Emissions and Performance of Liquefied Petroleum Gas as a Transportation Fuel: A Review

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October 3rd, 2017

Executive Summary

Liquefied petroleum gas (LPG) is used throughout the world as a fuel for cooking, heating, power generation, and transportation, among many other uses. It is produced mainly from crude oil refining and natural gas processing activities. LPG consists of light hydrocarbon compounds, predominantly propane and butane, with ratios depending on the region and feedstock. In raw form, LPG is not considered a greenhouse gas (GHG) and its vapors are non-toxic. Its relatively low vapor pressure allows it to be stored and transported as a liquid in simple steel containers.

LPG is an attractive transportation fuel, compared not only to conventional petroleum fuels such as gasoline and diesel, but also alternative fuels such as ethanol and natural gas. Its advantageous vaporization properties promote better air and fuel mixing compared to liquid fuels while providing better energy density than other alternative fuels. Furthermore, LPG exhibits a higher octane rating and a lower hydrogen-to-carbon ratio than conventional gasoline which can provide performance and emissions benefits.

This review examined over 50 different documents, including, but not limited to journal papers, databases and reports from regulatory agencies, industry literature, and other review studies. The information presented herein furthers the case for the expanded use of LPG as a transportation fuel based on its GHG and regulated emissions benefits. On a well-to-wheel basis, it is reported that LPG produces much lower carbon dioxide equivalent (CO_2e) emissions when juxtaposed against gasoline, and similar CO_2e emissions compared to diesel and compressed or liquefied natural gas. LPG powered vehicles have been observed to produce low oxides of nitrogen (NO_X), carbon monoxide (CO), and total hydrocarbon (THC) emissions similar to gasoline, while emitting less carbon dioxide (CO_2) and particulates. Applying LPG to modern spark-ignition, direct-injection technology provides even further benefits on particulates and improved brake thermal efficiency. Despite significant advances in diesel exhaust aftertreatment technology, data shows that similar powered LPG vehicles produce lower NO_X and particulates, albeit with significantly less complicated and costly exhaust aftertreatment systems. Compared to natural gas as a transportation fuel, LPG offers much less cumbersome storage and handling properties, while providing similar low carbon fuel benefits in comparison to gasoline and diesel. In summary, LPG is a well-established transportation fuel that emits lower GHG and regulated emissions than conventional fuels, at an advantageous cost and similar GHG footprint compared to other popular alternative fuels.

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List of Acronyms

A:F	Air-to-Fuel	**HC**	Hydrocarbon
BTE	Brake Thermal Efficiency	**HD**	Heavy-Duty
°C	Degrees Celsius	**kg**	kilogram
C_3H_8	Propane	**km**	kilometer
C_4H_{10}	Butane	**LNG**	Liquefied Natural Gas
CH_4	Methane	**LNT**	Lean NOX Trap
CI	Compression-Ignition	**LPG**	Liquefied Petroleum Gas
CNG	Compressed Natural Gas	**LSPI**	Low-Speed Pre-Ignition
CO	Carbon Monoxide	**MJ**	Mega-Joule
CO_2	Carbon Dioxide	**MON**	Motor Octane Number
CO_2e	Carbon Dioxide Equivalent	**N_2O**	Nitrous Oxide
DEF	Diesel Exhaust Fluid	**NH_3**	Ammonia
DI	Direct Injection	**NMHC**	Non-Methane Hydrocarbon
DOC	Diesel Oxidation Catalyst	**NO_X**	Oxides of Nitrogen
DPF	Diesel Particulate Filter	**OEM**	Original Equipment Manufacturer
E10	Gasoline with up to 10 Percent Ethanol	**PFI**	Port Fuel Injection
E15	Gasoline with up to 15 Percent Ethanol	**PM**	Particulate Matter
E85	Gasoline with up to 85 Percent Ethanol	**PN**	Particle Number
EGR	Exhaust Gas Recirculation	**RON**	Research Octane Number
E.P.A.	U.S.A. Environmental Protection Agency	**SCR**	Selective Catalytic Reduction
EU	European Union	**SI**	Spark-Ignited
g	grams	**THC**	Total Hydrocarbon
GDI	Gasoline Direct Injection	**TTW**	Tank-to-Wheel
GHG	Greenhouse Gas	**TWC**	Three-Way Catalyst
GREET	Greenhouse Gases, Regulated Emissions and Energy Use In Transportation	**U.S.A.**	United States of America
GWP	Global Warming Potential	**WTT**	Well-to-Tank
H:C	Hydrogen-to-Carbon	**WTW**	Well-to-Wheel

1. Introduction

Liquefied petroleum gas (LPG) is a mixture of light hydrocarbons, predominantly propane (C_3H_8) and butane (C_4H_{10}). It is used throughout the world as fuel for various applications, including cooking, heating, power generation, transportation, and many other purposes. At ambient pressure, LPG exists in a gaseous state; however, under moderate pressure it becomes a liquid providing a much higher energy density, which is advantageous for storage and transportation. LPG is most commonly produced as a byproduct of natural gas and crude oil extraction and processing, but can also be produced as a byproduct of bio-fuel processing and other industrial processes.

1.1. History of LPG as a Transportation Fuel

Shortly after its widespread emergence as a cooking and lighting fuel in the early 20th century, there is evidence of LPG usage as a fuel for internal combustion engines [1]. Spurred by the oil crises in the 1970s and rising costs of petroleum, there was a significant increase in LPG-fueled vehicles [2]. The majority of these vehicles were originally designed to operate on gasoline and later converted to operate on LPG. As fueling systems and emissions control technologies progressed, LPG conversion systems for on-highway vehicles followed suit and became more complex and integrated with existing vehicle hardware. Some original equipment manufacturers (OEMs) have offered dedicated LPG fueled vehicles from the factory. The next major opportunity for LPG converters and OEMs lies in direct fuel injection technology, where there is opportunity to reduce emissions while increasing performance relative to gasoline.

2. Fuel Properties

LPG is predominantly composed of propane, however depending on the region it was produced in or destined for sale in, as well as the fuel specification adhered to, its composition and constituents can vary. For example, the United States of America (U.S.A.) HD-5 standard for LPG is composed of a minimum of 90 percent by volume of propane, a maximum of 2.5 percent by volume of butane and heavier hydrocarbons, and a maximum of 5 percent by volume of propylene [3]. Other regions of the world utilize higher butane compositions, for example the butane content for certain countries in Europe ranges from 20 to 30 percent butane depending on the season [4], while Korea utilizes over 85 percent butane in LPG in the summer months [5]. The ratios at which these components exist can have significant effects on the fuel properties of LPG such as energy content, vapor pressure, and octane number.

The composition of LPG also determines its carbon intensity which is often quantified by the hydrogen-to-carbon (H:C) ratio of a fuel. Propane, the main constituent of natural gas has eight hydrogen atoms and three carbon atoms equating to a H:C ratio of approximately 2.67. The H:C ratio increases for lower order alkanes such as methane (4) and ethane (3) and decreases for higher order alkanes such as butane (2.5). On the other hand, conventional transportation fuels, i.e. gasoline and diesel, typically exhibit a H:C ratio ranging from 1.7 to 1.9 [6]. In theory, this results in higher carbon dioxide (CO_2) and soot production during combustion.

2.1. Energy Content

The energy content of a fuel can be expressed on a mass basis or volume basis and can be measured through different methods. Table 1 provides energy content via the lower heating value method and the density of several common transportation fuels. Note that on a mass basis, LPG exhibits one of the highest energy contents (MJ/kg), slightly lower than liquefied natural gas (LNG). However, on a volume basis LPG has a lower energy content than conventional fuels such as gasoline and diesel. As shown in Table 1, this is related to the lower density of LPG versus these conventional fuels. This requires more fuel on a volume basis to achieve the same output as conventional fuels. LPG exhibits a small advantage in this respect compared to other alternative fuels, such as LNG and ethanol.

Table 1: Energy Content (Lower Heating Value) and Density of Select Fuels [7]

Fuel	Density (kg/liter)	Lower Heating Value (MJ/Liter)	Lower Heating Value (MJ/kg)
LPG	0.508	23.7	46.6
Low-Sulfur Gasoline	0.748	31.7	42.4
Low-Sulfur Diesel	0.847	36.1	42.6
Liquefied Natural Gas	0.428	20.8	48.6
Ethanol	0.789	21.3	27.0

2.2. Volatility, Vapor pressure and Storage

For efficient combustion in an internal combustion engine, the fuel must vaporize and mix with the air at a proper ratio that facilitates ignition. The ability of a substance to vaporize is often referred to as its volatility. Liquid fuels such as gasoline and diesel have a lower volatility than gaseous fuels and must be injected under high pressure through small orifices to promote vaporization and mixing. Highly volatile fuels that exist in a gaseous state at moderate pressures, such as LPG readily vaporize without the need for high injection pressures. This higher volatility is advantageous for mixing and particularly beneficial for direct fuel injection systems. The higher volatility of gaseous fuels allows for lower injection pressures and subsequently lower parasitic losses to the engine from the high-pressure fuel pump. However, this enhanced vaporization is directly tied to the fuels vapor pressure, which dictates many requirements of the vessels used to store the fuel. LPG has a modest vapor pressure, for example, HD-5 propane exhibits a vapor pressure of approximately 13 bar at 37.8 °C. This allows for LPG to be stored in a liquid state at modest pressures in relatively inexpensive steel vessels. In comparison, natural gas must be highly compressed to pressures over 200 bar, or cryogenically frozen to liquid form at temperatures less than -160 °C to achieve energy densities suitable for transportation applications [8]. Thus, compressed natural gas (CNG) and LNG require much costlier storage tanks due to the more extreme pressure or temperature requirements.

2.3. Octane number

Compared to gasoline available at the pump, LPG has a relatively high octane number. Although the octane rating of LPG can vary based on its composition, HD-5 has an octane rating, average of research octane number (RON) and motor octane number (MON), of approximately 105. In the U.S.A, 93 octane (average of RON and MON) gasoline is typically the highest octane rating available at fueling stations while 87 octane is the most common [9]. Similarly, in the European Union (EU) the most commonly used gasoline is rated at 95 RON, which equates to approximately 91 octane (average of RON and MON) [10]. In general, as the percentage of hydrocarbons that are a higher order than propane, (e.g. butane) increases the octane number decreases and vice versa for lower order hydrocarbons, e.g. methane and ethane. The higher octane number of LPG relative to gasoline can offer performance and efficiency advantages. More advanced ignition timing and a higher compression ratio can be utilized with less susceptibility to pre-ignition or knock when compared to gasoline found at most fueling stations.

3. LPG fueling system technology

There are a variety of technologies to meter LPG for internal combustion engines. These technologies range in cost and complexity, as well as efficiency and emissions performance. Historically, LPG fueling technologies have closely followed those of gasoline powered engines. With regards to spark ignited engines, port fuel injection (PFI) and direct injection (DI) are the most relevant LPG fueling technologies at the present time.

3.1. Port Injection

PFI of LPG offers advantages over single point of injection fueling systems. LPG PFI systems are a close replica of electronically controlled multi-port fuel injection systems for gasoline fueled engines that have been widely used for the last two decades. In fact, many vehicles equipped with LPG port injection were originally designed for gasoline and later converted to operate on LPG. There are also a number of OEM LPG offerings, particularly in the European and Asian markets. There are two types of conversions; bi-fuel which allows the operator to switch between gasoline and LPG and dedicated which only allow for operation on LPG. Bi-fuel systems require the installation of additional fuel injectors for LPG while dedicated systems replace the gasoline injectors with LPG injectors. This is necessary due to the lower energy per volume of LPG and lubricity differences that require different injector designs.

Regardless of bi-fuel or dedicated applications, these systems use a dedicated injector per each cylinder and thus offer more refined control of A:F ratio on a per cylinder basis compared to single point injection systems. In a sequential PFI system, individual injectors can be controlled to deliver more or less fuel to specific cylinders based on air flow differences among the cylinders. This provides tighter A:F ratio control for the engine as a whole, and subsequently more efficient TWC operation to simultaneously reduce carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NO_X) in the exhaust. Furthermore, these injectors are generally located in the intake manifold relatively close to the intake valve offering quicker response to transient engine operation and commanded A:F ratio changes.

Sequential multi-port fuel injection of LPG can match and even provide lower levels of regulated and unregulated emissions when compared to gasoline engines. However, LPG conversions and even OEM LPG offerings are often at a disadvantage due to the fact that the engines were originally designed for gasoline. The higher octane number of LPG compared to conventional gasoline allows for more advanced ignition timing and higher compression ratios. Without modification of the OEM gasoline ignition timing maps or compression ratio, combustion efficiency can be lower ultimately producing higher engine out HC and CO emissions, at the tradeoff of lower engine out NO_X emissions. TWC for these vehicles are formulated for gasoline HCs which are higher order HC species compared to LPG which are inherently lower HC species. Thus, it is important when examining emissions from vehicles converted to operate on LPG relative to gasoline vehicle to consider the technology used, the existing gasoline aftertreatment systems, and the level of complexity of ignition timing and fueling control provided by the conversion system.

3.2. Direct Injection

The number of vehicles equipped with spark-ignited (SI) gasoline direct injection (GDI) engines has grown significantly in the last decade. The majority of automotive OEMs offer GDI engines primarily due to their fuel efficiency advantages. GDI engines utilize a high pressure fuel pump and in-cylinder fuel injector to directly inject fuel into the combustion chamber. This provides more precise control of the fuel injection event compared to PFI systems. This enhanced injection control allows for injection strategies that limit engine knock and support higher compression ratios without high octane fuel. By the same reasoning, GDI engines are more receptive to forced induction methods such as turbocharging and supercharging. A higher compression ratio and forced induction equates to higher power density and greater fuel efficiency particularly when the engine is downsized, i.e. lower displacement.

While GDI engines can offer greater fuel efficiency compared to PFI engines, they do have certain drawbacks. Typically, GDI engines use multiple injection events to suppress engine knock and allow for higher compression ratios. This approach can result in a more stratified air and fuel mixture compared to PFI engines which provide a longer time for the air and fuel to mix and thus a more homogeneous mixture. This stratified mixture consists of locally rich regions in the combustion chamber which increases the formation of particulate matter (PM) and CO. While a TWC can efficiently oxidize CO, increased PM emissions remain an issue for GDI engines. The most recent EU PM and particle number (PN) regulations have resulted in certain manufacturers introducing particulate filters for GDI engines. These undoubtedly increase the cost and complexity of vehicles in addition to potential reductions in fuel efficiency due to increased back pressure on the engine. It is anticipated that more manufacturers will follow suit, and other regions of the world will adopt similar standards making particulate filters for GDI engines commonplace. Alternatively, LPG has an inherent advantage with respect to PM formation compared to gasoline in SI DI engines. The higher volatility of LPG promotes mixing within the combustion chamber providing a less stratified air and fuel mixture reducing locally rich regions that are associated with soot production. The lower carbon intensity of LPG compared to gasoline reduces its propensity to produce soot and limits CO2 production. Furthermore, DI of LPG in liquid state maintains and can exceed the efficiency advantages of GDI engines.

Another phenomenon of GDI engines is low speed pre-ignition (LSPI). At low engine speeds and high loads, many GDI engines are susceptible to pre-ignition events. The research base and knowledge of this phenomenon is limited, but growing. In theory the higher octane rating of LPG compared to conventional gasoline would reduce the occurrence of LSPI events and allow for more advanced ignition timing. Furthermore, the lower carbon intensity of LPG and its associated lower soot production can reduce the formation of carbon deposits in the combustion chamber which can initiate LSPI events. However, none of the literature surveyed discussed LSPI and these theories should be investigated further.

3.3. Dual-Fuel Compression-Ignition

Compression-ignition (CI) engines, commonly referred to as diesel engines, historically offer better fuel economy than SI engines. This can be attributed to higher compression ratios and the lack of a throttle which reduces pumping losses. Furthermore, these engines typically operate at an overall lean A:F ratio. However, this lean A:F ratio requires the use of much more advanced exhaust aftertreatment systems to reduce NO_X emissions compared to SI engines and TWCs. A typical modern diesel engine utilizes a selective catalytic reduction (SCR) system to reduce NO_X which also requires diesel exhaust fluid (DEF), a urea and water based solution, to be carried on board the vehicle. Diesel fuel also has a lower H:C ratio compared to LPG and the DI system used on the vast majority of modern diesel engines results in locally rich regions that produce significantly higher levels of PM than SI engines. This increased PM production requires the use of diesel particulate filters (DPF) to meet regulatory standards for PM. A diesel oxidation catalyst (DOC) is generally also required to reduce tailpipe emissions of HC and CO to regulatory standards and provide proper exhaust conditions for the DPF and SCR system. In some instances, an ammonia (NH_3) slip catalyst is required after the SCR system. These components add up to a significantly more complex and costly aftertreatment system compared to a TWC, which cannot reduce NO_X in lean conditions.

The use of conventionally SI fuels, such as gasoline and LPG, in neat form in CI engines requires advanced technology and control, and has not been commercially adopted. However, high octane fuels such as LPG can be used in CI engines by substituting a portion of the diesel fuel with LPG. This technology is called dual-fuel. Typically, the LPG or other high octane fuel is injected through the intake port and a reduced quantity of diesel fuel is injected directly into the cylinder to ignite the LPG. Such a system allows for the use of LPG while retaining the fuel efficiency associated with conventional diesel engines. The lower carbon intensity of LPG can also help to reduce soot from these engines. Unfortunately, these engines still operate at an overall lean A:F ratio and require the use of complex modern diesel aftertreatment systems. Additionally, dual-fuel engines require the vehicle to carry two separate fuels which can be problematic on smaller vehicles where space is at a premium and thus typically relegates this technology to heavy-duty vehicles.

4. Transportation Fuels

When examining different fuels used for transportation it is important not only to consider the exhaust emissions produced from combustion of a fuel, but also the production, processing/refining, transportation/delivery, and other sources of emissions in the supply chain.

4.1. Production and Refining of Transportation Fuels

The majority of LPG is produced from two sources; crude oil processing (approximately 40 percent worldwide) and natural gas production and processing (approximately 60 percent worldwide) [11]. Each method of production has different criteria pollutant and greenhouse gas (GHG) emissions levels which can vary significantly. The share of LPG produced from each source varies throughout the world and even among different regions of a single country or continent. For example, in the Marcellus Shale region of the U.S.A., LPG is produced from natural gas production and processing, while in the Gulf of Mexico region significant quantities of LPG is produced from crude oil refining operations. The emissions from these activities can also vary based on the initial feedstock and the equipment used to extract and process natural gas or crude oil. Emissions from these activities are considered a portion of the "upstream emissions" in regards to the overall emissions from the use of LPG as a transportation fuel. Also included in the upstream emissions are those associated with the compression, transportation, and final delivery of LPG. The combination of all these upstream emissions is often referred to as the well-to-tank (WTT) emissions. The variation in production methods, transportation methods and distance make quantifying WTT emissions difficult. However, there are models that have been developed that use industry data and assumptions to quantify these emissions for both upstream and downstream activities associated with the transportation sector; the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model is one such tool that has been utilized by studies referenced in this document [12].

4.2. Crude oil: Gasoline and Diesel

Diesel and gasoline are the two most predominantly utilized transportation fuels in the world. Fossil fuel derived forms of these fuels are produced from crude oil extracted from the earth. Similar to other sources of energy such as natural gas, LPG, and coal, the emissions from crude oil extraction and transportation to the refinery can vary significantly depending on the region and equipment used. For example, some regions in the world import all of their oil from other regions and thus emissions associated with marine tankers, pipelines, railway, or trucking must be considered for an accurate well-to-wheels (WTW) assessment. The refining process for diesel and gasoline is also a major source of WTW energy consumption and emissions production.

4.3. Natural gas: LNG &CNG

The production and utilization of natural gas has increased dramatically over the last decade, particularly related to unconventional recovery techniques such as horizontal drilling and fracturing. The emissions associated with these activities vary with the breadth and scope of their use. Similar to other energy sources, emissions from the delivery and transportation of natural gas can vary significantly based on the region and the methods used. Furthermore, the primary component of natural gas, methane (CH_4) is a potent greenhouse gas itself. With a global warming potential (GWP) of 28 to 36 over a 100 year basis (CO_2 is given a GWP of 1), CH_4 emissions from the extraction, processing, and transportation of natural gas must also be considered for WTT and WTW GHG analyses of natural gas emissions [13]. With regards to WTW, and more specifically end use or tank-to-wheels (TTW) emissions in the transportation sector, the method of storage and associated energy required must also be considered. In order to achieve sufficient energy density for transportation use natural gas must be compressed to high pressures (CNG: approximately 200 to 250 bar) or cryogenically frozen to liquid form (LNG: approximately -160 °C) [8]. Both of these processes are energy intensive and add to the overall WTT and WTW emissions.

4.4. Ethanol

As a transportation fuel, ethanol is generally mixed with gasoline for performance and stability purposes. In the EU 72.4 percent of all gasoline sold in 2014 contained up to 5 percent ethanol (E5), while 10 percent contained up to 10 percent ethanol (E10) [10]. In the U.S.A. E10 is the most common blend and is sold for use in all vehicles. E15 (gasoline with up to 15 percent ethanol) is also available in certain areas of the U.S.A., but it is only certified for use in model year 2001 and newer vehicles [14]. Higher concentrations of ethanol e.g. E85 (gasoline containing up to 85 percent ethanol) can only be used in vehicles with purpose built fuel systems and engine controllers. Ethanol can be produced from a number of substances including sugar cane and corn through distillation. WTT or WTW emissions from ethanol derived from these renewable plant sources must also consider the production, distilling, and transportation of the fuel. However, ethanol from plant sources has a significant GHG benefit from photosynthesis that can offset its GHG emissions from farming, production, transportation, and end use.

5. Regulated Pollutants

For the proceeding analysis, data focused on empirically measured regulated emissions, including NO_X, CO, total hydrocarbons (THC), non-methane hydrocarbons (NMHC), CH_4, PM, and PN, was gathered from 13 different sources which are displayed in Table 2. Note that not all of these emissions are regulated for the transportation sector in all countries or regions. For example, CH_4 is regulated in the transportation sector as a GHG in the U.S.A. but not in the EU, while PN is regulated in the EU but not in the U.S.A. The two largest sources of data were, by far, a report by Atlantic Consulting title "A Comparative Environmental Impact Assessment of Car-and-Van Fuels" [15] that utilized the vehicle emissions database maintained by the KBA (Kraftfahrtbundesamt), Germany's Federal Agency for Motor Transport, and the U.S.A. Environmental Protection Agency (EPA) emissions certification database for vehicles and engines [16, 17]. These sources in addition to the others listed in Table 2 included data on diesel, gasoline, E10, E85 and CNG fueled vehicles and engines as compared to LPG. The data sources originated from multiple regions throughout the world and the model years considered ranged from 2000 to 2017, although the majority of the data came from post 2010 model year vehicles sold in the European and U.S.A. markets. Consequently, the engine, fuel injection system, and exhaust aftertreatment technology was wide ranging among the data. Data was extracted from these sources for further analysis and was only included when relatively direct comparisons could be made for a particular fuel and LPG. For SI fuels including gasoline, E10, E85, and CNG, comparisons were made to LPG with the same or relatively similar displacement engine and similar if not the same vehicles based on gross vehicle weight rating and curb weight. Comparing diesel to LPG is somewhat more complex given that diesel engines utilize CI. For these comparisons, a vehicle that offered a diesel engine, and LPG engine was used. Even with these constraints on comparisons there were still numerous factors that can influence or bias the individual comparisons. These are discussed further for individual fuels.

Table 2: Sources for Regulated Pollutant Data

Title	Author	Date	Fuels Compared to LPG	Region
Direct Injection LPG - Opportunity and Threat in Europe [18]	Atlantic Consulting	2017	Gasoline	Europe
A Comparative Environmental Impact Assessment of Car-and-Van Fuels [15]	Atlantic Consulting	2014	Gasoline, Diesel, CNG, E85	Germany
EETP: "European Emission Test Programme" Final Report [19]	INSTITUT FRANÇAIS DU PETROLE	2004	Gasoline, Diesel, CNG	Europe
Briefing note – the case for LPG taxis [20]	Calor	2015	Diesel	United Kingdom
Comparative Emission Analysis of Gasoline/LPG Automotive Bifuel Engine [21]	R.R. Saraf, S.S.Thipse, P.K.Saxena	2009	Gasoline	India
Performance and Emission Characterization of 1.2L MPI Engine with Multiple Fuels (E10, LPG and CNG) [22]	R. Muthu Shanmugam, Nilesh M. Kankariya, Jacques Honvault, L. Srinivasan, H. C. Viswanatha, Patrice Nicolas, N. Saravanan, Dias Christian	2010	Gasoline, CNG	India
Gasoline and LPG Vehicle Emission Factors in a Road Test [23]	Jerzy Merkisz, Jacek Pielecha, Wojciech Gis	2009	Gasoline	Poland
Emissions Testing of Gas-Powered Commercial Vehicles [24]	Brian Robinson	2017	Diesel	United Kingdom
JC08 Emission Data of LPG/Gasoline/Diesel [25]	National Institute for Environmental Studies, LPG Vehicle Promotion Association in Japan	2015	Gasoline, Diesel	Japan
Emission Characteristics of Gasoline and LPG in a Spray-Guided-Type Direct Injection Engine [26]	Cheolwoong Park, Yunseo Park, Seungmook Oh, Yonggyu Lee, Tae Young Kim, Hongsuk Kim, Young Choi, Kern-Yong Kang	2013	Gasoline	South Korea
The Evaluation Study on the Contribution Rate of Hazardous Pollutants from Passenger Cars Using Gasoline and LPG Fuel [5]	Yunsung Lim, Hyung Jun Kim	2013	Gasoline	South Korea
ELGAS HDDF LPG EMISSIONS DEMONSTRATION [27]	ABMARC	2015	Diesel	Australia
2015 Certified Vehicle Test Result Report Data (XLS) [16]	U.S.A Environmental Protection Agency	2015	Gasoline, CNG, E85	U.S.A
2016 Certified Vehicle Test Result Report Data (XLS) [16]		2016	Petro, Diesel, CNG, E85	U.S.A
2017 Certified Vehicle Test Result Report Data (XLS) [16]		2017	Petro, Diesel, CNG, E85	U.S.A

On-highway Heavy-duty Diesel and Gasoline FileMake Pro Certification Data for 2015 (XLS) [17]		2015	Gasoline, Diesel, CNG	U.S.A
On-highway Heavy-duty Diesel and Gasoline FileMake Pro Certification Data for 2016 (XLS) [17]		2016	Gasoline, Diesel, CNG	U.S.A
On-highway Heavy-duty Diesel and Gasoline Certification Data for 2017 (XLS) [17]		2017	Gasoline, CNG	U.S.A
Measuring Emission Performance of Autogas Cars in Real Driving Conditions [28]	European LPG Association	2017	Gasoline, Diesel	Europe

Emissions data from the sources in Table 2 was presented in variety of units including by volume and by mass. The data was also normalized by different metrics; predominantly by distance and brake power. In order to compare and contrast the results of multiple studies with various units, a percent differencing method was used to obtain a percent increase or decrease of emissions from a particular fuel with regards to LPG. This allowed for the data to be normalized for almost all of the studies, however, discrepancies can arise by the percent differencing method used, particularly the denominator used. For all but one of the studies, raw emissions data was extracted and the following equation was used to calculate the percent difference.

$$Percent\ Difference = \frac{Emissions_{LPG} - Emissions_{Fuel\ X}}{(Emissions_{LPG} + Emissions_{Fuel\ X})/_{2}}$$

Where the difference in emissions from LPG to the fuel being compared to (Fuel X), is normalized by the average of the emissions from both fuels. From this approach a negative percent difference indicates that LPG produced less of that emissions constituent and vice versa. This approach results in a maximum or minimum of 200 and -200 percent difference, respectively. The only data that was not available in raw form was from the study title "Direct Injection LPG - Opportunity and Threat in Europe" [18] in Table 2. Only a percent increase or decrease of gasoline emissions compared to LPG was provided (emissions from a single fuel in the denominator). Furthermore, it was unclear what fuel was used in the denominator. Another issue faced with some data sources was the available decimal places for certain emissions constituents. For example, some sources used zero for results in which the measured emissions level was beyond 2 decimal places. Additionally, some sources used zero when an emissions constituent was not reported. In instances where a zero was present, a percent difference was not calculated for the emissions constituent and the data was not included in the analysis. From the U.S.A. EPA certification database, there were sometimes multiple results for LPG for a specific vehicle or engine. In this situation the manufacturer or converter that had OEM support (e.g. Roush® for Ford® vehicles, and Power Solutions Inc.® for General Motors® vehicles) was chosen as the base to compare to. When this option wasn't available the best performing LPG vehicle or engine with respect to emissions was chosen as the comparator. These factors, as well as the broad range of vehicle model years and technologies created a data set that had a wide range of percent differences for the majority of the emissions constituents. This wide range can be observed in Figure 1.

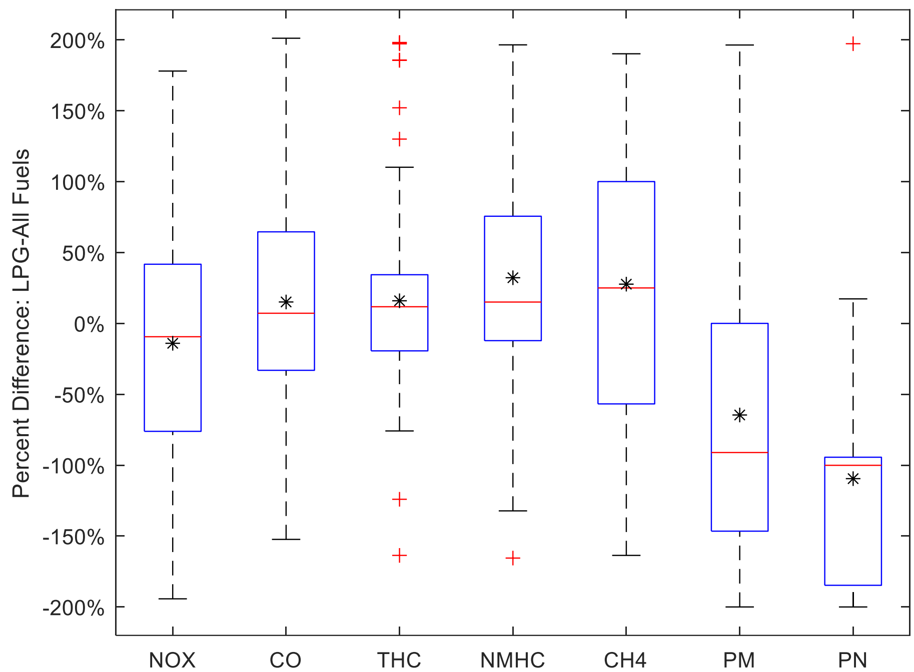

Figure 1: Regulated Emissions Data from All Fuels

The box and whisker chart presented by Figure 1 provides a visual explanation of the high standard deviation and coefficient of variation. The upper and lower ranges of the box represent the 75th and 25th quartile of the data while the upper and lower edges of the whiskers represent the maximum and minimum of the data. The line through the box indicates the median of the data, the asterisk represents the average of the data, and the independent crosses represent statistical outliers from the data set. A negative percent difference indicates that the LPG fueled vehicle produced lower emissions than the comparator and vice versa.

The wide ranging variation in the data make it difficult to draw accurate overarching conclusions about the data. For example, the average percent difference of NO_X emissions from LPG versus all other fuels was approximately -14 percent, i.e. LPG exhibited lower NO_X emissions on average than the average of all other fuels considered. However, the large span of the box and whiskers in Figure 1 demonstrates that there are instances where LPG produces significantly less and more NO_X emissions than other fuels. Thus the data should be examined on a fuel-by-fuel basis while considering the level of fuel injection and aftertreatment technology, as well as the region from which the technology was utilized and the emissions regulations that pertain to it.

5.1. Gasoline and E10

For the present analysis, gasoline and E10 have been considered together for comparison to LPG given that neat gasoline is not available in certain locations and only gasoline containing up to 10 percent ethanol (E10) is available. Furthermore, the data from “A Comparative Environmental Impact Assessment of Car-and-Van Fuels” [15], included data from bi-fuel vehicles operated in gasoline mode which were included in the gasoline analysis as well. Figure 2 displays box and whisker plots for all the gasoline and E10 regulated emissions data.

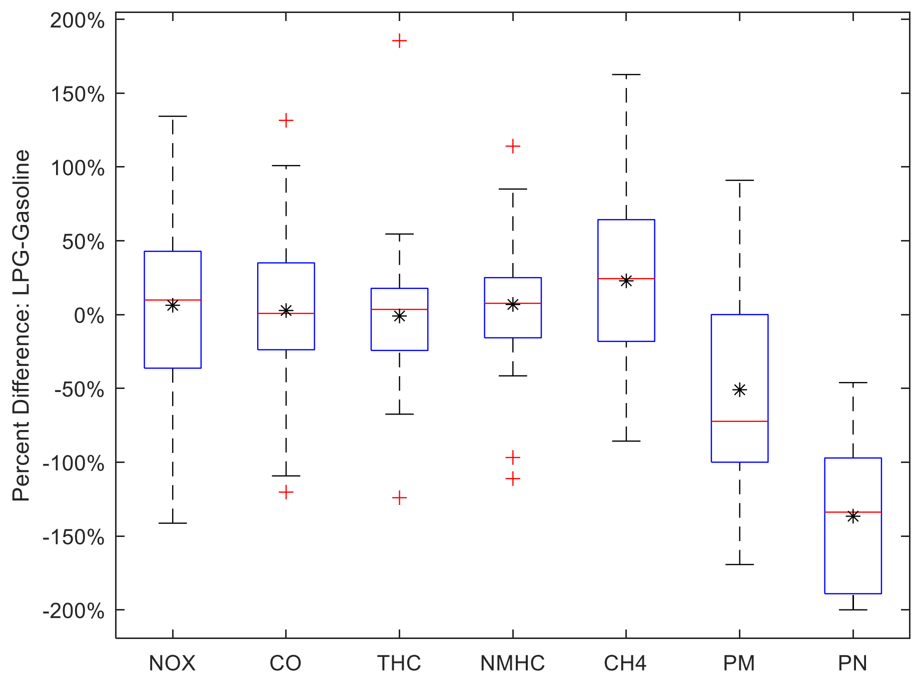

Figure 2: Regulated Emissions Data from Gasoline and E10

Comparing the box and whisker plots for gasoline versus LPG in Figure 2 to the plots for all fuels versus LPG in Figure 1, it is observed that the average NO_X emissions deviate from a decrease (-14 percent) for LPG to a slight increase (6 percent) for LPG when compared to gasoline only. The percent difference for CO and HC species (THC, NMHC, and CH_4) decrease from the values represented in Figure 1 for CO (3 percent) and for THC (-1 percent) when comparing LPG to gasoline. It should be noted that SI vehicles pursuant to modern emissions regulations produce relatively little NO_X, CO and THC emissions and a single digit percent difference represents a miniscule increase or decrease in total mass of emissions.

A wide spread of the range of data is present for nearly all emissions constituents. One potential explanation for variations in the range of percent differences for NO_X, CO, and HC species is that nearly all of the vehicles and engines surveyed were equipped with TWCs. For a TWC to operate properly the A:F ratio of the engine must dither between lean and rich about stoichiometric providing excess oxygen to oxidize CO and HCs and excess hydrocarbons to reduce NO_X emissions stored on the TWC substrate. If the A:F is not controlled properly in this way the TWC will not operate properly and either CO and HC emissions or NO_X emissions will decrease while the other increases.

There is a tradeoff between NO_X emissions versus CO and HC emissions from TWC equipped engines. In this respect many engines converted to operate on LPG are at a disadvantage compared to gasoline for several reasons. First, the engineering effort and support for LPG converters and even OEM LPG equipment is much less than for gasoline OEMs. In essence, an engineer must tune a LPG powered vehicle to meet the applicable emissions standards just as an engineer would do for a gasoline powered vehicle, however once emissions standards are met there is little incentive to refine the calibration especially with much smaller budgets and manpower than the major automotive OEMs. Second, the TWC installed on vehicles converted to LPG (and potentially OEM offerings) are designed for gasoline HCs which are generally higher order carbon compounds. Further complicating TWC operation is the stoichiometric A:F ratio of pure propane is 15.7 versus approximately 14.6 for gasoline [29]. If this is not accounted for in the engine controller the engine may not operate properly about stoichiometric which would reduce TWC efficiency. The composition of LPG can also negatively influence TWC operation if more butane or other compounds are present that alter the stoichiometric A:F ratio. Another factor in proper TWC operation is the placement of LPG injectors and other design parameters of the fueling system. If the LPG injectors are placed further upstream of the OEM fuel injectors, the response time for a fueling demand change from oxygen sensor feedback will be increased and thus the A:F ratio cannot be as tightly controlled.

Despite these inherent disadvantages the box and whisker plots in Figure 2 demonstrate that emissions of NO_X, CO, and THC for LPG vehicles are relatively the same. The averages of these compounds hover around zero and the 25th and 75th interquartile and the whiskers are distributed well about zero providing evidence that LPG vehicles can be tuned to perform the same as gasoline vehicles in regards to NO_X, CO, and THC. The results for PM and PN strongly indicate that LPG produces less particulates than gasoline which is supported by the fact that it has a higher H:C ratio than gasoline as well as its superior vaporization properties as discussed in section 2.2. This is particularly relevant for GDI engines which have demonstrated significantly increased particulate emissions compared to PFI gasoline engines.

5.2. E85

E85 is typically utilized in flex-fuel vehicles which can also operate on gasoline. Compared to neat gasoline or E10, E85 in theory can offer reduced NO_X and CO emissions. The NO_X emissions benefit is attributed to ethanol's higher heat of vaporization which results in lower intake charge temperatures (if injected in the port) and subsequently lower in-cylinder temperatures which ultimately reduce thermal NO_X formation. Furthermore, simulations have shown that pure ethanol and air mixtures exhibit a lower adiabatic flame temperature than gasoline and air mixtures [30]. However, lower combustion temperatures can result in a tradeoff of increased HC and CO emissions. On the other hand, ethanol is an alcohol which contains oxygen, thus E85 can also in theory provide CO and HC emissions reductions compared to neat gasoline due to the availability of more oxygen to oxidize CO and HC. Emissions data for E85 from the sources surveyed was limited to NO_X, CO, THC, NMHC, and CH_4 which is presented in Figure 3; no information on particulates was available.

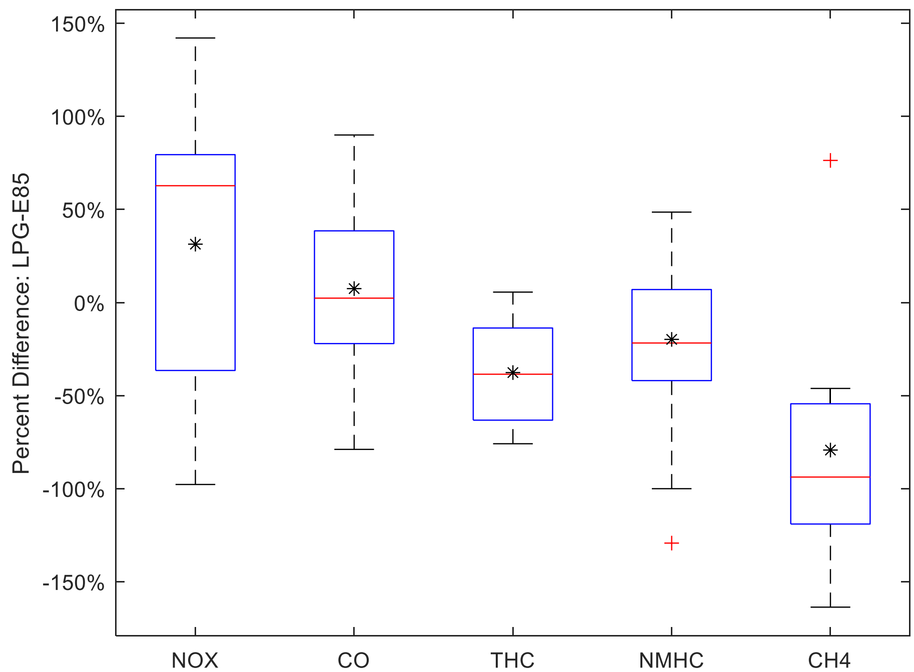

Figure 3: Regulated Emissions Data from E85

Relating the theoretical properties of E85 to LPG, Figure 3 reveals that, on average, vehicles and engines fueled with LPG produced 28% greater NO_X emissions than E85. This is also an increase from the average percent difference of NO_X emissions for LPG versus gasoline. Although there is a bias of higher NO_X emissions for LPG versus E85, Figure 3 also demonstrates that there is a wide range of NO_X emissions percent differences that include decreased NO_X emissions for LPG similar to the gasoline versus LPG comparison. CO emissions for LPG versus E85 based on an average percent difference demonstrate a slight increase, however the argument can be made that CO emissions are essentially equal between the two fuels for this analysis. Figure 3 provides evidence that the majority of the CO emissions data is centered around zero percent based on the location of the box. A tradeoff of increased NO_X emissions for LPG versus E85 is a reduction in THC, NMHC, and CH_4 which correlates with the theoretical performance of E85 as well as TWC operation.

5.3. Diesel

Aftertreatment technology for diesel powered vehicles has advanced significantly over the last 15 years. This has resulted in significant decreases in NO_X and PM emissions which have traditionally been the most troublesome regulated emissions to mitigate for diesel engines. However, this technology has significantly increased the cost and complexity of diesel powered vehicles, especially when compared to SI vehicles that utilize TWCs. TWCs are very effective at simultaneously reducing NO_X, HC, and CO emissions from SI engines, while diesel engines require more complex aftertreatment systems typically consisting of a DOC, DPF, and SCR system to achieve similar emissions levels. This can create differences when comparing LPG to diesel vehicles that may or may not use such advanced aftertreatment systems and must be considered when drawing conclusions. Furthermore, there has historically been different emissions standards for CI and SI engines. For example, EU 5 NO_X standards for CI (diesel) and SI equipped passenger vehicles are 0.18 g/km and 0.06 g/km, respectively. Although EU 6 emissions have reduced the discrepancy between CI and SI NO_X emissions standards, the limit for CI is still higher at 0.08 g/km while the standard for SI is 0.06 g/km. An additional consideration is the real-world emissions from diesel vehicles versus SI vehicles with TWCs. Recent findings have indicated that diesel powered vehicles produce significantly higher emissions in real-world situations compared to laboratory emissions certification results. SI vehicles with TWCs are less susceptible to this manipulation and generally produce real world emissions closer to their certification values. The majority of the emissions data presented in this section is from certification results. Although it is beyond the scope of this review, comparisons of real world emissions results from diesel powered vehicles compared to SI LPG powered vehicles equipped with TWCs might indicate a higher differential of certain emissions.

Figure 4 presents data for LPG versus diesel from all the sources with empirical results. Note that these sources contained vehicles and engines certified to EU 4, 5, and 6 standards as well as post 2010 EPA heavy-duty engine standards and Tier 2 EPA vehicle standards. As such the data contains varying levels of exhaust aftertreatment technology including none, DOCs, lean NO_X traps (LNTs), DPFs, and SCR systems. Despite these various levels of technology, the NO_X and PM emissions from LPG vehicles and engines are virtually unanimously lower than their diesel comparators, while CO and HC species display an opposing trend with higher averages for LPG. In fact, the PM emissions from the combustion of LPG compared to diesel were unanimously lower with the exception of two data points. These data were from dual-fuel heavy-duty trucks that used CI of diesel and LPG compared to neat diesel operation. This technology was a departure from SI of LPG and the increase in PM emissions for this technology can typically be attributed to transient events where the overall A:F ratio becomes rich due to limited control of the LPG fuel injection system.

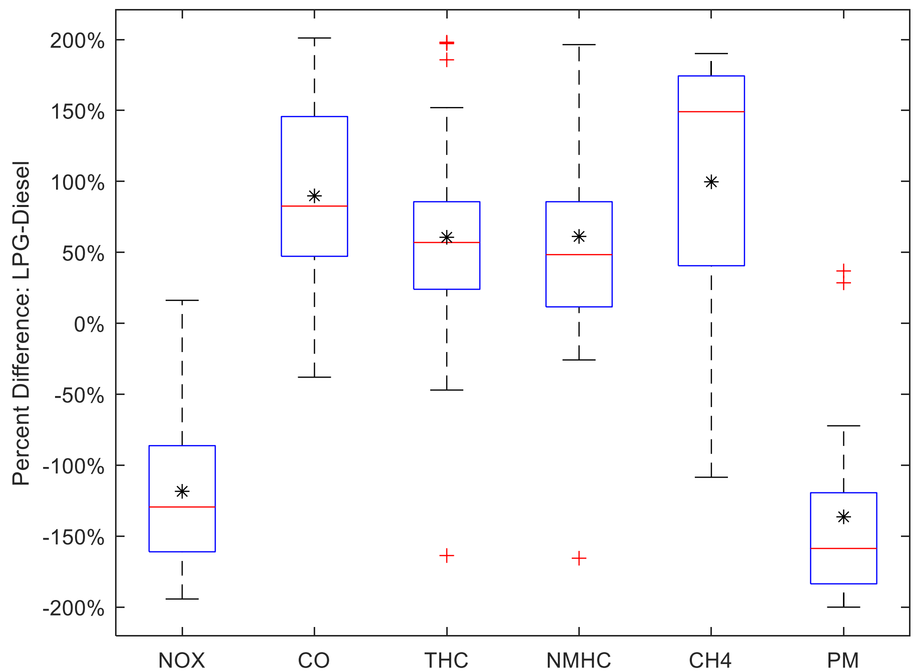

Figure 4: Regulated Emissions Data from Diesel

Given that the data collected for diesel vehicles and engines contained drastic differences in exhaust aftertreatment technology, the data was segregated and investigated further to determine the effect of such differences on the comparison of LPG versus diesel powered vehicles and engines. To accomplish this, data from the two sources with the largest number of entries were analyzed separately. These two sources were “A Comparative Environmental Impact Assessment of Car-and-Van Fuels” [15] which included only vehicles subjected to EU 5 and 6 standards and the U.S.A EPA certification database for model year 2015, 2016, and 2017 light-duty vehicles and heavy-duty engines. The data from diesel powered EU 5 and EU 6 vehicles included entries with no exhaust aftertreatment, LNTs, and SCR systems. The data from the EPA included engines and vehicles certified to post 2010 heavy-duty engine emissions standards and light-duty vehicle tier 2 emissions standards. The EPA entries unanimously used SCR systems to control NO_X emissions. Figure 5 presents data from the EU source, while Figure 6 presents data from the EPA source. Unfortunately, data for all the emissions constituents presented in Figure 4 were not available for each of the sources.

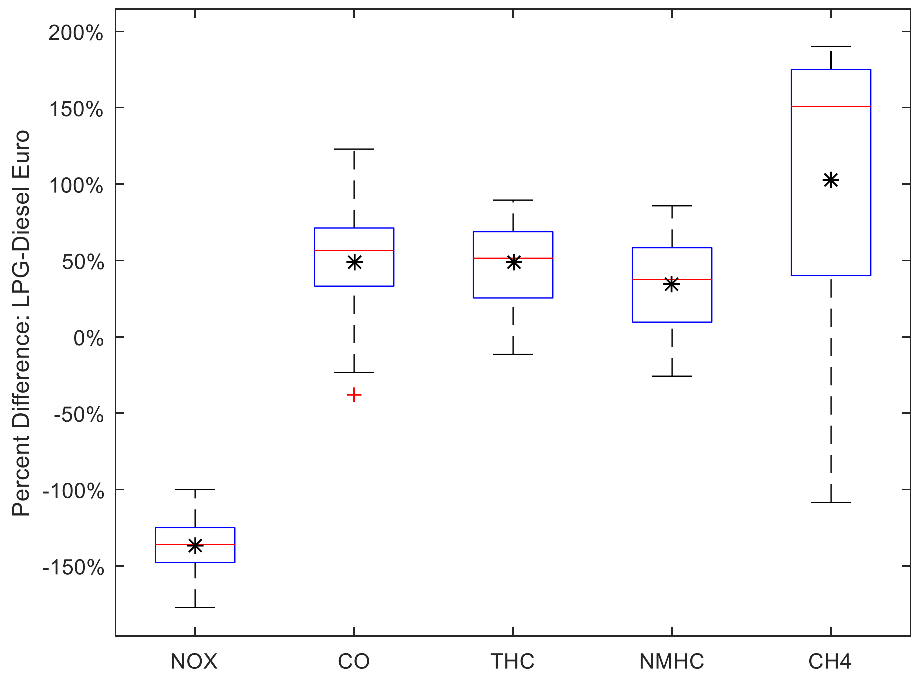

Figure 5: Regulated Emissions for Diesel from the KBA/EU Source

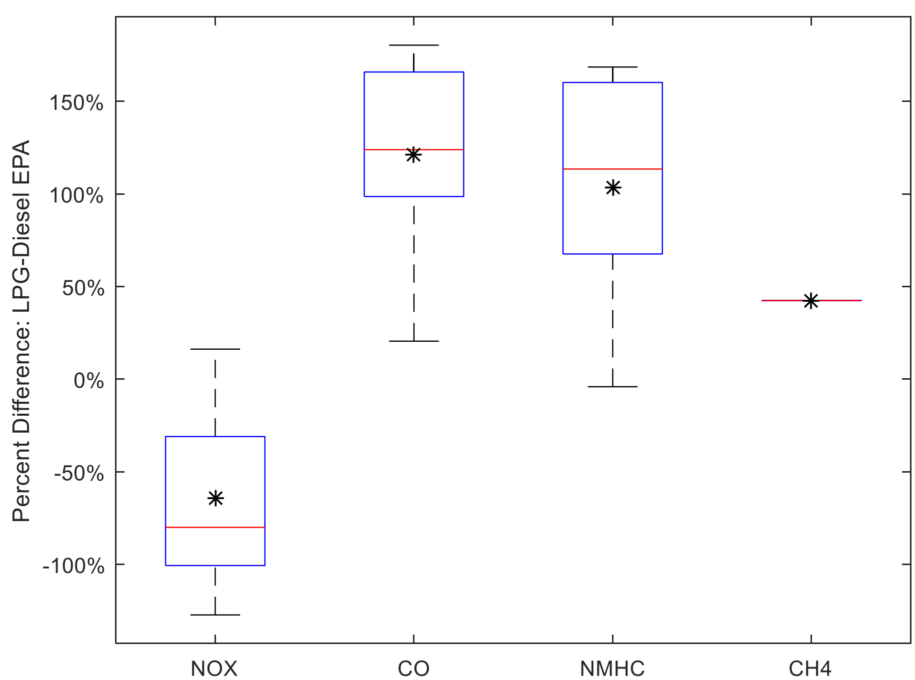

Figure 6: Regulated Emissions for Diesel from the EPA Source

Comparing Figure 5 to Figure 6 reveals that the average, as well as the range of the percent difference, of NO_X emissions from LPG versus diesel powered vehicles and engines is less for EPA certified vehicles versus EU certified vehicles. In other words, NO_X emissions for the EPA certified diesel vehicles and engines are closer to their LPG counterparts than that of the EU certified vehicles. However, the data from both sources demonstrate that even with complex aftertreatment systems such as SCR, NO_X emissions from LPG powered vehicles are notably lower on average than diesel powered vehicles. With regards to the other comparable emissions constituents in Figure 5 and Figure 6, it is observed that EPA certified LPG powered vehicles produce a higher differential of CO and NMHC when compared to diesel vehicles than their EU certified counterparts. This is potentially explained by the fact that the EPA certified diesel vehicles were all equipped DOCs, which are very effective at mitigating CO and NMHC, while not all of the EU vehicles were.

5.4. CNG

Similar to LPG, CNG has a relatively high H:C ratio (approximately 4:1) compared to gasoline due to its high content of CH_4. Although this high content of CH_4 can be beneficial for PM reduction, CH_4 has a high GWP and requires relatively high temperatures to oxidize with an oxidation catalyst. This phenomenon can be observed in Figure 7. The average percent difference for THC emissions (-7 percent) indicates that the use of LPG produces slightly less THC emissions than CNG, however the NMHC emissions (97 percent) are substantially greater for LPG and the CH_4 emissions (-113 percent) are substantially less for LPG. This is directly related to the majority content of CH_4 in CNG. Thus, while THC emissions are similar for CNG and LPG, the use of CNG releases substantially more CH_4 with a significant GWP, in contrast to predominantly propane or butane for LPG with little to no GWP.

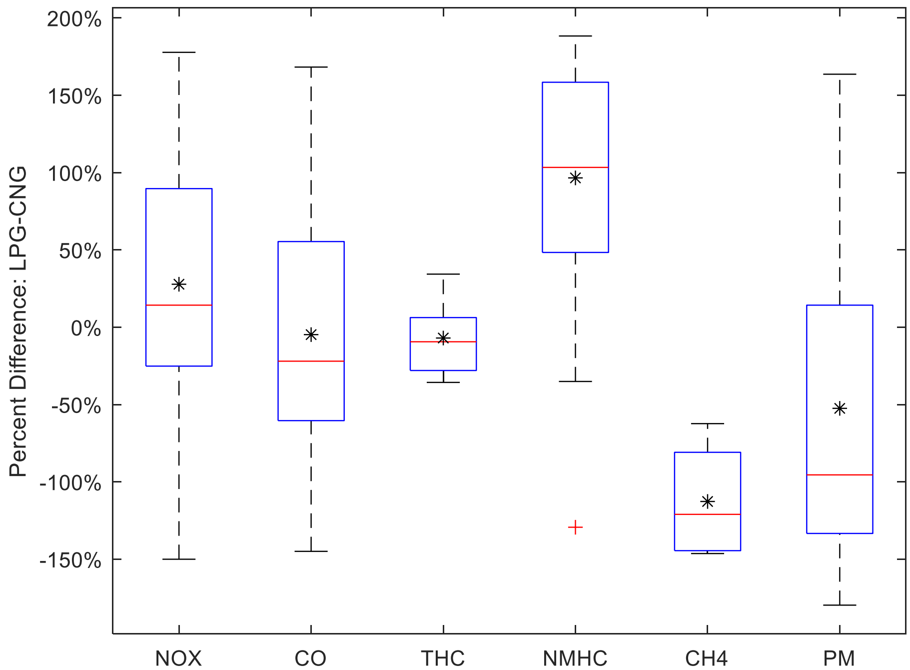

Figure 7: Regulated Emissions Data from CNG

The average percent difference for NO_X emissions (28 percent) suggests that the use of LPG produces greater NO_X emissions than CNG. However, Figure 7 demonstrates that there is a wide range of percent differences for not only NO_X emissions but also CO emissions. This suggests that while the average percent difference was higher for NO_X and lower for CO emissions (-5 percent) for LPG versus CNG, vehicles powered by LPG can produce similar NO_X and CO emissions. A similar conclusion can be made for PM emissions, especially given the small sample size that was available for PM.

6. Greenhouse Gas Emissions

In many regions of the world regulations exist limiting the GHG emissions of engines and vehicles. These GHGs typically include CO_2, CH_4, and nitrous oxide (N_2O). For analysis, GHGs are typically examined on a WTT, TTW, and WTW basis. Additionally, results are commonly presented on a CO_2 equivalent basis (CO_2e) that includes CH_4 and N_2O with their respective GWPs.

6.1. Well-to-Tank

Four of the studies reviewed contained citable information regarding the upstream or WTT GHG emissions of LPG compared to other fuels. Two of the studies, [31, 32], utilized the GREET model to estimate upstream GHG emissions factors for multiple fuels. The results from the first study used the GREET model version 1.8c and are displayed by Figure 8 [31]. The authors noted that the default values for the input parameters of the model were used with the exception of uncompressed natural gas. Uncompressed natural gas was modeled by setting the compression efficiency to 100 percent essentially removing emissions from compression. However, as it pertains to transportation uncompressed or un-liquefied natural gas is not feasible as a fuel due to its very low energy density. It should also be noted that the feedstock ratio of LPG was a required input to the model and the default values of 60 percent from natural gas processing and 40 percent from crude refining were used. With the exception of E85, the authors demonstrated that propane (i.e. LPG) produced the lowest WTT GHG emissions of all transportation fuels on a CO_2e basis. As discussed in section 4.4 the WTT CO_2 emissions of E85 are offset by photosynthesis from the growth of crops used to produce ethanol. On the other hand, the N_2O WTT emissions are significantly more than any other fuel.

	CO_2	CH_4	N_2O	Total CO_2 equivalent
Propane	9,195	115	0.16	12,124
Natural Gas*	5,480	239	0.09	11,471
Compressed Natural Gas (CNG)	11,468	247	0.17	17,684
Electricity	213,067	287	2.81	221,083
Gasoline	16,812	109	1.14	19,871
Diesel	15,488	105	0.25	18,175
E85	-10,464	109	30.64	1,385

Figure 8: Upstream Emissions Factors (grams per million BTU) Note: LPG is labeled as Propane [31]

A similar study was conducted several years later utilizing a newer version of the GREET model (2013) [32]. Again, default values were used for the calculation of WTT GHG emissions with the exception of the compression efficiency of un-compressed natural gas was set to 100 percent. The feedstock ratio of LPG was also adjusted to 70 percent from natural gas processing and 30 percent from crude oil refining to reflect the most recent market share data available. Although the absolute figures for WTT CO_2e generally increased for all fuels examined, the same trend held true, among the fuels that can be used for transportation, LPG produced the lowest WTT CO_2e emissions with the exception of E85.

	CO_2	CH_4	N_2O	TOTAL CO_2 EQUIVALENT
ETHANOL (E85)	-14,409	113	41.0	-387
NATURAL GAS	6,995	317	1.34	16,228
PROPANE	12,867	188	0.26	18,204
GASOLINE	16,010	118	3.95	20,368
COMPRESSED NATURAL GAS	10,985	324	1.40	20,429
DIESEL	18,727	118	0.31	22,104
FUEL OIL	18,727	118	0.31	22,104
ELECTRICITY	182,897	317	2.84	192,523

Figure 9:Upstream Emissions Factors (Grams per million BTU) Note: LPG is labeled as Propane [32]

A study commissioned by the European Commission Joint Research Centre utilized a software program provided by Ludwig-Bölkow-Systemtechnik GmbH to calculate the WTT GHG emissions factors for variety of fuels and numerous production pathways [33]. The author's made a direct comparison of WTT CO_2e emissions of conventional gasoline and LPG from a remote gas field imported to Europe displayed by Figure 10. In that context, LPG demonstrated significant reductions in WTT CO_2e emissions compared to conventional gasoline.

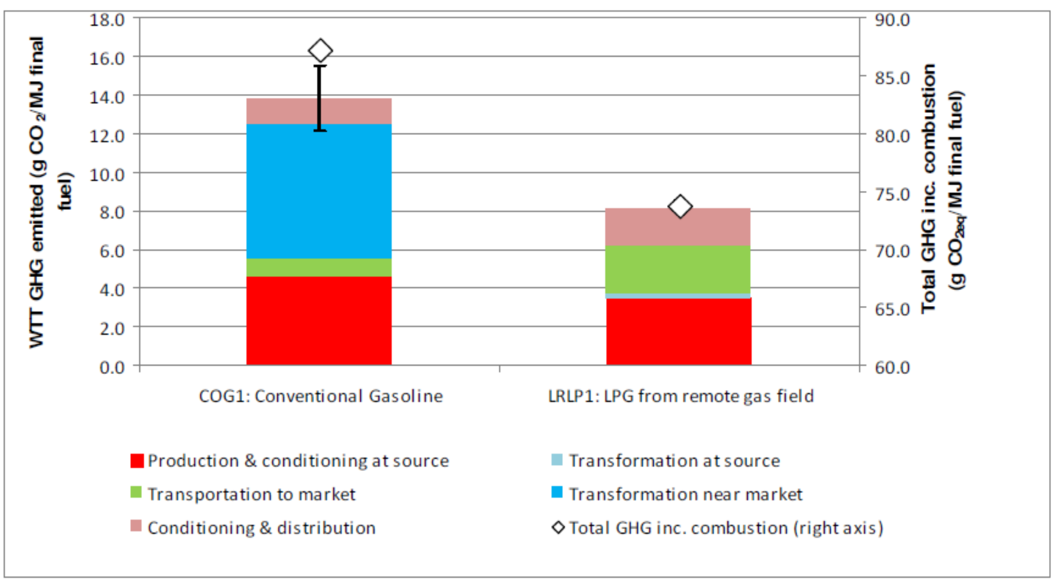

Figure 10: WTT GHG Balance of LPG Pathway [33]

Another study commissioned by the European Commission, evaluated regulations 443/2009 and 510/2011 on CO_2 emissions from light-duty vehicle [34]. The authors extracted information from the previously mentioned report [33] to provide a comparison among gasoline, diesel, CNG (listed as natural gas) produced within the EU, and LPG imported to the EU displayed by Figure 11. These results agree with others presented, LPG produces less WTT CO_2e emissions than the other fuels considered.

Fuel	Well-to-tank emission factor (gCO_2e/MJ)
Petrol	13.8
Diesel	15.4
Natural gas	13.0
LPG	8.0

Figure 11: WTT Emission Factors [34]

There are many variables in the feedstock, production methods, and transportation of a fuel that can influence its upstream GHG emissions. Furthermore, quantifying these emissions is not a trivial task and thus computer generated models are used to characterize them. These models generally rely on a combination of real world data, assumptions, and theory to provide estimates for a variety of situations. Regardless, LPG exhibits among the lowest upstream GHG emissions of all the fuels used for transportation.

6.2. Tank-to-Wheels

Empirical data on the TTW or tailpipe CO_2 emissions was collected from sources that were surveyed for regulated pollutants which are listed in Table 2 and were discussed in section 5. Figure 12 displays the percent difference of measured tailpipe CO_2 emissions for LPG compared to various fuels.

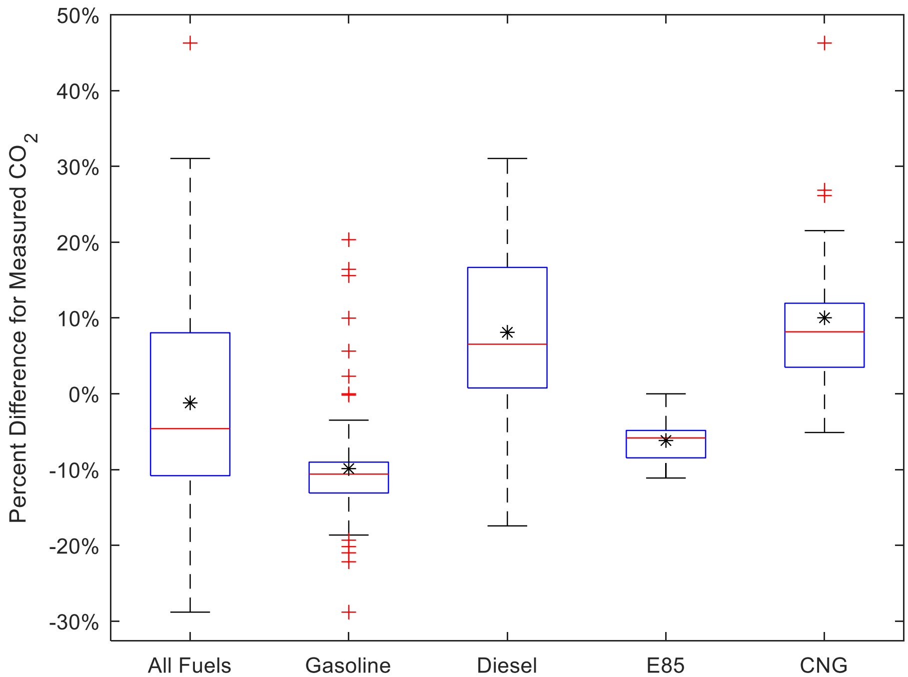

Figure 12: TTW Percent Difference of CO_2 Emissions for LPG Versus Other Fuels from Empiracle Data

Considering all the fuels surveyed, LPG produces slightly less tailpipe CO_2 emissions on average. Compared to gasoline, LPG produces lower on average CO_2 emissions. This is expected given that both fuels use spark ignition and LPG has a higher H:C ratio compared to gasoline. The range of the box and whisker plot and standard deviation provide further confidence in this assessment, noting that only data points deemed outliers (marked by crosses) demonstrated higher CO_2 for LPG compared to gasoline. E85 shares a similar percent difference trend. Diesel on the other hand displays a bias towards lower CO_2 emissions compared to gasoline. Although diesel has a similar H:C ratio as gasoline, CI engines are inherently more fuel efficient which equates to lower CO_2 production. As noted previously CNG and LPG fueling systems share many similarities and both require spark ignition, but the H:C ratio of CNG is higher than that of LPG providing it with an additional reduction in CO_2 emissions. However, it is important to reference Figure 7, where CH_4 tailpipe emissions for CNG are displayed to be significantly higher than LPG noting that CH_4 is a potent GHG.

6.3. Well-to-Wheels

Information regarding WTW emissions has been predominantly sourced from studies that utilized GHG WTW modeling tools such as GREET. As noted previously, these tools use models, assumptions and empirical data to provide GHG life cycle analysis for various energy sources and technologies. WTW studies originating from North America that were surveyed present data only on select on-road vehicle segments, including light-duty trucks and vans, school buses, and bob-tail LPG delivery vehicles [31, 32, 35]. The fuels encompassed by these comparisons to LPG include gasoline, diesel, E85, and CNG. The engines considered for LPG, gasoline, E85, and CNG were all SI V8 or V10 engines, while the diesel comparisons included V8 and inline 6 CI engines. For all the vehicles and fuels surveyed gasoline powered vehicles exhibited the highest WTW GHG emissions in mass of CO_2e per distance with one exception; a model year 2008 Ford F-250 Harley Davidson model with the 6.4L Power Stroke diesel engine presented in "Propane Reduces Greenhouse Gas Emissions: A Comparative Analysis [31]. However, in that study another diesel powered Ford F-250 diesel was presented, presumably a less equipped model than the top of the line Harley Davidson model, that retained lower GHG emissions than the gasoline model presented. The data from all the vehicles considered in these studies is presented in Figure 13 based on groupings of the fuel utilized.

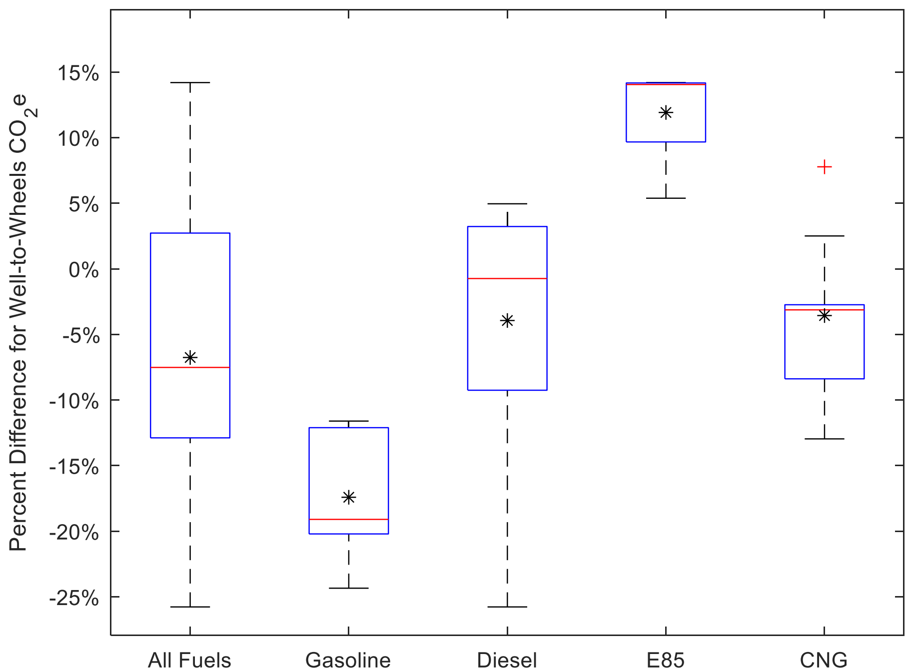

Figure 13: WTW Percent Difference of GHG CO_2e Emissions for LPG Versus Other Fuels

The WTW CO_2e emissions percent difference of LPG compared to all the other fuels considered in Figure 13 demonstrates that LPG is amongst the lower GHG producing fuels. As mentioned previously LPG unanimously produces less CO_2e emissions than gasoline over its life cycle from production to end use. In fact, E85 is the only fuel presented that resulted in an average CO_2e emissions that was less than LPG. This is directly related to the growth of crops and photosynthesis during the production of ethanol as noted previously. Although it is outside of the context of this study, there are current technologies that produce BioLPG as byproduct such as the process to hydrogenated vegetable oil diesel fuel from renewable feedstocks. As these technologies progress and more data is available, it is almost certain that the WTW footprint of BioLPG would certainly be on the order of E85.

Referring back to TTW CO_2 emissions in Figure 12, diesel and CNG both produce on average lower tailpipe CO_2 emissions, however on a well-to-wheel basis the average CO_2e is slightly lower for LPG with a range of data that favors lower CO_2e emissions for LPG. For diesel, this is a result of the energy and thus CO_2 emissions for refining crude oil. For CNG this is a result of the GWP of CH_4 and the associated emissions of CH_4 from natural gas production, processing, transportation, and end-use. Furthermore, as discussed in section 6.1, the compression of natural gas (CNG) to provide enough energy density for transportation use incurs additional energy and subsequent CO_2 penalties.

In a strictly EU context, the following values in Table 3 for life cycle CO_2e emissions are recognized as the default by the EU [36]. The percent differences shown in Table 3 further demonstrate that on an energy specific life cycle basis LPG produces among the lowest CO_2e emissions, close to CNG that is a mixture of domestic and imported natural gas. Note that all LPG is assumed to be imported, thus increasing its life cycle GHG intensity due to transportation.

Table 3: Average Life Cycle (WTW) GHG Intensity for various Transportation Fuels in the EU [36]

Fuel	Life Cycle GHG Intensity (gCO_2e/MJ)	Percent Difference from LPG
Gasoline - Conventional Crude	93.2	-24%
Diesel - Conventional Crude	95	-25%
LPG -All Fossil Sources	73.6	-
CNG - EU Mix	69.3	6%
LNG - EU Mix	74.5	-1%

The values represented in Table 3 were sourced from a previously cited study commissioned by the European Commission Joint Research Centre [33]. This study also provided WTW CO_2e emissions, although on a distance basis, for 2010 era vehicles which are displayed in Table 4.

Table 4: Average WTW CO_2e Emissions for Various Transportation Fuels and Applications in the EU [33]

Fuel	Application	Average WTW (g CO_2e/km)	Percent Difference from LPG for Same Application
Gasoline - Conventional Crude	2010 PISI	185	-14%
	2010 DISI	178	-14%
Diesel - Conventional Crude	2010 DICI	145	6%
LPG - Imported	2010 PISI	160	-
	2010 DISI	154	-
CNG - EU Mix	2010 PISI	163	-2%
	2010 DISI	148	4%

On a distance specific basis, CO_2e emissions from LPG vehicles were unanimously lower than gasoline vehicles, slightly higher than diesel vehicles, and similar to CNG vehicles.

7. Additional Considerations

In addition to the various facets of emissions from LPG powered vehicles versus other fuels, there are additional considerations including fuel economy, the application of LPG to new and emerging technologies, and the reliability and maintenance of LPG powered vehicles and engines. While data was limited on some of the aspects, results and intuitive information is presented in the subsequent sections.

7.1. Fuel Efficiency

When LPG is injected into the intake of an engine its gaseous state at near ambient pressure conditions occupies more volume than liquid fuels. This equates to a lower volumetric efficiency for a LPG PFI engine. Furthermore, the energy content on a volumetric basis of LPG is significantly lower than gasoline and diesel, while on a mass basis it is superior to gasoline and diesel as indicated by Table 1. Many comparisons of gasoline to LPG utilize a metric of distance per volume of fuel which favors gasoline over LPG and thus many studies surveyed that used this metric as well as PFI engines concluded that gasoline provided less liters of fuel consumed per distance than LPG. However, using a fuel consumption metric such as brake thermal efficiency (BTE) which normalizes the work output by the engine to the fuel energy input to the engine and considering modern DI technology, LPG fuel efficiency can surpass that of gasoline which is discussed further in section 7.2.

7.2. Direct Injection Technology

As noted previously the market share of GDI (i.e. SI direct-injection gasoline engines) has steadily increased in the past several years. GDI engines are capable of higher power density and improved fuel consumption when compared to PFI engines, however, they have been linked to increased PM and PN emissions. The majority of the studies and data comparing LPG to gasoline focused on PFI engines. There were, however, several studies that compared gasoline and LPG in SI DI engines. A review performed by Atlantic Consulting titled "Direct Injection LPG - Opportunity and Threat in Europe" examined several of these studies [18].

From the available results of Atlantic Consulting's survey, DI with LPG unanimously produced less CO_2, PM, PN, and CO emissions compared to GDI. These results are intuitive based on the lower H:C ratio of LPG benefitting CO_2, CO, and PM/PN as well as the superior vaporization properties of LPG benefiting PM/PN and CO on the basis of a more homogeneous air and fuel mixture. Results for NO_X and HC emissions were more difficult to evaluate noting that there was limited data (only provided for 3 studies) for NOX and HC emissions. Furthermore, the data that was available ranged from reductions to increases in NOX and HC emissions from DI LPG versus GDI.

A study by Park et al. titled "Emission Characteristics of Gasoline and LPG in a Spray-Guided-Type Direct Injection Engine" provided laboratory based research results [26]. Results from that study for LPG DI versus GDI for a single cylinder research engine at each fuels best operating point are presented in Figure 14.

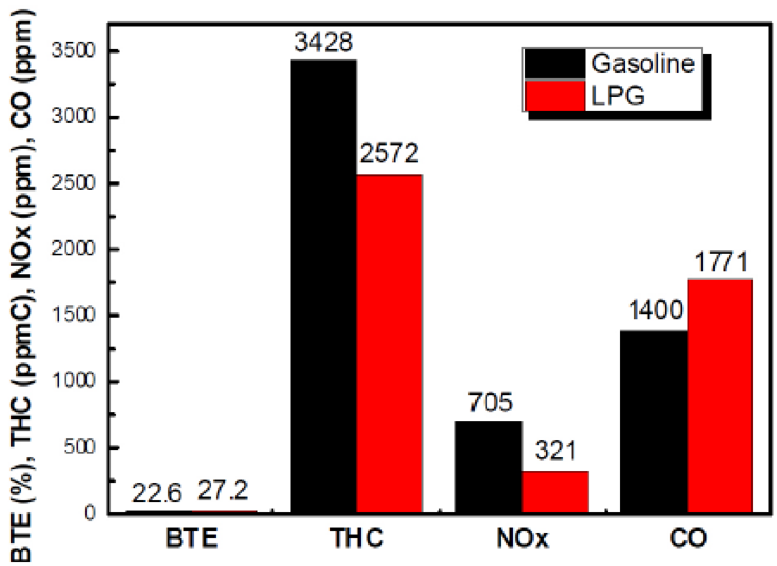

Figure 14: Comparison of performance and emission results for GDI and LPG DI at Lean Conditions [26]

Figure 14 displays lower THC and NO_X emissions, while the CO emissions are higher for LPG DI operation. However, it is important to note that these were engine out emissions while the much of the other emissions data analyzed for this composition were measured measured downstream of a TWC. As previously mentioned efficient TWC operation relies on tightly controlling the A:F ratio of the engine to balance CO and THC mitigation versus NO_X reduction.

Another study by Walls et al. titled “Impact of the Direct Injection of Liquid Propane on the Efficiency of a Light-Duty, Spark-Ignited Engine” examined 11 different speed and load operating points for LPG DI versus GDI on a 3.5 L Ford EcoBoost® engine [37]. The authors reported that engine out emissions of CO and HC were lower for the majority of modes tested while NO_X emissions were higher for the majority of modes tested for LPG DI operation versus GDI operation. Again, this doesn’t include emissions measurements downstream of a TWC which would be an integral part of examining a modern vehicle’s emissions. PM emissions from that study also agreed with the review performed by Atlantic Consulting. In essence, PM emissions from LPG DI operation were negligible compared to GDI operation. The ability of LPG to produce such low PM emissions in DI engines could eliminate the need for particulate filters which are poised to become commonplace on GDI engines due to increasing scrutiny from regulators. Furthermore, LPG DI has exhibited the ability to provide increased BTE compared to GDI as demonstrated in Figure 14 and Figure 15.

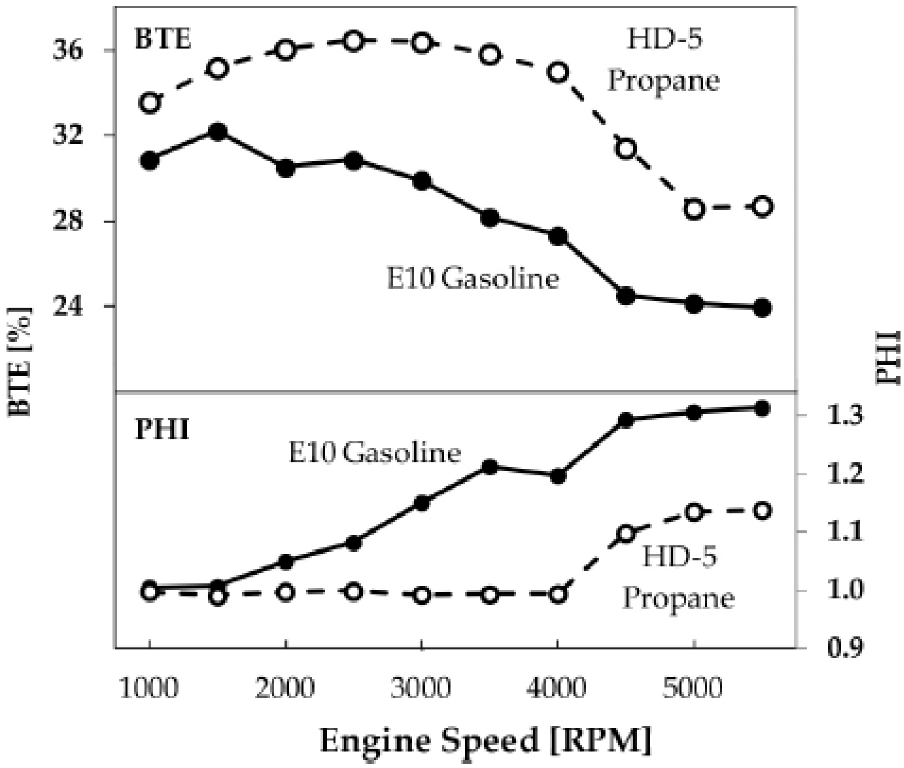

Figure 15: Full Load BTE and Equivalence Ratio for DI LPG versus GDI [37]

The improvement at full load for LPG DI operation versus GDI operation presented in Figure 15 was attributed to the need for less enrichment to keep turbine inlet temperatures down. Contrary to LPG PFI, LPG DI operation doesn't reduce volumetric efficiency of the engine, essentially allowing LPG to provide similar if not better fuel consumption compared GDI operation.

Emissions certification results from 3 vehicles equipped with a Prins LiquiMax DI LPG system installed on OEM GDI platforms were also examined [38]. The three vehicles were a Kia Ceed 1.6 L, Mercedes E-Class 2.0 L, and a Mazda CX-5 2.5 L all pursuant to Euro 6a emissions regulations. All vehicles resulted in over 90 percent reduction of PN emissions while achieving similar CO, HC and NO_X emissions compared to GDI operation that was well below the Euro 6a standards.

7.3. Reliability and maintenance

From the literature surveyed limited information was available regarding the reliability and maintenance intervals or costs for LPG powered vehicles. However, certain conclusions can be formed through intuition. Current regulatory standards for diesel engines and vehicles have forced the vast majority of new diesel trucks and many diesel passenger vehicles to be equipped with costly and complex exhaust aftertreatment systems consisting of a DOC, DPF, and SCR system. The SCR requires a urea based reductant, commonly referred to as DEF to also be carried on board the vehicle and periodically refilled. In addition to these exhaust aftertreatment technologies, the vast majority of modern diesel engines are also equipped with EGR to aid in the control of NO_X emissions.

Compare this diesel aftertreatment technology to TWCs, which are the only aftertreatment technology required for modern SI engines. TWCs are a proven and well established technology that are very effective at simultaneously reducing NO_X, HC, and CO emissions. Furthermore, the control of many SI engines with respect to the A:F ratio and TWC operation has progressed to the level that EGR is not needed. The lack of a complex exhaust aftertreatment systems and in some cases EGR for LPG powered engines and vehicles results in a much simpler and less failure prone propulsion system when compared to modern diesel powered vehicles equipped with DOC, DPF, and SCR aftertreatment technology.

8. Conclusions

The results presented in this document highlight the benefits of LPG compared to conventional and other alternative transportation fuels. The emissions benefits of LPG advocate for its utilization and its advantageous application to modern technologies such as DI further that case. Compared to gasoline powered vehicles, LPG has demonstrated an ability to produce similar NO_X, CO, and THC emissions with lower levels of PM, PN, and CO_2 emissions. With respect to GHGs, the utilization of LPG compared to gasoline produces significantly lower CO_2e emissions on a WTW basis. Evidence also suggests that the application of LPG to modern DI technology can improve the shortcomings of GDI such as increased PM and PN while delivering improved BTE.

Comparisons of LPG made to diesel powered vehicles demonstrated the capability to produce lower NO_X and PM emissions even when costlier and much more complex aftertreatment systems were applied to diesel vehicles. Although the utilization of diesel provided a lower TTW GHG footprint, on a WTW basis the use of LPG releases similar or less GHG emissions on average than diesel depending on the literature source. Compared to other alternative fuels, the argument for LPG is strong. On average tailpipe emissions of NO_X from CNG powered vehicles were lower while THC and CO emissions were higher compared LPG powered vehicles. Emissions of CH_4, a powerful GHG and primary components of CNG, were significantly higher for CNG compared to LPG powered engines and vehicles. The negative effect of CH_4 emissions for CNG was also observed on a WTW GHG emissions basis, where it has been demonstrated that the use of LPG offers very similar or even lower GHG emissions on a CO_2e basis compared to CNG depending on the literature source. Additionally, the properties of LPG versus CNG allow for significantly less costly storage tanks. Compared to E85, the average emissions from LPG powered vehicles and engines were displayed to be higher in NO_X emissions, lower in HC emissions, and similar in CO emissions. However, when comparing ethanol and LPG it is important to consider all aspects on production, noting that LPG does not share a food source for feedstock as ethanol commonly does, as well as significant requirements of land to grow the crops required to produce ethanol. Furthermore, recent BioLPG opportunities, such as those from renewable diesel fuel, may provide a WTW GHG footprint similar to ethanol blends.

Considering not only the tailpipe emissions of LPG, but also the WTW GHG emissions, the argument for LPG as a transportation fuel is strong. LPG offers a viable pathway to reduce regulated and GHG emissions compared to conventional fuels, while offering a less costly option and lower environmental impact compared to other popular alternative fuels.

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