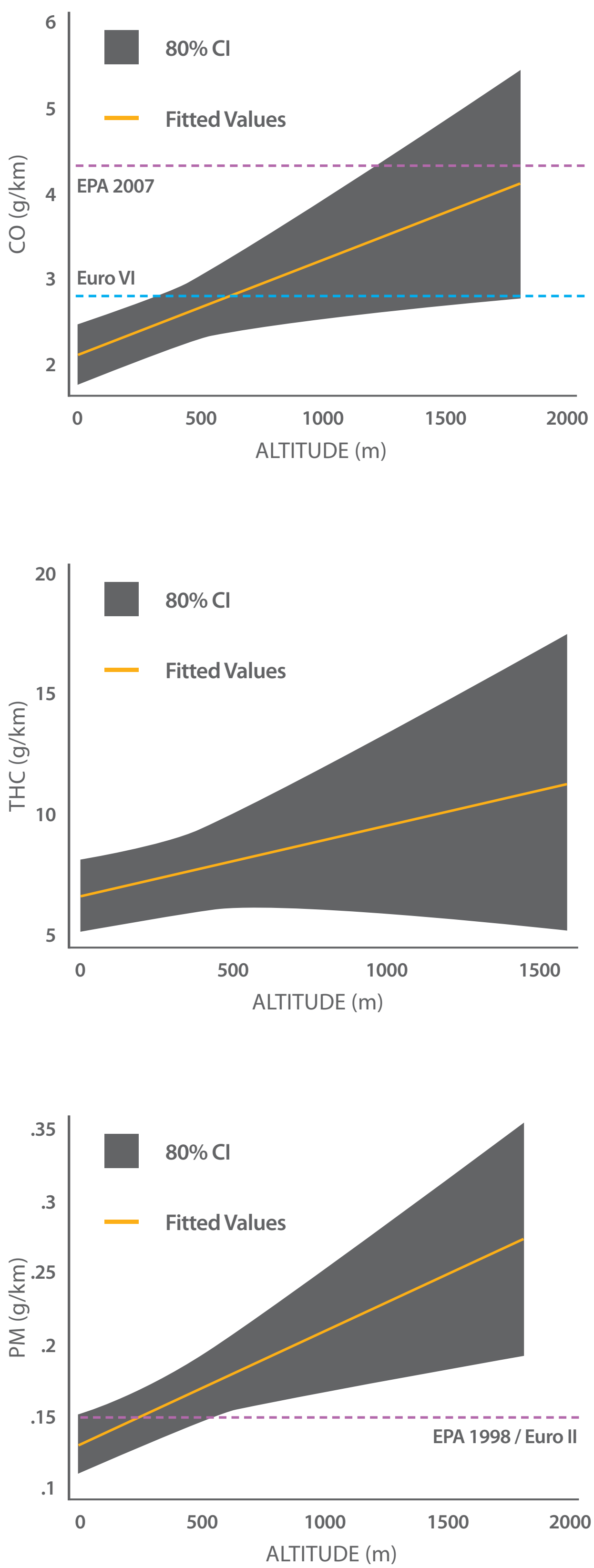


Figure 6 CO, THC, and PM Emissions Versus Altitude



Altitude: The analysis shows a correlation between CO, THC, PM emissions and altitude, although the analysis lacks sufficient data at higher altitudes to show a strong correlation. The range of expected values varies for each fuel type. CO shows an increase for diesel and hybrids of approximately 2 g/km per 1,500 meters of altitude increase. The range of CO values for diesel and hybrid is roughly 15 g/km. Therefore, an increase in CO by 2 g/km (as shown in figure 6) would be a 10 percent increase over a 1,500 meter altitude increase. For THC, only CNG showed an increase correlated with altitude. A similar analysis to CO shows that a 1,500 meter increase in altitude would result in approximately a 10 percent increase in THC. Considering biodiesel and diesel for PM, there is roughly a 10 percent increase also with a 1,500 meter increase in altitude. Figure 6 shows the relation between altitude and emissions for CO, THC, and PM. (See the Online Appendix for more data.)

Comparing NO_x, CO_2e, and PM Emissions: Both NO_x and PM are considered some of the most harmful local pollutants, while CO_2 equivalent is important for global warming. Plotting NO_x and CO_2e versus PM shows the fuel and technologies that perform best among these pollutants. Figures 7 and 8 below focus on NO_x and PM. Figure 7 shows mean values for each fuel and technology combination. The lower quadrant shows the fuels that perform best in both categories. Figure 8 is a close-up on the lower quadrant, which also shows the ranges (based on the confidence interval) for each of the combinations. This shows that CNG + 3WC is the best in terms of NO_x and, in some cases, PM. Figures 9 and 10 look at CO_2 equivalent, and show that B100 + SCR is generally the best fuel comparing CO_2e and PM. The figures show however, that the range of possible results does not make one fuel and technology combination always better than others. Some of the overall best benefits come from CNG + 3WC, B100 +SCR, D15 + SCR, and B100 +EGR.

Figure 7 NO_x Versus PM Emissions by Technology

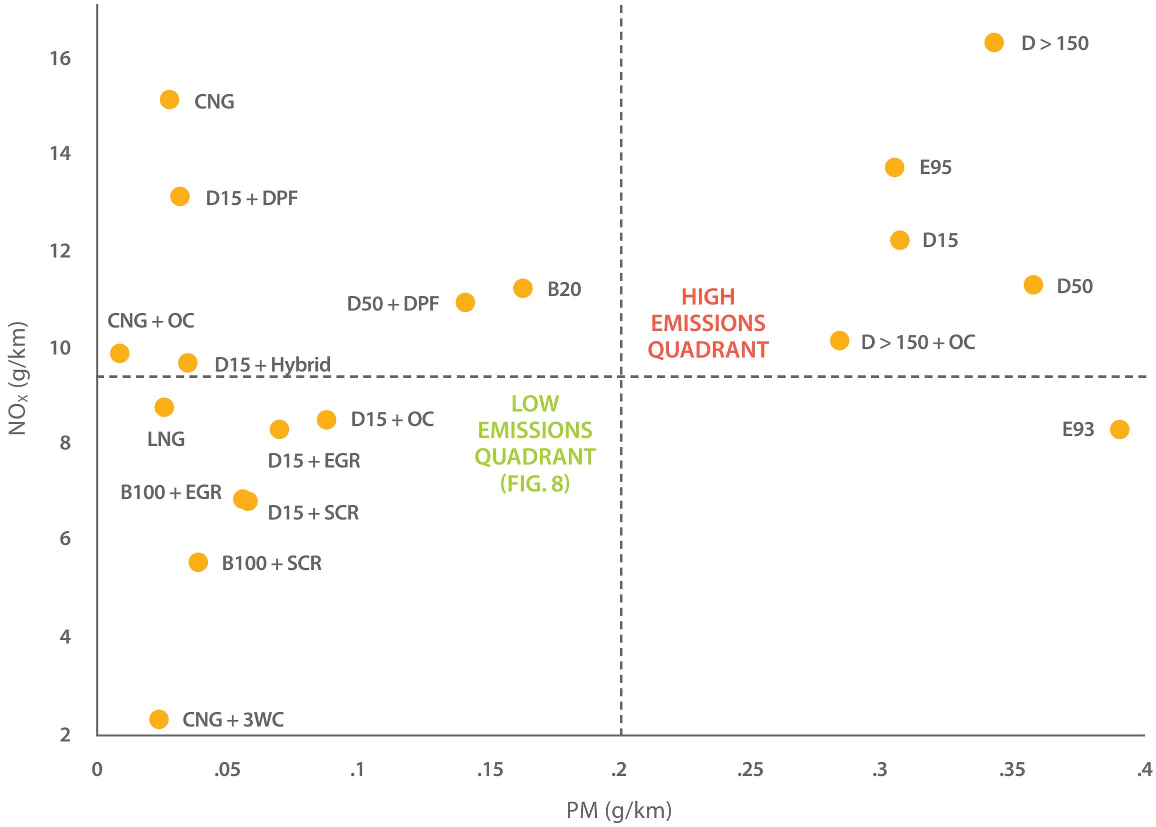


Figure 8 NO_x Versus PM Emissions, Close-up on Ranges for Low Emissions Quadrant

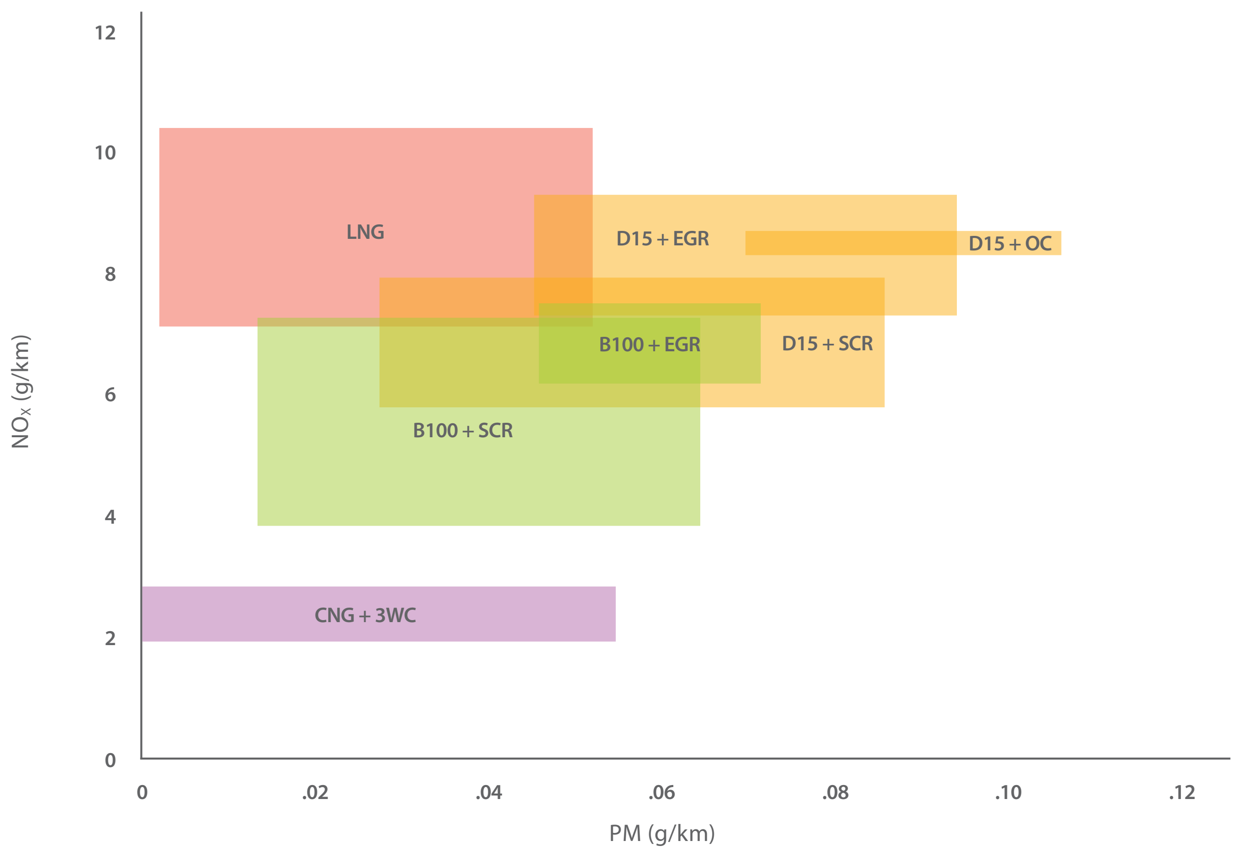


Figure 9 Comparison of CO_2e Versus PM Emissions by Technology

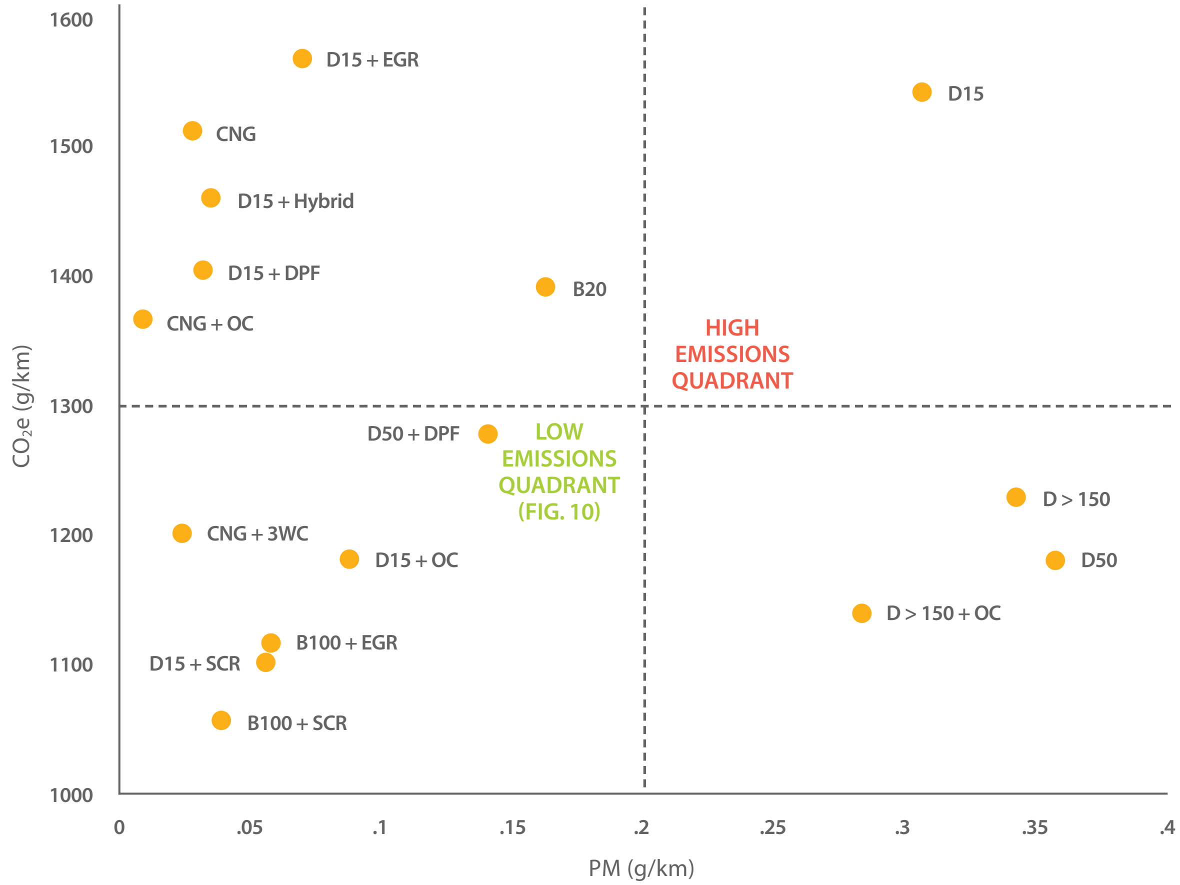
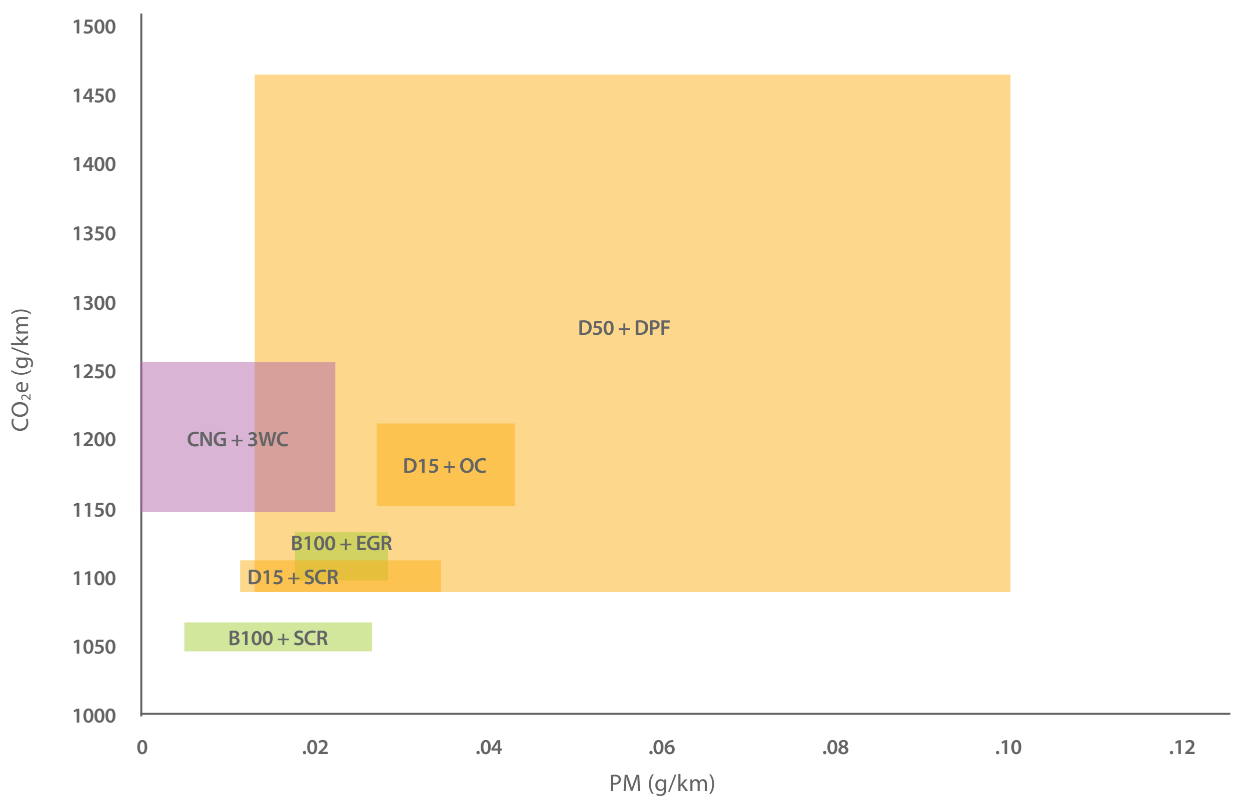


Figure 10 CO_2e Versus PM Emissions, Close-up on Ranges for Low Emissions Quadrant



6. EXHAUST EMISSION META-ANALYSIS RESULTS

The meta-analysis shows emissions values similar to the expected values or the emissions standards for each type of fuel and technology combination. The technologies produced the expected changes to emissions, both regulated and unregulated. This is seen clearly when looking at the fuels without technologies, D15, LNG, CNG, and Ethanol, as the data analyzed show emissions are high for each of these categories.

Because exhaust after-treatment technologies are often developed to meet emissions standards, the data show that the emissions standards are generally effective. However, the data also show that not all buses are meeting their expected emissions standards, specifically for NO_x and PM. This could also be a result of the different type of testing performed to certify engine emission levels compared to in-use transit bus testing shown here. The emissions standards, which do not consider GHGs yet, do not make an impact on CO_2 equivalent emissions.

There are many factors that can affect emissions. Drive cycle does have an effect on emissions, as shown in some of the source reports for this study. The urban drive cycle, with many stops and starts, shows higher emissions in all categories, but the effect is roughly consistent across all fuels and emission types. There are also differences in emissions values between field tests and lab tests of the same fuel type, although there is not a clear trend for all emissions. In field and lab tests, CO_2 emissions and NO_x emissions are roughly 10 percent and 20 percent higher for field tests compared to lab tests. The analysis also shows that there is a correlation between altitude and CO, PM, and THC. Each category showed roughly a 10 percent increase in emissions over a 1,500 meter increase in altitude for specific fuel types. In all cases, more data can improve the accuracy of the estimated effects of different driving cycles, field tests, and altitude.

Looking at the lifetime kilometers traveled by a vehicle versus emissions shows that increased mileage on a vehicle is a good predictor of NO_x emissions. This is likely because older buses will not have the most current technologies, and worn-out engines can have higher emissions (Nylund 2004). There is also a correlation between kilometers traveled and CO_2 equivalent emissions.

Overall, four technologies show the lowest emissions in important categories affecting pollution, health, and GHGs (NO_x, PM, and CO_2 equivalence): compressed Natural Gas with three way catalyst (CNG + 3WC), 100 percent biodiesel with selective catalyst reduction (B100 + SCR), diesel with 15 ppm sulfur content with SCR (D15 + SCR), and 100 percent biodiesel with exhaust gas recirculation (B100 + EGR). No one fuel shows a distinct advantage over the other fuels in all categories, but control technologies are an important factor in reducing emissions.

7. CONCLUSION

As part of the Sustainable Urban Transportation Fuels and Vehicles Program, this report aims to improve understanding of exhaust emissions and use a meta-analysis technique to identify the combination of fuels and exhaust after-treatment technologies that have the greatest impact on reducing emissions. The report looks at both local and global emissions to understand their impact on health and the environment. This report will help to inform bus fleet procurement specifically in Brazil, India, and Mexico.

The analysis shows that there can be a variety of emission values under different conditions, even for similar fuels and technologies. Compiling the large dataset presented here takes advantage of existing data to give agencies a summary of the most relevant data and allows for an improved understanding of representative values for each fuel and technology combination. This dataset also represents in-use transit buses, rather than buses tested prior to operation. Testing these buses shows how increased mileage can affect certain emissions types, even if the emissions-reduction technology is not meant to deteriorate over time. In general, high quality emissions testing data on a variety of technologies under a variety of conditions, altitudes, driving cycles, field or lab tests, and in specific countries is not always readily available due to the cost of testing. Therefore, there is an opportunity to improve the accuracy of results as additional data are gathered.

The meta-analysis looks at many factors that can contribute to increased or decreased emissions in addition to vehicle technology. Specific factors, like drive cycle, show that urban drive cycles have higher emissions than less aggressive drive cycles. This is important to understand for comparing emissions test results in addition to understanding how reducing aggressive driving can in itself reduce emissions. When looking at emissions with respect to altitude, the data show that there is roughly a 10 percent increase in emissions for some diesel, biodiesel, hybrids, and CNG for some pollutants.

Overall, the analysis shows that no one fuel is significantly better at reducing all exhaust emissions if the right control technologies are used; thus, these control technologies are a necessary part of reducing emissions. At the same time, fuels or technologies that may reduce one pollutant may increase other emissions, especially in the case of CO_2 and PM. Although all emissions are important, NO_x, CO_2e, and PM are particularly harmful emissions for global warming and public health. Efforts to improve emissions standards, which often drive new technology developments, have achieved emissions reductions in NO_x and PM. Including CO_2 in these standards, as the United States has planned for heavy-duty vehicles in 2014, should result in improved fuel economy and perhaps CO_2-reducing technologies.

Because the results do not recommend one specific fuel and technology combination, local conditions will be important in determining which fuels transit agencies should use. For example, if a location has high particulate matter due to other industries, CNG may be the best option. If CNG is not readily available in the country, using biodiesel or diesel with emissions-reduction technology is also a good option for minimizing exhaust emissions. However, if low-sulfur diesel is not available, the agency must balance the trade-offs between fuel costs and local pollution. For all of the potential fuel options, research on the local and human health effects is evolving and should be monitored to make recommendations using the most current data.

Exhaust emissions are important to consider and understand when making fuel choices, especially in a local context and with respect to the lag time in the uptake of new technologies. However, this research and analysis shows that innovation has the potential to make exhaust emissions nearly equal for all fuels. This highlights the need to better understand the lifecycle costs and lifecycle emissions of transit buses when making transit fuel choices. These two components raise many possible factors, either global or local, that can have an impact on final fuel and vehicle recommendations. Some of these factors include where and how fuels and buses are manufactured, the ability to train staff and maintain buses with different technologies, and future fuel and labor costs. These factors for costs and emissions, including exhaust emissions, show that there are global and local inputs as wells as global and local impacts. Understanding how fuels and technologies contribute to exhaust emissions is a first step in understanding the true costs and impacts of urban bus fleets.

References

Baumert, K.A., T. Herzog, and J. Pershing. 2005. Navigating the Numbers: Greenhouse Gas Data and International Climate Policy. Washington, DC: World Resources Institute.

Borenstein, M., L. Hedges, J. Higgins, and H. Rothstein. 2009. Introduction to Meta-Analysis. Chichester, UK: John Wiley & Sons, Ltd.

De Hartog, J.J., H. Boogaard, H. Nijland, and G. Hoek. 2010. "Do the Health Benefits of Cycling Outweigh the Risks?" Environmental Health Perspectives 118(8), August 2010, 1109-1116.

Department of Energy (DOE). 2012. Alternative fuels data sheet online at http://www.afdc.energy.gov/pdfs/afv_info.pdf .

Dieselnet. 2012. "Regulatory Framework." Online at http://dieselnet.com/standards/.

Environment Canada. 2011. "Global Warming Potentials." Online at http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=CAD07259-1.

Federal Transit Administration. 2006. "Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles". Online at http://www.fta.dot.gov/documents/Alternative_Fuels_Study_Report_to_Congress.pdf.

Healey, J. 2005. Statistics: A Tool for Social Research. Belmont, CA:Thomson Wadsworth.

Jayaratne, E., Z. Ristovski, N. Meyer, and L. Morawaska. 2009. "Particle and Gaseous Emissions from Compressed Natural Gas and Ultralow Sulphur Diesel-Fuelled Buses at Four Steady Engine Loads." Science of the Total Environment 407: 2845–2852.

Johnson Matthey. 2011. "Technologies." Online at http://ect.jmcatalysts.com/site.asp?siteid=833 Lindqvist, K. 2012. Emission Standards for Light and Heavy Road Vehicles. Gotenburg, Sweden: Air Pollution and Climate Secretariat.

Macias, J. M., H. Martínez, and A. Unal. 2010. "Bus Technology Meta-Analysis." Transportation Research Board Annual Meeting.

McCormick, R.L., M.S. Graboski, T.L. Alleman, and J. Yanowitz. 2000. "Idle Emissions from Heavy-Duty Diesel and Natural Gas Vehicles at High Altitude." Journal of the Air and Waste Management Association 50(11): 1992–1998.

Melendez, M., J. Taylor, J. Zuboy, W.S. Wayne, and D. Smith. 2005. Emission Testing of Washington Metropolitan Area Transit Authority (WMATA) Natural Gas and Diesel Transit Buses. Washington, DC: National Renewable Energy Laboratory Innovation for Our Energy Future.

Motta, R.P., P. Norton, and K. Kelly. 1996. Alternative Fuel Transit Buses. Golden, CO: National Renewable Energy Laboratory.

Murtonen, T., and P. Aakko-Saksa. 2009. Alternative Fuels with Heavy-Duty Engines and Vehicles. Helsinki, Finland: VTT Technical Research Centre of Finland.

Nylund, N.K., K. Erkkila, M. Lappi, and M. Ikonen. 2004. Transit Bus Emission Study: Comparison of Emissions from Diesel and Natural Gas Buses. Helsinki, Finland: VTT Technical Research Centre of Finland.

Roychowdhry, A. 2010. "CNG Programme in India: Future Challenges." New Delhi, India: Center for Science and Environment.

San Francisco Municipal Transportation Agency. 2002. "Alternative Fuel Pilot Program: Initial 6 Month Evaluation Results." Online at http://www.sfmta.com/cms/rclean/altpilot.htm.

Transit Cooperative Research Program (TCRP). 2011. TCRP Report 146: Guidebook for Evaluating Fuel Choices for Post-1020 Transit Bus Procurements. Washington, DC: Transportation Research Board.

TransLink. 2006. Bus Technology and Alternative Fuels Demonstration Project, Phase 1 –Test Program Report. Vancouver, Canada:TransLink.

United Nations Environment Programme (UNEP). 2007. "Opening the Door to Cleaner Vehicles in Developing and Transition Countries: The Role of Lower Sulphur Fuels." Report of the Sulphur Working Group of the Partnership for Clean Fuels and Vehicles (PCFV). Nairobi, Kenya.

UNEP. 2012a. "Status of Fuel Quality and Vehicle Emission Standards: Latin America and the Caribbean." Online at http://www.unep.org/transport/pcfv/PDF/Maps_Matrices/LAC/matrix/LAC_FuelsandVeh_June2012.pdf.

UNEP. 2012b. "Status of Fuel Quality and Vehicle Emission Standards in Asia-Pacific." Online at http://www.unep.org/transport/pcfv/PDF/Maps_Matrices/AP/matrix/AsiaPacific_Fuels_Vehicles_June2012.pdf.

UNEP. 2012c. "Current and Proposed Sulfur levels in Diesel in Asia, EU and USA." Online at http://www.unep.org/transport/pcfv/PDF/DataADBSulfurDiesel.pdf.

U.S. Environmental Protection Agency (EPA). 2012a. "Air Pollutants." Online at http://www.epa.gov/air/airpollutants.html.

U.S. EPA. 2012b. "Annex 1: Key Category Analysis. Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2010." Online at http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2012-Annex-1-Key-Category-Analysis.pdf.

U.S. EPA. 2012c. "Climate Change". Online at http://www.epa.gov/climatechange/index.html.

U.S. EPA. 1998. "Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors". Online at http://www.epa.gov/oms/models/mobile6/m6hde004.pdf.

Wayne, W.S., N.N. Clark, R.D. Nine, and D. Elefante. 2004. "A Comparison of Emissions and Fuel Economy from Hybrid-Electric and Conventional-Drive Transit Buses." Energy and Fuels18, 257–270.

World Business Council for Sustainable Development (WBCSD). 2004. Mobility 2030. London: World Business Council for Sustainable Development.

World Health Organization (WHO). 2006. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Online at http://www.who.int/phe/health_topics/outdoorair_aqg/en/.

Yanowitz, J., R. McCormick, and M. Graboski. 2000. In-Use Emissions from Heavy-Duty Diesel Vehicles. Environmental Science & Technology. 34 (5): 729–740.

Data References

Battelle, C.K. and L. Eudy. 2008. Fuel Cell Transit Buses: Third Evaluation Report. Alameda-Contra Costa Transit District. National Renewable Energy Laboratory. Technical Report NREL/ TP-560-43545-1
The agency, supported by the FTA, introduced 3 fuel cell buses on a trial basis into limited operating service over one year. The test showed the fuel cell buses were not as fuel efficient as the diesel buses. Fuel cell batteries still need improvement in lifetime length, and technicians need time to learn new vehicles. The total maintenance costs per mile were higher for fuel cells than for diesel; however, the fuel cell buses, required by California law, will continue to be in use.

Bose, R. and S. Sundar. 2005. Emissions Test Results from Diesel Buses, with and without Oxidation-Catalyst and Regenerating Particle-Trap, and CNG Buses with Three-Way Catalyst in India. 2005 SAE World Congress, April 11–14.
Eight Euro II-compliant buses, using diesel with different levels of sulphur and with and without emission control devices, and two Euro II-compliant CNG buses with three-way catalysts were tested on a chassis dynamometer using Mumbai Driving Cycle. Emissions of PM from buses using ultra-low sulphur (50 ppm maximum) diesel and fitted with particle traps and those from CNG-powered buses were comparable; CO and HC were lower from diesel buses and NO_x was lower from CNG buses. Although progressive reduction of sulphur lowered PM emissions, their levels were significantly lower when coupled with appropriate emission control devices.

Clark, N.N, M. Gautam, B.L. Rapp, D.W. Lyons, M.S. Graboski, R.L. McCormick, T.L. Alleman, and P. Norton. 1999. Diesel and CNG Transit Bus Emissions Characterization by Two Chassis Dynamometer Laboratories: Results and Issues. SAE International Spring Fuels and Lubricants, May 3-6.
This study tested three CNG and three diesel buses. The buses were evaluated using one of the West Virginia University Transportable Heavy Duty Emissions Testing Laboratories and the fixed base chassis dynamometer at the Colorado Institute for Fuels and High Altitude Engine Research. Both laboratories found that NO_x and PM emissions were substantially lower for the CNG buses than for the diesel buses. It was observed that, by varying the rapidity of pedal movement during accelerations in the Central Business District cycle (CBD), the driving styles could be characterized as aggressive and nonaggressive. PM emissions were far higher for the aggressive driving style. It is evident that driver habits may cause substantial deviation in emissions for the CBD cycle. When the CO emissions are used as a surrogate for driver aggression, a regression analysis shows that NO, and PM emissions from the two laboratories agree closely for equivalent driving style. Implications of driver habit for emissions inventories and regulations are briefly considered.

Coroller, P. and G. Plassat. 2003. Comparative Study on Exhaust Emissions from Diesel and CNG-Powered Urban Buses. French Agency of Environment and Energy Management (ADEME), Air and Transport Division, presented at the DEER 2003 Conference by Dr. Thierry SEGUELONG, Aaqius & Aaqius.
This study tested seven vehicles, both CNG and diesel, with a lab test drive cycle representing urban buses in Paris. The results showed that CNG vehicles had fewer emissions compared with Euro II diesel buses without post-treatment. However, using particulate filters and ultra low sulfur diesel made diesel and CNG emissions comparable.

Folkesson, A., C. Andersson, P. Alvforsa, M. Alakülab, and L. Overgaard. 2003. "Real-Life Testing of a Hybrid PEM Fuel Cell Bus." Journal of Power Resources 118: 349–357.
This article studies PEM hybrid fuel cell buses under various test conditions. The bus was a series hybrid, both battery and fuel cell powered. The bus was run under FTB 75 and Braunschweig duty cycles. The energy consumption was compared to similar energy consumption for diesel-fueled vehicles. The results show that the fuel cell consumes less energy than thecitywide average for diesel buses. Low noise levels, high comfort levels, and regenerative braking add to the vehicles appeal; however, improved durability and reducing costs are need before fuel cells become mass market vehicles.

Frey, H. C., N.M. Rouphail, H. Zhai, T.L. Farias, and G.A. Gonçalves. 2007. "Comparing Real-World Fuel Consumption for Diesel- and Hydrogen-Fueled Transit Buses and Implication for Emissions." Trasnportation Research Board Part D, 12: 281–291.
This report compares the fuel consumption of diesel and hydrogen-fueled transit buses in Porto, Portugal, with results from the EPA 2002 test for diesel buses in Ann Arbor, Michigan. The tests were conducted over one day on a 7.8 km route with significant grades (10 percent). Fuel consumption rates were related to speed, passenger loads, and vehicle-specific power. Overall, driving cycle fuel consumption for hydrogen transit vehicles is higher but similar to fuel consumption for diesel vehicles. Lifecycle CO_2 emissions are higher for hydrogen vehicles than diesel, but hydrogen vehicles produce less CO, NO_x, and HC.

Jalihal, S. A. and T. S. Reddy. 2006. "Assessment of the Impact of Improvement Measures on Air Quality: Case Study of Delhi". Journal of Transportation on Engineering 132: 482–488
In this study, carbon monoxide, nitrogen oxides, and particulate matter and hydrocarbons are estimated on the basis of vehicle kilometers traveled by different vehicles in the city during the course of time when the improvement measures were being effected on an incremental basis. The improvement was, as made out to be, not simply because of CNG conversion of buses but due to the combined effect of many other steps like improved vehicle technologies and fuel quality, phasing out the old diesel vehicles, conversion of auto rickshaws to CNG, etc.

Jayaratne, E., Z. Ristovski, N. Meyer, and L. Morawaska. 2009. "Particle and Gaseous Emissions from Compressed Natural Gas and Ultralow Sulphur Diesel-Fuelled Buses at Four Steady Engine Loads." Science of the Total Environment 407: 2845-2852
The study reported exhaust emissions for 13 CNG buses and nine ultra low sulfur diesel buses. The buses were tested at four engine loads: idle, 25, 50, and 100 percent of maximum power. As load increased, emissions increased for both fuels. The study showed that diesel had higher particle number emissions, although the difference was not statistically significant. The CO_2 values for CNG buses were also lower than the diesel buses.

Khillare, P.S., T. Agarwal, and V. Shridhar. 2008. "Impact of CNG Implementation on PAHs Doncentration in the Ambient Air of Delhi: A Comparative Assessment of Pre- and Post-CNG Scenario." Environmental Monitoring and Assessment 147: 223–233
The present study reports the comparative assessment of the status of air quality with respect to PM10 and PAH before and after the introduction of CNG in the public transportation system in Delhi. The study was carried out for two different time periods: 1998 and 2004. Following the total conversion of the public transportation system to CNG in 2002, Post-CNG data indicate a sharp reduction of 51–74 percent in the PM10 concentration and 58–68 percent in the TPAH concentration, as compared to the pre-CNG data.

Lowell, D.M., W. Parsley, C. Bush, and D. Zupo. 2003. "Comparison of Clean Diesel Buses to CNG Buses." MTA New York City Transit, Department of Buses, Research and Development.
Using previously published data on regulated and unregulated emissions, this paper compared the environmental performance of current generation transit buses operated on CNG and ULSD and incorporating diesel particulate filters (DPF). In addition, this paper compared the capital and operating costs of CNG and DPF-equipped buses. The cost comparison was primarily based on the experience of MTA New York City Transit in operating CNG buses since 1995 and DPF-equipped buses fueled with ULSD since 2001. The incremental cost (compared to "baseline" diesel) of operating a typical 200-bus depot is shown to be six times higher for CNG buses than for "clean diesel" buses. The contributors to this increased cost for CNG buses are almost equally split between increased capital costs for purchase of buses and installation of fueling infrastructure and increased operating costs for purchase of fuel, bus maintenance, and fuel station maintenance.

McCormick, R.L., A. Williams, J. Ireland, M. Brimhall, and R.R. Hayes. 2006. "Effects of Biodiesel Blends on Milestone Report." National Renewable Energy Laboratory. Milestone Report. NREL/MP-540-40554.
The objective of this study was to determine if testing entire vehicles, vs. just the engines, on a heavy-duty chassis dynamometer provides a better, more realistic measurement of the impact of B20 on regulated pollutant emissions. Eight heavy-duty diesel vehicles were tested, including three transit buses, two school buses, two Class 8 trucks, and one motor coach. Four met the 1998 heavy-duty emissions requirement of 4 g/bhp-h NO_x, and four met the 2004 limit of 2.5 g/bhp-h NO_x+HC. Driving cycles that simulate both urban and freeway driving were employed. Each vehicle was tested on a petroleum-derived diesel fuel and on a 20 volume percent blend of that fuel with soy-derived biodiesel. On average, B20 caused PM and CO emissions to be reduced by 16 to 17 percent and HC emissions to be reduced by 12 percent, relative to petroleum diesel. Emissions of these three pollutants nearly always went down, the exception being a vehicle equipped with a diesel particle filter that showed very low emissions of PM, CO, and HC; and there was no significant change in emissions for blending of B20. The NO_x impact of B20 varied with engine/vehicle technology and test cycle, ranging from -5.8 percent to +6.2 percent.

McKenzie, E.C. and P. Durango-Cohen. 2010. "Environmental Impact and Cost Effectiveness of Hydrogen Fuel Cell Buses: Going Beyond the CTTransit Demonstration Project." Transportation Research Board, Annual Meeting.
This paper used results from a demonstration project in Hartford, Connecticut, to conduct a life-cycle analysis of fuel cell buses and analyze the economic and environmental trade-offs that result. Economic Input-Output Life Cycle Analysis (EIOLCA) and data from the DOE are used to describe and analyze the greenhouse gas emissions from both fuel cell and diesel buses. Four main factors are identified as key differences between fuel cell and diesel buses: diesel engine combustion and fuel use, electricity generation, hydrogen production, and ZEBRA battery production. This paper also discusses the role of energy production in greenhouse gas emissions, and highlights the necessity of using clean energy sources to maximize the benefits of fuel cell vehicles. Cost effectiveness and the need for clean electricity generation are two barriers to implementation that need to be overcome in order for fuel cell buses to be a viable option for U.S. urban transit.

Moreira, J.R., S.T. Coelho, S.M.S.G. Velázquez, S.M. Apolinário, E.H. Melo, and P.H.B. Elmadjian. 2009. "BEST Project – contribution of Ethanol Usage in Public Urban Transport." Available at < http://cenbio.iee.usp.br/download/publicacoes/simea2008.pdf.>
This paper presents the BEST project – BioEthanol for Sustainable Transport, developed by the CENBIO–Brazilian Reference Center on Biomass. It's a European Union initiative, coordinated by the Stockholm City Hall, that aims to promote ethanol usage, replacing diesel, in urban public transportation. The paper evaluates ethanol usage as diesel fuel replacement in public transportation buses in Brazil by comparatively following the operational output of the experimental fleet (fuel consumption, performance and occurred failures), taking as a reference an equivalent diesel bus. The test vehicles were evaluated and monitored to demonstrate ethanol energetic efficiency. The ethanol bus reduce in up to 80 percent in greenhouse gas emissions responsible for global warming. The engine used in the tests is well advanced, even for European pollution standards.

Motta, R., P. Norton, K. Kelly, C.K. Battelle, L. Schumacher, and N. Clark. 1996. Alternative Fuel Transit Buses. Final Results from the National Renewable Energy Laboratory (NREL) Vehicle Evaluation Program.
The National Renewable Energy Laboratory, with funding from the U.S. Department of Energy, initiated a program to study the performance, reliability, costs, and emissions of alternative fuel transit buses (LNG, CNG, B20, ethanol, and methanol) versus conventional diesel buses (controls). The program involved collecting detailed operational and maintenance data from more than 100 buses at eight transit agencies across the country. A program goal was to have 10 test buses of each alternative fuel type, with 10 controls, split between two agencies, operating for 18 months. West Virginia University used its transportable chassis dynamometer to measure the emissions from the buses using a Central Business District driving cycle.

Murtonen, T. and P. Aakko-Saksa. 2009. "Alternative Fuels with Heavy-Duty Engines and Vehicles." VTT Working paper 128. VTT Finland.
This repot looks at heavy-duty vehicles using hydro-treated vegetable oil, ester-type biodiesel, GTL diesel, CNG, and selected blends in reference to fossil diesel fuel. Three engines and five city buses were used for the study of both regulated emissions (HC, CO, NO, PM) and unregulated emission compounds (CO_2, aldehydes, particle size distribution and total number, polyaromatic hydrocarbons, mutagenicity of particles, and several gaseous compounds with FTIR). Results show that, in most cases, all regulated emissions decrease with HVO, GTL, and RME fuels, compared to conventional EN590 diesel fuel. Alternative fuels have a positive effect on emissions, which are considered harmful to human health.

Nylund N. and K. Erkkilä. 2005. "Bus Emission Evaluation: 2002–2004 Summary Report." VTT Finland.
As part of the National Bus Study, VTT examined three Euro III diesel and four EEV CNG buses. VTT also examined the effectiveness of oxidation catalysts, three-way catalysts, and diesel particulate filters. The vehicles were tested in a lab with the Braunschweig and Orange County driving cycles. The results showed that diesel buses with filters and CNG buses with catalysts have significantly fewer emissions than diesel without after-treatment.

Pelkmans, L., D. de Keukeleere, H. Bruneel, and G. Lenaers. 2001. "Influence of Vehicle Test Cycle Characteristics on Fuel Consumption and Emissions of City Buses." SAEInternational Spring Fuels and Lubricants, May 7–9.
Three city bus technologies (diesel, CNG with stoichiometric fuel control and 3WC, and a CNG bus with lean burn fuel controls) were evaluated for fuel consumption and emissions both in real city traffic and test cycles. The purpose of the project was to look for clear relations between various test cycles in the IEA-AMF countries and the correspondence of these cycles with real traffic. The results show that the relation between real-city traffic and simulated city cycles differs from technology to technology. The acceleration capabilities of the bus are found to be very important, and the acceleration requirements of the simulated city cycle should match the actual capabilities of the bus.

Proc, K., R. Barnitt, R. Hayes, M. Ratcliff, and R. McCormick. 2006. "100,000-Mile Evaluation of Transit Buses Operated on Biodiesel Blends (B20)." SAE International.
Nine identical 40-ft. transit buses were operated on B20 and diesel for a period of two years. Five of the buses operated exclusively on B20 (20 percent biodiesel blend) and the other four on petroleum diesel. Each bus accumulated about 100,000 miles over the course of the study. B20 buses were compared to the petroleum diesel buses in terms of fuel economy, vehicle maintenance cost, road calls, and emissions. There was no difference between the on-road average fuel economy of the two groups based on the in-use data; however, laboratory testing revealed a nearly 2 percent reduction in fuel economy for the B20 vehicles. Engine and fuel system related maintenance costs were nearly identical for the two groups until the final month of the study. Laboratory chassis emissions tests comparing the in-use B20 and petroleum diesel on the CSHVC cycle showed reductions in all measured pollutants, including a reduction in nitrogen oxides.

Programme de démonstration en transport urbain Transports Canada. 2009. Rapport technique Technologie hybride.
This demonstration project by Transport Canada compared eight hybrid-electric buses and six standard diesel buses from the regional and city bus agencies. The buses met either EPA 2002 or 2007 standards. Emissions and fuel consumption of the buses were measured during a lab test on the Manhattan drive cycle. The effects of outdoor temperature and air conditioning were also considered. This was combined with more extensive field testing and track testing relating to other bus performance characteristics. The demonstration shows that, at low speeds, hybrids are advantageous. However, the report concludes that choosing an optimal bus fuel depends on the operational characteristics of the bus routes.

Pruebas en Campo de Autobuses de Tecnologías Alternativas en la Ciudad de México, Reporte Final. Equipo de Transporte y Cambio Climático Región Latinoamérica y Caribe Publicaciones de Desarrollo Sustentable, Secretaría del Medio Ambiente, México 2006.
This study was conducted by several international institutions (the Center for Sustainable Transportation-EMBARQ among them) for the Federal District Ministry of the Environment (Secretaría del Medio Ambiente del Distrito Federal), with the goal of supporting and sustaining information in order to expand the network of Bus Rapid Transit system strategic bus corridors in the Federal District. This analysis of bus technologies consisted of a series of comparative tests for buses that use alternative fuels and technologies (hybrids and CNG) and modern and normal diesel vehicles (regular diesel and ultralow sulfur diesel, 15 ppm and 50 ppm), to prove the technological, economical, environmental, and climate-related advantages for their operation in the conditions present in the Mexico City Metropolitan Area.

To evaluate the environmental impact, two pollutant measurement methods were used: a chassis dynamometer and an on-board vehicle emission measurement system (RAVEM). Before starting the tests, a representative route called "Mexico City Driving Cycle" was created using information obtained from different buses that circulate in the Federal District. The cycle is representative of the low- and medium-speed buses that operate in transportation corridor conditions.

Seven 12 m diesel buses were tested, as well as three articulated 18 m diesel buses, two diesel buses with DPF, one diesel hybrid without DPF, and three CNG buses with OxyCat. The buses were tested with a representative 70 percent passenger load.

One of the conclusions of the study was that using "particle traps" with ULSD significantly reduced PM10 emissions. With regard to NO_x emissions, it showed that diesel buses varied considerably, and many of them exceeded the emission standards for which they were certified. Supposedly, this is due to the fact that the motors were not calibrated (under atmospheric pressure) for Mexico City's altitude.

San Francisco Municipal Transportation Agency. 2002. Alternative Fuel Pilot Program: Initial 6 Month Evaluation Results. http://www.sfmta.com/cms/rclean/altpilot.htm.
SFMTA tested CNG, hybrid, and diesel buses on a CBD, New York Bus, and San Francisco Bus drive cycle. Diesel buses had the best fuel economy, while hybrid buses had the best fuel economy in demanding drive cycles. Emissions were low for hybrids and CNG buses, as well as diesel buses with particulate filters. However, CO emissions were high for CNG buses. CNG costs for fuel and maintenance were generally higher as well. The tests also noted that fuel economy may be affected by using poor quality diesel with a particulate filter, as this may clog the filter.

TransLink. 2006. Bus Technology and Alternative Fuels Demonstration Project, Phase 1 –Test Program Report. TransLink. Vancouver, Canada.
The transit agency tested ten buses: standard diesel, CNG, Hybrid with ULSD, 20 percent biodiesel, and diesel with post-treatment. The emissions testing was performed on a test track with a drive cycle meant to mimic urban low-speed services. Emissions were recorded using PEMS and DOES2 systems. Overall, the hybrids and then the diesel with post-treatment had the lowest emissions, followed by biodiesel and CNG. Reliability varied between buses of the same technology. Hybrids and CNG buses both had the lowest project fuel costs while hybrids used the least fuel per kilometer and CNG used the most fuel per kilometer.

Turrio-Baldassarria, L., C.L. Battistelli, L. Contia, R. Crebellia, B. De Berardisa, Na.L. Iamicelia, M. Gambinob, and S. Iannacconeb. 2004. "Emission Comparison of Urban Bus Engine Fueled with Diesel Oil and 'Biodiesel' Blend." Science of the Total Environment 327: 147–162.
The chemical and toxicological characteristics of emissions from an urban bus engine fueled with diesel and biodiesel blend were studied. Exhaust gases were produced by a turbocharged Euro 2 heavy-duty diesel engine, operating in steady-state conditions on the European test 13 mode cycle (ECE R49). Regulated and unregulated pollutants, such as carcinogenic polycyclic aromatic hydrocarbons (PAHs) and nitrated derivatives (nitro-PAHs), carbonyl compounds, and light aromatic hydrocarbons were quantified. The effect of the fuels under study on the size distribution of particulate matter (PM) was also evaluated. The use of biodiesel blend seems to result in small reductions of emissions of most of the aromatic and polyaromatic compounds; these differences, however, have no statistical significance at a 95 percent confidence level. Formaldehyde, on the

other hand, has a statistically significant increase of 18 percent with biodiesel blend. In vitro toxicological assays show an overall similar mutagenic potency and genotoxic profile for diesel and biodiesel blend emissions. The electron microscopy analysis indicates that PM for both fuels has the same chemical composition, morphology, shape, and granulometric spectrum, with most of the particles in the range of 0.06 to 0.3 mm.

U.S. Environmental Protection Agency (EPA). 2009. EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels.
EPA has analyzed the lifecycle GHG impacts of the range of biofuels currently expected to contribute significantly to meeting the volume mandates of EISA through 2022. EPA's draft results suggest that biofuel-induced land-use change can produce significant near-term GHG emissions; however, displacement of petroleum by biofuels over subsequent years can "pay back" earlier land conversion impacts. Therefore, the time horizon over which emissions is analyzed and the application of a discount rate to value near-term versus longer-term emissions are critical factors.

Wayne, W.S.; N.N. Clark, R.D. Nine, and D. Elefante. 2004. "A Comparison of Emissions and Fuel Economy from Hybrid-Electric and Conventional-Drive Transit Buses." Energy and Fuels 18: 257-270.
Hybrid-electric transit buses offer potential benefits over conventional transit buses of comparable capacity, including reduced fuel consumption, reduced emissions, and the use of smaller engines. Emissions measurements were performed on a 1998 New Flyer 40-foot transit bus equipped with a Cummins ISB 5.9-L diesel engine, an Engelhard DPX catalyzed particulate filter, and an Allison series-drive system. Results were compared to a conventional-drive, diesel powered bus that was equipped with an oxidation catalyst, and to a liquefied natural gas (LNG)-powered bus. Tests were performed according to the guidelines of SAE Recommended Practice J2711. On average, the oxides of nitrogen (NO_x) emissions from the hybrid bus were reduced by 50 percent, compared to the conventional-drive diesel bus, and 10 percent, compared to the LNG bus. Particulate matter (PM) emissions from the catalyzed filter-equipped hybrid bus were reduced by 90 percent, relative to those of the conventional diesel bus, and were comparable to those of the LNG bus.

Appendix 1: Emissions Standards and Conversions

Conversions to g/km were done using conversion factors provided by the EPA and Nylund et al. 2004 and the data conversions below.

Appendix Table 1 Euro Emissions Standards in g/kWh

Emission Standards	Date	CO	THC	NO_x	PM10
Euro I	1992	4.5	1.1	8	0.36
Euro II	1998	4	1.1	7	0.15
Euro III	2000	2.1	0.66	5	0.1
Euro IV	2005	1.5	0.46	3.5	0.02
Euro V	2008	1.5	0.46	2	0.02
EEV		1.5	0.25	2	0.02
Euro VI	2013	1.5	.13	.4	.01

Source: http://www.dieselnet.com/standards/eu/hd.php.

Appendix Table 3 Data Conversions

Conversion
1 mile = 1.609344 km
1 gallon = 3.78541 liters
1 foot= 0.3048 meters
4.679 bhp-hr/mile (EPA 1998)
37.95 kWh/gallon of diesel

Appendix Table 2 EPA Emissions Standards in g/bhp-hr

Emission Standards	CO	THC	NOx	NMHC	NMHC + NOx	PM
1994	15.5	1.3	5			0.07
1996	15.5	1.3	4			0.05
1998	15.5	1.3	4			0.05
2004 (1)	15.5	1.3			2.4	0.01
2004 (2)	15.5	1.3		1	2.5	0.01
2007	15.5	1.3	1.35	0.14		0.01
2010	15.5	1.3	0.2	0.14		0.01

Appendix 2: Meta-Analysis Results

Appendix Table 4 Result from Analysis – CO Emissions (g/km)

Fuel and Technology	Data Range	Minimum	Maximum	Mean	Std. Deviation
LNG	3.820	2.890	6.710	4.110	1.459
E95	26.470	11.620	38.090	26.020	8.538
E93	17.400	17.150	34.550	23.038	5.612
D50 + DPF	5.525	0.001	5.526	1.415	1.769
D50	8.313	0.005	8.318	2.789	2.575
D15 + SCR	8.720	0.070	8.790	3.904	4.371
D15 + OC	0.360	0.220	0.580	0.433	0.151
D15 + Hybrid	3.491	0.029	3.520	0.623	0.813
D15 + EGR	0.430	0.150	0.580	0.446	0.136
D15 + DPF	5.216	0.060	5.276	0.503	1.069
D15	13.316	0.017	13.333	2.256	2.969
Diesel > 150 + OC	6.660	0.360	7.020	2.488	2.208
Diesel > 150	19.303	0.026	19.329	3.785	3.462
CNG + OC	5.480	0.010	5.490	0.615	1.190
CNG + 3WC	2.780	0.400	3.180	1.507	0.644
CNG	42.660	0.150	42.810	8.523	9.519
B20	2.040	1.380	3.420	1.802	0.615
B100 + SCR	7.940	0.080	8.020	3.483	4.232
B100 + EGR	0.260	0.070	0.330	0.220	0.110

Appendix Table 5 Result from Analysis – CO_2 Emissions (g/km)

Fuel and Technology	Data Range	Minimum	Maximum	Mean	Std. Deviation
D50 + DPF	818.62	781.38	1600.00	1274.63	265.73
D50	1236.00	558.00	1794.00	1175.58	300.44
D15 + SCR	53.00	1070.00	1123.00	1095.64	17.77
D15 + OC	121.00	1129.00	1250.00	1178.57	39.15
D15 + Hybrid	1339.90	702.70	2042.60	1458.86	452.45
D15 + EGR	1009.76	1129.00	2138.76	1421.07	396.46
D15 + DPF	1365.26	773.50	2138.76	1444.90	440.35
D15	1947.10	644.00	2591.10	1538.21	691.89
Diesel > 150 + OC	785.90	766.10	1552.00	1133.66	218.19
Diesel > 150	1030.99	602.01	1633.00	1220.78	241.98
CNG + OC	1143.03	457.00	1600.03	1181.49	312.36
CNG + 3WC	947.00	580.00	1527.00	1158.55	174.70
CNG	827.50	806.50	1634.00	1314.85	278.37
B20	42.00	1366.00	1408.00	1387.00	29.70
B100 + SCR	6.00	1047.00	1053.00	1049.57	2.57
B100 + EGR	49.00	1087.00	1136.00	1113.43	20.21

Appendix Table 6 Result from Analysis – NO_x Emissions (g/km)

Fuel and Technology	Data Range	Minimum	Maximum	Mean	Std. Deviation
LNG	6.210	5.840	12.050	8.746	2.260
E95	12.000	8.820	20.820	13.694	3.766
E93	8.010	5.410	13.420	8.303	2.561
D50 + DPF	5.080	8.500	13.580	10.909	2.143
D50	15.200	4.600	19.800	11.272	4.687
D15 + SCR	3.390	5.260	8.650	6.852	1.621
D15 + OC	0.500	8.200	8.700	8.487	0.202
D15 + Hybrid	21.781	3.409	25.190	9.658	5.902
D15 + EGR	5.260	6.170	11.430	8.289	1.767
D15 + DPF	28.180	5.260	33.440	13.096	7.268
D15	25.775	2.735	28.510	12.193	6.976
Diesel > 150 + OC	9.550	5.850	15.400	10.121	3.214
Diesel > 150	41.467	2.213	43.680	16.272	9.546
CNG + OC	34.380	3.620	38.000	9.862	6.793
CNG + 3WC	6.000	0.500	6.500	2.305	1.218
CNG	65.780	4.560	70.340	15.095	11.262
B20	2.830	9.410	12.240	11.200	1.006
B100 + SCR	4.020	4.160	8.180	5.547	2.006
B100 + EGR	1.860	5.950	7.810	6.807	0.859

Appendix Table 7 Result from Analysis – PM Emissions (g/km)

Fuel and Technology	Data Range	Minimum	Maximum	Mean	Std. Deviation
LNG	0.100	0.010	0.110	0.026	0.034
E95	0.140	0.250	0.390	0.305	0.055
E93	0.410	0.140	0.550	0.391	0.144
D50 + DPF	0.401	0.009	0.410	0.141	0.154
D50	1.975	0.005	1.980	0.358	0.437
D15 + SCR	0.100	0.013	0.113	0.056	0.048
D15 + OC	0.061	0.064	0.125	0.088	0.024
D15 + Hybrid	0.190	0.000	0.190	0.035	0.042
D15 + EGR	0.131	0.010	0.141	0.070	0.045
D15 + DPF	0.314	0.000	0.314	0.032	0.063
D15	0.964	0.070	1.034	0.307	0.253
Diesel > 150 + OC	0.880	0.020	0.900	0.284	0.228
Diesel > 150	2.012	0.001	2.013	0.343	0.442
CNG + OC	0.030	0.000	0.030	0.009	0.010
CNG + 3WC	0.500	0.000	0.500	0.024	0.089
CNG	0.080	0.010	0.090	0.028	0.019
B20	0.410	0.076	0.486	0.163	0.124
B100 + SCR	0.064	0.011	0.075	0.039	0.034
B100 + EGR	0.036	0.039	0.075	0.058	0.017

Appendix Table 8 Result from Analysis – THC Emissions (g/km)

Fuel and Technology	Data Range	Minimum	Maximum	Mean	Std. Deviation
LNG	8.700	6.590	15.290	9.563	3.380
E95	12.120	5.030	17.150	9.591	4.434
E93	4.160	3.730	7.890	5.508	1.401
D50 + DPF	0.093	0.002	0.095	0.023	0.032
D50	0.500	0.000	0.500	0.074	0.142
D15 + SCR	0.030	0.000	0.030	0.014	0.011
D15 + OC	0.070	0.030	0.100	0.066	0.023
D15 + Hybrid	15.290	0.000	15.290	4.766	6.401
D15 + EGR	0.060	0.000	0.060	0.035	0.022
D15 + DPF	0.228	0.000	0.228	0.029	0.051
D15	0.431	0.000	0.431	0.169	0.124
Diesel > 150 + OC	0.610	0.060	0.670	0.222	0.180
Diesel > 150	2.394	0.006	2.400	0.509	0.532
CNG + OC	13.750	0.650	14.400	7.250	3.794
CNG + 3WC	1.460	0.040	1.500	0.397	0.377
CNG	48.150	1.250	49.400	13.952	13.124
B20	0.550	0.350	0.900	0.469	0.178
B100 + SCR	0.010	0.000	0.010	0.003	0.005
B100 + EGR	0.020	0.010	0.030	0.021	0.011

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