**ABSTRACT**

SINGH, SANJAM. Comparison of Fuel Economy and Gaseous Emissions of Gas-Direct Injection versus Port-Fuel Injection Light Duty Vehicles Based on Real-World Measurements. (Under the direction of Dr. H. Christopher Frey.)

Increasingly stringent U.S. fuel economy standards have led to the introduction of fuel saving light duty vehicle technologies. One such technology, gas-direct injection (GDI), has grown to 48.5% of the U.S. market since it was introduced in 2007. GDI engines typically run at a higher compression ratio than conventional port fuel injection (PFI) engines. Estimates are that vehicles with GDI engines are up to 30% more fuel efficient than comparable vehicles with PFI engines. Because of differences in fuel delivery and combustion dynamics, the particulate matter and gaseous emission characteristics of GDI engines are expected to differ from those of PFI engines. GDI engines are known to emit higher rates of ultrafine particles. However, there is comparatively little data regarding differences in real-world gaseous emissions from GDI versus PFI equipped vehicles. The objective of this work is to compare the fuel economy and gaseous emission rates of GDI and PFI vehicles. Comparisons are based on three sources of data: literature review, real-world measurements of GDI vehicles using a portable emission measurement system (PEMS), and fuel economy and emissions certification data from the U.S. Environmental Protection Agency (EPA). Field measurements with PEMS were conducted for selected GDI and PFI vehicles, each measured over 110 miles of predetermined routes. Based on PEMS data, vehicle specific power (VSP) modal and cycle average emission rates for $CO_2$, CO, NO, hydrocarbons (HC), and particulate matter (PM) were quantified. GDI and PFI vehicles were compared based on body type, engine displacement, horsepower, vehicle age, curb weight, transmission type, engine aspiration and applicable emission standard. Measurements were made for 27 GDI vehicles and 32 PFI vehicles. Each vehicle was compared either to a single similar vehicle or, in some cases, to the

average of two or more vehicles, when a single suitable match was not available. The latter are referred to as “composite” vehicles. Results include one-on-one comparisons of fifteen GDI versus PFI vehicles, nine GDI vehicles versus the composite of two or more PFI vehicles, and one “composite GDI” vehicle consisting of three GDI vehicles compared to a “composite PFI” vehicle. On average, based on PEMS data, GDI vehicles had 8% better fuel economy, 33% lower CO emission rates and 44% lower HC emission rates. These differences are statistically significant. The $NO_x$ emission rates are similar between GDI and PFI vehicles. The GDI fuel economy advantage was less pronounced for driving cycles with high average power demand, which means that the advantage of GDI vehicles is higher in city driving conditions. EPA chassis dynamometer test data are consistent with the differences found between the engine technologies based on PEMS data. For example, the chassis dynamometer data also indicate marginally higher fuel efficiency, lower CO and HC, and similar $NO_x$ cycle average emission rates for GDI versus PFI vehicles. However, except for HC emission rates, these differences are not statistically significant. The PEMS and chassis dynamometer results imply that the real-world fuel economy advantage of GDI vehicles may not be as great as originally anticipated. Furthermore, there is a trade-off with higher ultrafine particulate matter emission rates from prior findings, versus lower CO and HC emission rates found here.

Comparison of Fuel Economy and Gaseous Emissions of Gas-Direct Injection versus Port-Fuel Injection Light Duty Vehicles Based on Real-World Measurements

by
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## DEDICATION

To my ma, dad, sister, Bean, and Senna.

## BIOGRAPHY

Sanjam Singh was born in 1990 in New Delhi, India. He received his Bachelor of Engineering in Environmental Engineering from Delhi College of Engineering, University of Delhi in 2012. He joined Department of Civil, Construction, and Environmental Engineering at North Carolina State University in August 2015 to pursue a Master of Science degree. This thesis completes the requirements for that degree. His research focuses on the estimation and measurement of energy use and emissions from light duty gasoline vehicles.

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## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# CHAPTER 1

## INTRODUCTION

This chapter provides details of the two most commonly used contemporary fuel injection systems in light duty gasoline vehicles (LDGVs). This chapter includes discussions on the current market share, technical description and operation of the two types of fuel injection systems. Comparison of fuel economy and emission rates of engines using these fuel injection systems based on existing literature is discussed. Applicable fleet-wide fuel economy and emission standards on LDGVs is also discussed. Further, the need for this study and objectives of the study are discussed.

### 1.1 Background

Emissions from transportation, including emissions from passenger cars, light-duty trucks, medium- and heavy- duty trucks, commercial aircraft, rail, other aircraft, pipelines, and ships and boats, accounted for 36.1% of U.S. carbon dioxide ($CO_2$) emissions from fossil fuel combustion, and 28.5% of total U.S. greenhouse gas emissions in 2016. Light-duty vehicles (LDV), including passenger cars and light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans, accounted for 59.2% of $CO_2$ emissions from transportation activities in the U.S., which is equal to 1065 million metric tons $CO_2$ equivalent. $CO_2$ emissions from transportation have increased from 1990 to 2016 by 22% due to increased demand for travel (US EPA, 2018a).

The Corporate Average Fuel Economy (CAFE) and National Program for Greenhouse Gas (GHG) regulations, developed jointly by the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA), aim at reducing LDV GHG emissions. The CAFE and GHG standards have been phased. Phase I applied to light duty cars and trucks for model year (MY) 2012 to MY 2016. Phase II applies to MY 2017 to MY 2025. These standards were projected to result in an average industry fleet-wide $CO_2$ emission rate of 163 grams/mile in MY 2025, which is equivalent to an unadjusted fuel economy 54.5 miles per gallon (mpg), if achieved exclusively through fuel economy improvements. However, the current U.S. administration has rolled back these standards, and the previously specified targets may not be achieved (US EPA, 2018c).

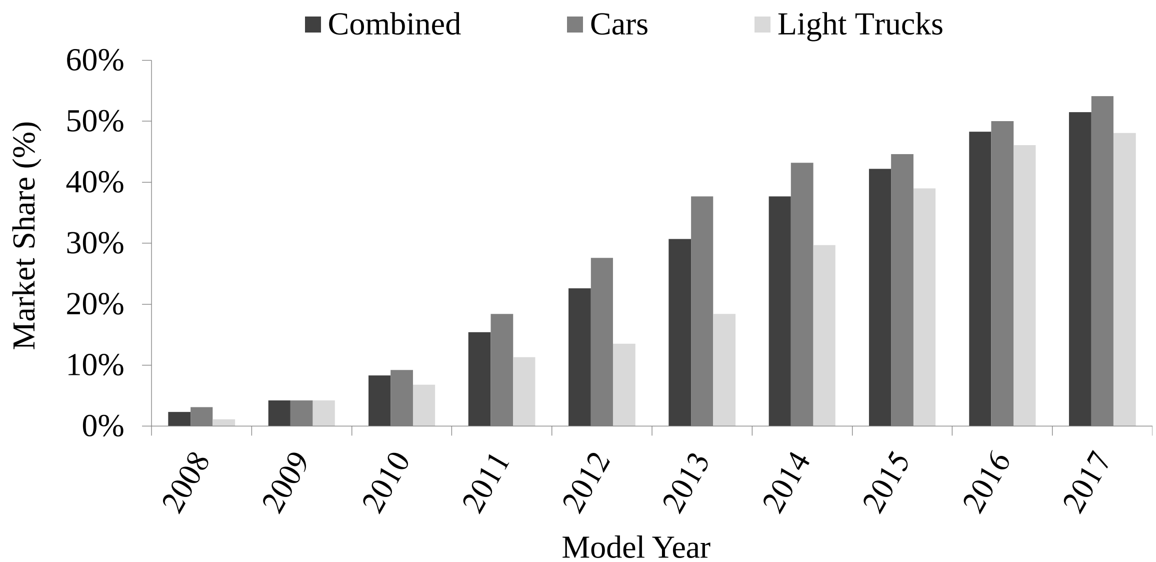
U.S. EPA annually publishes the trends in real-world tailpipe $CO_2$ emissions and fuel economy, and associated automotive technologies. In the latest report published by U.S. EPA, data for up to MY 2016 are final. Data for MY 2017 are preliminary and based on projected production data provided to the EPA by automakers for vehicle certification and labeling prior to MY 2017 sales. MY 2017 data will be finalized in 2019. The adjusted average fuel economy of the vehicle fleet in MY 2016, calculated as per U.S. EPA methodology, was 24.7 mpg, an increase of 0.1 mpg from MY 2015 (US EPA, 2018b). The preliminary data released by US EPA for MY 2017 estimates the fleetwide adjusted average fuel economy to be 25.2 mpg. Adjusted fuel economy values are about 20% lower than unadjusted fuel economy values, which implies that MY 2016 vehicle fleet unadjusted average fuel economy was approximately

29.6 mpg, 46% lower than the projected MY 2025 vehicle fleet unadjusted average fuel economy.

Increasingly aggressive CAFE standards have motivated the automotive industry to introduce new technologies to improve fuel efficiency. In recent years, Gas Direct Injection (GDI), which is an alternative to conventional Port-Fuel Injection (PFI), has had a significant increase in U.S. market share. Auto manufacturers have been adopting GDI engines because they provide higher fuel efficiency, increased specific power, and engine downsizing, especially when coupled with turbocharging (American Petroleum Institute 2013; National Research Council 2015). Engines using GDI were first introduced into the U.S. market with very limited production in MY 2007. In MY 2008, GDI engines were installed in less than 3% vehicles (Figure 1a). The U.S. market share for GDI in 2016 was 48.3%, including 50.0% for cars and 46.1% for light trucks (US EPA, 2018b). The US EPA projects GDI engines to be installed in 52% of new vehicles in MY 2017, including 54% for cars and 48% for light trucks (US EPA, 2018b). Compared to other fuel-efficient technologies such as engine stop-start, cylinder deactivation, gasoline hybrid, and turbocharging, GDI has gained a significantly higher market share (US EPA, 2018b).

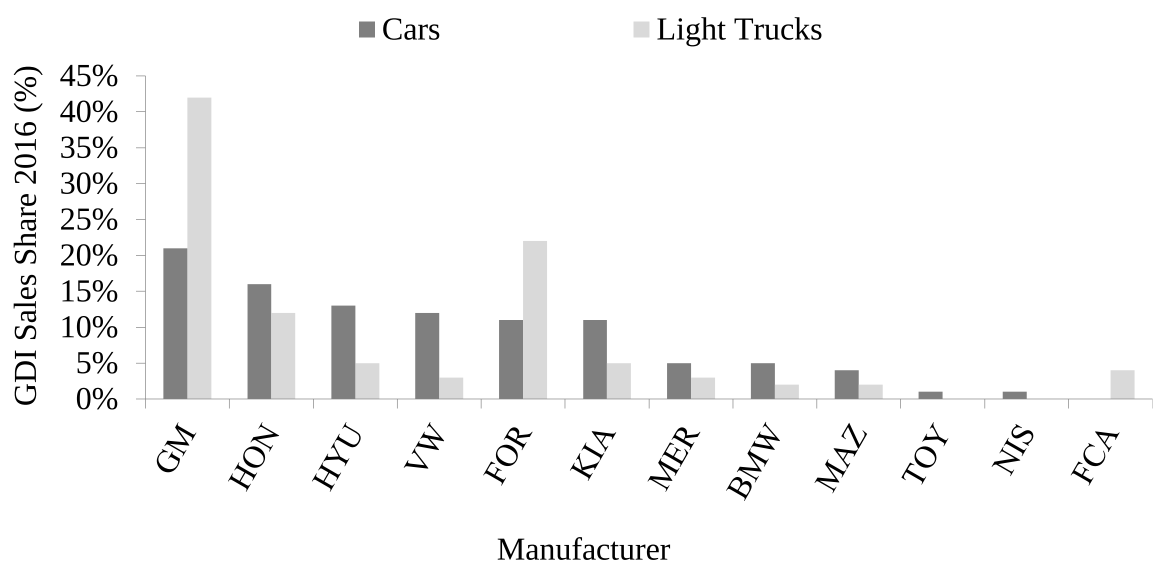
**Figure 1. GDI Market Share for Light-Duty Passenger Cars and Trucks in the U.S. (a) GDI Market Share by Vehicle Type, MY 2008-2017 (US EPA, 2018b); (b) GDI Manufacturers share of MY 2016 Total GDI Sales by Vehicle Type (ORNL, 2017); (c) GDI Vehicles Production Share for Manufacturers in MY 2017 (US EPA, 2018b)**

Light trucks include pickups, sport utility vehicles, and minivans. Manufacturers: GM = General Motors, HON = Honda, HYU = Hyundai, VW = Volkswagen, FOR = Ford, MER = Mercedes, MAZ = Mazda, TOY = Toyota, NIS = Nissan, FCA = Fiat Chrysler Automobiles.



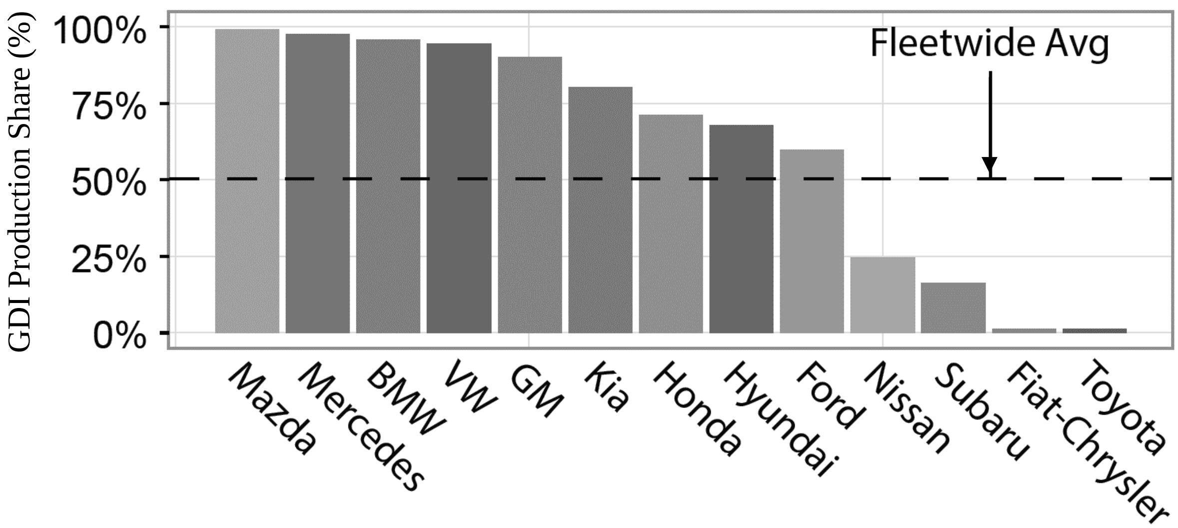
Combined
Cars
Light Trucks
60%
50%
40%
30%
20%
10%
0%
Market Share (%)
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Model Year


**(a)**



Cars
Light Trucks
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
GDI Sales Share 2016 (%)
GM
HON
HYU
VW
FOR
KIA
MER
BMW
MAZ
TOY
NIS
FCA
Manufacturer


**(b)**


GDI Production Share (%)
100%
75%
50%
25%
0%
Fleetwide Avg
Mazda
Mercedes
BMW
VW
GM
Kia
Honda
Hyundai
Ford
Nissan
Subaru
Fiat-Chrysler
Toyota

**(c)**

Automobile manufacturers offering vehicles with GDI engines include General Motors (GM), Honda, Hyundai, Volkswagen (VW), Ford, Kia, and others (Figure 1b). Figure 1(c) illustrates the percentage of GDI vehicles in MY 2017 new vehicle fleets of individual manufacturers. GDI vehicles comprise more than 50% of MY 2017 total vehicle fleet production for Mazda, Mercedes, BMW, VW, GM, Kia, Honda, Hyundai, and Ford.

## 1.2 Overview of GDI and PFI Technologies

PFI is a pressurized indirect injection system, in which the injection of fuel takes place in the inlet port, before the air enters in the combustion chamber. The electronic control unit (ECU) commands the amount of fuel per injection event by adjusting the length of time a fixed-orifice in the injector is open. Fuel is injected as a fine spray in the air inlet port, where homogenous mixing of fuel and air takes place. The homogenized combustible mixture, also known as 'charge', moves into the cylinder via the cylinder intake valve. The fuel is injected at a pressure slightly higher than the intake manifold pressure, so that the amount of fuel injected per injection event is determined only by the length of time the orifice in the injector is opened by the ECU. The length of time is known as the 'pulse width' of the injector. The engine fuel requirements change according to engine speed, load and temperature. The ECU tailors the amount of fuel injected based on these factors by modulating the pulse width of the injector, and the frequency of injection events. However, since the injection point is upstream of the intake valve, a liquid fuel film can form on the intake port walls and intake valve in PFI engines. Accumulation of liquid film on the walls alters in an uncontrolled manner the air-fuel ratio of the charge delivered to the cylinders, and causes lags and overshoots in the fuel flow with respect to the airflow delivered (Zhao *et al.*, 1999; Wyszynski *et al.*, 2002; Kašpar *et al.*, 2003; Golzari *et al.*, 2016).

In comparison, GDI is a high-pressure direct injection system. Similar to PFI, the ECU controls the amount of fuel injected per injection event by adjusting the length of time a fixed-orifice in the injector is open. Unlike PFI, the fuel is injected directly into the cylinder at a much higher pressure with the intent of creating heterogeneous variation in the fuel and air mixture, also known as a 'stratified charge'. Stratified charge in GDI can be used to ignite mixtures which are, on average, leaner than PFI, but are richer closer to the spark plug. GDI reduces fuel transport delay, which enables very precise control of injection timing and air-fuel ratio. The amount and timing of fuel injected in GDI can be better tailored to match variation in engine load than in PFI due to in-cylinder injection. Direct injection reduces errors in maintaining proper combustion stoichiometry, which are also known as fuel-metering errors. GDI also eliminates the formation of a liquid fuel film found on intake port walls and intake valves in PFI engines. However, fuel impingement can occur on cylinder walls and piston surface in the GDI. In GDI, the timing of fuel injection event can be varied, and there can be multiple injection events during intake stroke and/or compression stroke within the same combustion cycle. More than one injection pulse enables variation in the level of stratification in the combustion chamber. Injection events during the intake stroke result in homogenous charge and during the compression stroke result in heterogenous charge. Thus, more than one injection events enable staged combustion in GDI. Staged combustion helps prevent knock, which enables an increase in compression ratio for improved engine efficiency (Anderson *et* *al.,* 1996; Zhao *et al.,* 1999; Wyszynski *et al.,* 2002; Oh *et al.,* 2010; Na *et al.,* 2012; Myung *et al.,* 2012; Confer *et al.,* 2013; Su *et al.,* 2014; Golzari *et al.,* 2016).

Directly injected fuel vaporizes utilizing heat within combustion chamber, thereby producing a cooling effect. This results in a higher compression ratio and volumetric efficiency than a PFI engine (Anderson *et al.,* 1996; Wyszynski *et al.,* 2002).

Compression ratio, which is the ratio of the maximum to minimum volume in the cylinder, is limited by the temperature inside the combustion chamber at the end of the compression stroke. If the temperature at the end of the compression stroke is higher than the flash point of the fuel, the charge will auto-ignite, producing a ‘knock’. The cooling effect of the injection spray results in lower temperature at the end of the compression stroke, and allows GDI engines to have higher compression ratio than PFI engines by 1 to 2 ratios (Anderson *et al.,* 1996; Zhao *et al.,* 1999; Wyszynski *et al.,* 2002; Oh *et al.,* 2010; Golzari *et al.,* 2016).

Volumetric efficiency is the ratio of the mass of air and fuel mixture drawn into the cylinder during the intake stroke to the mass that would occupy the displaced volume of the cylinder if the air density in the cylinder were equal to the air density in the air intake manifold. Volumetric efficiency is, thus, a mass ratio and not a volume ratio. When the volume of final mixture decreases, the density of the mixture increases, which results in higher volumetric efficiency (Ferguson and Kirkpatrick, 2015).

The cooling effect of the spray increases volumetric efficiency of GDI engines over PFI engines. In a PFI engine, droplets of liquid fuel sprayed into the intake port wet the intake port wall and intake valve, and evaporate mainly by absorbing thermal energy from these surfaces. In contrast, in a GDI engine, fuel droplets are vaporized mainly by absorbing thermal energy from the air. This results in cooling of the mixture, which in turn leads to a decrease in the volume and increase in the density of the mixture (Anderson *et al.,* 1996; Wyszynski *et al.,* 2002; Oh *et al.,* 2010). Calculations and experiments to quantify the potential volumetric efficiency benefits and reduction in temperature of charge have been done by Anderson *et al.* (1996) and Wyszynski *et al.* (2002).

Anderson *et al.* (1996) calculated the change in final mixture volume compared to the volume of intake air for two extreme cases. Both cases consider typical conditions where initial intake air temperature is 100°C and fuel temperature is 50°C. A decrease of 5% in final mixture volume was estimated for a case in which fuel was completely evaporated by air, and an increase of 2% in final mixture volume was estimated for a case in which fuel was evaporated completely due to the intake port wall and intake valve surface. These extreme cases are unrealistic, as the fuel also absorbs heat from the air in a PFI engine, and from the cylinder walls in a GDI engine, but they serve to illustrate the potential differences. Anderson *et al.* postulated that the actual volumetric efficiency advantage of GDI engines over PFI engines lies in between these two ideal cases. If the intake air and fuel temperatures are varied, the estimated difference at constant pressure in charge temperatures for these extreme cases can be as large as 30ºC.

In experiments performed by Wyszynski *et al.* (2002), they found that changing from PFI to GDI in the same engine led to a 9% increase in volumetric efficiency. Wyszynski *et al.*

found that the improvement is between 50 and 70% of the theoretical maximum possible, which they have calculated separately under varying intake air and fuel temperatures. The improvement is limited by the finite time available for evaporation of the fuel droplets, and by direct impingement of the injection spray onto surfaces in the combustion chamber in a GDI engine.

Higher compression ratio and volumetric efficiency, coupled with better control of fuel and air staging, lead to higher specific power output, higher torque and increased engine efficiency (Anderson *et al.,* 1996; Zhao *et al.,* 1999; Wyszynski *et al.,* 2002).

For achieving higher injection pressure and more precisely timed fuel injection events, GDI engines require more sophisticated fuel injection hardware, a high-pressure fuel pump and a more complex engine control system compared to PFI engines (Anderson *et al.,* 1996; Zhao *et al.,* 1999). GDI engines are, therefore, more difficult to build, require better materials and higher precision in manufacturing. This increases the cost to design and manufacture GDI engines by $213 to $321, depending on the engine size (Kolwich, 2013). A high-pressure fuel pump also requires more electrical power to operate, which affects the fuel consumption (Zhao *et al.,* 1999).

## 1.3 Types of GDI Systems

In GDI engines, fuel is injected into the cylinder from a single point orifice, which can be located either on the side wall, or at the top of the cylinder. GDI engines in which fuel injector is mounted in the side wall are known as wall-guided (WG), whereas, GDI engines in which the injector is mounted at the top of the cylinder are known as spray-guided (SG). In WG systems, the fuel injector is located on the side of the cylinder near the corner of the cylinder head and the cylinder wall, and fuel-air mixing primarily relies on piston head geometry. The fuel spray is injected towards the piston head where it is redirected towards the spark plug for ignition. WG systems were employed in the first generation GDI engines. The major disadvantage of WG systems is fuel impingement on piston surface and cylinder walls, which results high particulate emissions. SG systems are an improvement over WG systems, due to their potential to reduce particulate emissions. In SG systems, the location of injector relative to the spark plug is such that some of the fuel is directed towards the spark plug for ignition, while the remaining fuel is dispersed into the remainder of the cylinder. The injected fuel-vapor cloud assumes a hollow conical shape inside the chamber. SG systems are designed to reduce fuel impingement on piston surface and cylinder walls. There has been a movement towards SG systems in lieu of WG systems. SG systems are being employed in the second generation GDI engines (Zhao *et al.*, 1999; Chen *et al.*, 2012; Zimmerman *et al.*, 2016; Zheng *et al.*, 2017).

## 1.4 Operation of GDI under Low and High Loads

The operation of GDI engines differs for low and high engine load conditions. For low engine loads, there is typically a single injection event in which fuel is injected near the end of the compression stroke. High injection pressure and heat from the intake air help atomize the fuel in the cylinder. Due to shorter mixing time, the charge is not well-mixed, and becomes stratified, resulting in pockets of fuel-rich and fuel-lean mixtures. Thus, the air-fuel ratio inside the cylinder varies depending on location within the cylinder. The fuel is injected such that the fuel-air mixture is richer close to the spark plug and leaner towards the wall of the cylinder. The overall average air-fuel ratio in the chamber can be as lean as 50:1, but close to the spark plug it is still rich enough to ignite easily (Anderson *et al.,* 1996; Zhao *et al.*, 1999; Wyszynski *et al.,* 2002; Chen *et al.,* 2012; Myung *et al.,* 2012; Na *et al.,* 2012; Golzari *et al.*, 2016).

At higher engine load, fuel is injected in multiple events. A portion of fuel is injected during the intake stroke so that the air flowing into the chamber can aid air-fuel mixing. This creates a homogenous charge, in which fuel is evenly distributed throughout the cylinder, similar to a PFI engine. However, the mixture is too lean to ignite. A second shot of fuel is injected as the piston comes up during the compression stroke, forming a fuel-rich mixture region near the spark plug surrounded by the fuel-lean mixture throughout the rest of the cylinder. This rich-lean stratification within the cylinder helps prevent uncontrolled combustion, or knocking and, along with the cooling effect of the spray mentioned earlier, enables a higher the compression ratio. Higher compression ratio increases engine torque and efficiency and, in turn, improves fuel economy. GDI engines are more fuel efficient to a large extent because of their higher compression ratios (Anderson *et al.*, 1996; Zhao *et al.*, 1999; Wyszynski *et al.*, 2002; Chen *et al.*, 2012; Myung *et al.*, 2012; Na *et al.*, 2012; Golzari *et al.*, 2016).

## 1.5 Fuel Economy of GDI versus PFI

There are varied reports of the fuel economy advantage of GDI vehicles when compared to conventional PFI vehicles. Early studies, such as Zhao *et al.* (1999) have theoretically estimated the fuel economy advantage to be close to 25% depending on the test cycle. Na *et al.* (2012) theoretically estimate the advantage at 20%. Graham *et al.* (2005) reported the measured advantage to be 20 to 30%, while another study estimated only a 1.5% decrease in fuel consumption (National Research Council, 2015). Confer *et al.* (2013) measured a 2% to 4% fuel economy advantage. Thus, there seems to be a lack of consensus regarding the fuel economy advantage of GDI engines over PFI engines. Recent studies focusing on particulate matter (PM) emissions from GDI engines, such as Bonatesta *et al.* (2014), Zimmerman *et al.* (2016), and Saliba et al. (2017) have cited the earlier studies, and EPA rated fuel economy data regarding the fuel economy advantage, but have not reported any new data. Moreover, the existing reports are based on either theory or lab-based dynamometer tests, and do not account for real world fuel economy.

## 1.6 Emission Rates of GDI versus PFI

Due to differences in fuel entry and combustion dynamics, GDI engines are expected to have different emission characteristics than PFI engines. GDI engines emit higher rates of ultrafine particles (UFPs) compared to PFI engines, both in terms of mass and particle number (Cole *et al.*, 1998; Zhao *et al.*, 1999; Maricq *et al.*, 1999; Graham 2005; Price *et al.*, 2006; Braisher *et al.,* 2010; Zhan *et al.,* 2010; Chan *et al.*, 2012; Myung *et al.*, 2012; Chen *et al.*, 2012; Spiess *et al.,* 2013; Bonatesta *et al.*, 2014; Su *et al.,* 2014; Golzari *et al.,* 2016; Zimmerman *et al.*, 2016; Zimmerman *et al.,* 2016; Saliba *et al.,* 2017). In GDI engines, when the fuel is injected late during compression stroke, the process of fuel vaporization and gas-phase mixing remains essentially incomplete, which leads to both fuel-rich and fuel-lean mixture pockets. Direct injection can also lead to impingement of fuel on the cylinder walls and the piston head. While impingement on piston surface is a part of WG systems design, uneven fuel flow due to carbon build-up and regular wear in the injectors in both WG and SG systems can result in fuel impingement on cylinder walls and piston surface. These surfaces create a "wall effect" because they tend to be much "cooler" than the flame temperature reached in the central part of the cylinder. Colder temperatures slow down combustion kinetics. Pockets of fuel rich mixtures, coupled with slower reaction kinetics, can lead to products of incomplete combustion (PIC). Fuel-rich combustion can produce UFP and unburned hydrocarbons (HCs). UFP formation is also attributed to incompletely volatilized fuel droplets in the unburnt gas (Cole *et al.*, 1998; Zhao *et al.,* 1999; Maricq *et al.,* 1999; Price *et al.,* 2006; Braisher *et al.,* 2010; Zhan *et al.,* 2010; Chan *et al.*, 2012; Myung *et al.*, 2012; Chen *et al.*, 2012; Bonatesta *et al.,* 2014).

The total soot particle number emitted by GDI engines is generally higher compared to PFI engines, and to diesel engines equipped with a Diesel Particulate Filter (DPF) (Braisher *et* *al.,* 2010). Zheng *et al.* (2017) reported that a GDI LDGV had black carbon (BC) emissions an order of magnitude higher than for PFI engine vehicles based on chassis dynamometer measurements. Automobile manufacturers have been trying to reduce PM emissions by improving engine designs and calibrations. First-generation WG GDI engines are known to have higher PM emissions than the second-generation SG GDI engines (Price *et al.,* 2006; Short *et al.*, 2017). BC emissions from vehicles measured on the Federal Test Procedure (FTP) and US06 for WG GDI were highest compared to SG GDI and PFI. In contrast, SG GDI BC emissions were lower on the aggressive US06 driving cycle, compared to PFI (Bahreini *et al.*, 2015). Higher particulate emissions from WG systems are largely because fuel spray in WG systems impinges on piston and cylinder surfaces more so than for SG systems, which leads to cooling of the fuel spray and more particle formation (Seo *et al.*, 2016).

Reduction in PM emissions from GDI engines can be achieved through improving variables such as air-fuel ratio, fuel injection timing, number of injections, injection pressure, coolant and engine temperatures (Chan *et al.,* 2012). Another solution to reduce PM emissions from GDI engines are Gasoline Particulate Filters (GPFs). GPFs have the same general operating principle as DPFs (Heck *et al.,* 2009.). GPFs are shown to control both PM mass and particle number emissions from GDI engines (Chan *et al.,* 2012; Speiss *et al.,* 2013). A prototype GPF, based on a design similar to a DPF, reduced BC emissions by 73 percent to 88 percent on the FTP and by 59 percent to 80 percent on the US06, depending on temperature (Chan *et al.*, 2012). As an added advantage, catalyzed GPFs could reduce emissions of other regulated pollutants (Speiss *et al.,* 2013). However, there are concerns related to the implementation of GPFs. GPFs are estimated to add approximately $100 to the cost of a vehicle (Minjares and Sanchez, 2011). GPFs have an influence on the system back pressure. Increase in system back pressure may cause an increase in fuel consumption (Chan *et al.,* 2012). Due to the concerns regarding implementation of GPFs, they are more likely to be required in markets that use the Euro 6 or similar particle number standards, than in in markets such as the U.S. where there are only PM mass emission standards (DieselNet, 2017). GPFs are now being used in Europe to meet the Euro 6 particle number standard of $6.0\times10^{11}$ particles per kilometer for direct injection engines that went into effect in 2017 (DieselNet, 2018).

For a PFI engine, as the air-fuel mixture becomes leaner from stoichiometric, $NO_x$ formation increases at first, due to availability of oxygen coupled with sufficiently high flame temperature. However, $NO_x$ levels drop as the mixture is leaned beyond 16:1 or 17:1 (Anderson *et al.,* 1996, Kašpar *et al.,* 2003). This is due to decrease in temperature in the reaction zone, which results in a decrease in $NO_x$ formation and engine-out $NO_x$ emission concentrations.

For a GDI engine, there are several competing factors that dictate the overall rate of $NO_x$ formation. Fuel-rich zone at the core of stratified charge reduces initial $NO_x$ formation. Fuel-rich zone followed by a fuel-lean secondary zone enables burn-out of PICs without forming additional $NO_x$. Thus, the rate of $NO_x$ formation is reduced due to staged combustion in GDI engines. However, rate of $NO_x$ formation tends to increase with pressure inside the combustion chamber. High compression ratio increases $NO_x$ formation in GDI engines. Cooling effect of fuel vaporization in the cylinder lowers the peak flame temperature in GDI engines, which tends to lower $NO_x$ formation. These competing phenomena tend to compensate each other (Cole *et al.*, 1998; Zhao *et al.*, 1999).

Anderson *et al.* (1996) found that when the fuel is injected early during the intake stroke in a GDI engine, $NO_x$ emissions of GDI nearly match PFI operation in the same cylinder head. This is due to creation of a homogenous charge inside the combustion chamber and similar residence time in both cases. In case of homogenous charge, $NO_x$ levels increase as the mixture is leaned from stoichiometric, and then decrease if leaned beyond 16:1 or 17:1, both for GDI and PFI engines. In contrast, if the fuel is injected during the compression stroke in GDI, the $NO_x$ levels for a stoichiometric overall air-fuel ratio are lower for late injection GDI than either case of homogenous mixing, i.e., early injection GDI and PFI. This indicates that a greater fraction of fuel combusts at an air-fuel ratio that is locally richer than stoichiometric. Leaning the charge further from stoichiometric overall air-fuel ratio results in monotonically increasing $NO_x$ emissions in the case of late injection GDI, which indicates that a substantial fraction of the fuel is combusting at local air-fuel ratios which produce higher levels of $NO_x$ than the overall air-fuel ratio would suggest.

Zimmerman *et al.* (2016) conducted field measurements using remote sensing for a total of seven GDI vehicles in Toronto, Canada, and compared their results with the Toronto vehicle fleet emission factors reported by Wang *et al.* (2015). The emission factors reported by Wang *et al.* (2015) are based remote sensing measurements of 100,000 vehicle-related plumes of the Toronto vehicle fleet, which is comprised of 94% gasoline-powered vehicles. Zimmerman *et al.* (2016) reported that for $NO_x$, the average fuel-based emission factors from

GDI vehicles were 52nd percentile of the total vehicle fleet, indicating that $NO_x$ emissions from GDI were in line with Toronto vehicle fleet. Saliba *et al.* (2017) found no statistically significant differences in $NO_x$ emissions from laboratory-based tests for GDI and PFI vehicles. Graham (2005) reported that cycle average $NO_x$ emission rates for GDI vehicles tested in laboratory-based chassis dynamometer test were on average lower by 30% than PFI vehicles that were tested.

CO is formed due to incomplete oxidation of fuel. In PFI engines, CO formation is high for homogenous fuel-rich mixtures, and decreases steeply at first as the homogenous mixture leans towards stoichiometric ratio. CO formation for stoichiometric charge, which is 14.6:1 air to fuel ratio, is considerably lower than if the ratio were 13:1 or 12:1. CO formation decreases further as the charge leans from stoichiometric ratio, however, the decrease is not as steep as between 13:1 and 14.6:1 (Kašpar *et al.,* 2003). In GDI engines, pockets of fuel-rich mixture in the stratified charge generate CO emissions, even if the overall combustion is relatively lean (Zhao *et al.,* 1999). However, while CO formation is higher in the fuel-rich pockets, it is possible for the CO produced from fuel-rich pockets to oxidize as it mixes with burnt fuel-lean charge, which will still be rich in oxygen. This is known as post-flame oxidation.

Zimmerman *et al*. (2016) report that CO was not detected in significant concentrations in the GDI exhaust, since the vehicles they tested were new. Low CO emissions can be attributed to the high effectiveness of three-way catalyst (TWC) in newer vehicles. The effectiveness of TWC decreases with age. Zimmerman *et al.* (2016) reported that CO concentrations in 65% to 90% of vehicle plumes from GDI vehicles they measured using remote sensing were below detectable limits, depending on the distance of the monitor from the roadside. Due to small sample size of plumes where CO emissions were detected, Zimmerman *et al.* (2016) concluded that the GDI CO emissions from the vehicles tested relative to the fleet are uncertain. Graham (2005) found that CO cycle average emissions were on average 40% lower for GDI vehicles than PFI vehicles. Saliba *et al.* (2017) found no statistically significant differences in CO emissions between GDI vehicles and PFI vehicles.

HC is formed either due to incomplete oxidation of fuel in fuel-rich mixtures, or when fuel-lean mixtures are not completely burned inside the combustion chamber, which results in emission of unburned HCs in vaporized fuel. For PFI engines, HC formation is high when the charge is fuel-rich, decreases as the mixture leans towards stoichiometric air-fuel ratio of 14.6:1, is nearly constant between an air-fuel mixture of 14:1 and 18:1, and increases after the mixture leans beyond air-fuel ratio of about 18:1 (Kašpar *et al.*, 2003).

In GDI engines, production of HCs is more complex than PFI engines due to stratification of charge. HC emissions are produced both due to fuel-rich pockets and fuel-lean pockets. Unburned HC emissions resulting from fuel-lean pockets depend on how far the flame propagates through the cylinder (Cole *et al.*, 1998). In addition, HC emissions are also produced in a GDI engine due to wetting of cylinder wall and piston head, which depend on design of the combustion chamber, timing of injection and location of the injector. Wetting of cylinder wall and piston head is typically more prevalent in WG GDI systems than SG GDI systems. Thus, HC formation is inherently higher in WG systems due to their design, compared to SG systems. Cooling effect of fuel spray, which lowers the charge temperatures by up to

30°C in the combustion chamber, reduces the degree of post-flame oxidation of HCs, leading to engine-out HC emissions (Anderson *et al.*, 1996).

For the case of multiple injection events, GDI and PFI are reported to have similar HC emissions for all overall air-fuel ratios. For the case of late injection during the compression stroke, HC emissions are reported to be similar for GDI and PFI at richer overall air-fuel ratios. However, combustion becomes unstable at overall ratios leaner than about 18:1, resulting in high engine-out HC emissions from GDI engines (Anderson *et al.*, 1996).

Zimmerman *et al.* (2016) reported benzene, toluene and ethylbenzene-xylenes (BTEX) instead of total HCs. They reported that BTEX emissions from seven GDI vehicles they measured were substantially higher compared to the Toronto fleet (range: $80^{th}$ − $90^{th}$ percentile), and suggested that GDI vehicles may increase ambient BTEX levels. Zimmerman *et al.* (2016) inferred that BTEX, which are soot precursors, may be elevated due to incomplete or fuel-rich combustion in the GDI engines. In contrast, Saliba *et al.* (2017), with results based on a larger fleet of 15 GDI vehicles tested, found no statistically significant differences in BTEX emission rates of GDI and PFI vehicles. GDI vehicles tested by Saliba *et al.* (2017) consisted of 11 WG and 2 SG GDI vehicles. 2 GDI vehicles were unclassified. Further, Saliba *et al.* (2017) also reported that for the GDI vehicles they tested, BTEX emissions mirrored total HC emissions. Saliba *et al.* (2017) also found no statistically significant difference in HC emission factors between GDI and PFI vehicles. However, Graham (2005) found that 3 GDI vehicles they tested had 45% less HC emissions than a fleet of PFI vehicles they tested.

## 1.7 U.S. EPA Rated Fuel Economy and Certification Level Data

Vehicles sold in the U.S. are rated for fuel economy based on chassis-dynamometer laboratory tests, including the Federal Test Procedure (FTP) and Highway Fuel Economy (HWFE) Test. The U.S. EPA reports fuel economy for a representative vehicle of each model sold in the U.S. (Code of Federal Regulations, 2013a). The U.S. EPA also reports measured "certification level" of FTP cycle average $NO_x$, HC, and CO emission rates for each representative vehicle. The U.S. EPA rated fuel economy and certification level data can be used to compare fuel economy and tailpipe exhaust emission rates, respectively, for GDI versus PFI equipped vehicles. The comparison of fuel economy and emission rates of GDI versus PFI vehicles based on U.S. EPA rated fuel economy and certification level data can be used as a benchmark for comparisons based on real-world fuel economy and emission rates of GDI versus PFI vehicles.

As a result of the Clean Air Act Amendment (CAAA) of 1990, two 'Tiers' of tailpipe emission standards, based on various combinations of pollutants and driving cycles, were defined by the U.S. EPA. The Tier I standards were adopted in 1991, and phased in from 1994 to 1997. Tier I standards were effective from 1994 until 2006. Under Tier I standards, all vehicles were required to meet the same emission limits. Tier II standards for LDVs were phased in from 2004 to 2007 (Code of Federal Regulations, 2013b). Under Tier II standards, manufacturers were required to meet a fleet average emission rate, and could select from among 'Bins' with regard to emission rate applicable to a given vehicle model. The Tier II standards were divided into 11 'Bins', Bin 1 being for the lowest emitting vehicles and Bin 11 being for the highest emitting. Tier II standards were effective from 2004 until 2016. Tier III standards are effective with the 2017 MY (Code of Federal Regulations, 2013b). Similar to the Tier II standards, Tier III standards have bins that manufacturer can choose for a given vehicle model, as long as their new car fleet meets a fleet average emission limit.

Vehicles are certified for emissions compliance by measuring tailpipe emissions in lab-based chassis-dynamometer tests, based on FTP, and other supplemental standard cycles, including US06 and SC03. The U.S. EPA reports the measured certification level of FTP cycle average $NO_x$, HC, and CO emission rates for each representative vehicle. The certification level is based on the cycle average emission rates combined with appropriate deterioration factors (DF). A DF is defined as a relationship between emission at the end of specified useful life, and emission at the stabilized mileage point selected for emission testing (Code of Federal Regulations, 2013c, 2013d). The relationship can be either additive or multiplicative. An additive DF is defined as the difference in emission rates between specified useful life mileage, e.g. 120,000 miles, and stabilized mileage point, e.g. 4,000 miles (Code of Federal Regulations, 2013d). A multiplicative DF is defined as the ratio of the emission rate at specified useful life mileage, e.g. 120,000 miles, to the emission rate at stabilized mileage point, e.g. 4,000 miles. As per the Code of Federal Regulation, DFs of selected test vehicles must be estimated using linear regression based on durability tests of emission rates. The certification level must be at or below the level of the applicable emission standard.

## 1.8 Need for the Study

Many studies, referenced earlier, that have reported the fuel use and/or emission rates of GDI and PFI vehicles, have used lab-based chassis-dynamometer tests, using standard driving cycles, including FTP, HWFE, US06, SC03, cold-start unified cycle and New European Drive Cycle (NEDC) (Cole *et al.*, 1998; Graham 2005; Braisher *et al.*, 2010; Zhan *et al.*, 2010; Chan *et al.*, 2012; Spiess *et al.*, 2013; Saliba *et al.*, 2017). Although the certification driving cycles are based on selected examples of real-world driving, they are not necessarily representative of the real-world operation of a given vehicle (Samuel *et al.*, 2002; U.S. Environmental Protection Agency, 2006; Nam, 2009). Zimmerman *et al.* (2016) reported real-world emission factors based on remote sensing data. However, data from remote sensing gives an instantaneous estimate of emissions at a specific location on a mixing ratio or fuel basis, and does not correlate emissions with vehicle activity and driving behavior (Frey *et al.*, 2003).

There is a need for comparison of GDI and PFI fuel economy and emission rates based on real-world data, which is correlated with real-world driving conditions. Fuel use and emission rate data representative of real-world vehicle operation can be obtained by driving vehicles on actual roads, and measuring fuel use and emissions using a Portable Emission Measurement System (PEMS). The advantage of using onboard instrumentation for measurement of vehicles during on-road operation is that it enables data collection under real-world conditions at any location traveled by the vehicle and under any weather conditions. No previous studies have compared GDI and PFI vehicles fuel use and emissions data based on real-world measurements obtained using PEMS.

North Carolina State University (NCSU) has developed and demonstrated an approach for the measurement and analysis of real-world vehicle activity, energy use, and emission rates based on PEMS (Frey *et al.*, 2003, 2008, 2010, 2012). In recent years, PEMS data have been collected on approximately 200 LDVs at NCSU. For each vehicle, measurements were made of the tailpipe exhaust $CO_2$, CO, HC, and $NO_x$ emission rates. A vehicle specific power (VSP) based modal model is used to express the average fuel use and emission rates of the measured vehicles. VSP is an indicator of engine load, and is highly correlated with fuel use and emission rates (Frey *et al.*, 2008). Average fuel use and emission rates from the measurements are reported for different VSP modes. The purpose of expressing average fuel use and emission rates in terms of VSP-based modal model is to interpret the variability of fuel use and emission rates with vehicle load. The VSP-based modal models for GDI and PFI vehicles so obtained can be used to compare their fuel use and emission rates over the entire range of vehicle load which is observed under real-world driving conditions. Comparison of GDI and PFI vehicles is expected to be variable over the range of loads the vehicles are subjected to under real-world driving conditions. The variability is expected because GDI engines operate differently under low and high load conditions, as described earlier. Further, cycle average fuel use and emission rates over entire driving cycles can be quantified based on VSP-based modal model, and be used to compare GDI and PFI fuel use and emission rates for multiple driving cycles, including standard driving cycles and real-world driving cycles.

No studies were identified which reported fuel economy comparison of GDI and PFI vehicles based on real-world data. Much focus of recent studies on GDI and PFI vehicles has been on comparison of PM emissions (Myung *et al.,* 2012; Zimmerman *et al.,* 2016, Saliba *et al.,* 2017). There also exists ambiguity between results of gaseous emissions from different studies. For example, while Zimmerman *et al.* (2016) reported that BTEX emissions from GDI vehicles are in the higher percentiles of Toronto vehicle fleet, Saliba et al. (2017) reported that the BTEX emissions from GDI and PFI vehicles are similar.

Apart from Saliba et al., the sample sizes of other studies were limited, which makes it hard to draw statistically significant conclusions. Further, while comparing GDI and PFI vehicles, previous studies have also not matched their characteristics. The effect of GDI can be isolated if the comparison is made between vehicles of similar size and characteristics. Since fuel use and emission rates for an LDGV depend on various factors, such as vehicle size, engine, transmission, engine aspiration, etc., for a true comparison between GDI and PFI, these factors need to be accounted for in the samples of GDI and PFI vehicles selected. For example, Zimmerman *et al.* (2016) have reported results for seven unique 2013 Ford Focus SE sedan, and compared them with the Toronto fleet. It is debatable if results from a single model of GDI can be generalized for other GDI vehicles, including hatchbacks, SUVs, minivans and pickup trucks, available in the market. A compact sedan such as Ford Focus will tend to have higher fuel economy and lower emission rates than a typical large SUV, irrespective of the fuel injection system in the large SUV. Thus, for example, if Zimmerman *et al.* (2016) had selected a large GDI SUV for their study, the mass-based emission factors of pollutants presumably would have been in the higher percentiles of the Toronto vehicle fleet. The higher percentiles in this case could not be attributed solely to the GDI. By the same logic, the present results of Zimmerman *et al.* (2016) cannot be attributed solely to GDI either. Saliba *et al.* (2017) reported results based on a larger fleet of 15 GDI vehicles. However, they have compared the 15 GDI vehicles to 61 PFI vehicles. Saliba *et al.* (2017) have selected GDI vehicles based on a number of factors, including a wide range of model years, vehicle types (passenger cars and light-duty trucks), emission certification standards, and manufacturers. Saliba *et al.* (2017) have also addressed the variability of emission rates between different tiers of emission standards the vehicles were certified to. However, Saliba *et al.* (2017) have not addressed if the selected GDI vehicle fleet matched the PFI vehicle fleet in terms of vehicle and engine sizes. If the vehicle size distribution of GDI and PFI vehicles was different, the difference in emission characteristics cannot be solely attributed to the use of GDI instead of PFI. Thus, there seems to be a need for a methodology for comparing GDI and PFI vehicles which addresses the variability in samples of GDI and PFI vehicles selected, so that the results obtained may be broadly generalizable for GDI vehicles.

## 1.9 Objectives

The key objectives of this study are:

- To describe a methodology for selection of vehicles for a balanced comparison of GDI and PFI vehicles;

- To quantify and compare, for selected vehicles with GDI and PFI engines, the real-world fuel economy, and $CO_2$, CO, HC, $NO_x$ and PM emission rates versus VSP;

- To compare real-world cycle average fuel economy, and $CO_2$, CO, HC, $NO_x$ and PM emission rates between GDI and PFI vehicles;

- To benchmark the results of field measurements with U.S. EPA rated fuel economy, U.S. EPA emission certification levels, and available published studies.

The study illustrates a methodology for real-world measurement of LDGVs, analysis of the data obtained, and comparison of results of GDI and PFI engine technologies.

# CHAPTER 2

## METHODOLOGY

This chapter provides details on vehicle selection, data collection routes, instrumentation, quality assurance, data analysis, and collection of chassis-dynamometer data.

### 2.1 Vehicle Selection

An important part of the study design was to identify comparable GDI and PFI vehicles. GDI vehicles were identified that are representative of the market distribution of GDI vehicle fleet. As shown in Figure 1, different manufacturers have adopted GDI engines in their vehicle fleet. Here, the goal was to have representative vehicles from GDI vehicle manufacturers that make up at least 80% of GDI vehicle sales, i.e., GM, Honda, Ford, Hyundai, Kia and VW. The sample of GDI vehicles selected also took into account different body types of vehicles, such as hatchbacks, sedans, wagons, SUVs, pickup trucks and minivans. The sample of GDI vehicles selected was, thus, representative of the current market in terms of manufacturers and body types; however, it was not proportional in terms of actual vehicle market sales.

For selecting comparable PFI vehicles, the following characteristics were considered: body type, engine displacement, engine configuration, engine aspiration, rated horsepower (HP), curb weight, ratio of HP to curb weight, transmission type and speeds, emission standards, drivetrain, hybrid power systems, age of the vehicle, and mileage. While comparing GDI and PFI vehicles, priority was given to the ratio of HP to curb weight, and curb weight of the vehicle. If these two characteristics matched, the other characteristics also matched. Curb weights of vehicles were considered to be comparable if they were within ±300 lbs. The ratio of HP to curb weight was usually within ±0.01 hp/lb. For example, a good comparison, observed in the 200-vehicle NCSU data set, was of a 2013 Chevrolet Impala GDI vs 2013 Dodge Avenger PFI. Both vehicles were large sedans, and have 3.6 L, V6 naturally aspirated engines, similar HP to curb weight ratio (within ±0.002 hp/lb), the same transmission type, and front-wheel drive (FWD). Table 1 illustrates specifications of the two vehicles.

**Table 1. Specifications of 2013 Chevrolet Impala (GDI) and 2013 Dodge Avenger (PFI)**

| Specification | 2013 Chevrolet Impala | 2013 Dodge Avenger |
|---|---|---|
| Injection System | GDI | PFI |
| Body Type | Large Sedan | Large Sedan |
| Engine Displacement (L) and Configuration | 3.6, V6 | 3.6, V6 |
| Engine Aspiration | Natural | Natural |
| Rated HP @ RPM | 300 @ 6500 RPM | 283 @ 6400 RPM |
| Curb Weight (lbs.) | 3639 | 3607 |
| HP/Curb Weight (Ratio) | 0.082 | 0.078 |
| Transmission Type | Auto 6-speed | Auto 6-speed |
| Emission Standard | Tier 2 Bin 4 | Tier 2 Bin 4 |
| Drivetrain | Front-Wheel Drive (FWD) | Front-Wheel Drive (FWD) |
| Hybrid | No | No |

When considering body types, preferably a hatchback was compared with a hatchback, a sedan with a sedan, and so on. In exceptional circumstances, a hatchback, for example, was compared with a sedan or a wagon if factors such as the HP to curb weight ratio, engine aspiration, curb weight, transmission type, emission standard, drivetrain, and others, matched. For example, a 2014 Ford Focus (GDI) hatchback was compared with a 2007 Nissan Sentra sedan. The Ford Focus and Nissan Sentra had HP to curb weight ratios of 0.054 hp/lb and

0.048 hp/lb, which were comparable at approximately 0.05 hp/lb. However, a sedan or a hatchback was typically not comparable to an SUV or a minivan. Usually SUVs and minivans are heavier. Furthermore, the body style of the vehicle partially determines the aerodynamic drag coefficient. Aerodynamic drag is an important factor in fuel efficiency, especially at highway speeds (Frey *et al.*, 2010). Whereas a hatchback and sedan may have similar drag coefficients, a sedan and an SUV typically would not.

Engine size and configuration play an important role in fuel efficiency (National Research Council, 2015). Engine configuration is the layout of the major components of an internal combustion engine (Ferguson and Kirkpatrick, 2015). These components include the cylinders, crankshafts and camshaft. For vehicles with similar curb weight and HP, or their ratio, the engine displacement and configuration were typically same or similar. An inline four-cylinder (I4) engine was typically compared with another I4, a V6 with a V6, and a V8 with a V8. The different configurations also imply different size. An I4 is usually smaller than a V6, which is usually smaller than a V8, and, hence, the engine displacement and configuration usually matched. There were two exceptions. In one case, a V6 and a V8 were compared as the vehicles matched in terms of HP to curb weight ratio. Similarly, in another case, an inline five-cylinder (I5) was compared to an I4, as the vehicles matched in terms of HP to curb weight ratio. In both the exceptional cases, the larger engine was downsized by using GDI and turbocharging in tandem. The downsized engine produced similar horsepower in both the cases.

Engine aspiration is known to affect fuel use and emission rates (National Research Council, 2015). Therefore, it was preferable to compare engines with the same type of aspiration. There are broadly two types of engine aspiration: natural aspiration and forced induction. Forced-induction engines include engines that are turbocharged, supercharged or twin-charged. In recent years, auto manufacturers have used forced induction and GDI in tandem to downsize the engine (National Research Council, 2015). Such vehicles typically have a smaller displacement engine capable of producing similar power, and have same HP-to-curb weight ratio as the larger naturally aspirated engine vehicles they have replaced. Typically, a forced-induction engine should not be compared with naturally aspirated engine. More realistically, since GDI and forced induction are used in tandem, it was not possible to completely isolate GDI in all comparisons. Thus, in cases where a forced-induction engine vehicle had no other comparable forced-induction engine vehicle available, and the forced-induction engine was designed to replace a naturally aspirated engine, the forced-induction vehicle was compared with single or multiple naturally aspirated vehicle, provided they had similar HP-to-curb weight ratio.

For example, the 2016 Ford F150 was produced with two engine configurations: a 3.5 L, V6 turbocharged GDI engine, and a 5.0 L, V8 naturally aspirated PFI engine (Table 2). Both vehicles shown in Table 2 have the same chassis, and have similar characteristics, including similar EPA rated fuel economy and certified levels of emission rates. The difference in curb weight was at least partly attributable to the higher weight of the larger 5.0 L V8 engine. Further, a better match was not available for the turbocharged vehicle.

**Table 2. Specifications of 2016 Ford F150 (GDI) and 2016 Ford F150 (PFI)**

| Specification | 2016 Ford F150 | 2016 Ford F150 |
|---|---|---|
| Injection System | GDI | PFI |
| Body Type | Pickup Truck | Pickup Truck |
| Engine Displacement (L) | 3.5 | 5.0 |
| Engine Configuration | V6 | V8 |
| Engine Aspiration | Turbocharged | Natural |
| Rated HP @ RPM | 365 @ 5000 RPM | 385 @ 5750 RPM |
| Curb Weight (lb) | 4687 | 4906 |
| HP/Curb Weight (hp/lb) | 0.078 | 0.078 |
| Transmission Type | Auto 6-speed | Auto 6-speed |
| Emission Standard | Tier 2 Bin 4 | Tier 2 Bin 4 |
| Drivetrain | 4-Wheel Drive (4WD) | 4-Wheel Drive (4WD) |
| Hybrid | No | No |

Different types of transmissions affect fuel economy (National Research Council, 2015). Here, automatic transmissions were divided into two broad categories: automatic transmission with ‘n’ speeds and continuously variable transmission (CVT). CVT is more fuel efficient than conventional automatic transmissions (National Research Council, 2015); therefore, it was preferable to compare vehicles that have similar transmissions.

Emission standards were considered in vehicle comparisons. Preferably, the compared vehicles were in the same ‘Tier’ and ‘Bin’ of the LDGV emission standards as defined by the U.S. EPA. However, from a more practical consideration, vehicles maybe comparable if they had similar certified levels of emission rates even if the applicable standard differs. For example, the 2016 Hyundai Sonata (GDI) was compared with the 2016 Chrysler 200 (PFI), as the vehicles were a good match in terms of engine power and vehicle weight, and had similar rated fuel economy and certified levels of emission rates. The Sonata was, however, certified to Tier 2 Bin 5, and the 200 was certified to Tier 2 Bin 4.

Three types of drivetrains were considered for comparison: front-wheel drive (FWD), all-wheel drive (AWD) and optional 4-wheel drive (4WD). In FWD, the front two wheels are connected to the engine, whereas in AWD and 4WD all four wheels are or can be driven by the engine. AWD and 4WD have technical differences, but since both require the engine to power all four wheels, they are less fuel-efficient than FWD (National Research Council, 2015). Thus, FWD was compared with FWD, AWD with AWD and 4WD with 4WD.

If a single vehicle PFI vehicle was not adequately comparable to a GDI vehicle, then multiple PFI vehicles were averaged as a “composite” vehicle to give a better match. Similarly, if more than one GDI vehicle had similar characteristics, and were comparable to a PFI vehicle, then a “composite GDI” vehicle was synthesized based on the average of the multiple GDI vehicles. For example, a 2016 Hyundai Accent GDI was compared with the average of three PFI vehicles: a 2007 Honda Civic, a 2009 Honda Civic, and a 2007 Nissan Sentra. Similarly, a composite GDI vehicle was formed by averaging three GDI vehicles: 2006 VW Jetta, 2007 VW Passat Wagon and 2009 VW Jetta. The composite GDI was compared to the average of two PFI vehicles: a 2006 VW Jetta and a 2012 VW Passat. All three GDI vehicles had the same 2.0 L VW TSI engine, and had similar curb weight.

There are various other fuel-saving technological features, such as multiple valves in engines, variable valve timing (VVT), higher number of gears in automatic transmissions, and continuously variable-lockup transmission, that affect fuel use, and, therefore, emission rates (National Research Council, 2015). These technologies are widely used in modern LDVs. For example, U.S. EPA reports that 98.8% of MY 2017 vehicles have some form of VVT, and 92.4% of MY 2017 vehicles have multiple valves (US EPA, 2018a). Since these technologies are used in-tandem with both GDI and PFI engines, it was difficult match every attribute for each one-on-one comparison.

## 2.2 Data Collection Routes

Four routes (Figure 2) designed by Frey *et al*. (2008) were used for data collection for each of the GDI and PFI vehicles. To account for variability in real-world vehicle operation, measurements were conducted between two origin/destination pairs: from NCSU to North Raleigh (NR) on Routes A and C, and from NR to Research Triangle Park (RTP) on Routes 1 and 3. Routes A and C have one-way distances of 10 mi and 11 mi, respectively, and, Routes 1 and 3 have one-way distances of 16 mi and 18 mi, respectively. The total travel distance of all routes combined is 110 miles. Route A includes city driving and is comparable to the FTP. Route 1 is a real-world freeway driving cycle.

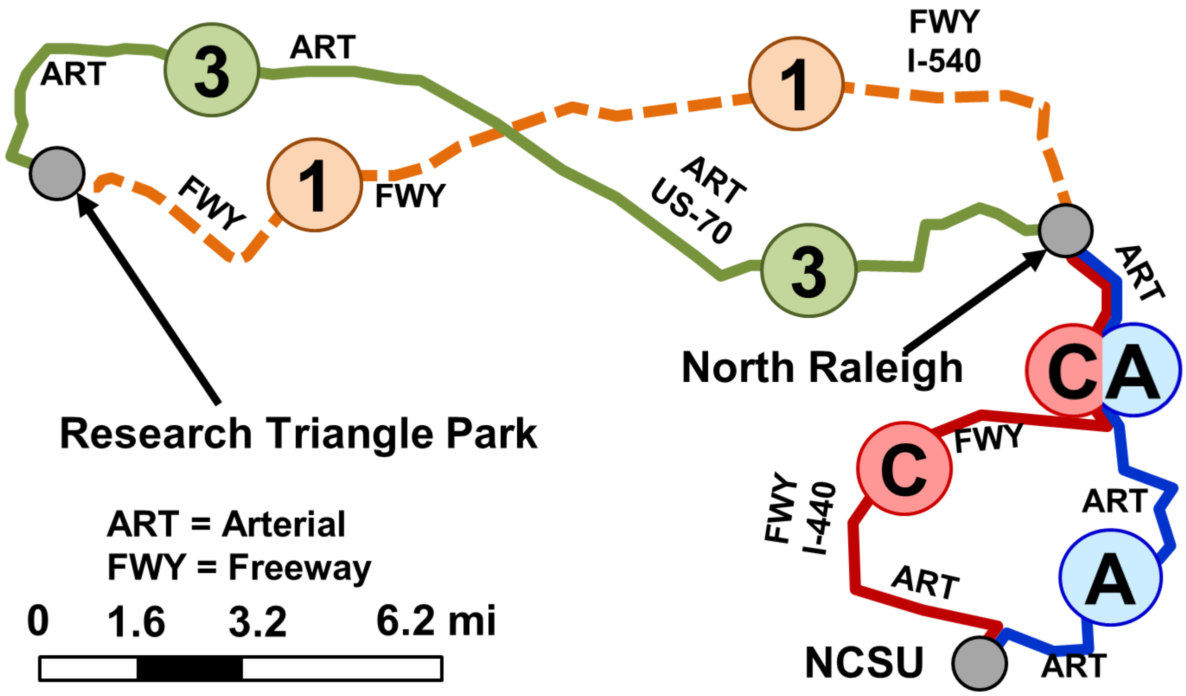



**Figure 2. Study routes used for field data collection in Raleigh and RTP area, NC.**

These routes cover a wide range of road types, including feeder/collector streets, minor arterials, primary arterials, ramps, and limited access freeways, with speed limits ranging from 25 mph to 70 mph. These routes represent typical commuting corridors in the local area. Data collection was typically carried out between 7:00 a.m. and 8:00 p.m. Route and time of day selection were aimed at ensuring broad coverage of the transportation network characteristics including road grade, road types, and traffic conditions. These routes produce a wide range of variability in VSP, which is an indicator of engine load. This wide range of variability is sufficient to calibrate VSP modal models of fuel use and emission rates for each measured vehicle (Frey *et al.*, 2008; Liu and Frey, 2015).

## 2.3 Instrumentation

PEMS measurements at 1 Hz were made of tailpipe concentrations of $CO_2$, CO, HC, NO, and PM using an OEM-2100 Montana or Axion PEMS. The PEMS were warmed up for 1 h prior to calibration and field measurement. They were calibrated periodically using a cylinder gas mixture. $CO_2$, CO, and HC were measured using non-dispersive infrared (NDIR) sensing. NO and $O_2$ were measured using electrochemical cells. PM emissions were measured using a laser particle-counting sensor. LDGV $NO_x$ exhaust is typically 95% NO (Ferguson and Kirkpatrick, 2015). Therefore, in this case NO is considered a good surrogate for $NO_x$. Battelle previously validated a similar model PEMS based on chassis dynamometer LDGV measurements under the EPA Environmental Technology Verification (ETV) Program (Myers *et al.*, 2003). Based on linear regression test results, PEMS measurement for cycle average $CO_2$ emission rates were ±3% of the dynamometer measurements. Cycle average CO emission rates were ± 5% of the dynamometer measurements, and cycle average $NO_x$ emission rates ranged between −8% and +3% of the dynamometer measurements. Cycle average HC emission rates were approximately 20% to 40% lower compared to the dynamometer. The relatively larger difference for HC can be attributed to the use of NDIR in the PEMS versus Flame Ionization Detection (FID) in the lab (Myers *et al.*, 2003; Stephens *et al.*, 1996; Singer *et al.*, 1998).

NDIR is based on measurement of energy absorption within a defined narrow range of infrared wavelength, and responds more to straight chain alkanes than other HCs such as benzene and toluene (Stephens *et al.*, 1996; Singer *et al.*, 1998). FID is based on measuring current flow from free electrons of ionized HCs which are produced when the HCs are burnt in a hydrogen flame. FID responds linearly to all kinds of HCs. A detection limit is defined as the smallest measured concentration that is significantly different from zero (Zhao and Frey, 2004). The detection limit of the PEMS NDIR sensor for HC is 13 ppm (Graver, 2016).

Conventional methods of handling measurement values below a detection limit include censoring, or replacing with zero, one-half of detection limit, or the detection limit. However, Zhao and Frey (2004) showed that mean estimates are not biased due to values below detection limit as long as the detection limit is less than the sample mean, and if unbiased methods for quantifying data below the detection limit are used (Zhao and Frey, 2004).

An On-board Diagnostic (OBD) data logger was used to record real-world activity including engine revolutions per minute (RPM), manifold absolute pressure (MAP), intake air temperature (IAT), and vehicle speed. Vehicle location and elevation were recorded using global position system (GPS) receivers with barometric altimeters, from which road grade was estimated using the approach of Yazdani and Frey (2014). Air-conditioning was used inside the vehicles for all measurements.

### 2.4 Quality Assurance

Data processing and quality assurance (QA) includes four major steps: (1) converting OBD data, which is broadcast at frequencies typically greater than 1 Hz, to a second-by-second basis; (2) synchronizing data from multiple instruments into one database; (3) range checks and data screening to correct or remove data errors; and (4) modal analysis of the data.

To ensure the integrity of data used for analysis, the raw data were screened for errors using techniques detailed by Sandhu and Frey (2013). Data with errors that could not be corrected were removed prior to analysis. Three most common sources of error requiring removal of data are brief periods of gas analyzers recording negative exhaust HC concentrations which are statistically different from zero, brief periods in which the gas analyzers failed to update values, and small periods of time with out-of-range values of engine RPM, IAT and MAP.

## 2.5 Data Analysis

VSP is a useful indicator of engine load and is highly correlated with fuel use and emission rates (Frey *et al.*, 2008). VSP is quantified in terms of 1 Hz speed, acceleration, and road grade and takes into account changes in kinetic and potential energy, rolling resistance, and aerodynamic drag (Jimenez-Palacios, 1998):

$$VSP = v \times \left[1.1 \times a + g \times (\sin(a\tan(\varphi)) + \psi\right] + \varsigma \times v^3 \quad (1)$$

Where,

VSP is vehicle specific power (kW/ton);

v is vehicle speed (m/s);

a is acceleration ($m/s^2$);

g is acceleration due to gravity (9.81 $m/s^2$);

$\varphi$ is road grade (Unit less slope);

$\psi$ is the rolling resistance coefficient (0.132 $m/s^2$); and

$\varsigma$ is the aerodynamic drag coefficient (0.000302 $m^{-1}$).

VSP is categorized into 14 modes, as defined in Table 3 (Frey *et al.*, 2002). Modes 1 and 2 are for negative values of VSP and represent deceleration, traveling downhill, or both. Mode 3 includes idling. Modes 3 to 14 have monotonically increasing positive VSP, which represents acceleration, steady-speed cruising, hill climbing, or combinations of these.

**Table 3. Definition of 14 VSP Modes** (Frey *et al.*, 2002)

| VSP Mode | Definition (kW/ton) | VSP Mode | Definition (kW/ton) |
|---|---|---|---|
| 1 | VSP < -2 | 8 | 13 ≤ VSP < 16 |
| 2 | -2 ≤ VSP < 0 | 9 | 16 ≤ VSP < 19 |
| 3 | 0 ≤ VSP < 1 | 10 | 19 ≤ VSP < 23 |
| 4 | 1 ≤ VSP < 4 | 11 | 23 ≤ VSP < 28 |
| 5 | 4 ≤ VSP < 7 | 12 | 28 ≤ VSP < 33 |
| 6 | 7 ≤ VSP < 10 | 13 | 33 ≤ VSP < 39 |
| 7 | 10 ≤ VSP < 13 | 14 | 39 ≤ VSP |

Average emission rates in grams per second for each vehicle were calculated for each VSP mode. To enable comparisons on the basis of different driving cycles, the VSP modal fuel use and emission rates were weighted based on the proportion of time spent in each mode for a given driving cycle:

$$CE_{p,c,v} = \sum_{m=1}^{14} F_{m,c} ER_{p,m,v} \quad (2)$$

Where

$CE_{p,c,v}$ is the cycle average emission rate for pollutant *p*, cycle *c*, and vehicle *v* (g/sec);

$F_{m,c}$ is the fraction of total cycle time in mode *m* for cycle *c* (fraction); and

$ER_{p,m,v}$ is the VSP modal average emission rate for pollutant *p*, mode *m*, and vehicle *v* (g/sec).

Driving cycles were quantified on the basis of fraction of time in each of the VSP Bins. For each route, an average cycle was estimated based on the average of all vehicle runs that satisfied a data completeness criterion. The criterion was that there must be at least 95% of valid 1 Hz vehicle activity data on the route compared to the total travel time from the origin to the destination of the route. Cycle average rates calculated from Equation (2) are in grams per second. Average cycle speed was used to convert this into grams per mile.

## 2.6 Chassis Dynamometer Data

For each measured vehicle, the EPA rated fuel economy and certification levels emission rates were obtained (U.S. EPA, 2017). EPA city and highway fuel economy ratings are based on chassis-dynamometer laboratory tests of vehicles on the FTP and HWFE driving cycles, respectively. EPA also rates combined fuel economy of each vehicle, which is a composite value derived from fuel economy values from the FTP and HWFE tests. Certification levels emission rates based on the FTP tests were compared for $NO_x$, HC, and CO emission rates.

Cycle average emission rates based on FTP certification were compared to: (1) real-world cycle average emission rates using PEMS-based VSP modal emission rates; (2) FTP and HWFE cycle based average emission rates using PEMS-based VSP modal emission rates.

Average emission rates for different cycles were calculated for each tested vehicle using the PEMS-based VSP derived emission rates weighted by the fraction of time spent in each VSP mode for the driving cycles based on activity data, as per Equation (2).

## 2.7 Statistical Significance

Average modal fuel use and emission rates, and average fuel economy and tailpipe exhaust emission rates for real-world driving cycles, were calculated for each vehicle. The 95% confidence intervals on the mean values were simulated either using student t-distribution, or bootstrap simulation based on 1800 replications (Efron and Tibshirani, 1993). Bootstrap simulation was used because some of the underlying sample data were highly skewed due to inter-vehicle variability, and the sample data within 95% confidence intervals must be non-negative. An analytical solution assuming a symmetric student t-distribution could erroneously predict confidence intervals that include negative values.

The sampling distributions of mean ratios of GDI to PFI for cycle average fuel economy and emission rates were simulated using bootstrap simulation, based on 1800 replications. From the 1800 mean replicates for each GDI to PFI ratio, 95% confidence intervals of the ratios were estimated.

For comparison between each pair of mean values, such as mean modal rates or mean cycle average rates, the statistical significance of the comparison was evaluated using a two-tailed pairwise t-test. The null hypothesis ($H_0$) was that the mean difference is zero. $H_0$ was rejected if the p-value of t-test was 0.05 or less (Devore, 2016). Thus, p-value of 0.05 or less indicated that the mean difference was statistically significant. P-values that were slightly greater than 0.05, in the range of 0.05 to 0.10, were considered as being suggestive of comparisons that may become statistically significant with additional data. However, for p-values such as 0.2 or higher, the comparisons were considered statistically not significant.

For evaluating if the mean ratios of GDI to PFI for cycle average fuel economy and emission rates were different from 1, the 95% confidence interval of the ratios were used. If the 95% confidence interval did not include 1, the ratio was statistically significantly different from 1.

In some cases, comparison of cycle average fuel economy and emission rates between GDI and PFI was evaluated using both the statistical techniques mentioned above: (1) differences in mean values, using paired t-test; and (2) ratios of mean, using 95% confidence interval simulated by bootstrapping. These two methods are based on different statistical techniques. Whereas the paired t-test is based on parametric Student t-distribution, bootstrapping is based on non-parametric Monte-Carlo simulations. The two methods may not give the same result for significance, but if both indicate a significant comparison, such a comparison was interpreted as being robust to differences in the methods.

To evaluate the trend of vehicle characteristics, and modal and cycle average fuel use and emission rates between the sets of GDI and PFI vehicles, coefficient of determination ($R^2$) is estimated for a linear regression model. $R^2$ varies from 0 to 1. A high $R^2$ denotes high positive or negative correlation or synonymy of trends between GDI and PFI data sets.

# CHAPTER 3

## RESULTS AND DISCUSSION

The VSP modal average fuel use and emission rates versus VSP were quantified and compared between samples of GDI and PFI vehicles. The cycle average fuel economy and emissions rates were estimated and compared between samples of GDI and PFI vehicles. EPA fuel economy data and certification test results are presented and evaluated for differences between GDI and PFI vehicles.

### 3.1 Vehicle Characteristics and Ambient Conditions

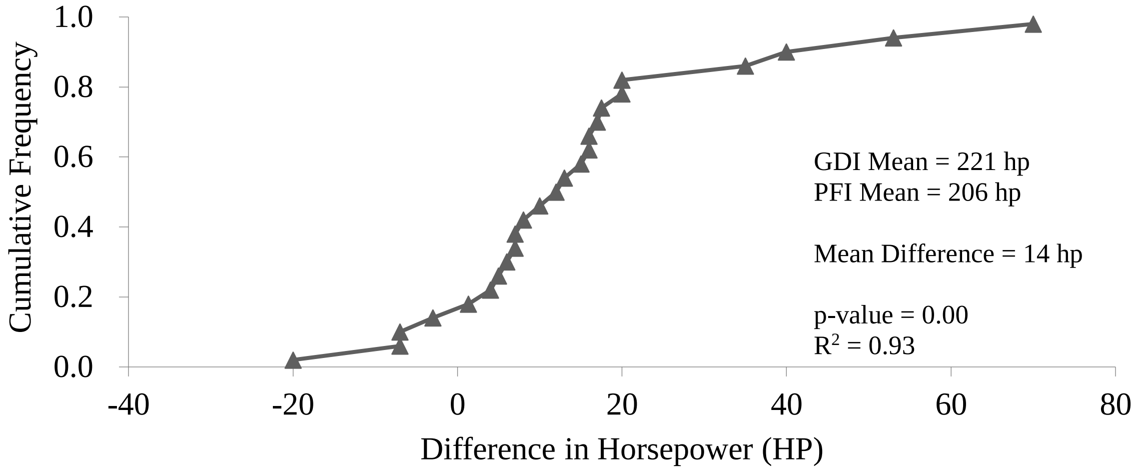
Data from 27 GDI vehicles and 32 PFI vehicles were used in the study. Twelve GDI and fifteen PFI vehicles were measured. Measured data for the remaining vehicles were obtained from previous studies done at NC State. Results are given for 25 paired comparisons, as detailed in Tables B1, B2, and B3 of Appendix B. Results are based on comparison of: 15 GDI vehicles, each versus one comparable PFI vehicle; 9 GDI vehicles, each versus the composite of two or more PFI vehicles; and one “composite GDI” vehicle consisting of three GDI vehicles, compared to a “composite PFI” vehicle. The 25 GDI “composite” vehicles are mutually exclusive of each other, however, 25 “composite” PFI vehicle are not mutually exclusive, i.e., results from some PFI vehicles are used in multiple “composite” PFI vehicles.

Cumulative distribution functions (CDF) in Figure 3 illustrate the comparison of selected characteristics of the 25 “composite” GDI and PFI vehicles used in the study, including differences in HP, curb weight, HP/lb ratio and compression ratio. Each observation is the difference between a paired GDI and PFI vehicle. Figure A1 in Appendix A shows the CDF for absolute HP, curb weight, HP/lb ratio and compression ratio. The HP of selected GDI vehicles ranges from 137 hp to 365 hp, and the HP of selected PFI vehicles ranges from 132 hp to 385 hp, as illustrated in Figure A1(a). The difference in HP between GDI and PFI vehicles ranges from -20 hp to +70 hp (Figure 3(a)). GDI vehicles have higher power in 21 out of the 25 pairs. GDI vehicles have, on average, 14 hp higher power for the selected set of vehicles, and the mean difference is statistically significant. This implies that GDI engines have higher HP for vehicles with similar-sized engine and chassis. The sets of paired GDI and PFI vehicles have high correlation in HP ($R^2 = 0.93$), indicating that the trend in HP for selected GDI and PFI vehicles is similar.

The curb weights of the selected GDI vehicles ranges from 2601 lb to 5545 lb versus 2798 lb to 5820 lb for the selected PFI vehicles, as illustrated in Figure A1(b). The frequency distributions in Figure A1(b) are visually similar. The mean curb weights of GDI and PFI vehicles are not significantly different, based on paired t-test. The range of differences in curb weights is -335 lb to +419 lb (Figure 3(b)). The mean difference between curb weights of the selected GDI and PFI vehicles is -11 lb. The trend in curb weight for selected GDI and PFI vehicles is similar, as indicated by the high correlation ($R^2 = 0.94$).

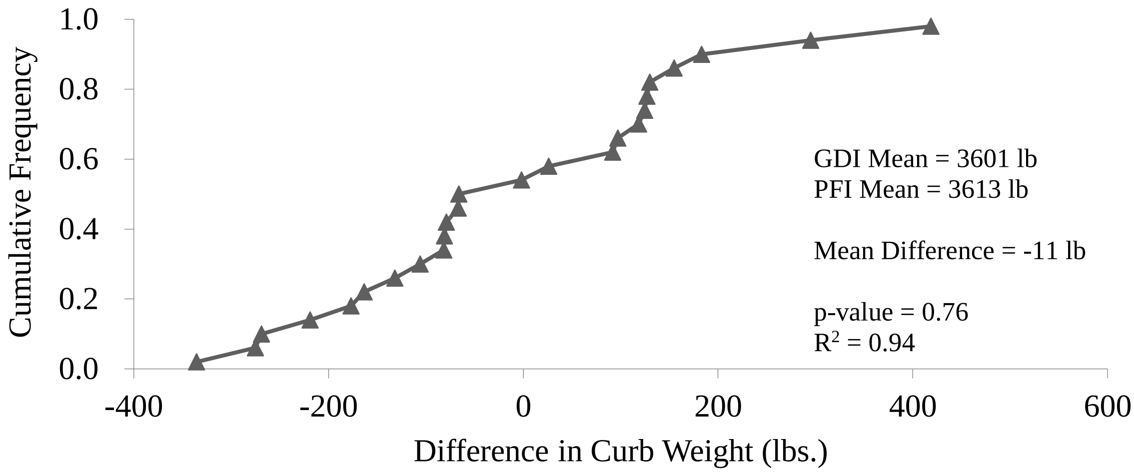
**Figure 3. CDF of differences between paired GDI and PFI vehicles (*GDI - PFI*), n = 25, in: (a) Horsepower; (b) Curb Weight; (c) HP/lb ratio; (d) Compression Ratio**

CDFs are plotted by ranking the difference between paired GDI and PFI vehicles from highest to lowest, and assigning cumulative frequency based on ranks, versus vehicle characteristics. P-value is calculated based on paired t-test on means, and $p<0.05$ signifies that the mean difference in vehicle characteristic is statistically significant. $R^2$ is the coefficient of determination for a linear regression model between the sets of 25 paired GDI and PFI vehicles.



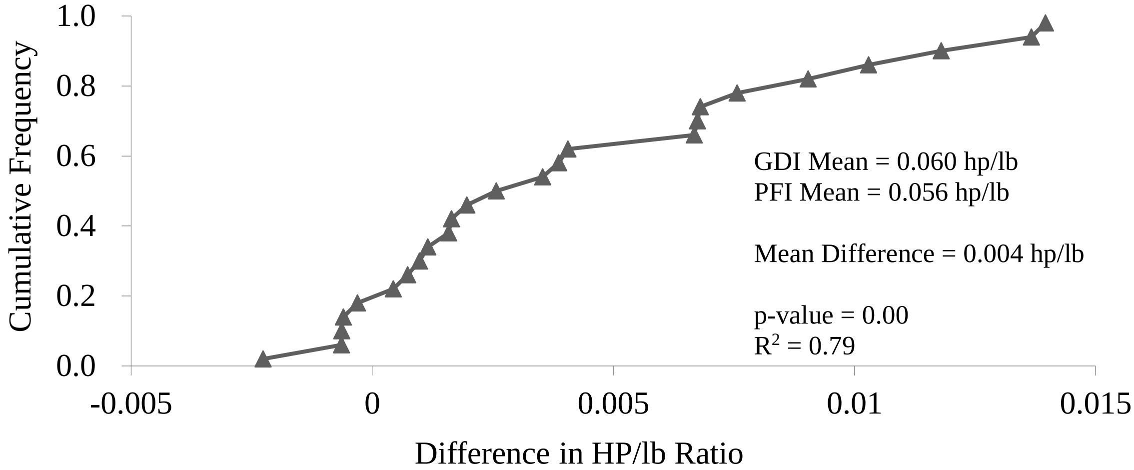
1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-40
-20
0
20
40
60
80
Difference in Horsepower (HP)
GDI Mean = 221 hp
PFI Mean = 206 hp
Mean Difference = 14 hp
p-value = 0.00
R2 = 0.93


**(a)**

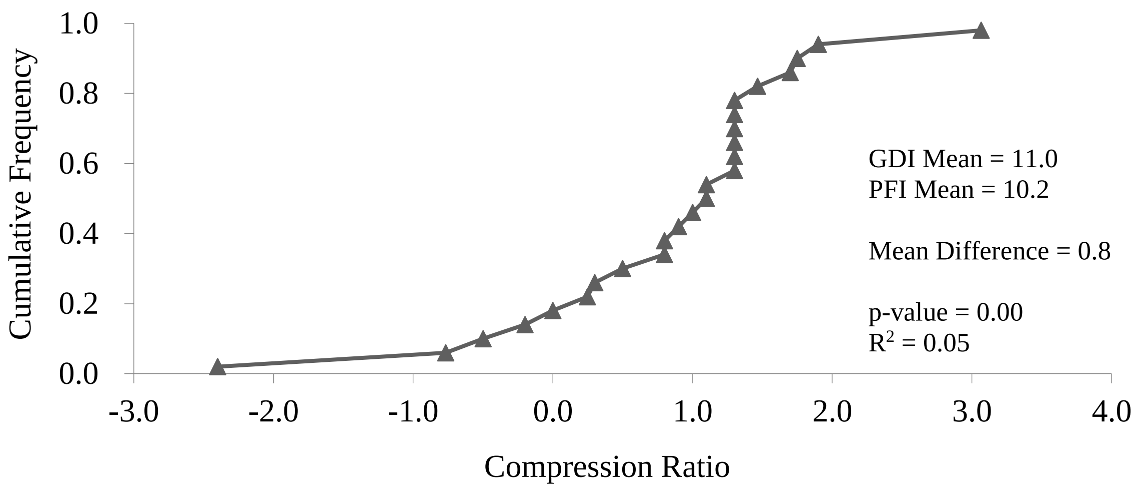


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-400
-200
0
200
400
600
Difference in Curb Weight (lbs.)
GDI Mean = 3601 lb
PFI Mean = 3613 lb
Mean Difference = -11 lb
p-value = 0.76
R2 = 0.94


**(b)**


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-0.005
0
0.005
0.01
0.015
Difference in HP/lb Ratio
GDI Mean = 0.060 hp/lb
PFI Mean = 0.056 hp/lb
Mean Difference = 0.004 hp/lb
p-value = 0.00
R2 = 0.79

**(c)**


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
Compression Ratio
GDI Mean = 11.0
PFI Mean = 10.2
Mean Difference = 0.8
p-value = 0.00
R2 = 0.05

**(d)**

The mean horsepower-to-weight ratio is statistically significantly higher by an average of 0.004 hp/lb for selected GDI vehicles than PFI vehicles (Figure 3(c)). The difference in horsepower-to-weight ratio ranges from -0.002 hp/lb to +0.014 hp/lb. Twenty out of 25 GDI vehicles have higher horsepower-to-weight ratio than the comparable PFI vehicles. The statistically significant difference implies that GDI vehicles, on average, have higher HP with similar curb weights. This indicates that by opting for GDI engines, auto-manufacturers are not downsizing the engines, but are providing extra power to the vehicles. Higher horsepower-to-weight ratio also confirms that the GDI vehicles have higher specific power, as is claimed in the existing literature (Anderson *et al.,* 1996; Zhao *et al.,* 1999; Wyszynski *et al.,* 2002). GDI vehicles, on average, have 7.5% higher specific power than comparable PFI vehicles. The high correlation ($R^2$ = 0.79) between horsepower-to-weight ratio for selected GDI and PFI vehicles indicates a balanced comparison.

The range of compression ratios for GDI vehicles is 9.3 to 13.0, and for PFI vehicles is 9.5 to 12.5 (Figure A1(d)). Figure 3(d) illustrates the difference in compression ratio for selected GDI and PFI vehicles. The difference in ratios ranges from -2.4 to +3.1. However, 21 GDI vehicles have higher compression ratio than comparable PFI vehicles, and, on average, GDI engines have 0.8 higher compression ratio. This difference is statistically significant. This indicates that GDI engines have higher compression ratio, as theorized in the literature (Anderson *et al.,* 1996; Zhao *et al.,* 1999; Wyszynski *et al.,* 2002; Oh *et al.,* 2010; Golzari *et al.,* 2016). Moreover, for the 4 paired vehicles for which GDI engines have lower compression ratio, the GDI engine is turbocharged, and the compared PFI engine is not turbocharged. It is inherent to the design of turbocharged engines to have lower compression ratio than similar naturally aspirated engines (Zhao *et al.*, 1999). This is due to the higher mass influx of air and fuel per combustion cycle in a turbocharged engine than a naturally aspirated engine, due to which the volume of charge is higher, and the engine generates more power. However, due to this, the compression ratio is designed to be lower, to prevent knocking (Zhao *et al.*, 1999).

Figure A1(e) in Appendix A shows the CDF of vehicle age at the time of measurement for the selected GDI and PFI vehicles. Vehicle age at the time of measurement ranged from 0 years to 7 years for selected GDI vehicles, and from 0 years to 5 years for selected PFI vehicles. However, 19 out of 25 composite GDI vehicles, and 17 out of 25 composite PFI vehicles are aged 1 year. The p-value of the difference between mean ages of GDI and PFI vehicles is 0.18, which indicates that the mean ages of GDI and PFI vehicles are not significantly different. The ranges of vehicle age for both GDI and PFI vehicles are not large enough to test for variability in fuel use and emission rates based on age.

Vehicles were not tested concurrently, and, therefore, the ambient conditions are different for each tested vehicle. Figure A2 in Appendix A shows the temperature and relative humidity (RH) for the measurements. The ambient temperature during measurements ranged from 37 °F to 91 °F, and the RH ranged from 27% to 100%. The mean temperature while measuring GDI vehicles was statistically significantly 8°F higher than the mean temperature while measuring PFI vehicles. The mean RH was, however, not different. Temperature and RH were not controllable in real-world testing conditions.

## 3.2 Driving Cycles

For the 27 selected GDI vehicles, an average of 11,510 seconds of valid 1 Hz data were available per vehicle. For the 32 selected PFI vehicles, an average of 11,649 seconds of valid 1 Hz data were available per vehicle. Each vehicle was measured on four real-world routes. Route A, which is a city driving cycle, has an average positive VSP of 6.87 kW/ton, and an average speed of 27.8 mph. Route A is comparable to the FTP standard cycle, which has an average positive VSP of 4.30 kW/ton, and an average speed of 21.2 mph. Route C, which is an alternative route to Route A, has an average positive VSP of 7.92 kW/ton, and an average speed of 30.2 mph. Route 1, which is a real-world highway driving cycle, has an average positive VSP of 13.33 kW/ton, and an average speed of 52.0 mph. Route 3, which is an alternative to Route 1, has an average positive VSP of 8.93 kW/ton, and an average speed of 33.7 mph. ‘All-Routes’, which is based on total 110-mile distance travelled, has an average positive VSP of 9.23 kW/ton, and an average speed of 34.9 mph. HWFE standard cycle has an average positive VSP of 7.55 kW/ton, and an average speed of 48.3 mph. HWFE cycle is comparable to Route 1 in terms of average speed, but has much lower average power demand.

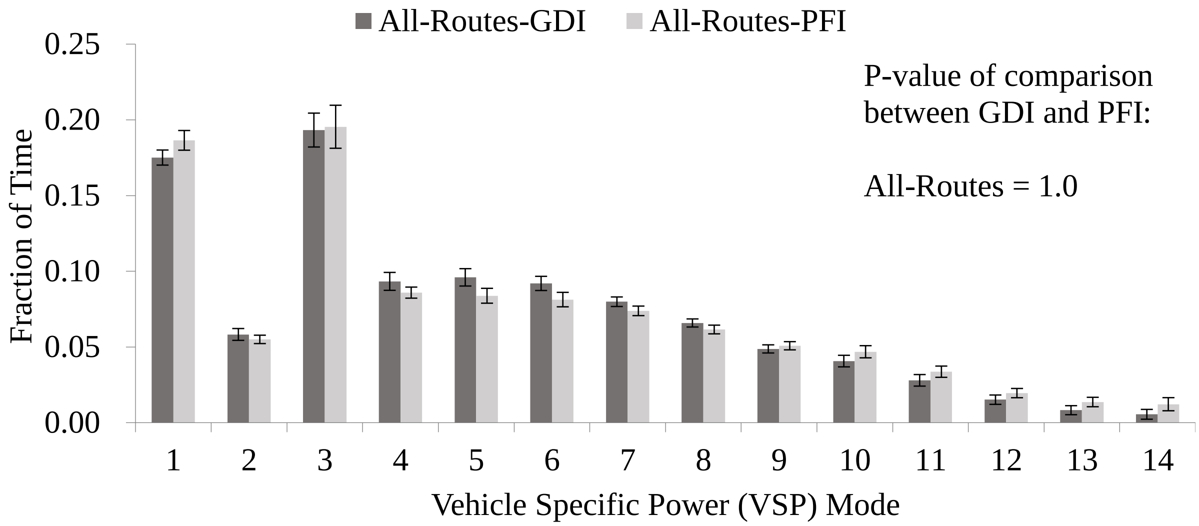
For comparing GDI and PFI vehicles, five different cycles have been selected from the real-world and standard driving cycles mentioned above: All-Routes, Route A, Route 1, FTP standard cycle, and HWFE standard cycle. Route A and Route 1 were selected out of the four real-world routes as they have, respectively, the lowest and highest average VSP and average speed. Route A and Route 1 are, therefore, expected to provide the upper and lower bounds on fuel use and emission rates, respectively.

The average driving cycle for each route is based on the average fraction of time spent in each of the 14 VSP modes, and the average total travel time for that cycle. Based on the real-world driving data from measurements of the 27 GDI vehicles and 32 PFI vehicles, the average driving cycles for All-Routes, Route A, and Route 1 are shown in Figure 4(a), 4(b) and 4(c), respectively. The overall average driving cycle for a given route was calculated based on average of all GDI and PFI vehicles which satisfied the data completeness criterion of 95% valid data.

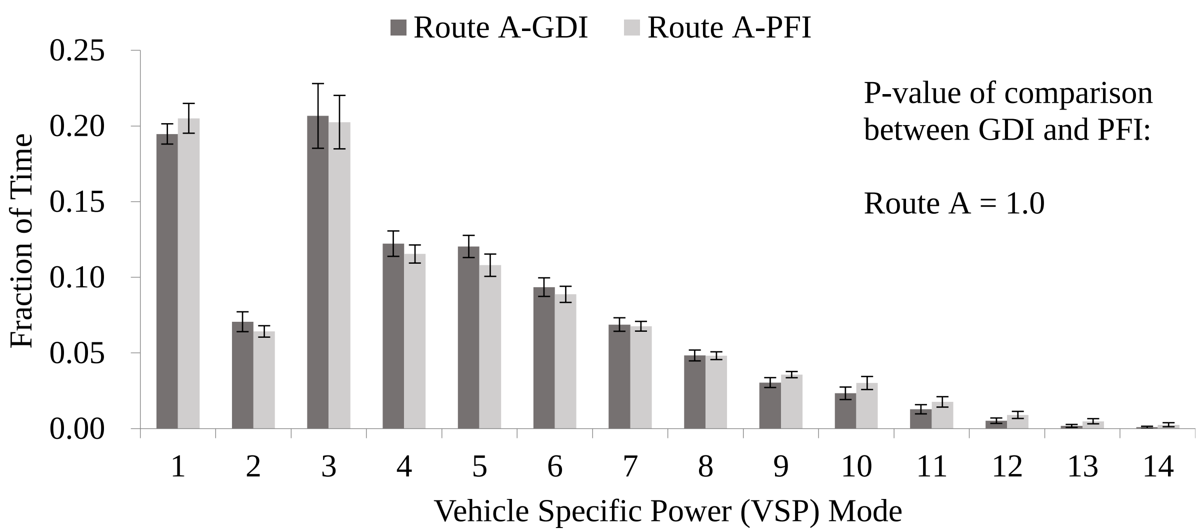
Based on paired t-tests, the average driving cycles for GDI vehicles and PFI vehicles were determined to be similar for All-Routes, Route A, and Route 1, with p-values > 0.05 for all three routes. The overall average real-world driving cycles (n=59), along with U.S. EPA standard driving cycles, are given in Table 4. The FTP standard cycle in Table 4 includes all three "bags", as defined by the U.S. EPA, but not the FTP cold-start cycle. The overall average driving cycles have been estimated to enable comparison of GDI and PFI vehicles on a consistent basis, by averaging out the inter-run variability of cycles, which may depend on factors such as traffic conditions and driver aggressiveness.

**Figure 4. Average Driving Cycles in Terms of Fraction of Time in Each VSP Mode: (a) All-Routes; (b) Route A; and (c) Route 1**

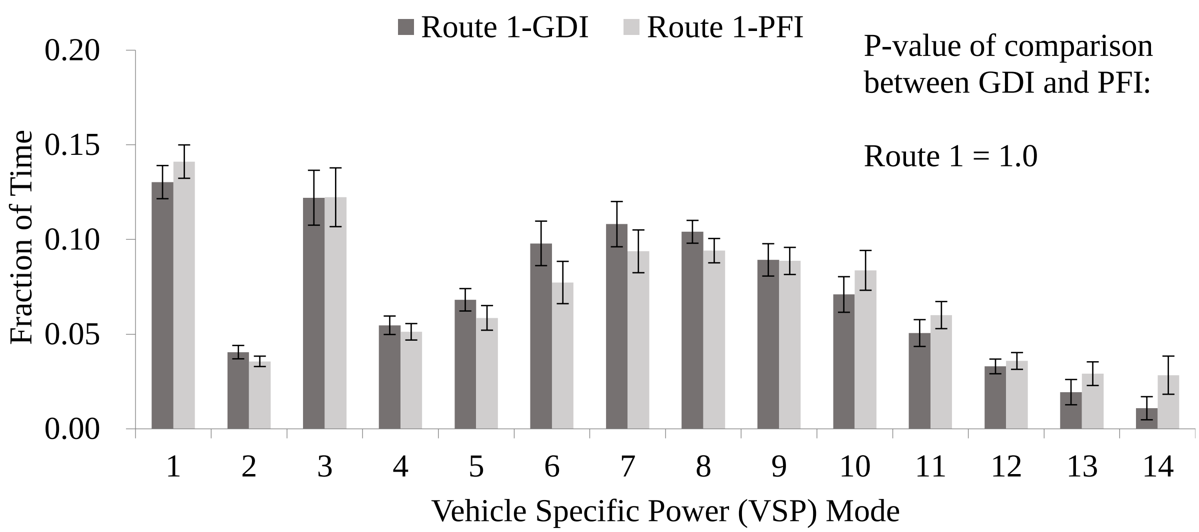
GDI vehicles (n = 27) and PFI vehicles (n = 32). Error bars shown here are 95% confidence intervals estimated using student t-distribution.


All-Routes-GDI
All-Routes-PFI
P-value of comparison
between GDI and PFI:
All-Routes = 1.0
Fraction of Time
Vehicle Specific Power (VSP) Mode
0.25
0.20
0.15
0.10
0.05
0.00
1
2
3
4
5
6
7
8
9
10
11
12
13
14

**(a)**


Route A-GDI
Route A-PFI
P-value of comparison
between GDI and PFI:
Route A = 1.0
Fraction of Time
Vehicle Specific Power (VSP) Mode
0.25
0.20
0.15
0.10
0.05
0.00
1
2
3
4
5
6
7
8
9
10
11
12
13
14

**(b)**


Route 1-GDI
Route 1-PFI
P-value of comparison between GDI and PFI:
Route 1 = 1.0
0.20
0.15
0.10
0.05
0.00
Fraction of Time
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Vehicle Specific Power (VSP) Mode

**(c)**

**Table 4. Overall Average Driving Cycles in Terms of Percent of Time in Each VSP Mode**

| VSP Mode | VSP Range (kW/ton) | Percent of Time in Each VSP Mode for Driving Cycle (%) | | | | |
|---|---|---|---|---|---|---|
| | | **All-Route** | **Route A** | **Route 1** | **FTP** | **HWFE** |
| 1 | VSP < -2 | 18.1 | 20.0 | 13.6 | 15.0 | 7.2 |
| 2 | -2 ≤ VSP < 0 | 5.7 | 6.8 | 3.8 | 7.9 | 2.2 |
| 3 | 0 ≤ VSP < 1 | 19.4 | 20.5 | 12.2 | 23.9 | 2.5 |
| 4 | 1 ≤ VSP < 4 | 9.0 | 11.9 | 5.3 | 20.0 | 10.1 |
| 5 | 4 ≤ VSP < 7 | 9.0 | 11.4 | 6.3 | 15.3 | 26.8 |
| 6 | 7 ≤ VSP < 10 | 8.7 | 9.1 | 8.8 | 8.0 | 32.7 |
| 7 | 10 ≤ VSP < 13 | 7.7 | 6.8 | 10.1 | 5.5 | 12.7 |
| 8 | 13 ≤ VSP < 16 | 6.4 | 4.8 | 9.9 | 2.7 | 4.7 |
| 9 | 16 ≤ VSP < 19 | 5.0 | 3.3 | 8.9 | 0.9 | 0.9 |
| 10 | 19 ≤ VSP < 23 | 4.4 | 2.7 | 7.7 | 0.5 | 0.3 |
| 11 | 23 ≤ VSP < 28 | 3.1 | 1.5 | 5.5 | 0.3 | 0.0 |
| 12 | 28 ≤ VSP < 33 | 1.7 | 0.7 | 3.4 | 0.0 | 0.0 |
| 13 | 33 ≤ VSP < 39 | 1.1 | 0.3 | 2.4 | 0.0 | 0.0 |
| 14 | 39 ≤ VSP | 0.9 | 0.2 | 1.9 | 0.0 | 0.0 |

*Note: Overall Average Driving Cycles for All-Route, Route A and Route 1 are based on the average of 59 selected GDI and PFI vehicles. FTP and HWFE cycles are taken from data published by U.S. EPA* (U.S. EPA, 2017). *Average positive VSP in kW/ton for: All-Route = 9.23, Route A = 6.87, Route 1 = 13.33, FTP = 4.30, and HWFE = 7.55.*

Modes 1 and 2, which represent deceleration or moving downhill, account for 17% to 27% of total travel time, depending on the real-world cycle (Table 4). Mode 3, which represents idling, has the most amount of time out of all modes for All-Routes and Route A driving cycles. Time spent in mode 3 for real-world cycles ranges from 12% to 20%. Moderate VSP modes, modes 4 to 11, account for 52% to 63% of total travel time, and represent time spent in steady-speed cruising, acceleration or climbing uphill. High VSP modes, modes 12 to 14, which represent cruising at high speed (>50 mph), acceleration or climbing uphill, account for 1% to 8% of total travel time.

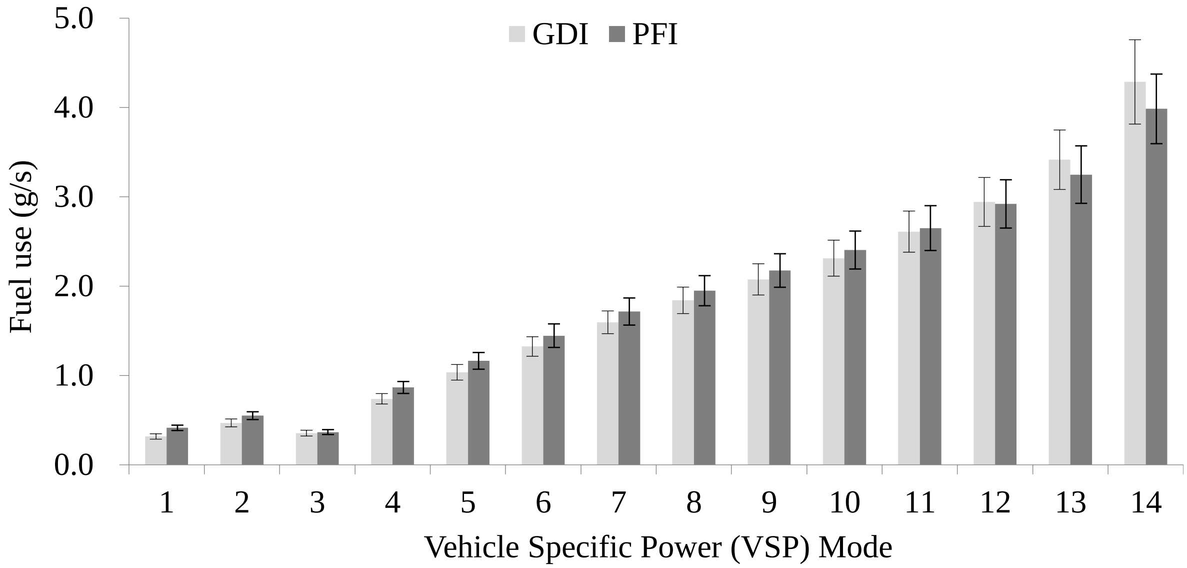
Vehicles tested in lab-based chassis dynamometer tests on FTP standard cycle spend no time in modes 12 to 14, and on HWFE standard cycle spend no time in modes 11 to 14. This indicates that these cycles do not fully capture real-world driving conditions.

### 3.3 Modal Fuel Use and Emission Rates

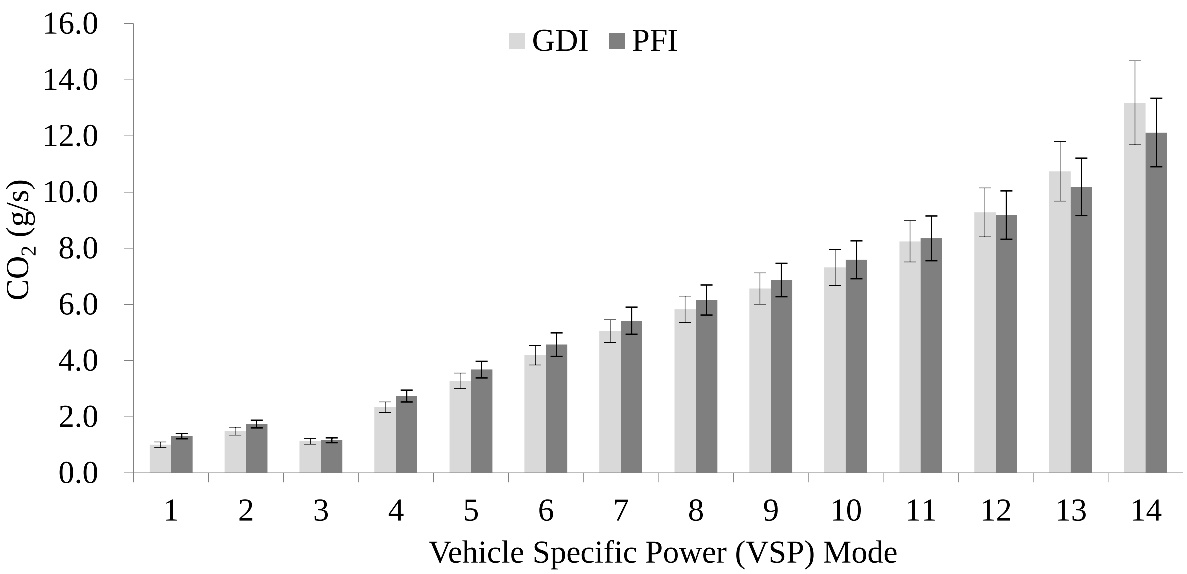
Modal average fuel use, and $CO_2$, NO, and CO emission rates based on 25 “composite GDI” and 25 “composite PFI” vehicles are shown in Figure 5. HC emission rates shown in Figure 5(e) are based on 24 “composite GDI” and 24 composite PFI vehicles. HC emissions data from one pair of vehicle was erroneous. PM emissions were measured for only 4 pairs of composite GDI and composite PFI vehicles. The results for PM emission rates are presented in Figure 5(f).

**Figure 5. Average VSP Modal Rates for (a) Fuel Use; (b) $CO_2$; (c) NO as $NO_2$; (d) CO; (e) HC; and (f) PM for selected GDI and PFI vehicles**

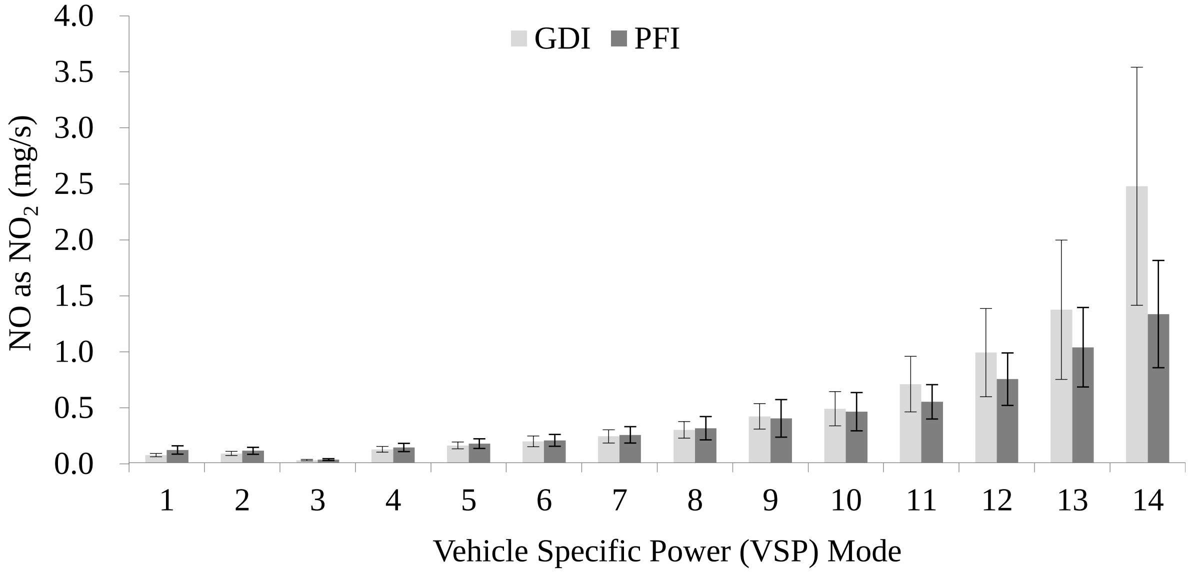
(a) Fuel Use (n = 25 “Composite GDI” and n = 25 “Composite PFI” vehicles); (b) $CO_2$ (n = 25 “Composite GDI” and n = 25 “Composite PFI” vehicles); (c) NO as $NO_2$ (n = 25 “Composite GDI” and n = 25 “Composite PFI” vehicles); (d) CO (n = 25 “Composite GDI” and n = 25 “Composite PFI” vehicles); (e) HC (n = 24 “Composite GDI” and n = 24 “Composite PFI” vehicles); and (f) PM (n = 4 “Composite GDI” and n = 4 “Composite PFI” vehicles). Error bars shown are 95% confidence intervals on mean values, simulated using Bootstrap Simulation.


GDI
PFI
Fuel use (g/s)
5.0
4.0
3.0
2.0
1.0
0.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Vehicle Specific Power (VSP) Mode

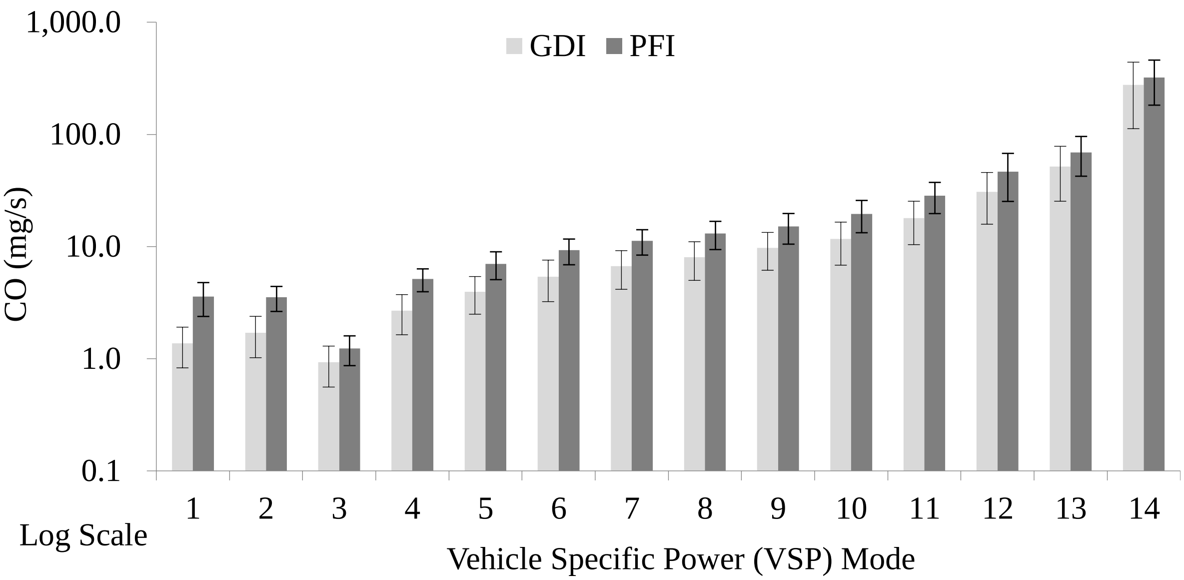
**(a)**


GDI
PFI
$CO_2$ (g/s)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Vehicle Specific Power (VSP) Mode

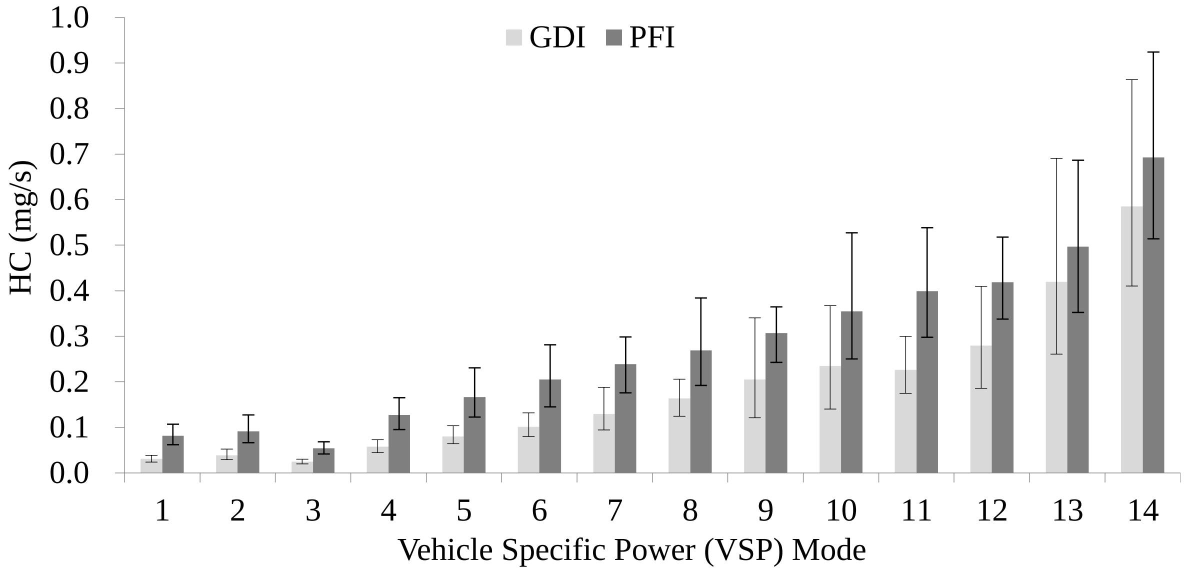
**(b)**


GDI
PFI
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
NO as $NO_2$ (mg/s)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Vehicle Specific Power (VSP) Mode

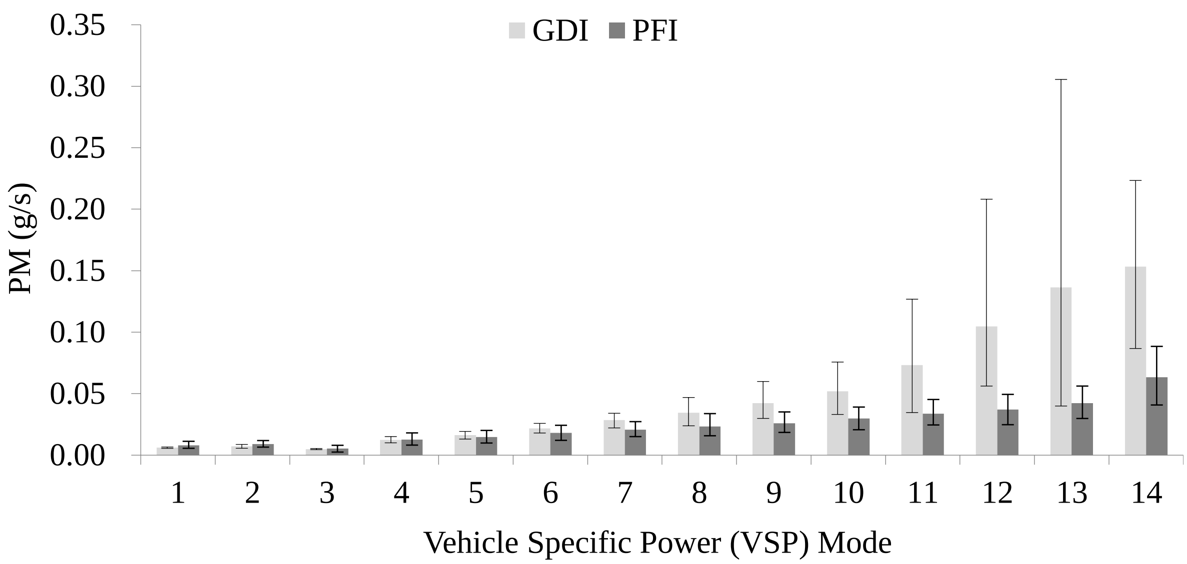
**(c)**


GDI
PFI
1,000.0
100.0
10.0
1.0
0.1
CO (mg/s)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Log Scale
Vehicle Specific Power (VSP) Mode

**(d)**


GDI
PFI
HC (mg/s)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Vehicle Specific Power (VSP) Mode

**(e)**


GDI
PFI
PM (g/s)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Vehicle Specific Power (VSP) Mode

**(f)**

Figure 5 illustrates that fuel use and emission rates are sensitive to VSP, which is an indicator of engine load, for both GDI and PFI vehicles. For GDI vehicles, the modal average fuel use rate increases monotonically with positive VSP for modes 3 to 14. In mode 1, which corresponds to negative VSP and represents deceleration or moving downhill, and in mode 3, which represents idling, GDI vehicles have average fuel use rates of 0.32 g/s and 0.36 g/s, respectively. For mode 2, which represents deceleration or moving downhill, the average fuel use rate is slightly higher at 0.47 g/s. The mode 2 fuel use rate is likely influenced by coupling between the engine and automatic transmission such that the engine is operating at elevated RPM even though it is not under load. For example, for the 2016 Ford F150 GDI, the average engine RPM in mode 1 and 2 were 1130 rpm and 1070 rpm, respectively, and the average vehicle speeds in mode 1 and 3 were 35 mph and 27 mph, respectively. Even though the average engine RPM and vehicle speed are higher in mode 1 than mode 2, the fuel use for mode 2 is 0.22 g/s higher than mode 1 for the Ford 150 GDI. For $1 \leq VSP < 28$ kW/ton in modes 4 to 11, which represent cruising, acceleration, or hill climbing, GDI vehicles have monotonically increasing average fuel use rates from 0.74 to 2.61 g/s. For $VSP \geq 28$ kW/ton in modes 12 to 14, which represent cruising at high speed (> 50 mph), acceleration or climbing uphill, the average fuel use rate increases from 2.94 to 4.29 g/s.

Fuel use rates of PFI vehicles are also sensitive to VSP. Modal average fuel use rates increase monotonically with positive VSP in modes 3 to 14 for both PFI and GDI. The average emission rates differ for GDI compared to PFI vehicles. These differences are statistically significant for modes 1, 2, and 4 to 8. For these VSP modes, the GDI vehicles have significantly lower fuel use rates by 6% to 23% compared to PFI vehicles. The largest relative differences are for modes 1, 2 and 4. At mode 3, or idling, GDI and PFI vehicles have a similar average fuel use rate. In modes 9 to 14, the differences in fuel use rates are not statistically significant. For modes 12 to 14, the modal average fuel use rates for GDI vehicles, are higher, but not significantly higher, compared to PFI vehicles. Thus, although the GDI vehicles have significantly lower fuel use rates at low power demand, they do not have significantly lower rates at high power demand. Therefore, fuel economy advantage for GDI vehicles is likely to be more pronounced for driving cycles with lower average power demand, or a high proportion of time in modes 1 to 8, compared to other cycles. The relative trend of $CO_2$ emission rates is similar to that of fuel use rates, since typically, over 99% of the carbon in the fuel is emitted as $CO_2$.

The modal average $NO_x$ emission rates increase nonlinearly with positive VSP, especially for modes 10 to 14, for both GDI and PFI vehicles, indicating that $NO_x$ emission rates are sensitive to higher power demand. On average, GDI vehicles have consistently lower $NO_x$ emission rates than PFI vehicles for modes 1 to 8, and consistently higher $NO_x$ emission rates for modes 9 to 14. $NO_x$ emission rates of GDI vehicles in modes 1 to 8 are lower by 4% to 37%, whereas in mode 9 to 14 are higher by 4% to 85%. However, these differences are significant for only two modes: in mode 1, GDI vehicles have 37% lower $NO_x$ emission rate ($p = 0.01$), and in mode 14, GDI vehicles have 85% higher $NO_x$ emission rate ($p = 0.03$).

In mode 1, which corresponds to negative power demand, the engine is typically operating at lean overall air-fuel ratio. For example, air-fuel ratio in mode 1 for 2017 Kia

Optima GDI was 32.3. Lower $NO_x$ emission rate of GDI versus PFI engines can be explained by the stratification of charge in GDI engines, resulting in lower overall temperature compared to PFI engines in lean burning conditions at low engine loads. In mode 14, which corresponds to the highest power demand, the engine is typically operating in overall fuel-rich conditions (< 14.7:1). For example, air-fuel ratio in mode 14 for 2017 Toyota Camry PFI, which is comparable to the 2017 Kia Optima GDI, was 14.5. PFI engines typically need to run under more fuel-rich condition to meet the higher power demand, compared to GDI engines. The air-fuel ratio in mode 14 for 2017 Kia Optima GDI was 14.7. GDI engines can have lower air-fuel ratio in fuel-rich pockets with stratification of charge, and still allow operation at slightly leaner overall air-fuel ratio compared to PFI engines. Higher $NO_x$ emissions from GDI versus PFI engines at high engine loads are counter-intuitive, due to staged combustion in GDI engines. Since GDI engines typically have higher specific power compared to PFI engines, and the power of a gasoline engine is positively correlated to the difference in temperature between the end and beginning of the power stroke, a possible reason for higher $NO_x$ emission rate at high engine load may be the higher overall temperature of combustion in GDI engines. However, higher $NO_x$ at high load for GDI engines compared to PFI engines needs further investigation. Whether cycle average $NO_x$ emission rates are lower or higher for GDI versus PFI vehicles will depend on the distribution of time among the VSP modes.

The modal average CO emission rates increase nonlinearly with positive VSP, especially for modes 12 to 14, for both GDI and PFI vehicles, indicating that CO emission rates are sensitive to higher power demand. On average, GDI vehicles have consistently lower

CO emission rates than PFI vehicles, for all modes, by 14% to 62%. GDI vehicles have statistically significantly lower CO emission rates in mode 1 and 2 by 62% and 52%, respectively. In mode 3, GDI vehicles have 25% lower CO emission rates than PFI vehicles, but the p-value is > 0.05, indicating that the difference is not significant. GDI vehicles also have statistically significantly lower CO emission rates in modes 4 to 8 by 39% to 48%. For modes 9 to 11, differences vary from 35% to 40%, and the p-values are 0.06, which are marginally higher than significance level of 0.05. Modal average CO emission rates for GDI vehicles are also lower for modes 12 to 14. However, the results are not statistically significant. Lower CO emissions for GDI versus PFI vehicles can be explained on the basis of more precise air-fuel ratio control in GDI engines (Zhao *et al.,* 1999).

For both GDI and PFI vehicles, the modal average CO emission rate for VSP mode 14 is more than four times as high as the mode 13 emission rate, and an order of magnitude higher than for the other VSP modes. Oxidation of CO to $CO_2$ in the catalytic converter is exothermic and depends on availability of sufficient oxygen. Under short-term conditions of high power demand, vehicles with catalytic converters will operate with a fuel-rich mixture of air and fuel to reduce the exhaust oxygen concentration, which reduces the fraction of CO oxidized to $CO_2$, and prevents overheating of the catalyst. This is known as open-loop operation (Nose *et al.*, 2013). For example, air-fuel ratio in both modes 13 and 14 for 2016 Ford F150 GDI is 14.6, and air-fuel ratio in modes 13 and 14 for 2016 Ford F150 PFI is 14.7 and 14.6, respectively. Both GDI and PFI vehicles seem to operate in open-loop mode for VSP modes 13 and 14. However, the average CO emission rate in mode 14 is 14% lower for GDI vehicles than PFI vehicles. The difference is not significant. However, lower CO emission rate in GDI engines for higher engine load, under fuel-rich condition, seems consistent with literature, as stratification of charge enables better post-flame oxidation in GDI engines, compared to PFI engines (Zhao *et al.*, 1999).

The modal average HC emission rates for both GDI and PFI vehicles are less sensitive to power demand than emission rates for other pollutants. For example, for GDI vehicles, the ratio of the highest to lowest modal average rate for HC is only 19, whereas for $NO_x$ it is 32 and for CO it is 202. Average modal HC emission rates for GDI and PFI vehicles increase non-linearly with positive VSP. For modes 3 to 14, HC emission rates increase from 0.02 mg/s to 0.59 mg/s for GDI vehicles, and from 0.08 g/s to 0.69 mg/s for PFI vehicles. For all VSP modes, GDI vehicles emit consistently lower HC. For modes 1 to 12, the GDI vehicles have significantly lower HC emission rates by 33% to 66%, compared to PFI vehicles. For modes 13 and 14, GDI vehicles have lower HC emission rates by 15% and 16%, respectively, compared to PFI vehicles. Differences in modes 13 and 14 are, however, not statistically significant. HC emission rates indicate that GDI engines have better air-fuel ratio control, and lower surface fuel-wetting than PFI engines, for all VSP modes.

Modal average PM emission rates for GDI vehicles are more sensitive to power demand than for PFI vehicles. The ratio of the highest to lowest modal average rate for PM for GDI vehicles is 25, whereas for PFI vehicles the ratio is 8. PM emission rates for GDI vehicles are lower than PFI vehicles for VSP modes 1 to 4 by 2% to 25%. For modes 5 to 14, GDI vehicles have higher PM emission rates by 9% to 223%. These differences are, however, not statistically significant due to small sample size. With a larger sample size, it is expected that differences in PM emission rates would have been significant.

### 3.4 Cycle Average Fuel Use and Emission Rates

The cycle average fuel use and $CO_2$, $NO_x$, CO, HC and PM emission rates, based on average VSP modal rates, and selected real-world driving cycles and standard cycles are given in Table 5 for GDI and PFI vehicles.

GDI vehicles have significantly higher fuel economy compared to PFI vehicles for all driving cycles. GDI vehicle fuel economy is 5.7% higher on Route 1, which is a freeway riving cycle, and 13.1% higher on the FTP standard cycle, which is a city driving cycle. The fuel economy advantage of GDI over PFI vehicles is sensitive to the driving cycle. Driving cycles with lower average power demand, such as Route A, the FTP cycle and the HWFE cycle have more fuel economy advantage for GDI versus PFI vehicles than cycles with higher average power demand, such as Route 1 and All-Routes.

**Table 5. Comparison of GDI versus PFI Vehicle Cycle Average Fuel Use and Emission Rates by Route: (a) Fuel Economy; (b) $CO_2$; (c) $NO_x$; (d) CO; (e) HC; (f) PM**

**(a) Fuel Economy (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles)**

| Route | Cycle Average VSP (kW/ton) | Fuel Economy (mpg) | | | |
|---|---|---|---|---|---|
| | | GDI | PFI | % Difference | p-value |
| A (City) | 6.87 | 24.6 | 22.2 | 10.6 | 0.01 |
| FTP-weighted | 4.30 | 22.6 | 20.0 | 13.1 | 0.00 |
| 1 (Freeway) | 13.33 | 29.0 | 27.5 | 5.7 | 0.04 |
| HWFE-weighted | 7.55 | 34.1 | 30.8 | 10.8 | 0.01 |
| All-Routes | 9.23 | 26.1 | 24.1 | 8.2 | 0.01 |

**(b) $CO_2$ (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles)**

| Route | Cycle Average VSP (kW/ton) | $CO_2$ (g/mi) | | | |
|---|---|---|---|---|---|
| | | GDI | PFI | % Difference | p-value |
| A (City) | 6.87 | 372 | 407 | -8.6 | 0.01 |
| FTP-weighted | 4.30 | 407 | 454 | -10.4 | 0.00 |
| 1 (Freeway) | 13.33 | 315 | 331 | -4.7 | 0.08 |
| HWFE-weighted | 7.55 | 269 | 296 | -9.2 | 0.01 |
| All-Routes | 9.23 | 351 | 376 | -6.7 | 0.02 |

**(c) $NO_x$ (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles)**

| Route | Cycle Average VSP (kW/ton) | $NO_x$ (g/mi) | | | |
|---|---|---|---|---|---|
| | | GDI | PFI | % Difference | p-value |
| A (City) | 6.87 | 0.022 | 0.023 | -5 | 0.66 |
| FTP-weighted | 4.30 | 0.021 | 0.024 | -12 | 0.27 |
| 1 (Freeway) | 13.33 | 0.023 | 0.021 | 12 | 0.49 |
| HWFE-weighted | 7.55 | 0.014 | 0.015 | -8 | 0.52 |
| All-Routes | 9.23 | 0.023 | 0.022 | 4 | 0.79 |

**Table 5 continued**

**(d) CO (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles)**

| Route | Cycle Average VSP (kW/ton) | CO (g/mi) | | | |
|---|---|---|---|---|---|
| | | GDI | PFI | % Difference | p-value |
| A (City) | 6.87 | 0.58 | 0.97 | -40 | 0.01 |
| FTP-weighted | 4.30 | 0.50 | 0.89 | -44 | 0.01 |
| 1 (Freeway) | 13.33 | 0.91 | 1.29 | -30 | 0.08 |
| HWFE-weighted | 7.55 | 0.34 | 0.60 | -43 | 0.01 |
| All-Routes | 9.23 | 0.79 | 1.19 | -33 | 0.04 |

**(e) HC (n = 24 "Composite GDI" and n = 24 "Composite PFI" vehicles)**

| Route | Cycle Average VSP (kW/ton) | HC (g/mi) | | | |
|---|---|---|---|---|---|
| | | GDI | PFI | % Difference | p-value |
| A (City) | 6.87 | 0.010 | 0.019 | -48 | 0.00 |
| FTP-weighted | 4.30 | 0.010 | 0.021 | -52 | 0.00 |
| 1 (Freeway) | 13.33 | 0.009 | 0.016 | -40 | 0.00 |
| HWFE-weighted | 7.55 | 0.007 | 0.013 | -50 | 0.00 |
| All-Routes | 9.23 | 0.010 | 0.018 | -44 | 0.00 |

**(f) PM (n = 4 "Composite GDI" and n = 4 "Composite PFI" vehicles)**

| Route | Cycle Average VSP (kW/ton) | PM (g/mi) | | | |
|---|---|---|---|---|---|
| | | GDI | PFI | % Difference | p-value |
| A (City) | 6.87 | 0.0022 | 0.0018 | 27 | 0.22 |
| FTP-weighted | 4.30 | 0.0022 | 0.0020 | 9 | 0.72 |
| 1 (Freeway) | 13.33 | 0.0023 | 0.0014 | 69 | 0.10 |
| HWFE-weighted | 7.55 | 0.0014 | 0.0012 | 19 | 0.47 |
| All-Routes | 9.23 | 0.0023 | 0.0016 | 46 | 0.11 |

*Note: FTP-weighted and HWFE-weighted denote cycle average rates for FTP standard and HWFE standard cycles, respectively. Values for standard cycles are calculated using average modal fuel use and emission rates, and fraction of time in each driving mode, using equation (2). P-values are calculated based on paired t-test on means, and $p < 0.05$ signifies that the difference is statistically significantly.*

*Percentage difference is value of* $\frac{GDI-PFI}{PFI}$%.

Significantly lower fuel rates of GDI vehicles in modes 1 to 8 compared to PFI vehicles, translate to higher fuel economy advantage of GDI versus PFI vehicles for cycles that have a higher proportion of travel time in these modes. The proportion of total travel time in low power demand modes 1 through 8 is 91.3% for Route A, 70.1% for Route 1, and 83.9% for All-Routes. Concomitantly, the fuel economy advantage of GDI vehicles is highest for Route A, and lowest for Route 1, amongst the selected real-world driving cycles. Route 1 has 7.1% of total travel time in modes 12 to 14, in which the GDI vehicles tend to be less fuel efficient than PFI vehicles, although not significantly. In contrast, Route A and All-Routes have 1.2% and 3.7% of total travel time in modes 12 to 14, respectively.

The proportion of total travel time in low power demand modes 1 through 8 is 98.3% for the FTP cycle, and 99.0% for the HWFE cycle. However, the fuel economy advantage of GDI versus PFI vehicles is higher for the FTP cycle. This is because the FTP cycle has 59.0% of total travel time in modes 1, 2 and 4, compared to the HWFE cycle, which has 19.9% of total travel time in these modes. GDI vehicles have 23%, 15% and 15% lower fuel use compared to PFI vehicles in modes 1, 2 and 4, respectively. These modes have the highest fuel economy advantage for GDI vehicles amongst modes 1 to 8.

The fuel economy advantage of GDI versus vehicles is more pronounced for standard cycles than for real-world cycles. This is because the FTP and HWFE cycles have no time in modes 12 to 14, and, thus, are not representative of real-world driving. The fuel economy advantage of GDI versus PFI vehicles may be overestimated by using FTP and HWFE standard cycles.

The trend in cycle average $CO_2$ emission rates is qualitatively the same as for fuel use. GDI vehicles have consistently lower cycle average $CO_2$ emission rates than PFI vehicles. The $CO_2$ emission rates for GDI versus PFI vehicles ranges from 4.7% lower for Route 1 to 10.4% lower for the FTP cycle. These differences are statistically significant, except for Route 1, for which the p-value of 0.08 is marginally higher than a significant value. Differences in $CO_2$ emission rates for GDI and PFI vehicles are higher for cycles with lower average power demand, such as Route A, the FTP cycle and the HWFE cycle, and is lower for cycles with higher average power demand, such as Route 1 and All-Routes.

Cycle average $NO_x$ emission rates are lower for GDI vehicles compared to PFI vehicles for Route A, the FTP cycle and the HWFE cycle by 5% to 12%, and are higher for Route 1 and All-Routes by 12% and 4%, respectively. However, these differences are not statistically significant. At lower power demand in VSP modes 1 to 8, the modal average $NO_x$ emission rates are lower for GDI, whereas, at higher power demand in modes 9 to 14, the modal average $NO_x$ emission rates are higher. Thus, for driving cycles such as Route A, the FTP cycle and the HWFE cycle, which have lower average power demand and have 1.0% to 8.7% of total time spent in modes 9 to 14, the average $NO_x$ emission rates are lower for GDI than PFI. In contrast, for driving cycles, such as Route 1 and All-Routes, that have higher average power demand and the proportion of total time spent in modes 9 to 14 ranges from 16.1% to 29.9%, the cycle average $NO_x$ emissions are higher for GDI.

Cycle average CO emission rates of GDI versus PFI vehicles are consistently lower for all driving cycles, ranging from 30% lower for Route 1, to 44% lower for the FTP cycle. These differences are statistically significant ($p < 0.05$), except for Route 1, for which the p-value of 0.08 is marginally higher than a significant value. The difference in cycle average CO emission rates of GDI and PFI vehicles is sensitive to driving cycles. For cycles with lower average power demand, such as Route A, FTP cycle and HWFE cycle, the difference in CO average emission rates is higher. This is because the difference in VSP modal average CO emission rates between GDI and PFI vehicles is significantly higher in modes 1, 2, and 4 to 8, and Route A, the FTP cycle and the HWFE cycle have 70.8%, 74.4% and 96.6% of total travel time in these modes, respectively. Cycles with higher average power demand, such as Route 1 and All-Routes have lower proportion of total travel time (57.8% and 64.4%) in modes 1, 2, and 4 to 8, and have higher proportion of travel time in modes 12 to 14 when compared to Route A, the FTP cycle and the HWFE cycle, resulting in a lower difference in cycle average CO emission rates between GDI and PFI vehicles.

Cycle average HC emission rates for GDI vehicles are consistently lower than PFI vehicles for all driving cycles. Cycle average HC emission rates for GDI vehicles are less sensitive to driving cycles than other pollutants. This is because HC modal average emission rates for GDI vehicles are less sensitive to VSP than other pollutants. Cycle average emission rates for PFI vehicles, however, are sensitive to driving cycles. Difference between GDI and PFI vehicles varies from 40% for Route 1 to 52% for FTP cycle. Differences for all cycles are significant. Differences are higher for cycles with lower average power demand, such as Route A, FTP cycle and HWFE cycle, which have higher proportion of travel time in modes 1 to 12, varying from 99.5% to 100%. Differences are lower for cycles with higher average power demand, such as Route 1 and All-Routes, which have lower proportion of travel time in modes 1 to 12, varying from 95.6% to 98.0%.

Cycle average PM emissions rates for GDI vehicles are higher than PFI vehicles for all driving cycles. Differences range from 9% for FTP cycle to 69% for Route 1. Differences are, however, not statistically significant. Difference in PM emission rates seem highly sensitive to driving cycle. For cycles with lower average power demand, such as Route A, FTP cycle and HWFE cycle, the difference is lower, varying from 9% to 27%, compared to cycles with higher average power demand, such as Route 1 and All-Routes, which have 69% and 46% differences, respectively.

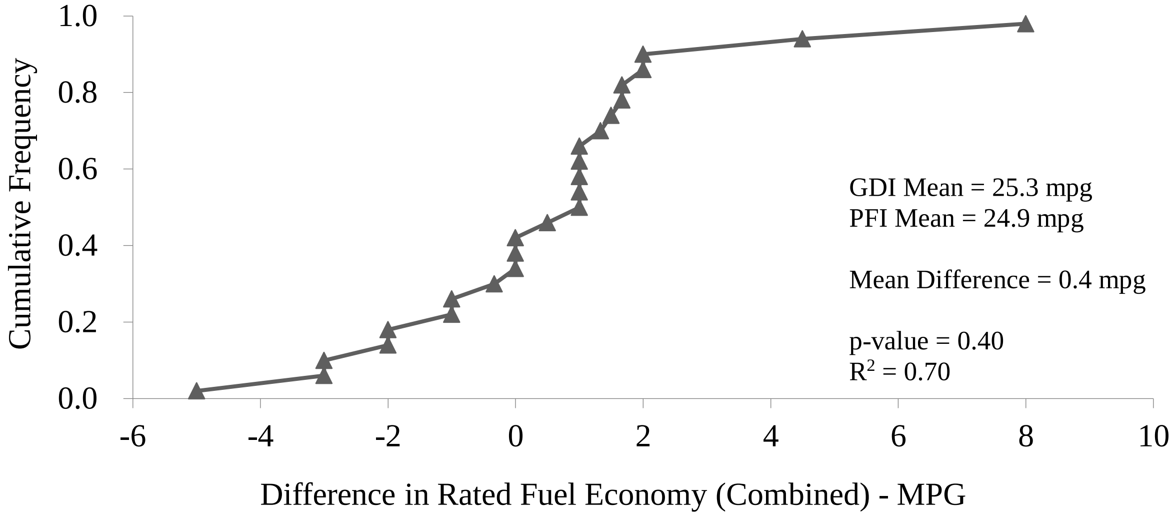
### 3.5 EPA Rated Fuel Economy and Certification Level Data

Figure 6 compares GDI and PFI vehicles based on U.S. EPA rated fuel economy and certification level emission rates for $NO_x$, CO and HC. Each data point is the difference between a paired GDI and PFI vehicle. Figure A3 in Appendix A compares the absolute fuel economy and certification level emission rates of GDI and PFI vehicle sets.

The city and highway fuel economy data are based on the FTP and HWFE cycles, respectively. Combined fuel economy data are based on a weighted average of city and highway estimates of fuel economy (U.S. EPA, 2018b). The certification level emission rates are based on the FTP cycle and EPA-applied emission DFs (U.S. EPA, 2017). All of the results are based on measurements done in laboratory on a chassis dynamometer (U.S. EPA, 2017). The data are published by U.S. EPA annually (U.S. EPA, 2017).

**Figure 6. Difference in EPA-rated Fuel Economy and Certification Level Data for selected pairs of GDI and PFI vehicles (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles) (a) Combined Fuel Economy; (b) City Fuel Economy; (c) Highway Fuel Economy; (d) $NO_x$; (e) CO; (f) HC**

CDFs are plotted by ranking the difference between paired GDI and PFI vehicles from highest to lowest, and assigning cumulative frequency based on ranks, versus EPA-rated fuel economy and certification level data. P-values are calculated based on paired t-test on means, and $p<0.05$ signifies that the difference in means is statistically significant. $R^2$ is the coefficient of determination for a linear regression model between the sets of 25 paired GDI and PFI vehicles.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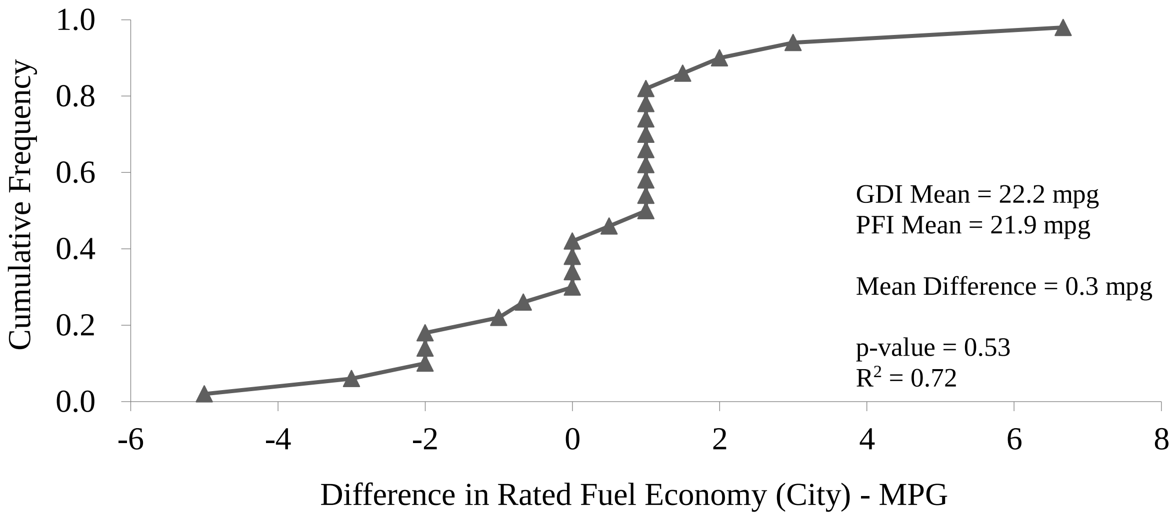
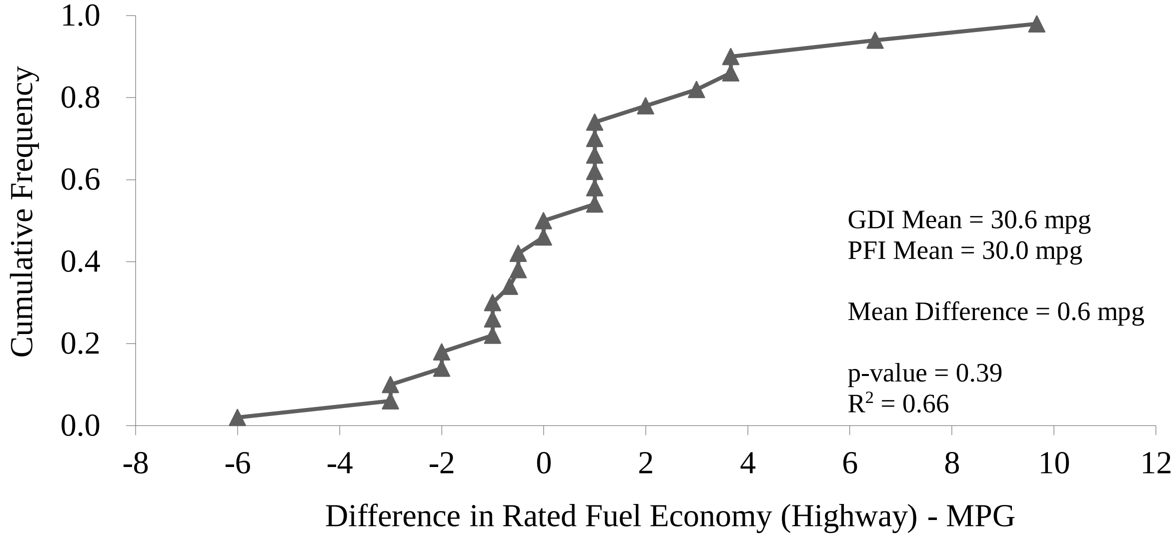
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-6
-4
-2
0
2
4
6
8
10
Difference in Rated Fuel Economy (Combined) - MPG
GDI Mean = 25.3 mpg
PFI Mean = 24.9 mpg
Mean Difference = 0.4 mpg
p-value = 0.40
R2 = 0.70

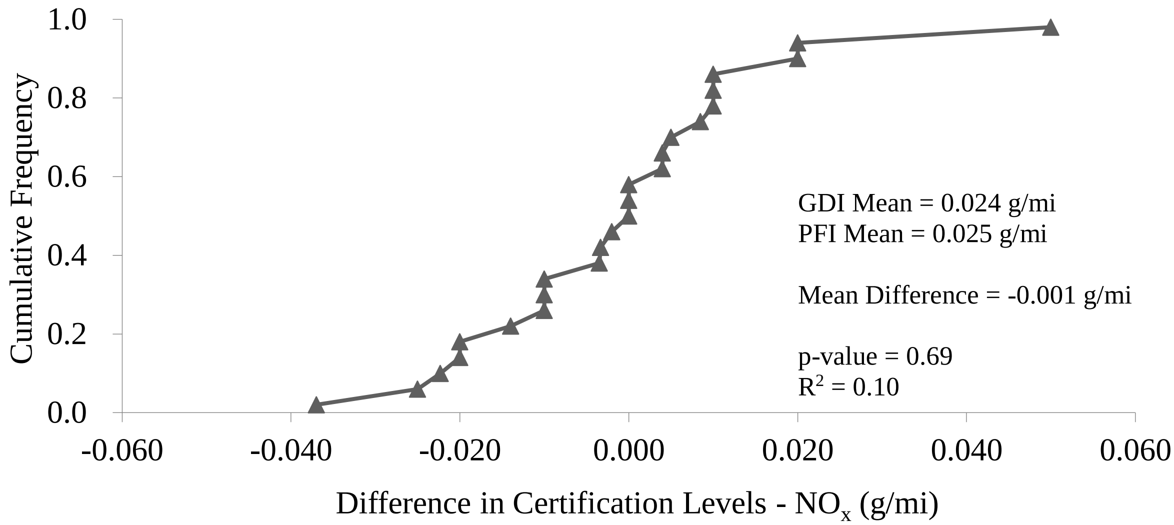
**(a)**


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-6
-4
-2
0
2
4
6
8
Difference in Rated Fuel Economy (City) - MPG
GDI Mean = 22.2 mpg
PFI Mean = 21.9 mpg
Mean Difference = 0.3 mpg
p-value = 0.53
R2 = 0.72

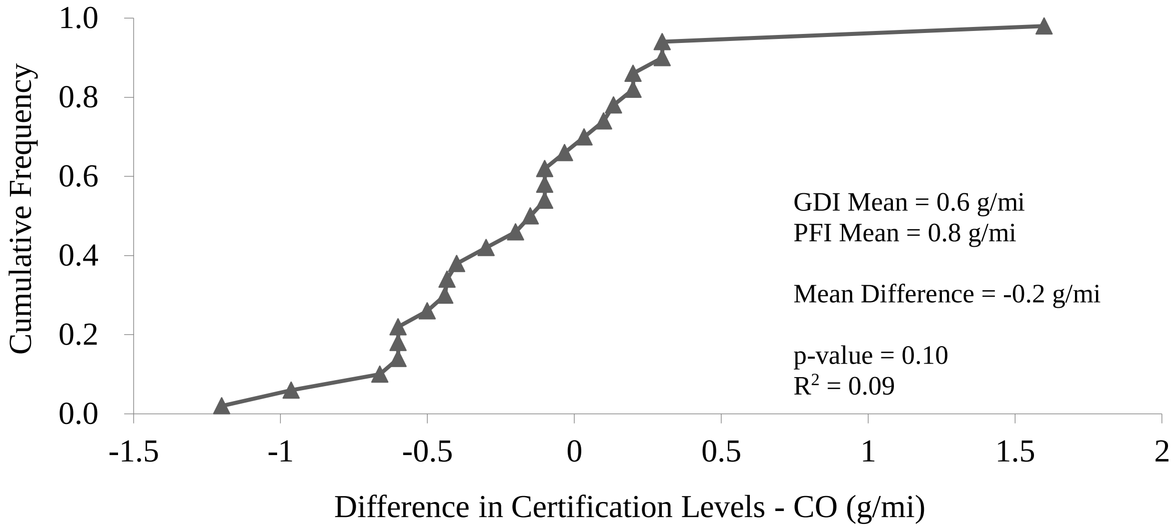
**(b)**


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-8
-6
-4
-2
0
2
4
6
8
10
12
Difference in Rated Fuel Economy (Highway) - MPG
GDI Mean = 30.6 mpg
PFI Mean = 30.0 mpg
Mean Difference = 0.6 mpg
p-value = 0.39
R2 = 0.66

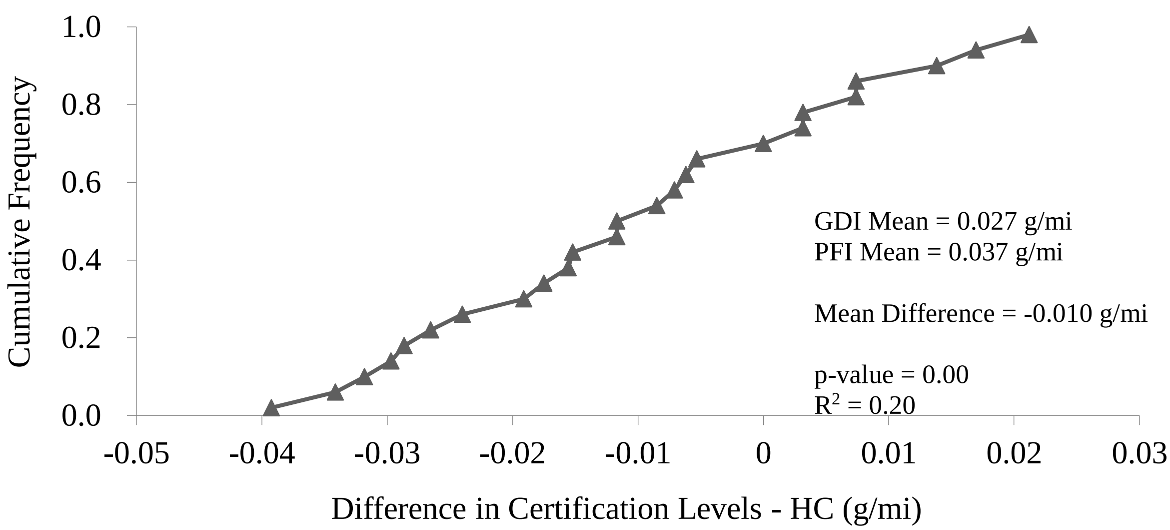
**(c)**


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-0.060
-0.040
-0.020
0.000
0.020
0.040
0.060
Difference in Certification Levels - NOx (g/mi)
GDI Mean = 0.024 g/mi
PFI Mean = 0.025 g/mi
Mean Difference = -0.001 g/mi
p-value = 0.69
R2 = 0.10

**(d)**


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-1.5
-1
-0.5
0
0.5
1
1.5
2
Difference in Certification Levels - CO (g/mi)
GDI Mean = 0.6 g/mi
PFI Mean = 0.8 g/mi
Mean Difference = -0.2 g/mi
p-value = 0.10
R2 = 0.09

**(e)**


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-0.05
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
Difference in Certification Levels - HC (g/mi)
GDI Mean = 0.027 g/mi
PFI Mean = 0.037 g/mi
Mean Difference = -0.010 g/mi
p-value = 0.00
R2 = 0.20

**(f)**

While making pairs for GDI and PFI comparison, vehicles are compared within the same Tier. This is done because Tier 2 vehicles were tested by the U.S. EPA on Tier 2 gasoline, which has no ethanol content, whereas, Tier 3 vehicles were tested on E10, which is a blend of 90% gasoline and 10% ethanol. Also, for Tier 2 certified vehicles, the certification level included a DF for 120,000 miles, whereas, for Tier 3 vehicles, the certification level included a DF for 150,000 miles.

Figure 6(a) shows the CDF of differences between EPA-rated combined fuel economy between paired GDI and PFI vehicles. The combined fuel economy of selected GDI vehicles varies from 18.0 mpg to 33.0 mpg, and of selected PFI vehicles varies from 17.0 mpg to 33.0 mpg (Figure A3(a)). The difference in rated combined fuel economy between GDI and PFI vehicles ranges from -5.0 mpg to +8.0 mpg. However, 90% of the differences, between $4^{th}$ and $94^{th}$ percentile, lie between -3.0 mpg to +2.0 mpg. The highest difference of +8.0 mpg is for a MY 2014 GDI vehicle that is compared to a "composite PFI" that consists of three vehicles of MY 2005, 2007 and 2008. The lowest difference of -5.0 mpg is for a GDI vehicle that has a 6-speed automatic transmission, whereas the compared PFI vehicle has a CVT with an overdrive gear. GDI vehicles have higher combined fuel economy for 14 out of 25 pairs, and lower combined fuel economy for 8 pairs. For 3 pairs, the combined fuel economy for GDI and PFI vehicles is the same. On average, the difference between rated combined fuel economy of selected GDI and PFI vehicles is +0.4 mpg. The difference is not statistically significant, which indicates that the GDI and PFI vehicles have similar combined fuel economies based on these chassis dynamometer data.

The difference in rated city and highway fuel economies follow a similar trend to combined fuel economy. For GDI vehicles, the rated city fuel economy varies from 16.0 mpg to 29.0 mpg, and for PFI vehicles, it varies from 15.0 mpg to 29.0 mpg. The difference in rated city fuel economy between paired GDI and PFI vehicle ranges from -5.0 mpg to +6.7 mpg (Figure 6(b)). On average, the difference is +0.3 mpg in favor of GDI vehicles. However, the difference is not statistically significant. Rated highway fuel economy for GDI vehicles ranges from 22.0 mpg to 39.0 mpg, and for PFI vehicles ranges from 21.0 mpg to 39.0 mpg. The difference varies from -6.0 mpg to +9.7 mpg (Figure 6(c)). On average, the difference is 0.6 mpg in favor of GDI vehicles. The difference is not statistically significant.

Based on EPA-rated chassis dynamometer rated fuel economy data, GDI and PFI vehicles have similar combined, city and highway fuel economies. GDI vehicles have marginally higher fuel economy by 1% to 2% in all three cases.

$NO_x$ emission rates based on certification level data for selected GDI vehicles range from 0.007 g/mi to 0.060 g/mi, and for selected PFI vehicles range from 0.008 g/mi to 0.044 g/mi (Figure A3(d)). The difference between paired GDI and PFI vehicles varies from -0.037 g/mi to +0.050 g/mi (Figure 6(d)). The distribution of differences is evenly spread around zero. Ten out 25 GDI vehicles have higher $NO_x$ emission rates, and 12 GDI vehicles have lower rates, compared to PFI vehicles. Three GDI vehicles have the same certified $NO_x$ emission rate as the PFI vehicles they are compared to. For the highest and the lowest differences, the GDI vehicles are turbocharged, whereas the compared PFI vehicles are naturally aspirated. Therefore, neither of the extreme differences can be attributed solely to forced induction.

Differences between the remaining 23 pairs vary from -0.025 g/mi to +0.020 g/mi. On average, the difference is -0.001 g/mi, which is not statistically significant. Thus, based on EPA certification level data, $NO_x$ emission rates for GDI and PFI vehicles are similar.

Figure A3(e) shows the CDF of certification level CO emission rates for GDI and PFI vehicles. Certification level CO emission rates vary from 0.1 g/mi to 1.3 g/mi for all but one of the GDI vehicles, and from 0.2 g/mi to 1.7 g/mi for PFI vehicles. A 2014 Ford Focus hatchback GDI vehicle with a CO emission rate of 2.4 g/mi seems to be an outlier from the group of the selected vehicles. The difference of certification level CO emission rate between selected GDI and PFI vehicles ranges from -1.2 g/mi to +1.6 g/mi (Figure 6(e)). Excluding the 2014 Ford Focus, the difference ranges from -1.2 g/mi to +0.3 g/mi. GDI vehicles have lower CO emission rates for 17 of the 25 pairs. On average, the difference is -0.2 g/mi. P-value of 0.10 indicates that the difference is not significant at the 95% confidence level. However, it is only marginally higher than a significant p-value. Further, excluding the 2014 Ford Focus from the comparison results in a statistically significant difference of -0.3 g/mi ($p = 0.00$) in favor of GDI vehicles. Thus, certification level CO emission rates suggest that GDI vehicles may have lower CO emission rates than PFI vehicles.

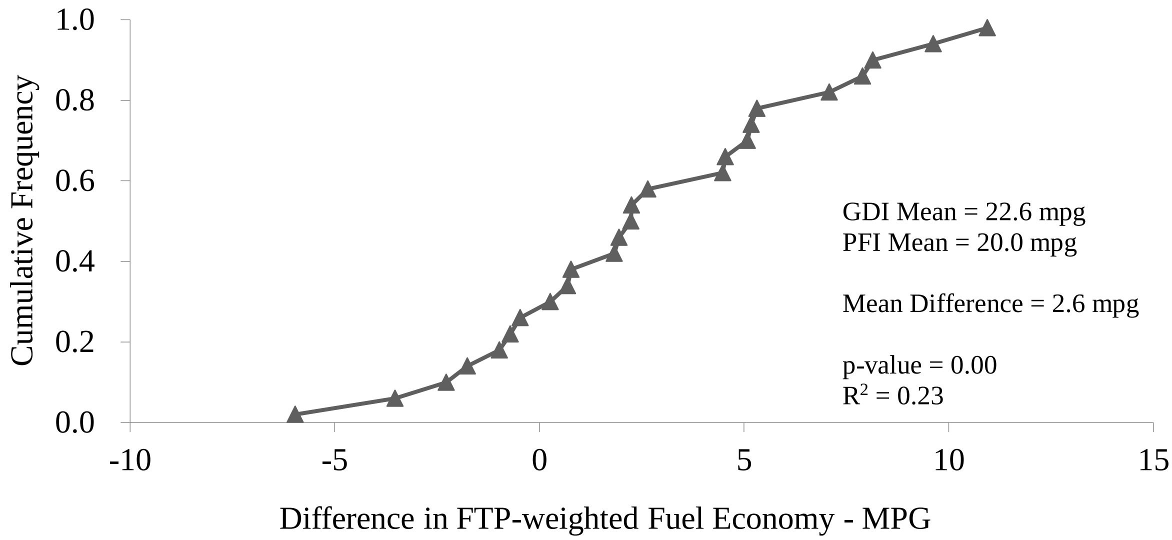
Certification level HC emission rates for selected GDI vehicles vary from 0.010 g/mi to 0.067 g/mi, and for selected PFI vehicles vary from 0.006 g/mi to 0.060 g/mi (Figure A3(f)). However, whereas HC emission rates of 17 out of 25 GDI vehicles are less than 0.030 g/mi, only 8 out of 25 PFI vehicles have HC emission rates lower than 0.030 g/mi. The difference in HC emission rates between paired GDI and PFI vehicles ranges from -0.039 g/mi to +0.021

g/mi. GDI vehicles have lower HC emission rate for 17 out of 25 pairs. On average, the difference is -0.010 g/mi, which is statistically significant ($p = 0.00$). Thus, EPA certification level data indicate that GDI vehicles have lower HC emission rates than comparable PFI vehicles.

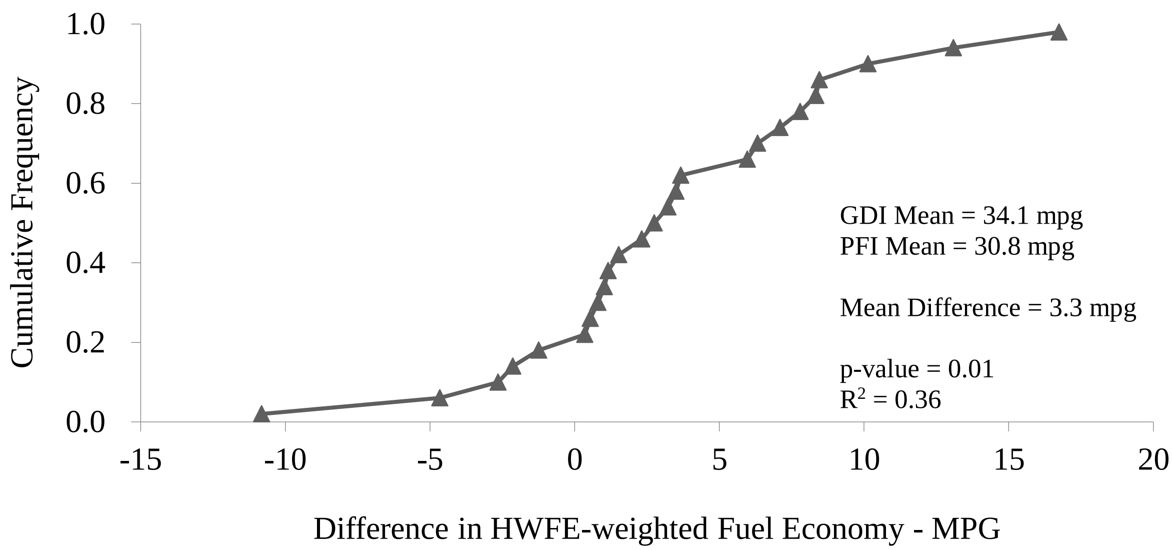
Figure 7 illustrates differences in the FTP and HWFE cycle average fuel economy and emission rates between paired GDI and PFI vehicles. The cycle average rates for the FTP and HWFE cycles are estimated using equation (2) based on VSP modal rates shown in Figure 5 and fraction of time spent in each VSP mode for the FTP and HWFE cycles as shown in Table 4. The terms 'FTP-weighted' and 'HWFE-weighted' average fuel use and emission rates are used here forth for cycle average rates calculated using equation (2) for the standard cycles. Each data point in Figure 7 is the difference between a paired GDI and PFI vehicle. Figure A4 in Appendix A shows the absolute FTP-weighted and HWFE-weighted cycle average fuel economy and emission rates for GDI and PFI vehicle sets.

**Figure 7. Difference in Standard Cycle Fuel Economy and Emission Rates for selected pairs of GDI and PFI vehicles based on VSP modal average rates (a) FTP-weighted Fuel Economy; (b) HWFE-weighted Fuel Economy; (c) $NO_x$ (FTP-weighted); (d) CO (FTP-weighted); and (e) HC (FTP-weighted)**

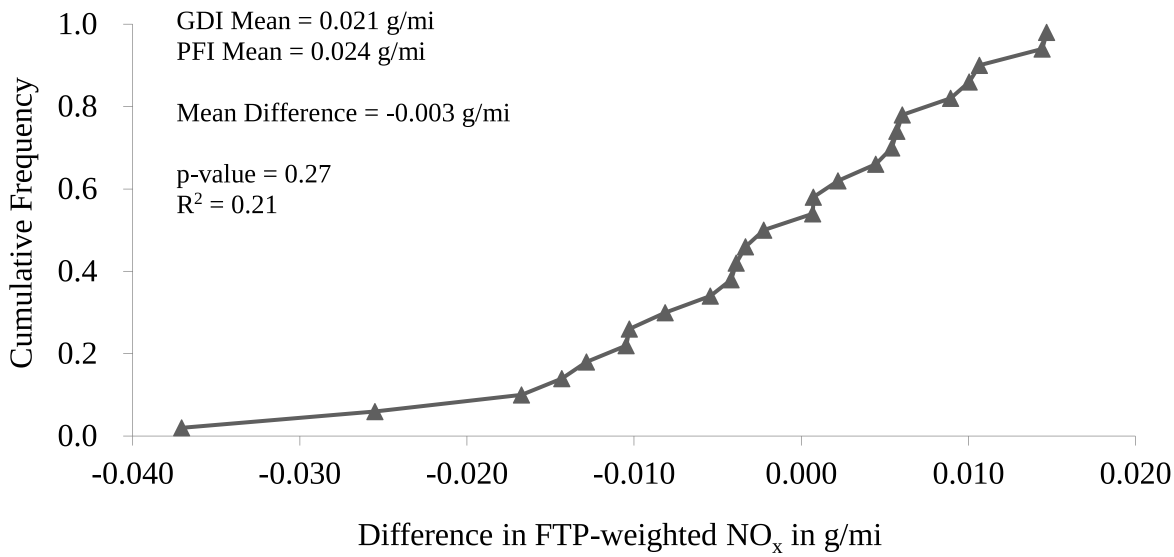
(a) FTP-weighted Fuel Economy (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles); (b) HWFE-weighted Fuel Economy (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles); (c) $NO_x$ (FTP-weighted) (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles); (d) CO (FTP-weighted) (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles); and (e) HC (FTP-weighted) (n = 24 "Composite GDI" and n = 24 "Composite PFI" vehicles). CDFs are plotted by ranking the difference between paired GDI and PFI vehicles from highest to lowest, and assigning cumulative frequency based on ranks, versus VSP-based standard cycle average fuel economy and emission rates. P-values are calculated based on paired t-test on means, and $p<0.05$ signifies that the difference in means is statistically significant. $R^2$ is the coefficient of determination for a linear regression model between the sets of 25 paired GDI and PFI vehicles.


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-10
-5
0
5
10
15
Difference in FTP-weighted Fuel Economy - MPG
GDI Mean = 22.6 mpg
PFI Mean = 20.0 mpg
Mean Difference = 2.6 mpg
p-value = 0.00
R2 = 0.23

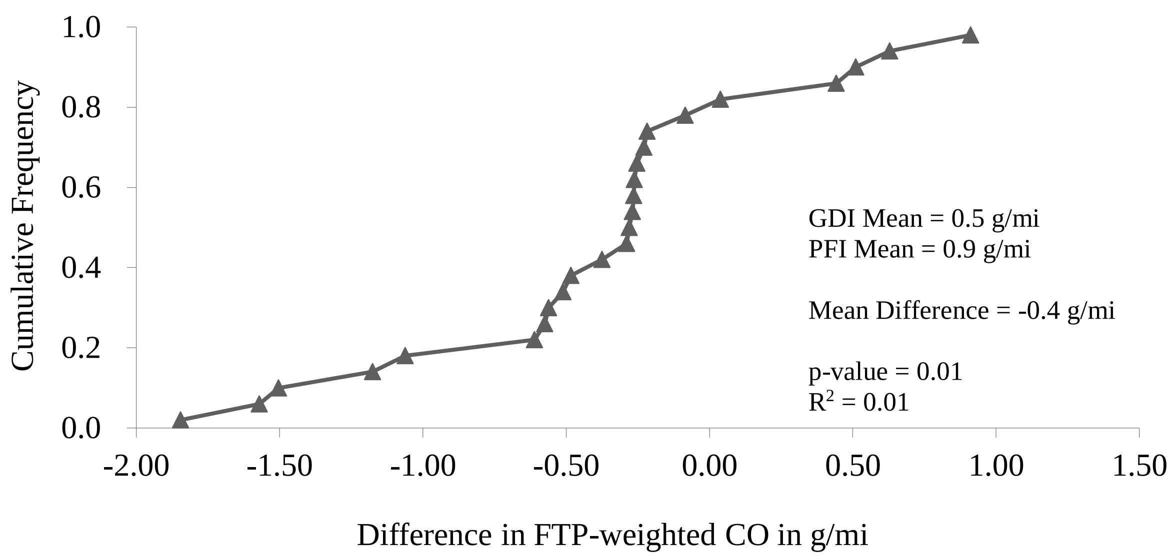
**(a)**


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Frequency
-15
-10
-5
0
5
10
15
20
Difference in HWFE-weighted Fuel Economy - MPG
GDI Mean = 34.1 mpg
PFI Mean = 30.8 mpg
Mean Difference = 3.3 mpg
p-value = 0.01
R2 = 0.36

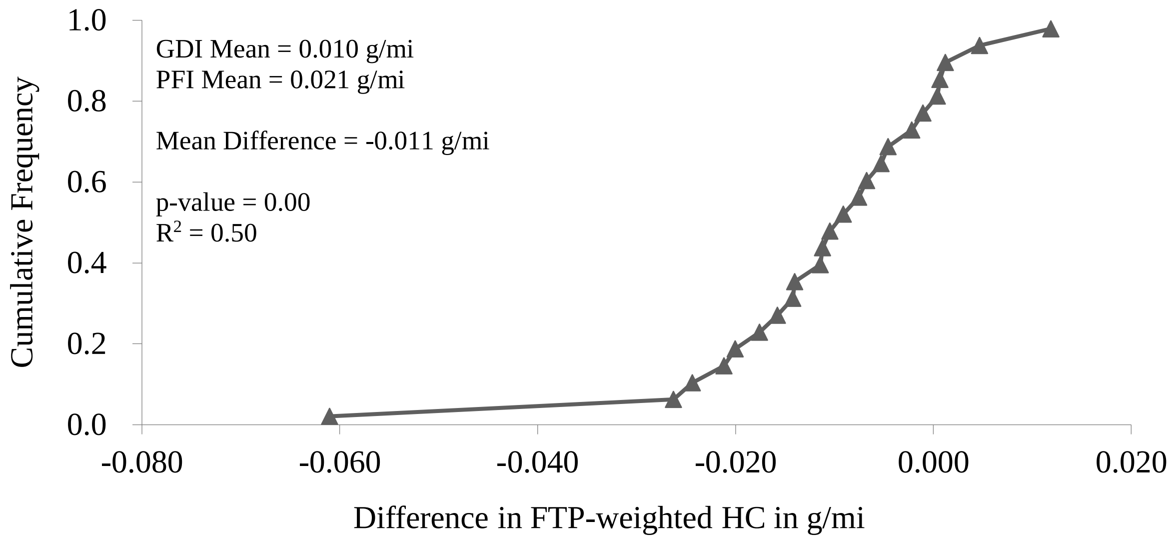
**(b)**


GDI Mean = 0.021 g/mi
PFI Mean = 0.024 g/mi
Mean Difference = -0.003 g/mi
p-value = 0.27
R2 = 0.21
Cumulative Frequency
1.0
0.8
0.6
0.4
0.2
0.0
-0.040
-0.030
-0.020
-0.010
0.000
0.010
0.020
Difference in FTP-weighted NOx in g/mi

**(c)**


GDI Mean = 0.5 g/mi
PFI Mean = 0.9 g/mi
Mean Difference = -0.4 g/mi
p-value = 0.01
R2 = 0.01
Cumulative Frequency
1.0
0.8
0.6
0.4
0.2
0.0
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Difference in FTP-weighted CO in g/mi

**(d)**


GDI Mean = 0.010 g/mi
PFI Mean = 0.021 g/mi
Mean Difference = -0.011 g/mi
p-value = 0.00
R2 = 0.50
Cumulative Frequency
1.0
0.8
0.6
0.4
0.2
0.0
-0.080
-0.060
-0.040
-0.020
0.000
0.020
Difference in FTP-weighted HC in g/mi

**(e)**

FTP-weighted cycle average fuel economy of selected GDI vehicles varies from 16.4 mpg to 31.4 mpg, and PFI vehicles ranges from 12.6 mpg to 24.8 mpg (Figure A4(a)). FTP-weighted mean fuel economies for GDI vehicles and PFI vehicles are 22.6 mpg and 20.0 mpg, respectively. Compared to EPA-rated city fuel economy, the FTP-weighted fuel economy for GDI vehicles is higher by 1.7%, and for PFI vehicles is lower by 9.0%. The difference between EPA-rated city and FTP-weighted fuel economy is not statistically significant for GDI vehicles, and is statistically significant for PFI vehicles. This indicates that FTP-weighted fuel economy based on real-world VSP-modal average data is more akin to lab-based chassis dynamometer city fuel economy for GDI vehicles, than for PFI vehicles.

Figure 7(a) shows the CDF in differences of FTP-weighted fuel economy between paired GDI and PFI vehicles. The difference ranges from -6.0 mpg to +10.9 mpg. However, 90% of the differences, between the $5^{th}$ percentile and $95^{th}$ percentile, range from -3.5 mpg to +9.6 mpg. For 18 out of 25 pairs, the GDI vehicle has higher modal-based city fuel economy than the comparable PFI vehicle. On average, the difference is +2.6 mpg. The difference is statistically significant ($p = 0.00$). This is similar to the result based on EPA-rated city fuel economy data, which indicates that GDI vehicles have higher city fuel economies. However, the FTP-weighted cycle average fuel economy data based on real-world modal rates is more favorable for GDI vehicles than similar lab-based data.

HWFE-weighted fuel economy of selected GDI vehicles ranges from 24.7 mpg to 49.3 mpg, and PFI vehicles ranges from 18.9 mpg to 40.9 mpg (Figure A4(b)). HWFE-weighted mean fuel economies for GDI vehicles and PFI vehicles are 34.1 mpg and 30.8 mpg, respectively. Compared to EPA-rated highway fuel economy, the HWFE-weighted fuel economy for GDI vehicles is higher by 11.7%, and for PFI vehicles is higher by 2.6%. The difference between EPA-rated highway and HWFE-weighted fuel economy is statistically significant for GDI vehicles, and is not statistically significant for PFI vehicles. This indicates that the HWFE-weighted fuel economy based on real-world VSP-modal average data is more akin to lab-based chassis dynamometer highway fuel economy for PFI vehicles, than for GDI vehicles.

Figure 7(b) shows the CDF of differences of HWFE-weighted fuel economy between paired GDI and PFI vehicles. The difference ranges from -10.8 mpg to +16.7 mpg. However, 90% of the differences, between $5^{th}$ percentile and $95^{th}$ percentile, range from -4.7 mpg to +13.1 mpg. For 20 out of 25 pairs, the GDI vehicle has higher HWFE-weighted fuel economy than the comparable PFI vehicle. On average, the difference is +3.3 mpg. The difference is statistically significant ($p = 0.01$). This is similar to the result based on EPA-rated highway fuel economy data, which indicates that GDI vehicles have higher highway fuel economies. However, HWFE-weighted cycle average fuel economy data based on real-world modal rates is more favorable for GDI vehicles than similar lab-based data.

The FTP-weighted cycle average $NO_x$ emission rates range from 0.004 g/mi to 0.039 g/mi for selected GDI vehicles and from 0.007 g/mi to 0.053 g/mi for selected PFI vehicles (Figure A4(c)). The mean FTP-weighted $NO_x$ emission rate is 0.021 g/mi for GDI vehicles and 0.024 g/mi for PFI vehicles. Compared to EPA certification level $NO_x$ emission rates, the FTP-weighted mean $NO_x$ average emission rate is lower by 10.1% for GDI vehicles, and is lower by 4.0% for PFI vehicles. However, these differences between certification level and FTP-weighted $NO_x$ emission rates are not statistically significant.

Figure 7(c) shows the CDF of differences of FTP-weighted cycle average $NO_x$ emission rate between paired GDI and PFI vehicles. The difference ranges from -0.037 g/mi to +0.015 g/mi. The distribution of difference is evenly spread around zero. For 12 out of 25 pairs, the GDI vehicles have higher FTP-weighted $NO_x$ emission rate, and for 13 out of 25 pairs, the PFI vehicles have higher FTP-weighted $NO_x$ emission rate. On average, the difference is -0.003 g/mi. However, the difference is not statistically significant. This is similar to the result based on certification level $NO_x$ emission rates. Both sets of data indicate that GDI and PFI vehicles have similar $NO_x$ emission rates.

Figure A4(d) shows the CDF of FTP-weighted cycle average CO emission rates for selected GDI and PFI vehicles. The FTP-weighted cycle average CO emission rates vary from 0.04 g/mi to 1.61 g/mi for selected GDI vehicles and from 0.20 g/mi to 1.93 g/mi for selected PFI vehicles. The 2014 Ford Focus, which has the highest certification level CO emission rate, also has the highest FTP-weighted cycle average CO emission rate amongst the selected GDI vehicles. The Mean CO rate for GDI vehicles is 0.50 g/mi, and for PFI vehicles is 0.89 g/mi. Compared to EPA certification level CO emission rates, the FTP-weighted mean CO emission rate is lower by 21.0% for GDI vehicles and is higher by 10.2% for PFI vehicles. These differences are not statistically significant.

Figure 7(d) shows the CDF of differences of FTP-weighted cycle average CO emission rate between paired GDI and PFI vehicles. The difference ranges from -1.84 g/mi to 0.91 g/mi. For 20 out of 25 pairs, the GDI vehicle has lower CO emission rate than the compared PFI vehicles. On average, the difference is -0.40 g/mi. The difference is statistically significant ($p = 0.01$). This result is similar to the result from certification level data. Certification level data also indicates that GDI vehicles have, on average, lower CO emission rate than PFI vehicles.

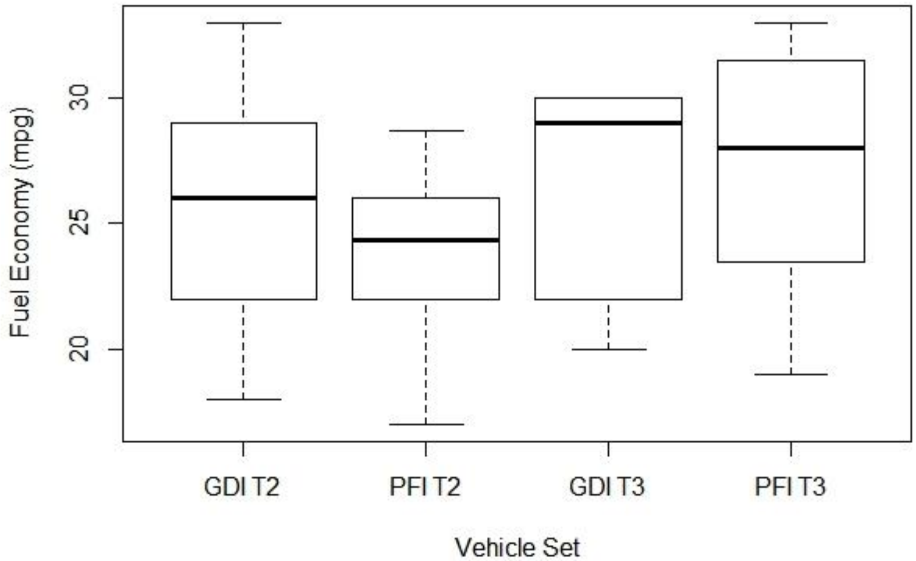
FTP-weighted cycle average HC emission rates range from 0.001 g/mi to 0.034 g/mi for selected GDI vehicles, and from 0.006 g/mi to 0.095 g/mi for selected PFI vehicles (Figure A4(e)). The mean FTP-weighted cycle average HC emission rate for selected GDI vehicles is 0.010 g/mi, and for selected PFI vehicles is 0.021 g/mi. One of the PFI vehicles, a 2013 GMC Yukon, seems to be a real-world high HC emitter. Apart from this vehicle, the HC emission rate for other PFI vehicles ranges from 0.006 g/mi to 0.038 g/mi. However, including this vehicle in the comparison does not affect the trends of results. Compared to the EPA certification level data, the FTP-weighted mean HC emission rate for GDI vehicles is 61.6% lower, and for PFI vehicles is 42.6% lower. These differences are statistically significant.

Figure 7(e) shows the CDF of differences of FTP-weighted cycle average HC emission rates between paired GDI and PFI vehicles. The difference ranges from -0.061 g/mi to +0.012 g/mi. For 19 out of 24 pairs, the GDI vehicle has lower HC emission rate than the compared PFI vehicle. On average, the difference is -0.011 g/mi, and it is statistically significant ($p = 0.00$). This is similar to the result obtained from certification level data, which also indicates that the GDI vehicles have significantly lower HC emission rates.

Comparisons of vehicle characteristics and EPA-rated fuel economy and certification level data between Tier 2 and Tier 3 certified GDI and PFI vehicles are shown in Figure A5 (Appendix A) and Figure 8, respectively. There are 17 pairs of composite GDI and PFI Tier 2 vehicles, and 8 pairs of composite GDI and PFI Tier 3 vehicles.

**Figure 8. EPA-rated Fuel Economy and Certification Level Data for selected pairs of 'Tier 2' (T2) and 'Tier 3' (T3) GDI and PFI vehicles (n = 17 'Tier 2' pairs and n = 8 'Tier 3' pairs) (a) Combined Fuel Economy; (b) City Fuel Economy; (c) Highway Fuel Economy; (d) $NO_x$; (e) CO; (f) HC**

The boxes within boxplots depict the 25th percentile, median and 75th percentile. The outside whiskers denote the range. Any points that are 1.5 times the interquartile range below the 1st quartile and above the 3rd quartile, are considered outliers. Outliers are plotted with open dots. P-values are calculated based on paired t-test on means, and $p<0.05$ signifies that the difference in means is statistically significant.



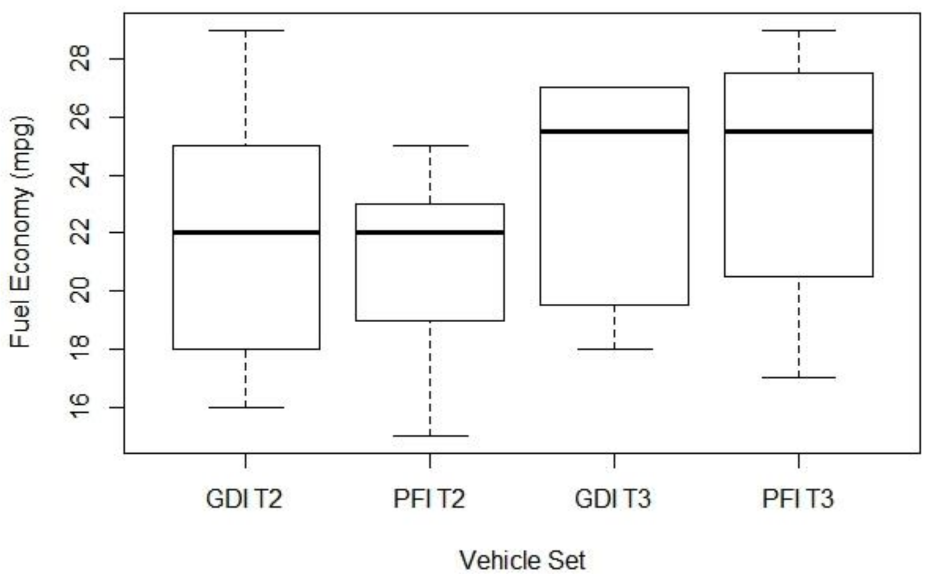

Tier 2

GDI Mean = 24.8 mpg
PFI Mean = 23.8 mpg
Mean Difference
= 1.0 mpg
p-value = 0.11

Tier 3

GDI Mean = 26.5 mpg
PFI Mean = 27.3 mpg
Mean Difference
= -0.8 mpg
p-value = 0.42

**(a)**



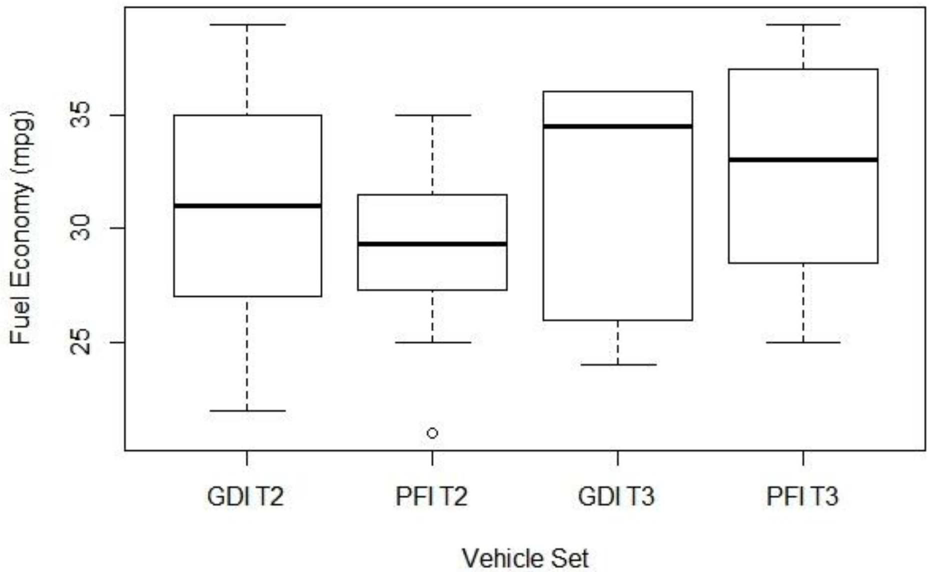

Tier 2

GDI Mean = 21.5 mpg
PFI Mean = 20.9 mpg
Mean Difference
= 0.6 mpg
p-value = 0.22

Tier 3

GDI Mean = 23.6 mpg
PFI Mean = 24.1 mpg
Mean Difference
= -0.5 mpg
p-value = 0.56

**(b)**



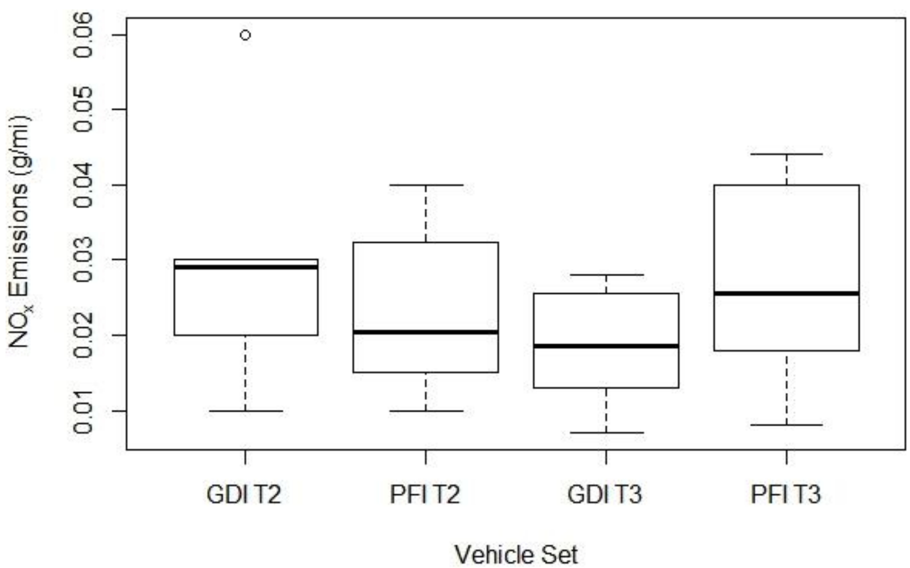

Tier 2

GDI Mean = 30.1 mpg
PFI Mean = 28.8 mpg
Mean Difference
= 1.3 mpg
p-value = 0.11

Tier 3

GDI Mean = 31.6 mpg
PFI Mean = 32.6 mpg
Mean Difference
= -1.0 mpg
p-value = 0.33

**(c)**



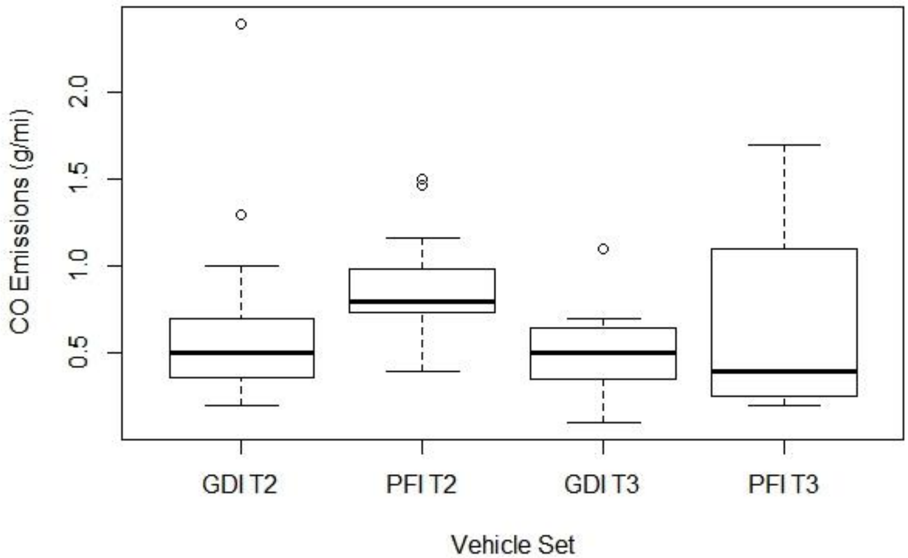

Tier 2

GDI Mean = 0.026 g/mi
PFI Mean = 0.024 g/mi
Mean Difference
= 0.002 g/mi
p-value = 0.65

Tier 3

GDI Mean = 0.019 g/mi
PFI Mean = 0.027 g/mi
Mean Difference
= -0.009 g/mi
p-value = 0.17

**(d)**



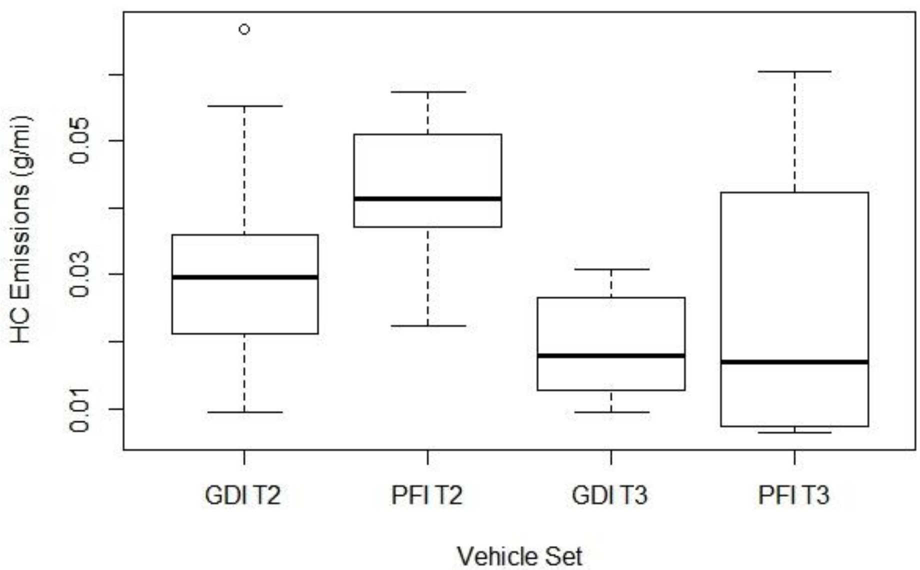

Tier 2

GDI Mean = 0.7 g/mi
PFI Mean = 0.9 g/mi
Mean Difference
= -0.2 g/mi
p-value = 0.17

Tier 3

GDI Mean = 0.5 g/mi
PFI Mean = 0.7 g/mi
Mean Difference
= -0.2 g/mi
p-value = 0.44

**(e)**




Tier 2

GDI Mean = 0.030 g/mi
PFI Mean = 0.043 g/mi
Mean Difference
= -0.013 g/mi
p-value = 0.00

Tier 3

GDI Mean = 0.019 g/mi
PFI Mean = 0.025 g/mi
Mean Difference
= -0.006 g/mi
p-value = 0.44

**(f)**

Figure A5(a) shows the HP of selected Tier 2 and Tier 3 GDI and PFI vehicles. Mean HP of Tier 2 and Tier 3 GDI vehicles are 230 hp and 201 hp, respectively. The difference of 29 hp between Tier 2 and Tier 3 GDI vehicles is not statistically significant ($p = 0.38$). Thus, Tier 2 and Tier 3 GDI vehicles are similar in terms of HP. Mean HP of Tier 2 and Tier 3 PFI vehicles are 213 hp and 193 hp, respectively. The difference of 8 hp between Tier 2 and Tier 3 PFI vehicles is not statistically significant ($p = 0.53$). Thus, Tier 2 and Tier 3 PFI vehicles are also similar in terms of HP. HP of Tier 2 GDI vehicles is 7.9% higher than Tier 2 PFI vehicles. The difference is statistically significant ($p = 0.01$). HP of Tier 3 GDI vehicles is 4.5% higher than Tier 3 PFI vehicles. The difference is statistically significant ($p = 0.02$). The relative differences in HP between Tier 2 GDI and PFI vehicles and Tier 3 GDI and PFI vehicles are consistent, i.e., GDI vehicles have significantly higher HP for both Tier 2 and Tier 3 vehicles.

Figure A5(b) shows the curb weight of selected Tier 2 an Tier 3 GDI and PFI vehicles. Mean curb weights of Tier 2 and Tier 3 GDI vehicles are 3650 lb and 3497 lb, respectively. The difference of 153 lb between Tier 2 and Tier 3 GDI vehicles is not statistically significant ($p = 0.64$). Thus, Tier 2 and Tier 3 GDI vehicles are similar in terms of curb weight. Mean curb weights of Tier 2 and Tier 3 PFI vehicles are 3665 lb and 3500 lb, respectively. The difference of 165 lb is not statistically significant ($p = 0.63$). Thus, Tier 2 and Tier 3 PFI vehicles are also similar in terms of curb weight. Curb weight of Tier 2 GDI vehicles is 0.4% lower than Tier 2 PFI vehicles. The difference is statistically not significant ($p = 0.74$). Curb weight of Tier 3 GDI vehicles is 0.1% lower than Tier 3 PFI vehicles. The difference is statistically not significant (p = 0.97). GDI vehicles and PFI vehicles have similar curb weights within both Tier 2 and Tier 3 vehicle sets.

Figure 8(a) shows the EPA-rated combined fuel economy of selected Tier 2 and Tier 3 GDI and PFI vehicles. Combined fuel economy of Tier 2 GDI vehicles ranges from 18.0 mpg to 33.0 mpg, Tier 2 PFI vehicles ranges from 17.0 mpg to 28.7 mpg, Tier 3 GDI vehicles ranges from 20.0 mpg to 30.0 mpg, and Tier 3 PFI vehicles ranges from 19.0 mpg to 33.0 mpg. Tier 3 vehicles have 10.7% higher (p-value = 0.051) combined fuel economy than Tier 2 vehicles, which is consistent with the knowledge that fuel economy is increasing for newer vehicles. Compared to Tier 2 GDI vehicles, Tier 3 GDI vehicles have 7.0% higher (p-value = 0.39) combined fuel economy. Tier 3 PFI vehicles have 14.6% higher (p-value = 0.06) combined fuel economy than Tier 2 PFI vehicles. Although the difference between Tier 2 and Tier 3 PFI vehicles is not statistically significant, the p-value of 0.06 is only marginally higher than a significant difference. With a larger sample size, the difference between Tier 2 and Tier 3 PFI vehicles is expected to be significant. Thus, while Tier 2 and Tier 3 GDI vehicles have similar EPA-rated combined fuel economy, Tier 3 PFI vehicles seem to be more fuel efficient than Tier 2 PFI vehicles.

Within Tier 2, GDI vehicles have 4.2% higher (p-value = 0.11) combined fuel economy than PFI vehicles, which is consistent with the expectation of higher fuel economy of GDI vehicles. For Tier 3 vehicles, GDI vehicles have 2.8% lower (p-value = 0.42) combined fuel economy than PFI vehicles. This difference is not significant. However, a possible cause for the lower combined fuel economy of GDI vehicles is that for 2 pairs of Tier 3 vehicles where

GDI vehicles have lower combined fuel economy, the PFI vehicles have CVT, whereas the GDI vehicles have 6-speed automatic gearboxes. However, for 2 separate pairs of Tier 3 vehicles, where both GDI and PFI vehicles have CVT, the combined fuel economy for GDI and PFI vehicles is similar. Thus, the lower combined fuel economy for Tier 3 GDI vehicles cannot be attributed solely to the difference in transmission. Also, p-value of 0.42 and a small sample size of 7 pairs means that the difference is not definitive.

Figure 8(b) shows the EPA-rated city fuel economy of selected Tier 2 and Tier 3 GDI and PFI vehicles. The city fuel economy of Tier 2 GDI vehicles ranges from 16.0 mpg to 29.0 mpg, Tier 2 PFI vehicles ranges from 15.0 mpg to 25.0 mpg, Tier 3 GDI vehicles ranges from 18.0 mpg to 27.0 mpg, and Tier 3 PFI vehicles ranges from 17.0 mpg to 29.0 mpg. On average, Tier 3 vehicles, including both GDI and PFI vehicles, have significantly higher (p-value = 0.02) city fuel economy than Tier 2 vehicles by 12.6%. This indicates that the Tier 3 vehicles are more fuel efficient in city driving conditions than the Tier 2 vehicles.

Compared to Tier 2 GDI vehicles, Tier 3 GDI vehicles have 9.7% higher (p-value = 0.23) city fuel economy, whereas, compared to Tier 2 PFI vehicles, Tier 3 PFI vehicles have 15.5% higher (p-value = 0.052) city fuel economy. Similar to the case of combined fuel economy, the p-value of 0.052 for the difference between Tier 2 and Tier 3 PFI vehicles is only marginally higher than a significant p-value. With a larger sample size, Tier 3 PFI vehicles are expected to have higher city fuel economy compared to Tier 2 PFI vehicles. Thus, while Tier 2 and Tier 3 GDI vehicles have similar EPA-rated city fuel economy, Tier 3 PFI vehicles seem to have higher city fuel economy than Tier 2 PFI vehicles.

Within Tier 2, GDI vehicles have 3.1% higher (p-value = 0.22) city fuel economy than PFI vehicles. For Tier 3 vehicles, GDI vehicles 2.1% lower (p-value = 0.56) fuel economy than PFI vehicles. These differences not significant. Thus, the city fuel economy for GDI and PFI vehicles are similar for both Tier 2 and Tier 3.

Figure 8(c) shows the EPA-rated highway fuel economy of selected Tier 2 and Tier 3 GDI and PFI vehicles. Highway fuel economy of Tier 2 GDI vehicles ranges from 22.0 mpg to 39.0 mpg, Tier 2 PFI vehicles ranges from 21.0 mpg to 35.0 mpg, Tier 3 GDI vehicles ranges from 24.0 mpg to 36.0 mpg, and Tier 3 PFI vehicles ranges from 25.0 mpg to 39.0 mpg. A 2016 Ford F150 Tier 2 PFI is shown as an outlier in Figure 8(c), as the highway fuel economy of the F150 below the 1$^{st}$ quartile by 1.5 times the interquartile range of Tier 2 PFI vehicles. Low highway fuel economy is expected for the F150, as it is a pickup truck with a 5.0L V8 engine. Compared to Tier 2 vehicles, Tier 3 vehicles, on average, have 9.2% higher (p-value = 0.08) EPA-rated highway fuel economy. Although the difference is not statistically significant, the p-value of 0.08 is only marginally higher than a significant p-value. With a larger sample size, Tier 3 vehicles are expected to have higher highway fuel economy than Tier 2 vehicles.

Tier 3 GDI vehicles have 5.2% higher (p-value = 0.51) highway fuel economy compared to Tier 2 GDI vehicles. Tier 3 PFI vehicles have 13.4% higher (p-value = 0.06) highway fuel economy compared to Tier 2 PFI vehicles. The latter difference is expected to be significant with a larger sample size. Thus, the while Tier 2 and Tier 3 GDI vehicles have similar EPA-rated highway fuel economy, Tier 3 PFI vehicles seem to be more fuel efficient under highway driving conditions, compared to Tier 2 PFI vehicles.

Within Tier 2, GDI vehicles have 4.5% higher (p-value = 0.11) highway fuel economy compared to PFI vehicles. Within Tier 3, GDI vehicles have 3.1% lower (p-value = 0.33) highway fuel economy compared to PFI vehicles. These differences are not statistically significant. The difference between Tier 2 GDI and PFI vehicles is expected to be significant with a larger sample size.

Figure 8(d) shows the EPA certification level $NO_x$ emission rates for Tier 2 and Tier 3 GDI and PFI vehicles. $NO_x$ emission rate of Tier 2 GDI vehicles ranges from 0.010 g/mi to 0.060 g/mi, Tier 2 PFI vehicles ranges from 0.010 g/mi to 0.040 g/mi, Tier 3 GDI vehicles ranges from 0.007 g/mi to 0.028 g/mi, and Tier 3 PFI vehicles ranges from 0.008 g/mi to 0.044 g/mi. A 2016 Ford Escape Tier 2 GDI, which has a certification level $NO_x$ emission rate of 0.060 g/mi, is shown as outlier in Figure 8(d), as the $NO_x$ emission rate of the Ford Escape is above the 3$^{rd}$ quartile by 1.5 times the interquartile range of Tier 2 GDI vehicles. On average, Tier 3 vehicles have 7.3% lower (p-value = 0.59) $NO_x$ emission rate than Tier 2 vehicles. However, the difference is not significantly different from zero, which means that Tier 2 and Tier 3 vehicles have similar $NO_x$ emission rates.

Tier 3 GDI vehicles, on average, have 27.9% lower (p-value = 0.11) $NO_x$ emission rate than Tier 2 GDI vehicles. Compared to Tier 2 PFI vehicles, Tier 3 PFI vehicles have 5% higher (p-value = 0.47) $NO_x$ emission rate. However, these differences are not statistically significant.

Within Tier 2, GDI vehicles have 8.5% higher (p-value = 0.65) $NO_x$ emission rate than PFI vehicles. Within Tier 3, GDI vehicles have 32.0% lower (p-value = 0.17) $NO_x$ emission rate than PFI vehicles. However, these differences are not statistically significant. Thus, certification level $NO_x$ emission rates of GDI and PFI vehicles are similar irrespective of the 'Tier' the vehicles are certified to.

Figure 8(e) shows the EPA certification level CO emission rates for Tier 2 and Tier 3 GDI and PFI vehicles. CO emission rate of Tier 2 GDI vehicles ranges from 0.20 g/mi to 2.40 g/mi, Tier 2 PFI vehicles ranges from 0.40 g/mi to 1.50 g/mi, Tier 3 GDI vehicles ranges from 0.10 g/mi to 1.10 g/mi, and Tier 3 PFI vehicles ranges from 0.20 g/mi to 1.70 g/mi. There are four outliers in Tier 2: 2014 Ford Focus GDI, 2016 Ford Fusion GDI, 2013 Dodge Avenger PFI, and a composite PFI of 2015 Dodge Grand Caravan, 2016 Dodge Grand Caravan and 2014 Chrysler Town and Country. Only one Tier 3 vehicle, a 2017 Kia Sorento GDI, is shown as an outlier in Figure 8(e). On average, Tier 3 vehicles have 22.4% lower (p-value = 0.21) CO emission rate than Tier 2 vehicles, but the difference is not significant.

Tier 3 GDI vehicles have, on average, 22.3% lower (p-value = 0.46) CO emission rate than Tier 2 GDI vehicles. Tier 3 PFI vehicles have, on average, 22.5% lower (p-value = 0.31) CO emission rate than Tier 2 PFI vehicles. Although the differences seem consistent with each other, they are not statistically significant.

Within Tier 2, GDI vehicles have 22.4% lower (p-value = 0.17) CO emission rates than PFI vehicles. The relatively low p-value implies that with a larger sample size, this difference might be statistically significant. Further, if the pair containing 2014 Ford Focus GDI, that has an abnormally high CO emission rate of 2.4 g/mi, is censored from the comparison, the Tier 2

GDI vehicles have statistically significantly lower CO emission rate by 33.0% (p-value = 0.00) compared to Tier 2 PFI vehicles. Within Tier 3, GDI vehicles have 22.2% lower (p-value = 0.44) CO emission rate than PFI vehicles. However, this difference is not statistically significant.

Figure 8(f) shows the EPA certification level HC emission rates for selected Tier 2 and Tier 3 GDI and PFI vehicles. HC emission rate of Tier 2 GDI vehicles ranges from 0.010 g/mi to 0.067 g/mi, Tier 2 PFI vehicles ranges from 0.022 g/mi to 0.057 g/mi, Tier 3 GDI vehicles ranges from 0.010 g/mi to 0.031 g/mi, and Tier 3 PFI vehicles ranges from 0.006 g/mi to 0.060 g/mi. A 2015 Chevrolet Tahoe GDI is shown as an outlier within the Tier 2 GDI vehicle set in Figure 8(f). On average, Tier 3 vehicles have significantly lower (p-value = 0.00) HC emission rate by 39.6% than Tier 2 vehicles.

Tier 3 GDI vehicles have, on average, 36.5% lower (p-value = 0.07) HC emission rate than Tier 2 GDI vehicles. The p-value is only marginally higher than a significant p-value. With a larger sample size, Tier 3 GDI vehicles are expected to have significantly lower HC emission rates than Tier 2 GDI vehicles. Tier 3 PFI vehicles have, on average, 41.7% lower (p-value = 0.01) HC emission rate than Tier 2 PFI vehicles. The difference is statistically significant, and indicates that Tier 3 PFI vehicles are lower HC emitters than Tier 2 PFI vehicles.

Within Tier 2, GDI vehicles, on average, have 29.1% lower (p-value = 0.00) HC emission rate than PFI vehicles. Within Tier 3, GDI vehicles have, on average, 22.8% lower (p-value = 0.44) HC emission rate than PFI vehicles. Based on these results, while Tier 2 GDI vehicles have significantly lower emission HC emission rates than Tier 2 PFI vehicles, Tier 3 GDI and PFI vehicles have similar HC emission rates.

### 3.6 Comparison of Real-World Data and Chassis Dynamometer Data

Figure 9 compares GDI and PFI vehicles based on two sets of data: (1) Real-world test results based on PEMS measurements; and (2) EPA fuel economy and certification level data based on in-laboratory chassis-dynamometer measurements.

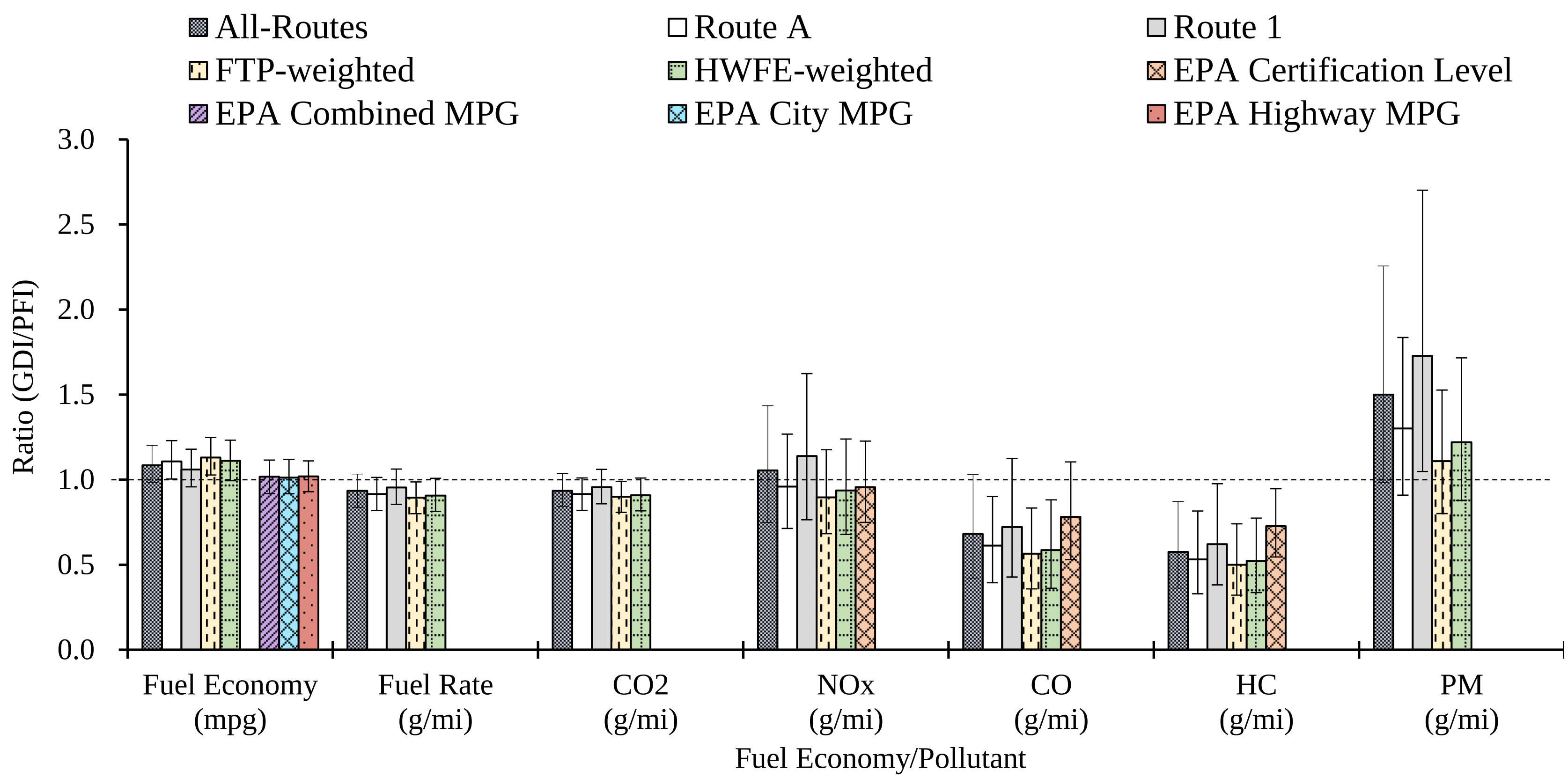



**Figure 9. Cycle Average Rates for GDI (n = 25 composite) versus PFI (n = 25 composite) for Selected Driving Cycles based on Real-World Data and EPA data**

*Note: Error bars shown here are 95% confidence intervals estimated using bootstrap simulation. Dotted line represents GDI/PFI ratio of 1. All-Routes, Route A, Route 1, Measured FTP Cycle and Measured HWFE cycle are based on PEMS data. EPA Certification Level, EPA Combined MPG, EPA City MPG and EPA Highway MPG are based on data published by the U.S. EPA.*

The mean ratios of fuel economies of GDI vehicles and PFI vehicles range from 1.06 to 1.11 for real-world driving cycles, including All-Routes, Route A and Route 1. The mean ratio is 1.11 and 1.13 for FTP-weighted and measured HWFE-weighted cycle average, respectively. The mean ratios for Route A and FTP-weighted cycle averages are significantly different from 1, as they do not include 1 in their 95% confidence intervals. In contrast, 95% confidence intervals for the ratios of All-Routes, Route 1 and HWFE-weighted cycle averages include 1, and these ratios are not statistically significantly different from 1. However, the p-values of paired t-tests on the mean fuel economies of GDI versus PFI, as shown in Table 5 (Page 68), indicate that cycle average fuel economies for All-Routes, Route A, Route 1, FTP-weighted and HWFE-weighted for GDI vehicles are significantly higher than PFI vehicles. Thus, significance of higher cycle average fuel economies of GDI vehicles compared to PFI vehicles for Route A and FTP-weighted are robust to differences in statistical methods of evaluation of significance.

The ratios indicate a fuel economy advantage of GDI vehicle vs PFI vehicles based on real-world VSP-modal data for city driving conditions. The fuel economy advantage seems to be sensitive to driving cycles. The advantage is significantly higher for city driving cycles Route A and FTP-weighted. The advantage is not significant for highway driving cycles Route 1 and HWFE-weighted.

The mean ratios of fuel economies of GDI and PFI vehicles range from 1.01 to 1.02 based on EPA rated fuel economy data, including EPA rated combined, city and highway fuel economies. The ratios are not significantly different from 1, and indicate that GDI and PFI vehicles have similar fuel economy per EPA data.

Results from PEMS data are indicative that fuel economy advantage is sensitive to driving cycles, compared to results from EPA data. Whereas the PEMS data indicates a significantly higher fuel economy advantage of GDI vehicles for city driving conditions than highway driving conditions, the EPA data indicates that GDI and PFI vehicles have similar fuel economies for all conditions.

Fuel use rates from real-world data indicate a GDI advantage, with mean GDI to PFI ratios varying from 0.89 to 0.95, depending on the driving cycle. $CO_2$ emission rates also follow a similar trend, with ratio of GDI to PFI rates based on real-world data ranging from 0.90 to 0.96.

The ratio of $NO_x$ emission rates of GDI and PFI vehicles based on real-world PEMS data ranges from 0.90 to 1.14. For real-world driving cycles All-Routes, Route A and Route 1, the ratios are 1.05, 0.96 ad 1.14, respectively. The ratio is 0.90 for FTP-weighted cycle, and is 0.94 for HWFE-weighted cycle. None of these ratios are significantly different from 1, which indicates that $NO_x$ emission rates are similar for GDI and PFI vehicles based on PEMS data.

The ratio of $NO_x$ emission rates of GDI and PFI vehicles based on EPA certification level data is 0.96. The ratio is not significantly different from 1, which indicates that $NO_x$ emission rates for GDI and PFI vehicles are similar based on EPA data, and corroborates with results from PEMS data. At 0.96, the ratio of $NO_x$ emission rates of GDI and PFI vehicles is the same for real-world city driving cycle Route A based on PEMS data, and EPA certification level data, which is based on FTP city driving cycle.

The mean ratio of cycle average CO emission rates of GDI and PFI vehicles based on PEMS data ranges from 0.56 to 0.72. For real-world driving cycles All-Routes, Route A and Route 1, the ratios are 0.68, 0.61 and 0.72, respectively. The ratio is 0.56 for FTP-weighted cycle, and is 0.59 for HWFE-weighted cycle. The ratios for Route A, FTP-weighted cycle and HWFE-weighted cycle are significantly different from 1, as the 95% confidence interval on these ratio does not include 1. The p-values of paired t-tests on the mean cycle average CO emission rates of GDI versus PFI, as shown in Table 5 (Page 69), indicate that cycle average CO emission rates for All-Routes, Route A, FTP-weighted and HWFE-weighted for GDI vehicles are significantly lower than PFI vehicles. Thus, the significance of lower cycle average CO emission rates of GDI vehicles compared to PFI vehicles for Route A, FTP-weighted and HWFE-weighted are robust to differences in statistical methods of evaluation of significance.

The ratios indicate that GDI vehicles have consistently lower CO emission rates than PFI vehicles. The difference in CO emission rates between GDI and PFI vehicles is sensitive to driving cycles. GDI vehicles have 40% lower CO emission rate for Route A and 30% lower emission rate for Route 1. Thus, the advantage of GDI vehicles in terms of lower CO emission rates is higher for real-world city driving conditions (Route A) than real-world highway driving conditions (Route 1). GDI vehicles have 44% lower CO emission rate for FTP-weighted cycle and 43% lower CO emission rate for HWFE-weighted cycle. Thus, the advantage of GDI vehicles in terms of lower CO emission rates is also higher for standard city driving cycle (FTP-weighted) than standard highway driving cycle (HWFE-weighted).

The ratio of CO emission rates of GDI and PFI vehicles based on EPA certification level data is 0.78. The ratio is not significantly different from 1. The ratio is suggestive of the fact that the CO emission rate of GDI vehicles is lower than PFI vehicle, which corroborates with the results from PEMS data. However, compared to the ratio based on real-world city driving cycle (Route A) from PEMS data, the ratio from EPA certification level data indicates a lower advantage of GDI vehicles in terms of lower CO emission rates by 17 percentage points.

The ratio of HC emission rates of GDI and PFI vehicles based on PEMS data ranges from 0.50 to 0.62. For real-world driving cycles All-Routes, Route A and Route 1, the ratios are 0.58, 0.53 and 0.62, respectively. The ratio is 0.50 for FTP-weighted cycle, and is 0.52 for HWFE-weighted cycle. The ratios are all significantly different from 1, which indicates that GDI vehicles have consistently lower HC emission rates than PFI vehicles based on real-world data. The ratios are less sensitive to driving cycles than other pollutants. Even so, GDI vehicles have 8 percentage points lower HC emission rates than PFI vehicles for real-world city driving cycle (Route A) compared to real-world highway driving cycle (Route 1). Similarly, GDI vehicles have 2 percentage points lower HC emission rates than PFI vehicles for the FTP-weighted cycle compared to HWFE-weighted cycle.

The ratio of HC emission rates of GDI and PFI vehicles based on EPA certification level data is 0.73. The ratio is significantly different from 1, which indicates that GDI vehicles have lower HC emission rate than PFI vehicles, and corroborates qualitatively with results from PEMS data. Compared to the ratio based on real-world city driving cycle Route A, the ratio based on EPA certification level data indicates 20 percentage points lower advantage of GDI vehicles in terms of lower HC emission rates.

# CHAPTER 4

## SUMMARY AND CONCLUSIONS

GDI engine technology has gained rapid market share since it was introduced in the year 2007 in the U.S. LDGV market. GDI engines provide, on average, 7.5% higher specific power and are, on average, 8% more fuel efficient than PFI vehicles. Manufacturers can choose to either downsize engines or provide the cars with extra horsepower by using GDI. GDI engines are more fuel efficient and powerful due to higher compression ratio and volumetric efficiency, coupled with better control of fuel and air staging. Due to the recent increase in the number of cars fitted with GDI engines in the U.S. market, it is important to study the fuel economy and emission rates of GDI vehicles, and compare them to conventional PFI vehicles.

Existing studies have focused largely on the higher UFP emissions from GDI vehicles compared to PFI vehicles. There is lack of real-world data comparing fuel use and gaseous emission rates of GDI and PFI vehicles. Previous studies reveal a lack of consensus about the fuel economy advantage of GDI vehicles over PFI vehicles. Estimates of the advantage vary from 2% to 30%. Recent studies also have inconsistent results of comparisons of gaseous emissions between GDI and PFI vehicles. Studies with limited sample sizes decrease the chances of the results obtained being statistically significant.

GDI vehicles were selected based on representativeness of the market. At least one GDI vehicle has been measured from each of the manufacturers that makes up 80% of GDI vehicle sales. PFI vehicles used for a one-on-one comparison, were selected by matching various characteristics, such as body type, engine displacement and configuration, rated horsepower to curb weight ratio and emission standards. In cases for where a single vehicle was not sufficiently similar, multiple vehicles were averaged to form a "composite" vehicle and compared.

This approach of selecting GDI and PFI vehicles was used to isolate the effect of GDI in vehicles, and compare the vehicles based on difference in fuel injection strategy. Even though it was not possible to match every attribute of selected vehicles, based on comparison of vehicle characteristics, the strategy was successfully employed in selecting comparable GDI and PFI vehicles in terms of matching curb weights and hp/lb ratios.

PEMS based real-world data from selected GDI and PFI vehicles indicates significant differences in fuel use rates, and CO and HC emission rates between GDI and PFI vehicles, both in terms of VSP modal average rates and cycle average emissions rates.

VSP modal average fuel use rates, based on real-world PEMS data, indicate that GDI vehicles have significantly lower fuel use rates compared to PFI vehicles for low vehicle specific power demand. For high vehicle specific power demand, the fuel use rates for GDI and PFI vehicles are similar. $CO_2$ emission rates follow the same trend as fuel use rates. Although $NO_x$ emission rates for GDI and PFI vehicles are similar, GDI vehicles tend to have lower $NO_x$ emission rates at low vehicle specific power demand and higher $NO_x$ emission rates at high vehicle specific power demand. CO emission rates of GDI vehicles are consistently lower than PFI vehicles for low vehicle specific power demand, and are similar to PFI vehicles for high vehicle specific power demand. GDI vehicles have lower HC emission rates compared to PFI vehicles for both low and high vehicle specific power demand. Modal average PM emission rates indicate that PM emissions of GDI vehicles are similar to PFI vehicles for low vehicle specific power demand, and are considerably higher than PFI vehicles for high vehicle specific power demand.

The cycle average fuel economy advantage of GDI vehicles over PFI vehicles, based on real-world PEMS data, is 5.7% to 10.6% for real-world driving cycles, which is in the middle of the reported range of 2% to 30%. The fuel economy advantage is sensitive to driving cycles. The fuel economy advantage is higher for city driving conditions compared to highway driving conditions. The GDI fuel economy advantage, estimated based on real-world modal average fuel use rates and standard cycles, is to 10.8% and 13.1% for standard driving cycles HWFE and FTP, respectively. However, the standard driving cycles are typically not representative of real world driving, and therefore, the advantage of GDI vehicles over PFI vehicles based on such cycles may be overstated compared to the real world.

GDI and PFI vehicles are found to have similar cycle average $NO_x$ emission rates. However, higher $NO_x$ at high load for GDI engines compared to PFI engines needs further investigation. In contrast, cycle average CO emission rates of GDI vehicles are significantly lower by 30% to 40% than for PFI vehicles, based on real-world driving cycles. Similarly, cycle average HC emission rates of GDI vehicles are significantly lower by 40% to 48% than PFI vehicles, based on real-world driving cycles. PM emissions of GDI vehicles are found to be higher by 27% to 69% compared to PFI vehicles. However, the results are not significant due to a small sample size of four pairs of GDI and PFI vehicles.

Whereas the fuel economy advantage of GDI vehicles based on cycle average fuel economy data from real-world PEMS measurements is statistically significant, certification level data is only suggestive of fuel economy advantage. Certification level data corroborates the finding that GDI vehicles have similar $NO_x$ emission rates, lower CO emission rates, and lower HC emission rates compared to PFI vehicles.

However, based on comparison of real-world cycle average emission rates and certification level data for the same cycle, GDI vehicles perform better in the real-world in terms of lower emission rates than PFI vehicles. For example, compared to EPA certification level CO emission rates, the modal-based FTP-weighted average CO emission rate is lower by 21.0% for GDI vehicles, and is higher by 10.2% for PFI vehicles. Although the differences are not statistically significant, they are suggestive that certification level data overestimates GDI CO emission rates, but underestimates PFI CO emission rates.

Overall, the higher fuel economy, lower CO, and lower HC emissions of GDI vehicles come with a trade-off of increased particulate matter emissions. This suggests that as GDI vehicle market penetration increases further, there may be positive and negative impacts on local air quality, especially in urban environments near roadways. Further investigation can be done to determine the potential impacts of changing vehicle fleet from GDI to PFI, by simulating near-road and local air quality.

A key limitation of this study is that the GDI vehicles could not be identified as WG GDI or SG GDI. Further investigation can be done to assess the impact of WG and SG systems on the fuel economy and emission rates of GDI vehicles. An implicit assumption in doing paired t-tests for the two sets of vehicles is that the only difference between the two sets was fuel injection strategy. Statistical analyses such as Analyses of Variance (ANOVA) can be used to determine the impact of variation due to body types, vehicle size, transmission, engine aspiration, drivetrain, ambient temperature and ambient RH on the comparison of GDI and PFI vehicles.

With the fuel economy advantage estimated from real-world data, GDI alone might not be sufficient to meet the 2025 CAFE target of 54.5 mpg. In 2016, more than 48% new LDGVs were equipped with GDI in the market, and the unadjusted fleet average fuel economy was 29.6 mpg. The increase in unadjusted fuel economy required to achieve the 2025 CAFE target is approximately 84%, and GDI alone cannot provide such a tremendous increase in fuel economy. However, GDI can be used in combination with other technologies, such as turbocharging, CVT, hybridization, and cylinder deactivation, as part of an overall solution.

## REFERENCES


American Petroleum Institute. 2013. "Future US Trends in the Adoption of Light-Duty Automotive Technologies." Integrated Final Report 092013. Washington, DC: American Petroleum Institute. http://www.api.org/~/media/files/policy/fuels-and-renewables/hds-092013-future-us-trends-in-adoption-of-ld-auto-technologies.pdf.

Anderson, W., Yang, J., Brehob, D., Vallance, J. et al., "Understanding the Thermodynamics of Direct Injection Spark Ignition (DISI) Combustion Systems: An Analytical and Experimental Investigation," SAE Technical Paper 962018, 1996, https://doi.org/10.4271/962018.

Bonatesta, F., E. Chiappetta, and A. La Rocca. 2014. "Part-Load Particulate Matter from a GDI Engine and the Connection with Combustion Characteristics." *Applied Energy* 124 (July): 366–76. https://doi.org/10.1016/j.apenergy.2014.03.030.

Bahreini, R., J. Xue, K. Johnson, T. Durbin, D. Quiros, S. Hu, T. Huai, A. Ayala, and H. Jung. 2015. Characterizing Emissions and Optical Properties of Particulate Matter from PFI and GDI Light-Duty Gasoline Vehicles. *J. Aerosol Sci.* 90 (December): 144–153. doi:10.1016/j.jaerosci.2015.08.011.

Braisher, M., Stone, R., and Price, P., "Particle Number Emissions from a Range of European Vehicles," SAE Technical Paper 2010-01-0786, 2010, https://doi.org/10.4271/2010-01-0786.

Chan, Tak W., Eric Meloche, Joseph Kubsh, Deborah Rosenblatt, Rasto Brezny, and Greg Rideout. 2012. "Evaluation of a Gasoline Particulate Filter to Reduce Particle Emissions from a Gasoline Direct Injection Vehicle." *SAE International Journal of Fuels and Lubricants* 5 (3): 1277–90. https://doi.org/10.4271/2012-01-1727.

Chen, Longfei, Richard Stone, and Dave Richardson. 2012. "A Study of Mixture Preparation and PM Emissions Using a Direct Injection Engine Fuelled with Stoichiometric Gasoline/Ethanol Blends." *Fuel* 96 (June): 120–30. https://doi.org/10.1016/j.fuel.2011.12.070.

Code of Federal Regulations, 2013a. Compliance with Emission Standards for the Purpose of Certification. Title 40, Chapter I, Sub-chapter C, Part 86, Subpart S, Section 86, p. 1841-01.

Code of Federal Regulations, 2013b. Emission Standards for Light-duty Vehicles, Light-duty trucks and Medium-duty Passenger Vehicles. Title 40, Chapter I, Sub-chapter C, Part 86, Subpart S, section 86, p. 1811-04.

Code of Federal Regulations, 2013c. Definitions. Title 40, Chapter I, Sub-chapter U, Part 1037, Subpart I, section 1037. 801.

Code of Federal Regulations, 2013d. Mileage Accumulation Requirements for Test Vehicles. Title 40, Chapter I, Sub-chapter C, Part 86, Subpart S, section 86, p. 1831-01.

Cole, R., Poola, R., and Sekar, R., "Exhaust Emissions of a Vehicle with a Gasoline Direct-Injection Engine," SAE Technical Paper 982605, 1998, https://doi.org/10.4271/982605.

Confer, K., Kirwan, J., and Engineer, N., "Development and Vehicle Demonstration of a Systems-Level Approach to Fuel Economy Improvement Technologies," SAE Technical Paper 2013-01-0280, 2013, https://doi.org/10.4271/2013-01-0280.

Devore, Jay L. 2016. *Probability and Statistics for Engineering and the Sciences*. Ninth edition. Boston, MA.

DieselNet. 2017. Gasoline Particulate Filters. DieselNet Technology Guide. *Gasoline Particulate Filters*. https://www.dieselnet.com/tech/gasoline_particulate_filters.php (accessed April 15, 2018).

DieselNet. 2018. Emission Standards: Europe: Cars and Light Trucks. https://www.dieselnet.com/standards/eu/ld.php#stds (accessed April 15, 2018).

Efron, Bradley, and Robert Tibshirani. 1993. *An Introduction to the Bootstrap*. New York: Chapman & Hall.

Ferguson, Colin R., and Allan Kirkpatrick. 2015. *Internal Combustion Engines: Applied Thermosciences*. Chichester, West Sussex, United Kingdom: Wiley, 2015. *eBook Collection (EBSCOhost)*, EBSCO*host* (accessed April 15, 2018).

Frey, H.C., Unal, A., Chen, J., Li, S., Xuan, C., 2002.Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission Estimation System. EPA420-R-02-027. Prepared by NC State University for U.S. Environmental Protection Agency, Ann Arbor, MI.

Frey, H. Christopher, Alper Unal, Nagui M. Rouphail, and James D. Colyar. 2003. “On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument.” *Journal of the Air & Waste Management Association* 53 (8): 992–1002.

Frey, H. Christopher, Kaishan Zhang, and Nagui M. Rouphail. 2008. “Fuel Use and Emissions Comparisons for Alternative Routes, Time of Day, Road Grade, and Vehicles Based on In-Use Measurements.” *Environmental Science & Technology* 42 (7): 2483–89. https://doi.org/10.1021/es702493v.

———. 2010. “Vehicle-Specific Emissions Modeling Based upon on-Road Measurements.” *Environmental Science & Technology* 44 (9): 3594–3600. https://doi.org/10.1021/es902835h.

Frey, H.C., Boroujeni, B.Y., Hu, J., Sandhu, G., Liu, B., Jiao, W., Graver, B. 2013. Field measurements of 1996 to 2013 model year light duty gasoline vehicles. Extended Abstract No. 12942, Proceedings, 106th Annual Meeting of the Air & Waste Management Association, Chicago, IL, June 24–28, 2013.

Golzari, Reza, Yuanping Li, and Hua Zhao. 2016. “Impact of Port Fuel Injection and In-Cylinder Fuel Injection Strategies on Gasoline Engine Emissions and Fuel Economy.” SAE Technical Paper 2016-01-2174. Warrendale, PA: SAE Technical Paper. https://doi.org/10.4271/2016-01-2174.

Graham, Lisa. 2005. “Chemical Characterization of Emissions from Advanced Technology Light-Duty Vehicles.” *Atmospheric Environment* 39 (13): 2385–98. https://doi.org/10.1016/j.atmosenv.2004.10.049.

Graver, B.M., 2016. “Measurement and Evaluation of Passenger Locomotive Fuel Use and Emissions Using a Portable Emissions Measurement System.” PhD Dissertation. North Carolina State University, Raleigh, NC.

Heck, Ronald M., Robert J. Farrauto, and Suresh T. Gulati. c2009. *Catalytic Air Pollution Control: Commercial Technology*. 3rd ed. Hoboken, N.J.: John Wiley.

Jimenez-Palacios, Jose Luis. 1998. “Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing.” Ph.D. Thesis, Cambridge, MA: Department of Mechanical Engineering, Massachusetts Institute of Technology.

Kašpar, Jan, Paolo Fornasiero, and Neal Hickey. 2003. “Automotive Catalytic Converters: Current Status and Some Perspectives.” *Catalysis Today*, Fundamentals of Catalysis and Applications to Environmental Problems, 77 (4): 419–49. https://doi.org/10.1016/S0920-5861(02)00384-X.

Kolwich, Greg. 2013. Light-Duty Technology Cost Analysis, Report on Additional Case Studies. EPA-420-R-13-008. Prepared by FEV, Inc. for U.S. Environmental Protection Agency, Ann Arbor, MI.

Liu, Bin, and H. Christopher Frey. 2015. “Variability in Light-Duty Gasoline Vehicle Emission Factors from Trip-Based Real-World Measurements.” *Environmental Science & Technology* 49 (20): 12525–34. https://doi.org/10.1021/acs.est.5b00553.

Maricq, M. Matti, Diane H. Podsiadlik, and Richard E. Chase. 1999. “Examination of the Size-Resolved and Transient Nature of Motor Vehicle Particle Emissions.” *Environmental Science & Technology* 33 (10): 1618–26. https://doi.org/10.1021/es9808806.

Minjares, R., and F. P. Sanchez. 2011. Estimated Cost of Gasoline Particulate Filters. Working Paper 2011–8. Washington, DC: International Council on Clean Transportation.

Myers, J., Kelly, T., Dindal, A., Willenberg, Z., Riggs, K., 2003. *Environmental Technology Verification Report*: Clean Air Technologies International, Inc. REMOTE On-Board Emissions Monitor. Prepared by Battelle for the US Environmental Protection Agency, Cincinnati, OH June. URL: https://archive.epa.gov/research/nrmrl/archive-etv/web/pdf/01_vr_oem_report3.pdf (Accessed 02.04.2018).

Myung, Cha-Lee, Juwon Kim, Kwanhee Choi, In Goo Hwang, and Simsoo Park. 2012. “Comparative Study of Engine Control Strategies for Particulate Emissions from Direct Injection Light-Duty Vehicle Fueled with Gasoline and Liquid Phase Liquefied Petroleum Gas (LPG).” *Fuel* 94 (April): 348–55. https://doi.org/10.1016/j.fuel.2011.10.041.

Na Wu, Wang Xibo, Qiu Xuyun, Tao Lili and Huang Fei, "Research on optimal control for gasoline engine emissions," *World Automation Congress 2012*, Puerto Vallarta, Mexico, 2012, pp. 1-4. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6321583&isnumber=6320876

Nam, E., 2009. *Drive cycle development and real-world data in the United States.* Working Paper No: WLTP 02-17, Worldwide Harmonized Light Vehicles Test Procedures Meeting. Geneva, Switzerland. U.S. Environmental Protection Agency January 15. URL: http://www.unece.org/fileadmin/DAM/trans/doc/2009/wp29grpe/WLTP-02-17e.pdf (Accessed 02.04.2018).

National Research Council. 2015. *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. Washington, DC: The National Academies Press. https://www.nap.edu/catalog/21744/cost-effectiveness-and-deployment-of-fuel-economy-technologies-for-light-duty-vehicles.

Nose, H., Inoue, T., Katagiri, S., Sakai, A. et al., "Fuel Enrichment Control System by Catalyst Temperature Estimation to Enable Frequent Stoichiometric Operation at High Engine Speed/Load Condition," SAE Technical Paper 2013-01-0341, 2013, https://doi.org/10.4271/2013-01-0341.

Oak Ridge National Laboratory. 2017. “2016 Vehicle Technologies Market Report.” Annual Report ORNL/TM-2017/238. Oak Ridge, TN: Oak Ridge National Laboratory. https://cta.ornl.gov/vtmarketreport/pdf/2016_vtmarketreport_full_doc.pdf.

Oh, Seungmook, Seokhwan Lee, Young Choi, Kern-Yong Kang, Junho Cho, and Kyoungok Cha. 2010. “Combustion and Emission Characteristics in a Direct Injection LPG/Gasoline Spark Ignition Engine.” SAE Technical Paper 2010-01-1461. Warrendale, PA: SAE Technical Paper. https://doi.org/10.4271/2010-01-1461.

Price, P., Stone, R., Collier, T., and Davies, M., "Particulate Matter and Hydrocarbon Emissions Measurements: Comparing First and Second Generation DISI with PFI in Single Cylinder Optical Engines," SAE Technical Paper 2006-01-1263, 2006, https://doi.org/10.4271/2006-01-1263.

Saliba, Georges, Rawad Saleh, Yunliang Zhao, Albert A. Presto, Andrew T. Lambe, Bruce Frodin, Satya Sardar, et al. 2017. “Comparison of Gasoline Direct-Injection (GDI) and Port Fuel Injection (PFI) Vehicle Emissions: Emission Certification Standards, Cold-Start, Secondary Organic Aerosol Formation Potential, and Potential Climate Impacts.” *Environmental Science & Technology* 51 (11): 6542–52. https://doi.org/10.1021/acs.est.6b06509.

Samuel, S., L. Austin, and D. Morrey. 2002. “Automotive Test Drive Cycles for Emission Measurement and Real-World Emission Levels-a Review.” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 216 (7): 555–64. https://doi.org/10.1243/095440702760178587.

Sandhu, Gurdas, and H. Frey. 2013. “Effects of Errors on Vehicle Emission Rates from Portable Emissions Measurement Systems.” *Transportation Research Record: Journal of the Transportation Research Board* 2340 (August): 10–19. https://doi.org/10.3141/2340-02.

Seo, J., H. Y. Kim, S. Park, S. C. James, and S. S. Yoon. 2016. Experimental and Numerical Simulations of Spray Impingement and Combustion Characteristics in Gasoline Direct Injection Engines under Variable Driving Conditions. *Flow Turbul. Combust.* 96 (2): 391–415. doi:10.1007/s10494-015-9678-1.

Short, D., D. Vu, V. Chen, C. Espinoza, T. Berte, G. Karavalakis, T. D. Durbin, and A. Asa-Awuku. 2017. Understanding Particles Emitted from Spray and Wall-Guided Gasoline Direct Injection and Flex Fuel Vehicles Operating on Ethanol and Iso-Butanol Gasoline Blends. *Aerosol Sci. Technol.* 51 (3): 330–341. doi:10.1080/02786826.2016.1265080.

Singer, B.C., Harley, R.A., Littlejohn, D., Ho, J., Vo, T., 1998. "Scaling of infrared remote sensor hydrocarbon measurements for motor vehicle emission inventory calculations." *Environmental Science & Technology* 32 (21): 3241–3248.

Spiess, Stephanie, Ka-Fai Wong, Joerg-Michael Richter, and Raoul Klingmann. 2013. "Investigations of Emission Control Systems for Gasoline Direct Injection Engines with a Focus on Removal of Particulate Emissions." *Topics in Catalysis* 56 (1–8): 434–39. https://doi.org/10.1007/s11244-013-9992-6.

Stephens, R.D., Mulawa, P.A., Giles, M.T., Kennedy, K.G., Grobiicki, P.J., Cadle, S.H., Knapp, K.T., 1996. "An experimental evaluation of remote sensing-based hydrocarbon measurements: a comparison to FID measurements." *J. Air Waste Manage. Assoc*. 46 (2), 148–158.

Su, Jianye, Min Xu, Peng Yin, Yi Gao, and David Hung. 2014. "Particle Number Emissions Reduction Using Multiple Injection Strategies in a Boosted Spark-Ignition Direct-Injection (SIDI) Gasoline Engine." *SAE International Journal of Engines* 8 (1): 20–29. https://doi.org/10.4271/2014-01-2845.

U.S. Environmental Protection Agency, 2017. Annual Certification Test Data for Vehicles and Engines. https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-test-data-vehicles-and-engines. Accessed date: November 2017.

U.S. Environmental Protection Agency. 2018a. "DRAFT Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2016." Annual Report EPA 430-P-18-001. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016.

U.S. Environmental Protection Agency. 2018b. "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2017." Annual Report EPA-420-R-18-001. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2018-01/documents/420r18001.pdf.

U.S. Environmental Protection Agency. 2018c. "Mid-Term Evaluation of Greenhouse Gas Emissions Standards for Model Year 2022–2025 Light-Duty Vehicles." Notice; withdrawal. EPA–HQ–OAR–2015–0827; FRL–9976–61– OAR. Federal Register Vol. 83, No. 72, p. 16077-87. April 13, 2018. https://www.gpo.gov/fdsys/pkg/FR-2018-04-13/pdf/2018-07364.pdf

Wang, J. M., Jeong, C.-H., Zimmerman, N., Healy, R. M., Wang, D. K., Ke, F., and Evans, G. J. 2015. "Plume-based analysis of vehicle fleet air pollutant emissions and the contribution from high emitters." *Atmos. Meas. Tech.*, 8, 3263-3275, https://doi.org/10.5194/amt-8-3263-2015.

Wyszynski, L., Stone, C., and Kalghatgi, G., "The Volumetric Efficiency of Direct and Port Injection Gasoline Engines with Different Fuels," SAE Technical Paper 2002-01-0839, 2002, https://doi.org/10.4271/2002-01-0839.

Yazdani Boroujeni, Behdad, and H. Christopher Frey. 2014. "Road Grade Quantification Based on Global Positioning System Data Obtained from Real-World Vehicle Fuel Use and Emissions Measurements." *Atmospheric Environment* 85 (March): 179–86. https://doi.org/10.1016/j.atmosenv.2013.12.025.

Zhan, R., Eakle, S., and Weber, P., "Simultaneous Reduction of PM, HC, CO and $NO_x$ Emissions from a GDI Engine," SAE Technical Paper 2010-01-0365, 2010, https://doi.org/10.4271/2010-01-0365.

Zhao, F, M. -C Lai, and D. L Harrington. 1999. "Automotive Spark-Ignited Direct-Injection Gasoline Engines." *Progress in Energy and Combustion Science* 25 (5): 437–562. https://doi.org/10.1016/S0360-1285(99)00004-0.

Zhao, Y., Frey, H.C., 2004. "Quantification of variability and uncertainty for censored data sets and application to air toxic emission factors." *Risk Anal*. 24 (4), 1019–1034.

Zheng, X., S. Zhang, Y. Wu, K. M. Zhang, X. Wu, Z. Li, and J. Hao. 2017. Characteristics of Black Carbon Emissions from In-Use Light-Duty Passenger Vehicles. *Environ. Pollut.* 231 (December): 348–356. doi:10.1016/j.envpol.2017.08.002.

Zimmerman, Naomi, Jonathan M. Wang, Cheol-Heon Jeong, Manuel Ramos, Nathan Hilker, Robert M. Healy, Kelly Sabaliauskas, James S. Wallace, and Greg J. Evans. 2016. "Field Measurements of Gasoline Direct Injection Emission Factors: Spatial and Seasonal Variability." *Environmental Science & Technology* 50 (4): 2035–43. https://doi.org/10.1021/acs.est.5b04444.

Zimmerman, Naomi, Jonathan M. Wang, Cheol-Heon Jeong, James S. Wallace, and Greg J. Evans. 2016. "Assessing the Climate Trade-Offs of Gasoline Direct Injection Engines." *Environmental Science & Technology* 50 (15): 8385–92. https://doi.org/10.1021/acs.est.6b01800.

Zimmerman, Naomi. 2016. "Linking Laboratory Engine Studies to Real-World Observations: Assessing the Air Quality Implications of Gasoline Direct Injection Engines." Ph.D. Thesis, Toronto, Ontario: Graduate Department of Chemical Engineering and Applied Chemistry, University of Toronto.

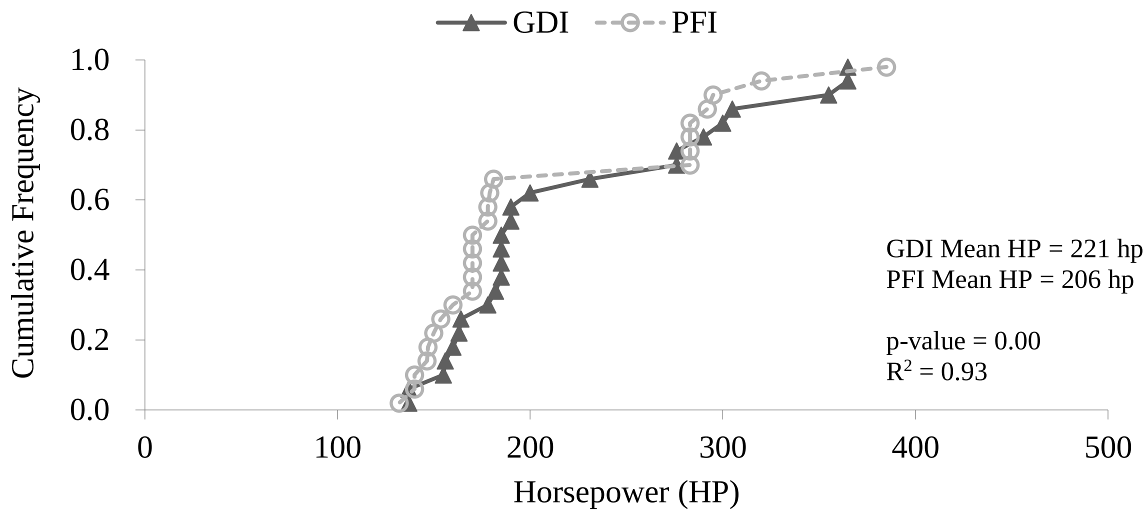
## APPENDICES

## Appendix A

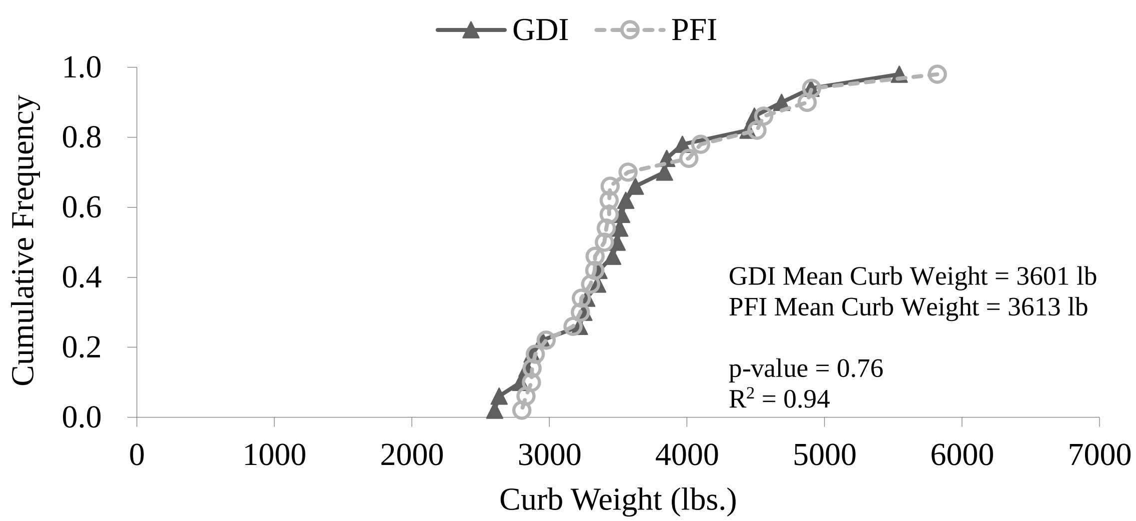
The following figures show supplemental data for GDI and PFI comparisons.

**Figure A1. Comparison of Characteristics of GDI (n = 25 "composite") and PFI (n = 25 "composite") vehicles based on: (a) Horsepower; (b) Curb Weight; (c) HP/lb ratio; (d) Compression Ratio; (e) Vehicle Age at the time of measurement; (f) Vehicle Mileage at the time of measurement**

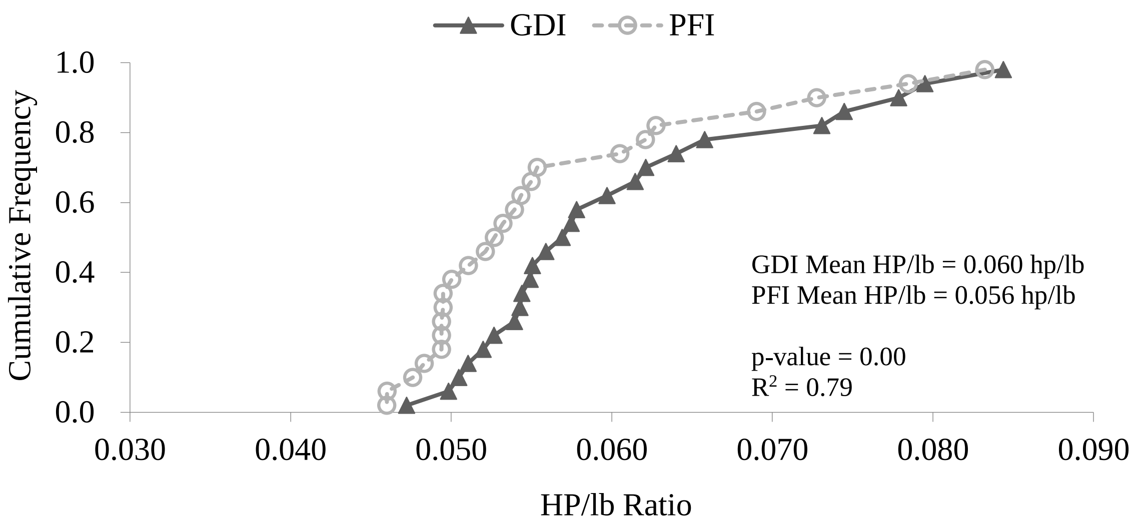
CDF graphs are plotted by ranking each set of vehicles, i.e., GDI and PFI, from highest to lowest, and assigning cumulative frequency based on ranks, versus vehicle characteristics. Since vehicles are ranked within the set, the graphs do not illustrate paired comparisons, but the range of each set of vehicles. However, p-value is calculated based on paired t-test on means. $R^2$ is the coefficient of determination for a linear regression model between the sets of 25 paired GDI and PFI vehicles.


GDI
PFI
Cumulative Frequency
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
Horsepower (HP)
GDI Mean HP = 221 hp
PFI Mean HP = 206 hp
p-value = 0.00
R2 = 0.93

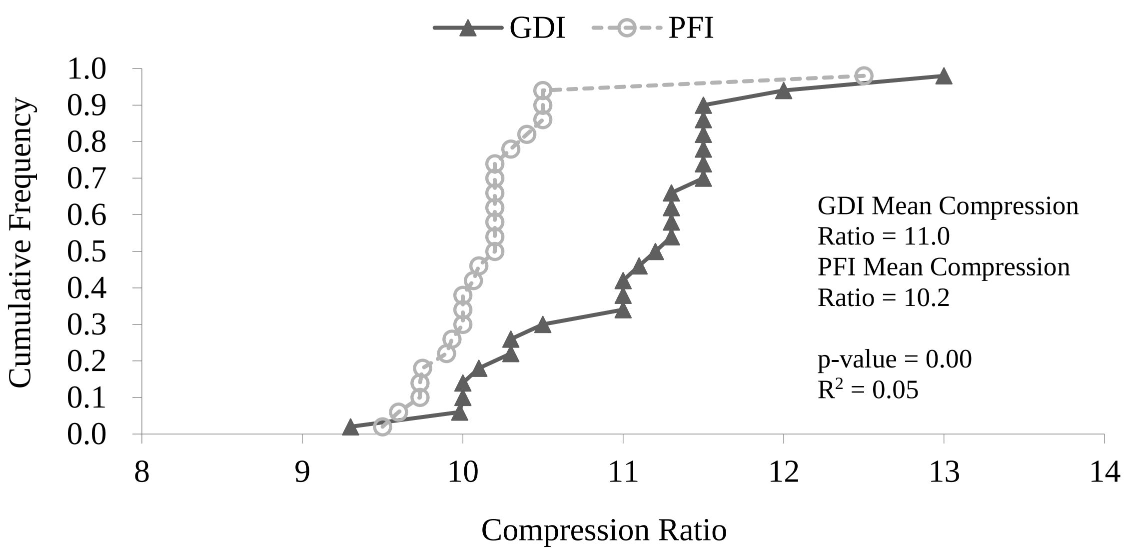
**(a)**


GDI
PFI
Cumulative Frequency
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
5000
6000
7000
Curb Weight (lbs.)
GDI Mean Curb Weight = 3601 lb
PFI Mean Curb Weight = 3613 lb
p-value = 0.76
R2 = 0.94

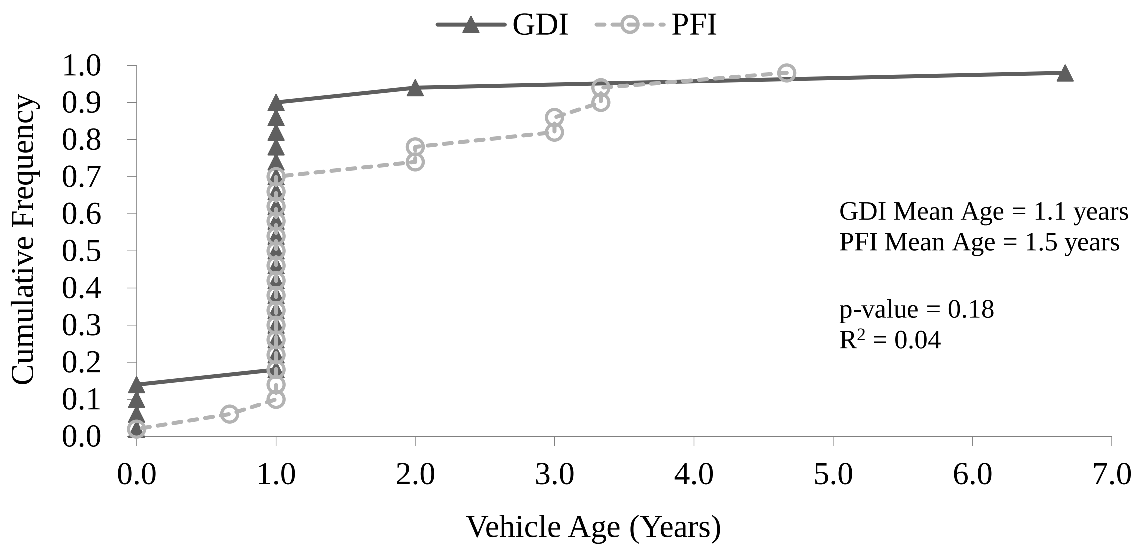
**(b)**


GDI
PFI
Cumulative Frequency
1.0
0.8
0.6
0.4
0.2
0.0
0.030
0.040
0.050
0.060
0.070
0.080
0.090
HP/lb Ratio
GDI Mean HP/lb = 0.060 hp/lb
PFI Mean HP/lb = 0.056 hp/lb
p-value = 0.00
R2 = 0.79

**(c)**


GDI
PFI
Cumulative Frequency
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
8
9
10
11
12
13
14
Compression Ratio
GDI Mean Compression Ratio = 11.0
PFI Mean Compression Ratio = 10.2
p-value = 0.00
R2 = 0.05

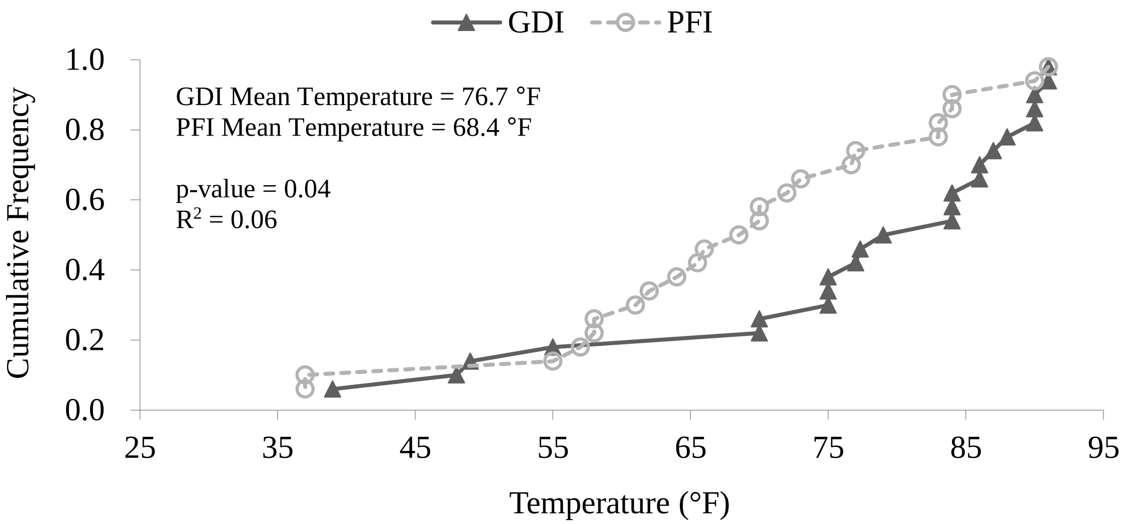
**(d)**


GDI
PFI
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative Frequency
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Vehicle Age (Years)
GDI Mean Age = 1.1 years
PFI Mean Age = 1.5 years
p-value = 0.18
R2 = 0.04

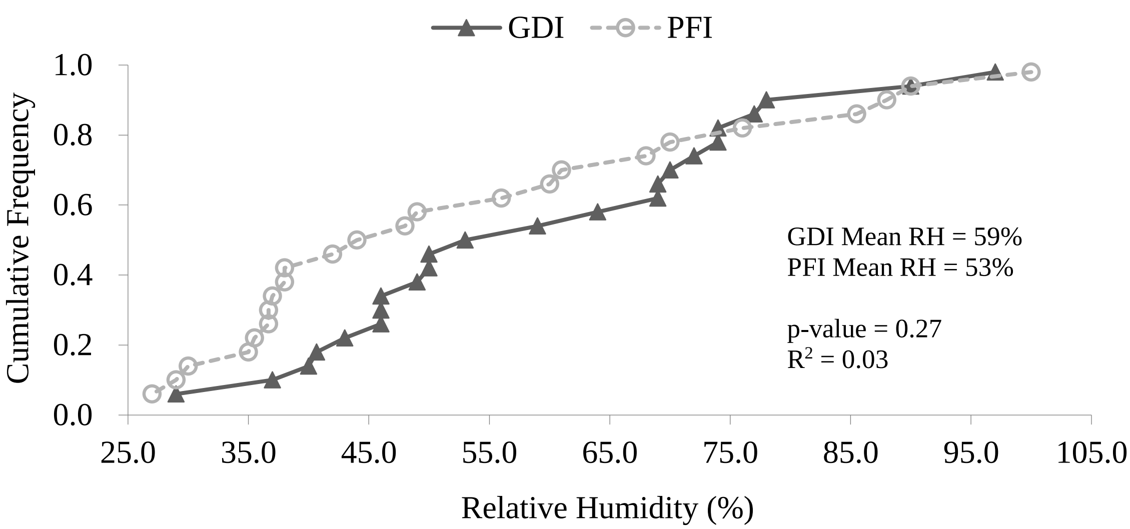
**(e)**

**Figure A2. Comparison of ambient conditions for GDI (n = 25 "composite") and PFI (n = 25 "composite") vehicles based: (a) Temperature; (b) Relative Humidity**

CDF graphs are plotted by ranking each set of vehicles, i.e., GDI and PFI, from highest to lowest, and assigning cumulative frequency based on ranks, versus ambient conditions. Since vehicles are ranked within the set, the graphs do not illustrate paired comparisons, but the range of each set of vehicles. However, p-value is calculated based on paired t-test on means. $R^2$ is the coefficient of determination for a linear regression model between the sets of 25 paired GDI and PFI vehicles.


GDI
PFI
GDI Mean Temperature = 76.7 °F
PFI Mean Temperature = 68.4 °F
p-value = 0.04
R2 = 0.06
Cumulative Frequency
1.0
0.8
0.6
0.4
0.2
0.0
25
35
45
55
65
75
85
95
Temperature (°F)

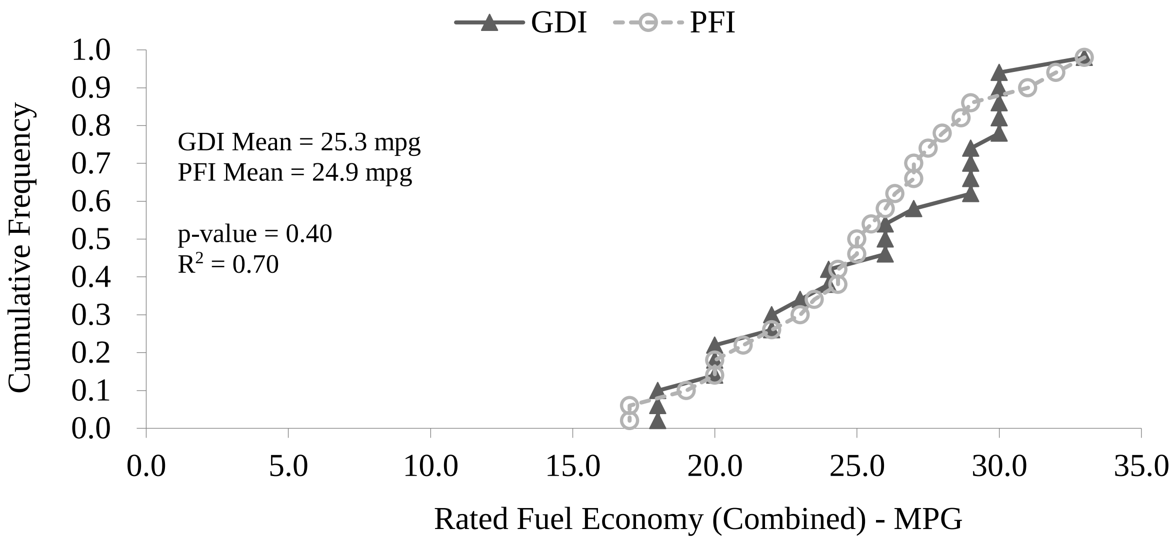
**(a)**


GDI
PFI
GDI Mean RH = 59%
PFI Mean RH = 53%
p-value = 0.27
R2 = 0.03
Cumulative Frequency
1.0
0.8
0.6
0.4
0.2
0.0
25.0
35.0
45.0
55.0
65.0
75.0
85.0
95.0
105.0
Relative Humidity (%)

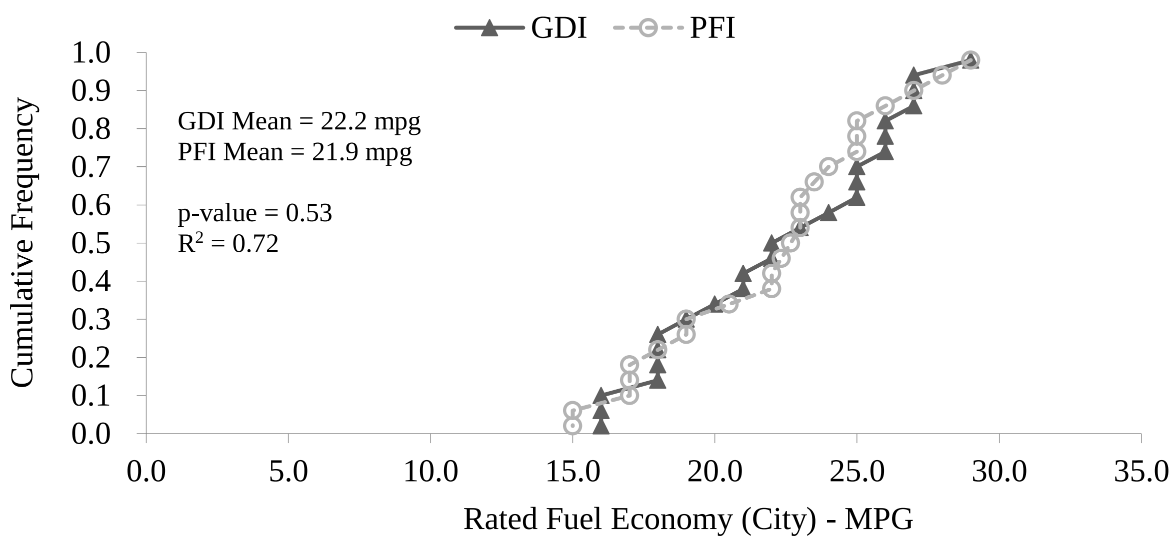
**(b)**

**Figure A3.** **EPA-rated Fuel Economy and Certification Level Data for selected pairs of GDI and PFI vehicles (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles) (a) Combined Fuel Economy; (b) City Fuel Economy; (c) Highway Fuel Economy; (d) $NO_x$; (e) CO; (f) HC**

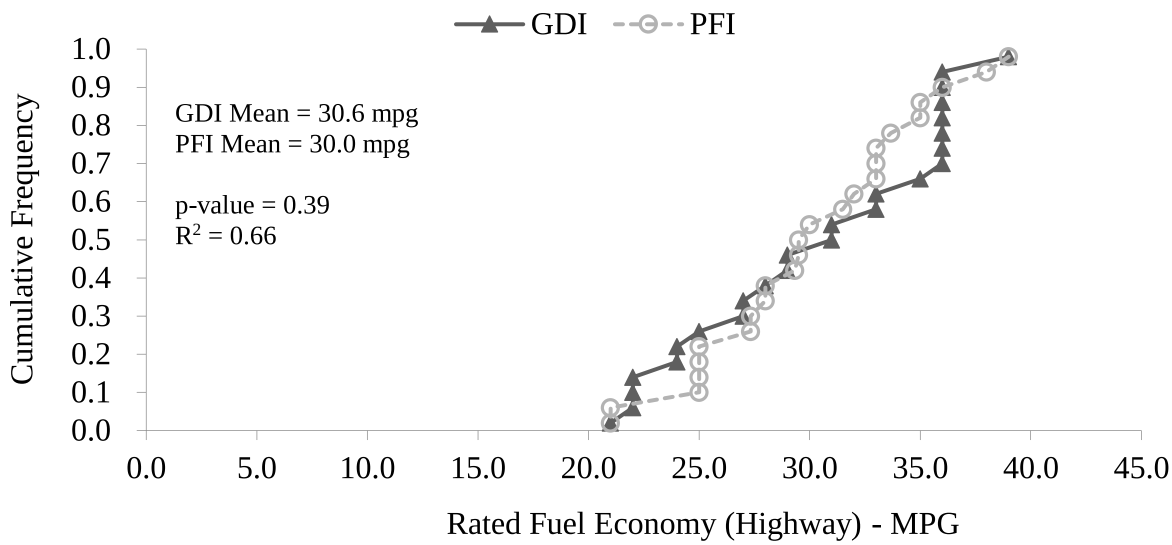
CDF graphs are plotted by ranking each set of vehicles, i.e., GDI and PFI, from highest to lowest, and assigning cumulative frequency based on ranks, versus EPA-rated fuel economy and certification level data. Since vehicles are ranked within the set, the graphs do not illustrate paired comparisons, but the range of each set of vehicles. However, p-value is calculated based on paired t-test on means. $R^2$ is the coefficient of determination for a linear regression model between the sets of 25 paired GDI and PFI vehicles.


GDI
PFI
Cumulative Frequency
GDI Mean = 25.3 mpg
PFI Mean = 24.9 mpg
p-value = 0.40
R2 = 0.70
Rated Fuel Economy (Combined) - MPG

**(a)**

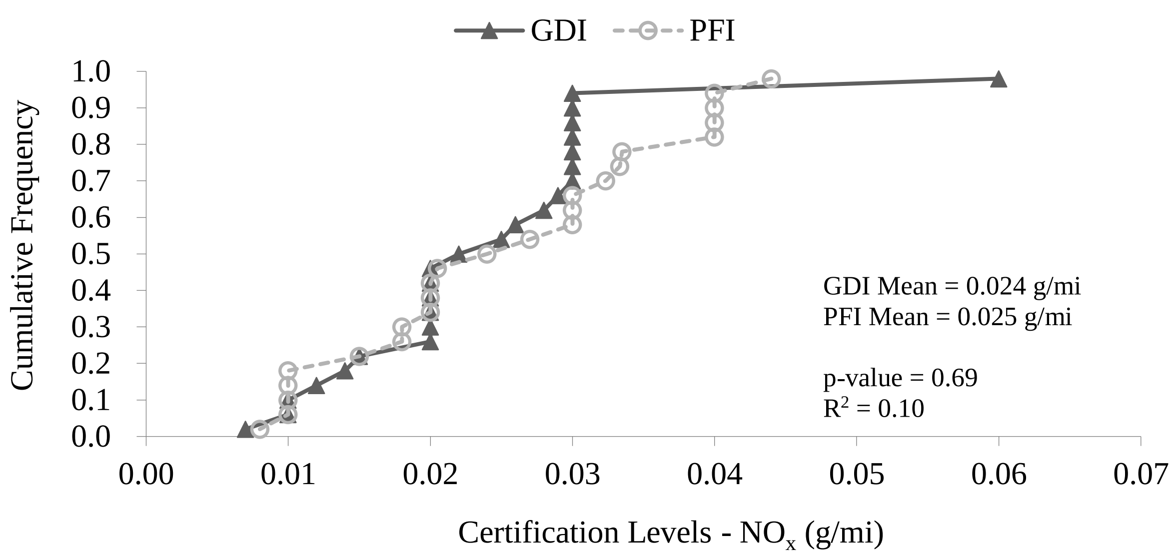

GDI
PFI
Cumulative Frequency
GDI Mean = 22.2 mpg
PFI Mean = 21.9 mpg
p-value = 0.53
R2 = 0.72
Rated Fuel Economy (City) - MPG

**(b)**



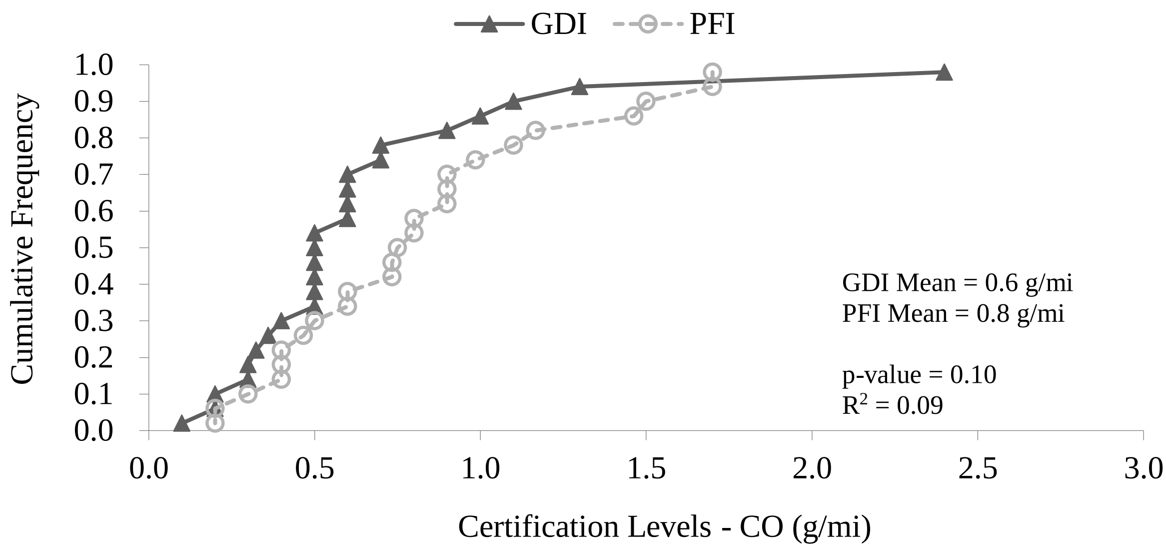
GDI
PFI
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative Frequency
GDI Mean = 30.6 mpg
PFI Mean = 30.0 mpg
p-value = 0.39
R2 = 0.66
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
Rated Fuel Economy (Highway) - MPG


**(c)**

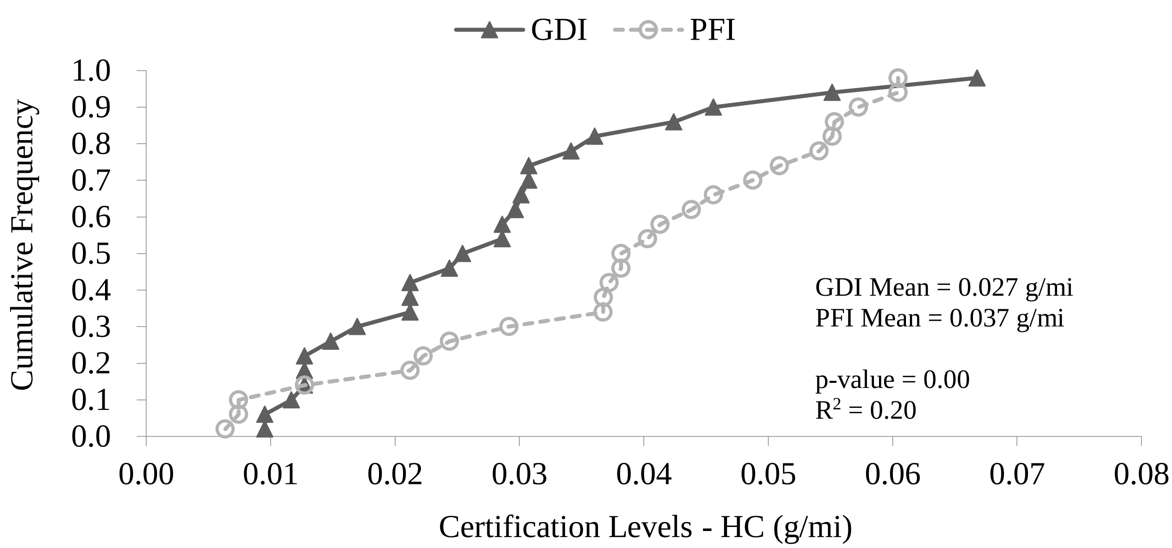


GDI
PFI
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative Frequency
GDI Mean = 0.024 g/mi
PFI Mean = 0.025 g/mi
p-value = 0.69
R2 = 0.10
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Certification Levels - NOx (g/mi)


**(d)**


GDI
PFI
Cumulative Frequency
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Certification Levels - CO (g/mi)
GDI Mean = 0.6 g/mi
PFI Mean = 0.8 g/mi
p-value = 0.10
R2 = 0.09

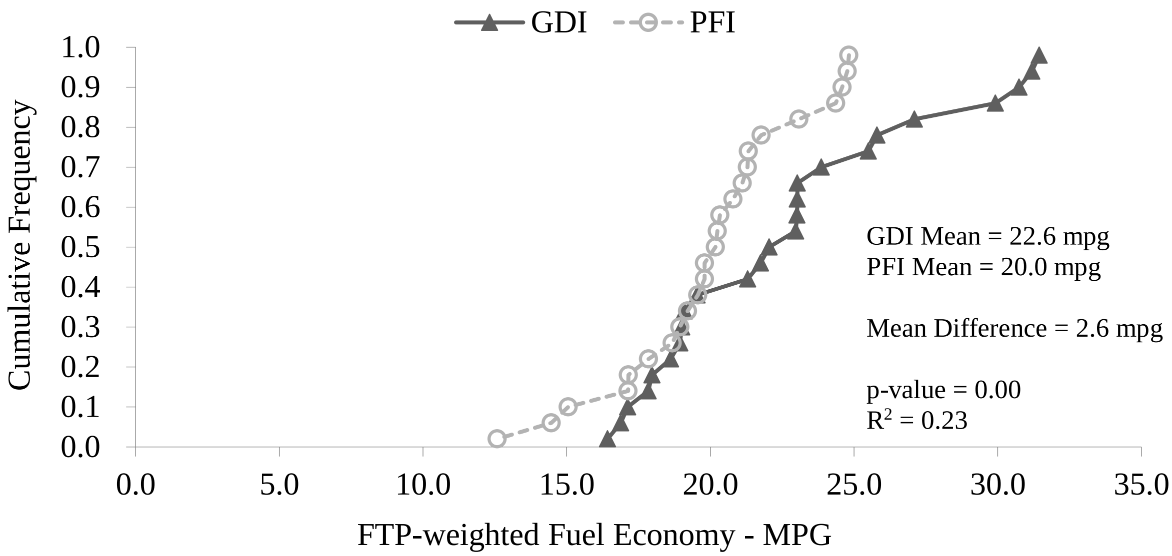
**(e)**


GDI
PFI
Cumulative Frequency
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Certification Levels - HC (g/mi)
GDI Mean = 0.027 g/mi
PFI Mean = 0.037 g/mi
p-value = 0.00
R2 = 0.20

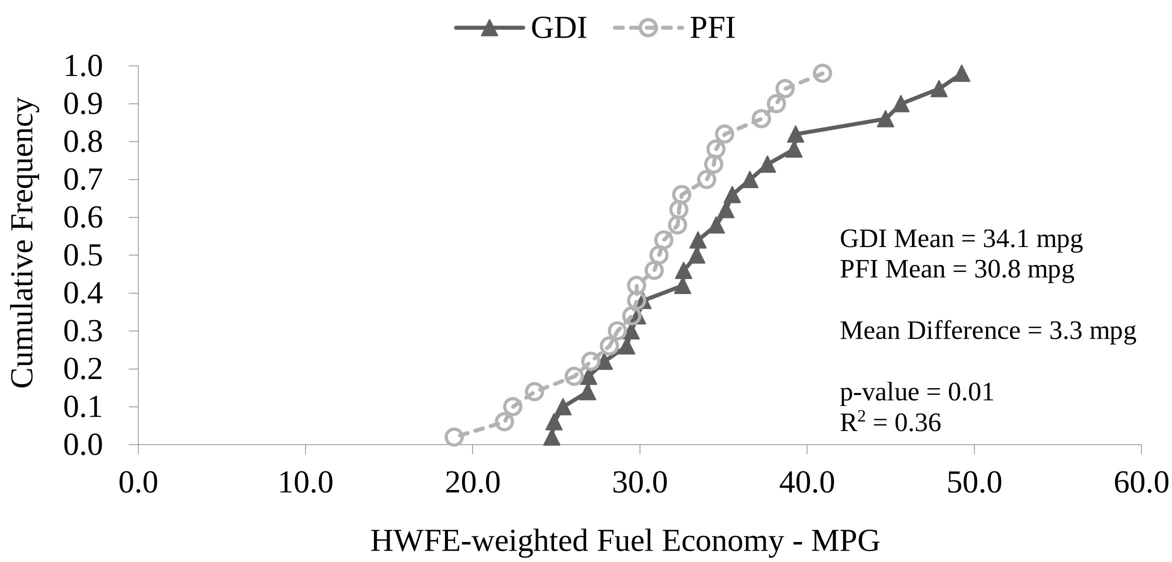
**(f)**

**Figure A4. Standard Cycle Average Fuel Economy and Emission Rates for selected pairs of GDI and PFI vehicles based on VSP modal average rates (a) FTP-weighted Fuel Economy; (b) HWFE-weighted Fuel Economy; (c) $NO_x$ (FTP-weighted); (d) CO (FTP-weighted); and (e) HC (FTP-weighted)**

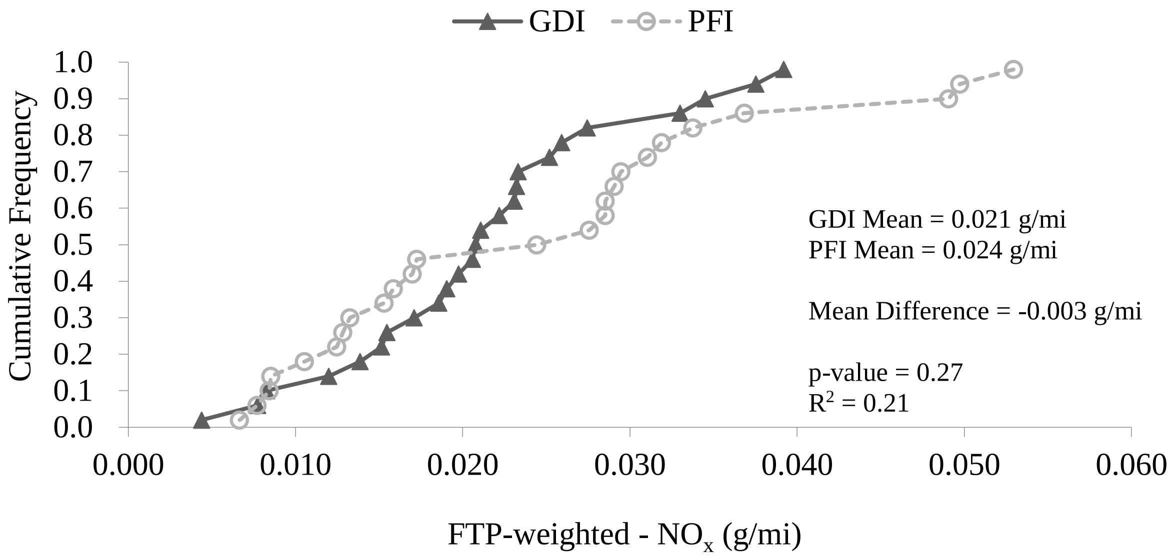
(a) FTP-weighted Fuel Economy (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles); (b) HWFE-weighted Fuel Economy (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles); (c) $NO_x$ (FTP-weighted) (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles); (d) CO (FTP-weighted) (n = 25 "Composite GDI" and n = 25 "Composite PFI" vehicles); and (e) HC (FTP-weighted) (n = 24 "Composite GDI" and n = 24 "Composite PFI" vehicles). CDF graphs are plotted by ranking each set of vehicles, i.e., GDI and PFI, from highest to lowest, and assigning cumulative frequency based on ranks, versus VSP-based standard cycle average fuel economy and emission rates. Since vehicles are ranked within the set, the graphs do not illustrate paired comparisons, but the range of each set of vehicles. However, p-values are calculated based on paired t-test on means, and $p<0.05$ signifies that the difference in means is statistically significant. $R^2$ is the coefficient of determination for a linear regression model between the sets of 25 paired GDI and PFI vehicles.


GDI
PFI
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative Frequency
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
FTP-weighted Fuel Economy - MPG
GDI Mean = 22.6 mpg
PFI Mean = 20.0 mpg
Mean Difference = 2.6 mpg
p-value = 0.00
R2 = 0.23

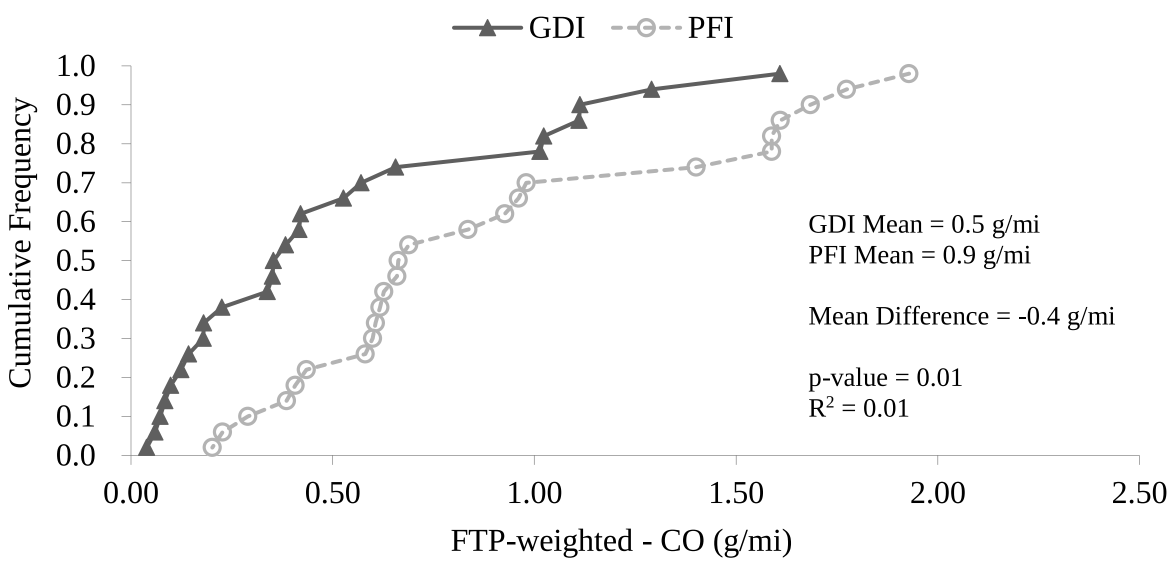
**(a)**


GDI
PFI
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative Frequency
0.0
10.0
20.0
30.0
40.0
50.0
60.0
HWFE-weighted Fuel Economy - MPG
GDI Mean = 34.1 mpg
PFI Mean = 30.8 mpg
Mean Difference = 3.3 mpg
p-value = 0.01
R2 = 0.36

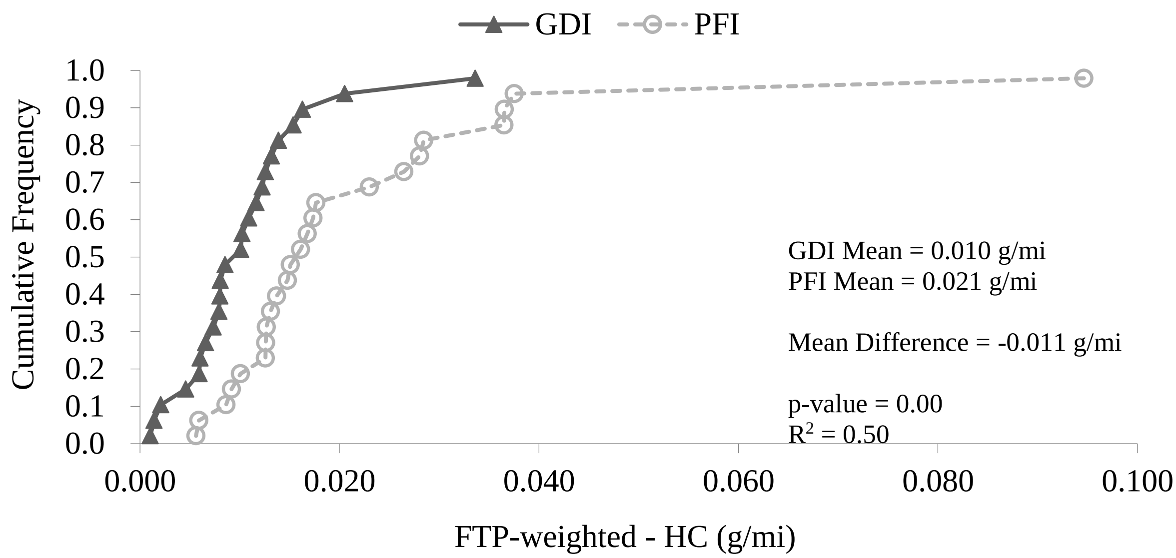
**(b)**


GDI
PFI
Cumulative Frequency
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.000
0.010
0.020
0.030
0.040
0.050
0.060
FTP-weighted - NOx (g/mi)
GDI Mean = 0.021 g/mi
PFI Mean = 0.024 g/mi
Mean Difference = -0.003 g/mi
p-value = 0.27
R2 = 0.21

**(c)**


GDI
PFI
Cumulative Frequency
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.50
1.00
1.50
2.00
2.50
FTP-weighted - CO (g/mi)
GDI Mean = 0.5 g/mi
PFI Mean = 0.9 g/mi
Mean Difference = -0.4 g/mi
p-value = 0.01
R2 = 0.01

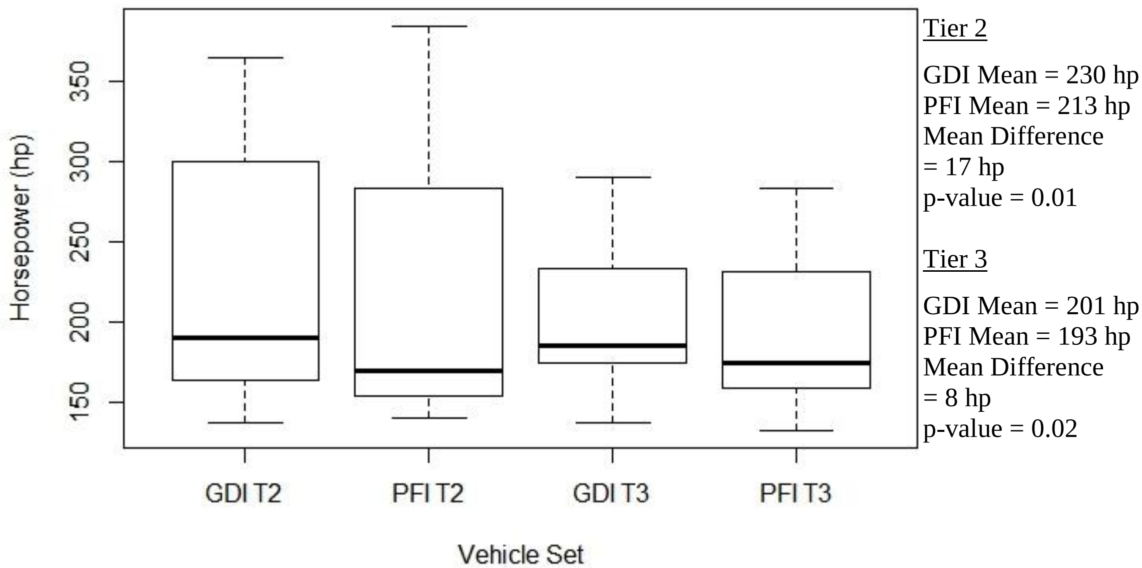
**(d)**


GDI
PFI
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative Frequency
GDI Mean = 0.010 g/mi
PFI Mean = 0.021 g/mi
Mean Difference = -0.011 g/mi
p-value = 0.00
R2 = 0.50
0.000
0.020
0.040
0.060
0.080
0.100
FTP-weighted - HC (g/mi)

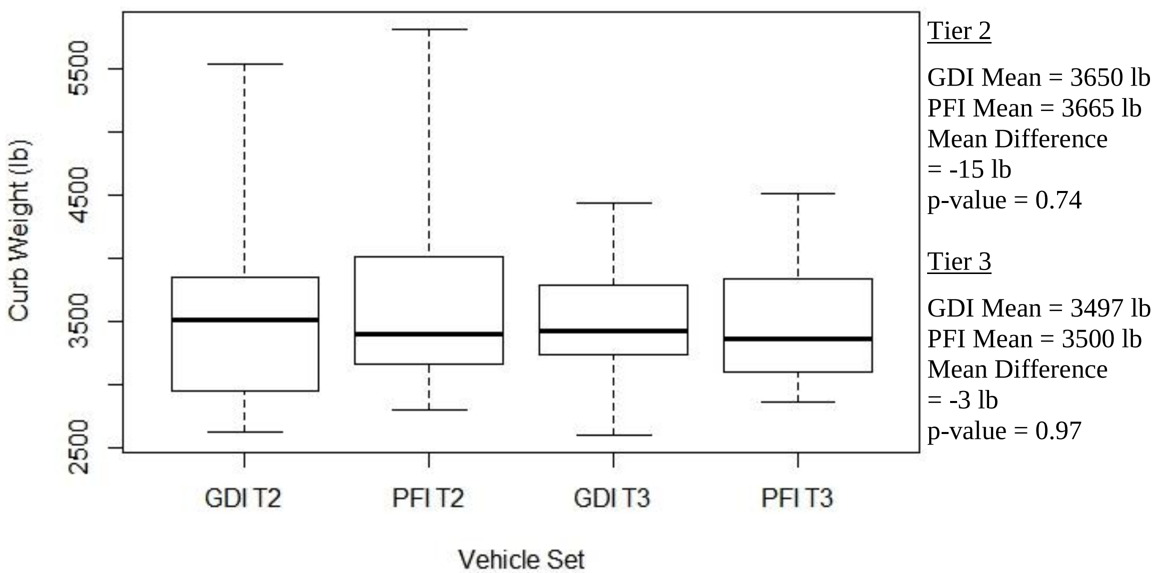
**(e)**

**Figure A5. Comparison of Vehicle Characteristics of 'Tier 2' (T2) and 'Tier 3' (T3) GDI and PFI vehicles (n = 17 'Tier 2' pairs and n = 8 'Tier 3' pairs) based on: (a) Horsepower; (b) Curb Weight; (c) HP/lb ratio**

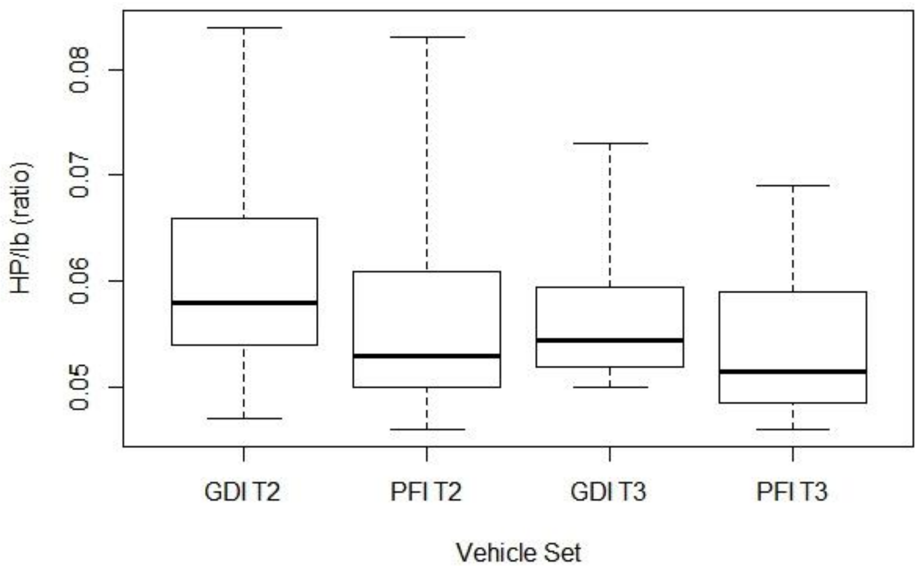
The boxes within boxplots depict the 25$^{th}$ percentile, median and 75$^{th}$ percentile. The outside whiskers denote the range. P-values are calculated based on paired t-test on mean values, and $p<0.05$ signifies that the difference in mean values is statistically significant.


Horsepower (hp)
150
200
250
300
350
GDI T2
PFI T2
GDI T3
PFI T3
Vehicle Set
Tier 2
GDI Mean = 230 hp
PFI Mean = 213 hp
Mean Difference
= 17 hp
p-value = 0.01
Tier 3
GDI Mean = 201 hp
PFI Mean = 193 hp
Mean Difference
= 8 hp
p-value = 0.02

**(a)**


Curb Weight (lb)
2500
3500
4500
5500
GDI T2
PFI T2
GDI T3
PFI T3
Vehicle Set
Tier 2
GDI Mean = 3650 lb
PFI Mean = 3665 lb
Mean Difference
= -15 lb
p-value = 0.74
Tier 3
GDI Mean = 3497 lb
PFI Mean = 3500 lb
Mean Difference
= -3 lb
p-value = 0.97

**(b)**




<u>Tier 2</u>

GDI Mean = 0.062
PFI Mean = 0.057
Mean Difference = 0.005
p-value = 0.00

<u>Tier 3</u>

GDI Mean = 0.057
PFI Mean = 0.054
Mean Difference = 0.003
p-value = 0.03

**(c)**

## Appendix B

Table B1 provides detailed characteristics and pairings of all 59 vehicles used in the study.

**Table B1 Detailed characteristics and pairings of all 59 vehicles**

| Pair No. | Injection Type | Model Year | Vehicle Make | Vehicle Model | Body Type | Engine (L) | Engine Type | Rated HP | Curb Weight (lb) | Gross Weight (lb) | HP/lb |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | GDI | 2013 | Chevrolet | Impala | Sedan | 3.6 | V6 | 300 | 3555 | 4583 | 0.084 |
| | PFI | 2013 | Dodge | Avenger | Sedan | 3.6 | V6 | 283 | 3400 | 4600 | 0.083 |
| 2 | GDI | 2016 | Chevrolet | Impala | Sedan | 3.6 | V6 | 305 | 3836 | 4785 | 0.080 |
| | PFI | 2016 | Chrysler | 300C | Sedan | 3.6 | V6 | 292 | 4013 | 5100 | 0.073 |
| 3 | GDI | 2016 | Ford | F150 | Pickup | 3.5 | V6 | 365 | 4687 | 6800 | 0.078 |
| | PFI | 2016 | Ford | F150 | Pickup | 5.0 | V8 | 385 | 4906 | 7000 | 0.078 |
| 4 | GDI | 2016 | Ford | Explorer Sport | SUV | 3.5 | V6 | 365 | 4901 | 6300 | 0.074 |
| | PFI | 2016 | Jeep | Grand Cherokee | SUV | 3.6 | V6 | 295 | 4875 | 6500 | 0.061 |
| 5 | GDI | 2017 | Kia | Sorento | SUV | 3.3 | V6 | 290 | 3968 | 5489 | 0.073 |
| | PFI | 2017 | Dodge | Journey | SUV | 3.6 | V6 | 283 | 4100 | 5450 | 0.069 |
| 6 | GDI | 2015 | Chevrolet | Tahoe | SUV | 5.3 | V8 | 355 | 5545 | 7300 | 0.064 |
| | PFI | 2013 | GMC | Yukon | SUV | 5.3 | V8 | 320 | 5820 | 7300 | 0.055 |
| 7 | GDI | 2016 | Ford | Fusion SE | Sedan | 2.0 | I4 | 231 | 3511 | 4540 | 0.066 |
| | PFI | 2016 | Chrysler | 200 | Sedan | 2.4 | I4 | 184 | 3473 | 4612 | 0.053 |
| | PFI | 2012 | Ford | Fusion | Sedan | 2.5 | I4 | 175 | 3342 | 4473 | 0.052 |
| | PFI | 2016 | Ford | Fusion | Sedan | 2.5 | I4 | 175 | 3427 | 4460 | 0.051 |

**Table B1 continued**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | GDI | 2006 | Volkswagen | Jetta | Sedan | 2.0 | I4 | 200 | 3308 | 4388 | 0.060 |
| | GDI | 2009 | Volkswagen | Jetta | Sedan | 2.0 | I4 | 200 | 3230 | 4388 | 0.062 |
| | GDI | 2007 | Volkswagen | Passat | Wagon | 2.0 | I4 | 200 | 3512 | 4775 | 0.057 |
| | PFI | 2012 | Volkswagen | Passat | Sedan | 2.5 | I5 | 170 | 3221 | 4431 | 0.053 |
| | PFI | 2006 | Volkswagen | Jetta | Sedan | 2.5 | I5 | 150 | 3230 | 4324 | 0.046 |
| 9 | GDI | 2016 | Kia | Sedona | Minivan | 3.3 | V6 | 276 | 4491 | 6085 | 0.061 |
| | PFI | 2015 | Dodge | Grand Caravan | Minivan | 3.6 | V6 | 283 | 4510 | 6050 | 0.063 |
| | PFI | 2014 | Chrysler | T&C | Minivan | 3.6 | V6 | 283 | 4652 | 6050 | 0.061 |
| | PFI | 2016 | Dodge | Grand Caravan | Minivan | 3.6 | V6 | 283 | 4510 | 6050 | 0.063 |
| 10 | GDI | 2017 | Kia | Sedona | Minivan | 3.3 | V6 | 276 | 4443 | 6085 | 0.062 |
| | PFI | 2017 | Dodge | Grand Caravan | Minivan | 3.6 | V6 | 283 | 4510 | 6050 | 0.063 |
| 11 | GDI | 2013 | Kia | Forte | Sedan | 2.0 | I4 | 156 | 2791 | 3691 | 0.056 |
| | PFI | 2007 | Nissan | Sentra | Sedan | 2.0 | I4 | 140 | 2897 | 3920 | 0.048 |
| 12 | GDI | 2016 | Hyundai | SantaFe Sport | SUV | 2.4 | I4 | 190 | 3459 | 4850 | 0.055 |
| | PFI | 2012 | Nissan | Rogue | SUV | 2.5 | I4 | 170 | 3329 | 4339 | 0.051 |
| 13 | GDI | 2017 | Hyundai | SantaFe Sport | SUV | 2.4 | I4 | 185 | 3624 | 4872 | 0.051 |
| | PFI | 2017 | Nissan | Rogue | SUV | 2.5 | I4 | 170 | 3441 | 4489 | 0.049 |
| 14 | GDI | 2014 | Mazda | 3 | Hatchback | 2.0 | I4 | 155 | 2873 | 4001 | 0.054 |
| | PFI | 2005 | Mazda | 3S | Sedan | 2.3 | I4 | 160 | 2762 | 3880 | 0.058 |
| | PFI | 2008 | Scion | tC | Coupe | 2.4 | I4 | 161 | 2965 | 3945 | 0.054 |
| | PFI | 2007 | Nissan | Sentra | Sedan | 2.0 | I4 | 140 | 2897 | 3920 | 0.048 |

**Table B1 continued**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 | GDI | 2014 | Ford | Focus | Hatchback | 2.0 | I4 | 160 | 2948 | 3990 | 0.054 |
| | PFI | 2005 | Mazda | 3S | Sedan | 2.3 | I4 | 160 | 2762 | 3880 | 0.058 |
| | PFI | 2007 | Nissan | Sentra | Sedan | 2.0 | I4 | 140 | 2897 | 3920 | 0.048 |
| 16 | GDI | 2016 | Hyundai | Sonata | Sedan | 2.4 | I4 | 185 | 3250 | 4497 | 0.057 |
| | PFI | 2016 | Chrysler | 200 | Sedan | 2.4 | I4 | 184 | 3473 | 4612 | 0.053 |
| | PFI | 2012 | Toyota | Camry | Sedan | 2.5 | I4 | 178 | 3190 | 4630 | 0.056 |
| 17 | GDI | 2016 | Hyundai | Accent | Hatchback | 1.6 | I4 | 137 | 2635 | 3549 | 0.052 |
| | PFI | 2009 | Honda | Civic | Sedan | 1.8 | I4 | 140 | 2747 | 3737 | 0.051 |
| | PFI | 2007 | Honda | Civic | Sedan | 1.8 | I4 | 140 | 2751 | 3737 | 0.051 |
| | PFI | 2007 | Nissan | Sentra | Sedan | 2.0 | I4 | 140 | 2897 | 3920 | 0.048 |
| 18 | GDI | 2016 | Ford | Escape | SUV | 1.6 | I4 | 178 | 3526 | 4620 | 0.050 |
| | PFI | 2011 | Nissan | Rogue | SUV | 2.5 | I4 | 170 | 3479 | 4526 | 0.049 |
| | PFI | 2012 | Nissan | Rogue | SUV | 2.5 | I4 | 170 | 3329 | 4339 | 0.051 |
| | PFI | 2011 | Subaru | Outback | SUV | 2.5 | I4 | 170 | 3495 | 4595 | 0.049 |
| 19 | GDI | 2016 | Kia | Soul | Hatchback | 2.0 | I4 | 164 | 2837 | 4101 | 0.058 |
| | PFI | 2011 | Chevrolet | HHR | SUV | 2.2 | I4 | 155 | 3155 | 4240 | 0.049 |
| | PFI | 2014 | Buick | Encore | SUV | 1.4 | I4 | 138 | 3190 | 4286 | 0.043 |
| 20 | GDI | 2013 | GMC | Terrain | SUV | 2.4 | I4 | 182 | 3853 | 4960 | 0.047 |
| | PFI | 2011 | Nissan | Rogue | SUV | 2.5 | I4 | 170 | 3479 | 4526 | 0.049 |
| | PFI | 2012 | Nissan | Rogue | SUV | 2.5 | I4 | 170 | 3329 | 4339 | 0.051 |
| | PFI | 2011 | Subaru | Outback | SUV | 2.5 | I4 | 170 | 3495 | 4595 | 0.049 |

**Table B1 continued**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | GDI | 2017 | Hyundai | Accent | Sedan | 1.6 | I4 | 137 | 2601 | 3527 | 0.053 |
| | PFI | 2017 | Toyota | Corolla | Sedan | 1.8 | I4 | 132 | 2870 | 3820 | 0.046 |
| 22 | GDI | 2017 | Honda | Accord | Sedan | 2.4 | I4 | 185 | 3360 | 4321 | 0.055 |
| | PFI | 2017 | Nissan | Altima | Sedan | 2.5 | I4 | 179 | 3233 | 4226 | 0.055 |
| 23 | GDI | 2017 | Honda | CRV | SUV | 1.5 | I4 | 190 | 3492 | 4695 | 0.054 |
| | PFI | 2017 | Nissan | Rogue | SUV | 2.5 | I4 | 170 | 3571 | 4679 | 0.048 |
| 24 | GDI | 2017 | Kia | Optima | Sedan | 2.4 | I4 | 185 | 3219 | 4497 | 0.057 |
| | PFI | 2017 | Toyota | Camry | Sedan | 2.5 | I4 | 178 | 3300 | 4630 | 0.054 |
| 25 | GDI | 2017 | Chevrolet | Malibu | Sedan | 1.5 | I4 | 163 | 3271 | 4087 | 0.050 |
| | PFI | 2017 | Hyundai | Elantra | Sedan | 2.0 | I4 | 147 | 2976 | 3924 | 0.049 |

Table B2 provides further details of the 59 vehicles used in the study.

**Table B2 Engine Aspiration, Transmission, Drivetrain and Vehicle Age at the time of test of all 59 vehicles**

| Pair No. | Injection Type | Model Year | Vehicle Make | Vehicle Model | Engine Aspiration | Transmission | Gears | Drive | Vehicle Age (Years) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | GDI | 2013 | Chevrolet | Impala | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2013 | Dodge | Avenger | Natural | Auto | 6 | FWD | 1 |
| 2 | GDI | 2016 | Chevrolet | Impala | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2016 | Chrysler | 300C | Natural | Auto | 8 | RWD | 1 |
| 3 | GDI | 2016 | Ford | F150 | Turbo | Auto | 6 | 4WD | 1 |
| | PFI | 2016 | Ford | F150 | Natural | Auto | 6 | 4WD | 1 |
| 4 | GDI | 2016 | Ford | Explorer Sport | Turbo | Auto | 6 | 4WD | 1 |
| | PFI | 2016 | Jeep | Grand Cherokee | Natural | Auto | 8 | 4WD | 1 |
| 5 | GDI | 2017 | Kia | Sorento | Natural | Auto | 6 | FWD | 0 |
| | PFI | 2017 | Dodge | Journey | Natural | Auto | 4 | FWD | 1 |
| 6 | GDI | 2015 | Chevrolet | Tahoe | Natural | Auto | 6 | 4WD | 1 |
| | PFI | 2013 | GMC | Yukon | Natural | Auto | 6 | 4WD | 0 |
| 7 | GDI | 2016 | Ford | Fusion SE | Turbo | Auto | 6 | FWD | 1 |
| | PFI | 2016 | Chrysler | 200 | Natural | Auto | 9 | FWD | 1 |
| | PFI | 2012 | Ford | Fusion | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2016 | Ford | Fusion | Natural | Auto | 6 | FWD | 0 |

**Table B2 continued**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 8 | GDI | 2006 | Volkswagen | Jetta | Turbo | Manual | 6 | FWD | 5 |
| | GDI | 2009 | Volkswagen | Jetta | Turbo | Auto | 6 | FWD | 6 |
| | GDI | 2007 | Volkswagen | Passat | Turbo | Auto | 6 | FWD | 9 |
| | PFI | 2012 | Volkswagen | Passat | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2006 | Volkswagen | Jetta | Natural | Manual | 5 | FWD | 3 |
| 9 | GDI | 2016 | Kia | Sedona | Natural | Auto | 6 | FWD | 0 |
| | PFI | 2015 | Dodge | Grand Caravan | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2014 | Chrysler | T&C | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2016 | Dodge | Grand Caravan | Natural | Auto | 6 | FWD | 1 |
| 10 | GDI | 2017 | Kia | Sedona | Natural | Auto | 6 | FWD | 0 |
| | PFI | 2017 | Dodge | Grand Caravan | Natural | Auto | 6 | FWD | 1 |
| 11 | GDI | 2013 | Kia | Forte | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2007 | Nissan | Sentra | Natural | Auto | CVT | FWD | 2 |
| 12 | GDI | 2016 | Hyundai | SantaFe Sport | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2012 | Nissan | Rogue | Natural | Auto | CVT | FWD | 1 |
| 13 | GDI | 2017 | Hyundai | SantaFe Sport | Natural | Auto | 6 | FWD | 0 |
| | PFI | 2017 | Nissan | Rogue | Natural | Auto | CVT | FWD | 1 |
| 14 | GDI | 2014 | Mazda | 3 | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2005 | Mazda | 3S | Natural | Auto | 4 | FWD | 4 |
| | PFI | 2008 | Scion | tC | Natural | Auto | 4 | FWD | 8 |
| | PFI | 2007 | Nissan | Sentra | Natural | Auto | CVT | FWD | 2 |
| 15 | GDI | 2014 | Ford | Focus | Natural | Auto | 6 | FWD | 2 |
| | PFI | 2005 | Mazda | 3S | Natural | Auto | 4 | FWD | 4 |
| | PFI | 2007 | Nissan | Sentra | Natural | Auto | CVT | FWD | 2 |

**Table B2 continued**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 16 | GDI | 2016 | Hyundai | Sonata | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2016 | Chrysler | 200 | Natural | Auto | 9 | FWD | 1 |
| | PFI | 2012 | Toyota | Camry | Natural | Auto | 6 | FWD | 1 |
| 17 | GDI | 2016 | Hyundai | Accent | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2009 | Honda | Civic | Natural | Auto | 5 | FWD | 5 |
| | PFI | 2007 | Honda | Civic | Natural | Auto | 5 | FWD | 2 |
| | PFI | 2007 | Nissan | Sentra | Natural | Auto | CVT | FWD | 2 |
| 18 | GDI | 2016 | Ford | Escape | Turbo | Auto | 6 | FWD | 1 |
| | PFI | 2011 | Nissan | Rogue | Natural | Auto | CVT | AWD | 5 |
| | PFI | 2012 | Nissan | Rogue | Natural | Auto | CVT | FWD | 1 |
| | PFI | 2011 | Subaru | Outback | Natural | Auto | CVT | AWD | 4 |
| 19 | GDI | 2016 | Kia | Soul | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2011 | Chevrolet | HHR | Natural | Auto | 4 | FWD | 1 |
| | PFI | 2014 | Buick | Encore | Turbo | Auto | 6 | FWD | 1 |
| 20 | GDI | 2013 | GMC | Terrain | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2011 | Nissan | Rogue | Natural | Auto | CVT | AWD | 5 |
| | PFI | 2012 | Nissan | Rogue | Natural | Auto | CVT | FWD | 1 |
| | PFI | 2011 | Subaru | Outback | Natural | Auto | CVT | AWD | 4 |
| 21 | GDI | 2017 | Hyundai | Accent | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2017 | Toyota | Corolla | Natural | Auto | CVT | FWD | 1 |
| 22 | GDI | 2017 | Honda | Accord | Natural | Auto | CVT | FWD | 1 |
| | PFI | 2017 | Nissan | Altima | Natural | Auto | CVT | FWD | 1 |

**Table B2 continued**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 23 | GDI | 2017 | Honda | CRV | Turbo | Auto | CVT | 4WD | 1 |
| | PFI | 2017 | Nissan | Rogue | Natural | Auto | CVT | 4WD | 1 |
| 24 | GDI | 2017 | Kia | Optima | Natural | Auto | 6 | FWD | 1 |
| | PFI | 2017 | Toyota | Camry | Natural | Auto | 6 | FWD | 1 |
| 25 | GDI | 2017 | Chevrolet | Malibu | Turbo | Auto | 6 | FWD | 1 |
| | PFI | 2017 | Hyundai | Elantra | Natural | Auto | 6 | FWD | 1 |

Table B3 provides EPA certified emission standards for 59 vehicles.

**Table B3 EPA Certified Emission Standards**

| Pair No. | Injection Type | Model Year | Vehicle Make | Vehicle Model | Emission Standards | |
|---|---|---|---|---|---|---|
| | | | | | Tier | Bin |
| 1 | GDI | 2013 | Chevrolet | Impala | Tier 2 | Bin 4 |
| | PFI | 2013 | Dodge | Avenger | Tier 2 | Bin 4 |
| 2 | GDI | 2016 | Chevrolet | Impala | Tier 2 | Bin 4 |
| | PFI | 2016 | Chrysler | 300C | Tier 3 | Bin 4 |
| 3 | GDI | 2016 | Ford | F150 | Tier 2 | Bin 4 |
| | PFI | 2016 | Ford | F150 | Tier 2 | Bin 4 |
| 4 | GDI | 2016 | Ford | Explorer Sport | Tier 2 | Bin 5 |
| | PFI | 2016 | Jeep | Grand Cherokee | Tier 2 | Bin 4 |
| 5 | GDI | 2017 | Kia | Sorento | Tier 3 | B125 |
| | PFI | 2017 | Dodge | Journey | Tier 3 | B110 |
| 6 | GDI | 2015 | Chevrolet | Tahoe | Tier 2 | Bin 4 |
| | PFI | 2013 | GMC | Yukon | Tier 2 | Bin 5 |
| 7 | GDI | 2016 | Ford | Fusion SE | Tier 2 | Bin 5 |
| | PFI | 2016 | Chrysler | 200 | Tier 2 | Bin 4 |
| | PFI | 2012 | Ford | Fusion | Tier 2 | Bin 5 |
| | PFI | 2016 | Ford | Fusion | Tier 2 | Bin 5 |

**Table B3 continued**

| | | | | | | |
|---|---|---|---|---|---|---|
| 8 | GDI | 2006 | Volkswagen | Jetta | Tier 2 | Bin 5 |
| | GDI | 2009 | Volkswagen | Jetta | Tier 2 | Bin 5 |
| | GDI | 2007 | Volkswagen | Passat | Tier 2 | Bin 5 |
| | PFI | 2012 | Volkswagen | Passat | Tier 2 | Bin 5 |
| | PFI | 2006 | Volkswagen | Jetta | Tier 2 | Bin 5 |
| 9 | GDI | 2016 | Kia | Sedona | Tier 2 | Bin 5 |
| | PFI | 2015 | Dodge | Grand Caravan | Tier 2 | Bin 4 |
| | PFI | 2014 | Chrysler | T&C | Tier 2 | Bin 4 |
| | PFI | 2016 | Dodge | Grand Caravan | Tier 2 | Bin 4 |
| 10 | GDI | 2017 | Kia | Sedona | Tier 3 | B125 |
| | PFI | 2017 | Dodge | Grand Caravan | Tier 3 | B110 |
| 11 | GDI | 2013 | Kia | Forte | Tier 2 | Bin 5 |
| | PFI | 2007 | Nissan | Sentra | Tier 2 | Bin 5 |
| 12 | GDI | 2016 | Hyundai | SantaFe Sport | Tier 2 | Bin 5 |
| | PFI | 2012 | Nissan | Rogue | Tier 2 | Bin 5 |
| 13 | GDI | 2017 | Hyundai | SantaFe Sport | Tier 3 | B70 |
| | PFI | 2017 | Nissan | Rogue | Tier 3 | B70 |
| 14 | GDI | 2014 | Mazda | 3 | Tier 2 | Bin 5 |
| | PFI | 2005 | Mazda | 3S | Tier 2 | Bin 5 |
| | PFI | 2008 | Scion | tC | Tier 2 | Bin 5 |
| | PFI | 2007 | Nissan | Sentra | Tier 2 | Bin 5 |

**Table B3 continued**

| | | | | | | |
|---|---|---|---|---|---|---|
| 15 | GDI | 2014 | Ford | Focus | Tier 2 | Bin 5 |
| | PFI | 2005 | Mazda | 3S | Tier 2 | Bin 5 |
| | PFI | 2007 | Nissan | Sentra | Tier 2 | Bin 5 |
| 16 | GDI | 2016 | Hyundai | Sonata | Tier 2 | Bin 5 |
| | PFI | 2016 | Chrysler | 200 | Tier 2 | Bin 4 |
| | PFI | 2012 | Toyota | Camry | Tier 2 | Bin 5 |
| 17 | GDI | 2016 | Hyundai | Accent | Tier 2 | Bin 5 |
| | PFI | 2009 | Honda | Civic | Tier 2 | Bin 5 |
| | PFI | 2007 | Honda | Civic | Tier 2 | Bin 5 |
| | PFI | 2007 | Nissan | Sentra | Tier 2 | Bin 5 |
| 18 | GDI | 2016 | Ford | Escape | Tier 2 | Bin 5 |
| | PFI | 2011 | Nissan | Rogue | Tier 2 | Bin 5 |
| | PFI | 2012 | Nissan | Rogue | Tier 2 | Bin 5 |
| | PFI | 2011 | Subaru | Outback | Tier 2 | Bin 5 |
| 19 | GDI | 2016 | Kia | Soul | Tier 2 | Bin 5 |
| | PFI | 2011 | Chevrolet | HHR | Tier 2 | Bin 4 |
| | PFI | 2014 | Buick | Encore | Tier 2 | Bin 4 |
| 20 | GDI | 2013 | GMC | Terrain | Tier 2 | Bin 4 |
| | PFI | 2011 | Nissan | Rogue | Tier 2 | Bin 5 |
| | PFI | 2012 | Nissan | Rogue | Tier 2 | Bin 5 |
| | PFI | 2011 | Subaru | Outback | Tier 2 | Bin 5 |
| 21 | GDI | 2017 | Hyundai | Accent | Tier 3 | B125 |
| | PFI | 2017 | Toyota | Corolla | Tier 3 | B125 |

**Table B3 continued**

| | | | | | | |
|---|---|---|---|---|---|---|
| 22 | GDI | 2017 | Honda | Accord | Tier 3 | B30 |
| | PFI | 2017 | Nissan | Altima | Tier 3 | B30 |
| 23 | GDI | 2017 | Honda | CRV | Tier 3 | B70 |
| | PFI | 2017 | Nissan | Rogue | Tier 3 | B70 |
| 24 | GDI | 2017 | Kia | Optima | Tier 3 | B70 |
| | PFI | 2017 | Toyota | Camry | Tier 3 | B125 |
| 25 | GDI | 2017 | Chevrolet | Malibu | Tier 3 | B110 |
| | PFI | 2017 | Hyundai | Elantra | Tier 3 | B70 |