CRC Report No. E-144/ PC-2023-1

Impact of Alternative Diesel Fuels on On-Board Diagnostics

Final Report

April 2026

COORDINATING RESEARCH COUNCIL, INC.

1 CONCOURSE PARKWAY • SUITE 800 • ATLANTA, GA 30328

The Coordinating Research Council, Inc. (CRC) is a non-profit corporation supported by the petroleum and automotive equipment industries with participation from other industries, companies, and governmental bodies on research programs of mutual interest. CRC operates through the committees made up of technical experts from industry and government who voluntarily participate. The five main areas of research within CRC are: air pollution (atmospheric and engineering studies); aviation fuels, lubricants, and equipment performance; heavy-duty vehicle fuels, lubricants, and equipment performance (e.g., diesel trucks); light-duty vehicle fuels, lubricants, and equipment performance (e.g., passenger cars); and sustainable mobility (e.g., decarbonization). CRC's function is to provide the mechanism for joint research conducted by industries that will help in determining the optimum combination of products. CRC's work is limited to research that is mutually beneficial to the industries involved. The final results of the research conducted by, or under the auspices of, CRC are available to the public.

LEGAL NOTICE

This report was prepared by FEV as an account of work sponsored by the Coordinating Research Council (CRC). Neither the CRC, members of the CRC, FEV, nor any person acting on their behalf: (1) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this report, or (2) assumes any liabilities with respect to use of, inability to use, or damages resulting from the use or inability to use, any information, apparatus, method, or process disclosed in this report. In formulating and approving reports, the appropriate committee of the Coordinating Research Council, Inc. has not investigated or considered patents which may apply to the subject matter. Prospective users of the report are responsible for protecting themselves against liability for infringement of patents.

Report FEV

Impact of Alternative Diesel Fuels on On-Board Diagnostics

Coordinating Research Council, INC.

Submitted by FEV Inc:

Rinav Raveendran Pillai
FEV North America, Inc.
4554 Glenmeade Lane
Auburn Hills, MI 48326
pillai_r@fev.com

List of Chapters

List of Figures

List of Tables

List of Appendices

Impact of Alternative Diesel Fuels on On-Board Diagnostics

Abstract

Availability of biofuels and renewable fuels is expected to increase, driven by federal and state policies like Federal Renewable Fuels Standards (RFS) and California Low Carbon Fuels Standard (LCFS) and other state mandates. While the impact of renewable fuels on engine and after-treatment performance has been studied in other projects, the impact of fuel properties on OBD (on-board diagnostics) robustness is not well understood. Since OBD monitor thresholds are determined based on vehicle performance on standard ULSD (Ultra-Low Sulfur Diesel) fuel, it is critical to understand the impact of alternative diesel fuels on key engine and after-treatment parameters that are used as inputs to OBD monitors to make decisions. Therefore, the goal of this project is to seek to understand the impact of these fuels on diagnostic robustness by investigating variation in key inputs to diagnostic strategies such as engine and aftertreatment sensor measurements.

To support the investigation of the impact of alternative diesel fuels on key inputs to diagnostic strategies, CRC outlined an approach to evaluate the impact of up to seven different fuel types which include ULSD, R99 (renewable diesel), R50U50, B20R80, B50U50, B50R50 and B100 (biodiesel) on four different vehicles. Chassis dynamometer testing is conducted using standard test cycles with engine and aftertreatment parameters recorded through vehicle CAN (Controller Area Network), to create a comprehensive dataset of transient vehicle data. This study uses a standard test sequence along with a homogeneous set of engine and aftertreatment parameters recorded across multiple vehicles to potentially develop a methodology to understand the impact of fuel properties on OBD monitor robustness.

Using detailed statistical analysis, this study investigates run-to-run variability in the recorded parameters within a test sequence using the same fuel as well as variability in recorded parameters between different fuels/fuel blends which could affect robustness of vehicle diagnostic strategies. The following are the key findings of this study:

- Alternative diesel fuel/fuel blends tested in this study showed some impact on the selected parameter identifier (PID) labels in this study. However, the largest impact of the fuels was seen on after-treatment system (ATS) temperatures, engine-out and tailpipe nitrogen oxide (NO_x) emissions, fuel consumption, carbon dioxide (CO_2) and engine-out soot emissions.
- Run-to-run and driver-to-drive variation had some impact on statistical analysis and reduced deductibility of trends for PID labels such as air flow, fuel rail pressure, lambda and O_2 sensor measurements and exhaust gas recirculation (EGR) and variable geometry turbocharger (VGT) positions.
- Vehicle response and adaptation to the different fuels/fuel blends tested varied differently across the vehicles tested and can be attributed to differences in engine and aftertreatment controls, adaptation and calibration.
- Table below summarizes the important trends observed for different PIDs with the alternative diesel fuel/fuel blends compared to ULSD fuel, across the four vehicles tested in this study

PID Labels	Units	Fuel					
		R99	R50U50	B20R80	B50U50	B50R50	B100
Engine Fuel Rate	**g/s**	± 5%	± 3%	± 5%	Up to 10% Higher	Up to 8% Higher	Up to 18% Higher
DOC Inlet Temp	**°C**	± 7°C	Up to 6°C Lower	Up to 11°C Lower	Up to 14°C Lower	Up to 20°C Lower	Up to 23°C Lower
DOC Outlet/DPF Inlet Temp	**°C**						
DPF Outlet/SCR Inlet Temp	**°C**						
SCR Outlet Temp	**°C**						
Engine Out NO_x Sensor	**ppm**	± 20 ppm	± 20 ppm	± 20 ppm	Up to 50 ppm Higher	Up to 30 ppm Higher	Up to 50 ppm Higher
Tailpipe NO_x Sensor	**ppm**	± 3 ppm	± 3 ppm	± 3 ppm	Up to 4 ppm Higher	± 2 ppm	± 2 ppm
Fuel Rail Pressure	**kPa**	± 2%	± 2%	± 2%	Up to 5% Higher	Up to 4% Higher	Up to 9% Higher
Total Cycle Fuel Consumption	**g**	± 5%	± 3%	± 5%	Up to 10% Higher	Up to 8% Higher	Up to 18% Higher
Engine-Out Soot	**mg**	Up to 60% Lower	Up to 33% Lower	Up to 67% Lower	Up to 54% Lower	Up to 86% Lower	Up to 83% Lower
Mass Air Flow Sensor	**g/s**	These PIDs showed some variation. But the trends observed were inconsistent and within expected run-to-run variation					
Intake Manifold Temp	**°C**						
Coolant Temp	**°C**						
EGR Valve A Position	**%**						
Main Injection Timing	**°**						
Intake Manifold Pressure	**kPa**						
Upstream O_2 Sensor	**%**						
VGT Position	**%**						
DEF Dosing	**%**						
Calculated Exhaust Flow Rate	**kg/h**						

- Based on pre and post OBD scans for all test cycles, all four vehicles, when tested with six different alternative diesel fuel/fuel blends did not set an OBD fault.
- Therefore, short-term impact of different fuels and fuel blends on OBD monitor robustness was not significant. However, long-term durability tests of vehicles with different fuels/fuel blends will be required to understand if observed trends result in OBD faults due to extended use of such fuels.
- Finally, re-testing of vehicles with ULSD fuel demonstrated that vehicles showed no degradation in performance after short-term testing with alternative diesel fuels/fuel blends.

Chapter 1 : Introduction

Section 1.1: Background

Increasing demand for liquid fuels, rising oil prices and the need to reduce greenhouse gas and exhaust emissions such as nitrogen oxides (NO_x) and particulate matter has driven the requirement for development and use of alternative fuels. Stringent federal and state policies have been implemented in the US as well as globally to increase the use of renewable fuels as an energy source for road transport. The United States Environmental Protection Agency's (US EPA) Renewable Fuel Standard Program under the Clean Air Act created under the Energy Policy of 2005 requires that a certain volume of renewable fuel be used to or replace the quantity of fossil fuel in transportation fuel, home heating oil, or jet fuel [1]. Similarly, the Low Carbon Fuel Standard program implemented by California Air Resources Board (CARB) is designed to reduce the life cycle carbon intensity of the transportation fuel pool used in California through the use of alternative fuels [2]. The European regulation of 2009 (directive 2009/28/EC) introduced new targets for European Union members. Each member state shall ensure that the share of energy from renewable sources in all forms of transport in 2020 is at least 10% of the total energy consumption [3]. These policies are expected to increase the use of alternative fuels used for on road transportation including diesel passenger cars.

Biofuels such as biodiesel and renewable diesel have emerged as viable alternatives to diesel fuel in road transportation. Biofuels are primarily made from renewable materials such as animal feedstock, vegetables, and biomass. Biodiesel is a type of biofuel made from the trans-esterification process and involves reaction of a feed stock, usually oil or fatty acids from oil, with an alcohol in the presence of a catalyst which creates a fatty acid methyl ester (FAME), known as biodiesel [4]. Biodiesel has several benefits over conventional fossil diesel; it is renewable, non-toxic, has greater lubricity and generally lower emissions compared to conventional fossil diesel [5]. Further, biodiesel blends up to B20 can be used in nearly all diesel engines and are compatible with most storage distribution equipment and these low-level blends generally do not require any engine modifications [6]. Higher blends, even B100, can be used in some engines with little or no modification [7].

Biodiesel has many properties that make it an attractive alternative to diesel fuel. These include lower life cycle carbon intensity, lower sulfur and aromatic content, higher cetane number, higher biodegradability as well as lower engine-out particulate matter (PM), HC and CO emissions [7]. Biodiesel contains high oxygen content (~11%) and very low sulfur. The higher oxygen content helps to improve combustion efficiency. Further, biodiesel has better lubricity than diesel which can help to extend engine life. Engine-out hydrocarbons (HC) and carbon monoxide (CO) emissions are lower due to higher oxygen content and lower C/H ratio [8]. Engine-out soot emissions are also reduced due to the higher cetane number and higher oxygen content of biodiesel compared to conventional diesel [8-12]. Tailpipe CO_2 emissions are lower or similar to diesel due to lower C/H ratio and better combustion efficiency. However, life cycle CO_2 emissions with biodiesel are lower and can be attributed to circular carbon economy. Biodiesel reduces net CO_2 emissions by ~80% compared to petroleum diesel. For B20, CO_2 emissions from urban buses drop ~16% [13].

Some properties of biodiesel also adversely impact emissions and engine performance. These include higher viscosity, lower energy content, higher cloud point and pour point, higher nitrogen oxides (NO_X) emissions, lower engine speed and power, injector coking, engine compatibility, high price, and higher engine wear [7]. Volume based net heating value of biodiesel is much lower than that of ULSD fuel, thereby increasing volumetric fuel consumption when using biodiesel. Cold start performance with biodiesel is of major concern due to poor cold flow properties of biodiesel such as higher cloud point and pour point. This restricts the use of biodiesel in regions with colder temperatures and requires the use of additives to improve cold flow properties of biodiesel. Biodiesel on average decreases power at rated speed by 5% compared to diesel fuel due to lower volumetric energy content. [7,8]. Higher cetane number and oxygen content also result in increased NO_x emissions when using biodiesel [7-12].

Since there are some disadvantages to using biodiesel in diesel engines, this can hinder the use of biodiesel as a direct replacement for diesel. Biodiesel blends with diesel have been studied in literature to understand fuel effects in diesel engines. Studies have reported that biodiesel blends with diesel can help to overcome some of the problems associated with biodiesel [14]. Researchers have suggested that B20 (20% Biodiesel 80% diesel blend) gives better engine performance compared to diesel fuel alone. They showed that B20 has improved density, viscosity, and flash point as well as a calorific value closer to diesel which led to better engine performance [14].

Renewable diesel is a non-oxygenated fuel produced from a thermo-catalytic process that involves the conversion of feed stock or fatty acids into straight chain n-alkanes through deoxygenation [18]. These straight chain alkanes can then be further processed to meet specification standards of the desired fossil fuel. The production process of renewable diesel is flexible enough to allow for the production of a wide variety of hydrocarbon fuels that can meet most fossil fuel standards [18]. An example of renewable diesel is Hydrotreated Vegetable Oil (HVO) which is a paraffinic bio-based liquid fuel originating from many kinds of vegetable oils, such as rapeseed, sunflower, soybean, and palm oil, as well as animal fats [3]. HVO can be used in conventional diesel engines, pure or blended with petroleum diesel. Although largely unproven, it is expected that HVO will substitute directly for or blend in any proportion with petroleum diesel, without modification of diesel engines [19]. However, in recent years, engine manufacturers have designed engines to use renewable diesel (R100) for e.g., various models of Cummins' vehicle engines and power generators are designed to accommodate the use of R100 without requiring any modifications, making the transition to renewable diesel seamless for fleet operators [20].

Renewable diesel (R100) is a class of fuels produced from new innovative processes and a wide range of sources of raw materials [3]. Therefore, R100 can have a wide range of properties depending on the source and the process used for renewable diesel production. In general, renewable diesels are de-oxygenated straight chained alkanes. Therefore, the oxygen content is low – similar to petroleum diesel. If renewable diesel consists mainly of long-chain alkanes, then this fuel will have a high cetane number. However, if it contains large amounts of shorter-chain and isomerized species, the cetane number will be lower [21]. In general, renewable diesels show higher cetane number than petroleum diesel. Improved low temperature properties of renewable diesel are also dependent on the absence of long-chain alkanes and presence of shorter chain and isomerized species [21]. The lubricity is very low due to the absence of aromatic compounds in the fuel; therefore, lubricating additives are required (as in conventional diesel) to protect the injection system [3]. The net heating value (mass) is higher than conventional diesel due to higher hydrogen content which could improve brake specific fuel consumption. However, even though mass-based net heating value of renewable diesel is higher than ULSD, the lower density of renewable diesel means that the volume-based net heating value is lower. Therefore, volumetric based fuel consumption is higher with renewable diesel compared to ULSD.

NO_x emissions were seen to be lower, for example, Hexadecane and dodecane reduced NO_x by 15 - 16% compared to petroleum diesel [21]. However, other studies have determined that the effect of renewable diesel fuel on NO_x emissions is not very clear due to the competing effect of NO_x reduction using different EGR strategies [3]. Other studies have also reported higher NO_x emissions compared to conventional diesel but lower compared to biodiesel [9]. The shorter ignition delay due to higher cetane number of renewable diesels has been shown to significantly reduce hydrocarbon and carbon monoxide emissions due to the longer combustion duration. The density and viscosity of renewable diesel is lower due to the paraffinic nature of the fuel which helps in better fuel atomization and better mixture formation [3]. Small reduction in CO_2 emissions has been reported due to the higher heating value and lower C/H ratio [3,18,19]. Studies have shown that engine-out soot emissions are lowered when using renewable diesels [9,10,18,19] because HVO is a paraffinic fuel with shorter molecular chain and higher H/C ratio, with almost zero aromatic, sulfur, and other mineral impurities content. Further cetane number is also higher, which increases combustion duration and promotes more complete combustion compared to conventional diesel fuel.

HVO (renewable diesel) is a non-fossil hydrocarbon fuel characterized by the same chemical structure as conventional diesel fuel. Therefore, it can be blended with conventional diesel fuel, can use the same fuel supply infrastructure, and does not require adaptation of the vehicle powertrain or engines [22]. Studies have also investigated using higher blends of renewable diesel with conventional diesel to analyze the impact of renewable diesel on diesel engine performance and emissions. With increase in renewable content, comparable or slightly higher power and comparable or slightly lower CO_2 emissions were seen [23,24]. Drops in CO & HC emissions were seen along with lower engine-out soot emissions for 30 to 100% renewable diesel fuel [23,24]. NO_x emissions were comparable or slightly higher than conventional diesel with 30% renewable diesel [24].

Therefore, biodiesel, renewable diesel (R100) and blends of biodiesel and R100 with conventional diesel (ULSD) can be used in modern diesel vehicles to improve performance and emissions of diesel engine compared to ULSD. However, as discussed, these fuels and blends can also result in deterioration in engine performance for e.g., cold start, increased fuel consumption, fuel pumping issues etc.

On-board diagnostics (OBD) are an integral part of the modern diesel vehicle and have been implemented on light-duty vehicles and trucks since model year (MY) 1996. The OBD system monitors many emission control and emission-related powertrain components, and the vehicle must be operated under specific conditions to enable this monitoring. As a result, state programs that typically required inspection of tailpipe emissions are now relying on and implementing diagnostic checks of OBD systems in lieu of tailpipe emissions inspections [25]. Due to the effect of alternative fuels and fuel blends on engine performance and emissions, there were concerns regarding OBD system monitoring capabilities when running with alternative fuels. Therefore, the

EPA allowed additional OBD monitoring flexibilities when operating with alternative fuels to eliminate the potential for false illumination of the malfunction indicator lamp (MIL) [25]. Therefore, Federal OBD regulations in 40 CFR 86.1806-05 allowed manufacturers of alternate fuel vehicles to request waivers from OBD monitoring during alternate fuel operation until MY 2004 [25]. This allowed for a reduced level of OBD monitoring when operating with alternative fuel. However, beyond MY 2005 this waiver was removed, and all vehicles are required to have full OBD monitoring capabilities regardless of any fuel type or blend. Therefore, even though the impact of renewable fuels on engine performance and emissions has been well documented, there is strong need to understand the impact of renewable fuels on OBD robustness.

Fuel properties such as oxygen content, cetane number, and heating value are expected to affect combustion performance such as air-fuel ratio and exhaust temperature. If combustion performance is altered, engine and aftertreatment sensors will measure the change in response. Differences in air fuel ratio may lead to differences in fuel system diagnostic response. Fuels with different composition (% of carbon, hydrogen and oxygen) can cause different oxygen concentrations in the exhaust stream for the same amount of fuel injected. The diesel engine has monitors for oxygen and NO_X sensors that implicitly rely on modeled O_2 concentration. A larger difference between measured and modeled oxygen concentration will decrease the separation between intact and faulty sensors and lead to increased Type 1 and Type 2 errors i.e., false pass or false fail decisions being made by OBD monitors.

Differences in heating value may lead to differences in exhaust temperature, affecting diagnostics based on exhaust energy, such as diesel oxidation catalyst (DOC) monitoring and cold start emissions reduction system (CSERS) monitoring. Because diagnostic thresholds are typically calibrated using standard fuel, a vehicle operating with an alternative diesel fuel may false fail diagnostics due to the changed sensor response exceeding diagnostic thresholds. Alkali and alkaline earth metals can be found in biodiesel at very low levels which can form exhaust ash and impact exhaust aftertreatment catalyst durability [26]. Studies have also shown impact of renewable fuels on diesel particulate filter (DPF) regeneration and DPF regeneration frequency due to differences in reactivity of soot from renewable fuels compared to conventional diesel [27,28].

Currently all the interactions between fuel properties and sensor response and impact on diagnostic system performance are not fully understood. This study therefore investigates this possible impact utilizing structured chassis dynamometer testing using standard test cycles on multiple vehicles and conventional diesel (ULSD), renewable diesel, diesel and blends of these fuels. In total, seven different fuel and fuel blends are tested on four different vehicles to evaluate the impact of fuel properties on OBD monitor robustness.

Section 1.2: Vehicles

In this study, chassis dynamometer testing was conducted on four different vehicles. The vehicles were sourced directly from the OEMs. The primary mode of data acquisition was CAN data from on-board sensors instrumented on the vehicle used for OBD monitoring. The vehicles have been anonymized and will be referred to as Vehicle A, Vehicle B, Vehicle C & Vehicle D.

Section 1.3: Fuels

Three fuels were tested in this work – ULSD, renewable diesel (R99) and biodiesel (B100) along with four different blends created using combinations of the fuels. The fuel test matrix is shown in Table 1.1.

Table 1.1: Fuel Test Matrix

Fuel #	Fuel/Blend
1	ULSD (high aromatic 28-35% & low CN 40-42)
2	B100
3	R100 (or R99 as available)
4	B50 / ULSD50 blend (B50U50)
5	R50 / ULSD 50 blend (R50U50)
6	B50 / R50 blend (B50R50)
7	B20 / R80 blend (B20R80)
8	Repeat fuel – ULSD (ULSD_2)

ULSD, ULSD_2, R99 and B100 fuel blends were sourced from off-site locations and fuel blends (B50/ULSD50, R50/ULSD50, B50/R50 and B20/R80) were blended on-site using volume-based blending and a mechanical stirrer to ensure uniform blending. Test 8 - ULSD fuel repeat was done after all tests were completed with the other 6 fuels and fuel blends. This was done to understand if there were any differences in vehicle performance after using alternative diesel fuels/fuel blends. The original intent was to use the same ULSD fuel (Test 1) to re-test the vehicles after all fuels had been tested. However, since enough ULSD fuel was not available for retesting, another batch of ULSD (ULSD_2) was used for the retesting the vehicles. Further, B50U50 blend was made using ULSD, while R50U50 blend was made using ULSD_2. Therefore, for analysis purposes, B50U50 results will be compared with ULSD and R50U50 results will be compared with ULSD_2.

To ensure that fuel blends had achieved required quality, each fuel and fuel blend were independently analyzed at Phillips66, Marathon and one of the OEM's test facilities to test for properties including density, net heating value, aromatics, carbon, hydrogen, oxygen, and sulfur content. These properties were further compared with known values in literature and calculated values based on volume-based calculations to ensure conformity. Detailed specification sheets for each fuel and fuel blend used in this study are provided in Appendix A.

Table *1.2*, Table 1.3 and Table 1.4 summarize the fuel properties of individual fuels, and four fuel blends created using combinations of ULSD/ULSD_2, R99 and B100 fuels. The test values are average values of the properties over the tests conducted at Phillips66, Marathon and one of the OEM's test facilities. Detailed specification sheets for each fuel and fuel blend used in this study are provided in Appendix A.

Table 1.2: Fuel Properties Summary

Fuel Properties	Units	ULSD	R99	B100	ULSD_2
Density @ 15ºC	kg/m3	848.8	782.6	884.2	845.5
Net Calorific Value	MJ/kg	42.55	44.02	37.20	42.84
Cetane Number	-	46.61	-	-	46.75
Oxygen	%	0	0	10.1	0
Sulphur	ppm	3.29	0.32	0.38	2.8
Carbon	%	86.82	84.99	77.95	86.38
Hydrogen	%	13.18	15.01	11.95	13.62
Aromatics	vol %	26.8	-	-	20.1
Aromatics	wt. %	27.8	-	-	21.6

Table 1.3: Fuel Blend Properties Summary I

Fuel Blend Properties	Units	R50U50 (ULSD_2)		B20R80	
		Calculated	Test	Calculated	Test
Density @ 15ºC	kg/m^3	814.03	814.7	802.92	802.6
Net Calorific Value	MJ/kg	43.43	43.37	42.66	42.52
Cetane Number	-	-	-	-	-
Oxygen	%	0.0	0.0	2.02	2.01
Sulphur	ppm	1.8	1.6	0.24	0.76
Carbon	%	85.69	85.58	83.58	83.68
Hydrogen	%	14.31	14.42	14.40	14.31
Aromatics	wt. %	10.8	12.57	0.0	0.065
Aromatics	vol %	10.03	10.45	0.0	0.1

Table 1.4: Fuel Blend Properties Summary II

Fuel Blend Properties	Units	B50U50 (ULSD)		B50R50	
		Calculated	Test	Calculated	Test
Density @ 15ºC	kg/m^3	866.5	865.86	833.4	832.7
Net Calorific Value	MJ/kg	39.87	39.50	40.61	40.59
Cetane Number	-	-	-	-	-
Oxygen	%	5.05	4.79	5.05	5.26
Sulphur	ppm	1.83	2.32	0.3	0.0
Carbon	%	82.38	82.50	81.47	80.68
Hydrogen	%	12.57	12.71	13.48	14.06
Aromatics	wt. %	13.9	13.38	0.0	0.81
Aromatics	vol %	13.4	14.49	0.0	1.41

As seen from Table 1.3 and Table 1.4, fuel blend properties tested at multiple facilities overall agreed well with calculated fuel blend properties. This indicates that fuel blends achieved expected quality standards to be tested on the vehicles.

Section 1.4: Test Procedure

Test Site:

All testing was conducted at FEV's Vehicle Development Center at Auburn Hills, Michigan. The test facility is a climate-controlled chassis dynamometer with ambient temperature and humidity control. Road-load for each vehicle was matched using EPA emission certification road load coefficients corresponding to each vehicle. The vehicles were also run in "Dyno Mode" using manufacturer specified procedures to disable Anti-lock Braking System (ABS), Traction Control System (TCS) and emergency braking system and fully enable vehicle operation on a chassis dynamometer as done for emissions testing. Further, headlights and Heating, Ventilation and Air Conditioning (HVAC) were also turned off during the testing.

Vehicle Instrumentation:

Vehicle instrumentation was limited. An ES 582 was used to collect OBD data VIA ODX tool kit in INCA for all vehicles except Vehicle B. Vehicle B used an ETK via INCA. The only external sensor was an ECM NH_3 sensor installed in a pipe that was attached in-between the vehicle tail pipe and the CVS connection. The vehicles were tested on a 4-wheel drive dyno equipped with Horiba emissions benches and a road speed fan. Soot emissions were measured on Vehicles C & D in the engine out location using an AVL Micro Soot Sensor. The vehicles were soaked in a soak room at 25°C with battery tenders on the 12V battery. The vehicles were moved from the chassis dyno after a test was completed and placed in the soak room. 12 - 36 hr. standard soak time was used, however as this study focused on the impact on OBD monitors, the soak times were extended when permitted.

Fuel Drain:

Fuel drains were performed by the prescribed method provided by the OEMs and CRC. The vehicles came equipped with a fuel drain installed. An external pump was connected to the vehicle fuel drains. Once the vehicle was empty, a 12V fuel pump with a volume gauge attached was used to fill the vehicles up to 40%. This was repeated three times per vehicle in succession. Once the final fuel fill was performed the vehicle was moved to the soak room to await testing.

Test Cycles:

Testing was conducted for each fuel following a test sequence (Figure 1.1) consisting of the following steps and test cycles –

1. Coast Down Sequence
2. Fuel Drain – 3 times
3. 3 Unified cycles (3 x LA92) – to condition system to new fuel
4. Service regeneration (For one of the four vehicles)
5. 12-hour soak for fuel temperature to stabilize
6. Three repeats of test sequence consisting of –
    a. Pre-conditioning FTP72 (Figure 1.2)
    b. Soak
    c. Cold-Start FTP75 (Figure 1.3)
    d. LA92 (Figure 1.4)
7. Regeneration on FTP72 cycle or stationary regeneration
8. Repeat Steps 1 to 7 on next fuel or fuel blend

Figure 1.2, Figure 1.3 and Figure 1.4 show the three test cycles used in the test sequence for this work. The target trace was followed as closely as possible based on CFR 1066 regulations. However, some cycles were allowed violations if vehicle was underpowered for that cycle trace as these were not certification tests. For FTP75 cycle (Fig 1.2), the hot soak section between 1400 – 2000 seconds is not considered for data analysis since PID labels during this time output unreasonable values.

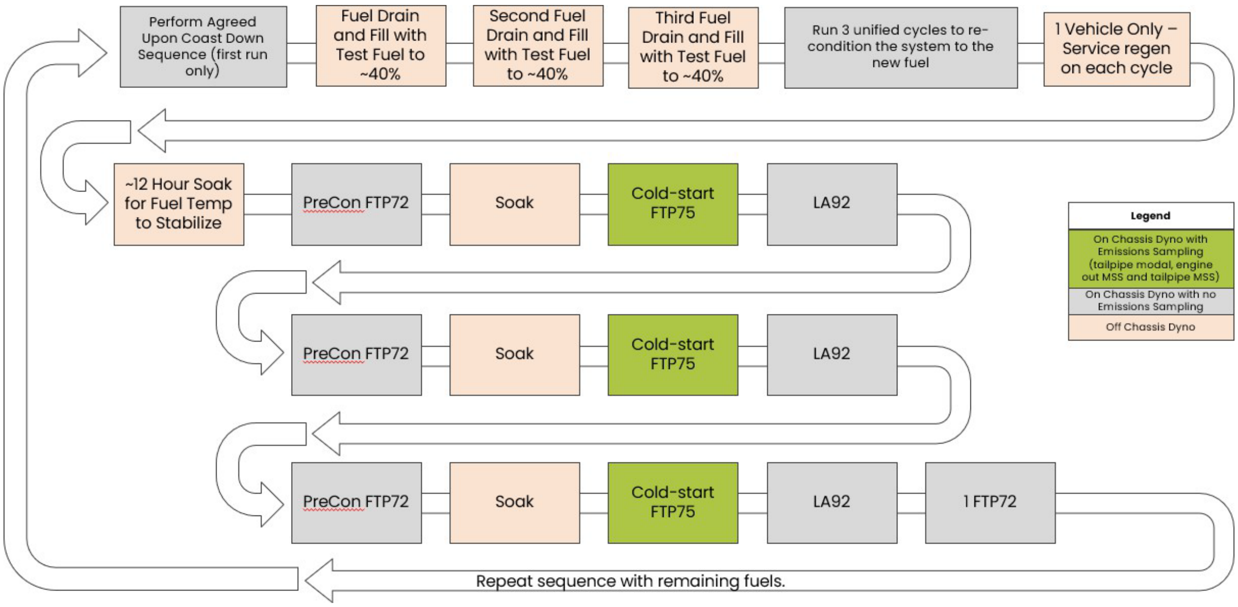

Figure 1.1: Vehicle Test Sequence

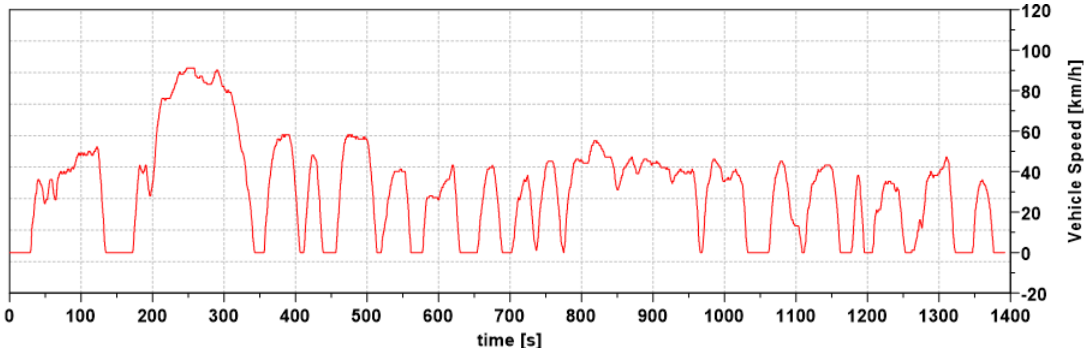

Figure 1.2: FTP72 Cycle

Coast Down:

Coast downs were performed by driving an EPA highway cycle followed by coast downs using an iterative method. This involved motoring the vehicle in neutral to 75 mph and letting the vehicle coast back down to 5 mph while trying to match the force curve derived from the target coefficients provided by the OEM. Once, a vehicle gets one run within the prescribed tolerances, two confirmation coast downs were run after. Once three back-to-back runs within the tolerance were achieved, the derived coefficients are calculated and applied to the vehicle through the dyno software (SPARC/STARSVETS).

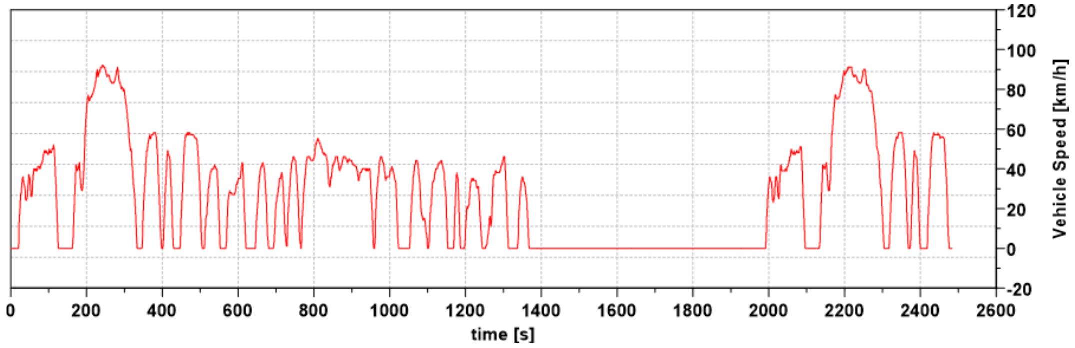

Figure 1.3: FTP75 Cycle

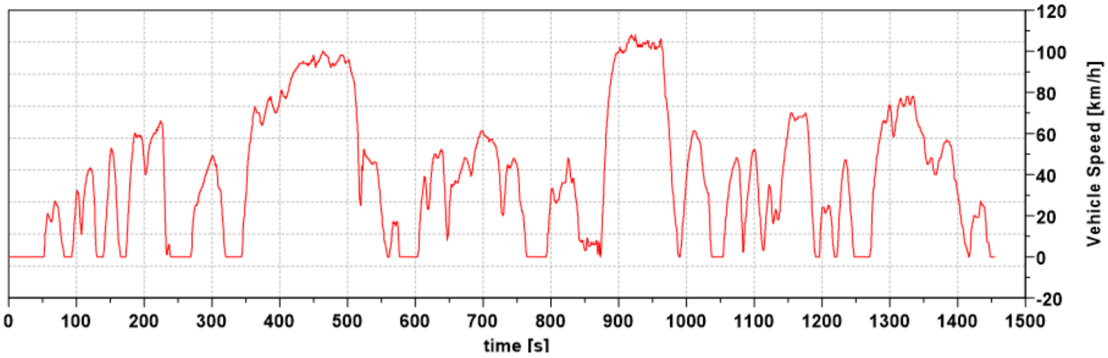

Figure 1.4: LA92 Cycle

Service Regeneration:

Service regens were performed using OEM specific tools and procedures as provided by OEMs.

FTP72 Regeneration/Steady State Regeneration:

This was performed after the completion of Step 6 of the test sequence before starting the fuel drain for the next fuel/fuel blend. DPF regeneration clears the soot accumulated in the DPF and resets the ammonia (NH_3) storage of the SCR. This ensures that the vehicle ATS state is reset before starting with the next fuel. Therefore, emissions and vehicle performance with the new fuel/fuel blend is tested without any residual effects from the previous fuel. Some vehicles allowed for triggering a DPF regeneration and running a FTP72 cycle to complete the regeneration. However, for other vehicles a steady state DPF regeneration was required. This depended on the OEM specific tools and procedures provided by the OEMs.

The original intent of the study was to also collect PID data when the vehicle was in DPF regeneration. However, data collection and triggering DPF regeneration were not possible simultaneously. A Y connector was used to collect data and trigger DPF regeneration using OEM specific tools using the OBD CAN port. However, this led to data dropouts and therefore, data was not collected during DPF regeneration.

Section 1.5: Data Collection, Pre-Processing & PID List

Data was collected using ETAS ODX (Vehicle B, Vehicle C and Vehicle D) & ETAS INCA (Vehicle A). Data was collected at ~ 3Hz using ETAS ODX tool for Vehicles A, C and D. This was the maximum possible frequency for data collection without data dropouts. This data was then resampled to 10Hz data using a Python script which uses a module (mdfreader) that converts the data from ~3 Hz to 10Hz using 1D interpolation. Data was resampled to 10 Hz to easily merge data with emissions data collected from chassis dynamometer at 10 Hz for FTP75 cycles. For Vehicle B, ETAS INCA data was collected at 10 Hz. SilverScan data was also collected at the start and end of each cycle to capture any On-Board Diagnostics (OBD) fault codes that appear during tests.

A list of key sensors to be monitored was compiled that would help to understand the impact of alternative diesel fuels on OBD monitors. These sensors are instrumented across different systems of the engine including air-path, fuel, coolant, exhaust and aftertreatment system (ATS). The PID labels were assigned priorities based on the potential impact of fuels on engine and aftertreatment operation. Further, this list was modified based on availability across all vehicles. This would ensure homogeneity when analyzing the data across multiple fuels and vehicles. The final compiled list of PIDs used for this work is shown in Table *1.5*.

An ammonia (NH_3) sensor was fitted on all the vehicles to acquire NH_3 slip data. NH_3 sensor was used because some diesel vehicles now or in the future might use NH_3 sensors. The addition of the NH_3 sensor could help to identify variation in the NH_3 sensor signal due to different alternative fuels/fuel blends compared to ULSD. Engine-out soot emissions were also collected during

FTP75 cycle for Vehicle C and Vehicle D to understand impact of fuels on particulate matter emissions. Engine-out soot emissions were only measured for Vehicles C and D, as only OEMs for vehicles C and D allowed for the provision of adding an exhaust port for measuring engine-out soot on the respective vehicles. Tailpipe emissions were also collected during FTP75 cycle which included nitrogen oxide (NO_x), carbon-dioxide (CO_2), carbon monoxide (CO), non-methane hydrocarbons (NMHC), total hydrocarbons (THC) and methane (CH_4) for all the vehicles. OBD data collected from FTP75 cycle was time-aligned with emissions data from chassis dynamometer.

Some pre-processing of the data collected was required before analysis. This included adding calculated values as well as cleaning of the data for ease of analysis. The pre-processing steps have been listed here:

1. Lambda values were calculated using air and fuel flow data for comparison against lambda sensor values. These would also be considered as substitute lambda values for vehicles that did not utilize lambda sensors. Vehicles A and C do not make use of a lambda sensor. Lambda was calculated using as follows:

$$\text{Calculated Lambda} = \frac{\frac{\text{Mass Flow Rate of Air (g/s)}}{\text{Engine Fuel Rate (g/s)}}}{\text{Stoichiometric Air} - \text{Fuel Ratio for Diesel}}$$

   Since exact composition of each fuel/fuel blend was not available, stoichiometric air-fuel ratio could not be calculated for each fuel/fuel blend. Therefore, stoichiometric air-fuel ratio of diesel fuel (14.5) was used to calculate lambda. Some inaccuracies are therefore expected for the lambda values calculated for fuels/fuel blends other than ULSD. If lambda sensor was unavailable, oxygen (O_2) sensor if available was used to make inferences along with the calculated lambda values.

2. Exhaust flow rate is calculated using air and fuel flow measured through CAN, to calculate mass-based engine-out and tailpipe NO_x emissions from on-board NO_x sensors. Since EGR flow rate was not available, EGR was not included in this calculation. Therefore, calculated exhaust flow rate and calculated NO_x emissions (g) are estimates and will have some inaccuracies.

3. Engine-out and tailpipe NO_x sensor values during sensor activation (> 2000 ppm) were set to 0 to calculate mass-based emissions and for ease of visualization.

4. Total fuel consumption over the cycle was calculated. Fuel consumption was calculated using the engine fuel flow rate PID from all the vehicles. The flow rate is in g/s and integrated over the test cycle to calculate fuel consumed in grams (g).

5. All pressures were converted to kPa for consistency.

Section 1.6: Data Analysis Methodology

For analyzing this data, since OBD monitor thresholds and robustness are determined by OEMs using ULSD, each fuel will be compared against ULSD as baseline. This would help to understand the potential impact of each fuel individually on OBD monitor robustness. The data analysis methodology has been divided into multiple sections:

Data Cleaning and Pre-processing:

At least 3 runs of each test cycle, FTP72, FTP75 and LA92 were tested on each vehicle. Different runs of FTP75 cycle were more consistent, since there was always a pre-conditioning cycle and cold soak before running FTP75 cycles. For FTP75 cycle, cycle time from 1400 – 2000 seconds (Phase 0 shown in Figure 1.3) was eliminated from the analysis since the vehicle is under soak during these conditions and values recorded from PIDs during key off are not useful.

Table 1.5: PIDs acquired from ODX/INCA based on priority

Priority	Parameter	PID Label	Units	PID #
1	Intake Manifold Temp	Intake Air Temperature IAT_Bank1_Sensor3	°C	**0F/68**
1	Intake Manifold Pressure	Intake Manifold Absolute Pressure	kPa	**87**
1	MAF	Air Flow Rate from Mass Airflow Sensor	g/s	**10/66**
1	Fuel rate	Engine Fuel Rate	g/s	**9D**
1	Engine speed	RPM	rpm	**0C**
1	Exhaust Pressure Sensor	ExhaustPressureSensorBank1Sensor1	kPa	**73**
1	O_2 Sensor Concentration	O2SensorConcentrationBank1Sensor1	%	**8C**
1	Lambda	O2SensorLambdaBank1Sensor1	-	**8C**
1	NO_x - SCR In	NOxSensorCorrectedConcentrationBank1Sensor1	ppm	**A1**
1	DPF Diff Pressure	ParticulateFilterBank1DeltaPressure	kPa	**7A**
2	DOC In Temp	ExhaustGasTemperatureBank1Sensor1	°C	**78**
2	DOC Out Temp	ExhaustGasTemperatureBank1Sensor2	°C	**78**
2	DPF In Temp	ExhaustGasTemperatureBank1Sensor2	°C	**78**
2	DPF Out Temp	ExhaustGasTemperatureBank1Sensor3	°C	**78**
2	SCR In Temp	ExhaustGasTemperatureBank1Sensor3	°C	**78**
2	SCR Out Temp	ExhaustGasTemperatureBank1Sensor4	°C	**78**
2	NO_x - SCR Out	NOxSensorCorrectedConcentrationBank1Sensor2 NOxSensorCorrectedConcentrationBank1Sensor3	ppm	**A1/A8**
2	Coolant Temp	Engine Coolant Temperature	°C	**05**
2	Rail Pressure	FuelRailPressure_A	kPa	**6D**
2	Fuel Injection timing	Fuel Injection Timing	deg	**5D**
2	VGT Position	VariableGeometryTurbo_A_Position	%	**71**
2	EGR position	ActualEGR_A_DutyCycle_Position ActualEGR_B_DutyCycle_Position	%	**69**
2	Wastegate Position	CommandedWastegate_A_Position	%	**72**
2	Boost Pressure	BoostPressureSensor_A	kPa	**70**
3	DEF dosing	Commanded DEF Dosing	%	**A5**
3	Vehicle Speed	Vehicle Speed Sensor	km/h	**0D**
3	Accelerator Pedal Position	Accelerator Pedal Position	%	**49**

However, since LA92 and FTP72 are pre-conditioning cycles, different soak times between runs could cause variations in starting and average coolant and after-treatment system temperatures. This could result in run-to-run variation in engine operation, even for the same vehicle and same fuel. Therefore, each test run was analyzed for mean, max and min coolant and after-treatment system temperatures to separate the runs into “cold” and “hot” cycles. Statistical analysis was then performed separately for the cold and hot runs to ensure that run-to-run variation is eliminated as much as possible and the data analysis is robust. A disadvantage to this approach is the elimination of test runs that did not fall in the “cold” or “hot” category. However, this was deemed acceptable to ensure robustness of data analysis and conclusions derived from the analysis.

Based on test sequence shown in Figure 1.1 and variations in LA92 and FTP72 cycles, the following in general is the number of test runs available for analysis for each test cycle for each fuel/fuel blend: 1 Cold FTP72, 2 Hot FTP72’s, 3 Cold FTP75’s and 3 Hot LA92’s. However, test run issues including vehicle entering DPF regeneration mode, data sampling or measurement issues or data dropouts led to removal of some test runs to ensure robustness of data analysis. Therefore, the number of test runs for each test cycle can vary from fuel to fuel. However, whenever possible the number of test runs were kept consistent between fuels.

Statistical Analysis:

From a statistical analysis perspective, multiple metrics and methods were considered. For each event, max, min and mean values were calculated. Due to the low data sampling frequency and resampling of data to 10 Hz, max and min values during an event could be contaminated by sampling errors. Therefore, directly comparing max and min values over an event or cycle could lead to improper conclusions. A mean-based statistical approach was therefore considered for this analysis. For Vehicle B, max and min values could be considered since data sampling frequency was 10 Hz, however, to keep the data analysis consistent across all vehicles, the statistical approach was restricted to a mean value approach.

Cycle Average Method:

Mean values of all the PID labels over each cycle are calculated to first understand the overall impact of fuels on engine and aftertreatment system operation. Since there are three runs of each test cycle, some run-to-run variation in the PID labels is expected. To handle this variation, after the runs have been separated into “cold” and “hot” categories, an “averaged cycle” is created using the average of the available test runs for each fuel. Then, the mean of each PID label is calculated for this “averaged cycle”. This metric is calculated for each test cycle (FTP72, FTP75 and LA92). Since mean of “averaged cycle” is only calculated for multiple runs of the same test cycle, the mean is taken over similar subsets and can be used to make meaningful conclusions about the trends due to the impact of a fuel or fuel blend on that PID label. The mean of the PID labels over the “averaged cycle” for each fuel is compared against ULSD to understand differences in engine and after-treatment operation using the fuel or fuel blend. This would provide a high-level understanding of the impact of fuel on the PID labels and therefore potentially on OBD monitors.

Area Under the Curve Method:

Further, an area under the curve method was used to understand differences in engine and after-treatment operation when running with different fuels. The "averaged cycle" was used for this analysis. Area under the curve was calculated for the PID labels for the "averaged cycle" for each fuel and compared against ULSD. The area under the curve calculations were done using Simpson's 1/3rd rule.

The percentage difference in the area under the curve for each fuel vs ULSD was calculated. This approach helps to eliminate the run-to-run variation and issues due to sampling error while providing a high-level understanding of differences in PID label over the cycle for each fuel compared to ULSD. For reporting trends, percentage differences were multiplied with mean absolute PID label values over the cycle to provide an absolute mean value for the trends and conclude if a significant difference/impact has been observed on an average over the cycle. This metric was used because percentage differences for different PID labels need to be normalized with respect to that PID label to effectively capture trends and derive meaningful conclusions. For example, a 10% difference in EGR or VNT position using cycle averaged or area under the curve method might not translate to a significant increase/decrease in absolute EGR/VNT position to impact OBD monitor robustness depending on engine speed and load.

This analysis was conducted for each vehicle individually since each vehicle has different hardware and engine and aftertreatment controls and calibrations. First, any trends identified for each vehicle will be presented. Further, any general trends identified across all vehicles will also be presented with possible impact on OBD monitor robustness.

Data Visualization & Analysis:

Further, to ensure that the statistical analysis results were robust, test runs for each fuel were compared with test runs for ULSD visually. Short sections of the second-by-second data (~200 seconds) were analyzed to look for differences in the PID labels from Table 1.5 compared to ULSD. The vehicle data collected over the chassis dynamometer tests is highly transient and since sampling rate is low (~ 3Hz), the data sometimes does not effectively capture highly transient events, for e.g., EGR position/VNT position changes during high accelerations. Therefore, it was necessary to visualize the observed trends in the "averaged" ULSD and alternative fuel/fuel blend cycles to confirm the trends calculated using statistical analysis methods.

Analysis Summary:

For the final analysis in this report, summary tables have been presented for each vehicle comparing each fuel/fuel blend with ULSD. The absolute/percentage differences calculated using area under the curve and cycle average methods are shown for PID labels with statistically significant trends to assess overall performance of each vehicle using each fuel. The legend for the tables is as follows:

No Difference: Using statistical analysis methods described above, the differences in PID label observed when testing with fuel/fuel blend compared to ULSD fuel were considered to not be significant enough to affect OBD monitor robustness.

Slightly Higher/Lower: Using statistical analysis methods described above, minor differences in PID label were observed when testing with fuel/fuel blend compared to ULSD fuel and values are presented. However, the observed differences were not large enough to be of concern to OBD monitor robustness.

Lower/Higher: Using statistical analysis methods described above, significant differences in PID label were observed when testing with fuel/fuel blend compared to ULSD fuel and values are presented. The observed differences could possibly affect OBD monitor robustness.

Further, the table uses colors to highlight possible improvements or negative effects due to fuel. **Yellow** is used to indicate trends that were somewhat negative. **Green** is used to indicate trends that would be considered as improvements. **Red** is used to indicate trends that could have some impact on OBD monitor robustness due to the fuel.

Plots and Color Legend Summary:

In each chapter, performance of the vehicles when tested with an alternative fuel/fuel blend is compared with ULSD. Each chapter is divided into sections for each vehicle A, B, C and D. Two sets of summary plots are shown to understand differences in vehicle performance due to the alternative fuel/fuel blend compared to ULSD. The first set of summary plots include fuel consumption, CO_2 and ATS temperatures. The second set of summary plots include fuel energy, engine-out NO_x and soot emissions as well as tailpipe NO_x emissions. Since six different fuels/fuel blends have been compared with ULSD, for ease of visualization colors have been assigned to each fuel/fuel blend. The color legend is shown in Table 1.6:

Table 1.6: Summary Plots Color Legend

Fuel	Color
ULSD/ULSD_2	Blue
R99	Orange
B100	Purple
R50U50	Light Coral
B20R80	Brown
B50U50	Cyan
B50R50	Magenta

Data Analysis Consistency and Constraints:

To ensure that analysis is consistent across all vehicles and fuel blends and to conform with the anonymity standards set by the team internally, some constraints were set on the data analysis. Further some constraints were seen within the test data due to vehicle operation. The constraints include:

1. PID Labels analyzed were kept consistent across all the vehicles
    i. For example, one of the vehicles tested had a dual loop EGR system (high pressure and low pressure EGR) along with wastegate. Therefore, only the high pressure EGR system (ActualEGR_A_DutyCycle_Position) was used for analysis since this PID was available across all vehicles. Also, it is difficult to fully understand the trends and impact of fuel on high pressure and low pressure EGR systems without having detailed knowledge of vehicle calibration and controls. Furthermore, this allows vehicle calibration and controls knowledge to be anonymous throughout the report while providing general insights into possible impact of fuels/fuel blends on the vehicles.

2. Data Analysis constraints due to run-to-run variation
    i. The vehicles tested had some features that were not consistent across all the test runs. This introduces run-to-run variations in PID labels even within the same fuel.
    ii. The test data also shows some variation due to driver-to-driver variations since only the target vehicle speed trace needs to be followed. Therefore, engine speed and fueling rate can be different even for same sections of the vehicle trace. This affects engine controls including mass flow rate of air, EGR, VGT, fuel rail pressure, lambda and O_2 sensor measurements and ultimately emissions and fuel consumption as well. Therefore, it becomes difficult to discern impact of fuel from impact of run-to-run variations in many cases. This has been stated as required throughout the report to provide clarifications for reported trends and explanations.
    iii. There are test sequence differences in test data with alternative diesel fuels/fuel blends compared to ULSD which result in differences in starting coolant and ATS temperatures. For example, even though the test sequences were kept consistent as much as possible for each fuel/fuel blend, due to testing/data collection issues, some runs were repeated. Therefore, the test sequences were not necessarily consistent for each fuel/fuel blend compared to ULSD. For example, LA92 Run 2 for R99 fuel might not have had the same cycles run before it compared to LA92 Run 2 for ULSD. This leads to run-to-run variations due to differences in coolant and ATS heating up as well differences in engine operation since vehicles have different warm-up modes based on coolant and ATS temperatures.
    iv. Further, due to differences in test sequence, the NH_3 storage of the SCR catalyst can vary resulting in more or less NH_3 slip. Similarly, DPF delta pressure also varies based on the amount of soot accumulated depending on the sequence. It cannot be completely discerned if trends observed for such PIDs are due to fuel or differences in test sequence. Therefore, NH_3 sensor and DPF delta pressure sensor measurements were not included in the analysis.

v. To quantify the variations described above, some thresholds were used for percentage differences and absolute differences to try and separate impact of fuel from impact of the different run-to-run and engine operation differences discussed.
    a. ± 2% variation was used as min and max threshold for percentage differences for PID labels including mass flow rate of air, engine fuel rate, lambda sensor as well as fuel rail pressure. Therefore, only percentage differences exceeding these thresholds and showing unidirectional trends (positive/negative) across all the cycles were used for making key observations and defining trends for each fuel/fuel blend compared to ULSD fuel.
    b. For all other PID labels, an absolute difference of ± 2 was used to find meaningful trends/impact of fuel. For e.g. a ± 2 ppm difference in NOx sensor measurements was considered to be well within the expected run-to-run variation. Again, only unidirectional trends were considered for making key observations and defining trends for each fuel/fuel blend compared to ULSD fuel.
    c. The analysis summary table (Section 1.6) shows this variation (percentage and absolute) in the "OBSERVATIONS" column.

3. Vehicle Speed Trace Violations: As mentioned in Section 1.4, the target vehicle speed trace was followed as closely as possible based on CFR 1066 regulations. However, some cycles were allowed violations if vehicle was underpowered for that cycle trace as these were not certification tests. However, since cycle work was not available for all the test cycles, another metric (fuel energy) was used to understand if cycle traces were followed as closely as possible compared to ULSD fuel. This was done to provide some insight into whether observed trends could have been impacted by vehicle speed traces not being followed comparably (compared to ULSD).
    i. Fuel energy (MJ): Fuel energy is the total energy used by the vehicle over a cycle which is a function of the total fuel consumption (g) and net heating value (NHV) of the fuel (MJ/kg) as shown below:

$$\text{Fuel Energy} = \text{Total fuel consumption (g)} \times \text{NHV of fuel} \left(\frac{\text{MJ}}{\text{kg}}\right)$$

    ii. If fuel energy over the cycle with a fuel/fuel blend varies significantly compared to ULSD, this could indicate that vehicle speed trace was not comparable to ULSD fuel i.e., lower or higher work was done over the cycle.
    iii. This metric is reported for each fuel to provide insights into impact of this variation on observed trends.

4. Data Issues and Impact on Analysis:
    i. Data analysis was modified to accommodate some issues in test data collected using first batch of ULSD fuel (ULSD) due to data sampling issues and some missing PID data for Vehicles B and C.
        a. Therefore, for Vehicle B and Vehicle C, all fuels/fuel blends have been compared with second ULSD fuel (ULSD_2).
        b. For Vehicle A and Vehicle D, all fuels/fuel blends have been compared with first ULSD fuel (ULSD) except for R50U50 fuel blend, since this blend

was made using ULSD_2 fuel (Section 1.3). Therefore, R50U50 blend data has been compared with ULSD_2 fuel for both these vehicles.

Chapter 2 : Fuel I: R99

This chapter describes the results and conclusions of the chassis dynamometer testing conducted on all four vehicles using R99 fuel utilizing the analysis approaches and metrics described in Section 1.6. The results have been divided into Sections 2.1, 2.2, 2.3 and 2.4 for Vehicles A, B, C and D respectively. Each section has the following that summarizes the results for R99 fuel compared to ULSD for each vehicle:

1. A table summarizing the results of the vehicle running on R99 compared to ULSD for all the test cycles. Key differences observed in engine performance and emissions when using R99 fuel compared to ULSD fuel using the "averaged" R99 and ULSD cycles for cold and hot FTP72 cycle, hot LA92 cycle and each phase of the FTP75 cycle are highlighted in this table.
2. Plots showing average ATS temperatures, fuel energy, total engine-out and tailpipe NO_x emissions, engine-out soot emissions (when available) and cycle fuel consumption differences for the vehicle when using R99 fuel blend compared to ULSD. The values in the plots have been normalized using min-max normalization, where minimum value = 0 and maximum value was the maximum value in the plot. This was done to present important trends in engine performance while preserving anonymity of emissions and fuel consumption values.
3. Trend plots (% difference) showing PID labels for which significant increasing or decreasing trends were observed when running with R99 fuel compared to ULSD for that vehicle. Negative percent difference indicates lower and positive indicates higher compared to ULSD.

A summary of key observations and trends analyzed for the vehicles when running with R99 fuel compared to ULSD and their possible impact on different OBD monitors is presented in Section 2.5

Section 2.1: Vehicle A: R99 vs ULSD

Table 2.1: Vehicle A Results Summary: R99 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Engine Fuel Rate	**g/s**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	2 to 4% Lower
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa

DOC Inlet Temp	**°C**	Slightly Lower	-	Slightly Lower	Slightly Lower	No Difference	-	Up to 7°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	-	Slightly Lower	Slightly Lower	No Difference	-	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	-	Slightly Lower	Slightly Lower	No Difference	-	
SCR Outlet Temp	**°C**	Slightly Lower	-	Slightly Lower	Slightly Lower	No Difference	-	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Engine Out NO_x Sensor	**ppm**	Slightly Lower	No Difference	No Difference	Slightly Lower	Slightly Lower	Slightly Higher	± 7 ppm
Tailpipe NO_x Sensor	**ppm**	No Difference	No Difference	No Difference	No Difference	No Difference	NH_3 Slip	± 2 ppm
Bench Tailpipe NO_x Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	N/A	N/A	N/A	N/A	N/A	N/A	
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
DEF Dosing	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NO_x	**g**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	No Difference	2 to 8% Lower
Calculated Tailpipe NO_x	**g**	Slightly Lower	Slightly Lower	N/A	Slightly Lower	Slightly Lower	NH_3 Slip	14 to 54% Lower
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Bench Tailpipe NO_x	**g**	-	-	Slightly Lower	Lower	No Difference	-	5 to 18% Lower
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	4 to 6% Lower
Total Cycle Fuel Consumption	**g**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	2 to 4% Lower
Engine-Out Soot	**mg**	-	-	-	-	-	-	

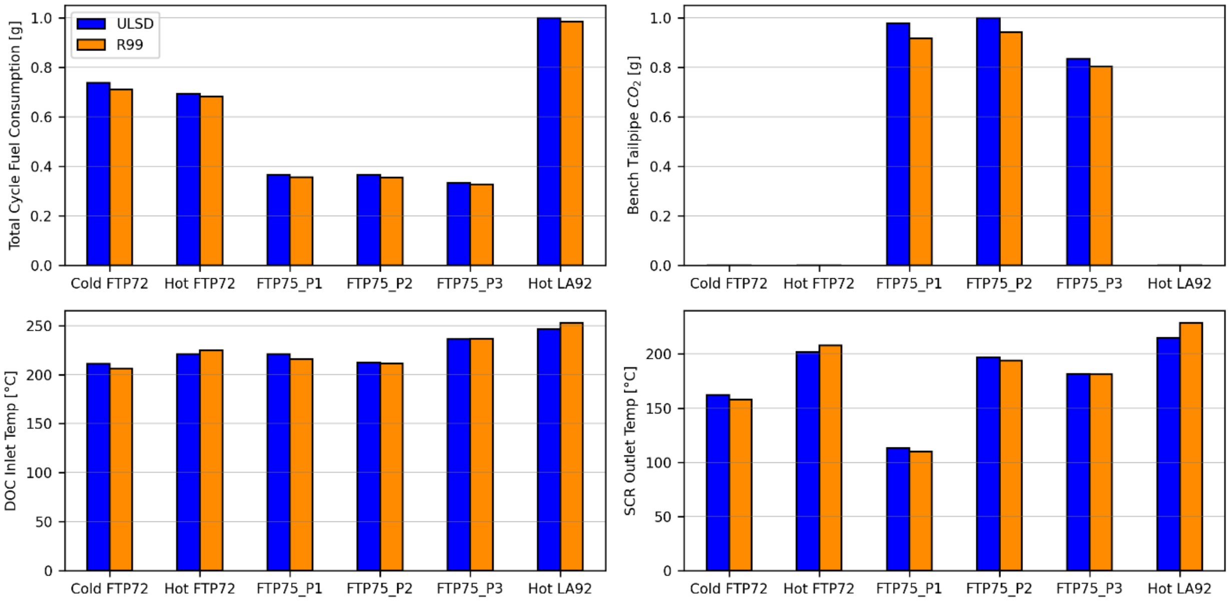

Figure 2.1: Vehicle A: R99 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

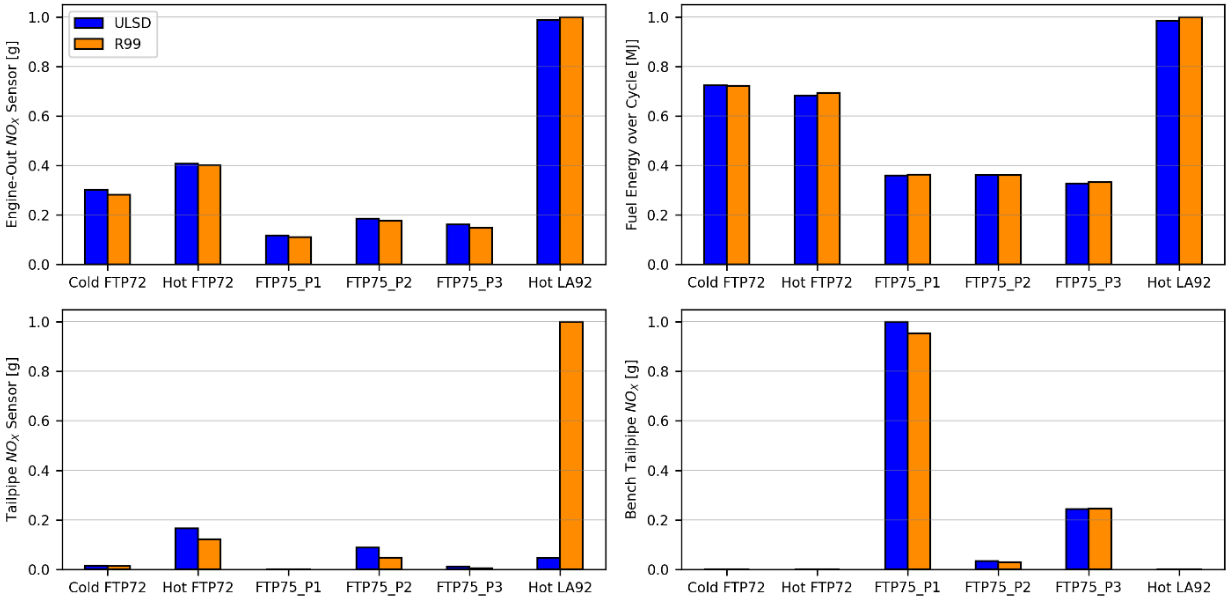

Figure 2.2: Vehicle A: R99 vs ULSD: Fuel Energy and NO_x Emissions

Key observations from Figure 2.1 and Figure 2.2 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 2 to 4% lower when running with R99 for the test cycles (Figure 2.1). R99 fuel has slightly higher net heating value per kg (~3%) compared to ULSD (Table 1.3) which could explain the lower fuel consumption observed over all test cycles. R99 fuel has lower density than ULSD, therefore net heating value based on volume is 5% lower compared to ULSD which could increase volumetric fuel consumption. However, the much higher cetane number of R99 compared to ULSD could help to improve combustion efficiency, thereby showing an overall reduction in fuel consumption.

The fuel energy used over all the cycles with R99 fuel was comparable to ULSD (± 2%) (Figure 2.2). Therefore, cycle work over the test cycles should be comparable to ULSD. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were ≤ 0.04 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were 4 to 6% lower compared to ULSD for FTP75 cycle. This could be explained by the 2% lower carbon content (% weight) in R99 fuel compared to ULSD as well as the 2-4% lower fuel consumption seen in Figure 2.1.

2. ATS temperatures (Figure 2.1): ATS temperatures were on average up to 7°C lower when running with R99 fuel for FTP75 and cold FTP72 cycle. For hot LA92 and hot FTP72 cycles the ATS temperatures were slightly higher (7-10°C). However, this higher temperature could be attributed to cycle-to-cycle difference (both cycles with R99 fuel had higher starting ATS temperatures compared to ULSD). Some of the differences in ATS temperatures observed could be attributed to run-to-run variation. However, higher cetane number of R99 fuel, shortening ignition delay and increasing combustion efficiency could lead to the observed lower ATS temperatures.

   However, from OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Overall, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 2.2. A trend of slightly lower engine-out NO_x emissions was observed over the test cycles (up to 7 ppm lower), except for hot FTP72 and LA92 cycles which showed slightly higher sensor values (up to 7 ppm higher). However, there could be some differences in sensor activation times due to differences in ATS temperatures, therefore some of the differences could be attributed to run-to-run variation. Trends in engine-out NO_x emissions have been unclear in studies with R99 fuel [3,9,21] and this uncertainty was observed in Vehicle A. However, the paraffinic nature of R99 fuel with lower aromatics could help to lower engine-out NO_x emissions by lowering local combustion temperatures [30].

   Tailpipe NO_x sensor emissions for FTP75 Phase 1 are unavailable since sensor is inactive. However, on other cycles tailpipe NO_x sensor emissions were comparable (± 2 ppm), except for LA92 cycle. On LA92 cycle more NH_3 slip was observed with R99 fuel possibly due to differences in sequence of cycles run before LA92 cycle between the two fuels. Cumulative bench tailpipe NO_x emissions with R99 (5-18% lower) on FTP75 cycle suggests a lower tailpipe NO_x trend with R99 fuel. This can be explained by the overall slightly lower engine-out NO_x emissions which would reduce overall tailpipe NO_x emissions. However, on a ppm basis < 2 ppm difference was observed on average compared to ULSD.

From an OBD monitor perspective these differences are well within sensor accuracy limits and may not be considered large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly higher SCR efficiency is expected due to lower engine-out NO_x emissions with R99 and ATS temperatures being somewhat similar, which could affect NO_x emissions OBD limits used to determine monitor decisions.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of R99 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle A using R99 fuel compared to ULSD fuel have been shown in Figure 2.3. The higher ATS trends observed for hot FTP72 and LA92 cycles are due to ATS temperatures at cycle start being higher for these cycles when running on R99 fuel compared to ULSD. However, in general ATS temperatures with R99 fuel were seen to be slightly lower as compared to ULSD fuel.

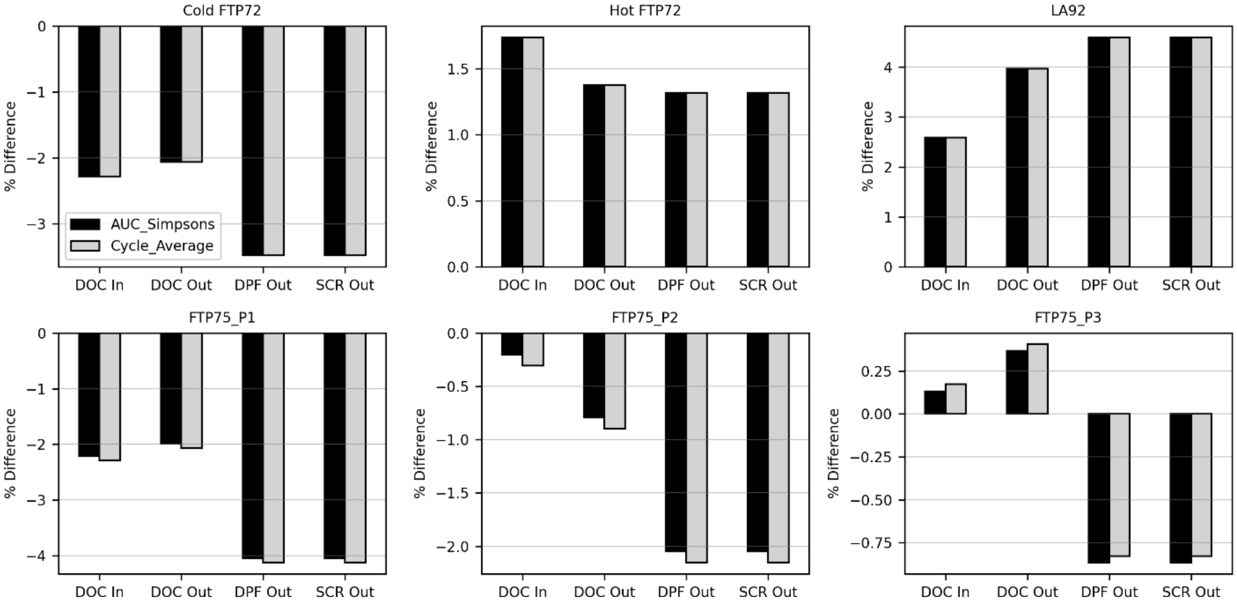

Figure 2.3: Vehicle A: R99 vs ULSD: ATS Temperature Trends

Based on results from Table 2.1 and key observations presented, it can be concluded that there could potentially be little to no impact of R99 fuel on OBD monitor robustness for Vehicle A. Overall, R99 fuel showed some impact on ATS temperatures and engine-out NO_x sensor values that could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management mode and DPF regeneration as well as SCR efficiency and NO_x sensor rationality monitors. However, post-test cycle OBD scans for test cycles tested with R99 fuel did not show any OBD fault codes for Vehicle A.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 2.1. However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 2.2: Vehicle B: R99 vs ULSD_2

Table 2.2: Vehicle B Results Summary: R99 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	Slightly Higher	-	Slightly Higher	Slightly Higher	Slightly Higher	-	Up to 6°C Higher
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Higher	-	Slightly Higher	Slightly Higher	Slightly Higher	-	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Higher	-	Slightly Higher	Slightly Higher	Slightly Higher	-	
SCR Outlet Temp	**°C**	Slightly Higher	-	Slightly Higher	Slightly Higher	Slightly Higher	-	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	**ppm**	No Difference	No Difference	Slightly Lower	No Difference	Slightly Lower	Slightly Lower	Up to 7 ppm Lower
Tailpipe NO_x Sensor	**ppm**	-	-	-	-	-	-	NH_3 slip
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Lower	No Difference	No Difference	-	Up to 2 ppm Lower
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4 mg/s
Calculated Engine-Out NO_x	**g**	Slightly Higher	Slightly Higher	Slightly Lower	Slightly Higher	Slightly Lower	Slightly Lower	± 5%
Calculated Tailpipe NO_x	**g**	-	-	-	-	-	-	NH_3 slip
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Bench Tailpipe NO_x	**g**	-	-	Slightly Lower	Lower	Lower	-	8 to 38% Lower

Bench Tailpipe CO_2	g	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 4% Lower
Total Cycle Fuel Consumption	g							± 2 %
Engine-Out Soot	mg	N/A	N/A	N/A	N/A	N/A	N/A	

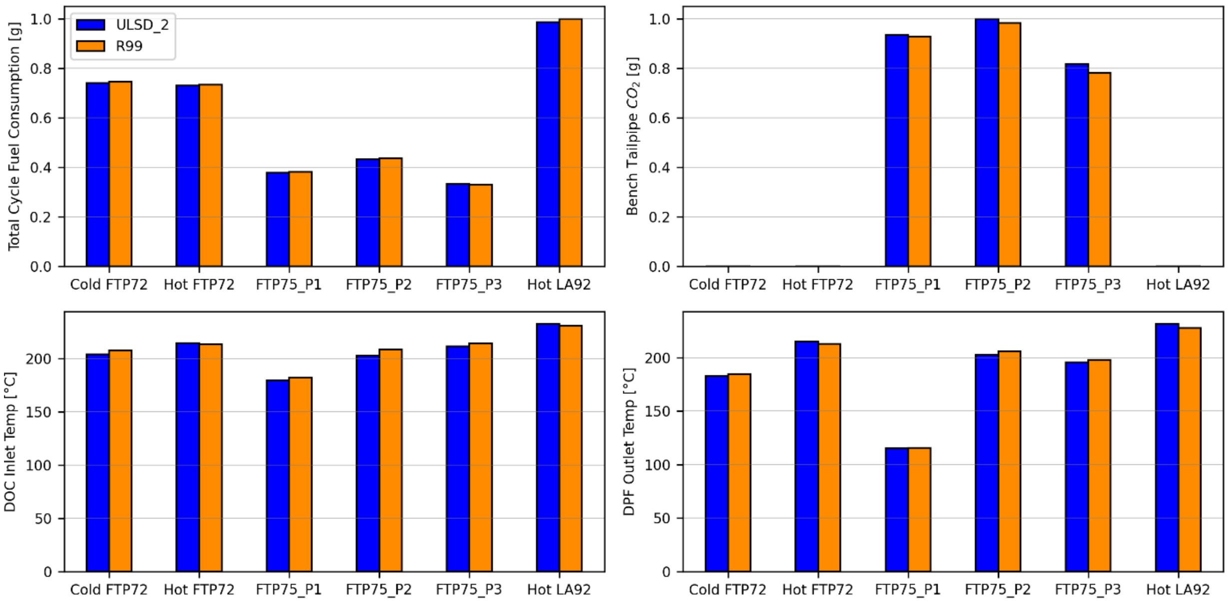

Figure 2.4: Vehicle B: R99 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

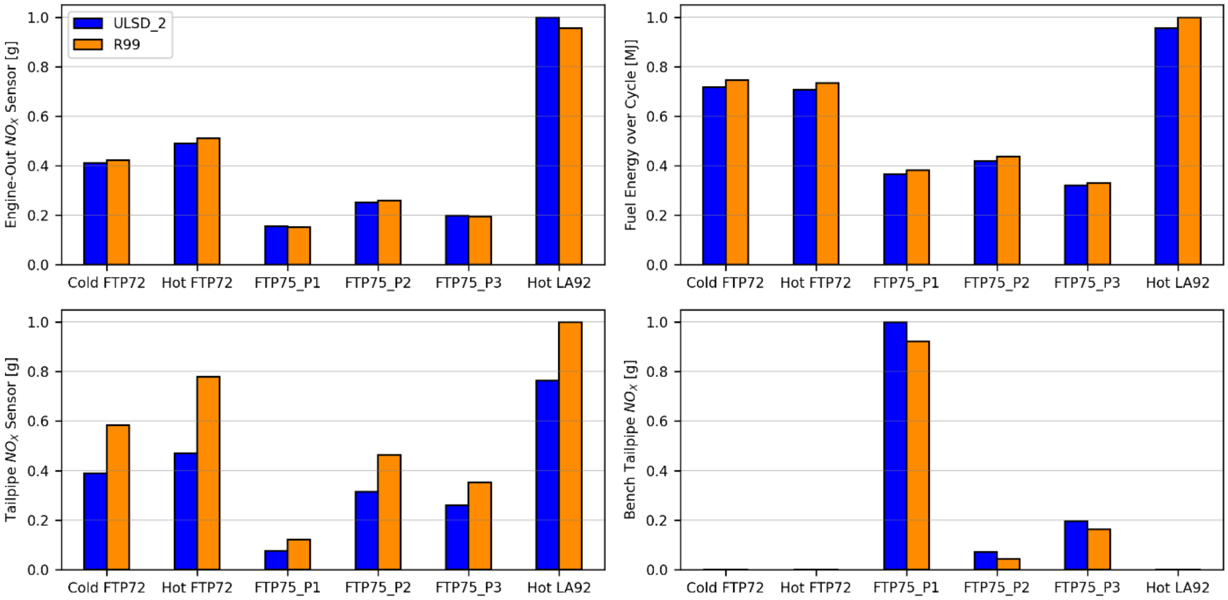

Figure 2.5: Vehicle B: R99 vs ULSD_2: Fuel Energy and NO_x Emissions

Key observations from Figure 2.4 and Figure 2.5 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle had very small variation when running with R99 fuel compared to ULSD (within ± 2%) (Figure 2.4). R99 fuel has 3% higher net heating value per kg compared to ULSD (Table 1.3), which could

contribute to some reduction in fuel consumption as observed in some cycles. However, this difference (± 2%) is well within run-to-run variation.

The fuel energy used over all the cycles with R99 fuel was slightly higher compared to ULSD (3-5%) (Figure 2.5). From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were within ± 0.02 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were ~4% lower compared to ULSD for FTP75 cycle. This could be explained by the 2% lower carbon content (% weight) in R99 fuel compared to ULSD.

2. ATS temperatures (Figure 2.4): ATS temperatures when running with R99 fuel were slightly higher (up to 6°C). For hot LA92 and hot FTP72 cycles the ATS temperatures were slightly lower. However, this could be attributed to cycle-to-cycle difference (both cycles with R99 had lower starting ATS temperatures compared to the cycles with ULSD). However, these differences in temperatures could be well within run-to-run variation.

   Therefore, from OBD perspective no significant impact is expected on monitor robustness for Vehicle B when running with R99 fuel.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 2.5. Engine-out NO_x emissions were up to 7 ppm lower. However, there could be some differences in sensor activation times due to differences in ATS temperature. Therefore, some differences could be attributed to run-to-run variation. Trends in engine-out NO_x emissions have been unclear in studies with R99 fuel [3,9,21], however some studies have reported lower NO_x emissions with R99 fuel [21]. The paraffinic nature of R99 fuel with lower aromatics could help to lower engine-out NO_x emissions by lowering local combustion temperatures [30].

   For Vehicle B, trends for tailpipe NO_x sensor emissions were inconclusive. This was primarily because all cycles on Vehicle B always showed some amount of NH_3 slip throughout the cycle which seemed to strongly affect tailpipe NO_x sensor values. This is due to the cross-sensitivity of NO_x sensors to NH_3 which increases tailpipe NO_x sensor measured NO_x values to higher than actual values. This was confirmed by the cumulative bench tailpipe NO_x values which show lower tailpipe NO_x emissions trend on FTP75 cycle with R99 (8-38% lower). On the other hand, tailpipe NO_x sensor values are consistently higher with R99 fuel. However, on a ppm basis < 2 ppm difference was observed on the bench for R99 fuel compared to ULSD. Therefore, overall, no significant impact is expected on tailpipe NO_x sensor measurements with R99 fuel.

   From an OBD monitor perspective these differences are well within sensor accuracy limits and may not be considered large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly higher SCR efficiency may be expected due to slightly lower engine-out NO_x emissions with R99, which could affect NO_x emissions OBD limits used to determine monitor decisions.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of R99 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle B using R99 fuel compared to ULSD fuel have been shown in Figure 2.6.

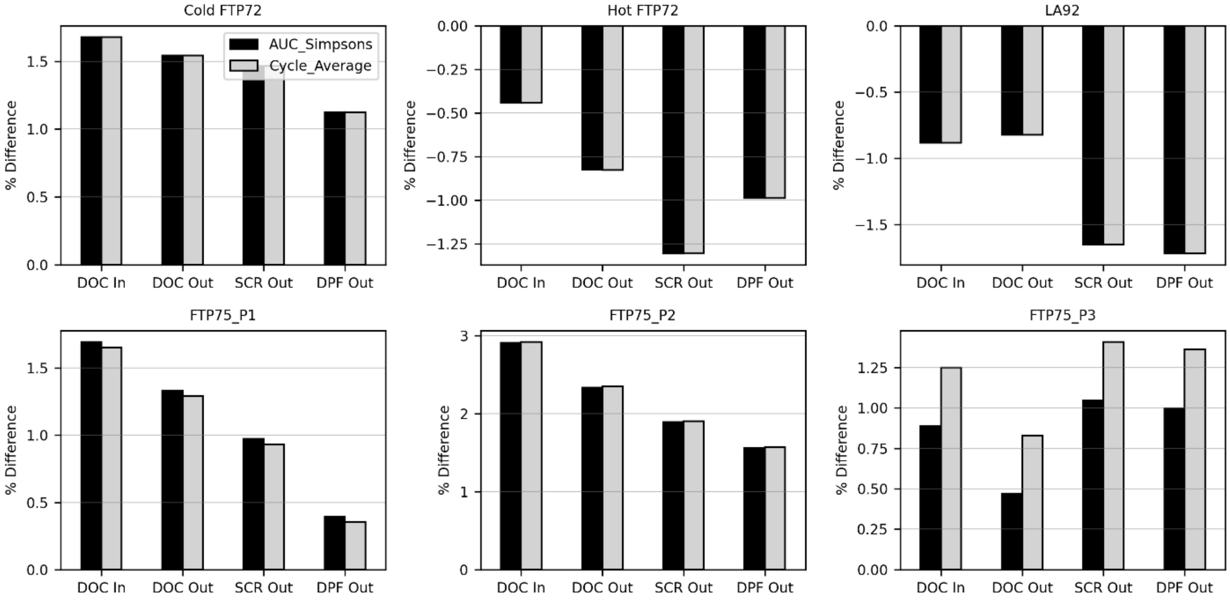

Figure 2.6: Vehicle B: R99 vs ULSD_2 ATS Temperature Trends

Based on results from Table 2.2 and key observations presented, it can be concluded that there could be little to no impact of R99 fuel on OBD monitor robustness for Vehicle B. Overall, R99 fuel showed small impact on ATS temperatures and engine-out NO_x that could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management mode, DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with R99 fuel also did not show any OBD fault codes for Vehicle B.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 2.2. However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 2.3: Vehicle C: R99 vs ULSD_2

Table 2.3: Vehicle C Results Summary: R99 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 5%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3°C

Coolant Temp	**°C**	-	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Engine Fuel Rate	**g/s**	Slightly Lower	Slightly Lower	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	± 5%
Exhaust Pressure	**kPa**	N/A	N/A	N/A	N/A	N/A	N/A	
DOC Inlet Temp	**°C**	-	Slightly Higher	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 5°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	-	Slightly Higher	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	-	Slightly Higher	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO$_x$ Sensor	**ppm**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 20 ppm
Tailpipe NO$_x$ Sensor	**ppm**	No Difference	No Difference	N/A	No Difference	No Difference	No Difference	± 1 ppm
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O$_2$ Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
DEF Dosing	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NO$_x$	**g**	Higher	Higher	Higher	Higher	Higher	Higher	Up to 34% Higher
Calculated Tailpipe NO$_x$	**g**	Higher	Higher	N/A	Lower	Higher	Higher	Up to 67% Higher
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 5%
Bench Tailpipe NO$_x$	**g**	-	-	Higher	Lower	Lower	-	20% Higher to 50% Lower
Bench Tailpipe CO$_2$	**g**	-	-	Lower	Lower	Lower	-	Up to 13% Lower
Total Cycle Fuel Consumption	**g**	Slightly Lower	Slightly Lower	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	± 5%
Engine-Out Soot	**mg**	-	-	Lower	Lower	Lower	-	Up to 60% Lower

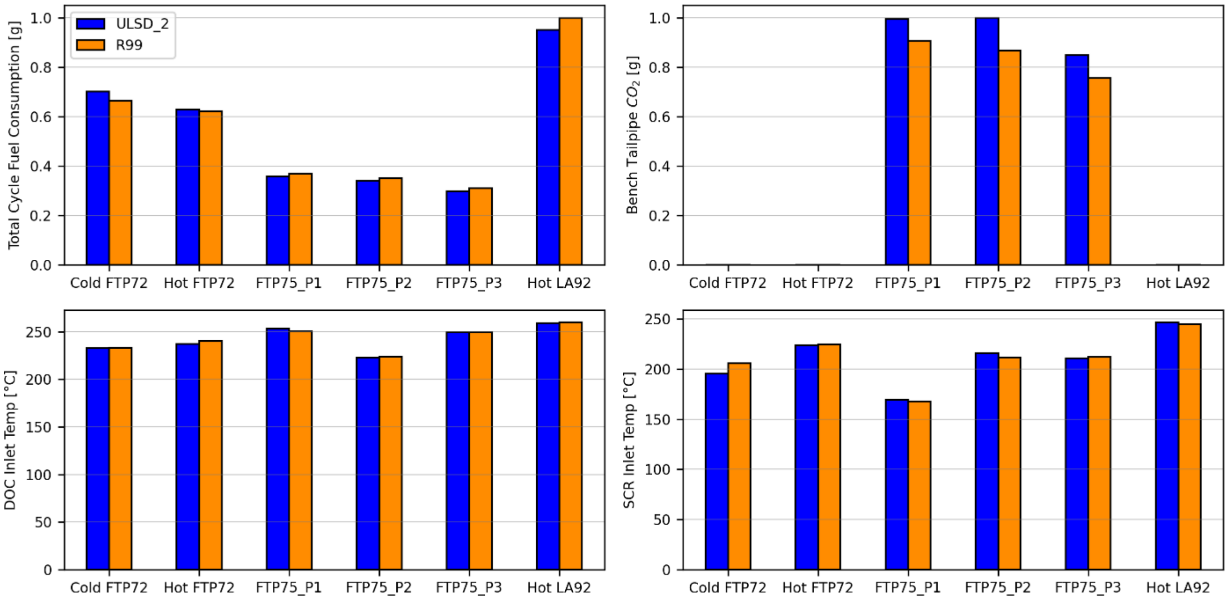

Figure 2.7: Vehicle C: R99 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

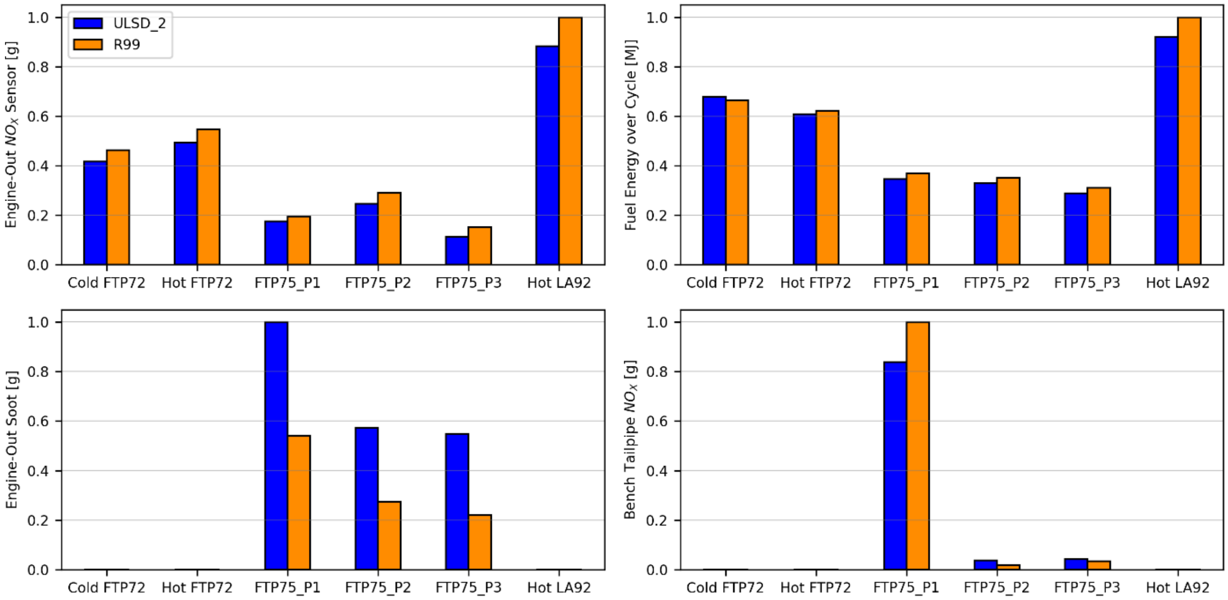

Figure 2.8: Vehicle C: R99 vs ULSD_2: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure 2.7 and Figure 2.8 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycles varied between ± 5% with R99 fuel. For Cold FTP72 cycle, fuel consumption is lower with R99 fuel due to higher starting coolant and ATS temperatures for the run with R99 fuel which could result in different engine operation. On FTP75 and LA92 cycles the fuel consumption was higher by up to 5% (Figure 2.7). R99 fuel has slightly higher net heating value per kg (~3%) compared to ULSD (Table 1.3) which could explain the lower fuel consumption observed on some test cycles. However, since R99 fuel has lower density compared to

ULSD (8%), volumetric fuel consumption will be higher (5% lower net heating value based on volume) which could have some negative impact fuel consumption.

The fuel energy used over all the cycles with R99 fuel had large variation compared to ULSD (from 2% lower to 9% higher) (Figure 2.8). Therefore, there could be differences in cycle work compared to ULSD. This difference may also be explained by the differences in engine operation due to a feature on Vehicle C, which was not consistent over each cycle. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were within ± 0.04 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were 13% lower compared to ULSD for FTP75 cycle. This could be explained by the 2% lower carbon content (% weight) in R99 fuel compared to ULSD as well as 4% lower fuel consumption observed over FTP75 cycle.

2. ATS temperatures (Figure 2.7): ATS temperatures were on average slightly higher on hot FTP72 cycle but slightly lower on FTP75 and LA92 cycles. However, this variation was within ± 5°C which is well-within run-to-run variation. An important observation was that with R99 fuel on hot FTP 72 cycle, engine entered a different operating mode (possibly thermal management) to raise ATS temperatures which was not seen with ULSD fuel. However, this may or may not be an impact of the fuel and could also be attributed to differences in temperatures normally seen between runs.

   Therefore, from OBD perspective no significant impact is expected on monitor robustness for Vehicle C when running with R99 fuel.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 2.8. A trend of higher engine-out NO_x emissions was observed over the test cycles (up to 20 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. Trends in engine-out NO_x emissions have been unclear in studies with R99 fuel [3,9,21]. However, R99 fuel has a higher cetane number, therefore, combustion (CA50) may be shifted to more advanced timings which could have resulted in the observed higher engine-out NO_x emissions.

   Tailpipe NO_x sensor values were seen to be very similar to ULSD. However, based on cumulative bench values (g) higher as well as lower tailpipe NO_x emissions were observed across the different phases of FTP75 cycle with R99. As phase 1 is cold start, the higher tailpipe NO_x emissions could be primarily due to the higher engine-out NO_x emissions. Once the SCR temperature gets hot enough (Phase 2 and Phase 3), the SCR efficiency could be high enough to not show increased tailpipe NO_x emissions. On a ppm basis however, this difference was < 2 ppm difference on average compared to ULSD.

   From an OBD monitor perspective these differences may be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults.

4. Soot Emissions (Figure 2.8): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to higher cetane number of R99 fuel improving combustion efficiency by reducing ignition delay. Also, renewable diesel fuel is a paraffinic fuel with shorter molecular chain and higher H/C ratio, with almost zero aromatic, sulfur, and other mineral impurities content which reduces the propensity for soot formation. Overall, 45-60% lower soot emissions were observed when running Vehicle C with R99 compared to ULSD.

   From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of R99 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle C using R99 fuel compared to ULSD fuel have been shown in Figure 2.9.

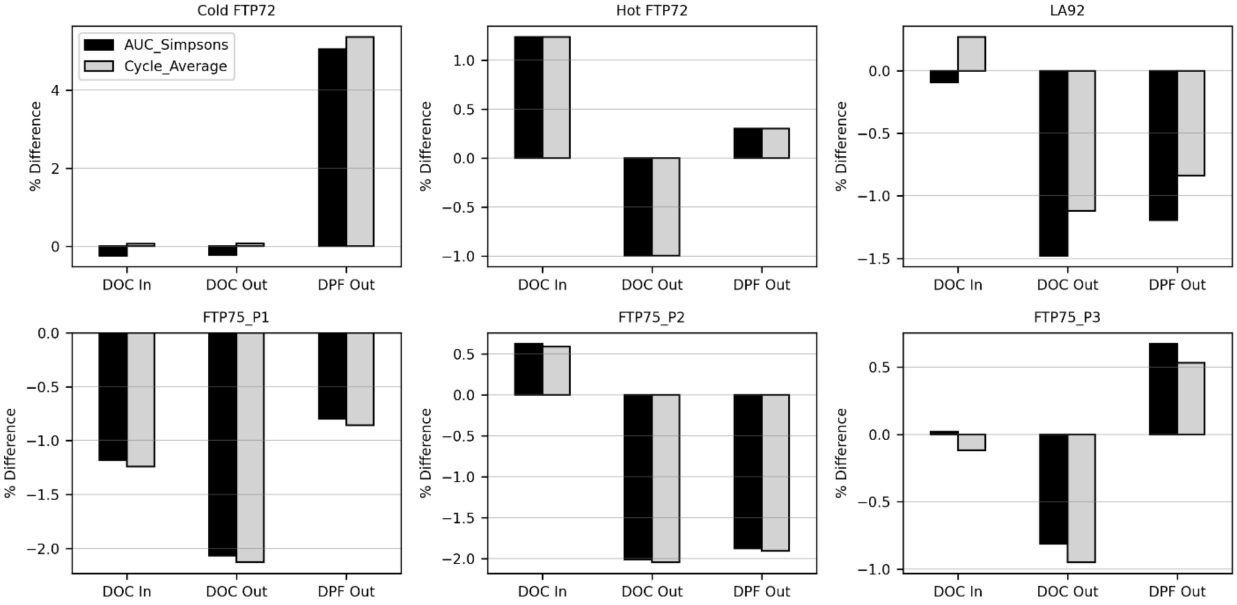

Figure 2.9: Vehicle C: R99 vs ULSD_2 ATS Temperature Trends

Based on results from Table 2.3 and key observations presented, it can be concluded that there could be little to no impact of R99 fuel on OBD monitor robustness for Vehicle C. Overall, R99 fuel showed some impact on engine-out NO_x and soot emissions which could possibly impact OBD monitor decisions including DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with R99 fuel did not show any OBD fault codes for Vehicle C.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 2.3. For example, boost pressure (± 2 kPa) and some differences in fuel rail pressure, air flow, calculated lambda, EGR and VGT positions. However, Vehicle C also had run to run differences due to a feature that was not consistent over the test cycles with ULSD and R99 fuel. Therefore, these observed variations were not considered to be significant enough to impact OBD robustness.

Section 2.4: Vehicle D: R99 vs ULSD

Table 2.4: Vehicle D Results Summary: R99 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Intake Manifold Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Engine Fuel Rate	**g/s**	Slightly Lower	No Difference	Slightly Lower	Slightly Lower	No Difference	No Difference	Up to 4% Lower
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	Slightly Lower	-	Slightly Higher	Slightly Higher	Slightly Higher	-	± 6°C
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	-	Slightly Higher	Slightly Higher	Slightly Higher	-	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	-	Slightly Higher	Slightly Higher	Slightly Higher	-	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	**ppm**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 15 ppm
Tailpipe NO_x Sensor	**ppm**	N/A	N/A	N/A	N/A	N/A	N/A	
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Lower	No Difference	No Difference	-	Up to 3 ppm Lower
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**mg/s**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Engine-Out NO_x	**g**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Lower	Slightly Lower	Up to 12% Lower
Calculated Tailpipe NO_x	**g**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Bench Tailpipe NO_x	**g**	-	-	Lower	Lower	Lower	-	18 to 34% Lower

Bench Tailpipe CO_2	g	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 3% Lower
Total Cycle Fuel Consumption	g	Slightly Lower	No Difference	Slightly Lower	Slightly Lower	No Difference	No Difference	Up to 4% Lower
Engine-Out Soot	mg	-	-	Lower	Lower	Lower	-	Up to 40% Lower

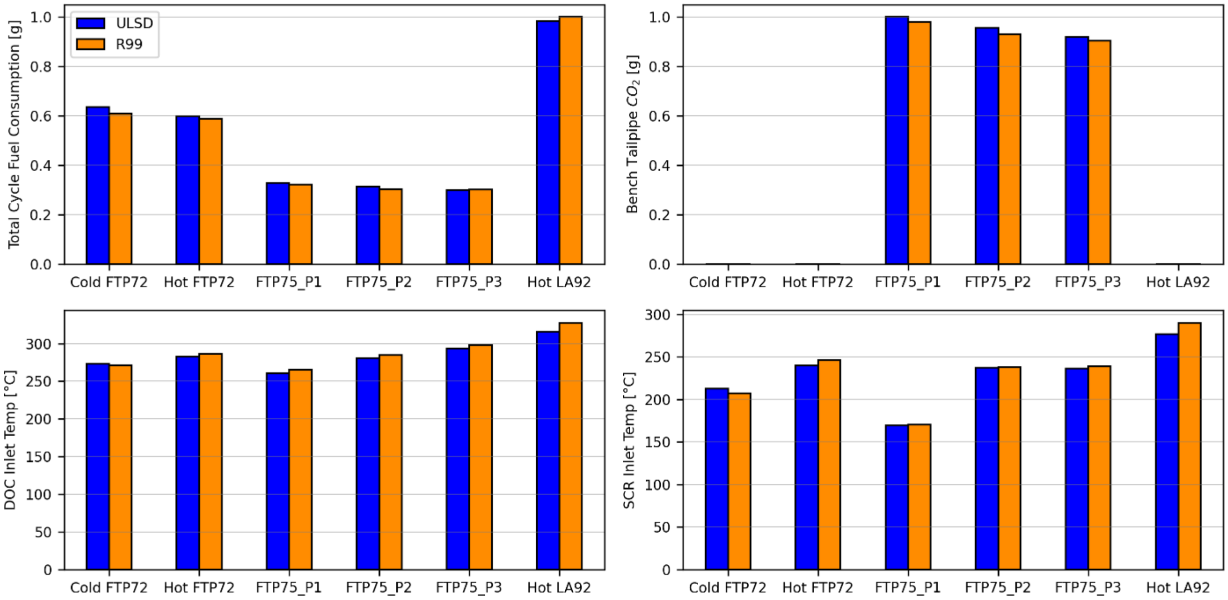

Figure 2.10: Vehicle D: R99 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

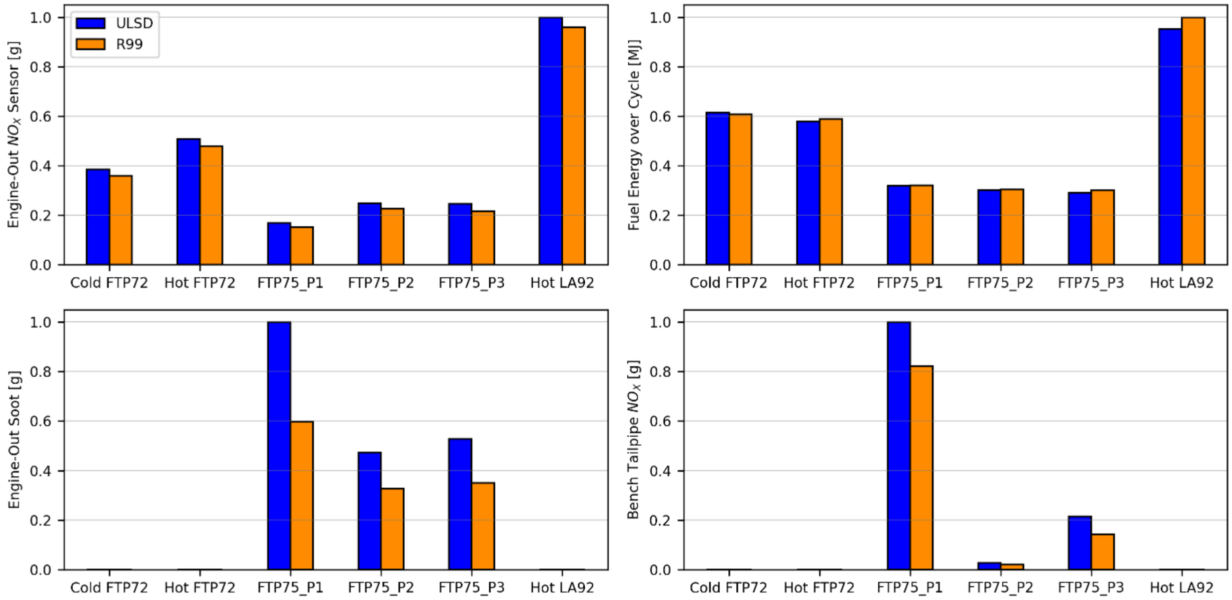

Figure 2.11: Vehicle D: R99 vs ULSD: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure 2.10 and Figure 2.11 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 2-4% lower when running with R99 for FTP72 and FTP75 cycle, while on LA92 cycle fuel

consumption was slightly higher (Figure 2.10). R99 fuel has slightly higher net heating value per kg (~3%) compared to ULSD (Table 1.3) which could explain the lower fuel consumption observed over all test cycles. However, since R99 fuel has lower density compared to ULSD (8%), volumetric fuel consumption will be higher (5% lower net heating value based on volume) which could have some negative impact on fuel consumption.

The fuel energy used over all the cycles with R99 fuel varied between 1% lower to 5% higher compared to ULSD (Figure 2.11). This variation in fuel energy could indicate some differences in cycle work compared to ULSD. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were ≤ 0.05 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were 2-3% lower compared to ULSD for FTP75 cycle. This could be explained by the 2% lower carbon content (% weight) in R99 fuel compared to ULSD as well as the lower fuel consumption seen in Figure 2.10.

2. ATS temperatures (Figure 2.10): ATS temperatures were on average slightly higher on FTP75 cycle and slightly lower on cold FTP72 cycles. However, this variation was within ± 6°C which could be well within run-to-run variation. For hot LA92 and hot FTP72 cycles the ATS temperatures were slightly higher (7-10°C). However, this higher temperature could be attributed to cycle-to-cycle difference as both cycles, when testing with R99, had higher starting ATS temperatures compared to ULSD.

   Therefore, from OBD perspective no significant impact is expected on monitor robustness for Vehicle D when running with R99 fuel.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 2.11. A trend of lower engine-out NO_x emissions was observed over the test cycles (up to 15 ppm lower). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. Lower engine-out NO_x emissions have been reported in some studies with R99 fuel [21]. The paraffinic nature of R99 fuel with lower aromatics could help to lower engine-out NO_x emissions by lowering local combustion temperatures [30].

   Lower tailpipe NO_x emissions trend was observed using cumulative bench tailpipe NO_x emissions (g) with R99 compared to ULSD (18-34% lower) on FTP75 cycle. This can be explained by the overall lower engine-out NO_x emissions which would reduce tailpipe NO_x emissions since ATS temperatures are comparable. However, on a ppm basis < 3 ppm difference was observed on average compared to ULSD.

   From an OBD monitor perspective these differences could be well within sensor accuracy limits and may not be considered large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly higher SCR efficiency is expected due to lower engine-out NO_x emissions with R99, which could affect NO_x emissions OBD limits used to determine monitor decisions.

4. Soot Emissions (Figure 2.11): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to higher cetane number of R99 fuel improving combustion efficiency by reducing ignition delay. Also, renewable diesel fuel is a paraffinic fuel with shorter molecular chain and higher H/C ratio, with almost zero aromatic, sulfur, and other mineral impurities content which reduces the propensity for soot formation. Overall, up to 30-40% lower soot emissions were observed when running Vehicle D with R99 compared to ULSD.

   From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

Overall, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of R99 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle D using R99 fuel compared to ULSD fuel have been shown in Figure 2.12. In general, ATS temperatures with R99 fuel were seen to be comparable to ULSD fuel.

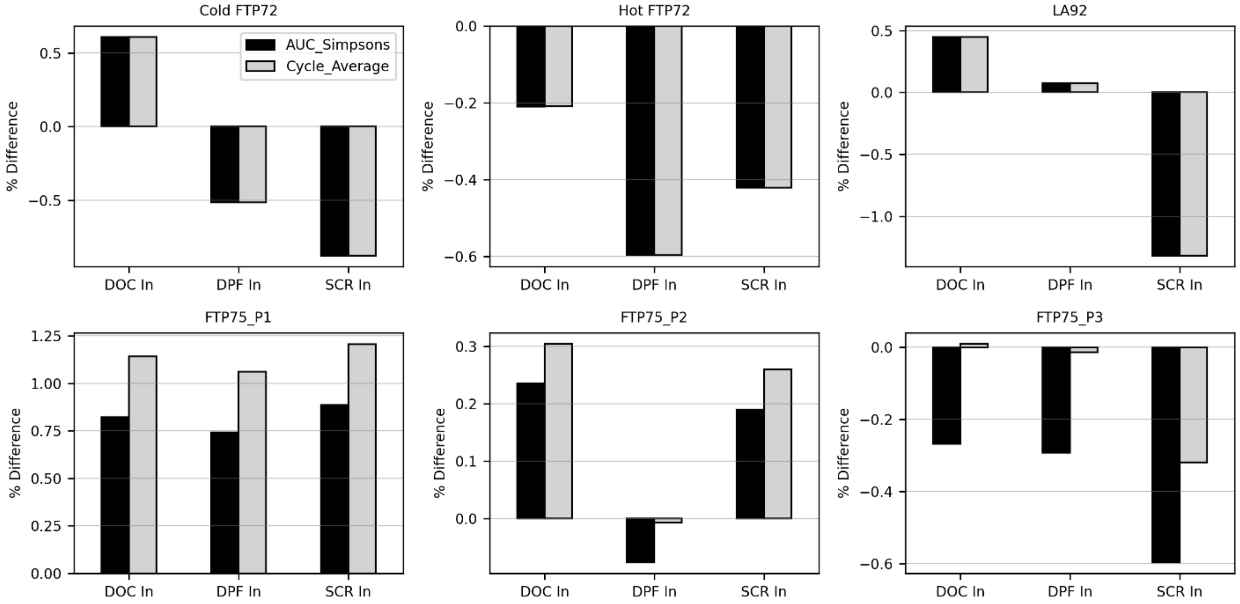

Figure 2.12: Vehicle D: R99 vs ULSD ATS Temperature Trends

Based on results from Table 2.4 and key observations presented, it can be concluded that there could potentially be little to no impact of R99 fuel on OBD monitor robustness for Vehicle D. Overall, R99 fuel showed some impact on engine-out NO_x and soot emissions that could possibly impact OBD monitor decisions including DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with R99 fuel did not show any OBD fault codes for Vehicle D.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 2.4. However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 2.5: R99 vs ULSD Summary

Based on analysis conducted using data from vehicles running with R99 fuel, the following were the key observations and their possible impact on OBD monitors:

Engine-Out Soot emissions:

A key observation on the vehicles that had engine-out soot emissions measurements (Vehicle C and Vehicle D) was a significant reduction in engine-out soot emissions (~40-60% lower) when running with R99 compared to ULSD. This can be explained by higher cetane number of R99 fuel compared to ULSD improving combustion efficiency. Further the lower aromatic content of R99 fuel also reduces soot formation.

OBD Impact:

Some differences can be expected between true and modeled engine-out soot which is based on ULSD. Therefore, DPF regeneration interval and frequency could be affected due to the lower soot. There could also be some impact on DPF differential pressure measurements (lower due to lower soot). This could impact DPF regeneration frequency monitor and DPF differential pressure sensor monitor robustness.

ATS Temperatures:

Some variation in ATS temperatures were observed when using R99 fuel compared to ULSD. Vehicles A and C showed slightly lower ATS temperatures while Vehicles B and D showed slightly higher ATS temperatures. The temperature differences were seen to be within ± 7°C. However, these temperatures can be well within run-to-run variation considering the differences in engine operating conditions due to the tests being conducted on chassis dynamometer.

OBD Impact:

The observed variation could impact ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values for each vehicle. The lower/higher ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Overall, there may potentially be little to no impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

NO_x Emissions:

Some variation was also observed for engine-out NO_x emissions compared to ULSD. For Vehicles A, B and D, engine-out NO_x emissions were lower (up to 15 ppm), however for Vehicle C, engine-out NO_x emissions were 20 ppm higher. Based on studies conducted [3,9,21], trends for engine-out NO_x emissions with R99 fuel have been unclear. However, the large variation in engine-out NO_x emissions can possibly be attributed to differences in engine calibration between vehicles. Since R99 fuel has higher cetane number, the combustion (CA50) will shift to more advanced timing which can increase NO_x emissions. Tailpipe NO_x emissions on average (ppm basis) were well within run-to-run variation (± 3 ppm). However, cumulative tailpipe NO_x emissions (g) on FTP75 measured using the bench showed lower tailpipe NO_x emissions for all vehicles with R99.

OBD Impact:

The variations in NO_x sensor values (ppm basis) observed could be large enough to affect NO_x sensor rationality monitor decisions. Some impact could be expected on the OBD thresholds for NO_x emissions used to determine SCR efficiency monitor decisions, since total tailpipe NO_x emissions over the cycle (for R99) measured by bench (g) were lower than ULSD for all the vehicles.

Fuel Consumption:

Fuel consumption variation was within ± 5% compared to ULSD. Some impact on fuel consumption is expected due to the higher cetane number and net heating value (mass) of R99 fuel compared to ULSD. However, since volume based net heating value is lower due to the lower density of R99, the overall trend in fuel consumption is unclear.

OBD Impact:

From OBD perspective, the average variation in engine fuel rate (g/s) was within ± 0.1 g/s. Therefore, no significant impact is expected on fuel flow OBD monitor decisions.

Other PID Labels:

Some differences in boost pressure (± 2kPa), rail pressure (± 2%), air flow (± 4%), EGR and VGT positions (± 3%) were observed, however these differences were well-within acceptable limits and run-to-run variation. Since the vehicles were tested using chassis dynamometer cycles, the engine operating conditions (engine speed and fueling) are not consistent between test runs due to driver-to-driver variation in running the same cycle. This results in different setpoints for air flow, EGR and VGT position during transient operation and therefore causes variations in the selected PID labels. The observed variations were therefore found to be well within this expected variation in engine operation.

Conclusion Summary for R99:

Based on data analysis conducted on chassis dynamometer data from all four vehicles on FTP75, FTP72 and LA92 cycles, it was concluded that R99 fuel showed little to no impact on the selected PID labels and therefore on OBD monitor robustness. This was further evidenced by the absence of OBD fault codes while running using R99 fuel on all vehicles.

Chapter 3 : Fuel II: R50U50 Blend

This chapter describes the results and conclusions of the chassis dynamometer testing conducted on all four vehicles using R50U50 fuel utilizing the analysis approaches and metrics described in Section 1.6. The results have been divided into Sections 3.1, 3.2, 3.3 and 3.4 for Vehicles A, B, C and D respectively. Each section has the following that summarizes the results for R50U50 fuel compared to ULSD for each vehicle.

1. A table summarizing the results of the vehicle running on R50U50 compared to ULSD for all the test cycles. Key differences observed in engine performance and emissions when using R50U50 fuel compared to ULSD fuel using the "averaged" R50U50 and ULSD cycles for cold and hot FTP72 cycle, hot LA92 cycle and each phase of the FTP75 cycle are highlighted in these tables.
2. Plots showing average ATS temperatures, fuel energy, total engine-out and tailpipe NO_x emissions, engine-out soot emissions (when available) and cycle fuel consumption differences for the vehicle when using R50U50 fuel blend compared to ULSD. The values in the plots have been normalized using min-max normalization, where minimum value = 0 and maximum value was the maximum value in the plot. This was done to present important trends in engine performance while preserving anonymity of emissions and fuel consumption values.
3. Trend plots (% difference) showing PID labels for which significant increasing or decreasing trends were observed when running with R50U50 fuel compared to ULSD for that vehicle. Negative percent difference indicates lower and positive indicates higher compared to ULSD.

A summary of key observations and trends analyzed for the vehicles when running with R50U50 blend compared to ULSD and their possible impact on different OBD monitors is presented in Section 3.5

Section 3.1: Vehicle A: R50U50 vs ULSD_2

Table 3.1: Vehicle A Results Summary: R50U50 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	Slightly Higher	No Difference	No Difference	No Difference	Slightly Higher	6-9% Higher
Engine Fuel Rate	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	1 to 3% Higher
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa

DOC Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 6°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Out NO_x Sensor	**ppm**	No Difference	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	No Difference	Up to 7 ppm Higher
Tailpipe NOx Sensor	**ppm**	-	No Difference	N/A	No Difference	N/A	-	± 2 ppm
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Higher	No Difference	No Difference	-	Up to 3 ppm Higher
Upstream O_2 Sensor	**%**	N/A	N/A	N/A	N/A	N/A	N/A	
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
DEF Dosing	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NOx	**g**	Slightly Lower	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	No Difference	2 to 9% Higher
Calculated Tailpipe NOx	**g**	NH_3 Slip	Slightly Lower	N/A	Higher	N/A	Slightly Lower	8% Lower to 40% Higher
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Bench Tailpipe NOx	**g**	-	-	Higher	Higher	Higher	-	9-24% Higher
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	1 to 2% Lower
Total Cycle Fuel Consumption	**g**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	1 to 3% Higher
Engine-Out Soot	**mg**	-	-	-	-	-	-	

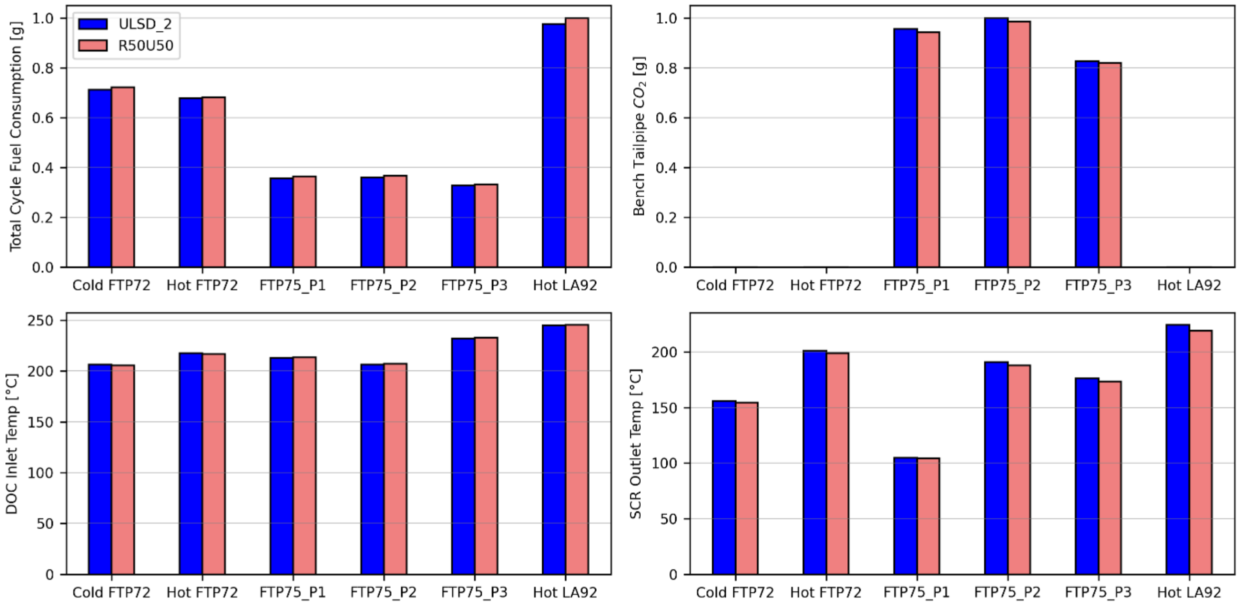

Figure 3.1: Vehicle A: R50U50 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

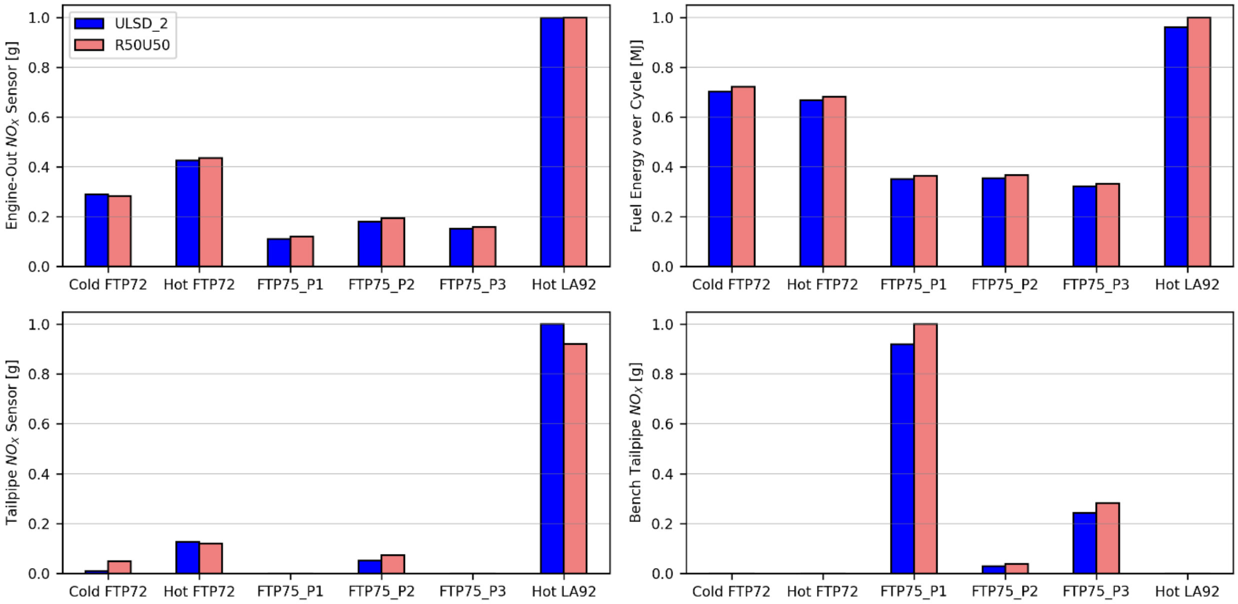

Figure 3.2: Vehicle A: R50U50 vs ULSD_2: Fuel Energy and NO_x Emissions

Key observations from Figure 3.1 and Figure 3.2 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 1-3% higher when running with R50U50 for the test cycles compared to ULSD_2 fuel (Figure 3.1). R50U50 blend has slightly higher net heating value per kg (~2%) compared to ULSD_2 (Table 1.3). However, since R50U50 blend has lower density compared to ULSD_2 (4%), volumetric fuel consumption will be higher (3% lower net heating value based on volume). Therefore, this could explain higher fuel consumption observed.

The fuel energy used over all the cycles with R50U50 blend was slightly higher compared to ULSD_2 (2-4%) (Figure 3.2). This could indicate differences in cycle work compared to ULSD which could also contribute to the observed higher fuel consumption. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were ≤ 0.05 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were 1 to 2% lower compared to ULSD for FTP75 cycle. This could be explained by the 1.5% lower carbon content (% weight) in R50U50 blend compared to ULSD_2.

2. ATS temperatures (Figure 3.1): ATS temperatures were on average ~ 6°C lower when running with R50U50 blend for all the cycles. However, some of the differences can be attributed to run-to-run variation. However, higher cetane number of R99 fuel in the blend, shortening ignition delay and increasing combustion efficiency could lead to the observed lower ATS temperatures.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 3.2. Slightly higher engine-out NO_x emissions were observed for all the cycles (up to 7 ppm higher). However, there could be some differences in sensor activation times due to differences in ATS temperatures, therefore, some differences could be attributed to run-to-run variation. Higher cetane number of R99 fuel in the blend would shorten ignition delay and result in earlier combustion and higher combustion temperatures leading to observed slightly higher engine-out NO_x.

   Tailpipe NO_x sensor measurements showed very small variations (± 2 ppm) which are well within run-to-run variation. However, on cold FTP72 more NH_3 slip was observed with R50U50 fuel (due to differences in sequence of cycles run before cold FTP72 cycle). Differences in cumulative bench tailpipe NO_x emissions (g) with R50U50 were slightly higher (9-24%) on FTP75 due to the slightly higher engine-out NO_x and lower ATS temperatures. However, on a ppm basis < 3 ppm difference was observed on an average compared to ULSD.

   From an OBD monitor perspective these differences can be well within sensor accuracy limits and may not be considered large enough to affect OBD monitor robustness in determining NO$_x$ sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency is expected due to the lower ATS temperatures observed with R50U50 blend, which could affect NO$_x$ emissions OBD limits used to determine monitor decisions.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of R50U50 blend was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle A using R50U50 fuel compared to ULSD_2 fuel have been shown in Figure 3.3. In general, ATS temperatures with R50U50 fuel were seen to be slightly lower as compared to ULSD fuel.

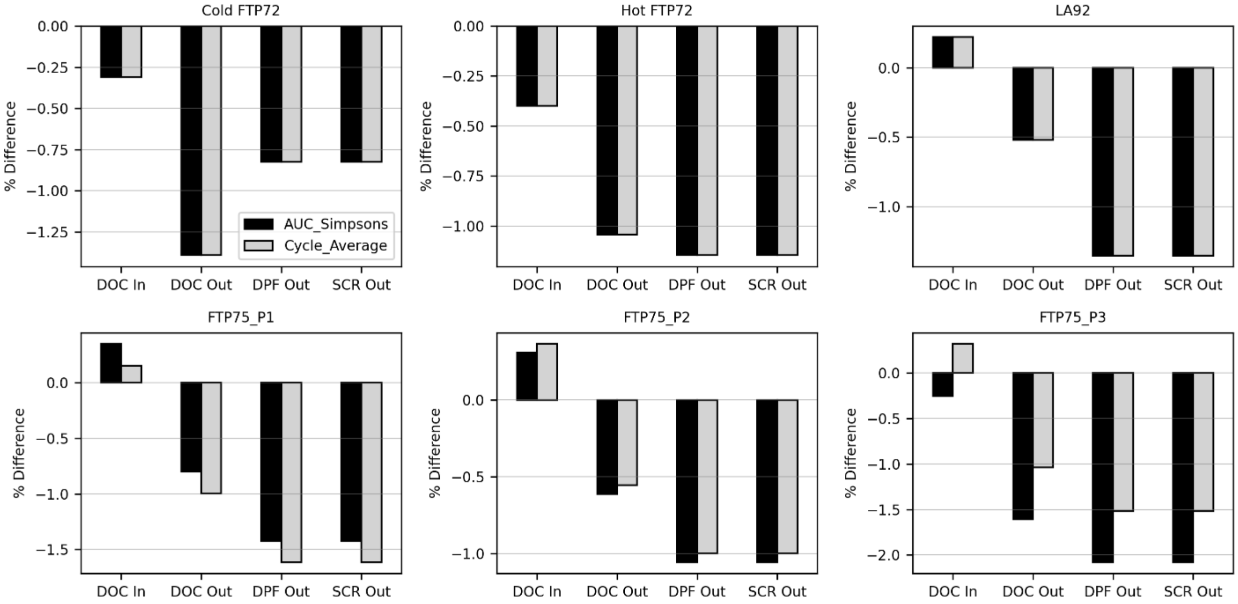

Figure 3.3: Vehicle A: R50U50 vs ULSD_2 ATS Temperature Trends

Based on results from Table 3.1 and key observations presented, it can be concluded that there is little to no impact of R50U50 blend on OBD monitor robustness for Vehicle A. Overall, R50U50 blend showed some impact on ATS temperatures and engine-out NO$_x$ sensor values that could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management mode, DPF regeneration, SCR efficiency and NO$_x$ sensor rationality. However, post-test cycle OBD scans for test cycles tested with R50U50 fuel did not show any OBD fault codes for Vehicle A.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 3.1. For example, boost pressure (± 2 kPa), small differences in VGT position (± 3%) and up to ± 2% differences in fuel rail pressure and air flow. However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness. EGR rate was slightly higher (more closed) for hot FTP72 and LA92 cycles. However, this could possibly be attributed to variations in engine operating conditions between the test cycles.

Section 3.2: Vehicle B: R50U50 vs ULSD_2

Table 3.2: Vehicle B Results Summary: R50U50 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 1%
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	-	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 5°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	-	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	-	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	-	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	**ppm**	Slightly Higher	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Lower	Up to 10 ppm Lower
Tailpipe NO_x Sensor	**ppm**	-	-	-	-	-	-	NH_3 Slip
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Higher	No Difference	No Difference	-	Up to 3 ppm Higher
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 5 mg/s
Calculated Engine-Out NO_x	**g**	Higher	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Lower	10% Higher to 13% Lower
Calculated Tailpipe NO_x	**g**	-	-	-	-	-	-	NH_3 Slip
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Bench Tailpipe NO_x	**g**	-	-	Slightly Higher	Higher	Higher	-	6 to 31% Higher
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	1 to 3% Lower
Total Cycle Fuel Consumption	**g**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 1%
Engine-Out Soot	**mg**	-	-	-	-	-	-	

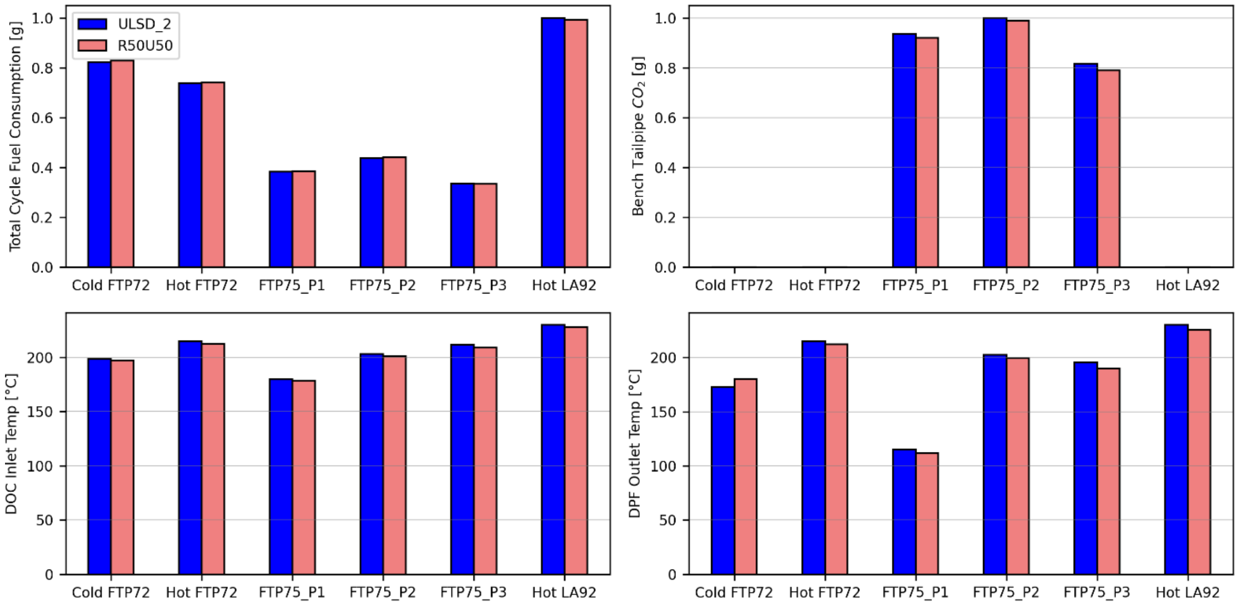

Figure 3.4: Vehicle B: R50U50 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

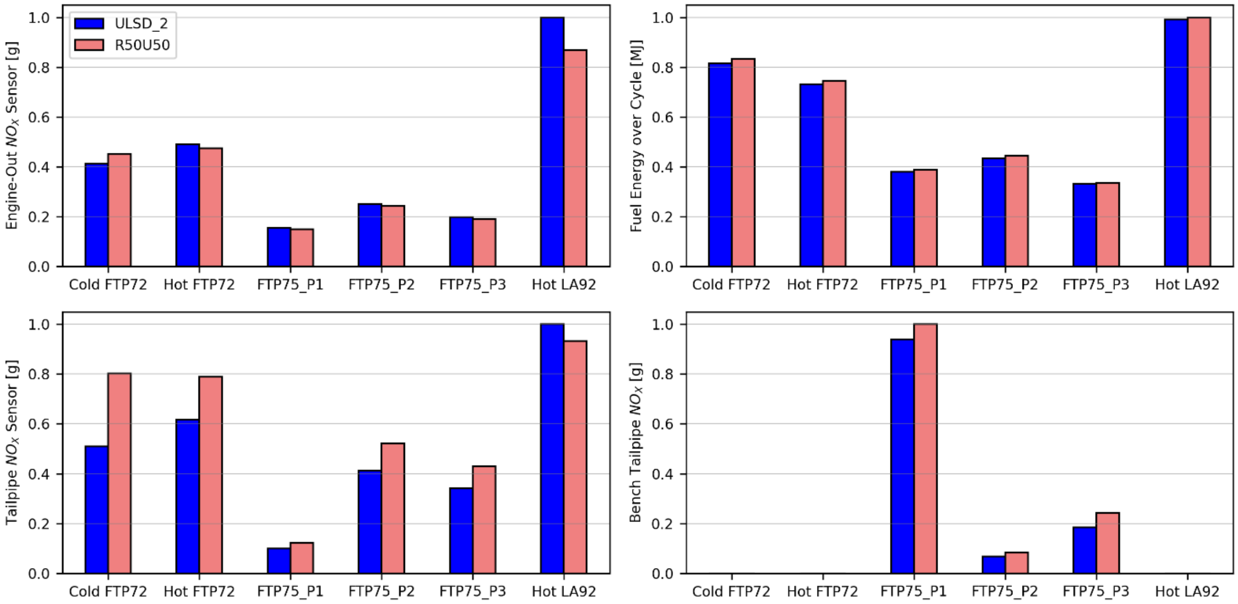

Figure 3.5: Vehicle B: R50U50 vs ULSD_2: Fuel Energy and NO_x Emissions

Key observations from Figure 3.4 and Figure 3.5 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle had very small variation when running with R50U50 fuel compared to ULSD (within ± 1%) (Figure 3.4). R50U50 blend has 2% higher net heating value per kg compared to ULSD (Table 1.3), which could contribute to some reduction in fuel consumption as observed in some cycles. However, this difference (± 1%) is well within run-to-run variation.

   The fuel energy used over all the cycles with R50U50 fuel was slightly higher compared to ULSD (1-2%) (Figure 3.5) which could indicate some differences in cycle work compared to ULSD. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were within ± 0.02 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were ~1-3% lower compared to ULSD for FTP75 cycle. This could be explained by the 1-2% lower carbon content (% weight) of R50U50 blend compared to ULSD.

2. ATS temperatures (Figure 3.4): ATS temperatures when running with R50U50 fuel were slightly lower (up to 5°C). For cold FTP72 cycles, the ATS temperatures were slightly higher (up to 7°C). However, this could be attributed to the cold FTP72 cycle with R50U50 blend entering thermal management mode to raise the ATS temperatures and the higher starting ATS temperature for cold FTP72 with R50U50 blend. However, it is unclear if this can be attributed to the impact of the fuel on ATS temperatures since run-to-run variation can also result in vehicles entering thermal management mode due to differences in ATS temperatures.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 3.5. A trend of slightly lower engine-out NO_x emissions was observed over the test cycles (up to 10 ppm lower). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. Lower engine-out NO_x emissions have been reported in some studies with R99 fuel [21]. The paraffinic nature of R99 fuel (50% of the blend) with lower aromatics could help to lower engine-out NO_x emissions by lowering local combustion temperatures [30]. For cold FTP72 cycle, slightly higher engine-out NO_x emissions were observed. However, this could be attributed to the slightly different engine operation conditions due to the vehicle entering thermal management mode to raise ATS temperatures with R50U50 blend.

   For Vehicle B, trends for tailpipe NO_x sensor emissions were inconclusive. This was primarily because all cycles on Vehicle B always showed some amount of NH_3 slip throughout the cycle which seemed to strongly affect tailpipe NO_x sensor values. This is due to the cross-sensitivity of NO_x sensors to NH_3 which increases tailpipe NO_x sensor measured NO_x values to higher than actual values. The cumulative bench tailpipe NO_x (g) showed higher tailpipe NO_x emissions trend on FTP75 cycle with R50U50 (6-31%).

However, on a ppm basis < 3 ppm difference was observed on the bench for R50U50 blend compared to ULSD. Therefore, overall, no significant impact is expected on tailpipe NO_x sensor measurements.

From an OBD monitor perspective these differences could be well within sensor accuracy limits and may not be considered large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the lower ATS temperatures with R50U50 blend, which could affect NO_x emissions OBD limits used to determine monitor decisions.

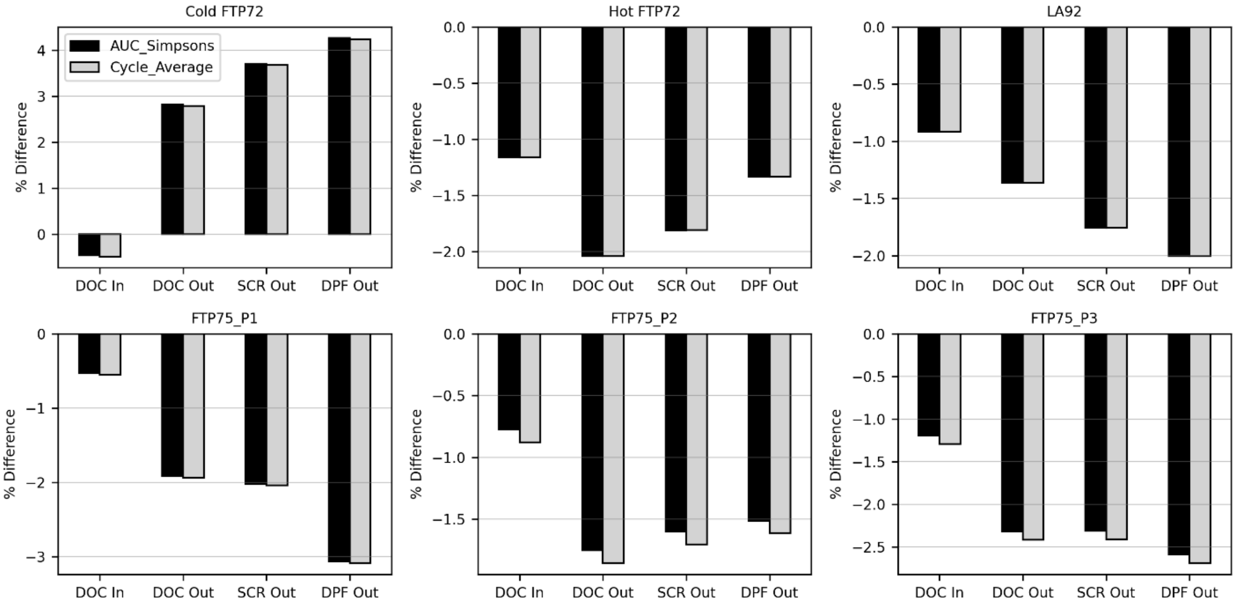

Figure 3.6: Vehicle B: R50U50 vs ULSD_2 ATS Temperature Trends

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of R50U50 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle B using R50U50 blend compared to ULSD fuel have been shown in Figure 3.6. Cold FTP72 cycle showed slightly higher ATS temperatures due to the cycle with R50U50 blend entering thermal management mode as explained before.

Based on results from Table 3.2 and key observations presented, it can be concluded that there could potentially be small impact of R50U50 blend on OBD monitor robustness for Vehicle B. Overall, R50U50 fuel showed some impact on ATS temperatures and engine-out NO_X emissions that could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management mode, DPF regeneration, SCR efficiency and NO_X sensor rationality. However, post-test cycle OBD scans for test cycles tested with R50U50 blend did not show any OBD fault codes for Vehicle B.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 3.2. However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 3.3: Vehicle C: R50U50 vs ULSD_2

Table 3.3: Vehicle C Results Summary: R50U50 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3°C
Coolant Temp	**°C**	-	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	Slightly Lower	Slightly Higher	No Difference	No Difference	No Difference	No Difference	± 5%
Engine Fuel Rate	**g/s**	Slightly Lower	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	1 to 3% Higher
Exhaust Pressure	**kPa**	N/A	N/A	N/A	N/A	N/A	N/A	
DOC Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 6°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	-	No Difference	No Difference	No Difference	No Difference	No Difference	± 5%
Engine Out NO_x Sensor	**ppm**	Slightly Lower	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	No Difference	Up to 24 ppm Higher
Tailpipe NO_x Sensor	**ppm**	No Difference	No Difference	N/A	No Difference	No Difference	Slightly Higher	± 3 ppm
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	-	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NO_x	**g**	Lower	Higher	Slightly Higher	Slightly Higher	Slightly Lower	No Difference	17% Lower to 19% Higher
Calculated Tailpipe NO_x	**g**	Higher	Higher	N/A	Higher	Higher	NH3 Slip	Up to 50% Higher
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Bench Tailpipe NO_x	**g**	-	-	Higher	Higher	No Difference	-	Up to 25% Higher
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	1 to 3% Lower
Total Cycle Fuel Consumption	**g**	Slightly Lower	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	1 to 3% Higher
Engine-Out Soot	**mg**	-	-	Lower	Lower	Lower	-	Up to 33% Lower

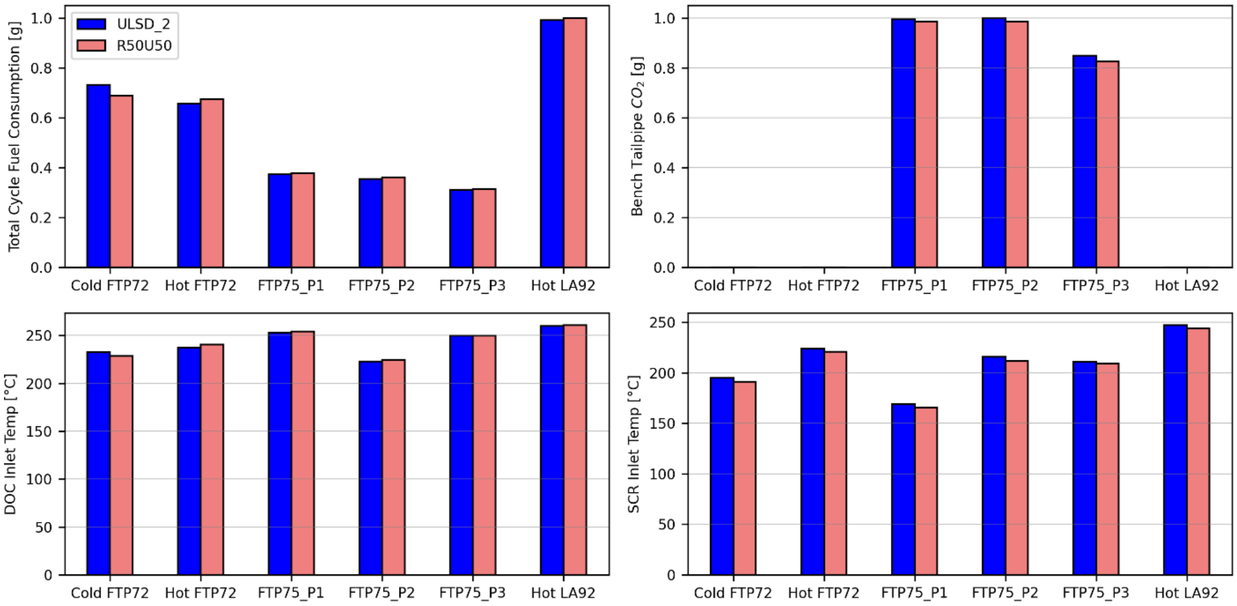

Figure 3.7: Vehicle C: R50U50 vs ULSD_2: Fuel Consumption, CO$_2$ Emissions and ATS Temperatures

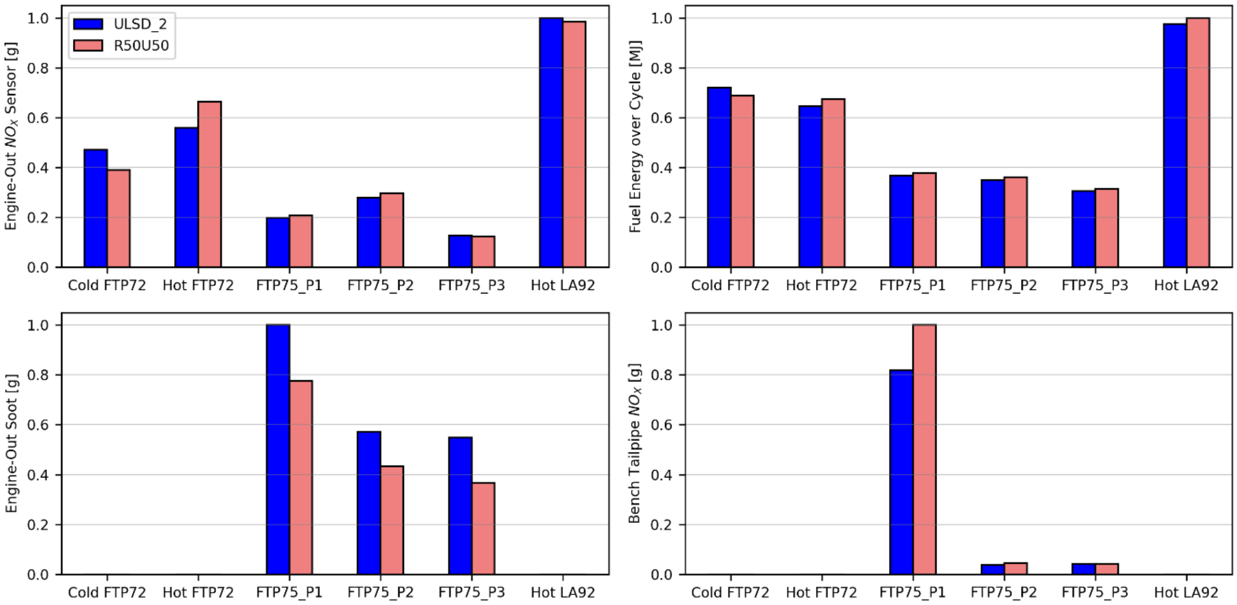

Figure 3.8: Vehicle C: R50U50 vs ULSD_2: Fuel Energy, Soot and NO$_x$ Emissions

Key observations from Figure 3.7 and Figure 3.8 are as follows:

1. Fuel consumption/CO$_2$ Emissions (g): For Cold FTP72 cycle, fuel consumption is lower due to higher starting coolant and ATS temperatures for the run with R50U50 blend. On FTP75 and LA92 cycles the fuel consumption was higher by up to 3% (Figure 3.7). R50U50 blend has slightly higher net heating value per kg (~2%) compared to ULSD (Table 1.3). However, since R50U50 blend has lower density compared to ULSD (4%), volumetric fuel consumption will be higher (3% lower net heating value based on volume) which could result in the observed higher fuel consumption.

The fuel energy used over all the cycles with R50U50 blend had large variation comparable to ULSD (from 4% lower to 6% higher) (Figure 3.8). This variation could indicate differences in cycle work compared to ULSD which would impact fuel consumption. This difference may also be explained by the differences in engine operation due to a feature on Vehicle C, which was not consistent over each cycle. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were within ± 0.04 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were ~3% lower compared to ULSD for FTP75 cycle. This could be explained by the 1.5% lower carbon content (% weight) in R50U50 blend compared to ULSD.

2. ATS temperatures (Figure 3.7): ATS temperatures were on average slightly lower on all the cycles (up to 6°C). However, this variation could be well-within run-to-run variation. One important observation was that with R50U50 blend on cold and hot FTP 72 cycle as well as phase 2 of FTP75 cycle, engine entered a different operating mode (possibly thermal management) to raise ATS temperatures which was not seen with ULSD fuel. However, this may or may not be due to impact of the fuel and could also be attributed to temperature differences normally seen between runs.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there can be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 3.8. A trend of higher engine-out NO_x emissions was observed over the test cycles (up to 24 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some difference could be attributed to run-to-run variation. Trends in engine-out NO_x emissions have been unclear in studies with R99 fuel [3,9,21]. Since R99 fuel in the blend has a higher cetane number, combustion (CA50) may be more advanced which could have resulted in the observed higher engine-out NO_x emissions.

   Tailpipe NO_x sensor values were seen to be very similar to ULSD. However, based on cumulative bench values, higher tailpipe NO_x emissions (g) were observed on FTP75 cycle with R50U50 blend (up to 25% higher). As phase 1 and phase 2 are relatively colder ATS temperatures, the higher tailpipe NO_x emissions could be primarily due to the higher engine-out NO_x emissions. Once the SCR temperature gets hot enough (Phase 3), the

SCR efficiency could be high enough to not show increased tailpipe NO_x emissions. On a ppm basis however, this difference was < 2 ppm difference on average compared to ULSD.

From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the lower ATS temperatures and higher engine-out NO_x emissions with R50U50 blend, which could affect NO_x emissions OBD limits used to determine monitor decisions.

4. Soot Emissions (Figure 3.8): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to higher cetane number of R99 fuel in the blend improving combustion efficiency by reducing ignition delay. Also, R50U50 blend has lower aromatics compared to ULSD which reduces the propensity for soot formation. Overall, up to 33% lower soot emissions were observed when running Vehicle C with R50U50 blend compared to ULSD.

   From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

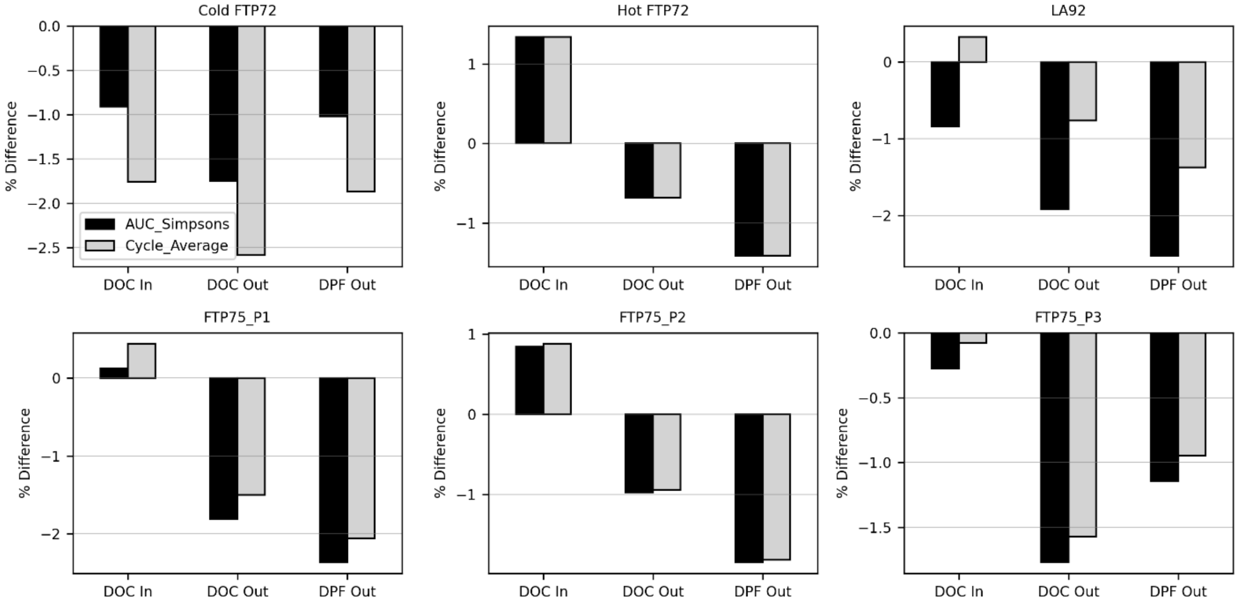

Figure 3.9: Vehicle C: R50U50 vs ULSD_2 ATS Temperature Trends

Based on results from Table 3.3 and key observations presented, it can be concluded that there could potentially be some impact of R50U50 blend on OBD monitor robustness for Vehicle C. Overall, R50U50 blend showed some impact on ATS temperatures, engine-out NO_x and soot emissions which could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management, DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with R50U50 blend did not show any

OBD fault codes for Vehicle C.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 3.3. However, Vehicle C also showed run-to-run differences due to a feature which was not consistent over the test cycles for the fuels tested. Overall, the observed variations were not considered to be significant enough to impact OBD robustness.

Section 3.4: Vehicle D: R50U50 vs ULSD_2

Table 3.4: Vehicle D Results Summary: R50U50 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	g/s	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Intake Manifold Temp	°C	N/A	N/A	N/A	N/A	N/A	N/A	
Coolant Temp	°C	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	%	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	g/s	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 3% Lower
Exhaust Pressure	kPa	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3 kPa
DOC Inlet Temp	°C	No Difference	No Difference	No Difference	No Difference	No Difference	Slightly Lower	Up to 3°C Lower
DOC Outlet/DPF Inlet Temp	°C	No Difference	No Difference	No Difference	No Difference	No Difference	Slightly Lower	
DPF Outlet/SCR Inlet Temp	°C	No Difference	No Difference	No Difference	No Difference	No Difference	Slightly Lower	
SCR Outlet Temp	°C	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	°	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	kPa	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	-	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Out NO_x Sensor	ppm	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 12 ppm Lower
Tailpipe NO_x Sensor	ppm	N/A	N/A	N/A	N/A	N/A	N/A	
Bench Tailpipe NOx Conc	ppm	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	%	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	kPa	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
VGT Position	%	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	mg/s	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Engine-Out NO_x	g	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 8% Lower

Calculated Tailpipe NO_x	**g**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Bench Tailpipe NO_x	**g**	-	-	Slightly Lower	Lower	Lower	-	18 to 37% Lower
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	4-6% Lower
Total Cycle Fuel Consumption	**g**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	2-3% Lower
Engine-Out Soot	**mg**	-	-	No Difference	Slightly Lower	Slightly Lower	-	Up to 15% Lower

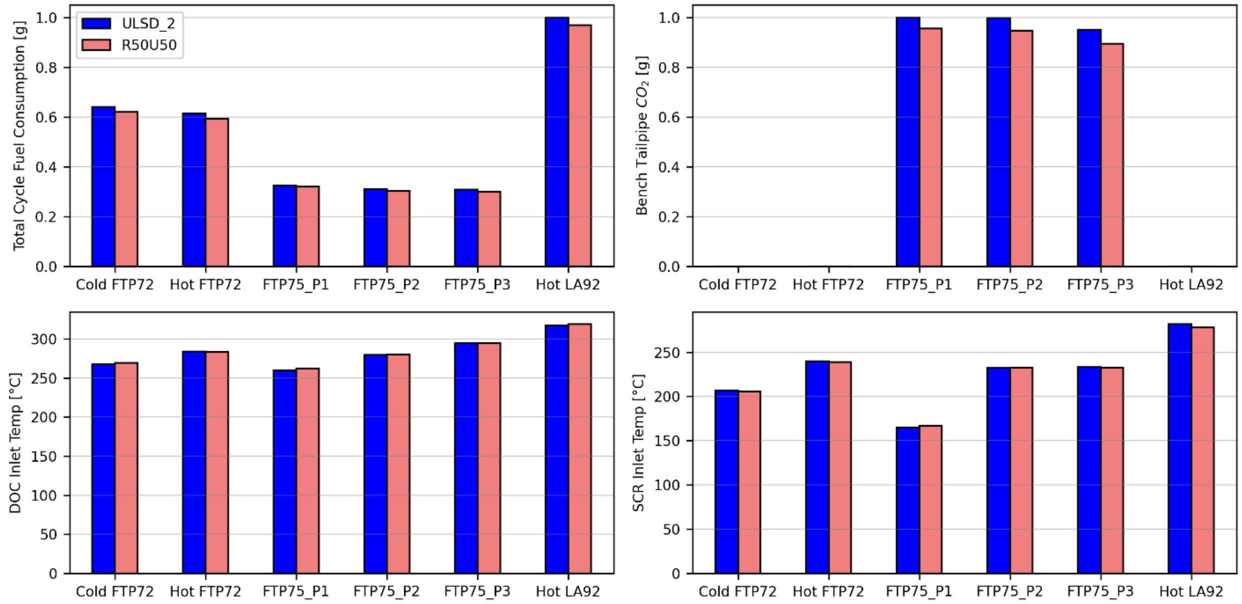

Figure 3.10: Vehicle D: R50U50 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

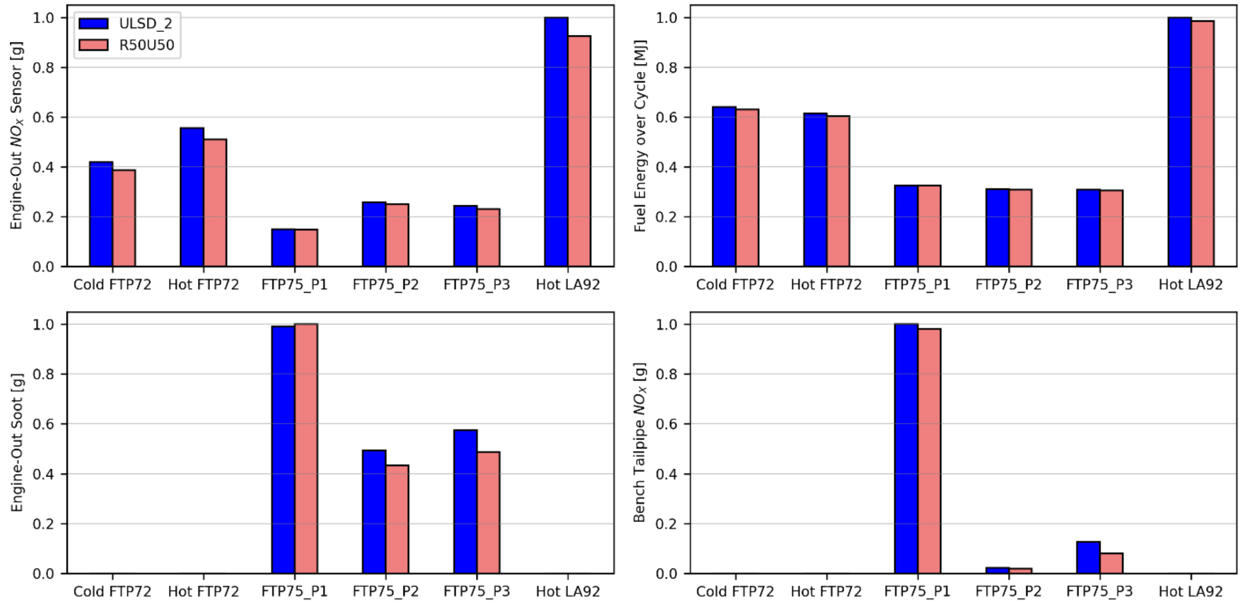

Figure 3.11: Vehicle D: R50U50 vs ULSD_2: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure 3.10 and Figure 3.11 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 3% lower when running with R50U50 for all cycles (Figure 3.10). R50U50 fuel has slightly higher net heating value per kg (~2%) compared to ULSD_2 (Table 1.3) which could explain the lower fuel consumption observed over all test cycles.

   The fuel energy used over all the cycles with R50U50 blend was slightly lower compared to ULSD_2 (1-2%) (Figure 3.11). From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were ≤ 0.05 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

   CO_2 emissions were slightly lower (4-6%) compared to ULSD_2 for FTP75 cycle which can be explained by the lower fuel consumption and 1.5% lower carbon content of R50U50 blend.

2. ATS temperatures (Figure 3.10): ATS temperatures were on average slightly lower on LA92 cycle (up to 3°C). On FTP72 and FTP75 cycles, ATS temperatures were comparable. However, this observed temperature difference could be well within run-to-run variation.

   Therefore, from OBD perspective, no impact is expected on OBD monitor robustness when using R50U50 fuel for Vehicle D.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 3.11. A trend of lower engine-out NO_x emissions was observed over the test cycles (up to 12 ppm lower). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. Lower engine-out NO_x emissions have been reported in some studies with R99 fuel [21] which could explain the observed trends. The paraffinic nature of R99 fuel (50% of the blend) with lower aromatics could help to lower engine-out NO_x emissions by lowering local combustion temperatures [30]. Further, fuel energy used, and fuel consumption was lower, which could also have contributed to lower engine-out NO_x emissions.

   Cumulative bench tailpipe NO_x emissions (g) on FTP75 cycle with R50U50 were lower (up to 37%). However, on a ppm basis < 2 ppm difference was observed on an average compared to ULSD_2. Lower tailpipe NO_x emissions can be explained by the overall lower engine-out NO_x emissions which would reduce overall tailpipe NO_x emissions since ATS temperatures are comparable to those observed with ULSD_2.

   From an OBD monitor perspective these differences can be well within sensor accuracy limits and may not be considered large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly higher SCR efficiency is expected due to similar ATS temperatures and lower engine-out NO_x emissions observed with R50U50 blend, which could affect NO_x emissions OBD limits used to determine monitor decisions.

4. Soot Emissions (Figure 3.11): Engine-out soot emissions on across Phase 2 and Phase 3 of FTP75 cycle were lower compared to ULSD_2 (~15%). However, Phase 1 soot emissions were seen to be comparable (~1% difference). It is expected that soot emissions are lower with R50U50 blend due to R99 fuel in the blend. This primarily can be attributed to higher cetane number of R99 fuel improving combustion efficiency by reducing ignition delay. Also, R50U50 blend has lower aromatics compared to ULSD which also lowers the propensity for soot formation.

   From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

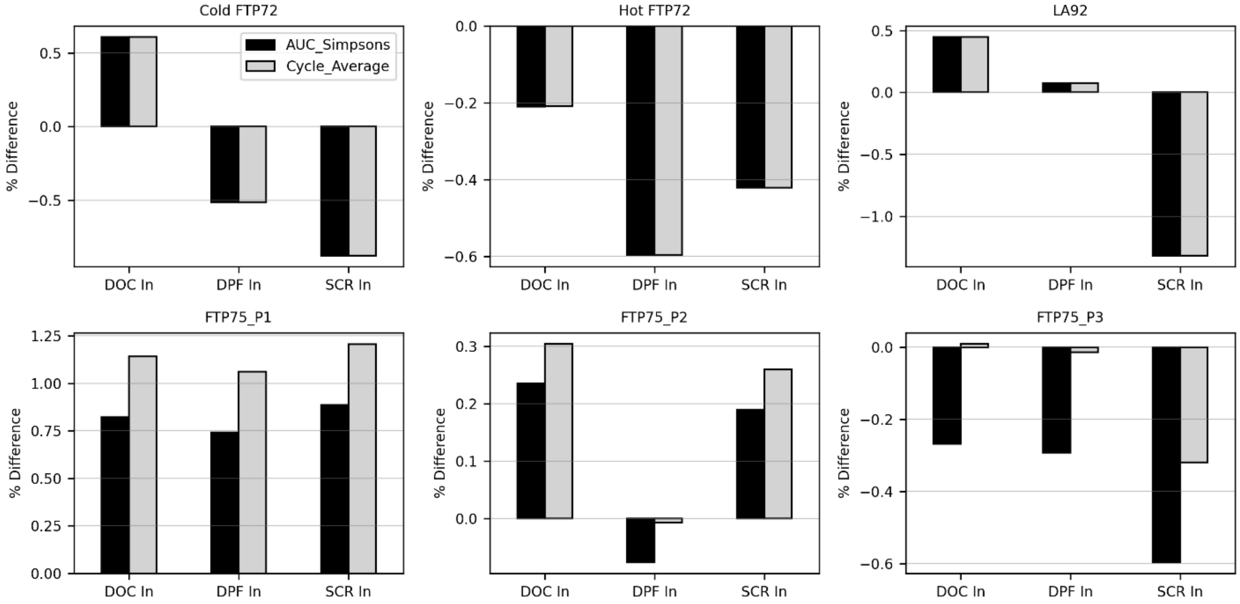

Figure 3.12: Vehicle D: R50U50 vs ULSD_2 ATS Temperature Trends

Overall, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of R50U50 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle D using R50U50 fuel compared to ULSD fuel have been shown in Figure 3.12. In general, ATS temperatures with R50U50 fuel were seen to be slightly lower as compared to ULSD fuel.

Based on results from Table 3.4 and key observations presented, it can be concluded that there is small impact of R50U50 fuel on OBD monitor robustness for Vehicle D. Overall, R50U50 fuel showed some impact on engine-out NO_x and soot emissions that could possibly impact OBD monitor decisions for SCR efficiency, NO_x sensor rationality and DPF regeneration. However, post-test cycle OBD scans for test cycles tested with R50U50 fuel did not show any OBD fault codes for Vehicle D.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 3.4 . However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 3.5: R50U50 vs ULSD_2 Summary

Based on analysis conducted using data from vehicles running with R50U50 blend, the following were the key observations and their possible impact on OBD monitors:

Engine-Out Soot emissions:

A key observation on the vehicles that had engine-out soot emissions measurements (Vehicle C and Vehicle D) was a significant reduction in engine-out soot emissions (~15-33% lower) when running with R50U50 blend compared to ULSD. This can be explained by higher cetane number of R99 fuel in the blend compared to ULSD improving combustion efficiency. Further the lower aromatic content of R50U50 blend also reduces the propensity for soot formation.

OBD Impact:

Some differences can be expected between true and modeled engine-out soot which is based on ULSD. Therefore, DPF regeneration interval and frequency could be affected due to the lower soot. There could also be some impact on DPF differential pressure measurements (lower due to lower soot). This could impact DPF regeneration frequency monitor and DPF differential pressure sensor monitor robustness.

ATS Temperatures:

Some variation in ATS temperatures were observed when using R50U50 blend compared to ULSD. All vehicles showed slightly lower ATS temperatures when running with R50U50 blend compared to ULSD. The temperature differences were seen to be ~6°C. However, these temperatures can be well within run-to-run variation considering the differences in engine operating conditions due to the tests being conducted on chassis dynamometer. The trend of slightly lower temperatures observed could be attributed to higher cetane number of R99 fuel in the blend, shortening ignition delay and increasing combustion efficiency.

OBD Impact:

The observed variation could impact ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values for each vehicle. The lower/higher ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Overall, there may potentially be little to no impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

NO_x Emissions:

Some variation was also observed for engine-out NO_x emissions compared to ULSD. For Vehicles B and D, engine-out NO_x emissions were lower (up to 12 ppm), however for Vehicles A and C, engine-out NO_x emissions were higher (up to 24 ppm). Based on studies conducted [3,9,21], trends for engine-out NO_x emissions with R99 fuel have been unclear. Since R99 fuel (50% of the blend) has higher cetane number, the combustion (CA50) will be more advanced which can increase NO_x emissions. Therefore, impact of the R50U50 blend on NO_x emissions will depend on engine calibration of each vehicle. Tailpipe NO_x emissions on average (ppm basis) were well within run-to-run variation (± 3 ppm). However, cumulative tailpipe NO_x emissions (g) on FTP75 measured using the bench showed lower tailpipe NO_x emissions for Vehicle D while Vehicles A, B and C showed higher tailpipe NO_x emissions with R50U50 blend. This variation can be attributed to differences in engine-out NO_x as well as SCR temperatures affecting SCR efficiency.

OBD Impact:

The variations in NO_x sensor values (ppm basis) observed could be large enough to affect NO_x sensor rationality monitor decisions. Some impact could be expected on the OBD thresholds for NO_x emissions used to determine SCR efficiency monitor decisions, since total tailpipe NO_x emissions over the cycle (for R50U50) measured by bench (g) showed some variation when compared to ULSD.

Fuel Consumption:

Fuel consumption variation was 1-3% higher for Vehicles A and C, 3% lower for Vehicle D and showed < 1% difference for Vehicle B compared to ULSD_2. Some impact on fuel consumption is expected due to the higher cetane number and net heating value (mass) of R50U50 blend compared to ULSD. However, since volume based net heating value is lower (3%) due to the lower density of R50U50 blend (4%), the overall trend in fuel consumption is unclear.

OBD Impact:

From OBD perspective, the average variation in engine fuel rate (g/s) was within ± 0.1 g/s. Therefore, no significant impact is expected on fuel flow OBD monitor decisions.

Other PID Labels:

Some differences in boost pressure (± 2kPa), rail pressure (± 3%), EGR and VGT positions (± 5%) were observed, however these differences were well-within acceptable limits and run-to-run variation. Since the vehicles were tested using chassis dynamometer cycles, the engine operating conditions (engine speed and fueling) are not consistent between test runs due to driver-to-driver variation in running the same cycle. This results in different setpoints for air flow, EGR and VGT position during transient operation and therefore causes variations in the selected PID labels. The observed variations were therefore found to be well within this expected variation in engine operation.

Conclusion Summary for R50U50:

Based on data analysis conducted on chassis dynamometer data from all four vehicles on FTP75, FTP72 and LA92 cycles, it was concluded R50U50 blend showed little to no impact on the selected PID labels. This was further evidenced by the absence of OBD fault codes while running using R50U50 blend on all vehicles.

Chapter 4 : Fuel III: B20R80 Blend

This chapter describes the results and conclusions of the testing conducted on all four vehicles using B20R80 fuel utilizing the analysis approaches and metrics described in Section 1.6. The results have been divided into Sections 4.1, 4.2, 4.3 and 4.4 for Vehicles A, B, C and D respectively. Each section has the following that summarizes the results for B20R80 fuel compared to ULSD for each vehicle.

1. A table summarizing the results of the vehicle running on B20R80 compared to ULSD for all the test cycles. Key differences observed in engine performance and emissions when using B20R80 fuel compared to ULSD fuel using the “averaged” B20R80 and ULSD cycles for cold and hot FTP72 cycle, hot LA92 cycle and each phase of the FTP75 cycle are highlighted in these tables.
2. Plots showing average ATS temperatures, fuel energy, total engine-out and tailpipe NO_x emissions, engine-out soot emissions (when available) and cycle fuel consumption differences for the vehicle when using B20R80 fuel blend compared to ULSD. The values in the plots have been normalized using min-max normalization, where minimum value = 0 and maximum value was the maximum value in the plot. This was done to present important trends in engine performance while preserving anonymity of emissions and fuel consumption values.
3. Trend plots (% difference) showing PID labels for which significant increasing or decreasing trends were observed when running with B20R80 fuel compared to ULSD for that vehicle. Negative percent difference indicates lower and positive indicates higher compared to ULSD.

A summary of key observations and trends analyzed for the vehicles when running with B20R80 fuel compared to ULSD and their possible impact on different OBD monitors is presented in Section 4.5.

Section 4.1: Vehicle A: B20R80 vs ULSD

Table 4.1: Vehicle A Results Summary: B20R80 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	Slightly Higher	No Difference	No Difference	No Difference	No Difference	Slightly Higher	Up to 6% Higher
Engine Fuel Rate	**g/s**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	1 to 3% Lower
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa

DOC Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 11°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	-	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	-	
SCR Outlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	-	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Out NO_x Sensor	**ppm**	Slightly Higher	Slightly Higher	No Difference	Slightly Higher	No Difference	Slightly Higher	Up to 12 ppm higher
Tailpipe NOx Sensor	**ppm**	No Difference	No Difference	N/A	No Difference	N/A	NH_3 Slip	± 2 ppm
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	N/A	N/A	N/A	N/A	N/A	N/A	
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	Slightly Higher	Up to 6% Higher
DEF Dosing	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Calculated Engine-Out NOx	**g**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Lower	Slightly Higher	2 to 6% Higher
Calculated Tailpipe NOx	**g**	Lower	Slightly Higher	N/A	Slightly Higher	N/A	NH_3 Slip	36% Lower to 5% Higher
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Bench Tailpipe NOx	**g**	-	-	Slightly Higher	Higher	Higher	-	Up to 24% Higher
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 7% Lower
Total Cycle Fuel Consumption	**g**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	1 to 3% Lower
Engine-Out Soot	**mg**	-	-	-	-	-	-	

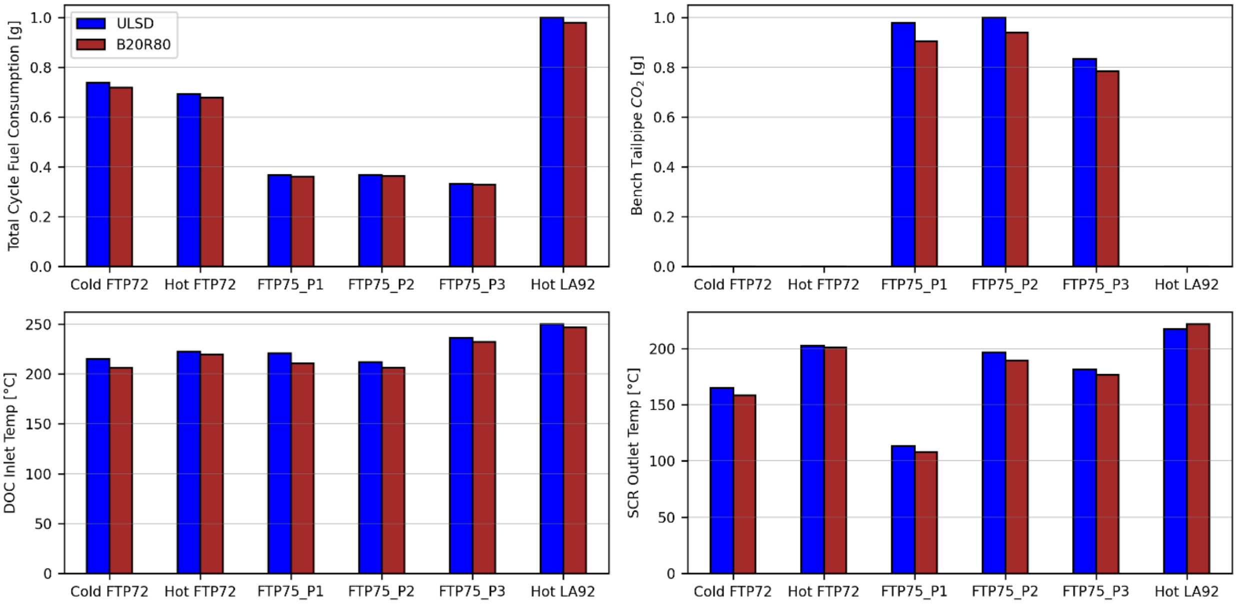

Figure 4.1: Vehicle A: B20R80 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

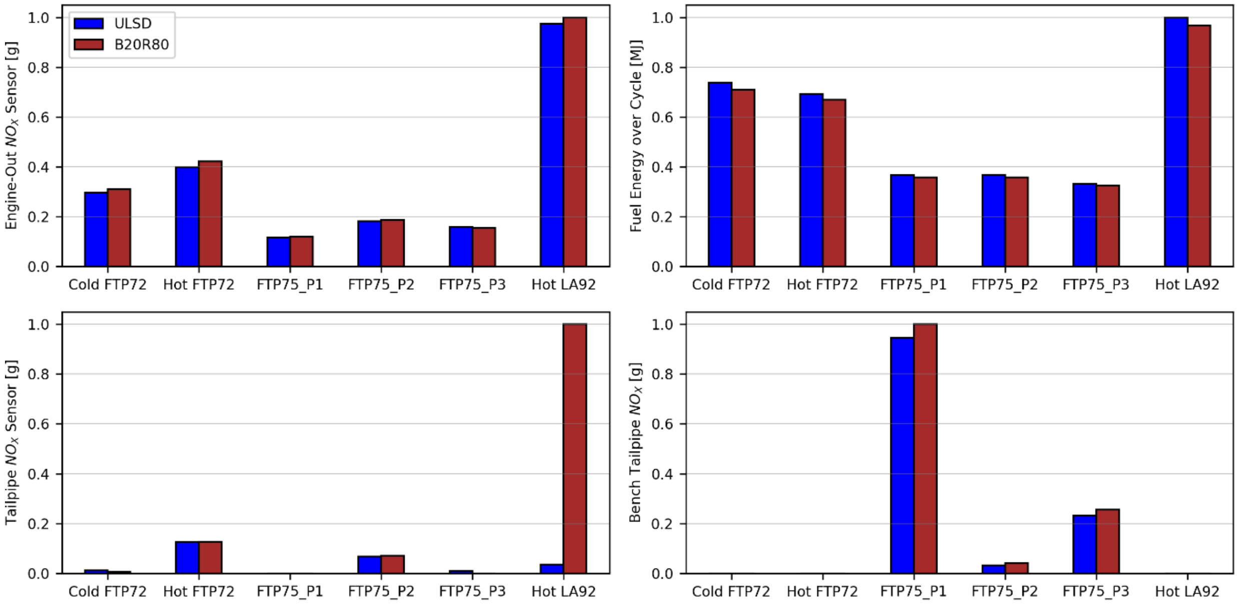

Figure 4.2: Vehicle A: B20R80 vs ULSD: Fuel Energy and NO_x Emissions

Key observations from Figure 4.1 and Figure 4.2 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 1 to 3% lower when running with B20R80 for the test cycles (Figure 4.1). B20R80 fuel has slightly lower net heating value per kg (~1%) compared to ULSD (Table 1.3), however the higher oxygen content of the fuel (due to biodiesel) and higher cetane number (due to R99 fuel) could improve combustion efficiency and lower fuel consumption.

The fuel energy used over all the cycles with B20R80 fuel was slightly lower compared to ULSD (3-4%) (Figure 4.2). Therefore, this could indicate differences in cycle work compared to ULSD which could also contribute to the observed lower fuel consumption. From an OBD perspective, differences in average engine fuel rate (g/s) were ≤ 0.04 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were about 7% lower compared to ULSD for FTP75 cycle. This could be explained by the 4% lower carbon content (% weight) in B20R80 blend compared to ULSD as well as the 1-3% lower fuel consumption seen in Figure 4.1.

2. ATS temperatures (Figure 4.1): ATS temperatures were on average ~11°C lower when running with B20R80 blend for FTP75 and FTP72 cycles. For LA92 cycles, the ATS temperatures were slightly higher (~5°C). However, this higher temperature could be attributed to cycle-to-cycle difference (LA92 cycles with B20R80 had higher starting ATS temperatures). The lower temperature could be attributed to higher combustion efficiency due to higher cetane number but could also be caused by the lower net heating value of B20R80 blend compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 4.2. Slightly higher engine-out NO_x emissions were observed in general for all the cycles (up to 12 ppm higher). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore, some differences could be attributed to run-to-run variation. Higher engine-out NO_x emissions can be attributed to the biodiesel fuel in the blend which increases O_2 concentration in the fuel.

   Tailpipe NO_x emissions showed very small variations (± 1 ppm) which are well within run-to-run variation. However, on LA92 cycle more NH_3 slip was observed with B20R80 fuel (due to differences in sequence of cycles run before LA92 cycle). Therefore, tailpipe NO_x emissions are higher on this cycle due to NH_3 to NO_x cross sensitivity of NO_x sensors. Higher cumulative bench tailpipe NO_x emissions (g) with B20R80 were observed (6-24%) on FTP75 cycle primarily due to slightly higher engine-out NO_x and lower ATS temperatures reducing SCR efficiency. However, on a ppm basis < 2 ppm difference was observed on an average compared to ULSD.

From an OBD monitor perspective these differences can be well within sensor accuracy limits and may not be considered large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency is observed due to slightly higher engine-out NO_x emissions and lower ATS temperatures with B20R80, which could affect NO_x emissions OBD limits used to determine monitor decisions.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B20R80 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle A using B20R80 fuel compared to ULSD fuel have been shown in Figure 4.3. The higher ATS trends observed for LA92 cycle with B20R80 are due to starting ATS temperatures being higher for B20R80 fuel compared to ULSD. However, in general ATS temperatures with B20R80 fuel were seen to be slightly lower as compared to ULSD fuel.

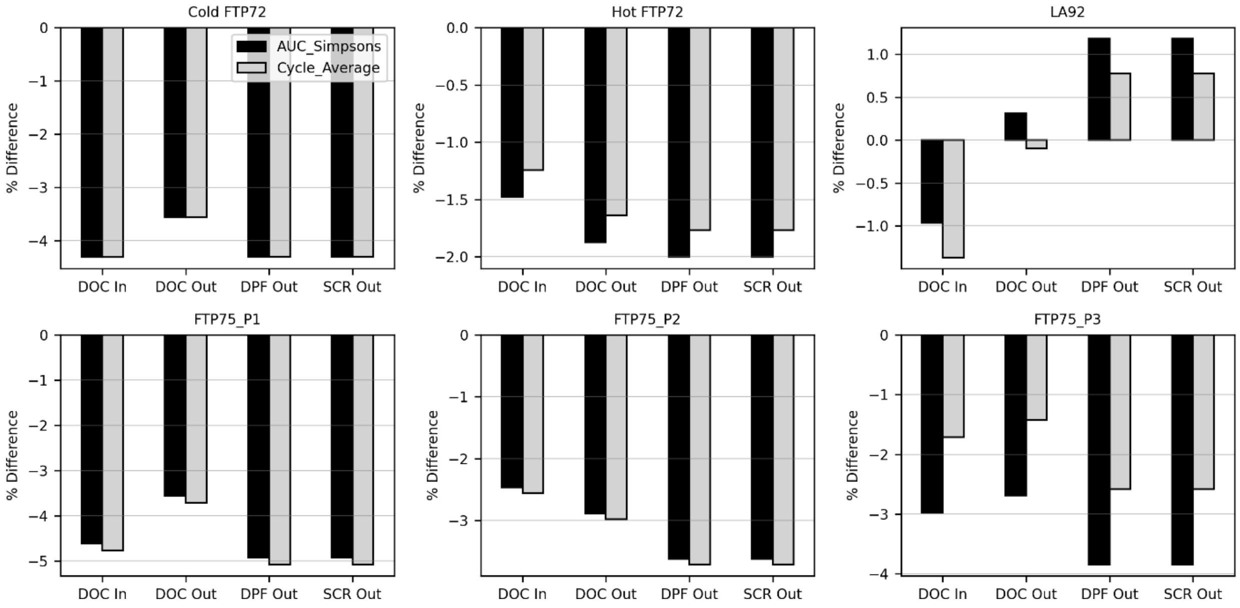

Figure 4.3: Vehicle A: B20R80 vs ULSD ATS Temperature Trends

Based on results from Table 4.1 and key observations presented, it can be concluded that there could potentially be some impact of B20R80 fuel on OBD monitor robustness for Vehicle A. Overall, B20R80 fuel showed some impact on ATS temperature as well as engine-out NO_x sensor values that could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management mode, DPF regeneration as well as NO_x sensor rationality and SCR efficiency monitors.

Other than the key observations presented, some variation was observed in all other PID labels as well - for example, ± 2 kPa difference in boost pressure, small differences in EGR and VGT position (± 2%) and up to ± 2% differences in fuel rail pressure and air flow. Slightly more closed EGR and more open VGT positions on average were observed for hot LA92 cycles with B20R80 blend. However, large differences were only observed when engine was idling. Overall, these were well within run-to-run variation and were not considered to be significant enough to impact

OBD robustness. Also, post-test cycle OBD scans for test cycles tested with B20R80 fuel did not show any OBD fault codes for Vehicle A.

Section 4.2: Vehicle B: B20R80 vs ULSD_2

Table 4.2: Vehicle B Results Summary: B20R80 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	3 to 5% Higher
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
DOC Outlet/DPF Inlet Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
DPF Outlet/SCR Inlet Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
SCR Outlet Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Out NO_x Sensor	**ppm**	Slightly Higher	Slightly Higher	No Difference	No Difference	Slightly Higher	Slightly Higher	Up to 10 ppm Higher
Tailpipe NO_x Sensor	**ppm**	-	-	-	-	-	-	NH_3 Slip
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	Up to 3 ppm Higher
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 3% Higher
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 7 mg/s
Calculated Engine-Out NO_x	**g**	Slightly Higher	Higher	No Difference	Slightly Higher	Slightly Higher	Higher	5 to 14% Higher
Calculated Tailpipe NO_x	**g**	-	-	-	-	-	-	NH_3 Slip
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Bench Tailpipe NO_x	**g**	-	-	Higher	Higher	Higher	-	Up to 2 times Higher

Bench Tailpipe CO_2	**g**	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	1 to 2% Higher
Total Cycle Fuel Consumption	**g**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	3 to 5% Higher
Engine-Out Soot	**mg**	-	-	-	-	-	-	

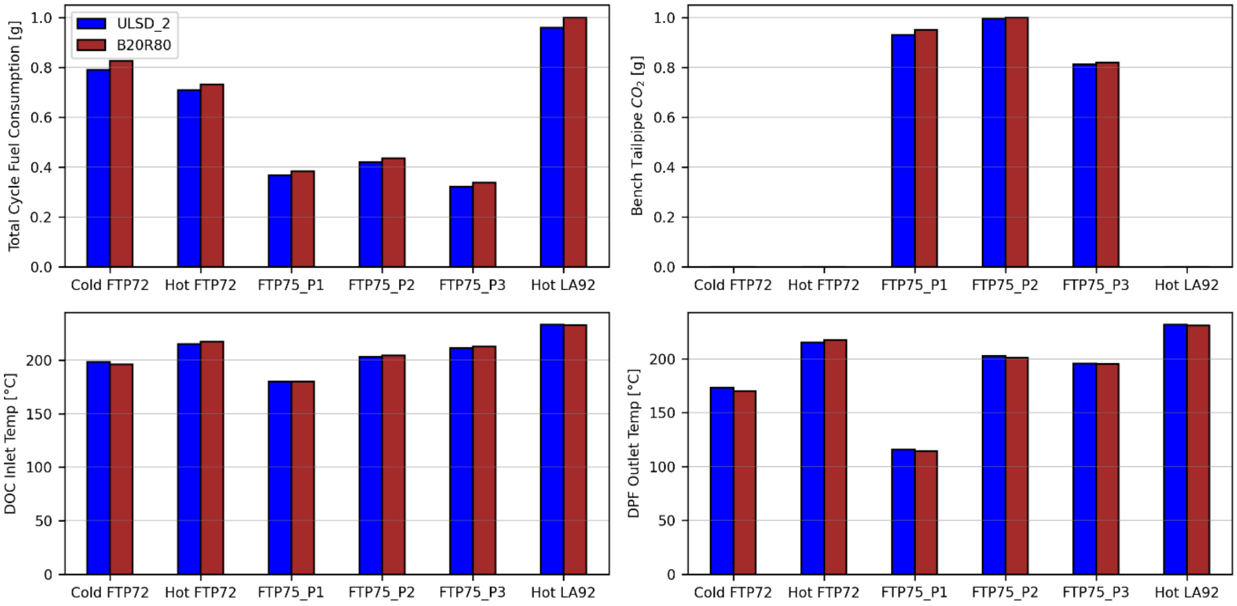

Figure 4.4: Vehicle B: B20R80 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

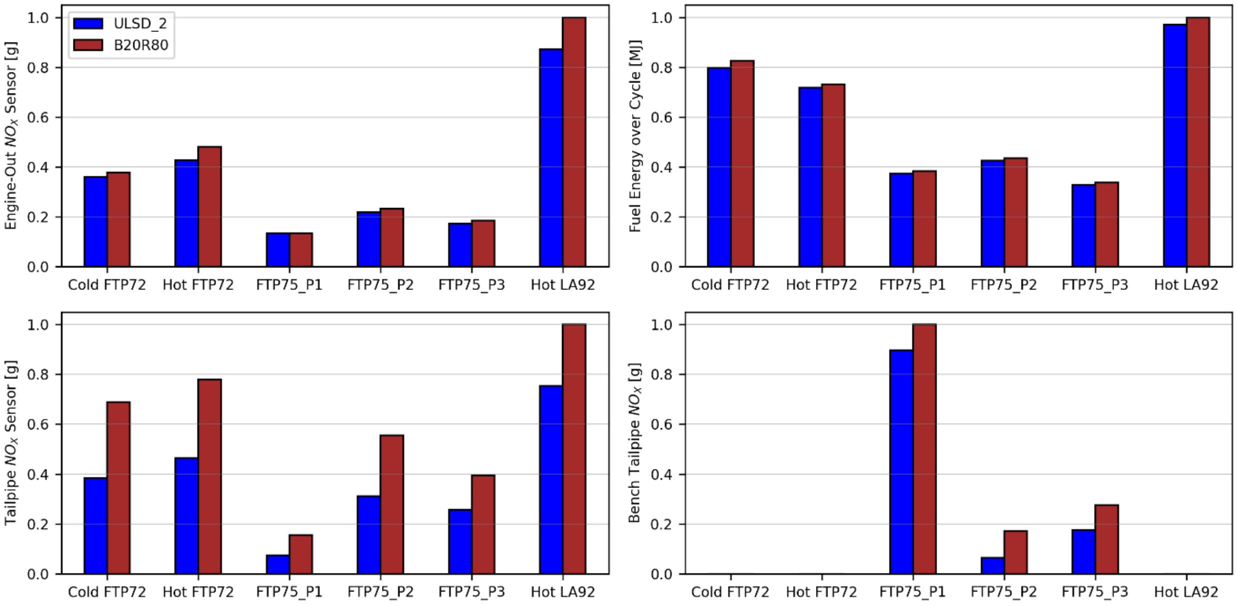

Figure 4.5: Vehicle B: B20R80 vs ULSD_2: Fuel Energy and NO_x Emissions

Key observations from Figure 3.4 and Figure 3.5 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycles increased by 3-5% when running with B20R80 fuel compared to ULSD (Figure 4.4). B20R80 fuel has

~1% lower net heating value per kg compared to ULSD (Table 1.3), which could contribute to some increase in fuel consumption as observed in some cycles. However, since density of B20R80 blend is 5% lower, volumetric fuel consumption will be higher (6% lower net heating value based on volume) which could result in the observed higher fuel consumption.

The fuel energy used over all the cycles with B20R80 fuel was slightly higher compared to ULSD (2-3%) (Figure 4.5). Therefore, this variation could indicate differences in cycle work compared to ULSD which could also increase overall fuel consumption. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were ≤ 0.07 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were ~1-2% higher compared to ULSD for FTP75 cycle. This could be explained by the 3-5% higher fuel consumption but 4% lower carbon content (% weight) of B20R80 fuel compared to ULSD.

2. ATS temperatures (Figure 4.5): ATS temperatures when running with B20R80 fuel were within ± 2°C compared to ULSD.

   Therefore, from OBD perspective, no impact is expected on OBD monitor robustness when using B20R80 fuel for Vehicle B

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 4.5. A trend of slightly higher engine-out NO_x emissions was observed over the test cycles (up to 10 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some of this difference could be attributed to run-to-run variation. Higher engine-out NO_x emissions can be attributed to the biodiesel fuel in the blend which increases O_2 concentration in the fuel. However, the presence of 80% renewable diesel could help to lower the NO_x emissions as seen for Vehicle B (Section 2.2). Overall, a trend of slightly higher engine-out NO_x emissions was observed for Vehicle B.

   For Vehicle B, trends for tailpipe NO_x sensor emissions were inconclusive. This was primarily because all cycles on Vehicle B always showed some amount of NH_3 slip throughout the cycle which seemed to strongly affect tailpipe NO_x sensor values. This is due to the cross-sensitivity of NO_x sensors to NH_3 which increases tailpipe NO_x sensor measured NO_x values to higher than actual values. The cumulative bench tailpipe NO_x (g) showed up to 2 times higher tailpipe NO_x emissions trend on FTP75 cycle with B20R80. However, on a ppm basis < 3 ppm difference was observed on the bench for B20R80 blend compared to ULSD. Therefore, overall, no significant impact is expected on tailpipe NO_x sensor measurements.

   From an OBD monitor perspective these differences could be well within sensor accuracy limits and may not be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the slightly higher engine-out NO_x emissions with B20R80 blend, which could affect NO_x emissions OBD limits used to determine monitor decisions.

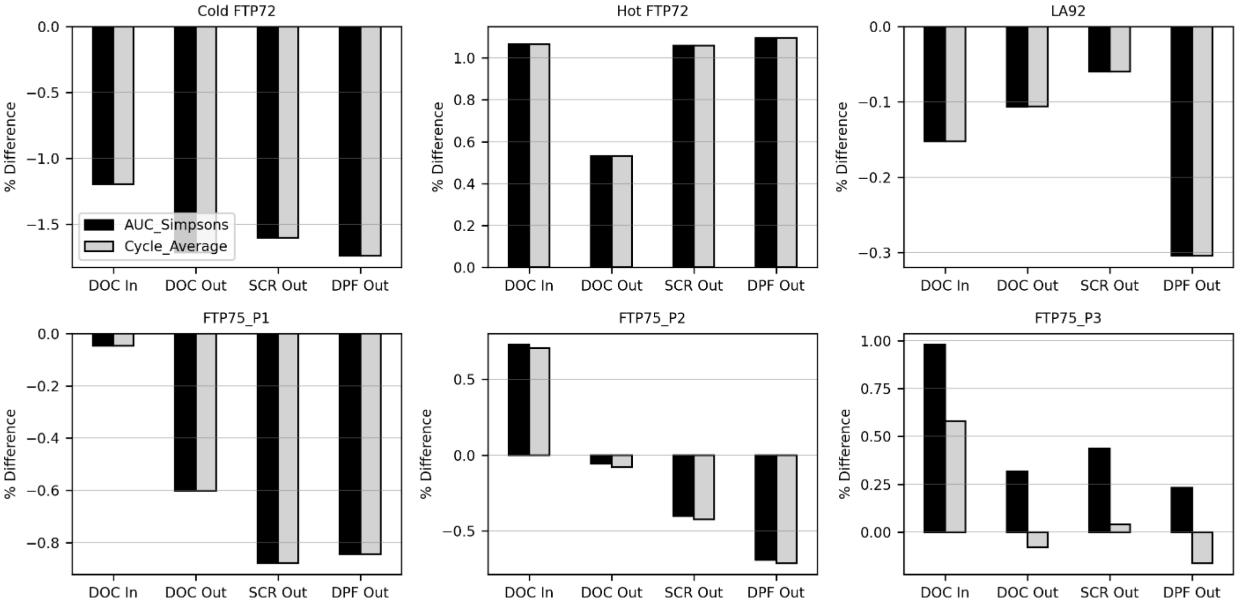

Figure 4.6: Vehicle B: B20R80 vs ULSD_2 ATS Temperature Trends

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B20R80 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle B using B20R80 blend compared to ULSD fuel have been shown in Figure 4.6.

Based on results from Table 4.2 and key observations presented, it can be concluded that there could potentially be small impact of B20R80 fuel on OBD monitor robustness for Vehicle B. Overall, B20R80 fuel showed some impact on engine-out NO_X emissions that could possibly impact OBD monitor decisions including SCR efficiency and NO_X sensor rationality. However, post-test cycle OBD scans for test cycles tested with B20R80 blend did not show any OBD fault codes for Vehicle B.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 4.2. Slightly higher fuel rail pressure was also observed (up to 3%) when Vehicle B was tested with B20R80. Overall, the observed variations were within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 4.3: Vehicle C: B20R80 vs ULSD_2

Table 4.3: Vehicle C Results Summary: B20R80 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	g/s	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Intake Manifold Temp	°C	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3°C
Coolant Temp	°C	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	%	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Engine Fuel Rate	g/s	Slightly Higher	Slightly Higher	Slightly Higher	No Difference	Slightly Higher	Slightly Higher	Up to 4% Higher
Exhaust Pressure	kPa	N/A	N/A	N/A	N/A	N/A	N/A	
DOC Inlet Temp	°C	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 10°C Lower
DOC Outlet/DPF Inlet Temp	°C	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	°C	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	°C	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	°	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	kPa	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	-	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Engine Out NO_x Sensor	ppm	Slightly Higher	Higher	Slightly Higher	Slightly Higher	Slightly Higher	Higher	Up to 23 ppm Higher
Tailpipe NO_x Sensor	ppm	No Difference	No Difference	N/A	No Difference	No Difference	No Difference	± 2 ppm
Bench Tailpipe NOx Conc	ppm	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	%	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Fuel Rail Pressure	kPa	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
VGT Position	%	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	mg/s	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NO_x	g	Slightly Higher	Higher	Slightly Higher	Slightly Higher	No Difference	Higher	4 to 24% Higher
Calculated Tailpipe NO_x	g	Lower	Lower	N/A	Slightly Higher	Higher	Higher	17% Lower to 70% Higher
Calculated Exhaust Flow Rate	kg/h	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Bench Tailpipe NO_x	g	-	-	Higher	Higher	Higher	-	Up to 2 times Higher
Bench Tailpipe CO_2	g	-	-	Lower	Lower	Lower	-	13 to 19% Lower
Total Cycle Fuel Consumption	g	Slightly Higher	Slightly Higher	Slightly Higher	No Difference	Slightly Higher	Slightly Higher	2 to 4% Higher
Engine-Out Soot	mg	-	-	Lower	Lower	Lower	-	55 to 67% Lower

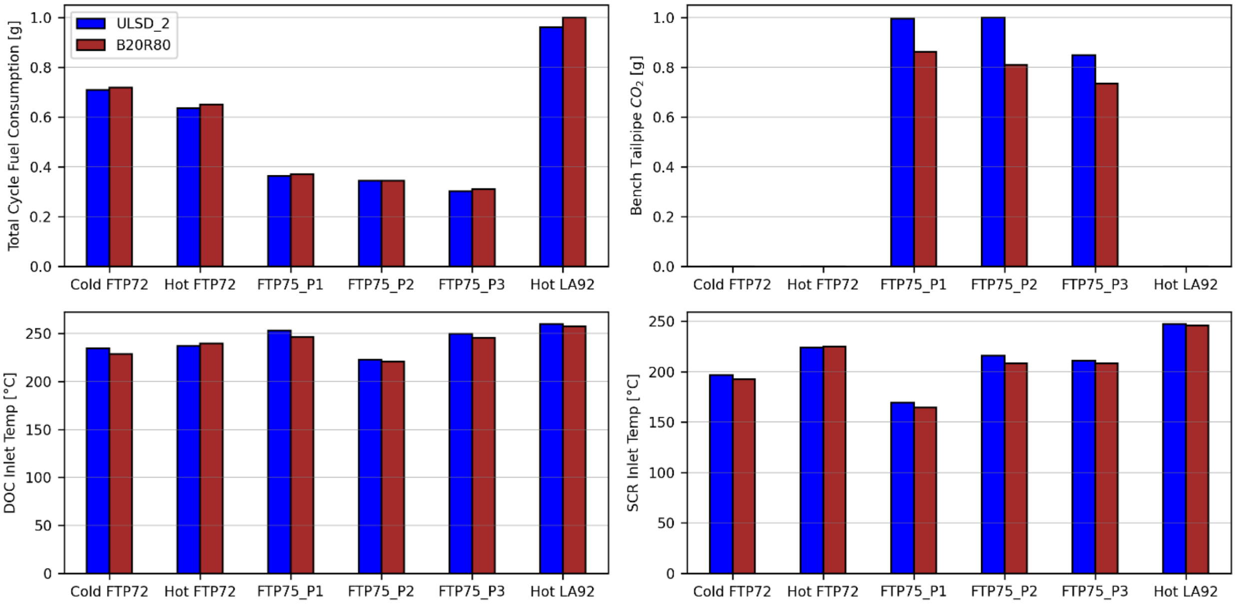

Figure 4.7: Vehicle C: B20R80 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

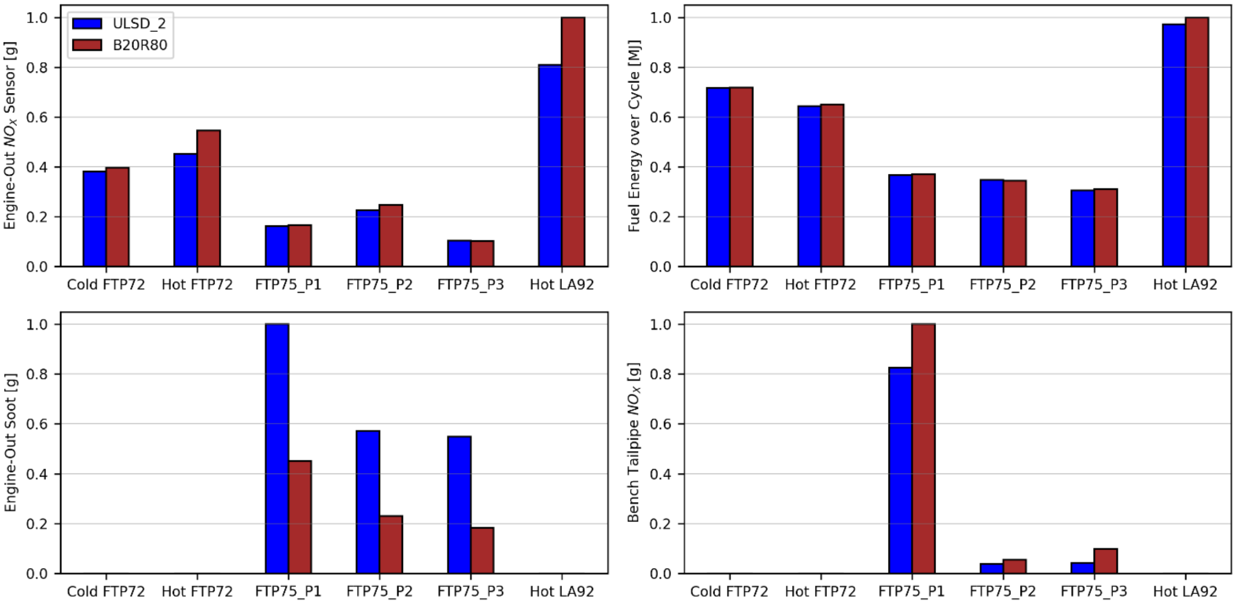

Figure 4.8: Vehicle C: B20R80 vs ULSD_2: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure *4.10* and Figure *4.11* and are as follows:

1. Fuel consumption/CO_2 Emissions (g): For Vehicle C, with B20R80 blend, the fuel consumption was higher by up to 4% (Figure 4.7). B20R80 fuel has slightly lower net heating value per kg (~1%) compared to ULSD (Table 1.3). However, the net heating value based on volume is 6% lower due to the lower density of B20R80 blend (~5%). This could explain higher fuel consumption seen on all the cycles.

The fuel energy used over all the cycles with B20R80 blend showed some variation compared to ULSD (± 2%) (Figure 4.8). Therefore, there could be differences in cycle work compared to ULSD. This difference may also be explained by the differences in cycles due to a feature on Vehicle C, which was not consistent over each cycle which could also increase overall fuel consumption. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were within ≤ 0.04 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were ~13 to 19% lower compared to ULSD for FTP75 cycle. This could be explained by the up to 4% lower carbon content (% weight) in B20R80 blend compared to ULSD.

2. ATS temperatures (Figure 4.10): ATS temperatures were on average slightly lower on all the cycles (up to 10°C). However, some of these differences could be due to run-to-run variation. The lower ATS temperatures may be explained by the 1-2% lower net heating value of B20R80 blend compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 4.11. A trend of higher engine-out NO_x emissions was observed over the test cycles (up to 23 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. Trends in engine-out NO_x emissions have been unclear in studies with R99 fuel [3,9,21]. Since R99 fuel (80% of the blend) has a higher cetane number, combustion (CA50) may be shifted to more advanced timings which could have resulted in the observed higher engine-out NO_x emissions. Further, the blend contains biodiesel which increases the oxygen content of the fuel thereby increasing NO_x emissions.

   Tailpipe NO_x sensor values were seen to be very similar to ULSD. However, based on cumulative bench values (g), up to 2 times higher tailpipe NO_x emissions were observed on FTP75 cycle with B20R80 blend. This could be explained by the higher engine-out NO_x and slightly lower ATS temperatures lowering SCR efficiency. On a ppm basis however, this difference was < 2 ppm difference on average compared to ULSD.

   From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the lower ATS temperatures and higher engine-out NO_x emissions with B20R80 blend, which could affect NO_x emissions OBD limits used to determine monitor decisions.

4. Soot Emissions (Figure 4.11): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to higher cetane number of R99 fuel in the blend improving combustion efficiency by reducing ignition delay. B20R80 blend also has very low aromatics compared to ULSD which lowers the propensity for soot formation. Further, biodiesel fuel in the blend increases oxygen content of the fuel thereby reducing soot production further. Overall, up to 67% lower soot emissions were observed when running Vehicle C with B20R80 blend compared to ULSD.

   From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

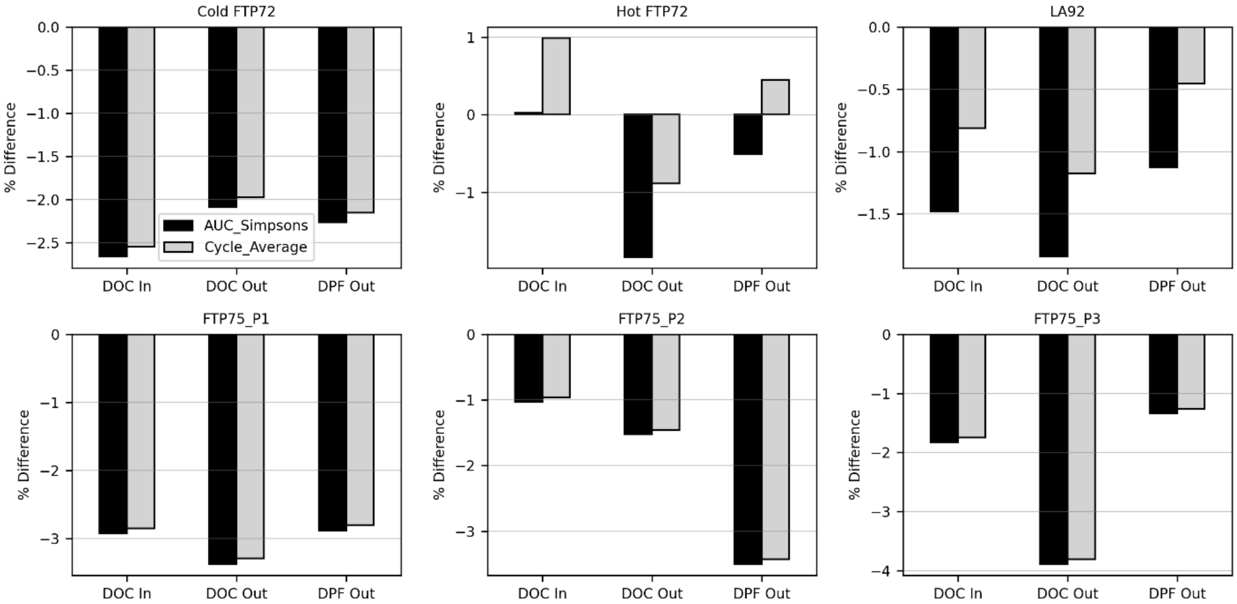

Figure 4.9: Vehicle C: B20R80 vs ULSD_2 ATS Temperature Trends

Based on results from Table 4.3 and key observations presented, it can be concluded that there could potentially be some impact of B20R80 fuel on OBD monitor robustness for Vehicle C. Overall, B20R80 blend showed some impact on ATS temperatures, engine-out NO_x and soot emissions which could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management, DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with B20R80 blend did not show any OBD fault codes for Vehicle C.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 4.3. For example, boost pressure (± 2 kPa) and some differences in fuel rail pressure, air flow, calculated lambda, EGR and VGT positions. However, Vehicle C also had run to run differences due to a feature that was inconsistent over the test cycles with ULSD_2 and B20R80 blend. Therefore, these observed variations were not considered to be significant enough to impact OBD robustness.

Section 4.4: Vehicle D: B20R80 vs ULSD

Table 4.4: Vehicle D Results Summary: B20R80 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Intake Manifold Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	**g/s**	Slightly Lower	Slightly Lower	No Difference	Slightly Lower	No Difference	No Difference	Up to 2% Lower
Exhaust Pressure	**kPa**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 10 kPa Lower
DOC Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 11°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	**ppm**	Slightly Lower	Slightly Higher	Slightly Lower	Slightly Lower	Slightly Lower	No Difference	Up to 14 ppm Lower
Tailpipe NO_x Sensor	**ppm**	N/A	N/A	N/A	N/A	N/A	N/A	
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
DEF Dosing	**%**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Engine-Out NO_x	**g**	Slightly Lower	Slightly Lower	Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 16% Lower
Calculated Tailpipe NO_x	**g**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%

Bench Tailpipe NO$_x$	g	-	-	Slightly Higher	Slightly Higher	Higher	-	Up to 55% Higher
Bench Tailpipe CO$_2$	g	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 8% Lower
Total Cycle Fuel Consumption	g	Slightly Lower	Slightly Lower	No Difference	Slightly Lower	No Difference	No Difference	Up to 2% Lower
Engine-Out Soot	mg	-	-	Lower	Lower	Lower	-	Up to 55% Lower

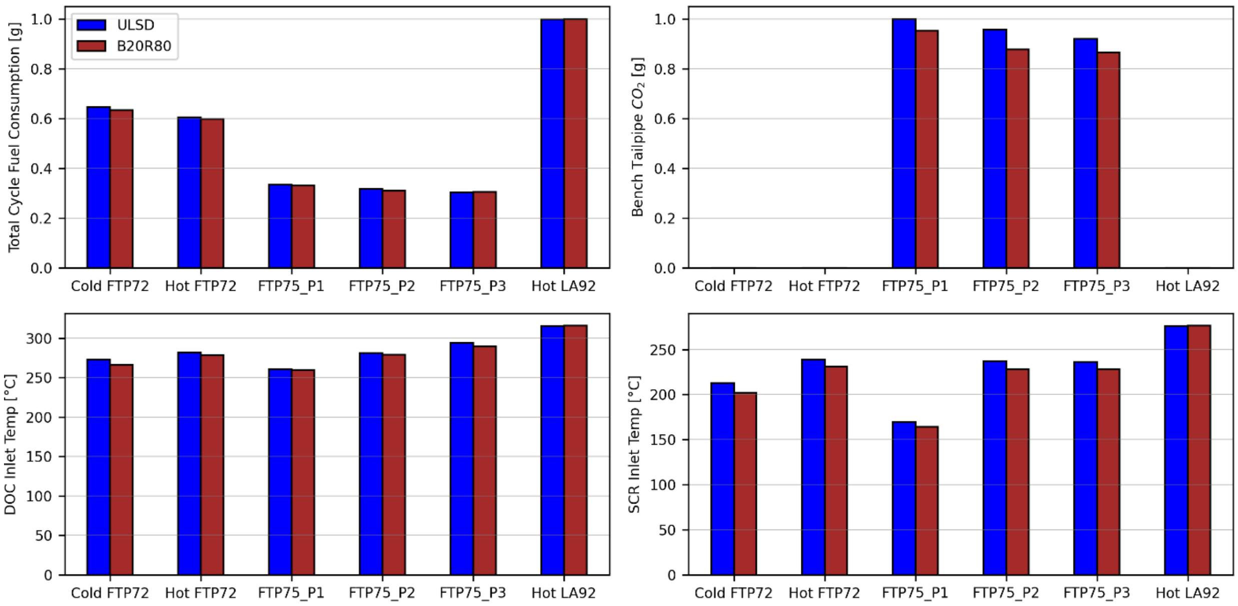

Figure 4.10: Vehicle D: B20R80 vs ULSD: Fuel Consumption, CO$_2$ Emissions and ATS Temperatures

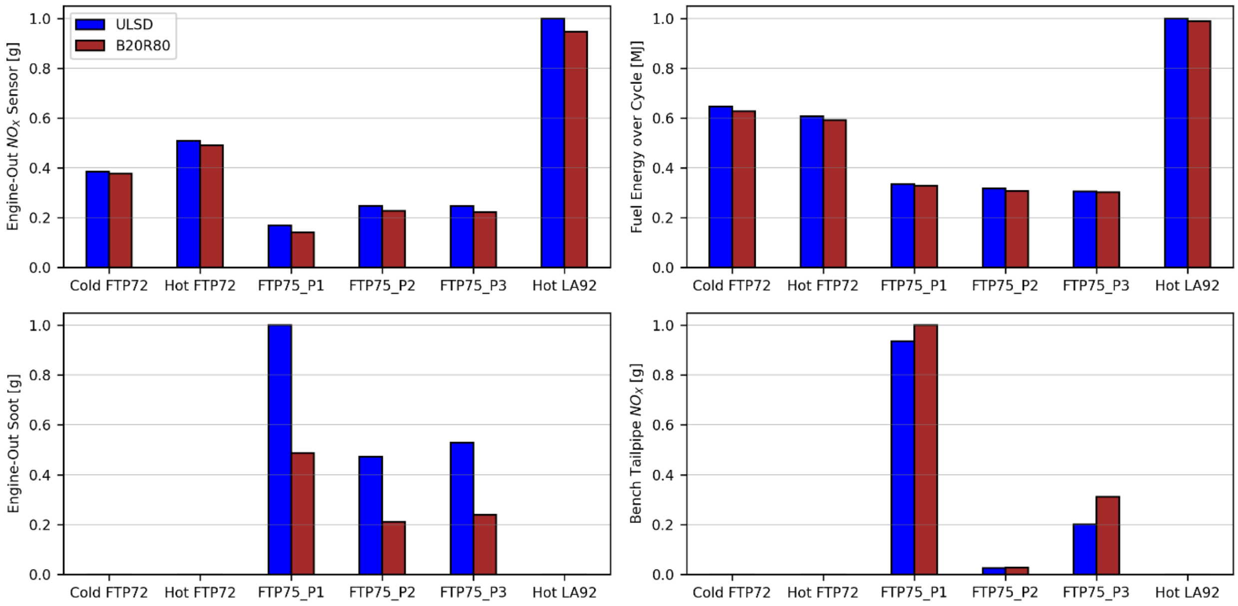

Figure 4.11: Vehicle D: B20R80 vs ULSD: Fuel Energy, Soot and NO$_x$ Emissions

Key observations from Figure 4.10 and Figure 4.11 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 1 to 2% lower when running with B20R80 for all cycles (Figure 4.10). B20R80 fuel has slightly lower net heating value per kg (~1%) compared to ULSD (Table 1.3), however the higher oxygen content of the fuel (due to biodiesel) and higher cetane number (due to R99 fuel) could be contributing to the observed lower fuel consumption. Overall, the fuel consumption variation is well within run-to-run variation.

   The fuel energy used over all the cycles with B20R80 fuel was slightly lower compared to ULSD (1-4%) (Figure 4.11). This could indicate differences in cycle work compared to ULSD which could also contribute to the observed lower fuel consumption. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were within ± 0.05 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

   CO_2 emissions differences were up to 8% lower compared to ULSD for FTP75 cycle. This could be explained by the 4% lower carbon content (% weight) in B20R80 blend compared to ULSD as well as the 2% lower fuel consumption seen in Figure 4.10.

2. ATS temperatures (Figure 4.10): ATS temperatures were on average lower on all cycles (up to 11°C). The lower ATS temperatures can be explained by the slightly lower fuel energy used over the cycles (3-4%) as well as lower net heating value (~1%) of B20R80 fuel compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 4.11. Lower engine-out NO_x emissions were observed in general across all the test cycles (up to 14 ppm lower). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. The combined effect of lower engine-out NO_x observed with R99 fuel (Section 2.4) and higher oxygen content of the fuel due to biodiesel could be contributing to the variations observed. However, since the blend has 80% renewable diesel, it could be overall reducing the engine-out NO_x emissions. Further, fuel energy used, and fuel consumption was lower, which could also have contributed to lower engine-out NO_x emissions.

Cumulative bench tailpipe NO_x emissions (g) with B20R80 were higher by up to 55% on FTP75 cycle. However, on a ppm basis < 2 ppm difference was observed on an average compared to ULSD. Higher tailpipe NO_x emissions can be explained by the overall lower ATS temperatures observed on all the cycles reducing SCR efficiency.

From an OBD monitor perspective these differences can be well within sensor accuracy limits and may not be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. However, from an SCR efficiency perspective, lower SCR efficiency due to lower ATS temperatures with B20R80, could affect NO_x emissions OBD limits used to determine monitor decisions.

4. Soot Emissions (Figure 4.11): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to higher cetane number of R99 fuel in the blend improving combustion efficiency by reducing ignition delay. B20R80 blend also has very low aromatics compared to ULSD which lowers the propensity for soot formation. Further biodiesel increases oxygen content of the fuel further contributing to soot reduction. Overall, up to 55% lower soot emissions were observed when running with B20R80 compared to ULSD.

   From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

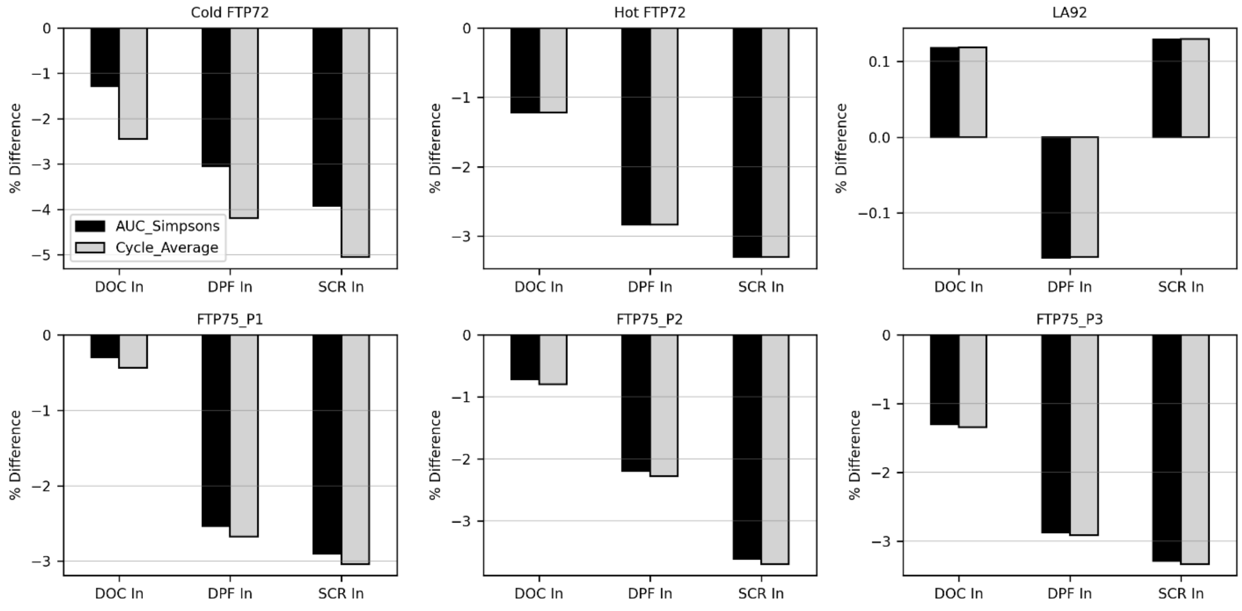

Figure 4.12: Vehicle D: B20R80 vs ULSD ATS Temperature Trends

Overall, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B20R80 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle D using B20R80 fuel compared to ULSD fuel have been shown in Figure 4.12. In general, ATS temperatures with B20R80 fuel were seen to be slightly lower as compared to ULSD fuel.

Based on results from Table 4.4 and key observations presented, it can be concluded that there could potentially be small impact of B20R80 fuel on OBD monitor robustness for Vehicle D. Overall, B20R80 fuel showed some impact on ATS temperatures, engine-out NO_x and soot emissions that could possibly impact OBD monitors including ATS temperature rationality, thermal management, DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with B20R80 fuel on Vehicle D did not show any OBD fault codes.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 4.4. Vehicle D showed slightly lower exhaust pressure values (up to 10 kPa) with B20R80 blend for all the cycles which could be due to differences in engine operation. No trends were seen in the test data to consider this as an impact of B20R80 blend on engine operation. It should be noted that ULSD test data had more repeat test runs compared to B20R80 in the test sequence due to issues with cycle and test data. This could have increased accumulated soot in the DPF and therefore increased exhaust pressure for ULSD while showing lower exhaust pressure for B20R80 tests. All other differences were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 4.5: B20R80 vs ULSD Summary

Based on analysis conducted using data from vehicles running with B20R80 blend, the following were the key observations and their possible impact on OBD monitors:

Engine-Out Soot emissions:

A key observation on the vehicles that had engine-out soot emissions measurements (Vehicle C and Vehicle D) was a significant reduction in engine-out soot emissions (~55-67% lower) when running with B20R80 blend compared to ULSD. This can be explained by higher cetane number of R99 fuel in the blend compared to ULSD improving combustion efficiency. The very low aromatic content of B20R80 blend also reduces the propensity for soot formation. Also, the presence of biodiesel in the blend increases oxygen content and reduces soot formation.

OBD Impact:

Some differences can be expected between true and modeled engine-out soot which is based on ULSD. Therefore, DPF regeneration interval and frequency could be affected due to the lower soot. There could also be some impact on DPF differential pressure measurements (lower due to lower soot). This could impact DPF regeneration frequency monitor and DPF differential pressure sensor monitor robustness.

ATS Temperatures:

Some variation in ATS temperatures were observed when using B20R80 blend compared to ULSD. Vehicles A, C and D showed slightly lower ATS temperatures when running with B20R80 blend compared to ULSD. The temperature differences were seen to be ~11°C. Vehicle B did not show any significant temperature differences (± 2°C). The lower temperatures may be attributed to the lower net heating value of B20R80 blend compared to ULSD. However, the observed differences in temperatures can be well within run-to-run variation considering the differences in engine operating conditions due to the tests being conducted on chassis dynamometer.

OBD Impact:

The observed variation could impact ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values for each vehicle. The lower/higher ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Overall, there may potentially be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

NO_x Emissions:

Some variation was also observed for engine-out NO_x emissions compared to ULSD. For Vehicles A, B and C, engine-out NO_x emissions were higher (up to 24 ppm), however for Vehicle D, engine-out NO_x emissions were lower (up to 14 ppm). Based on studies conducted [3,9,21], trends for engine-out NO_x emissions with R99 fuel have been unclear. Since R99 fuel (80% of the blend) has higher cetane number, the combustion (CA50) may be more advanced which can increase NO_x emissions. Further, biodiesel in the blend also increases oxygen content of the fuel which can increase NO_x emissions. However, since there is 80% R99 fuel in the blend, lower NO_x emissions trends observed with R99 fuel could lower NO_x emissions as seen in Vehicle D (Section 2.4). Tailpipe NO_x emissions on average (ppm basis) were well within run-to-run variation (± 3 ppm). Cumulative tailpipe NO_x emissions (g) on FTP75 measured using the bench showed higher tailpipe NO_x emissions with B20R80 blend. This can be attributed to increased engine-out NO_x emissions and lower SCR temperatures reducing SCR efficiency.

OBD Impact:

The variations in NO_x sensor values (ppm basis) observed may affect NO_x sensor rationality monitor decisions. Also, some impact could be expected on the OBD thresholds for NO_x emissions used to determine SCR efficiency monitor decisions, since total tailpipe NO_x emissions over the cycle (for B20R80) measured by bench (g) were higher when compared to ULSD.

Fuel Consumption:

Fuel consumption was 1-3% lower for Vehicles A and D and 3-5% higher for Vehicles B and C compared to ULSD. Some impact on fuel consumption is expected due to slightly lower net heating value (mass and volume based) of B20R80 blend compared to ULSD. Further, the fuel energy over the cycle also showed variation (± 4%) for all the vehicles which indicates differences in vehicle operation (cycle work). This could have also contributed to some differences observed in fuel consumption.

OBD Impact:

From OBD perspective, the average variation in engine fuel rate (g/s) was within ± 0.1 g/s. Therefore, no significant impact is expected on fuel flow OBD monitor decisions.

Other PID Labels:

Some differences in boost pressure (± 2kPa), rail pressure (± 3%), EGR and VGT positions (± 5%) were observed, however these differences were well-within acceptable limits and run-to-run variation. Since the vehicles were tested using chassis dynamometer cycles, the engine operating conditions (engine speed and fueling) are not consistent between test runs due to driver-to-driver variation in running the same cycle. This results in different setpoints for air flow, EGR and VGT position during transient operation and therefore causes variations in the selected PID labels. The observed variations were therefore found to be well within this expected variation in engine operation.

Conclusion Summary for B20R80:

Based on data analysis conducted on chassis dynamometer data from all four vehicles on FTP75, FTP72 and LA92 cycles, it was concluded B20R80 blend showed small impact on the selected PID labels. However, the absence of OBD fault codes while running using B20R80 blend on all vehicles shows that this impact was not significant enough to affect OBD monitor robustness.

Chapter 5 : Fuel IV: B50U50 Blend

This chapter describes the results and conclusions of the testing conducted on all four vehicles using B50U50 fuel utilizing the analysis approaches and metrics described in Section 1.6. The results have been divided into Sections 5.1, 5.2, 5.3 and 5.4 for Vehicles A, B, C and D respectively. Each section has the following that summarizes the results for B50U50 fuel compared to ULSD for each vehicle.

1. A table summarizing the results of the vehicle running on B50U50 compared to ULSD for all the test cycles. Key differences observed in engine performance and emissions when using B50U50 fuel compared to ULSD fuel using the "averaged" B50U50 and ULSD cycles for cold and hot FTP72 cycle, hot LA92 cycle and each phase of the FTP75 cycle are highlighted in these tables.
2. Plots showing average ATS temperatures, fuel energy, total engine-out and tailpipe NO_x emissions, engine-out soot emissions (when available) and cycle fuel consumption differences for the vehicle when using B50U50 fuel blend compared to ULSD. The values in the plots have been normalized using min-max normalization, where minimum value = 0 and maximum value was the maximum value in the plot. This was done to present important trends in engine performance while preserving anonymity of emissions and fuel consumption values.
3. Trend plots (% difference) showing PID labels for which significant increasing or decreasing trends were observed when running with B50U50 fuel compared to ULSD for that vehicle. Negative percent difference indicates lower and positive indicates higher compared to ULSD.

A summary of key observations and trends analyzed for the vehicles when running with B50U50 blend compared to ULSD and their possible impact on different OBD monitors is presented in Section 5.5.

Section 5.1: Vehicle A: B50U50 vs ULSD

Table 5.1: Vehicle A Results Summary: B50U50 vs ULSD

PID Labels	**Units**	**Test Cycle**						**Observations**
		FTP72		**FTP75**			**LA92**	
		Cold	**Hot**	**Phase 1 (Cold Start)**	**Phase 2 (Stabilized)**	**Phase 3 (Hot Start)**	**Hot**	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	Slightly Higher	No Difference	No Difference	No Difference	No Difference	Slightly Higher	± 4%
Engine Fuel Rate	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	3 to 5% Higher
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa

DOC Inlet Temp	**°C**	Lower	-	Lower	Lower	Lower	-	Up to 12°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Lower	-	Lower	Lower	Lower	-	
DPF Outlet/SCR Inlet Temp	**°C**	Lower	-	Lower	Lower	Lower	-	
SCR Outlet Temp	**°C**	Lower	-	Lower	Lower	Lower	-	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 4% Lower
Engine Out NO_x Sensor	**ppm**	Slightly Higher	Higher	Slightly Higher	Slightly Higher	Slightly Higher	Higher	Up to 50 ppm
Tailpipe NOx Sensor	**ppm**	No Difference	No Difference	N/A	No Difference	N/A	NH3 Slip	± 2 ppm
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	Up to 4 ppm
Upstream O_2 Sensor	**%**	N/A	N/A	N/A	N/A	N/A	N/A	
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NOx	**g**	Higher	Higher	Higher	Higher	Higher	Higher	Up to 32% Higher
Calculated Tailpipe NOx	**g**	Higher	Slightly Lower	No Difference	Slightly Lower	No Difference	NH3 Slip	Up to 21% Lower
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Bench Tailpipe NOx	**g**	-	-	Higher	Higher	Higher	-	Up to 2 times Higher
Bench Tailpipe CO_2	**g**	-	-	Slightly Higher	Higher	Slightly Higher	-	Up to 11% Higher
Total Cycle Fuel Consumption	**g**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	3 to 5% Higher
Engine-Out Soot	**mg**	-	-	-	-	-	-	

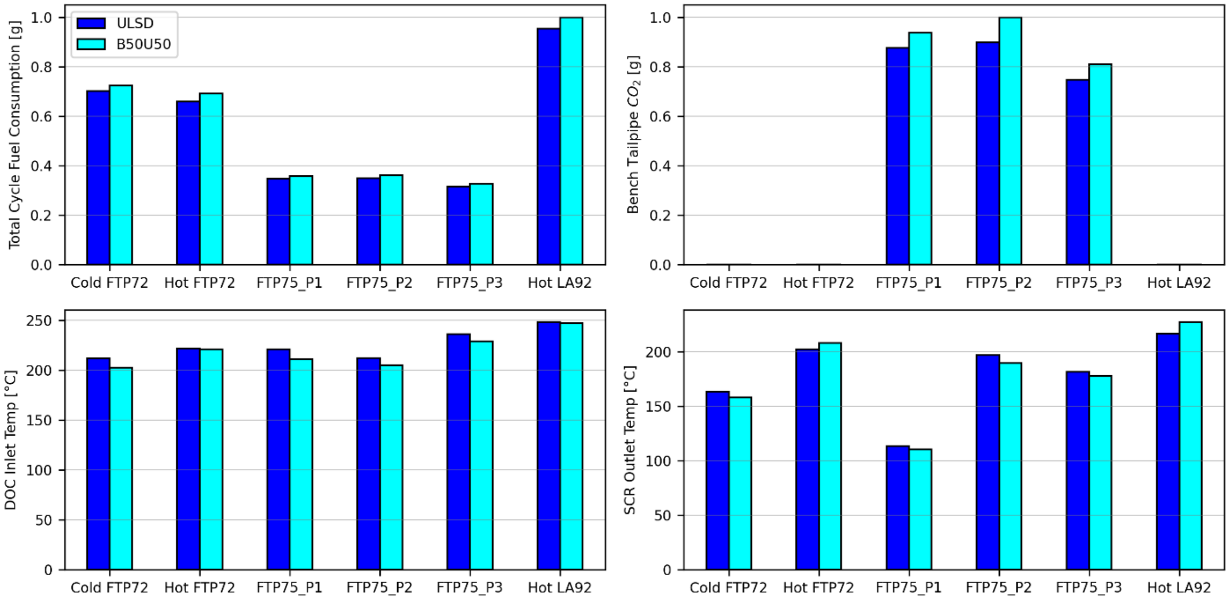

Figure 5.1: Vehicle A: B50U50 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

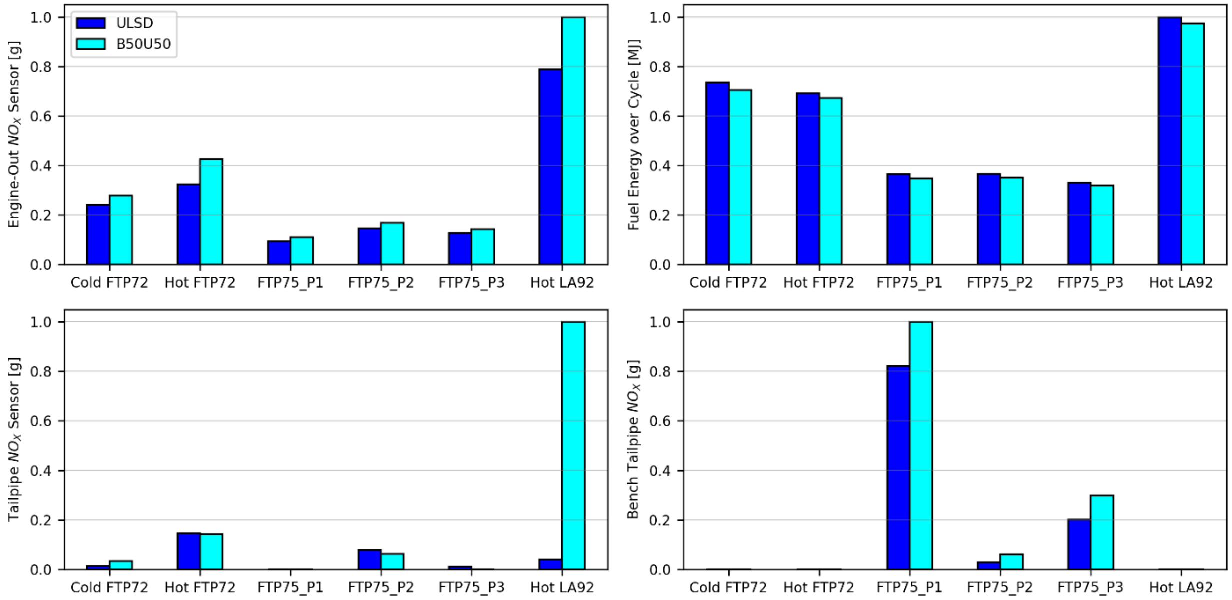

Figure 5.2: Vehicle A: B50U50 vs ULSD: Fuel Energy and NO_x Emissions

Key observations from Figure 5.1 and Figure 5.2 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 3 to 5% higher when running with B50U50 for the test cycles (Figure 5.1). B50U50 fuel has 7% lower net heating value per kg compared to ULSD (Table 1.3) which could explain the observed higher fuel consumption.

   The fuel energy used over all the cycles with B50U50 fuel was slightly lower compared to ULSD (3-5%) (Figure 5.2) which could indicate some differences in cycle work compared to ULSD. From an OBD perspective, differences in average engine fuel rate (g/s) were ≤ 0.07 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were about 7-11% higher compared to ULSD for FTP75 cycle. This could be explained by higher fuel consumption seen in Figure 5.1.

2. ATS temperatures (Figure 5.1): ATS temperatures were on average ~12°C lower when running with B50U50 blend for FTP75 and cold FTP72 cycles. For hot FTP72 and LA92 cycles the ATS temperatures were slightly higher (5-10°C). However, this higher temperature could be attributed to cycle-to-cycle difference (hot FTP72 and LA92 cycles with B50U50 had higher starting ATS temperatures compared to ULSD). The observed lower ATS temperatures could be attributed to 7% lower net heating value (by mass) of B50U50 blend compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 5.2. Higher engine-out NO_x emissions were observed in general for all the cycles. LA92 cycles on average showed up to 50 ppm higher engine-out NO_x emissions. However, there could be some differences in sensor activation times due to differences in ATS temperatures, therefore, some differences can be attributed to run-to-run variation. Higher engine-out NO_x emissions can be attributed to the biodiesel fuel in the blend which increases O_2 concentration in the fuel. Therefore, an increasing trend of engine-out NO_x emissions with B50U50 fuel is expected as observed in the test cycles.

   Tailpipe NO_x sensor emissions however showed very small variations (± 2 ppm) which are well within run-to-run variation. However, on LA92 cycle more NH_3 slip was observed with B50U50 fuel (due to differences in sequence of cycles run before LA92 cycle). Therefore, tailpipe NO_x emissions are higher on this cycle due to NH_3 to NO_x cross sensitivity of NO_x sensors. Higher cumulative bench tailpipe NO_x emissions (g) with B50U50 were observed on FTP75 cycle (up to 2 times higher), primarily due to higher engine-out NO_x and lower ATS temperatures lowering SCR efficiency. On a ppm basis < 5 ppm difference was observed on an average compared to ULSD.

   From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, lower SCR efficiency is expected due to higher engine-out NO_x emissions and lower ATS temperatures with B50U50, which could affect NO_x emissions OBD limits used to determine monitor decisions.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B50U50 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle A using B50U50 fuel compared to ULSD fuel have been shown in. The higher ATS trends observed for hot FTP72 and LA92 cycle are due to starting ATS temperatures being higher for B50U50 fuel compared to ULSD. However, in general ATS temperatures with B50U50 fuel were seen to be lower as compared to ULSD fuel.

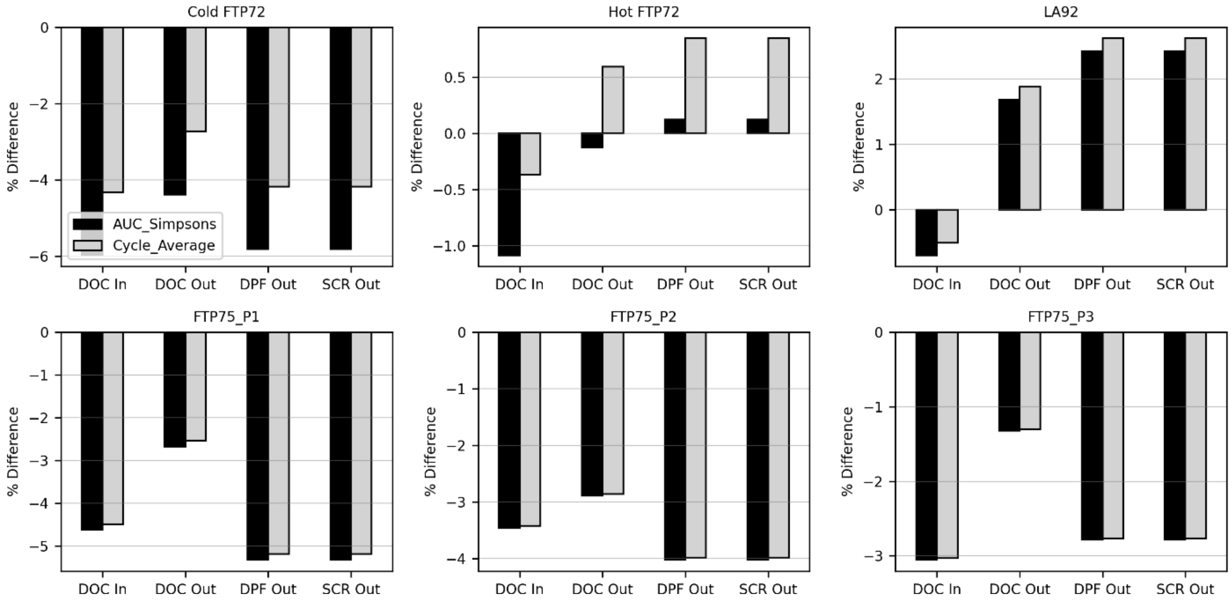

Figure 5.3: Vehicle A: B50U50 vs ULSD ATS Temperature Trends

Based on results from Table 5.1 and key observations presented, it can be concluded that there could potentially be some impact of B50U50 fuel on OBD monitor robustness for Vehicle A. Overall, B50U50 fuel showed some impact on ATS temperature as well as engine-out NO_x sensor values that could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management mode, DPF regeneration as well as NO_x sensor rationality and SCR efficiency monitor. However, post-test cycle OBD scans for test cycles tested with B50U50 fuel did not show any OBD fault codes for Vehicle A.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 5.1. Slightly lower calculated lambda values were observed (up to 4%), which can be attributed to the 3-5% higher fuel consumption. Overall, the observed differences were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 5.2: Vehicle B: B50U50 vs ULSD_2

Table 5.2: Vehicle B Results Summary: B50U50 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	Slightly Higher	Up to 5% Higher
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	**g/s**	Higher	Higher	Higher	Higher	Higher	Higher	9 to 10% Higher
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3°C
DOC Outlet/DPF Inlet Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
DPF Outlet/SCR Inlet Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
SCR Outlet Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	**ppm**	No Difference	Slightly Higher	No Difference	No Difference	Slightly Higher	Higher	Up to 17 ppm
Tailpipe NO_x Sensor	**ppm**	-	-	-	-	-	-	NH3 Slip
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	4-5% Higher
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 5 mg/s
Calculated Engine-Out NO_x	**g**	Slightly Higher	Higher	Slightly Higher	Slightly Higher	Slightly Higher	Higher	2 to 21% Higher
Calculated Tailpipe NO_x	**g**	-	-	-	-	-	-	NH3 Slip
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	Slightly Higher	Up to 5% Higher
Bench Tailpipe NO_x	**g**	-	-	Higher	Higher	Higher	-	16 to 90% Higher
Bench Tailpipe CO_2	**g**	-	-	Higher	Higher	Higher	-	12 to 14% Higher
Total Cycle Fuel Consumption	**g**	Higher	Higher	Higher	Higher	Higher	Higher	9 to 10% Higher
Engine-Out Soot	**mg**	-	-	-	-	-	-	

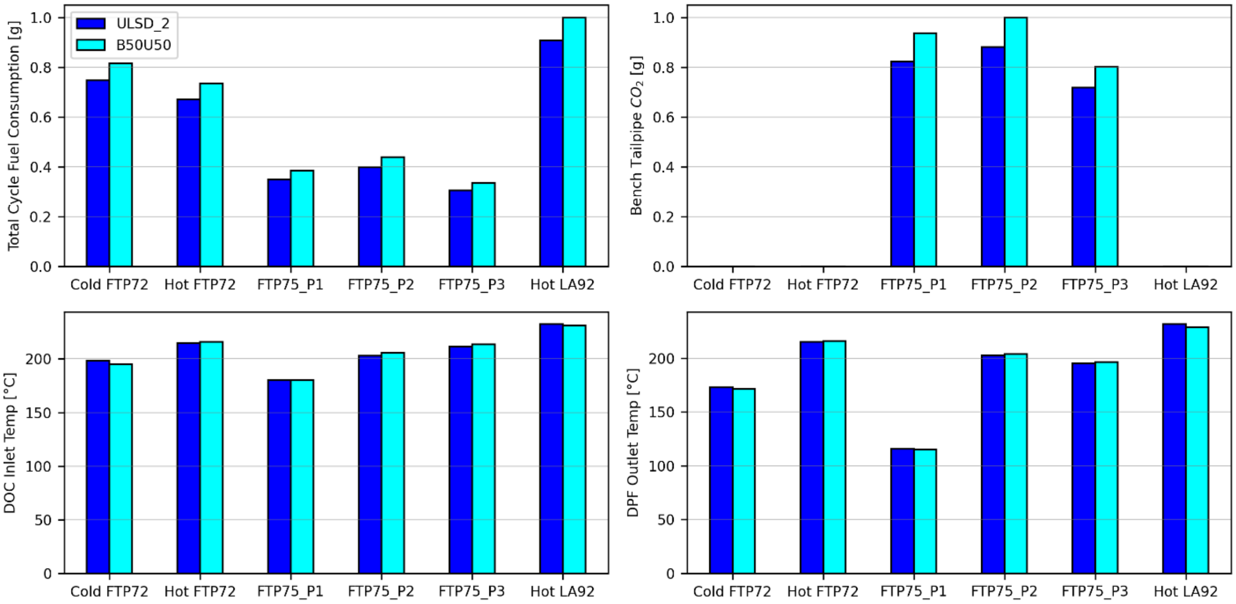

Figure 5.4: Vehicle B: B50U50 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

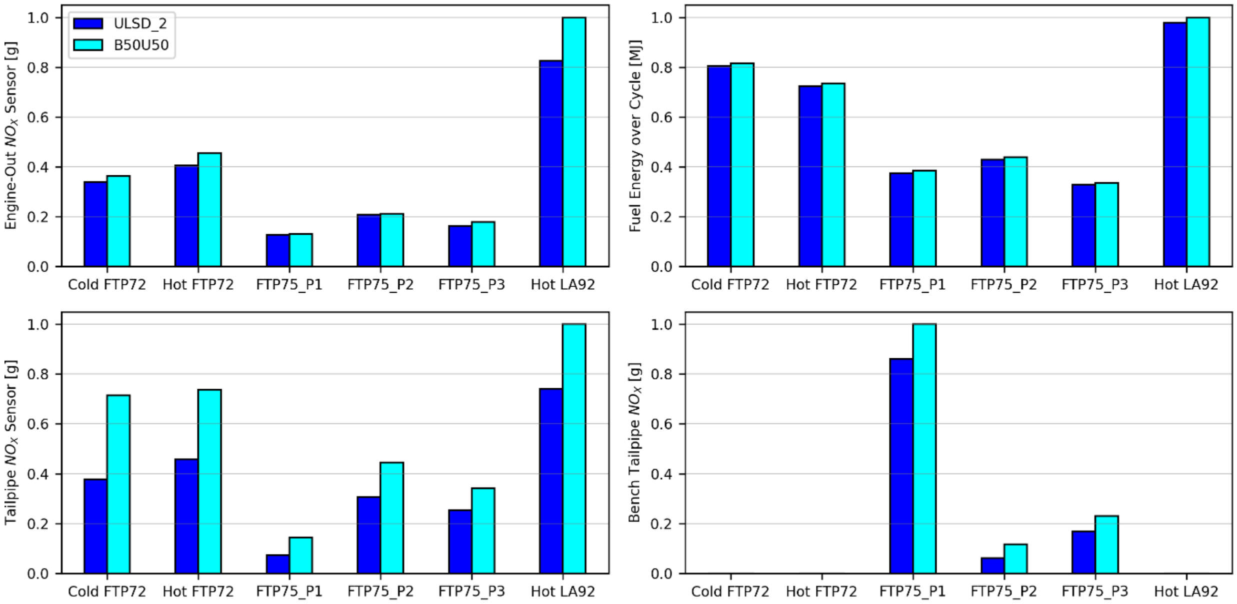

Figure 5.5: Vehicle B: B50U50 vs ULSD_2: Fuel Energy and NO_x Emissions

Key observations from Figure 5.4 and Figure 5.5 and are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycles increased by 9-10% when running with B50U50 fuel compared to ULSD (Figure 5.4). B50U50 fuel has 7% lower net heating value per kg compared to ULSD (Table 1.3), which could contribute to some increase in fuel consumption as observed in all the cycles.

The fuel energy used over all the cycles with B50U50 fuel was slightly higher compared to ULSD (1-2%) (Figure 5.5). This could indicate that the cycle work with B50U50 was higher compared to ULSD, which could have also contributed to the higher fuel consumption observed. From an OBD perspective, difference in average engine fuel rate (g/s) over the cycles was ~ 0.2 g/s. Therefore, there could be some impact on fuel flow OBD monitors.

CO_2 emissions were ~12-14% higher compared to ULSD for FTP75 cycle. This could be explained by the 9-10% higher fuel consumption compared to ULSD and slightly higher fuel energy (1-2%) used in all the cycles.

2. ATS temperatures (Figure 5.4): ATS temperatures when running with B50U50 fuel were within ± 3°C compared to ULSD.

   Therefore, from OBD perspective, no impact is expected on OBD monitor robustness when using B50U50 fuel for Vehicle B

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 5.5. A trend of slightly higher engine-out NO_x emissions was observed over the test cycles (up to 17 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. Higher engine-out NO_x emissions can be attributed to the biodiesel fuel in the blend which increases O_2 concentration in the fuel. Therefore, an increasing trend of engine-out NO_x emissions with B50U50 fuel is expected as observed in the test cycles.

   For Vehicle B, trends for tailpipe NO_x sensor emissions were inconclusive. This was primarily because all cycles on Vehicle B always showed some amount of NH_3 slip throughout the cycle which seemed to strongly affect tailpipe NO_x sensor values. This is due to the cross-sensitivity of NO_x sensors to NH_3 which increases tailpipe NO_x sensor measured NO_x values to higher than actual values. The cumulative bench tailpipe NO_x (g) showed up to 90% higher tailpipe NO_x emissions trend on FTP75 cycle with B50U50. However, on a ppm basis < 2 ppm difference was observed on the bench for B50U50 blend compared to ULSD. Therefore, overall, no significant impact is expected on tailpipe NO_x sensor measurements.

   From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the slightly higher engine-out NO_x emissions with B50U50 blend, which could affect NO_x emissions OBD limits used to determine monitor decisions.

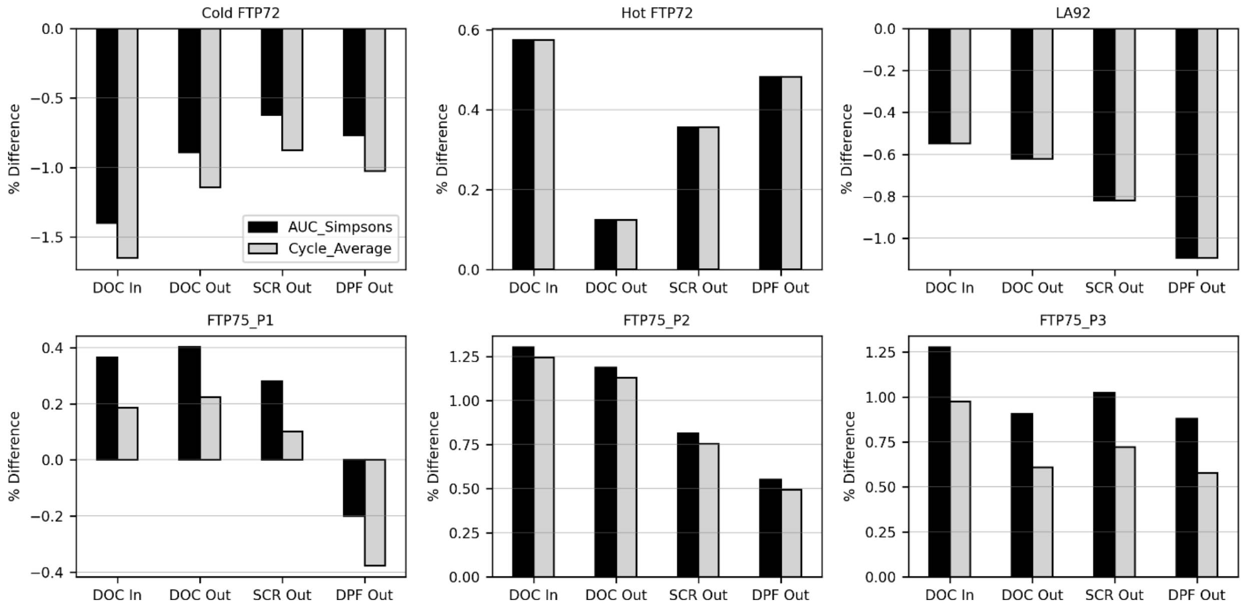

Figure 5.6: Vehicle B: B50U50 vs ULSD_2 ATS Temperature Trends

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B50U50 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle B using B50U50 blend compared to ULSD fuel have been shown in Figure 5.6.

Based on results from Table 5.2 and key observations presented, it can be concluded that there could potentially be some impact of B50U50 blend on OBD monitor robustness for Vehicle B. Overall, B50U50 fuel showed some impact on fuel flow and engine-out NO_X emissions that could possibly impact OBD monitors including fuel flow, SCR efficiency and NO_X sensor rationality. Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 5.2. For example, boost pressure (± 2 kPa), ± 4% variation in air flow and slightly higher rail pressure (up to 5%) possibly due to 2% higher density of B50U50 fuel. However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness. Also, post-test cycle OBD scans for test cycles tested with B50U50 blend did not show any OBD fault codes for Vehicle B.

Section 5.3: Vehicle C: B50U50 vs ULSD_2

Table 5.3: Vehicle C Results Summary: B50U50 vs ULSD_2

PID Labels	**Units**	**Test Cycle**						**Observations**
		FTP72		**FTP75**			**LA92**	
		Cold	**Hot**	**Phase 1 (Cold Start)**	**Phase 2 (Stabilized)**	**Phase 3 (Hot Start)**	**Hot**	
Mass Air Flow Sensor	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 5% Higher
Intake Manifold Temp	**°C**	No Difference	Slightly Lower	No Difference	No Difference	No Difference	No Difference	Up to 4°C Lower
Coolant Temp	**°C**	No	No	No	No	No	No	± 2°C

		Difference	Difference	Difference	Difference	Difference	Difference	
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Fuel Rate	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	No Difference	Slightly Higher	Slightly Higher	3 to 7% Higher
Exhaust Pressure	**kPa**	N/A	N/A	N/A	N/A	N/A	N/A	
DOC Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 8°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 6% Higher
Engine Out NO_x Sensor	**ppm**	Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Higher	Up to 35 ppm Higher
Tailpipe NO_x Sensor	**ppm**	No Difference	No Difference	N/A	No Difference	No Difference	Slightly Higher	Up to 4 ppm Higher
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	Slightly Higher	Slightly Higher	Slightly Higher	No Difference	No Difference	Slightly Higher	Up to 5% Higher
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NO_x	**g**	Higher	Higher	Higher	Slightly Higher	Higher	Higher	Up to 40% Higher
Calculated Tailpipe NO_x	**g**	Lower	Higher	N/A	Slightly Higher	Higher	Higher	Up to 3 times Higher
Calculated Exhaust Flow Rate	**kg/h**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 5% Higher
Bench Tailpipe NO_x	**g**	-	-	Higher	Lower	Higher	-	40% Lower to 17% Higher
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	5 to 9% Lower
Total Cycle Fuel Consumption	**g**	Slightly Higher	Slightly Higher	Slightly Higher	No Difference	Slightly Higher	Slightly Higher	3 to 7% Higher
Engine-Out Soot	**mg**	-	-	Lower	Lower	Lower	-	Up to 43% Lower

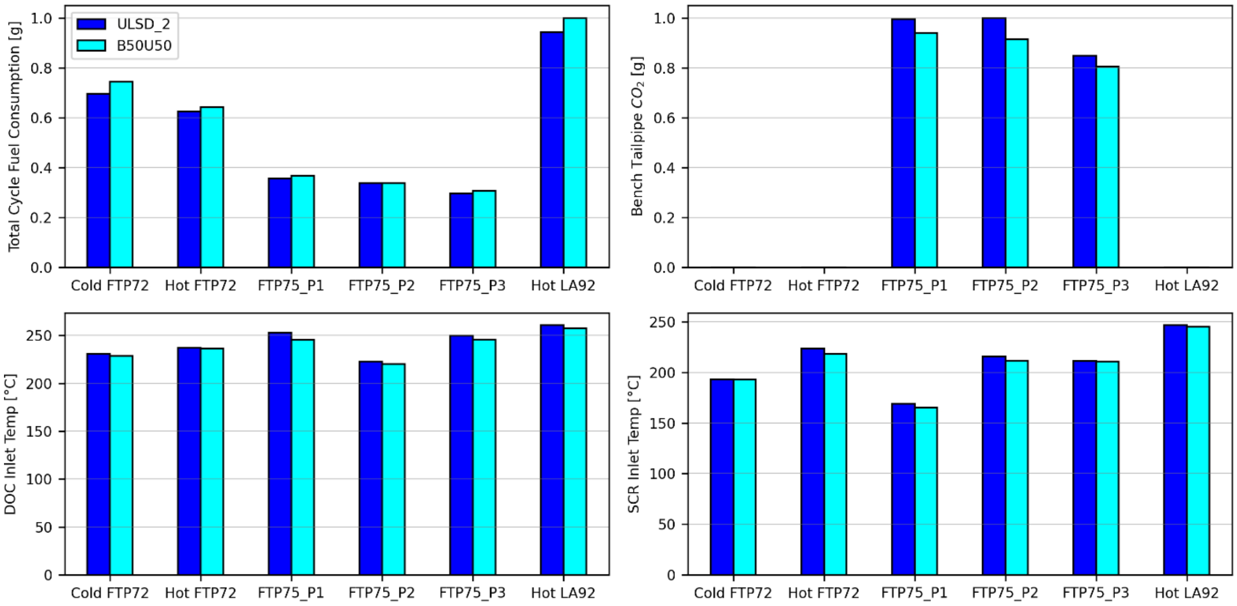

Figure 5.7: Vehicle C: B50U50 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

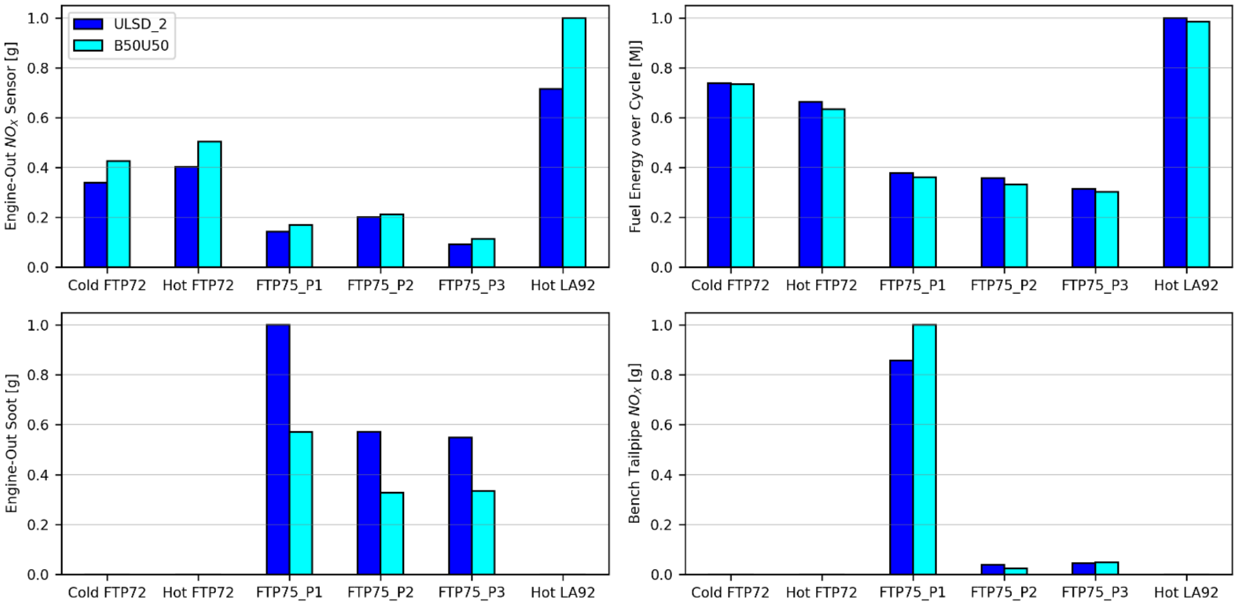

Figure 5.8: Vehicle C: B50U50 vs ULSD_2: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure 5.7 and Figure 5.8 are as follows:

1. Fuel consumption/CO_2 Emissions (g): For Vehicle C, with B50U50 blend, the fuel consumption was higher (3-7%) (Figure 5.7). B50U50 fuel has lower net heating value per kg (~7%) compared to ULSD (Table 1.3). This could explain higher fuel consumption seen on all the cycles.

   The fuel energy used over all the cycles with B50U50 blend was slightly lower compared to ULSD (up to 7%) (Figure 5.8). This could indicate some differences in cycle work compared to ULSD and could therefore have some impact on fuel consumption. From an

OBD perspective, differences in average engine fuel rate (g/s) over the cycles were ≤ 0.05 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were ~5 to 9% lower compared to ULSD for FTP75 cycle. This could be explained by the up to 5% lower carbon content (% weight) in B50U50 blend compared to ULSD.

2. ATS temperatures (Figure 5.7): ATS temperatures were on average slightly lower on all the cycles (up to 8°C). However, this variation could be well-within run-to-run variation. The lower ATS temperatures may be explained by the 7% lower net heating value of B50U50 blend compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 5.8. A trend of higher engine-out NO_x emissions was observed over the test cycles (up to 35 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. B50U50 blend contains 50% biodiesel which increases the oxygen content of the fuel, thereby increasing NO_x emissions.

   Tailpipe NO_x sensor values were seen to be very similar to ULSD. However, cumulative bench tailpipe NO_x emissions (g) were higher on FTP75 cycle with B50U50 blend (up to 17%). This could be explained by the higher engine-out NO_x and slightly lower ATS temperatures lowering SCR efficiency. On a ppm basis however, this difference was < 2 ppm difference on average compared to ULSD.

   From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the lower ATS temperatures and higher engine-out NO_x emissions with B50U50 blend, which could affect NO_x emissions OBD limits used to determine monitor decisions.

4. Soot Emissions (Figure 5.8): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to biodiesel fuel in the blend which increases oxygen content of the fuel thereby reducing soot production. Overall, up

to 43% lower soot emissions were observed when running Vehicle C with B50U50 blend compared to ULSD.

From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

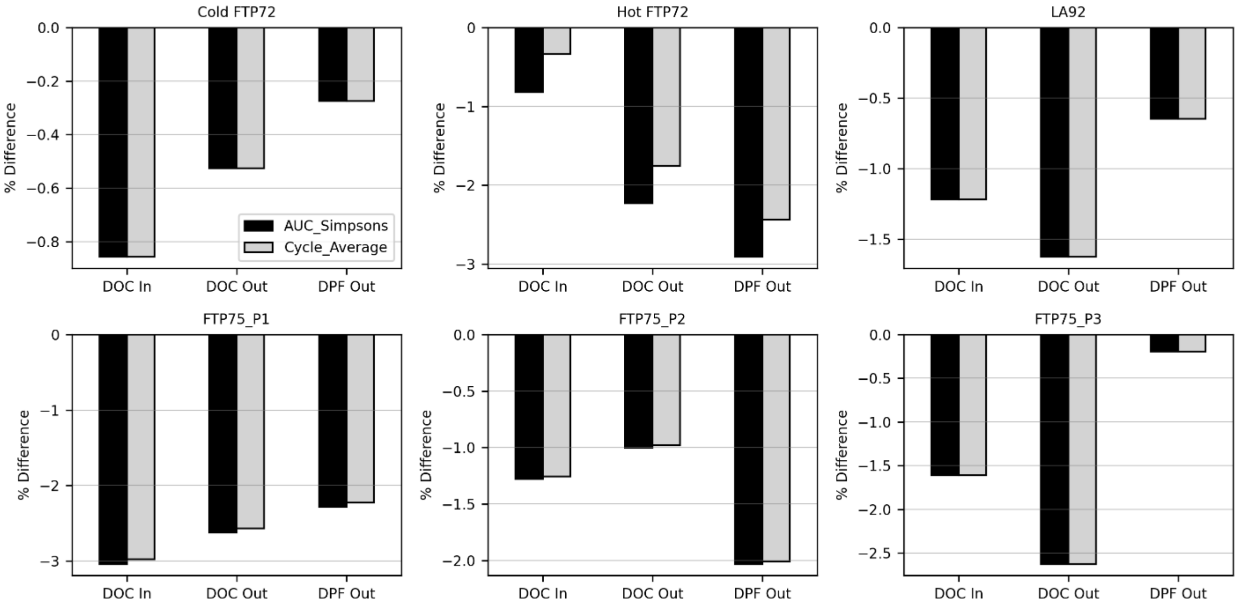

Figure 5.9: Vehicle C: B50U50 vs ULSD_2 ATS Temperature Trends

Based on results from Table 5.3 and key observations presented, it can be concluded that there could potentially be some impact of B50U50 fuel on OBD monitor robustness for Vehicle C. Overall, B50U50 blend showed some impact on ATS temperatures, engine-out NO_x and soot emissions which could possibly impact OBD monitor decisions including ATS temperature rationality, DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with B50U50 blend did not show any OBD fault codes for Vehicle C.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 5.3. For example, boost pressure (± 2 kPa) and some differences in fuel rail pressure, air flow, calculated lambda, EGR and VGT positions. Slightly higher mass flow rate of air (up to 5%) and subsequently slightly higher calculated lambda was also observed. However, Vehicle C also had run to run differences due to a feature that was inconsistent for the runs with ULSD and B50U50 blend. Therefore, these observed variations were not considered to be significant enough to impact OBD robustness.

Section 5.4: Vehicle D: B50U50 vs ULSD

Table 5.4: Vehicle D Results Summary: B50U50 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Intake Manifold Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	**g/s**	Slightly Lower	No Difference	Slightly Lower	Slightly Lower	No Difference	No Difference	2 to 4% Lower
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3 kPa
DOC Inlet Temp	**°C**	Lower	Lower	Lower	Lower	Lower	Lower	Up to 14°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Lower	Lower	Lower	Lower	Lower	Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Lower	Lower	Lower	Lower	Lower	Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	**ppm**	Slightly Higher	No Difference	Slightly Lower	Slightly Higher	Slightly Higher	Slightly Higher	Up to 17 ppm
Tailpipe NO_x Sensor	**ppm**	N/A	N/A	N/A	N/A	N/A	N/A	
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Higher	No Difference	Slightly Higher	-	Up to 10 ppm
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**mg/s**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Engine-Out NO_x	**g**	Slightly Higher	No Difference	Slightly Lower	Slightly Higher	Slightly Higher	Slightly Higher	Up to 12% Higher
Calculated Tailpipe NO_x	**g**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Bench Tailpipe NO_x	**g**	-	-	Higher	Higher	Higher	-	Up to 3 times Higher
Bench Tailpipe CO_2	**g**	-	-	No Difference	No Difference	No Difference	-	± 1%
Total Cycle Fuel Consumption	**g**	Slightly Lower	No Difference	Slightly Lower	Slightly Lower	No Difference	No Difference	2 to 4% Lower
Engine-Out Soot	**mg**	-	-	Lower	Lower	Lower	-	Up to 54% Lower

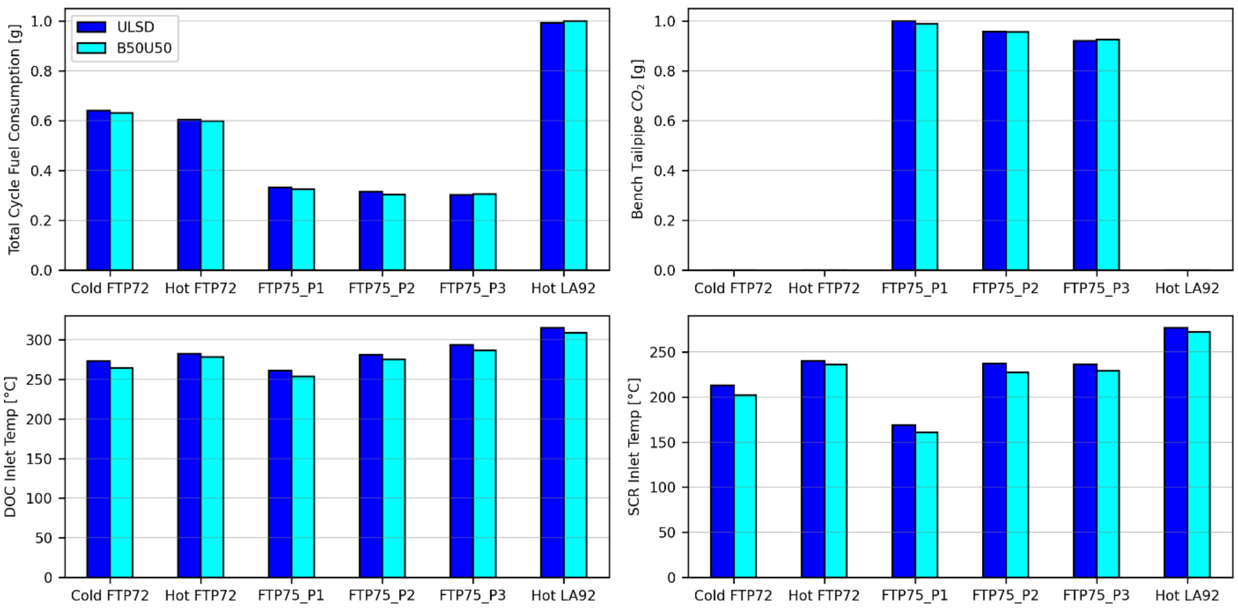

Figure 5.10: Vehicle D: B50U50 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

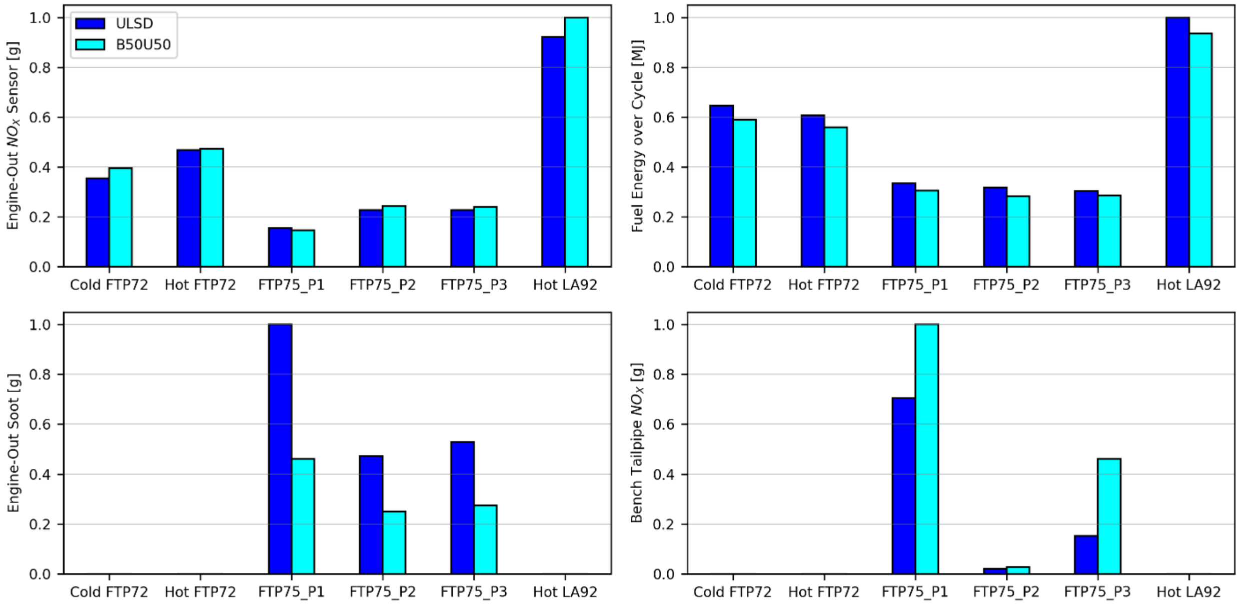

Figure 5.11: Vehicle D: B50U50 vs ULSD: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure 5.10 and Figure 5.11 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 2-4% lower when running with B50U50 fuel (Figure 5.10). B50U50 fuel has 7% lower net heating value per kg compared to ULSD (Table 1.3), however the higher oxygen content of the fuel (due to biodiesel) could improve thermal efficiency and lower fuel consumption.

   The fuel energy used over all the cycles with B50U50 fuel was 7-11% lower compared to ULSD (Figure 5.11). This could indicate that the cycle work was lower compared to ULSD which could also contribute to the lower fuel consumption observed. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were within ± 0.03 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions differences were within ± 1% compared to ULSD for FTP75 cycle.

2. ATS temperatures (Figure 5.10): ATS temperatures were on average lower on all cycles (up to 14°C). The lower ATS temperatures can be explained by the lower fuel energy used over the cycles (8-11%) as well as lower net heating values (7%) of B50U50 fuel compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 5.11. Overall higher engine-out NO_x emissions were observed in general across all the test cycles (up to 17 ppm) except for Phase 1 of FTP75 cycle. However, since Phase 1 of FTP75 cycle is cold, engine-out NO_x sensor is inactive for most of Phase 1, sensor may not have captured this increase. Further, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. Since B50U50 blend has 50% biodiesel, the higher oxygen content of the fuel is expected to increase engine-out Nox emissions.

   Cumulative bench tailpipe NO_x emissions (g) with B50U50 were up to 3 times higher on FTP75 cycle. Also, on a ppm basis ~10 ppm difference was observed on an average compared to ULSD. This higher tailpipe NO_x emissions can be explained by lower ATS temperatures combined with higher engine-out NO_x emissions observed leading to lower SCR efficiency.

   From an OBD monitor perspective these differences can be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults or SCR efficiency monitor decisions. From an SCR efficiency perspective, lower SCR efficiency due to higher engine-out lower ATS temperatures with B50U50, could affect NO_x emissions OBD limits used to determine monitor decisions.

4. Soot Emissions (Figure 5.11): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to higher oxygen content in

the blend due to biodiesel which reduces the propensity for soot formation. Overall, up to 54% lower soot emissions were observed when running with B50U50 compared to ULSD.

From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

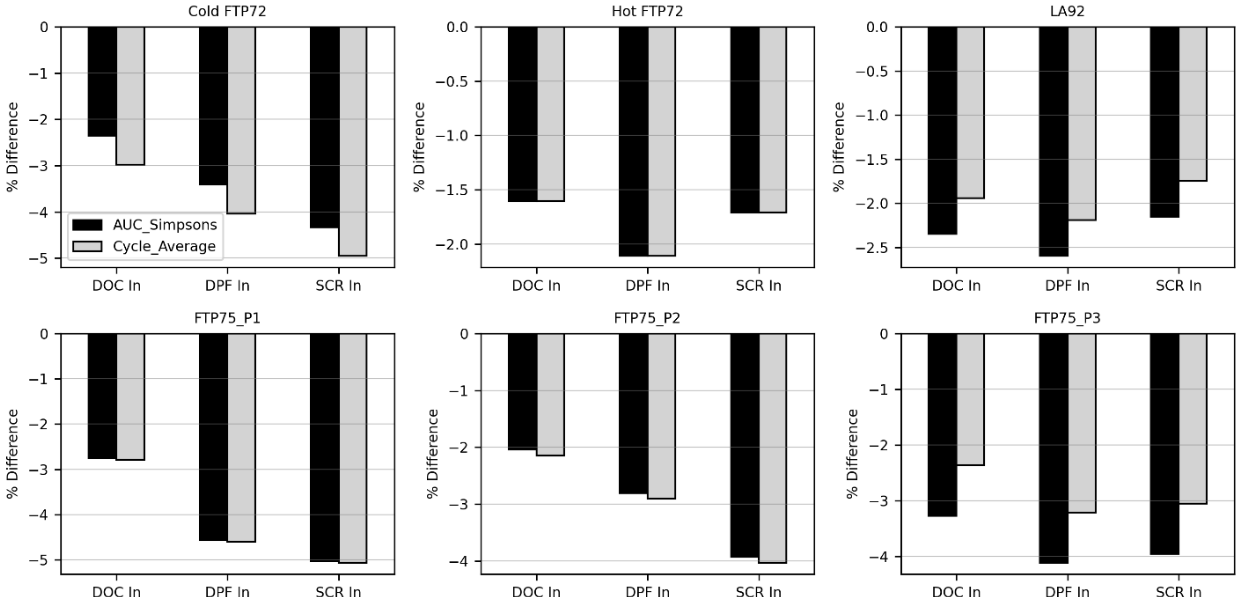

Figure 5.12: Vehicle D: B50U50 vs ULSD ATS Temperature Trends

Overall, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B50U50 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle D using B50U50 fuel compared to ULSD fuel have been shown in Figure 5.12. In general, ATS temperatures with B50U50 fuel were seen to be slightly lower as compared to ULSD fuel.

Based on results from Table 5.4 and key observations presented, it can be concluded that there could potentially be some impact of B50U50 fuel on OBD monitor robustness for Vehicle D. Overall, B50U50 fuel showed some impact on soot emissions that could possibly impact OBD monitor decisions for DPF regeneration. Lower ATS temperatures and higher engine-out NO_x emissions were also observed which could potentially impact ATS temperature rationality, DPF regeneration, NO_x sensor rationality and SCR efficiency monitors. However, post-test cycle OBD scans for test cycles tested with B50U50 fuel did not show any OBD fault codes for Vehicle D.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 5.4 - for example, boost pressure and fuel rail pressure (± 2%) as well as some variation in EGR and VGT position (± 2%). However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 5.5: B50U50 vs ULSD Summary

Based on analysis conducted using data from vehicles running with B50U50 blend, the following were the key observations and their possible impact on OBD monitors:

Engine-Out Soot emissions:

A key observation on the vehicles that had engine-out soot emissions measurements (Vehicle C and Vehicle D) was a significant reduction in engine-out soot emissions (~43-54% lower) when running with B50U50 blend compared to ULSD. This can be explained by the presence of biodiesel in the blend which increases oxygen content and reduces soot formation.

OBD Impact:

Some differences can be expected between true and modeled engine-out soot which is based on ULSD. Therefore, DPF regeneration interval and frequency could be affected due to the lower soot. There could also be some impact on DPF differential pressure measurements (lower due to lower soot). This could impact DPF regeneration frequency monitor and DPF differential pressure sensor monitor robustness.

ATS Temperatures:

Some variation in ATS temperatures were observed when using B50U50 blend compared to ULSD. Vehicles A, C and D showed slightly lower ATS temperatures when running with B50U50 blend compared to ULSD. The temperature differences were seen to be up to 14°C. Vehicle B did not show any significant temperature differences (± 3°C). However, some differences in temperatures can be well within run-to-run variation considering the differences in engine operating conditions due to the tests being conducted on chassis dynamometer. Overall, there was a trend seen for lower ATS temperatures with B50U50 blend possibly due to the 7% lower net heating value of B50U50 blend compared to ULSD.

OBD Impact:

The observed variation could impact ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values for each vehicle. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Overall, there may potentially be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

NO_x Emissions:

Some variation was also observed for engine-out NO_x emissions compared to ULSD. All vehicles showed higher engine-out NO_x emissions (up to 50 ppm). 50% biodiesel in the blend increases oxygen content of the fuel thereby increasing NO_x emissions. Tailpipe NO_x emissions on average (ppm basis) were slightly higher (up to 10 ppm). Cumulative tailpipe NO_x emissions (g) on FTP75 measured using the bench showed higher tailpipe NO_x emissions for all vehicles (up to 3 times higher in some phases of FTP75). This increase can be attributed to higher engine-out NO_x as well as lower SCR temperatures reducing SCR efficiency.

OBD Impact:

The variations in NO_x sensor values (ppm basis) observed could be large enough to affect NO_x sensor rationality monitor decisions. Some impact could also be expected on the OBD thresholds for NO_x emissions used to determine SCR efficiency monitor decisions, since total tailpipe NO_x emissions over the cycle (for B50U50) measured by bench (g) were higher when compared to ULSD.

Fuel Consumption:

Fuel consumption variation was 3-10% higher for Vehicles A, B and C compared to ULSD. However, Vehicle D showed lower fuel consumption. Some impact on fuel consumption is expected due to lower net heating value (mass and volume based) of B50U50 blend compared to ULSD. Vehicle D showed much lower fuel energy over test cycles with B50U50 compared to ULSD (8-11%), which could indicate differences in vehicle operation (cycle work) which could have contributed to some variation in fuel consumption. Slightly higher fuel rail pressure was also observed for Vehicles B & C (up to 5%) possibly due to the 2% higher density of B50U50 fuel.

OBD Impact:

From OBD perspective, the average variation in engine fuel rate (g/s) was within ± 0.1 g/s for Vehicles A, C and D. Therefore, no significant impact is expected on OBD monitor decisions. However, Vehicle B showed ~ 0.2 g/s difference on an average for some cycles which could impact fuel flow OBD monitor robustness.

Other PID Labels:

Some differences in boost pressure (± 2kPa), rail pressure (± 3%), EGR and VGT positions (± 5%) were observed, however these differences were well-within acceptable limits and run-to-run variation. Since the vehicles were tested using chassis dynamometer cycles, the engine operating conditions (engine speed and fueling) are not consistent between test runs due to driver-to-driver variation in running the same cycle. This results in different setpoints for air flow, EGR and VGT position during transient operation and therefore causes variations in the selected PID labels. The observed variations were therefore found to be well within this expected variation in engine operation.

Conclusion Summary for B50U50:

Based on data analysis conducted on chassis dynamometer data from all four vehicles on FTP75, FTP72 and LA92 cycles, it was concluded B50U50 blend showed some impact on the selected PID labels. However, the absence of OBD fault codes while running using B50U50 blend on all vehicles indicates that this impact was not large enough to impact OBD monitor robustness.

Chapter 6 : Fuel V: B50R50 Blend

This chapter describes the results and conclusions of the testing conducted on all four vehicles using B50R50 fuel utilizing the analysis approaches and metrics described in Section 1.6. The results have been divided into Sections 6.1, 6.2, 6.3 and 6.4 for Vehicles A, B, C and D respectively. Each section has the following that summarizes the results for B50R50 fuel compared to ULSD for each vehicle.

1. A table summarizing the results of the vehicle running on B50R50 compared to ULSD for all the test cycles. Key differences observed in engine performance and emissions when using B50R50 fuel compared to ULSD fuel using the "averaged" B50R50 and ULSD cycles for cold and hot FTP72 cycle, hot LA92 cycle and each phase of the FTP75 cycle are highlighted in these tables.
2. Plots showing average ATS temperatures, fuel energy, total engine-out and tailpipe NO_x emissions, engine-out soot emissions (when available) and cycle fuel consumption differences for the vehicle when using B50R50 fuel blend compared to ULSD. The values in the plots have been normalized using min-max normalization, where minimum value = 0 and maximum value was the maximum value in the plot. This was done to present important trends in engine performance while preserving anonymity of emissions and fuel consumption values.
3. Trend plots (% difference) showing PID labels for which significant increasing or decreasing trends were observed when running with B50R50 fuel compared to ULSD for that vehicle. Negative percent difference indicates lower and positive indicates higher compared to ULSD.

A summary of key observations and trends analyzed for the vehicles when running with B50R50 blend compared to ULSD and their possible impact on different OBD monitors is presented in Section 6.5.

Section 6.1: Vehicle A: B50R50 vs ULSD

Table 6.1: Vehicle A Results Summary: B50R50 vs ULSD

PID Labels	**Units**	**Test Cycle**						**Observations**
		FTP72		**FTP75**			**LA92**	
		Cold	**Hot**	**Phase 1 (Cold Start)**	**Phase 2 (Stabilized)**	**Phase 3 (Hot Start)**	**Hot**	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	Slightly Higher	Slightly Lower	No Difference	Slightly Lower	Slightly Lower	Slightly Higher	± 5%
Engine Fuel Rate	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	2 to 3% Higher
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa

DOC Inlet Temp	**°C**	Lower	-	Lower	Lower	Lower	-	Up to 18°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Lower	-	Lower	Lower	Lower	-	
DPF Outlet/SCR Inlet Temp	**°C**	Lower	-	Lower	Lower	Lower	-	
SCR Outlet Temp	**°C**	Lower	-	Lower	Lower	Lower	-	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 3% Lower
Engine Out NO_x Sensor	**ppm**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	No Difference	Up to 10 ppm
Tailpipe NOx Sensor	**ppm**	No Difference	No Difference	N/A	No Difference	N/A	NH3 Slip	± 2 ppm
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	Up to 4 ppm
Upstream O_2 Sensor	**%**	N/A	N/A	N/A	N/A	N/A	N/A	
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NOx	**g**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Lower	Up to 10% Higher
Calculated Tailpipe NOx	**g**	Higher	Lower	N/A	Lower	N/A	NH3 Slip	54% Lower to 3 times Higher
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Bench Tailpipe NOx	**g**	-	-	Slightly Higher	Higher	Higher	-	Up to 70% Higher
Bench Tailpipe CO_2	**g**	-	-	Lower	Lower	Lower	-	Up to 10% Lower
Total Cycle Fuel Consumption	**g**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	2 to 3% Higher
Engine-Out Soot	**mg**	-	-	-	-	-	-	

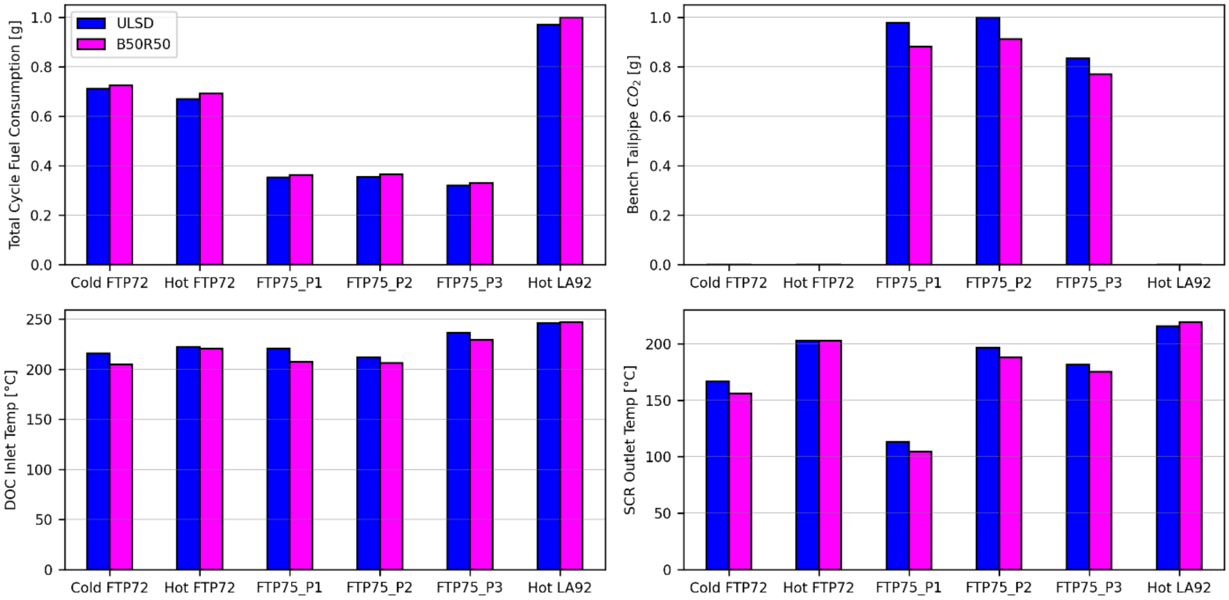

Figure 6.1: Vehicle A: B50R50 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

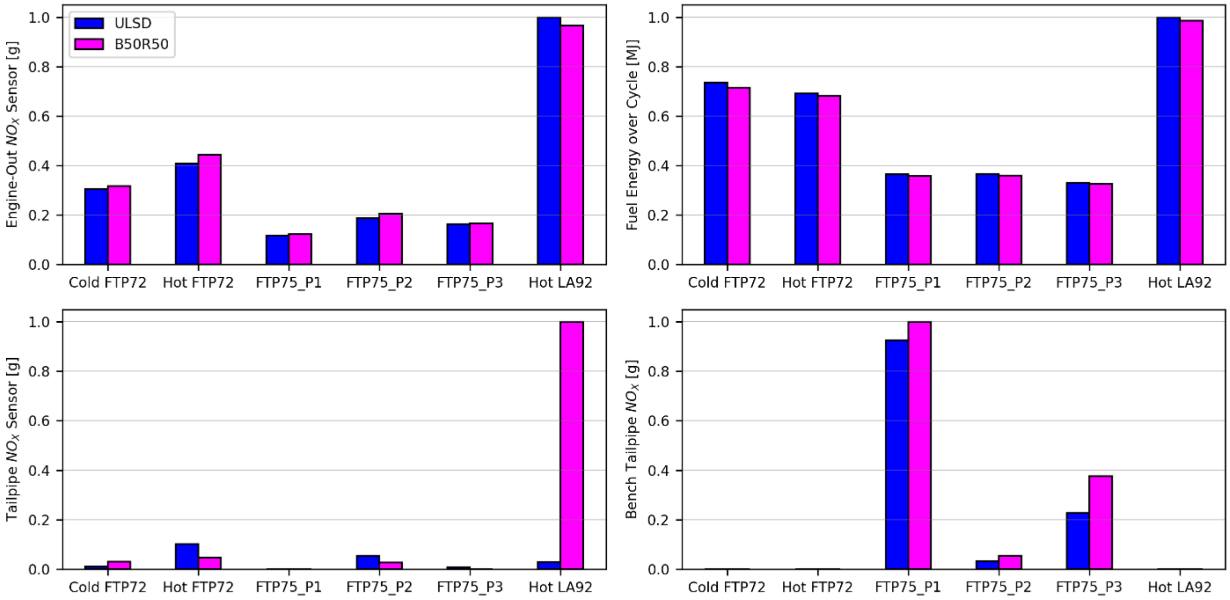

Figure 6.2: Vehicle A: B50R50 vs ULSD: Fuel Energy and NO_x Emissions

Key observations from Figure 6.1 and Figure 6.2 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 2 to 3% higher when running with B50R50 for the test cycles (Figure 6.1). B50R50 fuel has 5% lower net heating value per kg compared to ULSD (Table 1.3) which would explain the observed higher fuel consumption.

   The fuel energy used over all the cycles with B50R50 fuel was slightly lower compared to ULSD (2-3%) (Figure 6.2). This could indicate that cycle work was slightly lower compared to ULSD and therefore impact on fuel consumption could be higher than observed. From an OBD perspective, difference in average engine fuel rate (g/s) was ≤ 0.07 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were about 10% lower compared to ULSD for FTP75 cycle. This could be explained by 7% lower carbon content in B50R50 fuel compared to ULSD.

2. ATS temperatures (Figure 6.1): ATS temperatures were on average up to 18°C lower when running with B50R50 blend for FTP75 and cold FTP72 cycles. For hot FTP72 and LA92 cycles the ATS temperatures were slightly higher (5°C). However, this higher temperature could be attributed to cycle-to-cycle difference (hot FTP72 and LA92 cycles with B50R50 had higher starting ATS temperatures). The lower ATS temperatures could be attributed to the 5% lower net heating value (by mass) of B50R50 blend compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 6.2. Higher engine-out NO_x emissions were observed in general for all the cycles (up to 10 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore, some differences can be attributed to run-to-run variation. Higher engine-out NO_x emissions can be attributed to the biodiesel fuel in the blend which increases O_2 concentration in the fuel. Furthermore, cetane number of B50R50 blend could be higher due to R99 fuel in the blend which shortens ignition delay and contributes to increasing NO_x emissions.

   Tailpipe NO_x sensor emissions however showed very small variations (± 2 ppm) which are well within run-to-run variation. However, on LA92 cycle more NH_3 slip was observed with B50R50 fuel (due to differences in sequence of cycles run before LA92 cycle). Therefore, tailpipe NO_x emissions are higher on this cycle due to NH_3 to NO_x cross sensitivity of NO_x sensors. Higher cumulative bench tailpipe NO_x emissions (g) with B50R50 were observed (up to 70% higher) on FTP75 cycle primarily due to higher engine-out NO_x and lower ATS temperatures lowering SCR efficiency. On a ppm basis up to 4 ppm difference was observed on average compared to ULSD.

   From an OBD monitor perspective these differences may not be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, lower SCR efficiency is expected due to higher engine-out NO_x emissions and lower ATS temperatures with B50R50, which could affect NO_x emissions OBD limits used to determine monitor decisions.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B50R50 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle A using B50R50 fuel compared to ULSD fuel have been shown in. The higher ATS trends observed for LA92 cycle are due to starting ATS temperatures being higher for B50R50 fuel compared to ULSD. However, in general ATS temperatures with B50R50 fuel were seen to be lower as compared to ULSD fuel.

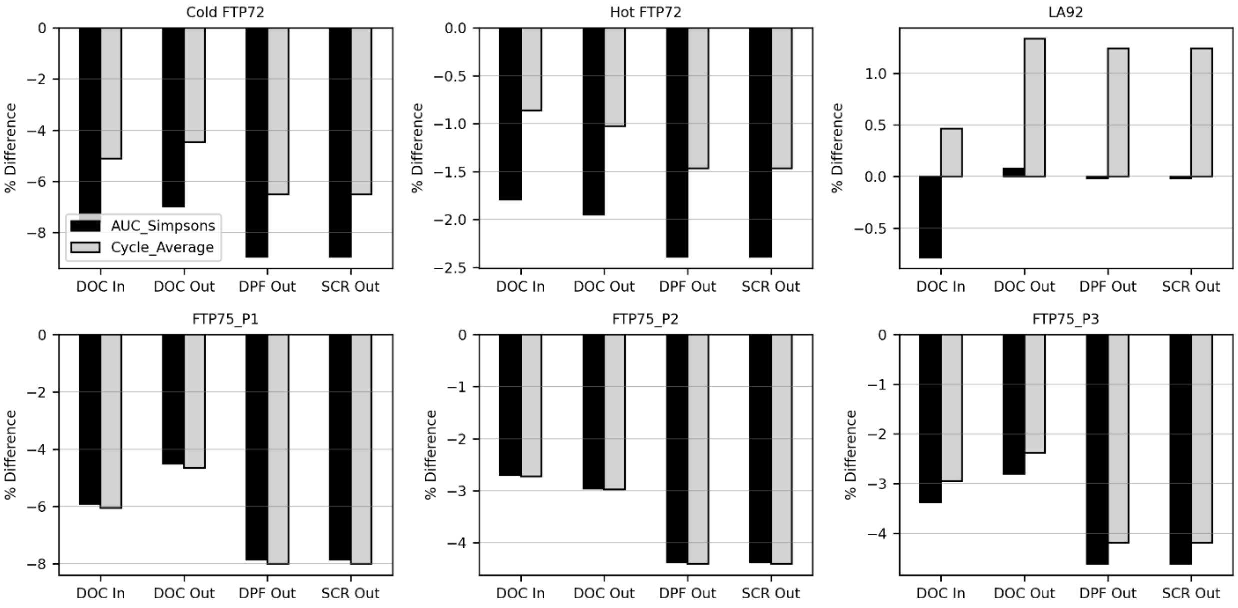

Figure 6.3: Vehicle A: B50R50 vs ULSD ATS Temperature Trends

Based on results from Table 6.1 and key observations presented, it can be concluded that there could potentially be some impact of B50R50 fuel on OBD monitor robustness for Vehicle A. Overall, B50R50 fuel showed some impact on ATS temperature as well as engine-out NO_x sensor values that could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management mode, DPF regeneration as well as NO_x sensor rationality and SCR efficiency monitors.

Other than the key observations presented, some variation was observed in all other PID labels as well - for example, slightly lower boost pressure (up to 2kPa), small differences in EGR (± 5%), slightly more closed VGT position (up to 4%) and up to ± 2% differences in fuel rail pressure and air flow. However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness. Also, post-test cycle OBD scans for test cycles tested with B50R50 fuel did not show any OBD fault codes for Vehicle A.

Section 6.2: Vehicle B: B50R50 vs ULSD_2

Table 6.2: Vehicle B Results Summary: B50R50 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	Slightly Higher	No Difference	Slightly Lower	No Difference	Slightly Higher	± 5%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Fuel Rate	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	5 to 8% Higher
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	7 to 14°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Engine Out NO_x Sensor	**ppm**	Slightly Lower	Slightly Higher	No Difference	No Difference	Slightly Higher	Slightly Higher	± 11 ppm
Tailpipe NO_x Sensor	**ppm**	-	-	-	-	-	-	NH3 Slip
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	Up to 6 ppm Higher
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	3-4% Higher
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	≤ 5 mg/s
Calculated Engine-Out NO_x	**g**	Slightly Lower	Higher	Slightly Higher	Slightly Lower	Higher	Higher	6% Lower to 17% Higher
Calculated Tailpipe NO_x	**g**	-	-	-	-	-	-	NH3 Slip
Calculated Exhaust Flow Rate	**kg/h**	No Difference	Slightly Higher	No Difference	Slightly Lower	No Difference	Slightly Higher	± 5%
Bench Tailpipe NO_x	**g**	-	-	Higher	Higher	Higher	-	Up to 2 times Higher
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	1 to 3% Lower
Total Cycle Fuel Consumption	**g**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	5 to 8% Higher
Engine-Out Soot	**mg**	-	-	-	-	-	-	

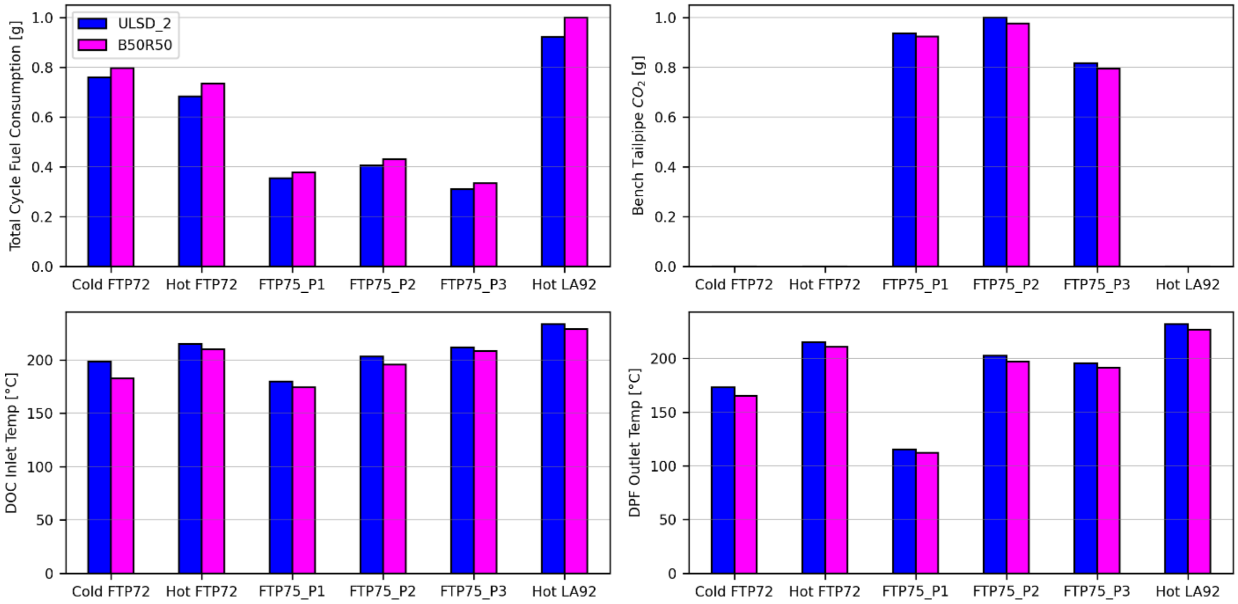

Figure 6.4: Vehicle B: B50R50 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

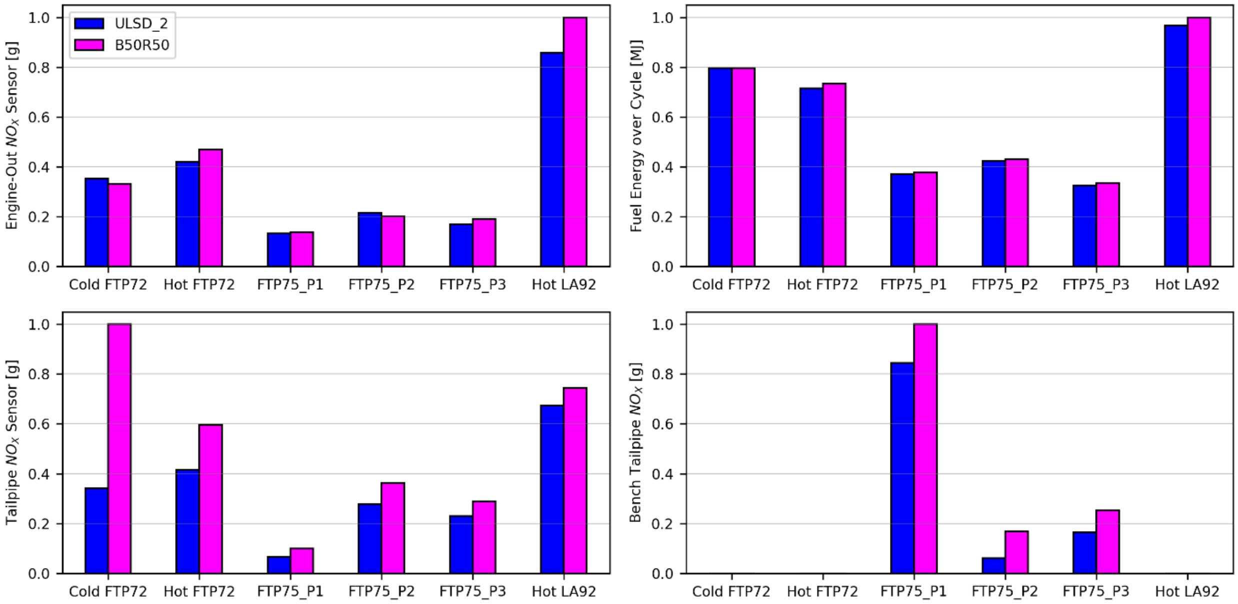

Figure 6.5: Vehicle B: B50R50 vs ULSD_2: Fuel Energy and NO_x Emissions

Key observations from Figure 6.4 and Figure 6.5 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycles increased by 5-8% when running with B50R50 fuel compared to ULSD (Figure 6.4). B50R50 fuel has 5% lower net heating value per kg compared to ULSD (Table 1.3), which could contribute to some increase in fuel consumption as observed in some cycles.

The fuel energy used over all the cycles with B50R50 fuel was slightly higher compared to ULSD (1-3%) (Figure 6.5). This could indicate that the cycle work was higher compared to ULSD which could also contribute to the higher fuel consumption observed. From an OBD perspective, difference in average engine fuel rate (g/s) over the cycles was ~ 0.12 g/s. Therefore, there could be some impact on fuel flow OBD monitors.

CO_2 emissions were ~1-3% lower compared to ULSD for FTP75 cycle. This could be explained by the 4-8% higher fuel consumption but 7% lower carbon content (by weight) of B50R50 fuel compared to ULSD.

2. ATS temperatures (Figure 6.4): ATS temperatures when running with B50R50 fuel were slightly lower (up to 14°C) compared to ULSD. This could be attributed to the 5% lower net heating value of B50R50 fuel compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 6.5. Engine-out NO_x emissions variation was seen to be within ± 11 ppm. However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some of this difference could be attributed to run-to-run variation. Higher engine-out NO_x emissions are expected due to biodiesel in the blend which increases O_2 concentration in the fuel. However, renewable diesel in the blend could be lowering engine-out NO_x emissions (as seen in Section 2.2). Therefore, the trend of engine-out NO_x emissions with B50R50 fuel is unclear in the test cycles for Vehicle B.

   For Vehicle B, trends for tailpipe NO_x sensor emissions were inconclusive. This was primarily because all cycles on Vehicle B always showed some amount of NH_3 slip throughout the cycle which seemed to strongly affect tailpipe NO_x sensor values. This is due to the cross-sensitivity of NO_x sensors to NH_3 which increases tailpipe NO_x sensor measured NO_x values to higher than actual values. The cumulative bench tailpipe NO_x (g) showed up to 2 times higher tailpipe NO_x emissions trend on FTP75 cycle with B50R50. However, on a ppm basis up to 6 ppm difference was observed on the bench for B50R50 blend compared to ULSD. Therefore, overall, no significant impact is expected on tailpipe NO_x sensor measurements.

From an OBD monitor perspective these differences could be well within sensor accuracy limits and may not be considered large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the slightly higher engine-out NO_x emissions and overall lower ATS temperatures observed with B50R50 blend, which could affect NO_x emissions OBD limits used to determine monitor decisions.

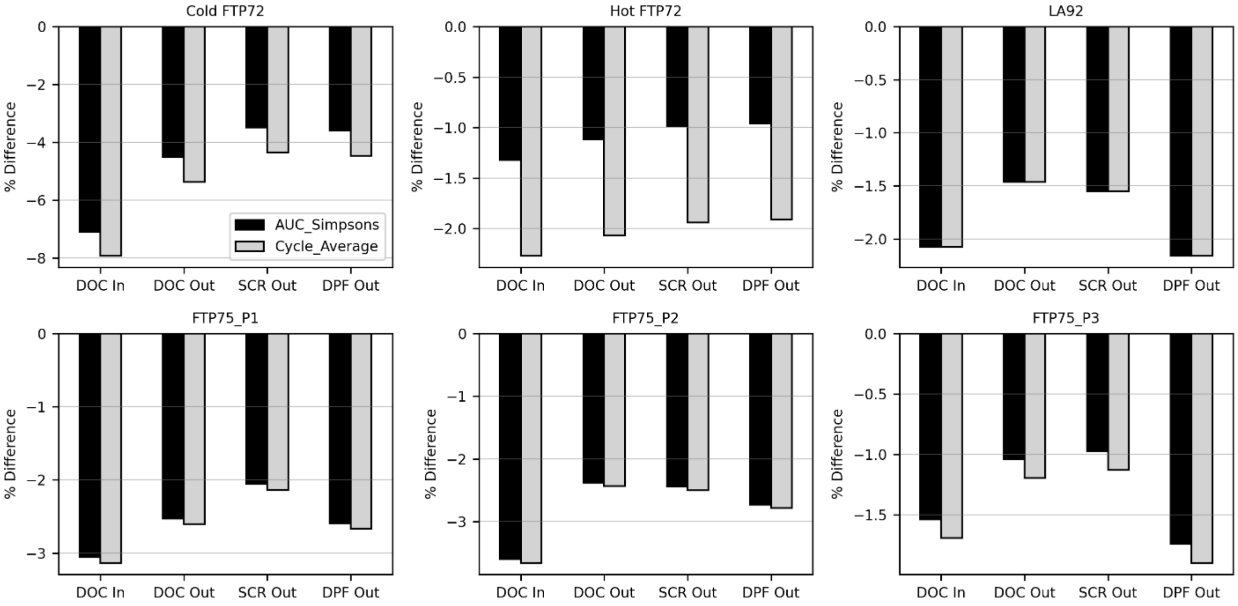

Figure 6.6: Vehicle B: B50R50 vs ULSD_2 ATS Temperature Trends

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B50R50 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle B using B50R50 blend compared to ULSD fuel have been shown in Figure 6.6.

Based on results from Table 6.2 and key observations presented, it can be concluded that there could potentially be some impact of B50R50 blend on OBD monitor robustness for Vehicle B. Overall, B50R50 blend showed some impact on ATS temperatures and engine-out NO_X emissions which could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management mode, DPF regeneration, SCR efficiency and NO_X sensor rationality.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 6.2. For example, boost pressure (± 2 kPa), ± 5% variation in air flow and slightly higher fuel rail pressure (3-4%) possibly due to presence of higher density biodiesel in the blend. However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness. Also, post-test cycle OBD scans for test cycles tested with B50R50 blend did not show any OBD fault codes for Vehicle B.

Section 6.3: Vehicle C: B50R50 vs ULSD_2

Table 6.3: Vehicle C Results Summary: B50R50 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
Exhaust Pressure	**kPa**	N/A	N/A	N/A	N/A	N/A	N/A	
DOC Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 13°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 5%
Engine Out NO_x Sensor	**ppm**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Higher	Up to 30 ppm
Tailpipe NO_x Sensor	**ppm**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 ppm
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	Slightly Higher	No Difference	No Difference	No Difference	No Difference	No Difference	Up to 5% Higher
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NO_x	**g**	Slightly Higher	Higher	Slightly Higher	Higher	Higher	Higher	Up to 32% Higher
Calculated Tailpipe NO_x	**g**	Slightly Higher	Higher	N/A	Higher	Higher	Higher	Up to 87% Higher
Calculated Exhaust Flow Rate	**kg/h**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
Bench Tailpipe NO_x	**g**	-	-	Higher	Higher	Higher	-	Up to 2 times Higher
Bench Tailpipe CO_2	**g**	-	-	Lower	Lower	Lower	-	15 to 19% Lower
Total Cycle Fuel Consumption	**g**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
Engine-Out Soot	**mg**	-	-	Lower	Lower	Lower	-	Up to 74% Lower

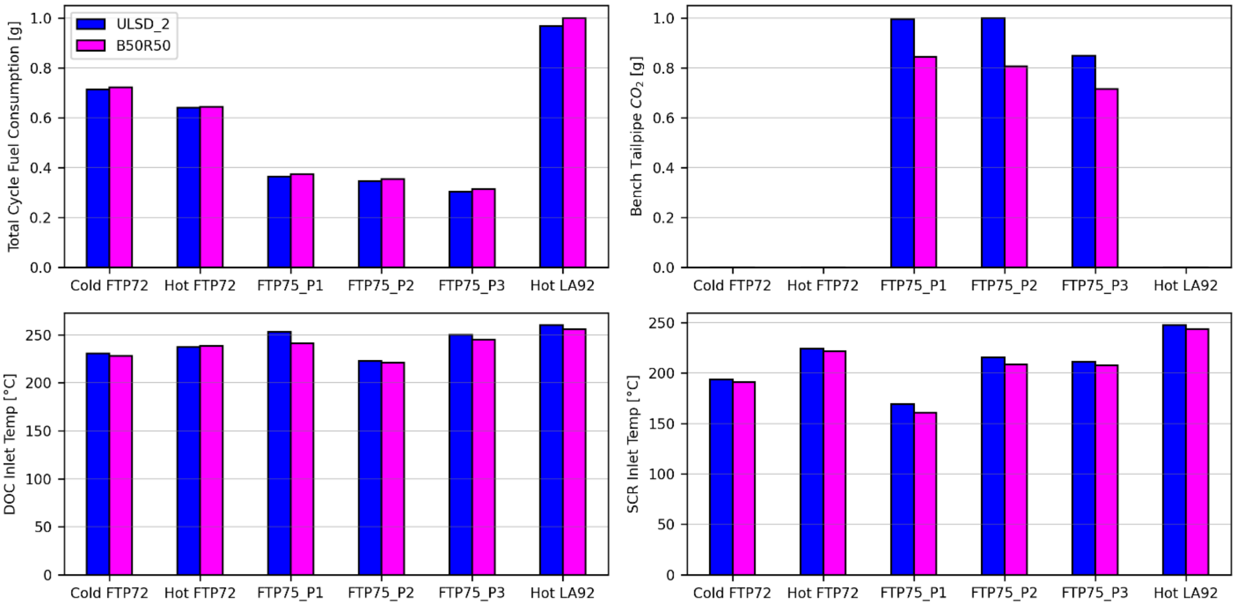

Figure 6.7: Vehicle C: B50R50 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

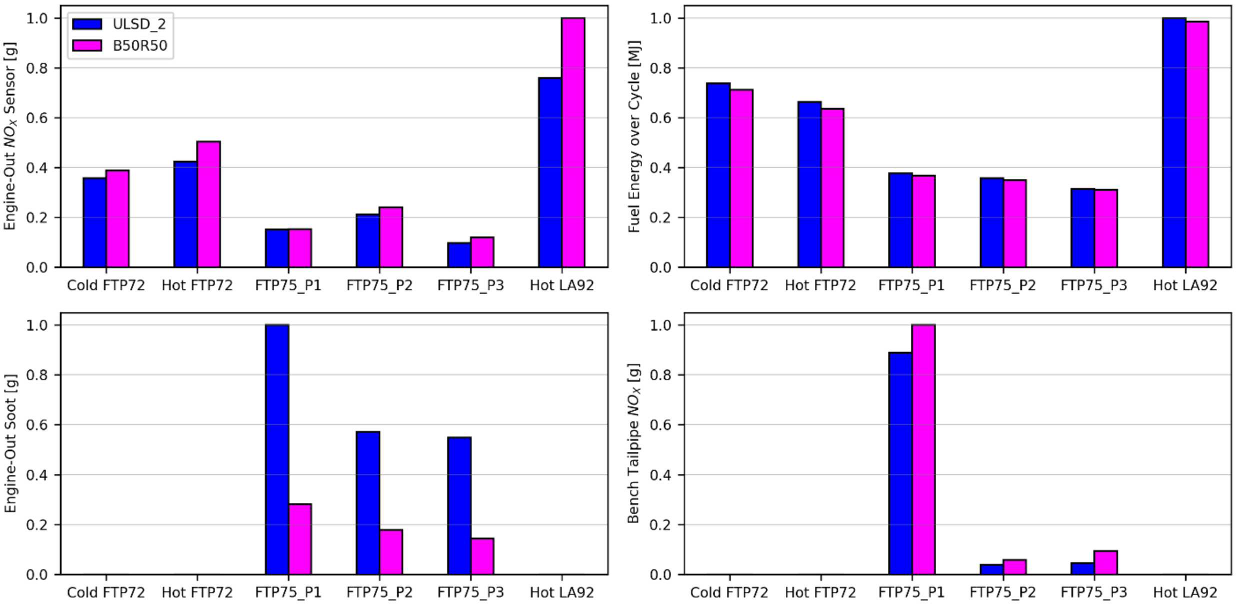

Figure 6.8: Vehicle C: B50R50 vs ULSD_2: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure 6.7 and Figure 6.8 are as follows:

1. Fuel consumption/CO_2 Emissions (g): For Vehicle C, with B50R50 blend, the fuel consumption was higher (up to 4%) (Figure 6.7). B50R50 fuel has lower net heating value per kg (~5%) compared to ULSD (Table 1.3). This could explain higher fuel consumption seen on all the cycles.

   The fuel energy used over all the cycles with B50R50 blend was slightly lower compared to ULSD (up to 4%) (Figure 6.8). This could indicate differences in cycle work compared to ULSD. From an OBD perspective, difference in average engine fuel rate (g/s) over the cycles was within ≤ 0.05 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions were ~15 to 19% lower compared to ULSD for FTP75 cycle. This could be explained by the 6% lower carbon content (% weight) in B50R50 blend.

2. ATS temperatures (Figure 6.7): ATS temperatures were on average slightly lower on all the cycles (up to 13°C). The lower ATS temperatures may be explained by the 5% lower net heating value of B50R50 blend compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 6.8. A trend of higher engine-out NO_x emissions was observed over the test cycles (up to 30 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. B50R50 blend contains 50% biodiesel which increases the oxygen content of the fuel increasing NO_x emissions. Trends in engine-out NO_x emissions have been unclear in studies with R99 fuel (50% of the blend) [3,9,21]. Since R99 fuel has a higher cetane number, combustion (CA50) may be advanced which could have resulted in the observed higher engine-out NO_x emissions.

   Tailpipe NO_x sensor values were seen to be very similar to ULSD. However, based on cumulative bench higher tailpipe NO_x emissions (g) were observed on FTP75 cycle with B50R50 blend (up to 2 times higher). This could be explained by the higher engine-out NO_x and slightly lower ATS temperatures lowering SCR efficiency. On a ppm basis however, this difference was < 2 ppm difference on average compared to ULSD.

   From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the lower ATS temperatures and higher engine-out NO_x emissions with B50R50 blend, which could affect NO_x emissions OBD limits used to determine monitor decisions.

4. Soot Emissions (Figure 6.11): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to biodiesel fuel in the blend

which increases oxygen content of the fuel thereby reducing soot production. Further B50R50 blend has almost zero aromatics which reduces the propensity for soot formation. Overall, up to 74% lower soot emissions were observed when running Vehicle C with B50R50 blend compared to ULSD.

From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

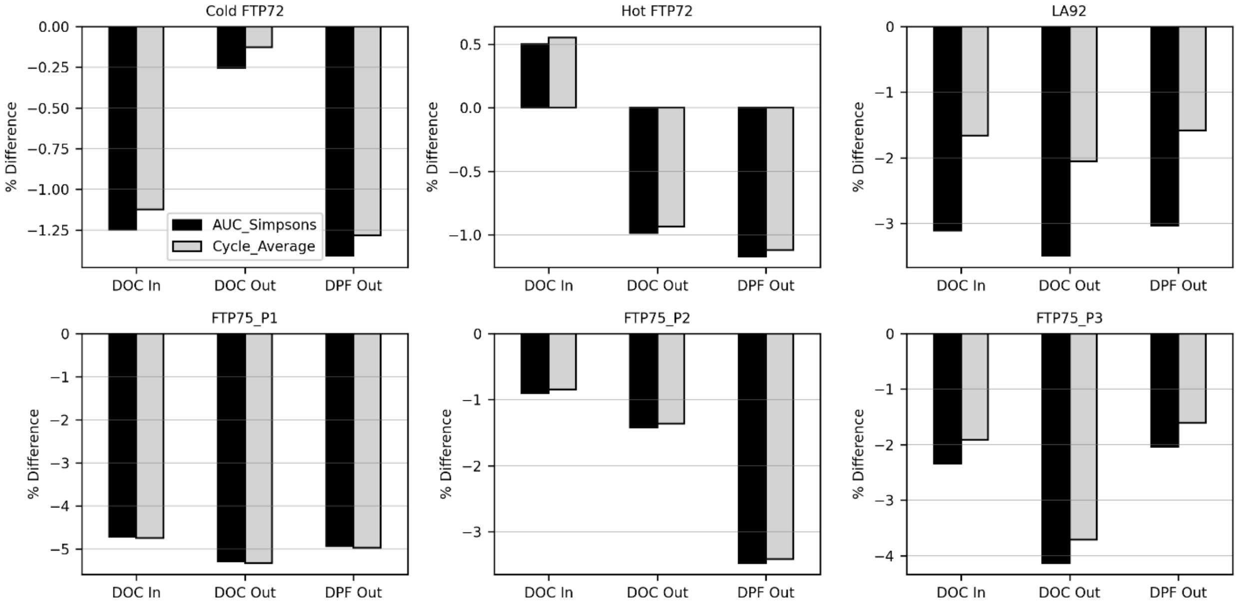

Figure 6.9: Vehicle C: B50R50 vs ULSD_2 ATS Temperature Trends

Based on results from Table 6.3 and key observations presented, it can be concluded that there could potentially be some impact of B50R50 fuel on OBD monitor robustness for Vehicle C. Overall, B50R50 blend showed some impact on ATS temperatures, engine-out NO_x and soot emissions which could possibly impact OBD monitor decisions including ATS temperature rationality, DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with B50R50 blend did not show any OBD fault codes for Vehicle C.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 6.3. For example, boost pressure (± 2 kPa) and some differences in fuel rail pressure, air flow, calculated lambda, EGR and VGT positions. However, Vehicle C also had run-to-run differences due to a feature that was inconsistent for runs with ULSD and B50R50 blend. Therefore, these observed variations were not considered to be significant enough to impact OBD robustness.

Section 6.4: Vehicle D: B50R50 vs ULSD

Table 6.4: Vehicle D Results Summary: B50R50 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 7% Lower
Intake Manifold Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	**g/s**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	No Difference	Slightly Lower	Up to 7% Lower
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	Lower	Lower	Lower	Lower	Lower	Lower	Up to 20°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Lower	Lower	Lower	Lower	Lower	Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Lower	Lower	Lower	Lower	Lower	Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	**ppm**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Higher	Slightly Lower	No Difference	Up to 12 ppm Lower
Tailpipe NO_x Sensor	**ppm**	N/A	N/A	N/A	N/A	N/A	N/A	
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	Up to 10 ppm Higher
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**mg/s**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Engine-Out NO_x	**g**	Slightly Lower	Slightly Lower	No Difference	No Difference	No Difference	Slightly Lower	Up to 12% Lower
Calculated Tailpipe NO_x	**g**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Exhaust Flow Rate	**kg/h**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 7% Lower
Bench Tailpipe NO_x	**g**	-	-	Higher	Higher	Higher	-	Up to 3 times Higher
Bench Tailpipe CO_2	**g**	-	-	Lower	Lower	Lower	-	Up to 12% Lower
Total Cycle Fuel Consumption	**g**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	No Difference	Slightly Lower	Up to 7% Lower
Engine-Out Soot	**mg**	-	-	Lower	Lower	Lower	-	Up to 86% Lower

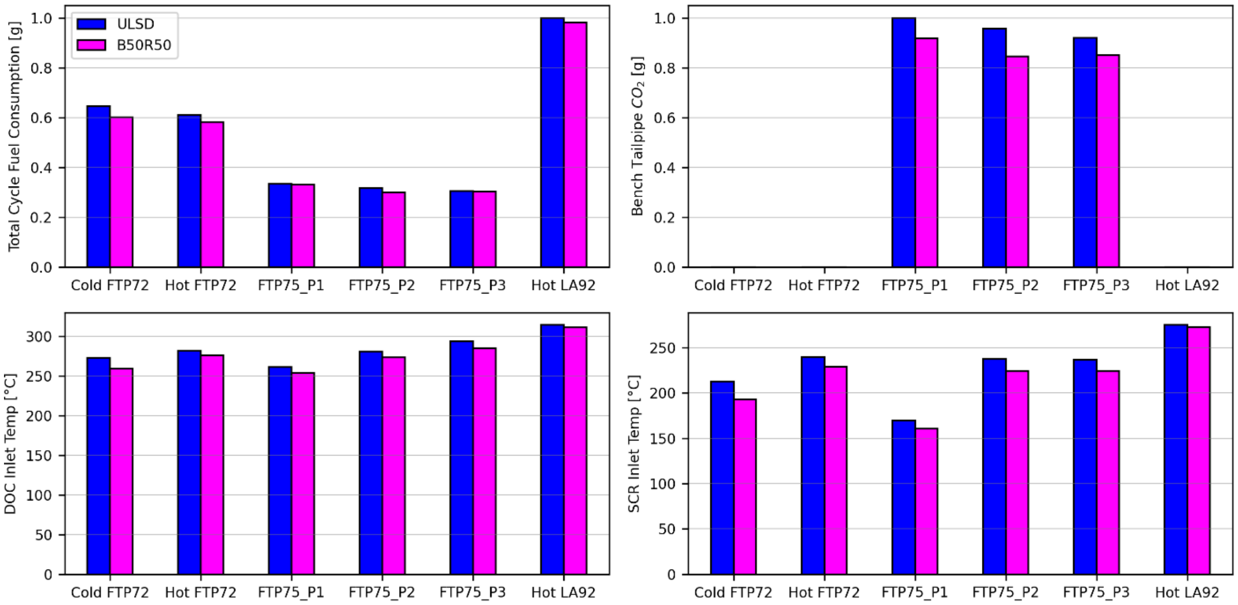

Figure 6.10: Vehicle D: B50R50 vs ULSD: Fuel Consumption, CO₂ Emissions and ATS Temperatures

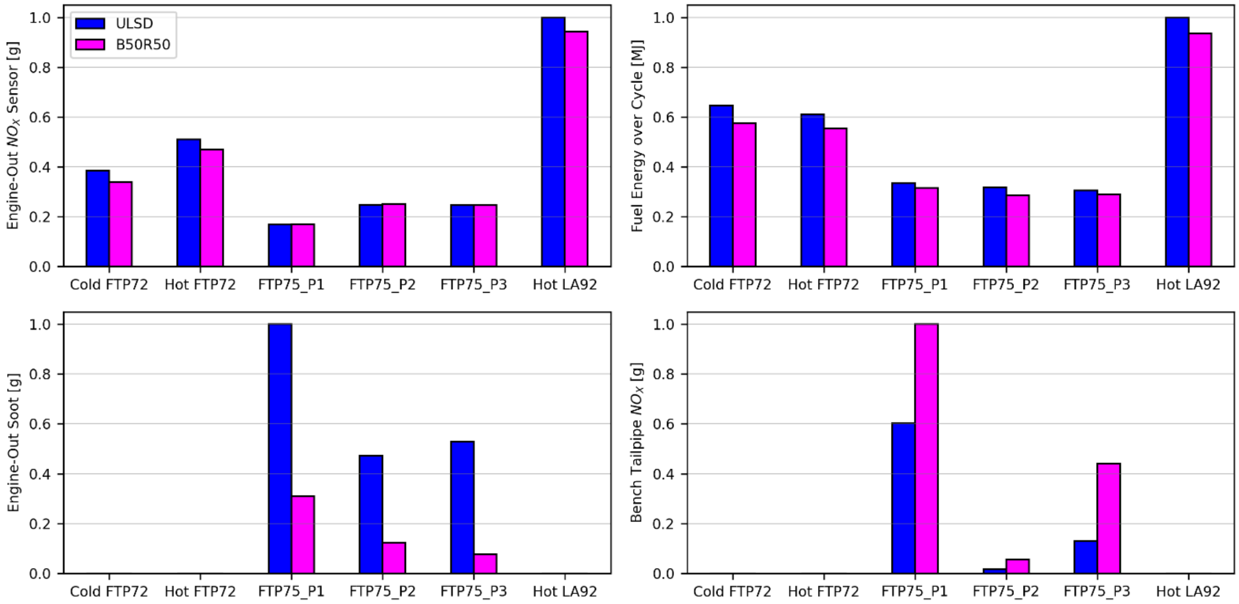

Figure 6.11: Vehicle D: B50R50 vs ULSD: Fuel Energy, Soot and NOₓ Emissions

Key observations from Figure 6.10 and Figure 6.11 are as follows:

1. Fuel consumption/CO$_2$ Emissions (g): Total fuel consumption over the cycle was up to 7% lower when running with B50R50 (Figure 6.10). B50R50 fuel has 5% lower net heating value per kg compared to ULSD (Table 1.3). However, the fuel energy used over all the cycles with B50R50 fuel was up to 11% lower compared to ULSD (Figure 6.11). This could indicate differences between vehicle operation (lower cycle work) when running with B50R50 compared to ULSD which could also explain the overall lower fuel consumption.

From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were ≤ 0.08 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness.

CO_2 emissions differences were about 12% lower for FTP75 cycle which can be explained by 6% lower carbon content of B50R50 fuel as well as lower fuel energy used compared to ULSD.

2. ATS temperatures (Figure 6.10): ATS temperatures were on average lower on all cycles (up to 20°C). The lower ATS temperatures can be explained by the lower fuel energy used over the cycles (5-11%) as well as lower net heating value (5%) of B50R50 fuel compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 6.11. Overall, some variation in engine-out NO_x emissions were observed across all the test cycles (± 10 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some difference could be attributed to run-to-run variation. The unclear trend in NO_x emissions might also be due to the lower fuel energy over the cycles with B50R50 leading to lower NO_x emissions.

   Cumulative bench tailpipe NO_x emissions (g) with B50R50 were up to 3 times higher on FTP75 cycle. Also, on a ppm basis ~10 ppm difference was observed on an average compared to ULSD. This higher tailpipe NO_x emissions can be explained by the lower ATS temperatures (up to 20°C) observed leading to lower SCR efficiency.

   From an OBD monitor perspective these differences can be well within sensor accuracy limits and may not be considered large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults or SCR efficiency monitor decisions. However, from an SCR efficiency perspective, lower SCR efficiency due to the lower ATS temperatures with B50R50, could affect OBD NO_x emissions limits used to determine monitor decisions.

4. Soot Emissions (Figure 6.11): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to higher oxygen content in

the blend due to biodiesel which reduces the propensity for soot formation. Further B50R50 blend has almost zero aromatics which reduces the propensity for soot formation. Overall, up to 86% lower soot emissions were observed when running with B50R50 compared to ULSD.

From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

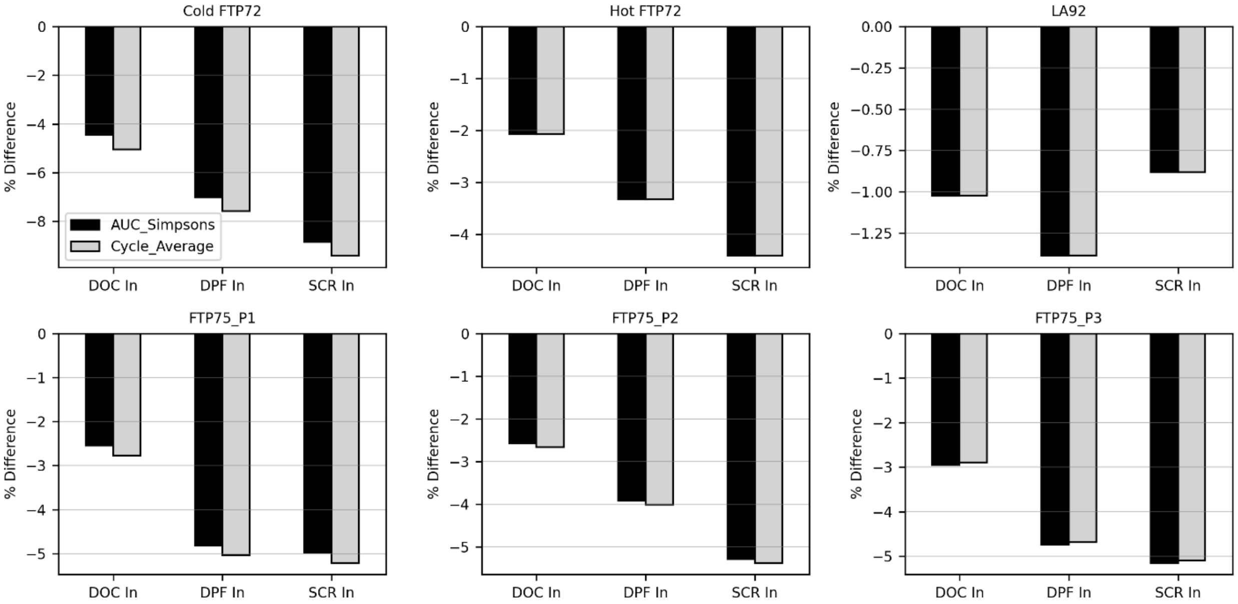

Figure 6.12: Vehicle D: B50R50 vs ULSD ATS Temperature Trends

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B50R50 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle A using B50R50 fuel compared to ULSD fuel have been shown in Figure 6.12. In general, ATS temperatures with B50R50 fuel were seen to be lower as compared to ULSD fuel.

Based on results from Table 6.4 and key observations presented, it can be concluded that there could potentially be some impact of B50R50 fuel on OBD monitor robustness for Vehicle D. Overall, B50R50 fuel showed some impact on ATS temperatures, engine-out NO_x and soot emissions that could possibly impact OBD monitor decisions for ATS temperature rationality, thermal management, DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with B50R50 fuel did not show any OBD fault codes.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 6.4. Slightly lower boost pressure (up to 3 kPa), fuel rail pressure (up to 4%) was observed as well as some variation in EGR and VGT position (± 2%). However, fuel energy used over the cycles with B50R50 were lower than the cycles with ULSD which indicates differences in vehicle operating conditions which could cause the observed variations. Therefore, it cannot be conclusively determined if these variations are due to impact of B50R50 fuel on the PID labels.

Section 6.5: B50R50 vs ULSD Summary

Based on analysis conducted using data from vehicles running with B50R50 blend, the following were the key observations and their possible impact on OBD monitors:

Engine-Out Soot emissions:

A key observation on the vehicles that had engine-out soot emissions measurements (Vehicle C and Vehicle D) was a significant reduction in engine-out soot emissions (~74-86% lower) when running with B50R50 blend compared to ULSD. This can be explained by higher cetane number of R99 fuel in the blend compared to ULSD improving combustion efficiency. The almost zero aromatic content of B50R50 blend also reduces the propensity for soot formation. Also, the presence of biodiesel in the blend increases oxygen content and reduces soot formation.

OBD Impact:

Some differences can be expected between true and modeled engine-out soot which is based on ULSD. Therefore, DPF regeneration interval and frequency could be affected due to the lower soot. There could also be some impact on DPF differential pressure measurements (lower due to lower soot). This could impact DPF regeneration frequency monitor and DPF differential pressure sensor monitor robustness.

ATS Temperatures:

Some variation in ATS temperatures were observed when using B50R50 blend compared to ULSD. All vehicles showed lower ATS temperatures when running with B50R50 blend compared to ULSD. The temperature differences were seen to be up to 20°C on average. However, some differences in temperatures can be due to run-to-run variation considering the differences in engine operating conditions due to the tests being conducted on chassis dynamometer. Overall, there was a trend seen for lower ATS temperatures with B50R50 fuel which could be due to the 5% lower net heating value (by mass) of B50R50 blend compared to ULSD.

OBD Impact:

The observed variation could impact ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values for each vehicle. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Overall, there may potentially be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

NO_x Emissions:

Some variation was also observed for engine-out NO_x emissions compared to ULSD. Vehicles A, B and C showed higher engine-out NO_x emissions (up to 30 ppm). 50% biodiesel in the blend increases oxygen content of the fuel thereby increasing NO_x emissions. However, 50% R99 fuel in the blend could also help to reduce tailpipe NO_x emissions. Vehicle D showed slightly lower engine-out NO_x emissions. However, this could be attributed to the lower fuel energy observed for Vehicle D for all the cycles with B50R50 which could indicate differences in vehicle operation rather than fuel impact. Tailpipe NO_x emissions on average (ppm basis) differences were within ± 2 ppm. However, cumulative tailpipe NO_x emissions (g) on FTP75 measured using the bench showed higher tailpipe NO_x emissions for all vehicles (up to 3 times higher in some phases of FTP75). This increase can be attributed to higher engine-out NO_x as well as lower SCR temperatures reducing SCR efficiency.

OBD Impact:

The variations in NO_x sensor values (ppm basis) observed could be large enough to affect NO_x sensor rationality monitor decisions. Also, some impact could be expected on the OBD thresholds for NO_x emissions used to determine SCR efficiency monitor decisions, since total tailpipe NO_x emissions over the cycle (for B50R50) measured by bench (g) was higher compared to ULSD.

Fuel Consumption:

Fuel consumption variation was 3-8% higher for Vehicles A, B and C compared to ULSD. However, Vehicle D showed lower fuel consumption. Some impact on fuel consumption is expected due to lower net heating value (mass and volume based) of B50R50 blend compared to ULSD. Vehicle D showed much lower fuel energy with B50R50 compared to ULSD for all the cycles (8-11% lower), which could indicate differences in vehicle operation (cycle work) which could have also contributed to some variation in fuel consumption.

OBD Impact:

From OBD perspective, the average variation in engine fuel rate (g/s) was within ± 0.1 g/s for Vehicles A, C and D. Therefore, no significant impact is expected on OBD monitor decisions. However, Vehicle B showed ~ 0.12 g/s difference on average for some cycles which may impact fuel flow OBD monitor robustness.

Other PID Labels:

Some differences in boost pressure (± 2kPa), rail pressure (± 3%), EGR and VGT positions (± 5%) were observed, however these differences were well-within acceptable limits and run-to-run variation. Since the vehicles were tested using chassis dynamometer cycles, the engine operating conditions (engine speed and fueling) are not consistent between test runs due to driver-to-driver variation in running the same cycle. This results in different setpoints for air flow, EGR and VGT position during transient operation and therefore causes variations in the selected PID labels. The observed variations were therefore found to be well within this expected variation in engine operation.

Conclusion Summary for B50R50:

Based on data analysis conducted on chassis dynamometer data from all four vehicles on FTP75, FTP72 and LA92 cycles, it was concluded B50R50 blend showed some impact on the selected PID labels. However, the absence of OBD fault codes while running using B50R50 blend on all vehicles indicates that this impact was not large enough to impact OBD monitor robustness.

Chapter 7 : Fuel VI: B100

This chapter describes the results and conclusions of the testing conducted on all four vehicles using B100 fuel utilizing the analysis approaches and metrics described in Section 1.6. The results have been divided into Sections 7.1, 7.2, 7.3 and 7.4 for Vehicles A, B, C and D respectively. Each section has the following that summarizes the results for B100 fuel compared to ULSD for each vehicle.

1. A table summarizing the results of the vehicle running on B100 compared to ULSD for all the test cycles. Key differences observed in engine performance and emissions when using B100 fuel compared to ULSD fuel using the “averaged” B100 and ULSD cycles for cold and hot FTP72 cycle, hot LA92 cycle and each phase of the FTP75 cycle are highlighted in these tables.
2. Plots showing average ATS temperatures, fuel energy, total engine-out and tailpipe NO_x emissions, engine-out soot emissions (when available) and cycle fuel consumption differences for the vehicle when using B100 fuel blend compared to ULSD. The values in the plots have been normalized using min-max normalization, where minimum value = 0 and maximum value was the maximum value in the plot. This was done to present important trends in engine performance while preserving anonymity of emissions and fuel consumption values.
3. Trend plots (% difference) showing PID labels for which significant increasing or decreasing trends were observed when running with B100 fuel compared to ULSD for that vehicle. Negative percent difference indicates lower and positive indicates higher compared to ULSD.

A summary of key observations and trends analyzed for the vehicles when running with B100 fuel compared to ULSD and their possible impact on different OBD monitors is presented in Section 7.5.

Section 7.1: Vehicle A: B100 vs ULSD

Table 7.1: Vehicle A Results Summary: B100 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	Slightly Lower	No Difference	No Difference	No Difference	No Difference	Up to 5% lower
Engine Fuel Rate	**g/s**	Higher	Higher	Higher	Higher	Higher	Higher	Up to 14% Higher
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa

DOC Inlet Temp	**°C**	Lower	Slightly Lower	Lower	Lower	Lower	Slightly Lower	Up to 23°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Lower	Slightly Lower	Lower	Lower	Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Lower	Slightly Lower	Lower	Lower	Lower	Slightly Lower	
SCR Outlet Temp	**°C**	Lower	Slightly Lower	Lower	Lower	Lower	Slightly Lower	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 10% Lower
Engine Out NO_x Sensor	**ppm**	Higher	Higher	Higher	Higher	Higher	Higher	Up to 50 ppm
Tailpipe NOx Sensor	**ppm**	-	-	-	-	-	-	NH_3 Slip
Bench Tailpipe NOx Conc	**ppm**	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	Up to 15 ppm
Upstream O_2 Sensor	**%**	N/A	N/A	N/A	N/A	N/A	N/A	
Fuel Rail Pressure	**kPa**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	2-5%
VGT Position	**%**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 3% Higher
DEF Dosing	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
Calculated Engine-Out NOx	**g**	Higher	Higher	Higher	Higher	Higher	Higher	Up to 43% Higher
Calculated Tailpipe NOx	**g**	-	-	-	-	-	-	NH_3 Slip
Calculated Exhaust Flow Rate	**kg/h**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
Bench Tailpipe NOx	**g**	-	-	Higher	Higher	Higher	-	Up to 6 times Higher
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 5% Lower
Total Cycle Fuel Consumption	**g**	Higher	Higher	Higher	Higher	Higher	Higher	Up to 14% Higher
Engine-Out Soot	**mg**	-	-	-	-	-	-	

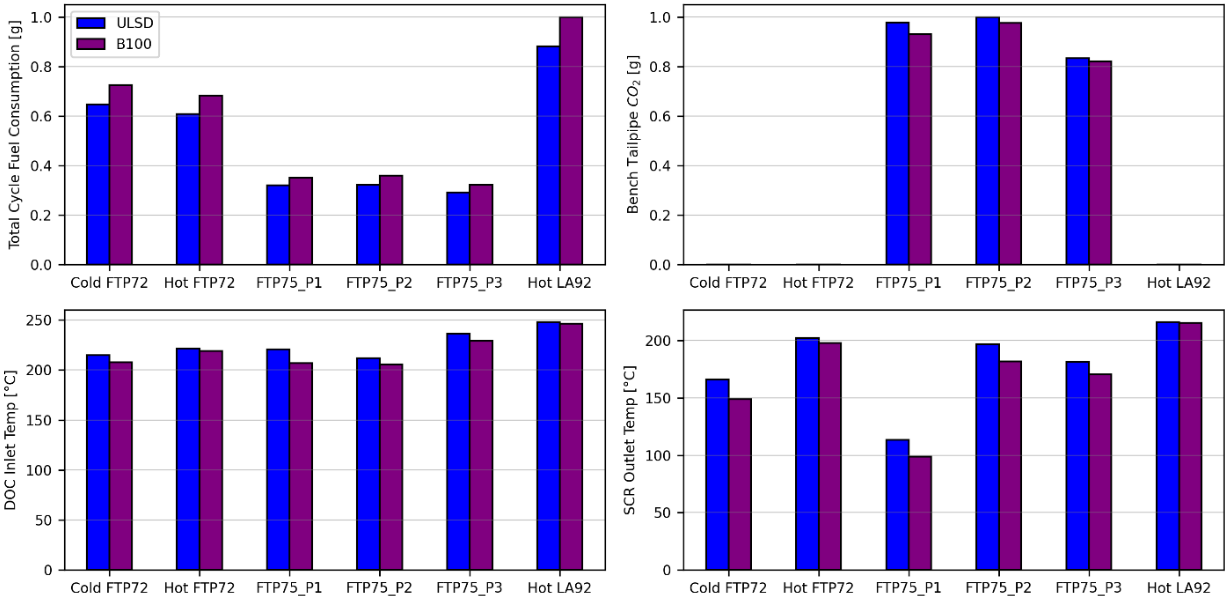

Figure 7.1: Vehicle A: B100 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

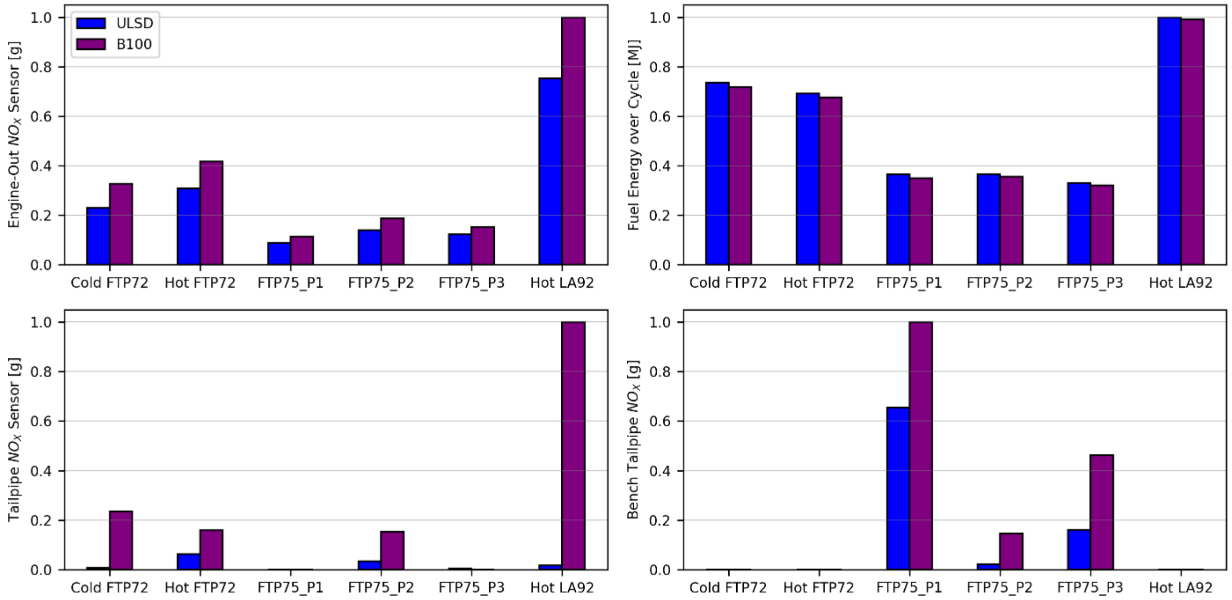

Figure 7.2: Vehicle A: B100 vs ULSD: Fuel Energy and NO_x Emissions

Key observations from Figure 7.1 and Figure 7.2 are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 14% higher when running with B100 for the test cycles (Figure 7.12). B100 fuel has 13% lower net heating value per kg compared to ULSD (Table 1.3) which would explain the observed higher fuel consumption.

   The fuel energy used over all the cycles with B100 fuel was slightly lower compared to ULSD (3-4%) (Figure 7.2). This could indicate some differences in cycle work which could also impact fuel consumption. From an OBD perspective, differences in average engine fuel rate (g/s) were ~ 0.2 g/s. Therefore, there could be some impact on OBD monitor robustness.

CO_2 emissions were about 5% lower compared to ULSD for FTP75 cycle. This could be explained by 10% lower carbon content in B100 fuel compared to ULSD.

2. ATS temperatures (Figure 7.1): ATS temperatures were on average ~23°C lower when running with B100 fuel for FTP75 and cold FTP72 cycles. For hot FTP72 and LA92 cycles the ATS temperatures were about 10°C lower. However, this smaller difference in ATS temperatures could be attributed to cycle-to-cycle difference (hot FTP72 and LA92 cycles with B100 had higher starting ATS temperatures compared to ULSD). The lower ATS temperatures could be attributed to the 13% lower net heating value (by mass) of B100 fuel compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 7.2. Higher engine-out NO_x emissions were observed in general for all the cycles (up to 50 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore, some differences can be attributed to run-to-run variation. Higher engine-out NO_x emissions can be attributed to higher O_2 in the fuel as well as lower effectiveness of EGR due to higher O_2 in the exhaust [29].

   Tailpipe NO_x sensor emissions trends were inconclusive because test cycles with B100 showed higher NH_3 slip than test cycles with ULSD. Therefore, tailpipe NO_x emissions are much higher due to NH_3 to NO_x cross sensitivity of NO_x sensors. However, this is possibly due to differences in test sequences between B100 and ULSD cycles. Impact of fuel on NH_3 slip cannot be conclusively understood without more data such as NH_3 storage of SCR. Higher cumulative bench tailpipe NO_x emissions with B100 for FTP75 cycle were observed (up to 6 times higher for Phase 2) primarily due to higher engine-out NO_x and lower ATS temperatures lowering SCR efficiency. On a ppm basis up to 15 ppm difference was observed on an average compared to ULSD.

   From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, lower SCR efficiency is expected due to higher engine-out NO_x emissions and lower ATS temperatures with B100, which could affect NO_x emissions OBD limits used to determine monitor decisions.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B100 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle A using B100 fuel compared to ULSD fuel have been shown in Figure 7.3. Overall, ATS temperatures with B100 fuel were seen to be lower as compared to ULSD fuel.

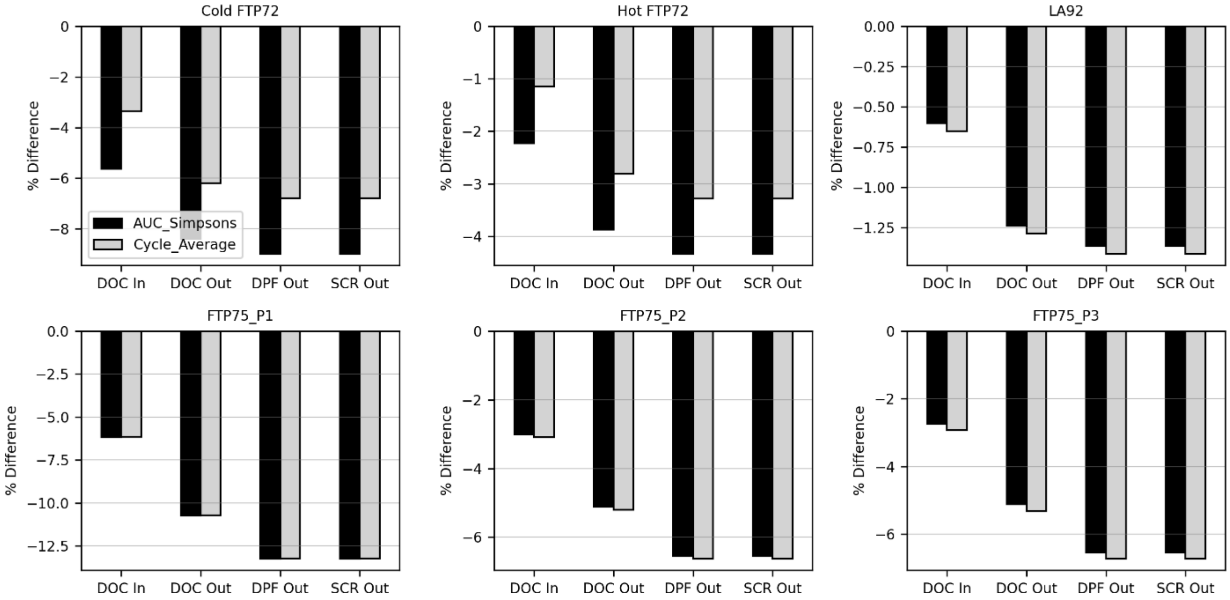

Figure 7.3: Vehicle A: B100 vs ULSD ATS Temperature Trends

Slightly higher fuel rail pressure was also seen for all the cycles, which could be attributed to the 4% higher density of biodiesel compared to ULSD. Trends for fuel rail pressure are shown in Figure 7.4.

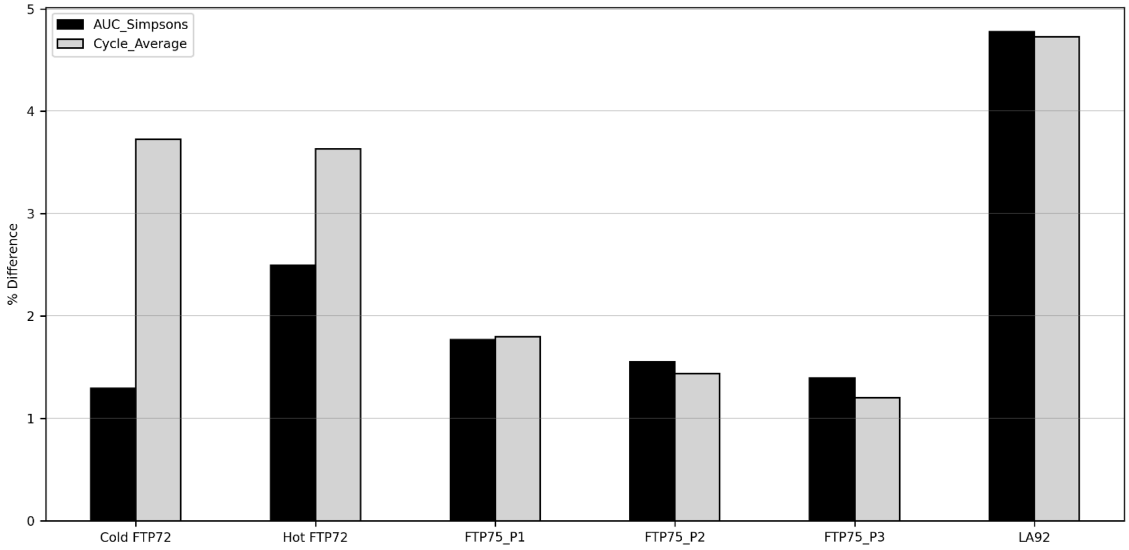

Figure 7.4: Vehicle A: B100 vs ULSD Fuel Rail Pressure Trends

Based on results from Table 7.1 and key observations presented, it can be concluded that there could potentially be some impact of B100 fuel on OBD monitor robustness for Vehicle A. Overall, B100 fuel showed some impact on ATS temperatures as well as engine-out and tailpipe NO_x sensor values that could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management mode, DPF regeneration as well as NO_x sensor rationality and SCR efficiency monitor.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 7.1. Slightly higher calculated lambda was observed due to increase in fuel flow (up to 10%). Slightly higher fuel rail pressure was also observed (up to 5%) possibly due to 4% higher density of B100 fuel. However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness. This was further confirmed by post-test cycle OBD scans for test cycles tested with B100 fuel which did not show any OBD fault codes for Vehicle A.

Section 7.2: Vehicle B: B100 vs ULSD_2

Table 7.2: Vehicle B Results Summary: B100 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	Slightly Lower	Slightly Higher	No Difference	Lower	No Difference	Slightly Higher	± 10%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	Slightly Higher	No Difference	No Difference	± 5°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	Slightly Higher	No Difference	No Difference	Slightly Higher	No Difference	No Difference	4-5% Higher
Engine Fuel Rate	**g/s**	Higher	Higher	Higher	Higher	Higher	Higher	15 to 18% Higher
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	5 to 12°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	Lower	No Difference	No Difference	8% Lower
Engine Out NO_x Sensor	**ppm**	Slightly Lower	Slightly Higher	Slightly Lower	Slightly Lower	Slightly Higher	Higher	10 ppm Lower to 20 ppm Higher
Tailpipe NO_x Sensor	**ppm**	-	-	-	-	-	-	NH_3 Slip
Bench Tailpipe	**ppm**	-	-	Slightly Higher	No Difference	Slightly Higher	-	Up to 4 ppm

NOx Conc				🟨		🟨		Higher
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
Fuel Rail Pressure	**kPa**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	6-9% Higher
VGT Position	**%**	Slightly Higher	No Difference	Slightly Higher	Slightly Higher	No Difference	No Difference	Up to 4% Higher
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 5 mg/s
Calculated Engine-Out NO_x	**g**	Lower	Higher	Lower	Lower	Higher	Higher	± 27%
Calculated Tailpipe NO_x	**g**	-	-	-	-	-	-	
Calculated Exhaust Flow Rate	**kg/h**	Slightly Lower	Slightly Higher	No Difference	Lower	No Difference	Slightly Higher	± 10%
Bench Tailpipe NO_x	**g**	-	-	Higher	Higher	Higher	-	Up to 2 times Higher
Bench Tailpipe CO_2	**g**	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	6 to 8% Higher
Total Cycle Fuel Consumption	**g**	Higher	Higher	Higher	Higher	Higher	Higher	15 to 18% Higher
Engine-Out Soot	**mg**	-	-	-	-	-	-	

Key observations from Figure 7.5 and Figure 7.6 and are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycles increased by 15-18% when running with B100 fuel compared to ULSD (Figure 7.5). B100 fuel has 13% lower net heating value per kg compared to ULSD (Table 1.3), which could contribute to some increase in fuel consumption as observed in some cycles.

   The fuel energy used over all the cycles with B100 fuel was slightly higher compared to ULSD (1-3%) (Figure 7.6). This could indicate that cycle work with B100 was higher compared to ULSD. This could also be due to the differences in engine operating conditions. For Vehicle B with B100 fuel, it was seen that during cold start cycles such as Cold FTP72 cycle and Phase 2 of FTP75 cycle, the vehicle operation was different compared to ULSD possibly due to some type of fuel adaptation logic in the calibration. This could also contribute to the higher fuel consumption observed. From an OBD perspective, difference in average engine fuel rate (g/s) over the cycles was ~ 0.26 g/s. Therefore, there could be some impact on fuel flow OBD monitors.

   CO_2 emissions were ~6-8% higher compared to ULSD for FTP75 cycle. This could be explained by the 15-18% higher fuel consumption but 10% lower carbon content (by weight) of B100 fuel compared to ULSD.

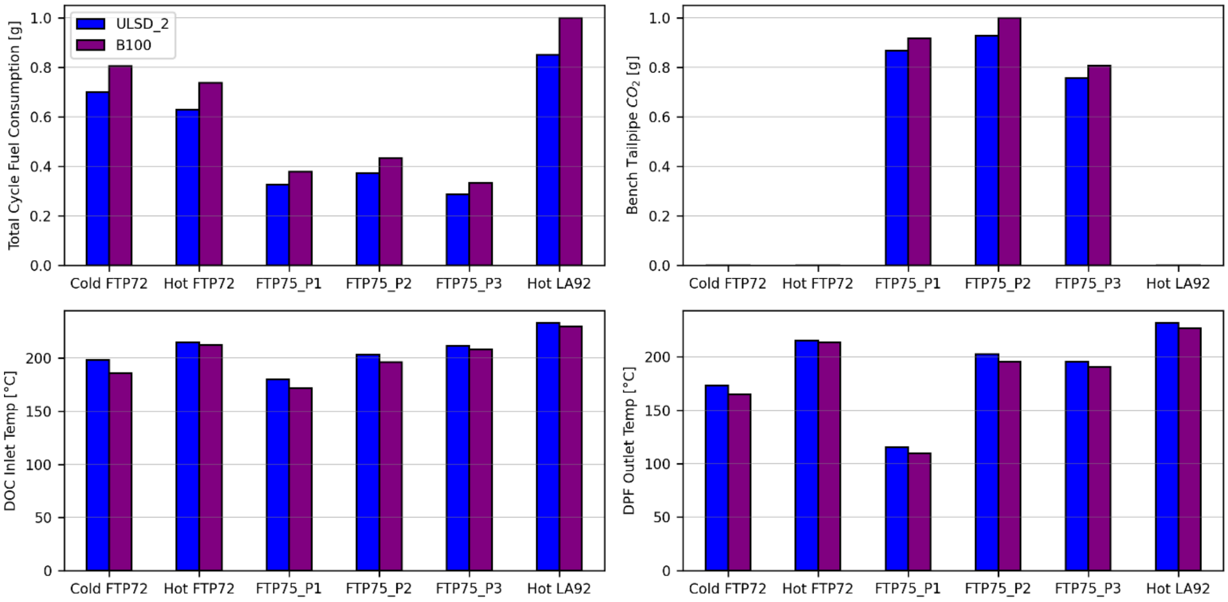

Figure 7.5: Vehicle B: B100 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

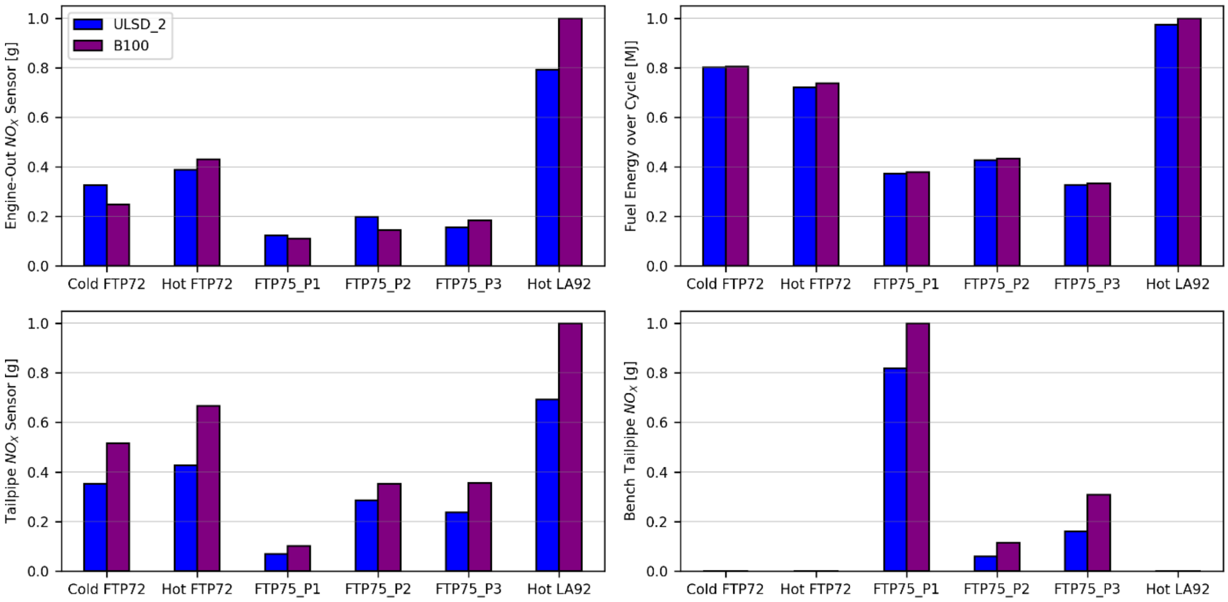

Figure 7.6: Vehicle B: B100 vs ULSD_2: Fuel Energy and NO_x Emissions

2. ATS temperatures (Figure 7.5): ATS temperatures when running with B100 fuel were lower (5-12°C) compared to ULSD. This could be attributed to the 13% lower net heating value of B100 fuel compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 7.6. Engine-out NO_x emissions variation was seen to be within ± 20 ppm. However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some of this difference could be attributed to run-to-run variation. However, higher engine-out NO_x emissions are expected due to biodiesel in the blend which increases O_2 concentration in the fuel. For Vehicle B with B100 fuel, it was seen that during cold start cycles such as Cold FTP72 cycle and Phase 2 of FTP75 cycle, the vehicle operation was different compared to ULSD possibly due to some type of fuel adaptation logic in the calibration. This could be the reason for the observed lower engine-out NO_x emissions for these cycles.

   For Vehicle B, trends for tailpipe NO_x sensor emissions were inconclusive. This was primarily because all cycles on Vehicle B always showed some amount of NH_3 slip throughout the cycle which seemed to strongly affect tailpipe NO_x sensor values. This is due to the cross-sensitivity of NO_x sensors to NH_3 which increases tailpipe NO_x sensor measured NO_x values to higher than actual values. The cumulative bench tailpipe NO_x (g) showed up to 2 times higher tailpipe NO_x emissions on FTP75 cycle with B100. However, on a ppm basis up to 4 ppm difference was observed on the bench for B100 compared to ULSD. Therefore, overall, no significant impact is expected on tailpipe NO_x sensor measurements.

   From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the slightly higher engine-out NO_x emissions and overall lower ATS temperatures observed with B100 fuel, which could affect NO_x emissions OBD limits used to determine monitor decisions.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B100 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle B using B100 blend compared to ULSD fuel have been shown in Figure 7.7.

Further, slightly higher fuel rail pressure (6-9%) was seen for all the cycles. This could be due to 4% higher density of B100 fuel. Trends for fuel rail pressure for Vehicle B have been shown in Figure 7.8.

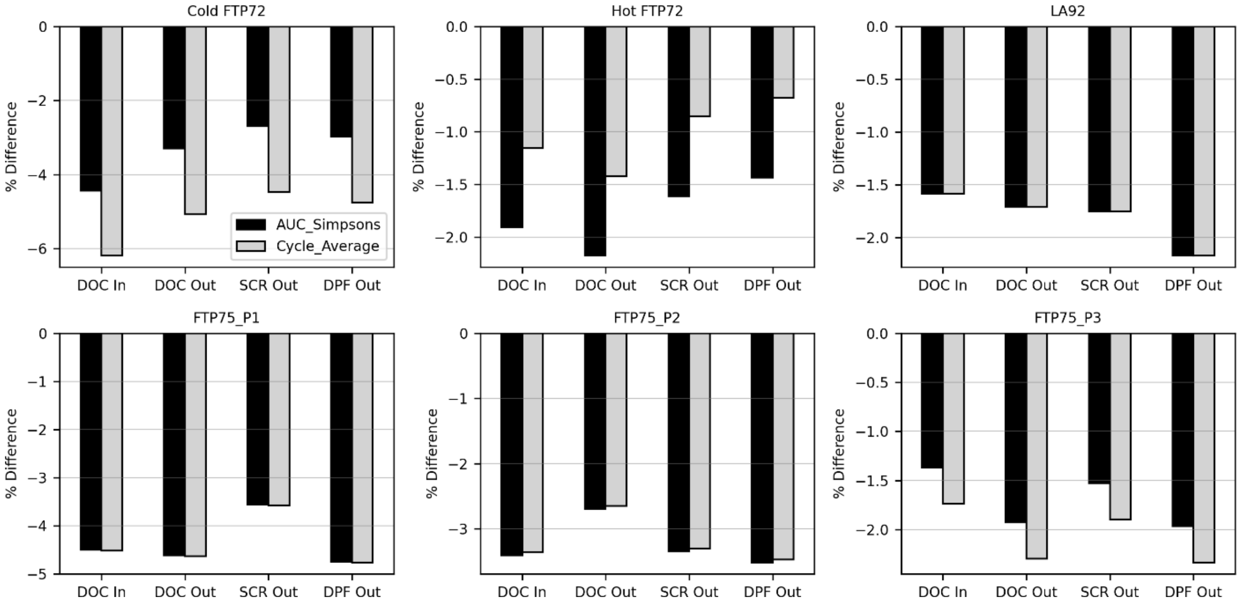

Figure 7.7: Vehicle B: B100 vs ULSD_2 ATS Temperature Trends

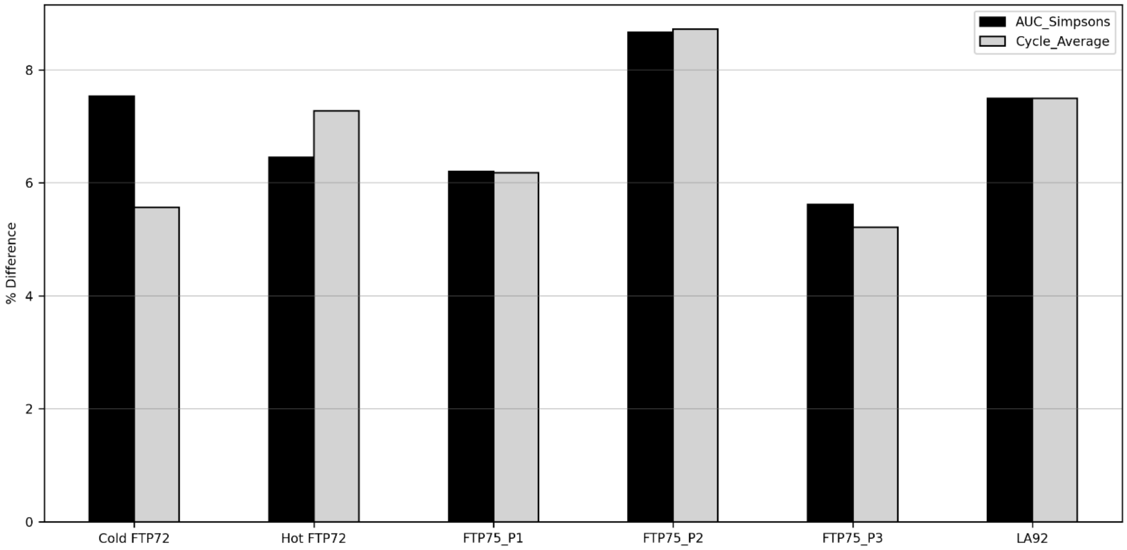

Figure 7.8: Vehicle B: B100 vs ULSD_2 Fuel Rail Pressure Trends

Based on results from Table 7.2 and key observations presented, it can be concluded that there could potentially be some impact of B100 on OBD monitor robustness for Vehicle B. Overall, B100 fuel showed some impact on ATS temperatures and engine-out NO_X emissions that could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management, DPF regeneration as well as SCR efficiency and NO_X sensor rationality.

Other than the key observations presented, some variation was observed in all other PID labels as well as shown in Table 7.2. For example, boost pressure (± 2 kPa), ± 10% variation in air flow and slightly higher EGR and VGT positions for some cycles. However, this can be attributed to the different mode of operation (possibly fuel adaptation) observed for Vehicle B with B100 fuel.

Further, slightly higher fuel rail pressure (6-9%) was observed, possibly due to the higher density (4%) of biodiesel compared to ULSD. However, overall, these differences were not significant enough to impact OBD robustness. This was further confirmed by post-test cycle OBD scans for test cycles tested with B100 fuel which did not show any OBD fault codes for Vehicle B.

Section 7.3: Vehicle C: B100 vs ULSD_2

Table 7.3: Vehicle C Results Summary: B100 vs ULSD_2

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 5% Higher
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Fuel Rate	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	2 to 5% Higher
Exhaust Pressure	**kPa**	N/A	N/A	N/A	N/A	N/A	N/A	
DOC Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Lower	Slightly Lower	Lower	Slightly Lower	Up to 14°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Lower	Slightly Lower	Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Lower	Slightly Lower	Lower	Slightly Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	Slightly Higher	Slightly Lower	No Difference	Slightly Higher	Slightly Higher	No Difference	3% Lower to 12 % Higher
Engine Out NO_x Sensor	**ppm**	Slightly Higher	Slightly Higher	Higher	Slightly Higher	Slightly Higher	Higher	Up to 24 ppm Higher
Tailpipe NO_x Sensor	**ppm**	No Difference	No Difference	N/A	No Difference	N/A	NH_3 Slip	± 2 ppm
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NO_x	**g**	Higher	Higher	Higher	Higher	Higher	Higher	Up to 37% Higher
Calculated Tailpipe NO_x	**g**	Slightly Lower	Slightly Lower	N/A	Higher	N/A	NH3 Slip	Up to 42% Higher
Calculated Exhaust Flow Rate	**kg/h**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 5% Higher

Bench Tailpipe NO_x	g	-	-	Higher	Higher	Higher	-	Up to 2 times Higher
Bench Tailpipe CO_2	g	-	-	Slightly Lower	No Difference	Slightly Higher	-	± 2 %
Total Cycle Fuel Consumption	g	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	2 to 5% Higher
Engine-Out Soot	mg	-	-	Lower	Lower	Lower	-	Up to 83% Lower

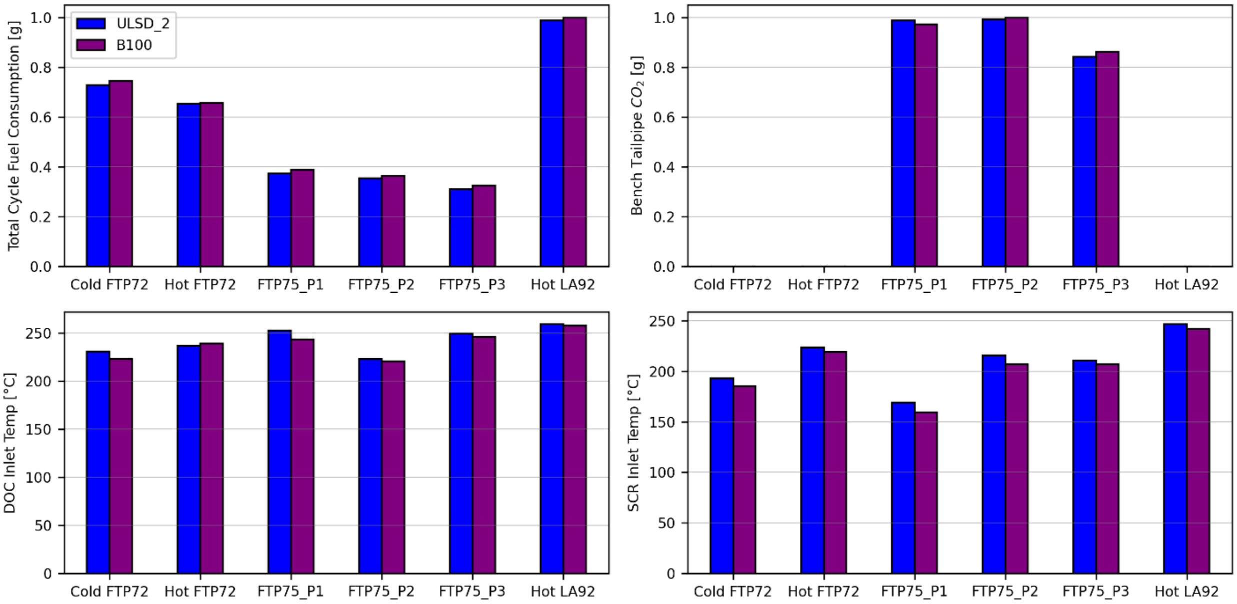

Figure 7.9: Vehicle C: B100 vs ULSD_2: Fuel Consumption, CO_2 Emissions and ATS Temperatures

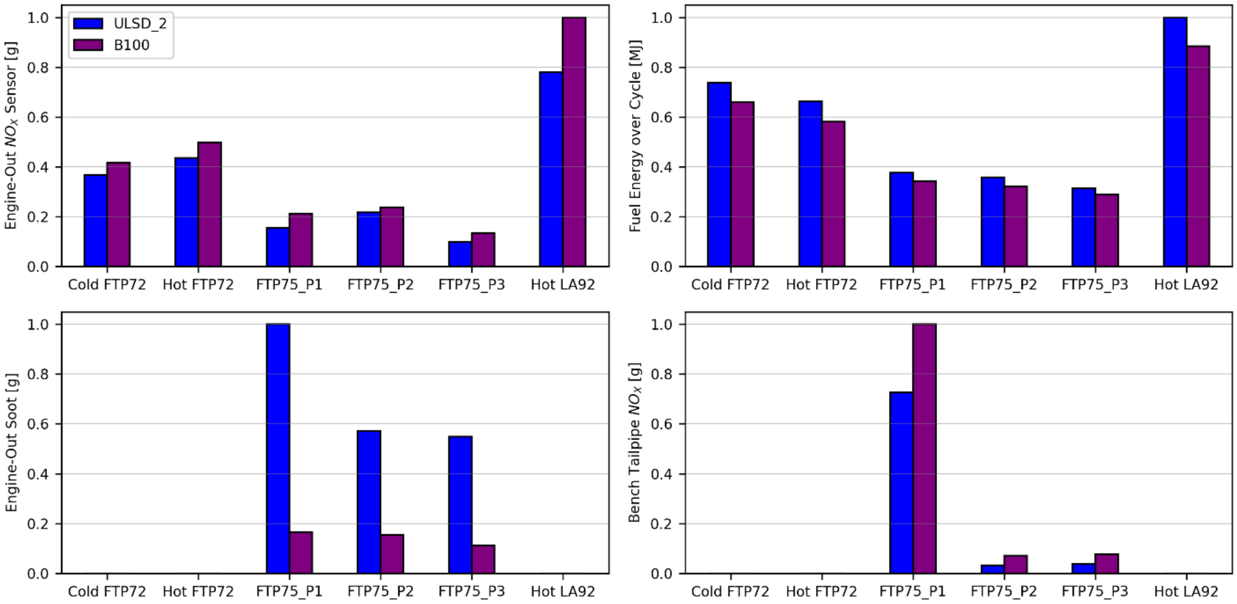

Figure 7.10: Vehicle C: B100 vs ULSD_2: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure 7.9 and Figure 7.10 are as follows:

1. Fuel consumption/CO_2 Emissions (g): For Vehicle C, with B100 fuel, the fuel consumption was higher (up to 5%) (Figure 7.9). B100 fuel has lower net heating value per kg (~13%) compared to ULSD_2 (Table 1.3). This could explain higher fuel consumption seen on all the cycles.

   The fuel energy used over all the cycles with B100 fuel was lower compared to ULSD (up to 12%) (Figure 7.10). The lower fuel energy used with B100 could indicate that lower cycle work was done with B100 compared to ULSD. This could explain the lower impact on fuel consumption. This difference may also be explained by the differences in engine operation due to a feature on Vehicle C, which was not consistent over each cycle. From OBD perspective, differences in average engine fuel rate (g/s) over the cycles were ≤ 0.05 g/s. Therefore, this difference in fuel rate may not be significant enough to impact fuel flow OBD monitor robustness. However, since overall cycle work was lower compared to ULSD, there could be a higher difference which may impact OBD monitor robustness.

   CO_2 emissions were within ± 2% of ULSD for FTP75 cycle. This could be explained by up to 10% lower carbon content (% weight) but higher fuel consumption with B100 blend compared to ULSD.

2. ATS temperatures (Figure 7.9): ATS temperatures were on average slightly lower on all the cycles (up to 14°C). The lower ATS temperatures may be explained by the 13% lower net heating value of B100 fuel compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 7.10. A trend of higher engine-out NO_x emissions was observed over the test cycles (up to 24 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some difference could be attributed to run-to-run variation. The observed higher NO_x emissions can be explained by the higher oxygen content of biodiesel fuel which increases NO_x emissions.

   Tailpipe NO_x sensor values were comparable (± 2 ppm). However, on LA92 cycle more NH_3 slip was observed with B100 fuel (due to differences in sequence of cycles run before LA92 cycle). Therefore, tailpipe NO_x emissions are higher on this cycle due to NH_3 to NO_x cross sensitivity of NO_x sensors. Based on cumulative bench higher tailpipe NO_x emissions (g) were observed on FTP75 with B100 fuel (up to 2 times higher). This could be explained by the higher engine-out NO_x and lower ATS temperatures lowering SCR efficiency. On a ppm basis however, this difference was < 2 ppm difference on average compared to ULSD.

From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults. From an SCR efficiency perspective, slightly lower SCR efficiency may be expected due to the lower ATS temperatures and higher engine-out NO_x emissions with B100 fuel, which could affect NO_x emissions OBD limits used to determine monitor decisions.

4. Soot Emissions (Figure 7.10): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to higher oxygen content of biodiesel fuel reducing soot production. Overall, up to 83% lower soot emissions were observed when running Vehicle C with B100 compared to ULSD.

   From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

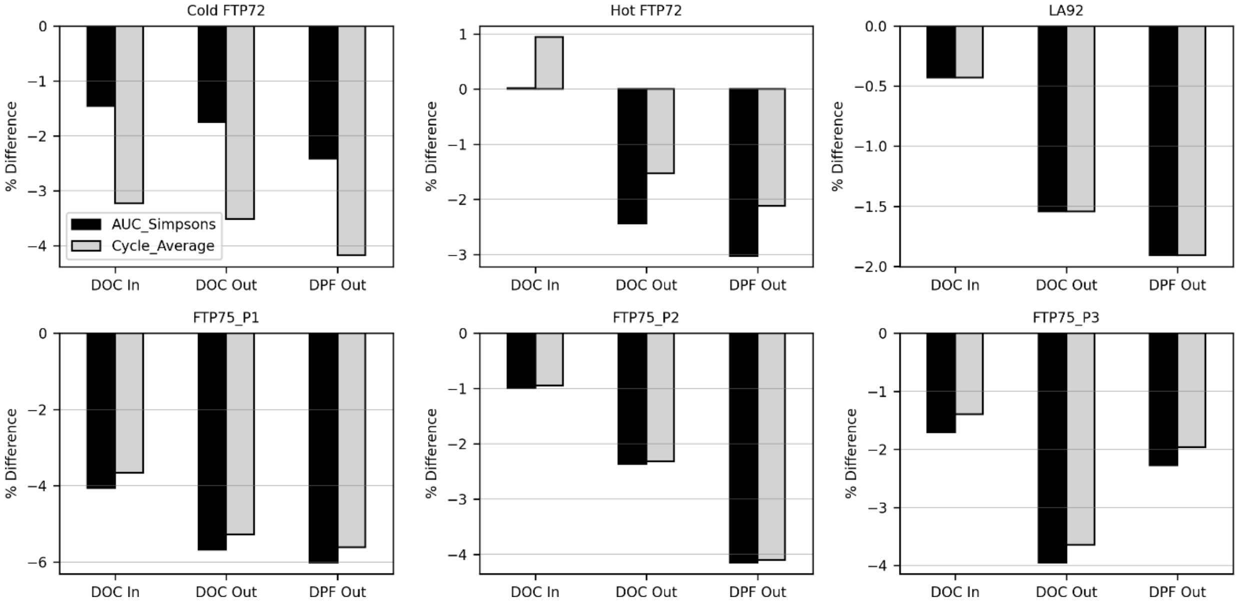

Figure 7.11: Vehicle C: B100 vs ULSD_2 ATS Temperature Trends

Based on results from Table 7.3 and key observations presented, it can be concluded that there could potentially be some impact of B100 fuel on OBD monitor robustness for Vehicle C. Overall, B100 fuel showed some impact on ATS temperatures, engine-out NO_x and soot emissions which could possibly impact OBD monitor decisions including ATS temperature rationality, thermal management, DPF regeneration, SCR efficiency and NO_x sensor rationality. However, post-test cycle OBD scans for test cycles tested with B100 fuel did not show any OBD fault codes for Vehicle C.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 7.3. For example, boost pressure (± 2 kPa) and some differences in fuel rail pressure, air flow, calculated lambda, EGR and VGT positions. However, Vehicle C also had run to run differences in engine operation due to a feature that was inconsistent over the test cycles with ULSD and B100 fuel. Therefore, these observed variations were not considered to be significant enough to impact OBD robustness.

Section 7.4: Vehicle D: B100 vs ULSD

Table 7.4: Vehicle D Results Summary: B100 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Intake Manifold Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 °C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
Engine Fuel Rate	**g/s**	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	Lower	Lower	Lower	Lower	Lower	Lower	0 to 20°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Lower	Lower	Lower	Lower	Lower	Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Lower	Lower	Lower	Lower	Lower	Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	**ppm**	No Difference	Higher	Higher	Higher	Higher	Higher	Up to 26 ppm
Tailpipe NO_x Sensor	**ppm**	N/A	N/A	N/A	N/A	N/A	N/A	
Bench Tailpipe NOx Conc	**ppm**	-	-	Higher	Higher	Higher	-	Up to 23 ppm
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
DEF Dosing	**mg/s**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Engine-Out NO_x	**g**	Slightly Higher	Higher	Higher	Higher	Higher	Higher	Up to 21% Higher
Calculated Tailpipe NO_x	**g**	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Bench Tailpipe NO_x	**g**	-	-	Higher	Higher	Higher	-	Up to 6 times

								Higher
Bench Tailpipe CO_2	g	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	Up to 6% Higher
Total Cycle Fuel Consumption	g	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
Engine-Out Soot	mg	-	-	Lower	Lower	Lower	-	Up to 83% Lower

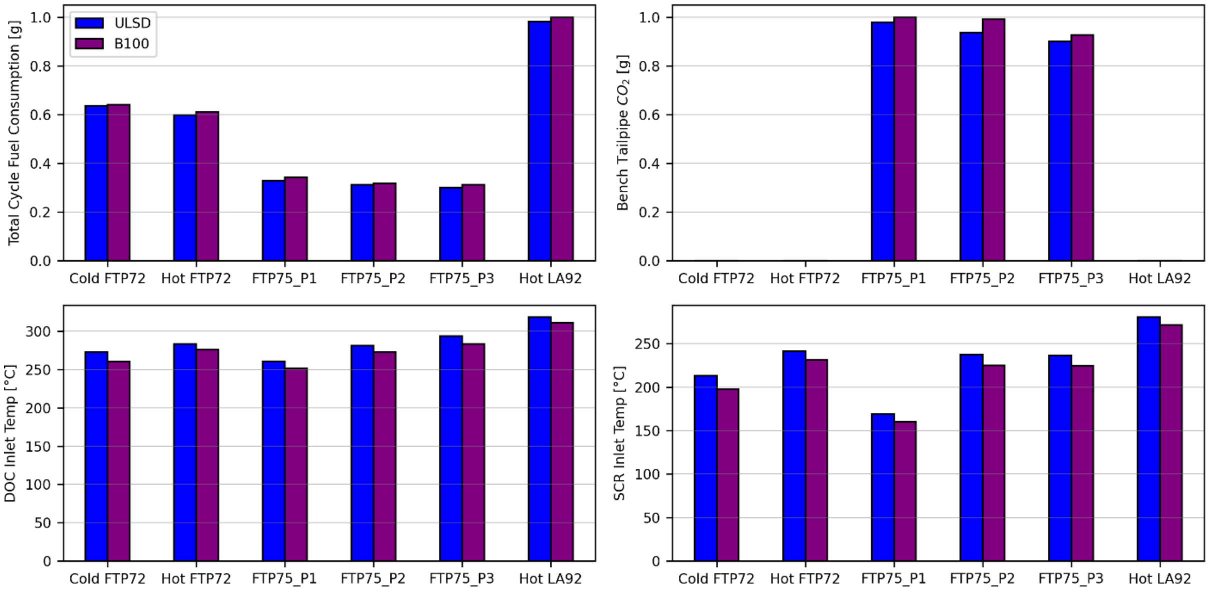

Figure 7.12: Vehicle D: B100 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

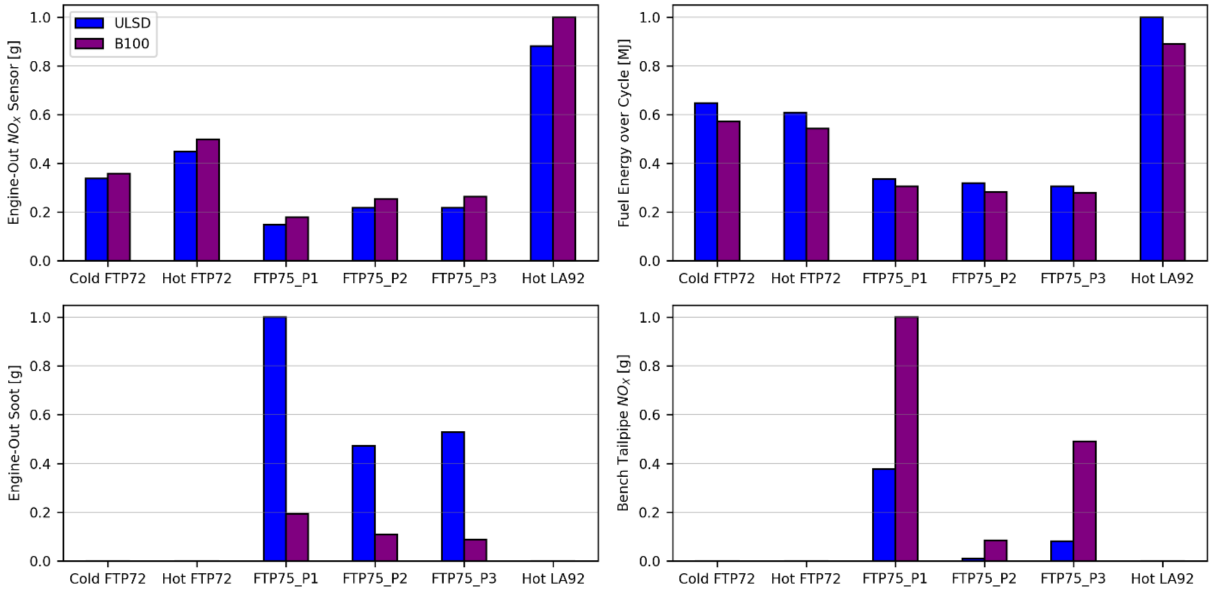

Figure 7.13: Vehicle D: B100 vs ULSD: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure *7.12* and Figure *7.13* are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 1-4% higher when running with B100 (Figure 7.12). B100 fuel has 13% lower net heating value per kg compared to ULSD (Table 1.3).

   However, the fuel energy used over all the cycles with B100 fuel was 9-12% lower compared to ULSD (Figure 7.13). The lower fuel energy used with B100 could indicate that lower cycle work was done with B100 compared to ULSD. This could explain the lower impact on fuel consumption. From an OBD perspective, differences in average engine fuel rate (g/s) over the cycles were ≤ 0.06 g/s. However, since overall cycle work was lower compared to ULSD, there could be a higher difference which could impact OBD monitor robustness.

   CO_2 emissions differences were about 6% higher for FTP75 cycle which can be explained by overall higher fuel consumption with B100 compared to ULSD.

2. ATS temperatures (Figure 7.12): ATS temperatures were on average lower on all cycles (up to 20°C). The lower ATS temperatures can be explained by the lower fuel energy used over the cycles (9-12%) as well as lower net heating values (13%) of B100 fuel compared to ULSD.

   From OBD perspective, the lower ATS temperatures could affect ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Therefore, there could be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 7.13. Overall, higher engine-out NO_x emissions were observed across all the test cycles (up to 26 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some differences could be attributed to run-to-run variation. The higher O_2 concentration in biodiesel is expected to increase engine-out NO_x emissions as observed on Vehicle D.

   Cumulative bench tailpipe NO_x emissions (g) with B100 were up to 6 times higher on FTP75 cycle. Also, on a ppm basis ~23 ppm difference was observed on an average compared to ULSD. This higher tailpipe NO_x emissions can be explained by the lower ATS temperatures (up to 20°C) and higher engine-out NO_x emissions observed leading to lower SCR efficiency.

   From an OBD monitor perspective these differences could be large enough to affect OBD monitor robustness in determining NO_x sensor rationality faults or SCR efficiency monitor decisions. From an SCR efficiency perspective, lower SCR efficiency due to the lower ATS temperatures with B100, could affect OBD NO_x emissions limits used to determine monitor decisions.

4. Soot Emissions (Figure 7.13): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD. This can be attributed to higher oxygen content in the blend due to biodiesel which reduces the propensity for soot formation. Overall, up to 83% lower soot emissions were observed when running with B100 compared to ULSD.

   From OBD perspective, lower soot emissions will lower DPF regeneration frequency and may lower DPF differential pressure. Therefore, there could be some impact on the robustness of DPF regeneration OBD monitors.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of B100 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle A using B100 fuel compared to ULSD fuel have been shown in Figure 7.14. In general, ATS temperatures with B100 fuel were seen to be lower as compared to ULSD fuel.

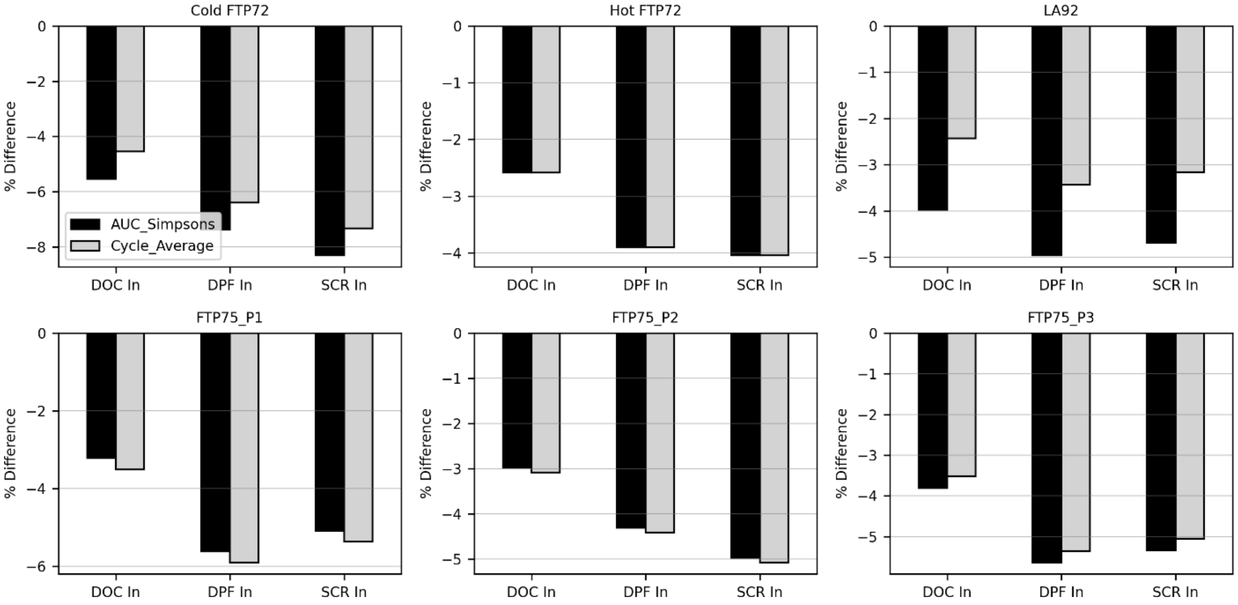

Figure 7.14: Vehicle D: B100 vs ULSD ATS Temperature Trends

Based on results from Table 7.4 and key observations presented, it can be concluded that there could potentially be some impact of B100 fuel on OBD monitor robustness for Vehicle D. Overall, B100 fuel showed some impact on ATS temperatures as well as engine-out NOx and soot emissions that could possibly impact OBD monitor decisions for ATS temperature rationality, DPF regeneration, thermal management as well as NO_x sensor rationality and SCR efficiency. However, post-test cycle OBD scans for test cycles tested with B100 fuel did not show any OBD fault codes.

Other than the key observations presented, some variation was observed in all other PID labels as shown in Table 7.4. For example, boost pressure and fuel rail pressure (± 2%) as well as some variation in EGR and VGT position (± 2%). However, all of these were well within run-to-run variation and were not considered to be significant enough to impact OBD robustness.

Section 7.5: B100 vs ULSD Summary

Based on analysis conducted using data from vehicles running with B100 fuel, the following were the key observations and their possible impact on OBD monitors:

Engine-Out Soot emissions:

A key observation on the vehicles that had engine-out soot emissions measurements (Vehicle C and Vehicle D) was a significant reduction in engine-out soot emissions (~83% lower) when running with B100 fuel compared to ULSD. This can be attributed to the higher oxygen content of biodiesel (~10%) which reduces the propensity for soot formation.

OBD Impact:

Some differences can be expected between true and modeled engine-out soot which is based on ULSD. Therefore, DPF regeneration interval and frequency could be affected due to the lower soot. There could also be some impact on DPF differential pressure measurements (lower due to lower soot). This could impact DPF regeneration frequency monitor and DPF differential pressure sensor monitor robustness.

ATS Temperatures:

Some variation in ATS temperatures were observed when using B100 fuel compared to ULSD. All vehicles showed lower ATS temperatures when running with B100 compared to ULSD. The temperature differences were seen to be up to 23°C on average over the test cycles. However, some differences in temperatures can be due to run-to-run variation considering the differences in engine operating conditions due to the tests being conducted on chassis dynamometer. Overall, there was a trend seen for lower ATS temperatures with B100 fuel which can be explained by the 13% lower net heating value (by mass) of B100 fuel compared to ULSD.

OBD Impact:

The observed variation could impact ATS temperature sensor rationality monitors depending on expected differences between modeled and sensor values for each vehicle. The lower ATS temperatures could also affect thermal management mode operation which uses these as thresholds for activation and deactivation. Though DPF regeneration was not available in the test data, the observed drop in ATS temperatures may also affect DPF regeneration temperatures which could affect DPF regeneration duration and frequency. However, since no data is available regarding the vehicles DPF regeneration feedback control, this variation could be within the feedback control limits to increase/decrease fueling and maintain required DPF regeneration temperatures. Overall, there may potentially be some impact on OBD monitors relating to ATS temperature sensor rationality, thermal management mode and DPF regeneration.

NO_x Emissions:

All vehicles overall showed higher engine-out NO_x emissions (up to 50 ppm). The 10% oxygen content in biodiesel increases NO_x emissions. Further the lower effectiveness of EGR due to higher O_2 levels also increases NO_x emissions [29]. Some cycles on Vehicles B showed lower tailpipe NO_x emissions. However, this can be attributed to a different mode of vehicle operation on Vehicle B compared to ULSD (possibly fuel adaptation). Bench tailpipe NO_x emissions (ppm basis) differences on FTP75 cycle were also slightly higher (up to 23 ppm). Cumulative tailpipe NO_x emissions (g) on FTP75 measured using the bench also showed higher tailpipe NO_x emissions for all vehicles (up to 6 times higher in some phases of FTP75). This increase can be attributed to higher engine-out NO_x as well as lower SCR temperatures reducing SCR efficiency.

OBD Impact:

The variations in NO_x sensor values (ppm basis) observed could be large enough to affect NO_x sensor rationality monitor decisions. Also, some impact could be expected on the OBD thresholds for NO_x emissions used to determine SCR efficiency monitor decisions, since total tailpipe NO_x emissions over the cycle (for B100) measured by bench (g) were higher compared to ULSD.

Fuel Consumption:

Fuel consumption was 4-20% higher for all the vehicles. Some impact on fuel consumption is expected due to lower net heating value (mass and volume based) of B100 compared to ULSD. Vehicles C and D showed much lower fuel energy over the cycle (up to 12%) which could indicate differences in vehicle operation which could have contributed to some variation in fuel consumption. Higher fuel rail pressure was also observed on Vehicles A & B (up to 9%) possibly due to the 4% higher density of B100 fuel.

OBD Impact:

From OBD perspective, the average variation in engine fuel rate (g/s) was ~ 0.26 g/s for Vehicles A and B. Therefore, some impact is expected on fuel flow OBD monitor robustness. Vehicles C and D showed a smaller variation. However, since the fuel energy over the cycles was lower (~12%) for these vehicles, the impact on fuel flow could be larger and may affect fuel flow OBD monitors.

Other PID Labels:

Some differences in boost pressure (± 2kPa), EGR and VGT positions (± 5%) were observed. Slightly higher fuel rail pressure was also observed for Vehicles A and B (up to 9%) possibly due to the 4% higher density of B100 fuel. However, these differences were not significant enough to set any OBD faults. Since the vehicles were tested using chassis dynamometer cycles, the engine operating conditions (engine speed and fueling) are not consistent between test runs due to driver-to-driver variation in running the same cycle. This results in different setpoints for air flow, EGR and VGT position during transient operation and therefore causes variations in the selected PID labels. The observed variations were therefore found to be well within this expected variation in engine operation.

Conclusion Summary for B100:

Based on data analysis conducted on chassis dynamometer data from all four vehicles on FTP75, FTP72 and LA92 cycles, it was concluded B100 fuel showed some impact on the selected PID labels. However, the absence of OBD fault codes while running using B100 fuel on all vehicles indicates that this impact was not large enough to impact OBD monitor robustness.

Chapter 8 : Fuel VII: ULSD vs ULSD_2

This chapter describes the results and conclusions of the testing conducted on all four vehicles using ULSD fuel again after all tests were completed with the other 6 fuels and fuel blends. This was done to understand if there were any differences in vehicle performance after using different fuel blends on each vehicle. The original intent was to use the same ULSD fuel used before the tests with other fuels to re-test the vehicles after all fuels had been tested. However, since there was not enough ULSD fuel available for retesting, another batch of ULSD (ULSD_2) was used for the retesting the vehicles. The summary provided utilizes the analysis approaches and metrics described in Section 1.6. The results have been divided into Sections 8.1, 8.2, 8.3 and 8.4 for Vehicles A, B, C and D respectively. Each section has the following that summarizes the results for ULSD_2 fuel compared to ULSD for each vehicle.

1. A table summarizing the results of the vehicle running on ULSD_2 compared to ULSD for all the test cycles. Key differences observed in engine performance and emissions when using ULSD_2 fuel compared to ULSD fuel using the "averaged" ULSD_2 and ULSD cycles for cold and hot FTP72 cycle, hot LA92 cycle and each phase of the FTP75 cycle are highlighted in these tables. The table provides an understanding of any perceived degradation in vehicle performance after using different fuel/fuel blends.
2. Plots showing average ATS temperatures, fuel energy, total engine-out and tailpipe NO_x emissions, engine-out soot emissions (when available) and cycle fuel consumption differences for the vehicle when using ULSD_2 fuel compared to ULSD. The values in the plots have been normalized using min-max normalization, where minimum value = 0 and maximum value was the maximum value in the plot. This was done to present important trends in engine performance while preserving anonymity of emissions and fuel consumption values.
3. Trend plots (% difference) showing PID labels for which significant increasing or decreasing trends were observed when running with ULSD_2 fuel compared to ULSD for that vehicle. Negative percent difference indicates lower and positive indicates higher compared to ULSD.

A summary of key observations and trends analyzed for the vehicles when running with ULSD_2 fuel compared to ULSD and any observed differences in vehicle operation is presented in Section 8.5.

Section 8.1: Vehicle A: ULSD_2 vs ULSD

Table 8.1: Vehicle A Results Summary: ULSD_2 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	g/s	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%

Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 5%
Engine Fuel Rate	**g/s**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 4% Lower
Exhaust Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 10°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	-	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	-	
SCR Outlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	-	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	**ppm**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	No Difference	Up to 10 ppm Lower
Tailpipe NOx Sensor	**ppm**	No Difference	No Difference	No Difference	No Difference	No Difference	NH3 Slip	± 2 ppm
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	N/A	N/A	N/A	N/A	N/A	N/A	
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
DEF Dosing	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Calculated Engine-Out NOx	**g**	Slightly Lower	No Difference	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 10% Lower
Calculated Tailpipe NOx	**g**	Slightly Higher	Higher	N/A	Slightly Higher	N/A	NH_3 Slip	Up to 37% Higher
Calculated Exhaust Flow Rate	**kg/h**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Bench Tailpipe NOx	**g**	-	-	Slightly Lower	Lower	Slightly Lower	-	Up to 14% Lower
Bench Tailpipe CO_2	**g**	-	-	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 4% Lower
Total Cycle Fuel Consumption	**g**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 4% Lower
Engine-Out Soot	**mg**	-	-	-	-	-	-	

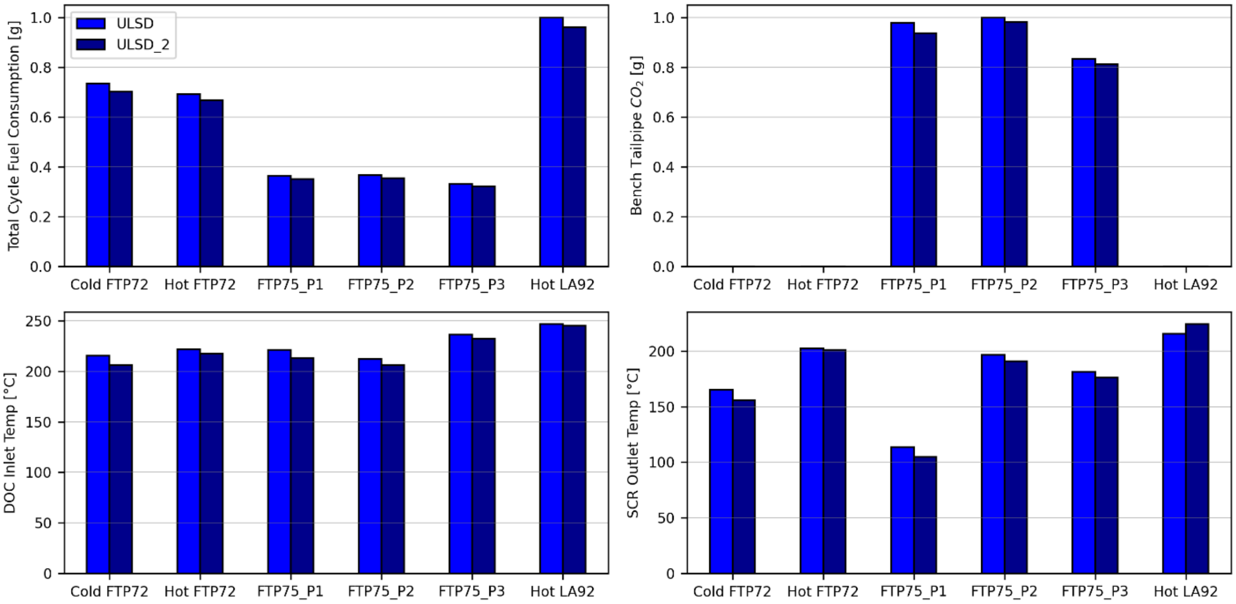

Figure 8.1: Vehicle A: ULSD_2 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

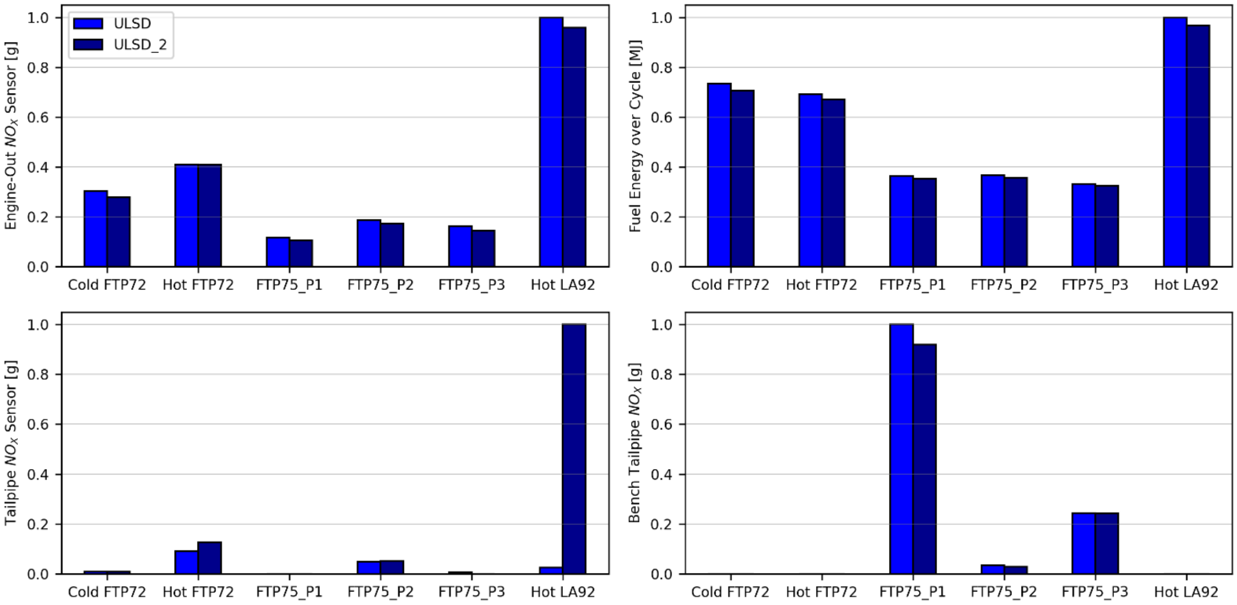

Figure 8.2: Vehicle A: ULSD_2 vs ULSD: Fuel Energy and NO_x Emissions

Key observations from Figure *8.1* and Figure *8.2* are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 4% lower when running with ULSD_2 for the test cycles (Figure 8.1). The ULSD fuels showed similar net heating value per kg (Table 1.3) therefore the observed lower fuel consumption could be attributed to run-to-run variation. Also, the fuel energy used over all the cycles with ULSD_2 was slightly lower compared to ULSD (2-4%) (Figure 8.2). This could indicate differences in cycle work compared to tests with ULSD. From an OBD perspective,

differences in average engine fuel rate (g/s) were ~ 0.06 g/s. CO_2 emissions were about 4% lower compared to ULSD for FTP75 cycle. This could be explained by 4% lower fuel consumption compared to ULSD.

2. ATS temperatures (Figure 8.1): ATS temperatures were on average ~10°C lower when running with ULSD_2 fuel for FTP75 and cold FTP72 cycles. For LA92 cycle the ATS temperatures were slightly higher. However, the observed differences in ATS temperatures could be attributed to cycle-to-cycle difference (LA92 cycle with ULSD_2 had higher starting ATS temperatures compared to ULSD). Some of the observed differences in ATS temperatures can be attributed to the lower fuel energy used over the cycles when using ULSD_2 compared to ULSD.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 8.2. Slightly lower engine-out NO_x emissions were observed in general for all the cycles (up to 10 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore, some differences can be attributed to run-to-run variation.

   Tailpipe NO_x sensor emissions were also seen to be comparable. However, on LA92 cycle more NH_3 slip was observed with ULSD_2 fuel (due to differences in sequence of cycles run before LA92 cycle). Therefore, tailpipe NO_x emissions are much higher on this cycle due to NH_3 to NO_x cross sensitivity of NO_x sensors. Cumulative bench tailpipe NO_x emissions (g) on FTP75 cycle with ULSD_2 were slightly lower compared to ULSD. However, on a ppm basis this difference was < 2 ppm.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since some difference was observed for ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle A using ULSD_2 fuel compared to ULSD fuel have been shown in Figure 8.3. In general, ATS temperatures with ULSD_2 fuel were seen to be slightly lower as compared to ULSD fuel.

Based on results from Table 8.1 and key observations presented, it can be concluded that no significant differences were observed in vehicle performance for Vehicle A before and after testing with the different fuel blends. Overall, slightly lower ATS temperatures as well as engine-out and tailpipe NO_x sensor values were observed but these were well-within run-to-run variation. There could also be differences due to fuel-to-fuel variation (ULSD_2 vs ULSD) and some differences due to overall lower fuel energy observed with ULSD_2 compared to ULSD. Post-test cycle OBD scans for test cycles tested with ULSD_2 fuel did not show any OBD fault codes for Vehicle A.

Other than the key observations presented, some variation was observed in all other PID labels as well in Table 8.1. For example, small differences in boost pressure, EGR and VGT position (± 2%) and up to ± 2% differences in fuel rail pressure and air flow. However, all of these were well within run-to-run variation and were not considered to be significant enough to conclude that there were any changes in Vehicle A’s performance.

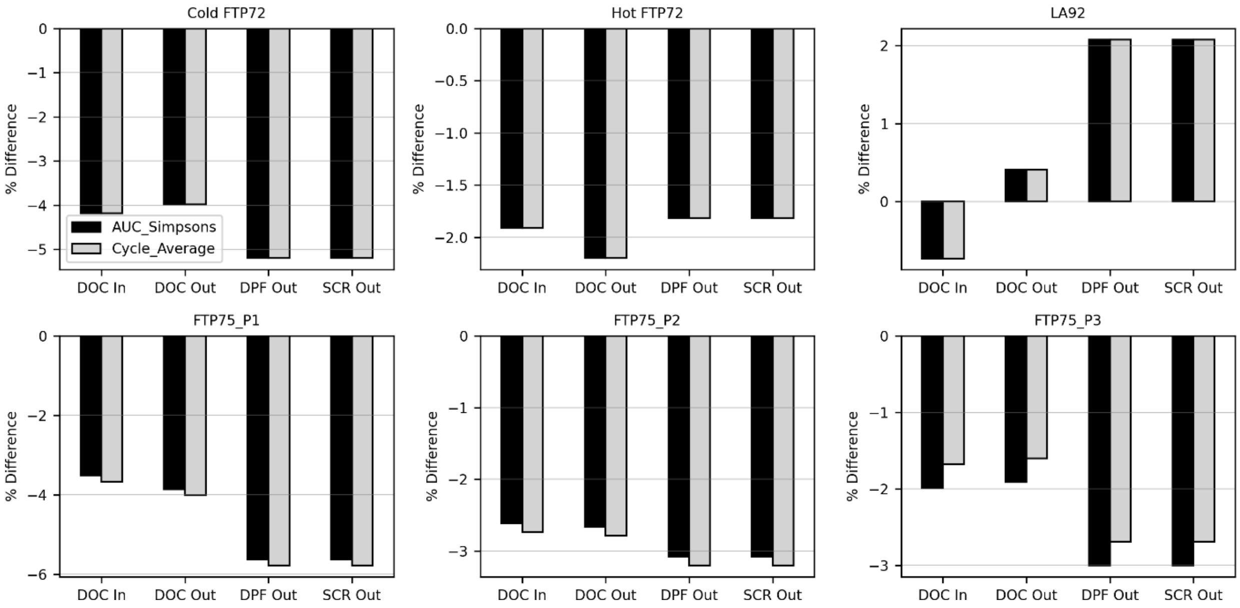

Figure 8.3: Vehicle A: ULSD_2 vs ULSD ATS Temperature Trends

Section 8.2: Vehicle B: ULSD_2 vs ULSD

For Vehicle B, there were some issues with data sampling rate for ULSD for hot FTP72 cycle, therefore comparison with ULSD_2 fuel data was not possible. The differences in starting coolant and ATS temperatures were too large to compare cold FTP72 cycles with ULSD and ULSD_2 fuels. Therefore, cold FTP72 cycle was also removed from the analysis. The results summary for FTP75 and LA92 cycles has been provided below in Table 8.2.

Table 8.2: Vehicle B Results Summary: ULSD_2 vs ULSD

PID Labels	**Units**	**Test Cycle**						**Observations**
		FTP72		**FTP75**			**LA92**	
		Cold	**Hot**	**Phase 1 (Cold Start)**	**Phase 2 (Stabilized)**	**Phase 3 (Hot Start)**	**Hot**	
Mass Air Flow Sensor	**g/s**	-	N/A	No Difference	No Difference	No Difference	No Difference	± 4%
Intake Manifold Temp	**°C**	-	N/A	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	-	N/A	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	-	N/A	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	**g/s**	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 7% Lower
Exhaust Pressure	**kPa**	-	N/A	No Difference	No Difference	No Difference	No Difference	± 2 kPa
DOC Inlet Temp	**°C**	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Higher	14°C Lower to 5°C Higher
DOC Outlet/DPF Inlet Temp	**°C**	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Higher	

DPF Outlet/SCR Inlet Temp	°C	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Higher	
SCR Outlet Temp	°C	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Higher	
Main Injection Timing	°	-	N/A	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	kPa	-	N/A	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	-	-	N/A	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 6% Higher
Engine Out NO_x Sensor	ppm	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 6 ppm Lower
Tailpipe NO_x Sensor	ppm	-	N/A	-	-	-	-	NH_3 Slip
Bench Tailpipe NOx Conc	ppm	-	N/A	No Difference	No Difference	No Difference	-	± 3 ppm
Upstream O_2 Sensor	%	-	N/A	Slightly Higher	Slightly Higher	Slightly Higher	Slightly Higher	Up to 4% Higher
Fuel Rail Pressure	kPa	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	2-4% Lower
VGT Position	%	-	N/A	No Difference	No Difference	No Difference	No Difference	± 2%
DEF Dosing	mg/s	-	N/A	No Difference	No Difference	No Difference	No Difference	± 6 mg/s
Calculated Engine-Out NO_x	g	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 8% Lower
Calculated Tailpipe NO_x	g	-	N/A	-	-	-	-	
Calculated Exhaust Flow Rate	kg/h	-	N/A	No Difference	No Difference	No Difference	No Difference	± 4%
Bench Tailpipe NO_x	g	-	N/A	Higher	Higher	Higher	-	Up to 2 times Higher
Bench Tailpipe CO_2	g	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 7% Lower
Total Cycle Fuel Consumption	g	-	N/A	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 7% Lower
Engine-Out Soot	mg	-	N/A	-	-	-	-	

Key observations from Figure *8.4* and Figure *8.5* and are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycles was lower by up to 7% with ULSD_2 fuel compared to ULSD (Figure 8.4). As both ULSD fuels have similar properties (Table 1.3) and this is much higher than expected run-to-run variation, it can concluded that this difference is possibly arising due to differences in actual engine operation – for e.g., for cold FTP72 cycle, engine speed was observed to be 50 rpm higher on an average for the test cycle with ULSD_2.

   The fuel energy used over all the cycles with ULSD_2 fuel was lower compared to ULSD (2-9%) (Figure 8.5). This could indicate differences in cycle work compared to tests with ULSD and could contribute to the observed lower fuel consumption. Difference in average engine fuel rate (g/s) over the cycles was ≤ 0.15 g/s. CO_2 emissions were ~7% lower compared to ULSD for FTP75 cycle. This could be explained by the lower fuel consumption with ULSD_2 fuel.

2. ATS temperatures (Figure 8.4): ATS temperatures when running with ULSD_2 fuel were lower (up to 14°C) compared to ULSD. As both fuels are ULSD with similar properties, this can also possibly be attributed to differences in actual engine operation and also possibly due to the lower fuel energy observed with ULSD_2 fuel.

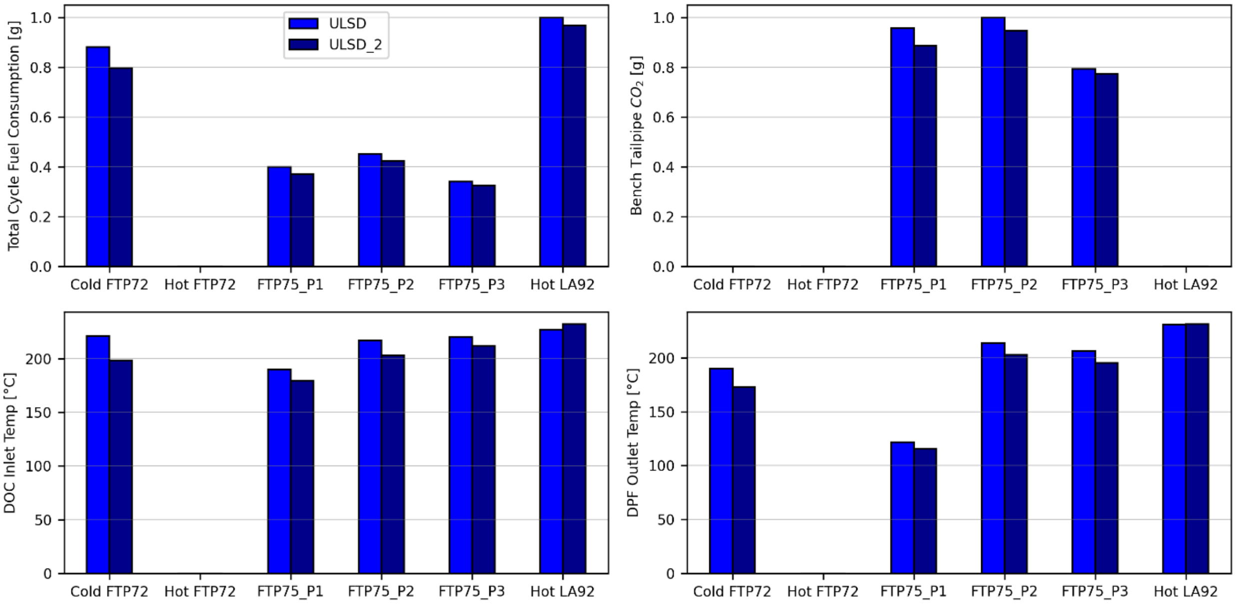

Figure 8.4: Vehicle B: ULSD_2 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

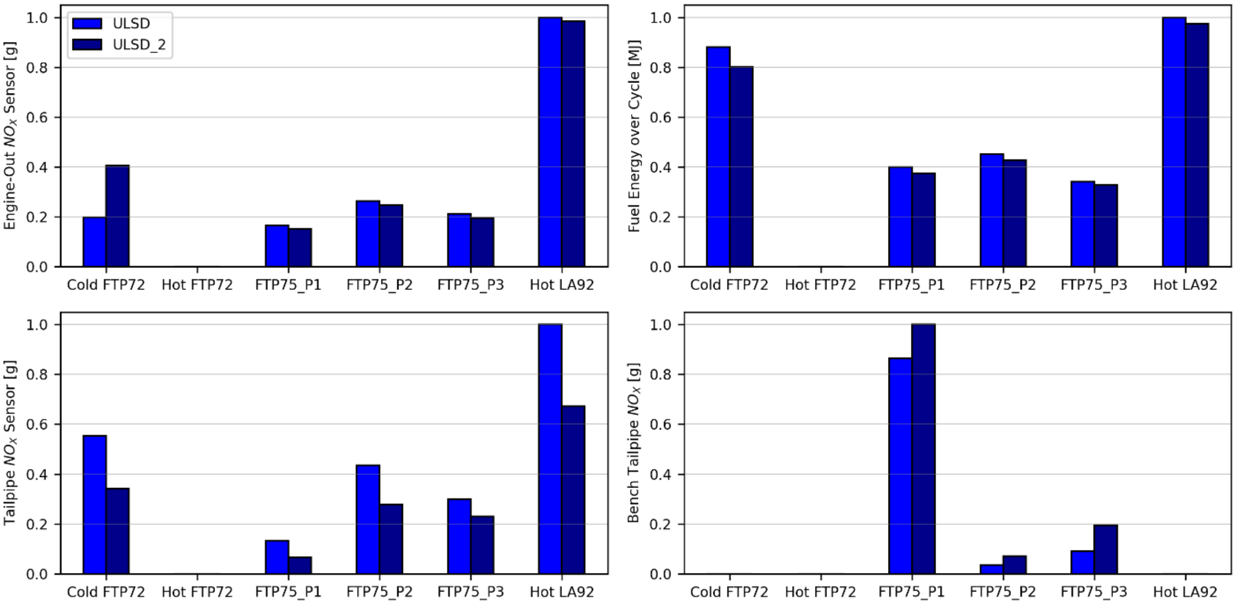

Figure 8.5: Vehicle B: ULSD_2 vs ULSD: Fuel Energy and NO_x Emissions

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 8.5. Engine-out NO_x emissions were slightly lower (up to 6 ppm). However, there could be some differences in sensor activation times due to differences in ATS

temperature, therefore some of this difference could be attributed to run-to-run variation. For example, the large difference in engine-out NO_x emissions seen for cold FTP72 cycle (Figure 8.5) is due to sensor being inactive for most of the cycle for the test cycle with ULSD fuel.

For Vehicle B, trends for tailpipe NO_x sensor emissions were inconclusive. This was primarily because all cycles on Vehicle B always showed some amount of NH_3 slip throughout the cycle which seemed to strongly affect tailpipe NO_x sensor values. This is due to the cross-sensitivity of NO_x sensors to NH_3 which increases tailpipe NO_x sensor measured NO_x values to higher than actual values. The cumulative bench tailpipe NO_x (g) showed up to 2 times higher tailpipe NO_x emissions trend on FTP75 cycle with ULSD_2. However, on a ppm basis < 2ppm difference was observed on the bench. The higher tailpipe NO_x can be attributed to overall lower ATS temperatures when running with ULSD_2 fuel.

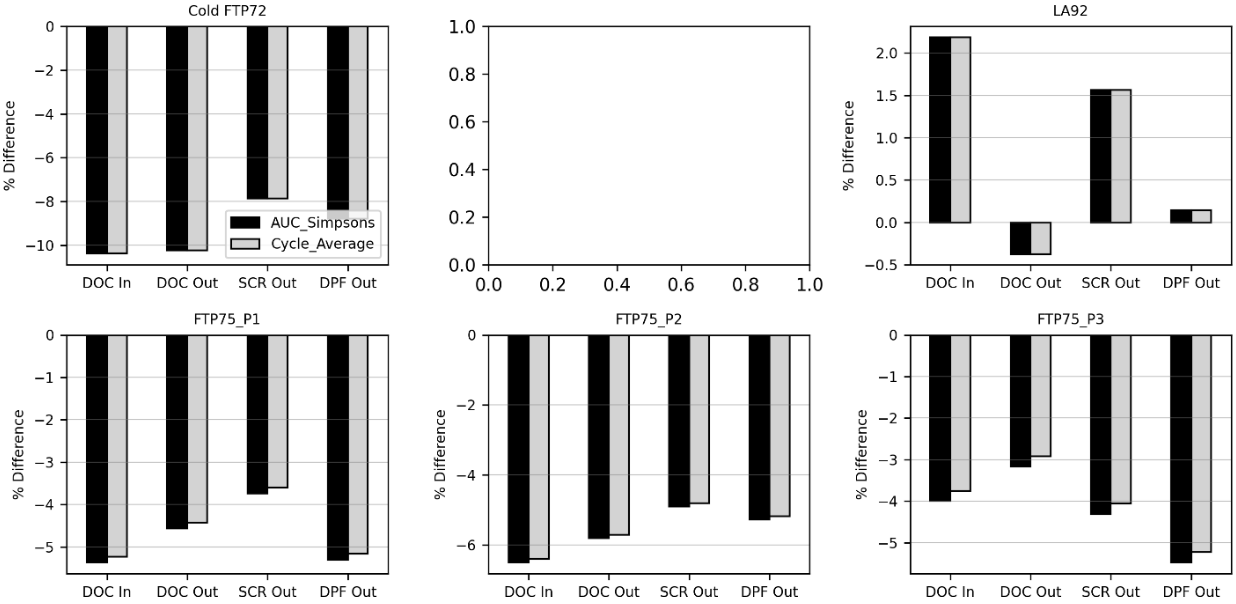

Figure 8.6: Vehicle B: ULSD_2 vs ULSD ATS Temperature Trends

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of ULSD_2 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle B using ULSD_2 compared to ULSD fuel have been shown in Figure 8.6.

Based on results from Table 8.2 and key observations presented, it can be concluded that overall, no significant differences were observed in vehicle performance for Vehicle B before and after testing with the different fuel blends. Overall, slightly lower ATS temperatures and engine-out NO_x sensor values were observed but these were attributed to differences in cycle work (lower fuel energy) and fuel-to-fuel variation.

Other than the key observations presented, some variation was observed in all other PID labels as well in Table 8.2. For example, differences in EGR and VGT position as well as differences in fuel rail pressure, air flow and fuel flow were seen. The observed differences were seen to be primarily coming from differences in engine operation (engine speed and fueling). Therefore, it cannot be concluded that there were any changes in Vehicle B's performance due to the fuels tested. Further, post-test cycle OBD scans for test cycles tested with ULSD_2 fuel did not show any OBD fault codes for Vehicle B.

Section 8.3: Vehicle C: ULSD_2 vs ULSD

For Vehicle C, tailpipe NO_x sensor values were not available for ULSD data. Therefore, comparison with ULSD_2 fuel data was not possible for tailpipe NO_x sensor measurements. The results summary for all other PID labels has been provided below in Table 8.3.

Table 8.3: Vehicle C Results Summary: ULSD_2 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	**g/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 6%
Intake Manifold Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
Coolant Temp	**°C**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2°C
EGR Valve A Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Fuel Rate	**g/s**	Slightly Lower	Slightly Lower	Slightly Lower	No Difference	Slightly Lower	Slightly Lower	Up to 6% Lower
Exhaust Pressure	**kPa**	N/A	N/A	N/A	N/A	N/A	N/A	
DOC Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 10°C Lower
DOC Outlet/DPF Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
DPF Outlet/SCR Inlet Temp	**°C**	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	
SCR Outlet Temp	**°C**	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	**°**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Calculated Lambda	**-**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Engine Out NO_x Sensor	**ppm**	Slightly Higher	Slightly Lower	Slightly Higher	Slightly Higher	Slightly Lower	Slightly Lower	±15 ppm
Tailpipe NO_x Sensor	**ppm**	N/A	N/A	N/A	N/A	N/A	N/A	
Bench Tailpipe NOx Conc	**ppm**	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Fuel Rail Pressure	**kPa**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
VGT Position	**%**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
DEF Dosing	**mg/s**	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%

Calculated Engine-Out NO$_x$	g	Higher	Lower	Slightly Higher	Slightly Higher	Slightly Lower	Slightly Lower	± 20 %
Calculated Tailpipe NO$_x$	g	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Exhaust Flow Rate	kg/h	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 6%
Bench Tailpipe NO$_x$	g	-	-	Slightly Higher	Higher	Slightly Higher	-	Up to 2 times Higher
Bench Tailpipe CO$_2$	g	-	-	Slightly Lower	Slightly Higher	Slightly Higher	-	Up to 6% Higher
Total Cycle Fuel Consumption	g	Slightly Lower	Slightly Lower	Slightly Lower	No Difference	Slightly Lower	Slightly Lower	Up to 4% Lower
Engine-Out Soot	mg	-	-	Lower	Slightly Lower	Lower	-	Up to 25% Lower

Key observations from Figure 8.7 and Figure 8.8 are as follows:

1. Fuel consumption/CO$_2$ Emissions (g): For Vehicle C, with ULSD_2, the fuel consumption was lower (up to 6%) (Figure 8.7). As both ULSD fuels have similar properties (Table 1.3) and this is much higher than expected run-to-run variation, it can concluded that this difference is possibly arising due to differences in actual engine operation – primarily the feature on Vehicle C being inconsistent across the test cycles.

   The fuel energy used over all the cycles with ULSD_2 fuel was slightly lower compared to ULSD (Up to 5%) (Figure 8.8). This could indicate differences in cycle work compared to ULSD and explain the observed lower fuel consumption with ULSD_2 fuel. Differences in average engine fuel rate (g/s) over the cycles were ≤ 0.05 g/s. CO$_2$ emissions were slightly higher (up to 6%) compared to ULSD for FTP75 cycle.

2. ATS temperatures (Figure 8.7): ATS temperatures were on average slightly lower on all the cycles (up to 9°C). However, this variation could be well-within run-to-run variation. As both fuels are ULSD with similar properties, this can also be possibly attributed to differences in actual engine operation. Vehicle C also had a feature that was inconsistent over the cycles which caused some run-to-run variation in engine operation. Lower fuel consumption seen with ULSD_2 could also contribute to the observed lower ATS temperatures.

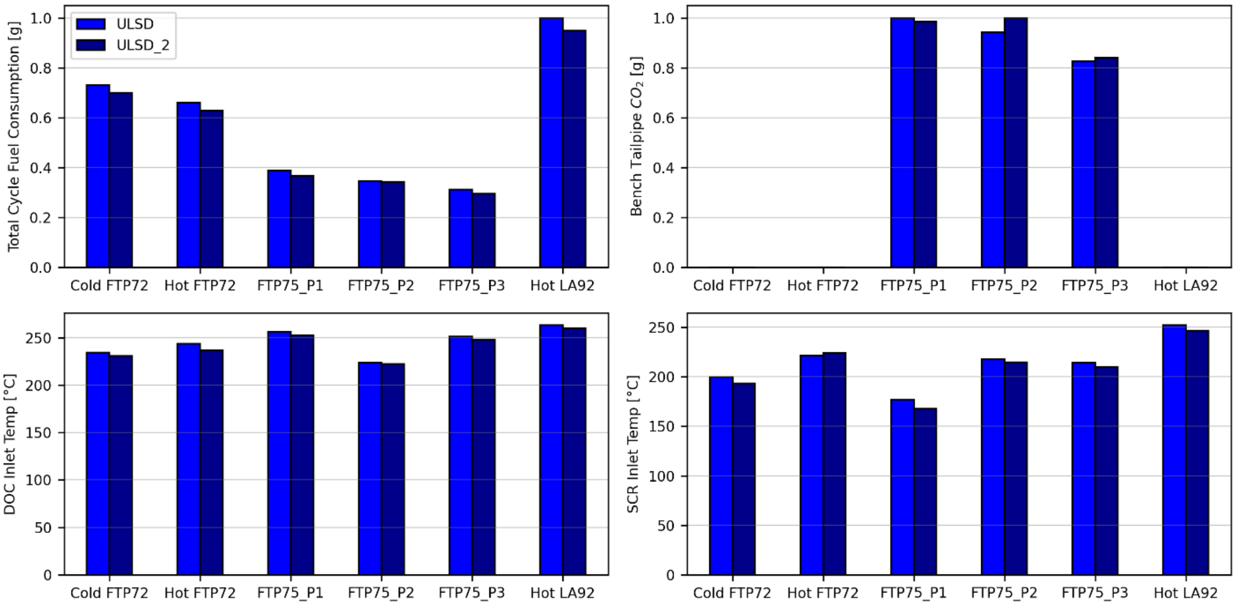

Figure 8.7: Vehicle C: ULSD_2 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

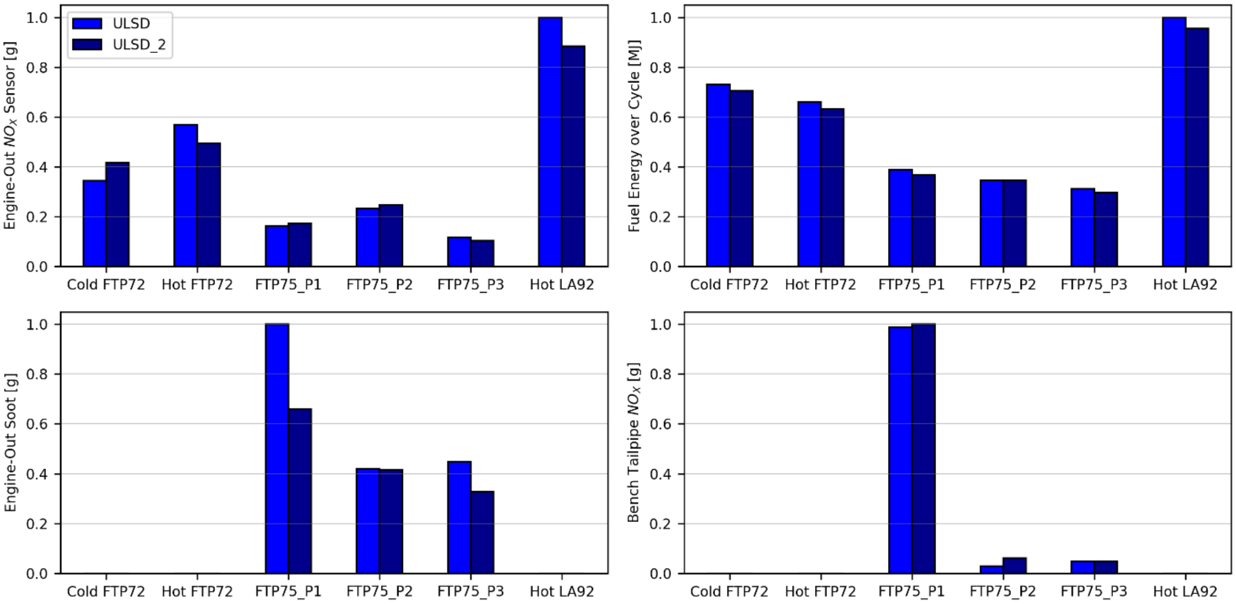

Figure 8.8: Vehicle C: ULSD_2 vs ULSD: Fuel Energy, Soot and NO_x Emissions

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 8.8. Engine-out NO_x emissions showed some variation (± 15 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some of this difference could be attributed to run-to-run variation.

   Tailpipe NO_x sensor measurements were comparable for Vehicle C. However, cumulative bench tailpipe NO_x (g) showed up to 2 times higher tailpipe NO_x emissions trend on FTP75 cycle with ULSD_2. However, on a ppm basis < 2 ppm difference was observed on the bench. The higher tailpipe NO_x can be attributed to overall lower ATS temperatures when running with ULSD_2 fuel.

4. Soot Emissions (Figure 8.8): Engine-out soot emissions across all three phases of FTP75 cycle were lower compared to ULSD (up to 25% over the 3 phases). This can be attributed lower aromatics in ULSD_2 fuel (20.2% vol) compared to ULSD (26.8% vol) (Table 1.2) which reduces the propensity for soot formation.

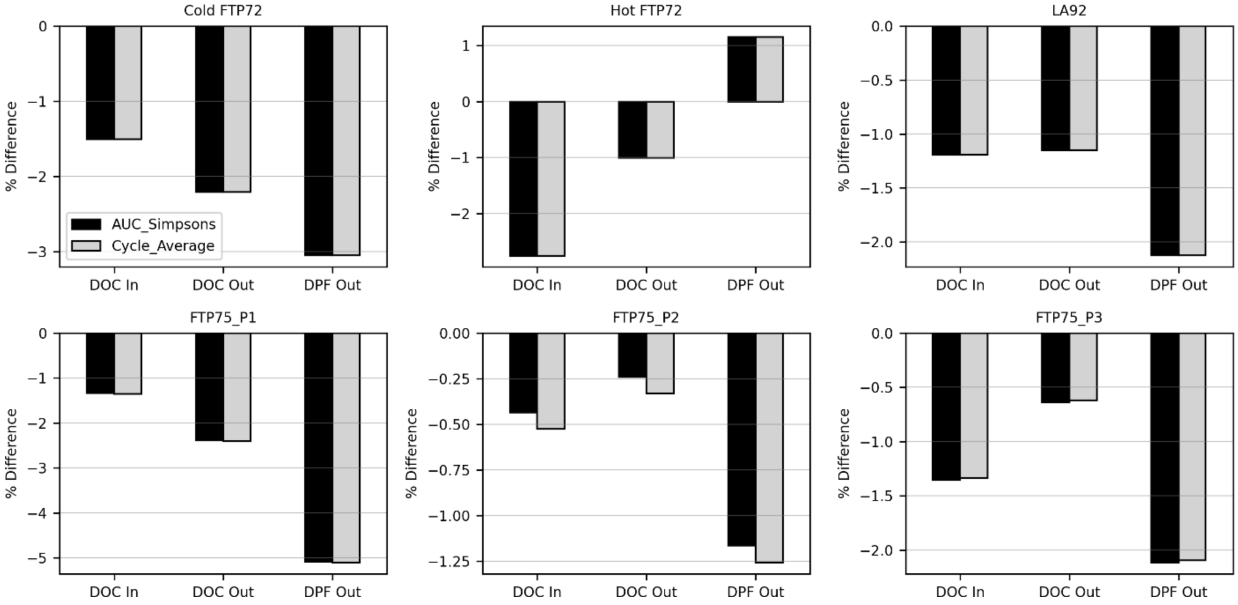

Figure 8.9: Vehicle C: ULSD_2 vs ULSD ATS Temperature Trends

Based on results from Table 8.3 and key observations presented, it can be concluded that no significant differences were observed in vehicle performance for Vehicle C before and after testing with the different fuel blends. Overall, slightly lower ATS temperatures and engine-out soot values were observed possibly due to fuel-to-fuel variation (ULSD_2 vs ULSD)

Other than the key observations presented, some variation was observed in all other PID labels as well in Table *8.3*. For example, differences in EGR and VGT position as well differences in fuel rail pressure, air flow and fuel flow were seen. The observed differences were seen to be primarily coming from differences in engine operation. Primarily, the inconsistent feature on Vehicle C being active or inactive possibly resulted in the observed differences. Therefore, it cannot be concluded that there were any changes in Vehicle C’s performance due to the fuels tested. Further, post-test cycle OBD scans for test cycles tested with ULSD_2 fuel did not show any OBD fault codes for Vehicle C.

Section 8.4: Vehicle D: ULSD_2 vs ULSD

Table 8.4: Vehicle D Results Summary: ULSD_2 vs ULSD

PID Labels	Units	Test Cycle						Observations
		FTP72		FTP75			LA92	
		Cold	Hot	Phase 1 (Cold Start)	Phase 2 (Stabilized)	Phase 3 (Hot Start)	Hot	
Mass Air Flow Sensor	g/s	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Intake Manifold Temp	°C	N/A	N/A	N/A	N/A	N/A	N/A	
Coolant Temp	°C	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 °C
EGR Valve A Position	%	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2%
Engine Fuel Rate	g/s	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 5% Lower
Exhaust Pressure	kPa	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
DOC Inlet Temp	°C	Slightly Lower	-	Slightly Lower	Slightly Lower	Slightly Lower	-	Up to 6°C Lower
DOC Outlet/DPF Inlet Temp	°C	Slightly Lower	-	Slightly Lower	Slightly Lower	Slightly Lower	-	
DPF Outlet/SCR Inlet Temp	°C	Slightly Lower	-	Slightly Lower	Slightly Lower	Slightly Lower	-	
SCR Outlet Temp	°C	N/A	N/A	N/A	N/A	N/A	N/A	
Main Injection Timing	°	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	
Intake Manifold Pressure	kPa	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 kPa
Upstream Lambda Sensor	-	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 3%
Engine Out NO_x Sensor	ppm	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 13 ppm
Tailpipe NO_x Sensor	ppm	N/A	N/A	N/A	N/A	N/A	N/A	
Bench Tailpipe NOx Conc	ppm	-	-	No Difference	No Difference	No Difference	-	± 2 ppm
Upstream O_2 Sensor	%	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
Fuel Rail Pressure	kPa	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
VGT Position	%	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 2 %
DEF Dosing	%	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Engine-Out NO_x	g	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 12% Lower
Calculated Tailpipe NO_x	g	N/A	N/A	N/A	N/A	N/A	N/A	
Calculated Exhaust Flow Rate	kg/h	No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	± 4%
Bench Tailpipe NO_x	g	-	-	Lower	Lower	Lower	-	Up to 24% Lower
Bench Tailpipe CO_2	g	-	-	Slightly Higher	Slightly Higher	Slightly Higher	-	Up to 7% Higher
Total Cycle Fuel Consumption	g	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Slightly Lower	Up to 5% Lower
Engine-Out Soot	mg	-	-	Lower	Lower	Lower	-	Up to 25% Lower

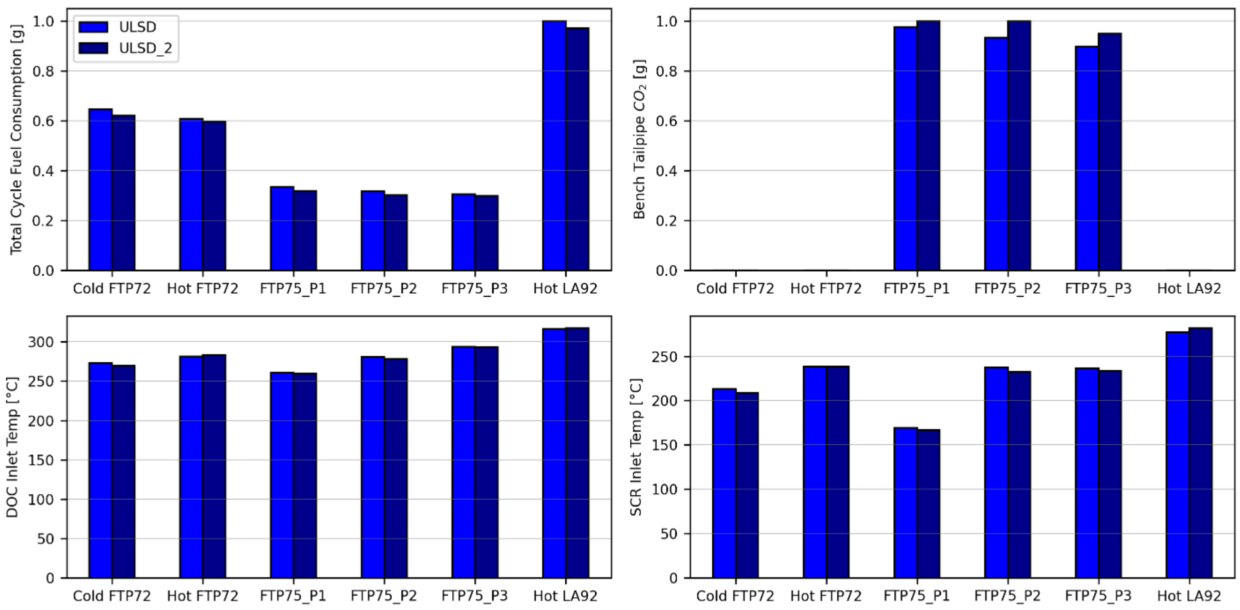

Figure 8.10: Vehicle D: ULSD_2 vs ULSD: Fuel Consumption, CO_2 Emissions and ATS Temperatures

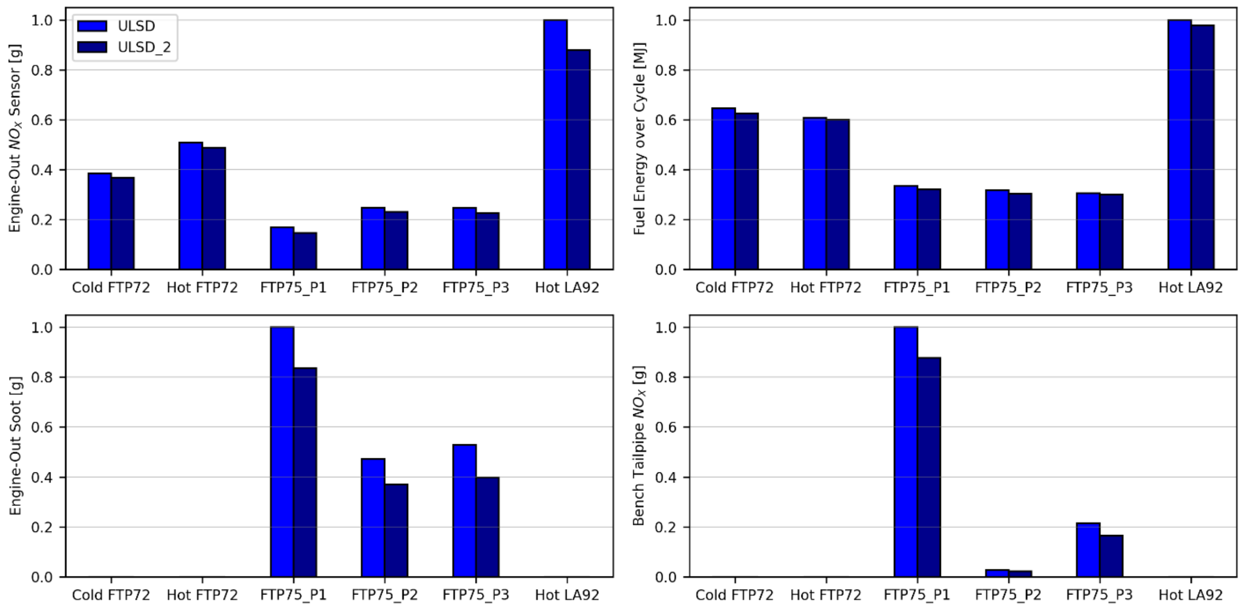

Figure 8.11: Vehicle D: ULSD_2 vs ULSD: Fuel Energy, Soot and NO_x Emissions

Key observations from Figure *8.10* and Figure *8.11* are as follows:

1. Fuel consumption/CO_2 Emissions (g): Total fuel consumption over the cycle was about 5% lower when running with ULSD_2 (Figure 8.10). As both ULSD fuels have similar properties (Table 1.2) and this is much higher than expected run-to-run variation, it can be concluded that this difference is possibly arising due to differences in actual engine operation.

The fuel energy used over all the cycles with ULSD_2 fuel was lower compared to ULSD (Up to 5%) (Figure 8.11). This could indicate differences in cycle work compared to the tests with ULSD which would lower fuel consumption. Differences in average engine fuel rate (g/s) over the cycles were ≤ 0.1 g/s. CO_2 emissions were slightly higher (up to 7%) compared to ULSD for FTP75 cycle.

2. ATS temperatures (Figure 8.10): ATS temperatures were on average slightly lower on all the cycles (up to 6°C). However, this difference is well-within run-to-run variation.

3. NO_x Sensors: Some differences were observed in engine-out NO_x trends as shown in Figure 8.11. Engine-out NO_x emissions were slightly lower (up to 13 ppm). However, there could be some differences in sensor activation times due to differences in ATS temperature, therefore some of this difference could be attributed to run-to-run variation. Also, the lower fuel energy observed could be contributing to the observed lower NO_x emissions with ULSD_2.

   Tailpipe NO_x sensor measurements were comparable for Vehicle C. However, cumulative bench tailpipe NO_x (g) showed lower tailpipe NO_x emissions trend (up to 24%) on FTP75 cycle with ULSD_2. However, on a ppm basis < 2 ppm difference was observed on the bench. The lower tailpipe NO_x can be attributed to lower engine-out NO_x emissions and similar ATS temperatures leading to better SCR efficiency when running with ULSD_2 fuel.

4. Soot Emissions (Figure 8.11): Engine-out soot emissions across all three phases of FTP75 cycle were lower (up to 25%) compared to ULSD. This can be attributed lower aromatics in ULSD_2 fuel (20.2% vol) compared to ULSD (26.8% vol) (Table 1.2) which reduces the propensity for soot formation.

In general, trends seen using Area under the curve and cycle averaged methods were similar for all the PID labels. Since largest impact of ULSD_2 fuel was seen on ATS temperatures, trends (percent difference) for ATS temperatures for Vehicle D using ULSD_2 fuel compared to ULSD fuel have been shown in Figure 8.12.

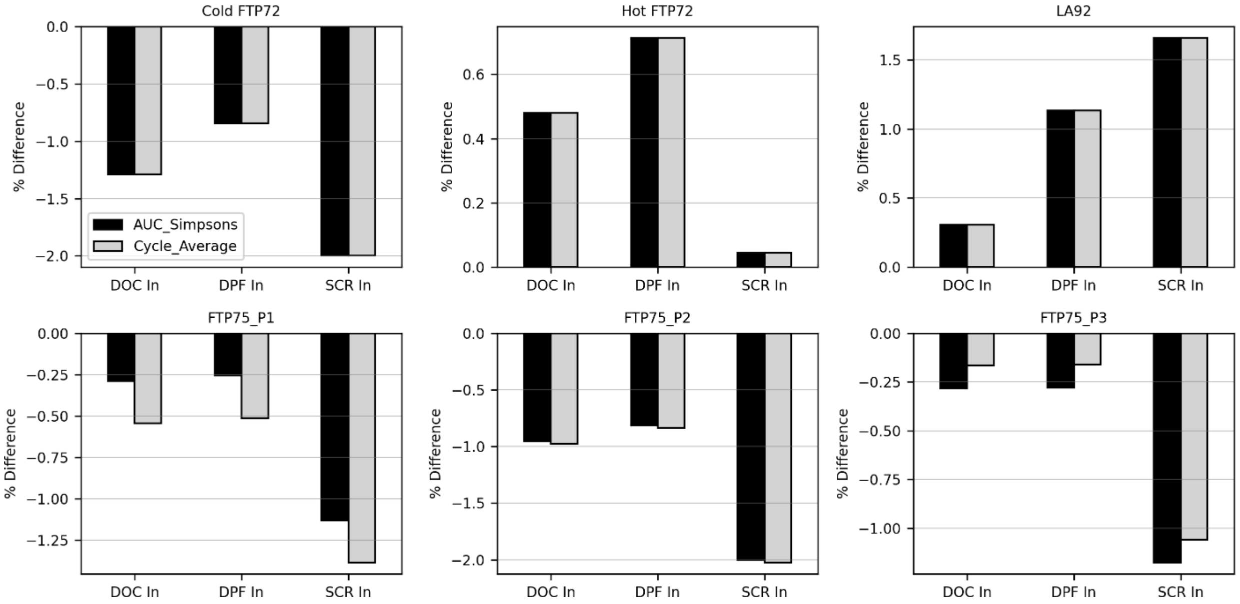

Figure 8.12: Vehicle D: ULSD_2 vs ULSD ATS Temperature Trends

Based on results from Table 8.4 and key observations presented, it can be concluded that overall, no significant differences were observed in vehicle performance for Vehicle D before and after testing with the different fuels. Overall, slightly lower ATS temperatures, engine-out NO_x and soot values were observed.

Other than the key observations presented, some variation was observed in all other PID labels as well in Table 8.4. For example, differences in EGR and VGT position as well differences in fuel rail pressure, air flow and fuel flow were seen. The observed differences were seen to be primarily coming from differences in engine operation. Therefore, it cannot be concluded that there were any changes in Vehicle D's performance due to the fuels tested. Further, post-test cycle OBD scans for test cycles tested with ULSD_2 fuel did not show any OBD fault codes for Vehicle D.

Section 8.5: ULSD_2 vs ULSD Summary

Based on the analysis presented, comparison of test data with ULSD and ULSD_2 fuels did not show any significant degradation or differences in vehicle performance after testing with the fuels and fuel blends in this study. Some differences were observed in fuel consumption, ATS temperatures and NO_x emissions which were concluded to be primarily coming from run-to-run and fuel-to-fuel variation. Engine-out soot emissions were seen to be lower in Vehicles C and D (up to 25%); however, this was due to the lower aromatics in ULSD_2 fuel compared to ULSD. Differences observed in other PID labels such as air flow, EGR and VGT positions, lambda and O_2 sensor measurements were concluded to be well within expected values and arising primarily due to run-to-run variation and lower fuel energy (lower cycle work) observed for all vehicles with ULSD_2 fuel.

Chapter 9 : Summary and Conclusions

This study attempted to understand the impact of alternative diesel fuels on OBD monitor robustness of diesel vehicles using climate-controlled chassis dynamometer testing. To determine this, seven different fuel and fuel blends were tested on four different vehicles to analyze OBD and emissions data to develop statistical analysis methods to understand trends in a selective list of common PID labels across the four vehicles. Three base fuels ULSD/ULSD_2, R99 and biodiesel (B100) were used to make four fuel blends – R50U50, B20R80, B50U50 and B50R50. Further, the vehicles were re-tested with ULSD fuel (ULSD_2) to determine any changes to vehicle performance after testing with different alternative diesel fuels and fuel blends. The investigation tried to answer the following questions:

1. Can impact of different alternative diesel fuels on OBD monitor robustness be determined using a homogeneous set of PID labels from different vehicles?
2. Can trends observed in selected PID labels be used to determine possible impact on OBD monitor decisions due to the fuel?
3. If OBD faults are observed, can data from selected PID labels be used to determine impact of fuel on OBD monitor decisions?

Based on the testing conducted, none of the vehicles exhibited any OBD fault codes due to impact of any alternative diesel fuel/fuel blend. Variations observed for most PID labels were well within run-to-run variation and expected differences in vehicle operation due to drive-to-driver variation. However, most significant impact was seen on ATS temperatures, fuel consumption, CO_2 emissions, engine-out soot and NO_x emissions as well as tailpipe NO_x emissions.

Using a climate-controlled chassis dynamometer, vehicles instrumented for testing and PID labels from OBD, the acquired test data was successful in capturing important trends in PID labels that could provide understanding of possible impact on OBD monitor robustness. However, based on the results presented, the short-term tests conducted in this study did not show any OBD faults due to any of the alternative diesel fuels/fuel blends tested.

Some data consistency issues and constraints were identified during the analysis which reduced the deductibility of trends for some PID labels. This included the following:

- Due to requirements of anonymity, complete knowledge of key OBD and base engine control strategies was unavailable to fully understand some observed trends and form conclusions. For example, vehicles tested exhibited the presence of thermal management, fuel adaptation strategies and other features which can affect engine operation even between test runs of the same fuel. Therefore, without a full understanding of the strategies and controls, some trends could not be analyzed – for example, EGR and VGT positions, fuel injection timing etc.
- Though significant efforts were made to keep test sequences consistent across the different test fuels, vehicle testing related issues such as data dropouts and measurement issues led to differences in test sequences between ULSD (base fuel for comparison) and other alternative diesel fuels/fuel blends. Therefore, some PID labels such as exhaust pressure, DPF delta pressure and NH_3 slip could not be analyzed without additional information such as accumulated soot and NH_3 storage which were proprietary labels not available for measurement.

- Target vehicle speed traces for each test cycle were followed as closely as possible based on CFR 1066 regulations. However, as these were not certification tests, violations were allowed that exceeded these regulations if the vehicle was underpowered for a test cycle. Therefore, cycle work over the test cycles were not kept consistent, which allowed for run-to-run variation in engine operation which affected the selected PID labels for this analysis. Therefore, fuel energy calculation was used as a metric to understand if test cycles with alternative diesel fuel were comparable to those with ULSD.
- Due to first batch of ULSD fuel (ULSD) being used up over the course of testing, a second batch of ULSD fuel (ULSD_2) was used to complete the tests. Therefore, the analysis uses the first batch of ULSD (ULSD) for analyzing Vehicles A and D and second batch of ULSD (ULSD_2) for analyzing Vehicles B and C. However, since ULSD_2 was used to make R50U50 blend, all vehicles were compared with ULSD_2 for R50U50 blend.

To ensure robustness of data analysis therefore, percentage and absolute difference-based thresholds were defined to try and separate run-to-run variations and the impact of the fuel. A ± 2% difference and ± 2 absolute differences were used as thresholds. Only PID labels that showed variations exceeding these thresholds were used to determine any impacts due to alternative diesel fuels compared to ULSD.

Using these thresholds and statistical analysis methods defined in Section 1.6 the following is the summary of the key conclusions from this study:

- **Biodiesel (B100) fuel** showed the most significant impact on the selected PID labels for all the vehicles. This included lower ATS temperatures, higher fuel consumption, higher engine and tailpipe NO_x emissions, lower engine-out soot emissions and slightly higher fuel rail pressure compared to ULSD. This could therefore impact OBD monitors for ATS temperature rationality, thermal management, DPF regeneration, fuel flow, NO_x sensor rationality and SCR efficiency. However, no OBD fault codes were observed while running with B100 fuel. But the absence of OBD fault codes in the short testing period of this study does not eliminate the possibility of OBD faults in the long term due to extended use of B100 fuel.
- **B50U50 and B50R50 fuels** showed some impact on the selected PID labels for all the vehicles. This included lower ATS temperatures, higher fuel consumption, engine-out and tailpipe NO_x emissions and lower engine-out soot emissions compared to ULSD. This could therefore impact OBD monitors for ATS temperature rationality, thermal management, DPF regeneration, NOx sensor rationality, SCR efficiency and fuel flow. However, no OBD fault codes were observed while running with either fuel. But the absence of OBD fault codes in the short testing period of this study does not eliminate the possibility of OBD faults in the long term due to extended use of these fuels.
- **B20R80, R50U50 and renewable diesel (R99) fuels** showed very small impact on the selected PID labels for all the vehicles. This included slightly lower ATS temperatures and lower engine-out soot emissions. Some differences in fuel consumption and engine-out and tailpipe NO_x emissions were also observed. This could therefore impact OBD monitors for ATS temperature rationality, thermal management, DPF regeneration and possibly NOx sensor rationality. However, no OBD fault codes were observed while running with these fuels.
- Vehicles re-tested with ULSD after testing with alternative diesel fuels/fuel blends did not show any major degradation in performance. Some variations were observed which were

concluded to be well within run-to-run and fuel-to-fuel variation between the two batches of ULSD fuels.

Further, specific fuel/fuel blend properties lead to differences/trends in PID labels compared to ULSD. The following is the summary of the impact of these fuel properties on the PID labels:

- **Cetane Number:** R99 fuel has higher cetane number compared to ULSD and biodiesel. Higher cetane number shortens the ignition delay and leads to more complete combustion. Therefore, it was observed that engine-out soot formation was lower with R99 fuel and blends with R99 fuel (R50U50, B20R80 and B50R50). However, the higher combustion efficiency due to shorter ignition delay could lower the exhaust gas temperatures and thereby the ATS temperatures as was observed for R99 fuel and blends with R99 fuel (R50U50, B20R80 and B50R50).
- **%O_2 in Fuel:** Biodiesel fuel has higher O_2 concentration compared to ULSD and R99 fuel (biodiesel used in this study had 10% O_2). The higher O_2 concentration reduces the propensity for soot formation and thereby results in the lower engine-out soot as observed for B100 and blends with B100 (B20R80, B50U50 and B50R50) compared to ULSD. However, the increased concentration of oxygen also results in increased engine-out NO_x emissions as seen with B100 fuel and B100 fuel blends.
- **Aromatics:** Aromatics is the measure of polycyclic aromatic hydrocarbons (PAH) in the fuel. Higher aromatics in the fuel increases soot emissions as these are harder to break down during combustion. Therefore, lower aromatic fuels such as R99 and B100 and blends of these fuels showed lower engine-out soot emissions compared to ULSD which has higher aromatics. Further, higher aromatics can also increase engine-out NO_x formation by increasing local combustion temperatures [30]. Therefore, lower aromatic fuels such as R99 and blends with R99 were seen to show some trends of lower engine-out NO_x emissions as compared to ULSD on some vehicles.
- **Net Heating Value (MJ/kg or MJ/L):** Net heating value is the measure of heat released when fuel undergoes complete combustion with oxygen. Therefore, if a fuel/fuel blend has lower net heating value, the energy derived from the fuel is lower and therefore more fuel is required to complete the same cycle work. Therefore, fuels/fuel blends with lower net heating value showed trends of higher fuel consumption compared to ULSD. Fuels/fuel blends with lower net heating value compared to ULSD were also observed to show lower ATS temperatures due to lower exhaust energy available after combustion.
- **Density (kg/m^3):** It was observed that with higher density fuels such as biodiesel and blends of biodiesel, some vehicles showed slightly higher fuel rail pressures compared to ULSD (up to 5-9%). Higher fuel rail pressures may be required to compensate for the higher density of biodiesel to maintain required fuel injection quantity. This was observed for biodiesel (B100) and blends of biodiesel with 50% biodiesel (B50U50 and B50R50).

Chapter 10 : Recommendations

This study has demonstrated that short-term use of alternative diesel fuels in the vehicles tested did not significantly impact OBD monitor robustness. This was evidenced by the absence of OBD faults throughout the testing of all the vehicles. However, long term durability tests of vehicles will be required to understand the effect on OBD monitors due to extended use of such fuels/fuel blends in these vehicles. Therefore, this study recommends the following based on the testing and analysis constraints discussed:

- Long-term durability tests of vehicles with alternative diesel fuels are recommended to gain more insight into the impact of these fuels when used for an extended period.
- To understand the impact of fuels on specific OBD monitoring strategies, targeted tests need to be conducted such as steady state testing at different engine speed/loads or at idle. This could also include targeted tests based on commonly used OBD monitor strategies for some monitors which could provide more insights into how these fuels/fuel blends impact specific OBD monitor decisions.
- More controlled tests like engine dynamometer tests would reduce variations in engine operation and thereby reduce variations in key PID labels such as air flow, fuel flow, EGR and VGT positions. This would improve statistical analysis results to get clearer trends in PID labels and improve detectability of variations in PID labels due to fuel alone.
- As the test sequence used in this study was long, if there were test cell or data collection related issues with a test cycle, the whole sequence could not be restarted. Therefore, test cycles would be repeated to make up for the test cycles with issues. This resulted in inconsistencies between the test sequences used for different fuels/fuel blends compared to ULSD. Therefore, key parameters such as NH_3 storage and soot accumulation would vary between fuels due to differences in test sequence. This would directly affect the amount of NH_3 slip observed as well DPF delta pressure and it was not possible to analyze and understand impact of a fuel/fuel blend on these PID labels. Therefore, these labels had to be eliminated from the analysis. Shorter test sequences would allow for ease of repeatability and re-testing of test sequences if there are any testing related issues. This would allow for a more robust data analysis between test data from different fuels.
- Though DPF regeneration was carried out on each vehicle before starting with new fuel/fuel blend, it was not possible to record regeneration data along with using the tools provided by OEMs to trigger DPF regeneration using the OBD CAN port. Therefore, alternative methods are required to collect DPF regeneration when conducting similar studies.
- PID labels from OBD CAN data used in this study were successful in demonstrating trends in vehicle operation due to the use of alternative diesel fuels. However, to gain a complete understanding of their effects on key OBD monitors other parameters would be required - for example, EGR feedback, VGT feedback or NH_3 storage.

However, the trends presented in this report should help to guide OBD calibrators to understand the expected impact of these alternative diesel fuels/fuel blends and calibrate/modify OBD monitoring strategies to accommodate these trends and improve OBD monitor robustness.

Chapter 11 : Acknowledgments

This program would like to thank the following contributors for all their hard work and participation:

- Alexander Muller
- Amitabh Gautam
- Brendan Sherry
- Frank Richardson
- Henning Kleeberg
- Jake Tuttle
- Rade Milanovic
- Rahul Suresh
- Sarathnandan Chaluvally Sadasivan
- Shravani Dighole

Chapter 12 : References

1. Overview of the Renewable Fuel Standard Program | US EPA - https://www.epa.gov/renewable-fuel-standard/overview-renewable-fuel-standard-program.

2. Low Carbon Fuel Standard | California Air Resources Board - https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard.

3. Dimitriadis A, Natsios I, Dimaratos A, Katsaounis D, Samaras Z, Bezergianni S and Lehto K (2018) Evaluation of a Hydrotreated Vegetable Oil (HVO) and Effects on Emissions of a Passenger Car Diesel Engine. Front. Mech. Eng. 4:7. doi: 10.3389/fmech.2018.00007.

4. Knothe G, Van Gerpen J, Krahl J. The biodiesel handbook, Illinois. Champaign: AOCS Press; 2005.

5. Agarwal AK. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Prog Energy Combust Sci 2007;33:233–71.

6. Mustafa Balat, Potential alternatives to edible oils for biodiesel production – A review of current work, Energy Conversion and Management, Volume 52, Issue 2, 2011, Pages 1479-1492, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2010.10.011.

7. Ayhan Demirbas, Importance of biodiesel as transportation fuel, Energy Policy, Volume 35, Issue 9, 2007, Pages 4661-4670, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2007.04.003.

8. Subhash Lahane, K.A. Subramanian, Effect of different percentages of biodiesel–diesel blends on injection, spray, combustion, performance, and emission characteristics of a diesel engine, Fuel, Volume 139, 2015, Pages 537-545, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2014.09.036.

9. Devendra Singh, K.A. Subramanian, S.K. Singal, Emissions and fuel consumption characteristics of a heavy-duty diesel engine fueled with Hydroprocessed Renewable Diesel and Biodiesel, Applied Energy, Volume 155, 2015, Pages 440-446, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2015.06.020.

10. Kwangsam Na, Subhasis Biswas, William Robertson, Keshav Sahay, Robert Okamoto, Alexander Mitchell, Sharon Lemieux, Impact of biodiesel and renewable diesel on emissions of regulated pollutants and greenhouse gases on a 2000 heavy duty diesel truck, Atmospheric Environment, Volume 107, 2015, Pages 307-314, ISSN 1352-2310, https://doi.org/10.1016/j.atmosenv.2015.02.054.

11. Stella Bezergianni, Athanasios Dimitriadis, Comparison between different types of renewable diesel, Renewable and Sustainable Energy Reviews, Volume 21, 2013, Pages 110-116, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2012.12.042.

12. Hunicz, J., Krzaczek, P., Gęca, M. et al. Comparative study of combustions and emission of diesel engine fuelled with FAME and HVO. *Combustion Engines*. 2021, **184**(1), 72-78. https://doi.org/ 10.19206/CE-135066

13. An Overview of Biodiesel and Petroleum Diesel Life Cycles - https://doi.org/10.2172/1218368

14. M.M. Hasan, M.M. Rahman, Performance and emission characteristics of biodiesel–diesel blend and environmental and economic impacts of biodiesel production: A review, Renewable and Sustainable Energy Reviews, Volume 74, 2017, Pages 938-948, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2017.03.045.

15. G. Karavalakis, T. Durbin, K. Johnson, M. Hajbabaei, CARB Comprehensive B5/B10 Biodiesel Blends in Heavy-Duty Engine Dynamometer Testing, final report by CE-CERT, U. Cal. Riverside for CARB, Jun. 2014

16. T. Durbin, G. Karavalakis, K. Johnson, M. Hajbabai, CARB B20 Biodiesel Preliminary and Certification Testing, final report by CE-CERT, U. Cal. Riverside for CARB, Jul. 2013

17. T. Durbin, G. Karavalakis, K. Johnson, M. Hajbabaei, CARB B5 Biodiesel Preliminary and Certification Testing, final report by CE-CERT, U. Cal. Riverside for CARB, Apr. 2013

18. Dolanimi Ogunkoya, William L. Roberts, Tiegang Fang, Nirajan Thapaliya, Investigation of the effects of renewable diesel fuels on engine performance, combustion, and emissions, Fuel, Volume 140, 2015, Pages 541-554, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2014.09.061.

19. Soo-Young No, Application of hydrotreated vegetable oil from triglyceride based biomass to CI engines – A review, Fuel, Volume 115, 2014, Pages 88-96, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2013.07.001.

20. A deep dive into renewable diesel - https://www.cummins.com/news/2024/05/16/deep-dive-renewable-diesel

21. Gerhard Knothe, Biodiesel and renewable diesel: A comparison, Progress in Energy and Combustion Science, Volume 36, Issue 3, 2010, Pages 364-373, ISSN 0360-1285, https://doi.org/10.1016/j.pecs.2009.11.004.

22. Ricardo Suarez-Bertoa, Marina Kousoulidou, Michael Clairotte, Barouch Giechaskiel, Jukka Nuottimäki, Teemu Sarjovaara, Laura Lonza, Impact of HVO blends on modern diesel passenger cars emissions during real world operation, Fuel, Volume 235, 2019, Pages 1427-1435, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2018.08.031.

23. Ivan Bortel, Jiří Vávra, Michal Takáts, Effect of HVO fuel mixtures on emissions and performance of a passenger car size diesel engine, Renewable Energy, Volume 140, 2019, Pages 680-691, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2019.03.067.

24. Federico Millo, Biplab Kumar Debnath, Theodoros Vlachos, Claudio Ciaravino, Lucio Postrioti, Giacomo Buitoni, Effects of different biofuels blends on performance and emissions of an automotive diesel engine, Fuel, Volume 159, 2015, Pages 614-627, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2015.06.096.

25. On-Board Diagnostics (OBD) Inspection and Maintenance (I/M) Program Implementation for Flexible Fuel Vehicles (FFVs) - https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1007UXP.pdf

26. Impact of Biodiesel Metals on Aftertreatment System Durability - https://www.energy.gov/eere/vehicles/articles/impact-biodiesel-metals-aftertreatment-system-durability

27. José Rodríguez-Fernández, Magín Lapuerta, Jesús Sánchez-Valdepeñas, Regeneration of diesel particulate filters: Effect of renewable fuels, Renewable Energy, Volume 104, 2017, Pages 30-39, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2016.11.059.

28. Impact of FAME Content on the Regeneration Frequency of Diesel Particulate Filters (DPFs) - https://www.concawe.eu/wp-content/uploads/2017/01/rpt_16-14.pdf

29. S. Kent Hoekman, Curtis Robbins, Review of the effects of biodiesel on NOx emissions, Fuel Processing Technology, Volume 96, 2012, Pages 237-249, ISSN 0378-3820, https://doi.org/10.1016/j.fuproc.2011.12.036.

30. Yoshiyuki Kidoguchi, Changlin Yang, Ryoji Kato, Kei Miwa, Effects of fuel cetane number and aromatics on combustion process and emissions of a direct-injection diesel engine, JSAE Review, Volume 21, Issue 4, 2000, Pages 469-475, ISSN 0389-4304, https://doi.org/10.1016/S0389-4304(00)00075-8.

Definitions/Abbreviations

ATS – Exhaust After-treatment System

AUC – Area Under the Curve

B100 – Biodiesel

C – Carbon

CA50 – Crank Angle at which 50% of heat from combustion has been released

CAN – Controller Area Network (Communications Protocol)

CFR – Code of Federal Regulations

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

DEF – Diesel Exhaust Fluid

DOC – Diesel Oxidation Catalyst

DPF – Diesel Particulate Filter

EGR – Exhaust Gas Recirculation

FTP72/FTP75 - Federal Test Procedure test cycles (drive cycles)

H – Hydrogen

HC – Hydrocarbon

HVO – Hydrogenated Vegetable Oil

LA92 – California Unified cycle (drive cycle)

N/A – PID or data not available

NH3 – Ammonia

NHV – Net Heating Value

NO_x – Nitrogen Oxides

O_2 – Oxygen

OBD – On Board Diagnostics

OEM – Original Equipment Manufacturer

PIDs – Parameter Identifiers

PM – Particulate Matter

Ppm – parts per million

R99/R100 – Renewable Diesel

SCR – Selective Catalytic Reduction

ULSD – Ultra Low Sulfur Diesel

VGT – Variable Geometry Turbocharger

VNT – Variable Nozzle Turbocharger

Appendix

APPENDIX A: Fuel Inspection Sheets

Table A-1: ULSD Fuel

Fuel			ULSD			
Laboratory			Marathon	P66	OEM	Paragon
Property	ASTM Test Method	Units				
API Gravity @ 60°F	D4052	API		35.08		
Density at 15°C	D4052	g/cm3		0.8486	0.849	
Cetane Number	D7668	-	46.61			
Net Calorific Value	D240	MJ/kg		42.55		
Carbon	Calculation	% wt.		86.82		
Hydrogen	D7171	% wt.		13.18		
Oxygen	UOP730	% wt.		0		
Water	D6304	ppm			63.85	
Sulphur	D7039/D5453	ppm		3.87	2.7	
Flash Point	D7094	°C			60.8	
Aromatics	D5186	% wt.			27.8	
Aromatics	D5186	% vol			26.8	
Viscosity at 40°C	D445	mm^2/s				
Cloud Point	D5771	°C				
Distillation @ Atmospheric Pressure	D86					
Initial Boiling Point		°C				
5%		°C				
10%		°C				
20%		°C				
30%		°C				
40%		°C				
50%		°C				
60%		°C				
70%		°C				
80%		°C				
90%		°C				
95%		°C				
FBP		°C				
Recovery		% vol				
Residue		% vol				
Total Recovery		% vol				
Loss		% vol				
Corrected Loss		% vol				
Corrected % Recovery		% vol				
Corrected Total % Recovery		% vol				

Table A-2: ULSD_2 Fuel

Fuel			ULSD_2			
Laboratory			Marathon	P66	OEM	Paragon
Property	ASTM Test Method	Units				
API Gravity @ 60°F	D4052	API	35.8			35.8
Density at 15°C	D4052	g/cm3	0.8457			0.8452
Cetane Number	D6890/D613		48.2			45.3
Net Calorific Value	D4809	MJ/kg	42.84			
Carbon	D5291D	% wt.				86.38
Hydrogen	D5291D	% wt.				13.62
Oxygen	D5622A	% wt.				< 0.05
Water	D6304	ppm				
Sulphur	D4294/D5453	ppm	< 15			2.8
Flash Point	D93	°C	58.88			60.8
Aromatics	D5186/D8368M	% wt.				21.6
Aromatics	D5186/D8368M	% vol	20.2			19.9
Viscosity at 40°C	D445	mm^2/s				2.767
Cloud Point	D2500	°C				-15
Distillation @ Atmospheric Pressure	D86					
Initial Boiling Point		°C				155.2
5%		°C				187.8
10%		°C				202.7
20%		°C				222.3
30%		°C				238.5
40%		°C				252
50%		°C				263.3
60%		°C				275.7
70%		°C				289.1
80%		°C				305
90%		°C				326.7
95%		°C				344
FBP		°C				358.9
Recovery		% vol				97.8
Residue		% vol				1.3
Total Recovery		% vol				
Loss		% vol				0.9
Corrected Loss		% vol				
Corrected % Recovery		% vol				
Corrected Total % Recovery		% vol				

Table A-3: R99 Fuel

Fuel			R99			
Laboratory			Marathon	P66	OEM	Paragon
Property	ASTM Test Method	Units				
API Gravity @ 60°F	D4052	API		49.17		
Density at 15°C	D4052	g/cm3		0.7824	0.7828	
Cetane Number						
Net Calorific Value	D240/D3338-MOD	MJ/kg		43.97	44.07	
Carbon	Calculation/D3338-MOD	% wt		84.99	89.45	
Hydrogen	D7171/D3338-MOD	% wt		15.01	10.55	
Oxygen	D3338-MOD/UOP730	% wt		0	0	
Water	D6304	ppm			29.65	
Sulphur	D7039/D5453	ppm		0.32	0.1	
Flash Point	D7094	°C			77.8	
Aromatics	D5186	% wt				
Aromatics	D5186	% vol				
Viscosity at 40°C	D445	mm2/s			3.1968	
Cloud Point	D5771	°C			-2.2	
Distillation @ Atmospheric Pressure	D86					
Initial Boiling Point		°C			182.5	
5%		°C			246.2	
10%		°C			268.2	
20%		°C			281.9	
30%		°C			287.3	
40%		°C			289.9	
50%		°C			291.9	
60%		°C			293.7	
70%		°C			295.5	
80%		°C			297.5	
90%		°C			300.2	
95%		°C			303.3	
FBP		°C			318.2	
Recovery		% vol			98.6	
Residue		% vol			1.3	
Total Recovery		% vol			99.9	
Loss		% vol			0.1	
Corrected Loss		% vol			0.2	
Corrected % Recovery		% vol			98.5	
Corrected Total % Recovery		% vol			99.8	

Table A-4: B100 Fuel

Fuel			B100			
Laboratory			Marathon	P66	OEM	Paragon
Property	ASTM Test Method	Units				
API Gravity @ 60°F	D4052	API		28.37		
Density at 15°C	D4052	g/cm3		0.8842		
Cetane Number						
Net Calorific Value	D240	MJ/kg		37.15	37.24	
Carbon	Calculation	% wt		77.95		
Hydrogen	D7171	% wt		11.95		
Oxygen	UOP730	% wt		10.1		
Water	D6304	ppm				
Sulphur	D5453	ppm		0.38		
Flash Point	D7094	°C				
Aromatics	D5186	% wt				
Aromatics	D5186	% vol				
Viscosity at 40°C	D445	mm2/s				
Cloud Point	D5771	°C				
Distillation @ Atmospheric Pressure	D86					
Initial Boiling Point		°C				
5%		°C				
10%		°C				
20%		°C				
30%		°C				
40%		°C				
50%		°C				
60%		°C				
70%		°C				
80%		°C				
90%		°C				
95%		°C				
FBP		°C				
Recovery		% vol				
Residue		% vol				
Total Recovery		% vol				
Loss		% vol				
Corrected Loss		% vol				
Corrected % Recovery		% vol				
Corrected Total % Recovery		% vol				

Table A-5: R50U50 Blend

Fuel			R50U50			
Laboratory			Marathon	P66	OEM	Paragon
Property	ASTM Test Method	Units				
API Gravity @ 60°F	D4052	API		42.18		
Density at 15°C	D4052	g/cm3	0.8148	0.8139	0.8155	
Cetane Number						
Net Calorific Value	D240	MJ/kg		43.37		
Carbon	Calculation	% wt	85.32	85.83		
Hydrogen	D7171	% wt	14.68	14.17		
Oxygen	UOP730	% wt	0	0		
Water	D6304	ppm				
Sulphur	D5453	ppm		1.6		
Flash Point	D7094	°C				
Aromatics	D5186/D8368M	% wt	11.52	13.1	13.1	
Aromatics	D5186/D8368M	% vol	10.45			
Viscosity at 40°C	D445	mm2/s				
Cloud Point	D5771	°C				
Distillation @ Atmospheric Pressure	D86					
Initial Boiling Point		°C				
5%		°C				
10%		°C				
20%		°C				
30%		°C				
40%		°C				
50%		°C				
60%		°C				
70%		°C				
80%		°C				
90%		°C				
95%		°C				
FBP		°C				
Recovery		% vol				
Residue		% vol				
Total Recovery		% vol				
Loss		% vol				
Corrected Loss		% vol				
Corrected % Recovery		% vol				
Corrected Total % Recovery		% vol				

A-6: B20R80 Blend

Fuel			B20R80			
Laboratory			Marathon	P66	OEM	Paragon
Property	ASTM Test Method	Units				
API Gravity @ 60°F	D4052	API		44.46		
Density at 15°C	D4052	g/cm3		0.8025	0.8027	
Cetane Number						
Net Calorific Value	D240/Calculation	MJ/kg		42.33	42.7	
Carbon	Calculation	% wt		83.68		
Hydrogen	D7171	% wt		14.31		
Oxygen	UOP730	% wt		2.01		
Water	D6304	ppm				
Sulphur	D7039/D5453	ppm		0.42	1.1	
Flash Point	D7094	°C				
Aromatics	D5186/D8368M	% wt		0.03	0.1	
Aromatics	D5186/D8368M	% vol			0.1	
Viscosity at 40°C	D445	mm2/s				
Cloud Point	D5771	°C				
Distillation @ Atmospheric Pressure	D86					
Initial Boiling Point		°C				
5%		°C				
10%		°C				
20%		°C				
30%		°C				
40%		°C				
50%		°C				
60%		°C				
70%		°C				
80%		°C				
90%		°C				
95%		°C				
FBP		°C				
Recovery		% vol				
Residue		% vol				
Total Recovery		% vol				
Loss		% vol				
Corrected Loss		% vol				
Corrected % Recovery		% vol				
Corrected Total % Recovery		% vol				

A-7: B50U50 Blend

Fuel			B50U50			
Laboratory			Marathon	P66	OEM	Paragon
Property	ASTM Test Method	Units				
API Gravity @ 60°F	D4052	API		31.76		
Density at 15°C	D4052	g/cm3	0.8486	0.8659		
Cetane Number						
Net Calorific Value	D240/Calculation	MJ/kg		39.92	39.09	
Carbon	Calculation	% wt	81.78	83.21		
Hydrogen	D7171	% wt	12.89	12.54		
Oxygen	UOP730	% wt	5.33	4.25		
Water	D6304	ppm				
Sulphur	D7039/D5453	ppm		2.32		
Flash Point	D7094	°C				
Aromatics	D5186/D8368M	% wt	15.19	11.56		
Aromatics	D5186/D8368M	% vol	14.49			
Viscosity at 40°C	D445	mm2/s				
Cloud Point	D5771	°C				
Distillation @ Atmospheric Pressure	D86					
Initial Boiling Point		°C				
5%		°C				
10%		°C				
20%		°C				
30%		°C				
40%		°C				
50%		°C				
60%		°C				
70%		°C				
80%		°C				
90%		°C				
95%		°C				
FBP		°C				
Recovery		% vol				
Residue		% vol				
Total Recovery		% vol				
Loss		% vol				
Corrected Loss		% vol				
Corrected % Recovery		% vol				
Corrected Total % Recovery		% vol				

A-8: B50R50 Blend

Fuel			B50R50			
Laboratory			Marathon	P66	OEM	Paragon
Property	ASTM Test Method	Units				
API Gravity @ 60°F	D4052	API		38.42		
Density at 15°C	D4052	g/cm3	0.8335	0.8319	0.8326	
Cetane Number						
Net Calorific Value	D240/Calculation	MJ/kg		40.45	40.72	
Carbon	Calculation/D3343-MOD	% wt	81.01	82.36	78.68	
Hydrogen	D7171/D3343-MOD	% wt	13.39	13.39	15.4	
Oxygen	UOP730/D3343-MOD	% wt	5.6	4.25	5.92	
Water	D6304	ppm				
Sulphur	D7039/D5453	ppm			0	
Flash Point	D7094	°C			89	
Aromatics	D5186/D8368M	% wt	0.12		1.5	
Aromatics	D5186/D8368M	% vol	0.11		2.7	
Viscosity at 40°C	D445	mm2/s			3.4523	
Cloud Point	D5771	°C			-1.4	
Distillation @ Atmospheric Pressure	D86					
Initial Boiling Point		°C			202.2	
5%		°C			283.1	
10%		°C			294	
20%		°C			302.5	
30%		°C			305.9	
40%		°C			309.8	
50%		°C			313.9	
60%		°C			318.1	
70%		°C			323.5	
80%		°C			329.4	
90%		°C			336.3	
95%		°C			342	
FBP		°C			349.1	
Recovery		% vol			98.8	
Residue		% vol			1.2	
Total Recovery		% vol			100	
Loss		% vol			0	
Corrected Loss		% vol			0.2	
Corrected % Recovery		% vol			98.6	
Corrected Total % Recovery		% vol			99.8	