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Evaluating heavy-duty diesel engine aftertreatment devices with a split exhaust configuration

Eric Roy Corrigan
West Virginia University

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**Evaluating Heavy-Duty Diesel Engine Aftertreatment
Devices with a Split Exhaust Configuration**

By

Eric R. Corrigan

A THESIS

Submitted to
The College of Engineering and Mineral Resources
at
West Virginia University

in partial fulfillment of the requirements
for the degree of

Master of Science
in
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Nigel N. Clark, Ph.D., Chair
W. Scott Wayne, Ph.D.
Gregory J. Thompson, Ph.D.

Department of Mechanical and Aerospace Engineering

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ABSTRACT

EVALUATING HEAVY-DUTY DIESEL ENGINE AFTERTREATMENT DEVICES WITH A SPLIT EXHAUST CONFIGURATION

By Eric R. Corrigan

West Virginia University evaluated diesel oxidation catalysts (DOC) and lean-NO_x catalysts as part of the Diesel Emissions Control-Sulfur Effects (DECSE) program. In order to perform thermal aging of the DOC and lean-NO_x catalysts simultaneously and economically, each catalyst was sized to accommodate half of the engine exhaust flow. Simultaneous catalyst aging was then achieved by splitting the engine exhaust into two streams such that approximately half of the total exhaust flowed through the DOC and half through the lean-NO_x catalyst. This necessitated splitting the engine exhaust into two streams during emissions measurements. The fraction of exhaust entering the measurement system was calculated based on a comparison of measured CO₂ concentrations taken during a full flow exhaust run and a partial flow exhaust run. Emissions sampled from the partial exhaust stream were then corrected based on these measured CO₂ concentrations to reflect the original full flow levels. Integrated engine-out emissions measured in the split exhaust streams during transient operation generally agreed well with emissions measured using the full exhaust stream. Measured emissions in the partial exhaust configuration remained within 5% of a 50/50 split except at idle or low power operation. When these results from a split flow test were corrected back to full flow levels, all measured emissions were within 11% of the full exhaust case for transient tests and 13% for steady state tests. Split exhaust emissions levels were hard to quantify at low exhaust flow rates.

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Nomenclature

CFV	Critical Flow Venturi
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CVS	Constant Volume Sampling
DECSE	Diesel Emissions Control-Sulfur Effects
DOC	Diesel Oxidation Catalyst
EERC	Engine and Emission Research Center
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
ESC4	Steady-state cycle conducted on the Cummins
FTP	Federal Test Procedure, Transient heavy-duty cycle
FTP75	Transient cycle conducted on the Navistar
g/bhp-hr	grams per brake horsepower hour
H ₂ O	Water
HC	Hydrocarbon
Hp	horsepower
in H ₂ O	inches of water
ISO	International Organization for Standardization
NAV4	Steady-state cycle conducted on the Navistar
N ₂	Nitrogen
NO	Nitrogen Monoxide
NO ₂	Nitrogen Dioxide
NO _x	Oxides of Nitrogen
O ₂	Oxygen
PM	Particulate Matter
ppm	parts per million
scfm	standard cubic feet per minute
SCR	Selective catalytic reduction
SO ₂	Sulfur Dioxide
SO ₃	Sulfate
SSC	Steady-state cycle used for the split exhaust validation
TEOM	Tapered Element Oscillating Microbalance
UDDS	Urban Driving Dynamometer Schedule
WVU	West Virginia University

1. Introduction and Objectives

Heavy-duty diesel emissions are being scrutinized for their effect on the environment. The United States Environmental Protection Agency (EPA) regulates various components of the exhaust produced from the diesel engine. Hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM) are the chemical species currently regulated by the EPA. Mainly, NO_x and PM are the components of concern to the public because PM has been classified as “highly likely” to be a carcinogen while NO_x promotes the formation of smog [22]. The EPA has proposed and is finalizing heavy-duty diesel emissions standards for the 2007 model year. These standards are coupled with a proposal that will reduce sulfur content in diesel fuel in June of 2006 from 500 parts per million (ppm) cap to 15ppm cap. In 2007, when the proposed standards take effect, heavy-duty trucks and buses will contribute more than half of the NO_x and PM from all highway vehicles [5]. The proposal requiring the conversion to low-sulfur diesel fuel enables technologies with aftertreatment of the diesel exhaust that will aid in meeting the 2007 emissions standards.

West Virginia University evaluated two catalyst technologies as part of the Diesel Emissions Control-Sulfur Effects (DECSE) program. The DECSE program is a joint government/industry program to determine the impact of diesel fuel sulfur levels on emission control systems whose use could lower emissions of NO_x and PM from on-highway trucks in the 2002 and 2004 model years [3]. Two types of diesel oxidation catalysts (DOC) and two types of lean- NO_x catalysts were evaluated with four different sulfur levels of diesel fuel namely 3ppm, 30ppm, 150ppm, and 350ppm. High temperature diesel oxidation and lean- NO_x catalysts were tested on a Cummins ISM370 ESP (10.8 liter, 370 horsepower) engine typical of heavy-duty line haul truck applications. Low temperature diesel oxidation and

lean-NO_x catalysts were tested on a Navistar T444E (7.3 liter, 210 horsepower) engine typical of medium-duty applications. Each catalyst was aged for 250 hours with evaluations occurring at the beginning, 50 hours, 150 hours, and at the end of the aging period. In order to age the DOC and the lean-NO_x catalysts simultaneously and economically, catalysts were designed for half of the diesel exhaust flow. Catalyst aging was achieved by splitting the diesel exhaust into two different streams so that approximately half of the exhaust flowed through the DOC and half through the lean-NO_x catalyst. Since each catalyst could only accommodate half of the exhaust, it was necessary to split the exhaust during catalyst-out emissions evaluations. For testing catalyst performance, half of the exhaust passed through the catalyst and into a full-scale dilution tunnel for emissions measurement while the other half of the exhaust was directed into a bypass catalyst and vented into the atmosphere.

The objective for this thesis was to determine the validity of exhaust splitting for evaluation of aftertreatment devices. This was accomplished by examining full flow exhaust CO₂ concentrations with no catalyst and comparing them to “half-flow” engine-out CO₂ concentrations. Results from a split flow validation study, which include measured exhaust flow through each catalyst branch, are presented. Catalyst performance on an accumulated basis is also discussed.

2. Literature Review

This chapter provides background information about emissions standards and emissions reduction practices. Different types of aftertreatment methods, both catalysts and adsorbers, are described as well as a review on Mini-dilution tunnels. Several flow measurement devices are discussed regarding flow principles and device governing equations.

2.1 Emissions standards

Emissions standards play a major role in the design of the modern diesel engine. These regulations require that all diesel engines produced by the manufacturer must meet or exceed the standard for the model year of the engine. The regulated limits are specified in brake-specific units of grams per brake horsepower hour (g/bhp-hr). Table 2.1 lists past and present standards as well as proposed future standards for on-highway heavy-duty compression-ignition engines performing the Federal Test Procedure (FTP) cycle [4]. Required levels for CO and HC are moot because modern diesel engines produce CO and HC well below the standards

Table 2.1: FTP heavy-duty diesel emissions standards comprised by the EPA.

Year	CO	HC	NO _x	PM
The units for the values are g/bhp-hr.				
1990	15.5	1.3	6.0	0.60
1991	15.5	1.3	5.0	0.25
1994	15.5	1.3	5.0	0.10
1998	15.5	1.3	4.0	0.10
2004*	15.5	1.3	2.4	0.10
2007*	15.5	1.3	0.2	0.01

* designates proposed standards, 2004 NO_x standard can also be 2.5 when combined with HC

The creation of the FTP heavy-duty transient cycle provided a universal schedule used in evaluating exhaust produced by the engine. The FTP was developed to mimic actual heavy-duty truck and bus operation in and around urban areas of the United States. A DC or AC dynamometer capable of supplying and absorbing power is required to perform the cycle because of the transient nature of and certain motoring segments of the FTP. The transient cycle is 20 minutes in length and usually is performed three times for emissions certification. The first cycle is labeled as a cold start FTP that is conducted after the engine's coolant and oil temperatures have stabilized between 68°F and 86°F for 15 minutes. The second cycle is called a warm start FTP and begins 20 minutes after completion of the first cycle. The third cycle is the same as the second cycle. These two cycles' emissions values are then combined by using one seventh of the cold start test and six sevenths of the warm start test to yield emissions results that must satisfy or exceed the emissions standards from the EPA for that given engine's year of production [1,12]. In practice, several warm start tests are conducted.

2.2 Emissions reduction practices

The compression-ignition engine has experienced substantial improvement over the years from an emissions point of view. Various techniques have been implemented in the design and control strategies of the diesel engine to increase the power while reducing emissions. One method used in NO_x reduction is retarding the timing of the fuel injection into the cylinder. This decreases the maximum temperature of the combustion process and also reduces the time that the gases spend at high temperatures and since NO_x formation is highly dependent upon temperature, reducing the temperature will reduce NO_x. The penalty suffered for retarding the timing of fuel injection is a decrease in power output of the engine

as well as an increase in hydrocarbons and particulate matter in the exhaust. The compromise between NO_x and PM minimization is termed the NO_x / PM trade-off [20].

Exhaust gas recirculation (EGR) has also been an effective way to decrease NO_x . EGR reduces available oxygen in the cylinder and introduces H_2O and CO_2 into the cylinder, which increases the thermal capacity of the in-cylinder charge. The combination of less oxygen and added heat capacity decreases the combustion temperature. NO_x reduction is achieved from the decrease in temperature as well as the presence of less oxygen in the exhaust gases. However, black smoke and fuel consumption increase with an increase in the rate of EGR [17].

NO_x has been reduced with a control strategy termed injection rate shaping. Rate shaping involves injecting part of the diesel fuel into the cylinder to initiate combustion and injecting the remaining quantity of fuel after the combustion process begins. This reduces the pressure spike that occurs during the premix burn of the combustion, which decreases the in-cylinder temperature thus reducing NO_x . Ghaffarpour and Baranescu [9] report a 50% reduction of NO_x at certain operating conditions using an intercooler and rate shaping without significant change in performance or PM production.

Some techniques used in decreasing PM are increasing in-cylinder charge motion (swirl), increasing fuel injection pressure, and using injectors with finer sprays. With PM formation being a function of unburned and partly burned fuel, anything that allows for a more complete combustion will decrease PM. An increase in swirl promotes better mixing between the air and fuel which achieves a more complete burn while the increase in injection pressure and finer injector sprays allow an increase in atomization of the fuel. The engine operating on lower sulfur fuel decreases sulfate formation thus lower PM.

2.3 Exhaust aftertreatment

The emission reduction practices mentioned above have enabled engine manufacturers to meet the EPA's past and present emission standards. In the next few years, the regulated emissions for NO_x and PM will be substantially reduced from current standards as demonstrated in Table 2.1. Current technologies applied to reduce emissions will not be enough to achieve the future standards. Exhaust aftertreatment along with diesel engine emissions reduction practices will have to be combined to satisfy the upcoming standards. Some aftertreatment devices proposed to assist in the emissions reduction are oxidation catalysts, lean- NO_x catalysts, PM filters (traps), NO_x adsorbers, and the injection of urea ahead of a catalyst, which is termed selective catalytic reduction (SCR). A brief description of each technology is given in Table 2.2.

Table 2.2: Description of aftertreatment technologies.

Aftertreatment Device	Description
Oxidation Catalyst	Oxidizes the exhaust species HC, CO, and SO_2 . HC changes to H_2O and CO_2 , which decreases PM. The creation of sulfates (SO_3) from SO_2 is minimal. CO becomes CO_2 in the oxidation process [8].
Lean- NO_x Catalyst	Converts NO_x to nitrogen (N_2) and oxygen (O_2). HC, diesel fuel, must be introduced upstream of the catalyst for the reaction to occur which decreases fuel economy. These types of catalysts operate only at certain temperatures [7].
PM Traps	Collects PM for a period of engine operation. The accumulated PM is then combusted with external thermal energy such as an electric heating or the use of a catalyst [14].
NO_x Adsorbers	Stores NO_x under lean operation, which is reduced during rich operation. NO is oxidized to form NO_2 that is adsorbed on an oxide surface. Resulting nitrate decomposes to O_2 and NO which is then reduced to N_2 and O_2 . Generally used in gasoline engines [7].
Injection of Urea	Similar to a lean- NO_x catalyst except that urea serves as the reductant injected instead of diesel fuel. In this system, urea is injected upstream of a selective catalytic reduction catalytic converter in the engine's exhaust [11].

All of the catalysts mentioned suffer from sulfur poisoning. Sulfur is used in diesel fuel as a lubricant for the fuel system. Catalyst poisoning occurs when an undesired compound or ion occupies the active sites, which are locations in a catalyst where the reactants attach themselves to the catalyst wall to promote the chemical reaction. Other means of poisoning that may occur are changing the catalyst selectivity, physical blockage of the activation site, or changing the catalyst structure [19]. Once a poisoning compound or ion, sulfur in this case, attaches to the site, the compound or ion generally stays at that site which decreases the performance of the catalyst. When the catalyst stops functioning because the poisoning agent occupies all of the activation sites, the catalyst is termed dead. The solution to sulfur poisoning is to remove the sulfur from the diesel fuel. The EPA is doing exactly that with a proposal that will reduce the sulfur content in diesel fuel from 500ppm by weight to 15ppm by weight. This change has been estimated to increase the cost of diesel fuel by 3 to 4 cents per gallon and will take effect in June of 2006 [25]. Some contend that 15ppm is not low enough, particularly the engine and catalyst manufacturers. Also, the lubricating oil may contribute sulfur to the exhaust at a level equivalent to roughly 10ppm in the fuel.

2.4 Review of mini-dilution tunnels

Mini-tunnels are used to measure all regulated emissions by only analyzing part of the exhaust. They combine an exhaust slipstream with dilution air for analysis. Either mass flow controllers, valves or a combination of both control the dilution air flow and the exhaust sample flow. A mixing chamber and pumps for pulling the samples complete the basic design of a mini-tunnel. PM is collected on filters and measured gravimetrically while gaseous emissions are obtained through analyzing raw exhaust with no dilution. Carbon

Dioxide is usually measured in the exhaust (raw CO₂) and through the mini-tunnel (dilute CO₂) to obtain the dilution ratio. The dilution ratio is used to determine the emissions produced by the engine since only a portion of the exhaust is being analyzed. Japanese and European sampling systems for the purpose of exhaust emissions certification consist of mini-dilution tunnels for non-United States diesel engines. Several mini-tunnels have been accepted as a means of measuring emissions but are limited to narrow engine-output ranges unless considerable modifications are made [10].

Hirakouchi, et al. [13] determined that a 37-tube mini-tunnel and a full flow dilution tunnel had the same measurement characteristics on steady-state testing as well as transient operation. The number of tubes determines the amount of dilution that takes place in the mini-tunnel. Mini-tunnels with 61 tubes and 91 tubes were compared to the 37 tube mini-tunnel with good correlation with negligible effects of performance. The authors concluded that multi-tube type mini-dilution tunnels would be an excellent exhaust emissions measurement apparatus. This type of tunnel was capable of changing dilution ratios easily and at low cost enabling emissions measurement on any size engine without modification to any existing facilities.

A major advantage to mini-tunnels is portability while full flow dilution tunnels are generally stationary. Also, mini-tunnels cost approximately one third, are physically smaller, and require less capital to operate than that of full flow tunnels [13]. Graze discusses a mini-tunnel that is intensive of engine size and points out that size constraints limit full flow dilution tunnels to evaluate engines up to approximately 500 horsepower (hp) maximum. Graze's mini-tunnel was designed and developed to measure particulates for Caterpillar's entire line of engines, which range from 60hp to 7,000hp [10]. Caterpillar's mini-tunnel,

termed a fractional sampler, filtered and diluted the sample directly on the engine's exhaust stack. This fractional sampling system was correlated with full flow particulate measurements. Composite results of the International Organization of Standardization (ISO) 8178 C1 steady-state cycle demonstrated that the mini-tunnel gave results that were within 1% of the full flow tunnel values with respect to particulate emissions.

The EPA began certifying off-highway heavy-duty diesel engines between 175hp to 750hp in 1996. The International Organization for Standardization introduced a universal procedure for exhaust measurement, ISO 8178, of these off-highway engines that was applied worldwide. The ISO 8178 allows the use of a full flow dilution tunnel for emissions measurement but prefers the use of a raw sampling system (mini-tunnel). Stotler and Human conducted an experiment to correlate a full flow sampling system and a raw sampling system. A 300 hp Cummins LTA-10 operating on off-highway number 2 diesel fuel executed an 8-mode steady-state cycle (ISO 8178 C1) with emissions measured via a mini-tunnel and a full flow dilution tunnel. Both measurement systems sampled gaseous and particulate emissions for 10 minutes following a 10-minute stabilization period for each mode. The correlation of gaseous emissions between the two sampling systems; HC, NO_x, and CO were within 7.0%, 3.0%, and 1.0% respectively. PM correlated within 2.5% between the mini-tunnel and the full flow tunnel [24].

Rankin [21] designed, developed, and evaluated a particulate filtration system with microwave regeneration using a split exhaust configuration. Exhaust from a MWM D916-6 mining engine was split into two branches. One branch bypassed the filtration unit going directly to a dilution tunnel while the other branch was passed through the filtration system prior to entering the dilution tunnel. Since the filter was not of sufficient volume to capture

the entire exhaust, an automated throttling valve was placed on the bypass branch for flow adjustment. Critical flow orifices placed before the split and in the bypass leg measured the respective flows. Rankin's conclusion that microwave regeneration was an effective way to heat, and thus remove, the collected diesel PM would not have been possible without the use a split exhaust configuration.

2.5 Flow measurement

ASME/ANSI MFC-7M-1987 specifies the geometry requirements for measuring flow with critical flow venturies. This paper also provides the procedures for operation and the conditions required when measuring mass flow rate with venturies. The principle behind critical flow venturies is that the mass flow rate of gas through the device is maintained at a constant value once the gas flow reaches sonic conditions [23]. Explanations of flow and device parameters such as static pressure and discharge coefficients were discussed. Flow rate equations were presented for both the ideal case of one-dimensional isotropic flow and the real case that corrects for compressibility and viscous effects. Equation 2.1 determines the flow rate through a critical flow venturi operating under real conditions. Venturies possess a unique characteristic that flow is independent of downstream pressure if critical flow conditions are achieved [16].

$$q_m = A^* C C_R \sqrt{Z_O P_O \rho_O} \quad (2.1)$$

In Equation 2.1, q_m represents the mass flow rate, A^* represents the area of the throat, C represents the discharge coefficient for the device, C_R represents the real gas critical flow coefficient, Z_O represents the compressibility factor at stagnation temperature and pressure, P_O represents the absolute stagnation pressure at the device inlet, and ρ_O represents the gas density at stagnation temperature and pressure at the device inlet [16].

Orifice meters of 6mm to 40mm line size are discussed in ASME MFC-14M-1995. This national standards paper specifies geometry requirements and operational procedures and conditions required when measuring flow rate with these devices. Only steady subsonic flow throughout the measuring section of the orifice was considered in the publication. Unlike critical flow venturies, orifices require the differential pressure across the primary device to calculate flow through the device. Equation 2.2 determines the flow rate through an orifice placed in subsonic flow [15].

$$q_m = \frac{\rho}{4} C \epsilon_1 d^2 \sqrt{\frac{2 \Delta p p_{f1}}{1 - B}} \quad (2.2)$$

In Equation 2.2, q_m represents the mass flow rate, C represents the discharge coefficient for the device, ϵ_1 represents the expansion factor based on upstream pressure, d represents the diameter of the device, Δp represents the differential pressure across the device, p_{f1} represents the static pressure upstream of the device, and B represents a ratio of the orifice diameter to the upstream pipe diameter [15].

Laminar flow elements (LFE) function similarly to venturies and orifice meters in that the differential pressure across a flow obstruction is correlated to volume flow rate. The LFE obstruction is a honeycomb structure. A calibration curve provided by the manufacturer and differential pressure across the device obstruction determines the flow rate passing through the device. The calibration curve provided by Merium Instruments was a second-order polynomial [21].

Annubars operate on the same principle as orifices in that differential pressure across the device can be related to flow rate. Diamond type II+ annubars contain a rigid multiple-tube structure that embodies dual averaging chambers with a diamond cross-section. This

device has multiple ports on the upstream and downstream sides of the probe that is placed into the moving fluid. The upstream ports (high pressure side) correspond to the measurement of the stagnation pressure while the downstream ports (low pressure side) correspond to the measurement of the reference pressure [2]. Equation 2.3 determines the flow through the annubar [2].

$$q_m = C^* K d^2 y_a \sqrt{\Delta p p} \quad (2.3)$$

In Equation 2.3, q_m represents the mass flow rate, C^* represents the correction coefficient that contains device and flow parameter corrections [2], K represents the device coefficient, d represents the diameter of pipe in which the fluid flowing, y_a represents the expansion factor, Δp represents the differential pressure across the device, and p represents the static pressure downstream of the device.

3. Experimental Set-up and Procedures

This chapter discusses the Engine and Emission Research Center (EERC) at West Virginia University and hardware used in this facility for emission measurement. Cycles used for the DECSE program and for the split exhaust validation are also presented. The exhaust system is described in detail along with procedures performed while conducting a split exhaust test run.

3.1 Test engines

A total of four diesel engines was used throughout the DESCE program. Two identical heavy-duty Cummins diesel engines and two identical medium-duty Navistar diesel engines aged and evaluated two types of aftertreatment technologies. One of each respective engine evaluated catalysts in the emissions test cell, which is described in Section 3.2, while the other respective engines were located in an adjacent room and used for catalyst aging. For the purpose of clarity in this thesis, engines used for catalyst aging will be called aging engines and engines performing the aftertreatment performance assessment will be termed the evaluation engines.

3.1.1 Cummins ISM370 ESP

Two direct-injected, turbocharged 1999 Cummins ISM370 ESP heavy-duty diesel engines were used for the high temperature catalyst aging and evaluations. Engine specifications are listed in Table 3.1. Figure 3.1 illustrates engine power and torque curves for the Cummins engine. The split exhaust system validation was completed with the Cummins evaluation engine. A photograph of the Cummins evaluation engine is shown in Figure 3.2.

Table 3.1: Engine specifications.

Engine	Cummins ISM370 ESP	Navistar T444E
Displacement (l)	10.8	7.3
Bore / Stroke (in)	4.92 / 5.79	4.11 / 4.18
Power Rating (hp)	370 @ 2100 rpm	210 @ 2300 rpm
Torque Rating (ft-lb)	1350 @ 1200 rpm	520 @ 1500 rpm
Configuration	In-line 6 cylinder	V8 cylinder
Compression Ratio	16.3 : 1	16.1 : 1

Figure 3.1: Cummins ISM370 ESP power torque map.

Figure 3.2: Cummins ISM370 connected to GE dynamometer.

3.1.2 Navistar T444E

Two direct-injected, turbocharged 1999 Navistar T444E medium-duty diesel engines were used for the low temperature catalyst aging and evaluations. Engine specifications are listed in Table 3.1. Figure 3.3 illustrates engine power and torque curves and a picture of the Navistar evaluation engine is shown in Figure 3.4.

Figure 3.3: Navistar T444E power torque map.

Figure 3.4: Navistar T444E connected to GE dynamometer.

3.2 Fuel specifications

Number-2 diesel fuel, supplied by Phillips Petroleum Company, with four different levels of sulfur was used during the DECSE program. All of the fuel used was blended from the same base stock. A certain amount of sulfur additives was added to the base stock to yield the desired sulfur fuel level. Sulfur fuel concentration levels of approximately 3ppm, 30ppm, 150ppm, and 350ppm were used throughout the DECSE program. The validation of the split exhaust system utilized 30ppm diesel fuel. Certificates of fuel analysis were provided by Phillips Petroleum can be seen in Appendix A.

3.3 Catalyst specifications

Two versions of a diesel oxidation catalyst and two versions of a lean-NO_x catalyst were evaluated during the DESCE project. Catalyst geometry and properties of both catalyst technologies are given in this section. Table 3.1 includes specifications for both the diesel oxidation catalysts while Table 3.2 provides specifications for the lean-NO_x catalysts [3].

Table 3.1: DOC catalyst specifications.

Catalyst Type	Pt Loading	Substrate Size	Volume	# of	Cell Density	Converter Size
	(g Pt / ft ³)	OD x Length (cm)	(liters)	Substrates	(cpsi)	OD x Length (cm)
High Temperature	2	19.1 x 15.9	4.5	1	400	20.3 x 66.0
Low Temperature	>50	17.8 x 11.8	2.92	1	400	19.1 x 40.6

Table 3.2: Lean-NO_x catalyst specifications.

Catalyst Type	Formulation	Substrate Size	Volume	# of	Cell Density	Converter Size
	(g Pt / ft ³)	OD x Length (cm)	(liters)	Substrates	(cpsi)	OD x Length (cm)
High Temperature	Zeolite Base	26.7 x 15.2	8.5	1	400	27.3 x 51.4
Low Temperature	Precious Metals	17.8 x 12.7	6.4	2	400	19.1 x 55.9

3.4 Emissions measurement

Research grade gaseous emissions analyzers for HC, CO, NO_x, and CO₂ are used in conjunction with a full-scale dilution tunnel which is described in Section 3.5.1. Analyzers

were calibrated at the beginning of each set of tests, test series, as well as zeroed and spanned daily. A test series involved evaluation of both catalysts as well as engine-out emissions measured from full exhaust and split exhaust configurations described in Section 3.7.2. Zeroing analyzers entails passing a known gas that contains no chemical species that the instruments detects through the analyzers and setting the output of the analyzer to zero. Spanning analyzers is conducted in the same way except that the instrument detects the span gas, which represents the maximum concentration that the analyzer can detect for the current calibration, and the output is set to 100%. A background bag of the dilution air used to dilute the exhaust was taken and analyzed for the regulated emissions with each engine test. The background was subtracted from the “cycle integrated” results to yield the gaseous emissions produced by the engine. PM was collected on fiberfilm filters as well as with a Tapered Element Oscillating Microbalance (TEOM). For an in-depth explanation of the gaseous emissions instruments used at the EERC, refer to Evans [6] and Shade [23].

3.4.1 Gaseous emissions instruments

Hydrocarbons were measured with the method of flame ionization used by a Rosemount Analytical model 402 heated FID analyzer. The exhaust sample pressure of the analyzer was set at 3psi and temperature at 375°F, as required by the CFR 40. The analyzer was zeroed using HC free air produced by a Balston 75-87 zero air generator and spanned with 15ppm propane which was also used in calibration of the FID. For evaluation of the high temperature lean-NO_x catalyst with the Cummins evaluation engine, 100ppm propane was used as the HC span gas because of the extra hydrocarbons introduced from the catalyst reductant. The low temperature lean-NO_x catalyst required 50ppm propane as the span gas.

A “FID peak” which optimizes detector response was performed as needed to maximize the efficiency of the combusting 40% hydrogen / 60% helium fuel required by the instrument.

A Rosemount Analytical model 955 analyzer was the instrument for measuring oxides of nitrogen of the diesel exhaust. The 955 NO_x analyzer uses chemiluminescence as the method of detection and operates in NO_x mode with a sample pressure of 4psi and ozone pressure of 21psi. Ultra-pure nitrogen was used to zero the analyzer while 500ppm nitric oxide was utilized as the span gas for all catalyst and engine-out testing for the Cummins evaluation engine. The Navistar evaluation engine required 250ppm NO_x as the span gas for full flow testing and 175ppm NO_x was utilized for all split exhaust testing. A periodic NO_x converter efficiency test on the NO_x analyzer was performed with Rosemount Analytical NO_x efficiency tester.

Carbon monoxide measurements were taken via a Rosemount Analytical model 880A, which uses Non-Dispersive Infrared (NDIR) as its method of detection. The zero gas used for the 880A CO analyzer was ultra-pure nitrogen while 250ppm carbon monoxide was utilized as the span gas for testing conducted with the Cummins evaluation engine. All of the Navistar engine testing was performed with a span gas of 100ppm. Carbon monoxide of 490ppm concentration was required as the span gas for testing the high temperature lean-NO_x catalyst due to CO generated from the catalyst injection system.

A Beckman Industrial model 868 instrument was used to measure carbon dioxide produced by the engine. This analyzer employs Non-Dispersive Infrared (NDIR) as its method of detecting CO₂. During testing, the analyzer was zeroed with ultra-pure nitrogen and spanned with 5% (50,000ppm) carbon dioxide (CO₂) for Cummins engine testing and full flow Navistar testing. Split exhaust testing with the Navistar engine utilized 3%

(30,000ppm) CO₂ as the span gas. Figure 3.1 shows the analyzer bench at the EERC along with the pumps and mass flow controller for the PM sampling system.

Figure 3.1: Gaseous emissions instruments.

3.4.2 Particulate matter measurement

PALLFLEX membrane filters made by Pall Gelman Sciences were used to collect PM during the testing. These filters were of the type fiberfilm T60A20 with a size of 70mm in diameter. Two filters were placed in series at the bottom of a secondary tunnel attached to the primary dilution tunnel. This secondary dilution tunnel is used to control the temperature of the sample at the filter face by further diluting the exhaust sample. The CFR 40 requires that the temperature at the filter may not exceed 125°F. Dilution air was used in the

secondary tunnel to decrease the temperature of the gas sample flowing through the filter during steady-state test cycles. Secondary dilution is generally not needed during transient test cycles.

The PM filters were conditioned in a Thermotron SM-80 chamber at 45% ($\pm 8\%$) humidity and 22°C ($\pm 3^\circ\text{C}$) for at least one hour before used to collect PM [1]. Once conditioned, the filter's weight was determined with a Cahn C-32 microbalance ($\pm 1\mu\text{g}$) and the filters were placed in filter holders for testing. After the emissions test, the filters were placed back into the conditioning chamber and recondition prior to measuring the post test weight. A background filter, a PM filter that collects PM only from the tunnel without the engine running, was taken at the end of each testing day. The background filter weight was subtracted from the test filter weights to yield PM produced by the engine during the cycle.

Certain cycles (ESC4, NAV4, and SSC which are described below) collected PM at the end of each steady-state mode, not on a continuous basis. This type of PM collection was required for two reasons: to avoid overloading the filter during the long modes and to allow for stabilization of catalyst temperatures prior to data collection. A bypass system was constructed to permit this type of PM collection. An electronic three-way valve allowed exhaust to either pass through the filter to collect PM or to bypass the filter when allowing the exhaust to stabilize. Refer to Evans for a schematic of the bypass system used for collecting PM.

3.5 Discussion of Engine and Emission Research Center at WVU

Experiments were conducted at West Virginia University's Engine and Emission Research Center (EERC). The EERC maintains and operates a full flow dilution tunnel critical flow venturi (CFV) constant volume sampling (CVS) system. WVU's dilution tunnel

meets all of the requirements provided by the Code of Federal Regulations 40 Part 86 Subpart N [1]. A description of various components used during emissions characterization at this facility is presented in this section.

3.5.1 Full flow dilution tunnel

Dilution tunnels combine engine exhaust and conditioned air to simulate what actually takes place in the real world if the test engine was in a truck driving down a road. The dilution tunnel at the EERC was 18 inches in diameter with a length of 40 feet and contains a mixing orifice 3 feet from the tunnel entrance. Sample probes that draw a small portion of the diluted exhaust for analysis were placed 15 feet downstream of the tunnel inlet. A 75hp blower draws the air/exhaust mixture through the tunnel [23]. Flow rates were selected with four critical flow venturies (one nominal 400scfm and three nominal 1000scfm) that may be applied in any combination to yield nominal flow rates between 400scfm and 3400scfm. At the present time, the facility is capable of a maximum flow rate of 2400scfm due to the capacity of the blower. A secondary dilution tunnel, used to collect PM, was connected to the main dilution tunnel at the sampling plane. This smaller tunnel's capability for additional dilution provides temperature control during the collection of PM on the filters. Section 3.4.2 provides an in-depth description on the collection of particulates.

3.5.2 Engine dynamometer

Emissions testing entails loading and motoring the engine, which was accomplished via an engine dynamometer. The EERC dynamometer used for this testing was a direct current (DC) General Electric model DYC 243. This piece of equipment has the capability of absorbing 550-hp and motoring up to 500-hp. Engine speed was determined with a digital encoder. Torque was measured with a load cell that was attached to the housing of the

dynamometer. The measured torque was also compensated for dynamometer inertia. The engine and dynamometer were directly connected together with a driveshaft and a rubber coupler.

3.5.3 Critical flow venturies

Principles of critical flow venturies were discussed in Section 2.5. The EERC at WVU contains four venturies; one designed to operate at 400 scfm and three designed to operate at 1000 scfm. When testing with the Cummins engine, described in Section 3.1.1, a nominal flow rate of 2400 scfm was used for full flow testing and nominal flow rate of 1400 scfm was used for split exhaust testing. The Navistar, described in Section 3.1.2, required a nominal flow rate of 1400 scfm for full flow testing and 1000 scfm for split exhaust testing. The criteria in selecting tunnel flow rates involve maximizing resolution associated with gaseous emissions instrumentation. Good engineering practice limits the maximum output of the gas analyzer to approximately 80% of full scale during the entire test run.

3.5.4 Data acquisition

Data collected during emissions testing, such as analyzer, thermocouple, and pressure transducer outputs, at the EERC were recorded using in-house software and data acquisition hardware. This hardware includes RTI-815 analog-to-digital acquisition boards attached to the computer and 3B modules made by Analog Devices for signal conditioning. During the testing, data was recorded as ADC code and converted to engineering units when data reduction was completed [23].

3.5.5 Data reduction

Data reduction for the DECSE program and the split exhaust validation was executed with in-house software on the EERC's reduction machine. Procedures and calculations were

base from the CFR 40 for transient FTP test runs and from the Official Journal of the European Communities for steady-state test runs [1] [18]. split flow emissions results of NO_x, HC, CO, and CO₂ were corrected with the reduction program to reflect full flow levels. This was accomplished by calculating a split ratio based on CO₂ concentration, refer to Section 3.8.2, and applying the inverse of this ratio to the split flow data yielding “split flow corrected” results. The reasoning behind correcting the split flow data was to provide agreement with full flow data on a brake-specific basis. Equations 3.1 through 3.4 provide the equations used to correct the split flow gaseous data.

$$NO_{X(corrected)} = \frac{CO_{2(full-flow)}}{CO_{2(split-flow)}} \cdot NO_{X(split-flow)} \quad (3.1)$$

$$HC_{(corrected)} = \frac{CO_{2(full-flow)}}{CO_{2(split-flow)}} \cdot HC_{(split-flow)} \quad (3.2)$$

$$CO_{(corrected)} = \frac{CO_{2(full-flow)}}{CO_{2(split-flow)}} \cdot CO_{(split-flow)} \quad (3.3)$$

$$CO_{2(corrected)} = \frac{CO_{2(full-flow)}}{CO_{2(split-flow)}} \cdot CO_{2(split-flow)} \quad (3.4)$$

3.6 Cycles

The FTP transient cycle and a modified European steady-state cycle called the ESC4 were used in evaluation of the high-temperature diesel oxidation catalyst with the Cummins ISM370 engine. The ESC4 was the only cycle used to evaluate the performance of the high-temperature lean-NO_x catalyst. Only steady-state conditions were used in both lean-NO_x catalysts evaluations which alleviated problems associated the injecting the reductant on a transient basis. Figure 3.2 provides an engine speed trace of the FTP cycle and a torque trace is provided in Figure 3.3. Set points and mode times for the ESC4 are listed in Table 3.3.

Figure 3.2: FTP engine speed.

Figure 3.3: FTP engine torque.

Cycles performed by the Navistar T444E were a mimicked FTP75 and a steady-state test similar to the ESC4 termed the NAV4. The FTP75 cycle was derived from the Urban Driving Dynamometer Schedule (UDDS) chassis schedule that is commonly called the FTP75. Engine speed was obtained by taking the chassis schedule and applying the gear reductions (Table 3.5) that occur in the driveline of a Ford F-250 pick-up truck. The load trace of the mimicked FTP75 was determined by using the road load equation (3.1) and characteristics of the same F-250 pick-up truck, which are included in Table 3.5.

$$P = \left(\frac{\rho C_d A v^3}{2} \right) + (m g v) + (m a v) \quad (3.5)$$

For Equation 3.1, ρ is air density, C_d is the drag coefficient for the truck, A is the frontal area of the truck, v is the vehicle's velocity, μ is the rolling resistance of the truck, m is the vehicle mass, g is the acceleration due to gravity, and a is the vehicle's acceleration. Figure 3.4 provides an engine speed trace of the mimicked FTP75 cycle while a torque trace is provided in Figure 3.5. The FTP75 and NAV4 cycles were used to test the performance of the low-temperature oxidation catalysts while only the NAV4 was performed to evaluate the low-temperature lean-NO_x catalysts.

Table 3.3: Set-points of the ESC4 steady-state cycle performed.

ESC4 (Cummins ISM)				
Mode	Time (min)	Speed (rpm)	Torque (ft-lb)	Sample Time (s)
1	2	700	0	0
2	20	1888	248	100
3	20	1585	595	200
4	20	1888	992	160
5	20	1282	1244	160
6	5	1200	0	0

Table 3.4: Set-points of the NAV4 steady-state cycle performed.

NAV4 (Navistar T444E)				
Mode	Time (min)	Speed (rpm)	Torque (ft-lb)	Sample Time (s)
1	2	700	0	0
2	20	1000	81	170
3	20	1250	122	280
4	20	2000	122	190
5	20	2200	406	360
6	5	1200	0	0

Table 3.5: Parameters used in the development of the FTP75.

Gear	Reduction	Parameter	Value	Unit
1	5.79	Mass	3632	kg
2	3.31	Tire Diameter	0.8125	m
3	2.1	Drag Coefficient	0.88	
4	1.31	Rolling Resistance	0.0098	
5	1	Air Density	1.177	kg/m ³
6	0.72	Frontal Area	5	m ²
Differential	3.73

Figure 3.4: Mimicked FTP75 engine speed.

Figure 3.5: Mimicked FTP75 engine torque.

Catalyst aging with the Navistar and the Cummins was completed by repeating a steady-state cycle with set points and mode times listed in Table 3.6 until the proper aging period was achieved. The aging cycles contain the same modes as the evaluation steady-state cycles but the evaluation cycles were performed in the order of increasing exhaust temperature. Modes 1 and 4 of the AgeISM cycle were switched to obtain the ESC4 cycle. The modes of the AgeNav were arranged in the order of increasing exhaust temperature therefore the NAV4 modes are in the same order.

Table 3.6: Steady-state cycles for catalyst aging.

Mode	AgeISM (Cummins ISM)			AgeNav (Navistar T444E)		
	Time (min)	Speed (rpm)	Torque (ft-lb)	Time (min)	Speed (rpm)	Torque (ft-lb)
1	24	1282	1244	12	1000	81
2	6	1585	595	12	1250	122
3	24	1888	992	12	2000	122
4	6	1888	248	24	2200	406

The validation of the split exhaust system was conducted on the Cummins evaluation engine. Only the FTP and an ad hoc steady-state cycle (SSC) were used for this validation. Set points, sampling times, and duration of the SSC modes are listed in Table 3.7.

Table 3.7: Steady-state cycle for split exhaust validation.

Mode Number	Engine Speed	Load	Duration	Sample Time	Percent Load
	(rpm)	(ft-lb)	(s)	(s)	
1	700	0	240	90	Idle
2	1200	640	240	90	50
3	1800	1080	240	90	100
4	1200	1280	240	90	100
5	1800	540	240	90	50
6	700	0	240	90	Idle

3.7 Split Exhaust Systems

The DECSE program implemented a split exhaust configuration to accelerate the aging process by simultaneously aging the DOC and lean-NO_x catalysts. The Cummins split exhaust systems for aging and evaluation were constructed of 5 inch diameter aluminized steel exhaust pipe. The same type of exhaust pipe was utilized for the Navistar split exhaust systems except with a pipe diameter of 4 inches. Flanges were welded onto the ends of all the components in the exhaust and attached together with exhaust clamps. Figure 3.6 illustrates the split exhaust configuration for simultaneous aging of both catalyst technologies.

Figure 3.6: Picture of set-up for catalyst aging.

3.7.1 Aging engine's exhaust set-up

A Go-Power Model DT-2000 water-break dynamometer was connected to both respective engines to provide load while conducting catalyst aging. Water required for the Go-Power dynamometers was provided from the building's water supply. The same water supply was utilized for the cooling system of the engine. The engine's exhaust was split into two branches. The DOC was placed in the top branch of the exhaust system while the lean-NO_x catalyst was placed in the lower branch. The lean-NO_x branch was outfitted with injectors to supply the supplemental HC reductant required by the catalyst. A flow metering orifice and throttling valve in each branch completes the hardware of the aging split exhaust system. Figure 3.7 illustrates the exhaust system used for aging the catalysts.

Figure 3.7: Exhaust configuration for aging the catalyst.

3.7.2 Evaluation engine's exhaust set-up

The DECSE program requires three types of testing. The first type involves typical engine dynamometer testing by introducing the entire engine exhaust stream into a dilution tunnel. This testing was named full flow because the entire exhaust flows into the dilution

tunnel. split flow engine-out testing implies splitting the exhaust into two branches and passing one branch into the dilution tunnel while the other branch is discarded into the atmosphere. No aftertreatment occurs in the split flow engine-out tests. The last type of testing involves catalyst evaluation. The catalyst, either the oxidation catalyst or the lean- NO_x catalyst, was placed in the exhaust branch that was connected to the dilution tunnel while the other branch contained a bypass catalyst that provided similar flow restrictions as the active catalyst. The bypass catalyst contains the same honeycomb as the active catalyst but the honeycomb was not washcoated. This aided in balancing the flows between each exhaust branch of the split exhaust system. Refer to Section 3.8 for the procedure used to balance the exhaust flows in each branch. Metering orifices and throttling valves complete the set-up for the evaluation split exhaust system. Figure 3.8 is a schematic of the exhaust split system used for the catalyst evaluations.

Figure 3.8: Exhaust configuration for evaluation of catalysts.

3.7.3 Split flow validation exhaust set-up.

The split exhaust system used for catalyst evaluation and described in Section 3.7.2 was used for the validation with some modifications. To increase accuracy, Diamond II+

Annubars, described in Section 2.5, replaced the flow metering orifices for exhaust flow measurement in each exhaust branch. An annubar placed in a 5 inch diameter pipe was used to measure the flow in the catalyst branch while an annubar placed in a 4 inch diameter pipe was used to measure flow in the bypass branch. Due to size limitations in the engine test cell, the catalyst annubar was placed after the throttling valve and the bypass annubar had to be placed before its respective throttling valve. Extra care was taken to prevent leaks when connecting the split exhaust system so annubar data from both instruments in the two different positions was reliable.

3.8 Flow balancing procedures.

Exhaust flows through each leg of the exhaust system were balanced before either an aging cycle or evaluation cycle was initiated. Throttling valves were used as the hardware to change the flow in both aging and evaluation exhaust systems. Motorola model MPX5010DP pressure transducers were used to measure the differential pressure across the orifices.

3.8.1 Procedure for balancing aging split exhaust configuration.

Metering orifices are utilized to measure the exhaust flow in each branch of the split exhaust. These orifices were calibrated against a Meriam Instrument laminar flow element (LFE). A calibration curve for each orifice was created to relate flow through the orifice to differential pressure across the orifice. The flow in each branch was balanced with the engine operating at rated speed and full load while measuring the differential pressure across the orifice. Flow was inferred from the orifice calibration curve produced from the LFE comparison. The butterfly valves were positioned so that the differential across each orifice corresponded to approximately the same flow in each leg while maintaining the specified

engine backpressure (32in. H₂O for the Navistar and 41in. H₂O for the Cummins) at the rated power conditions. Two calibration curves for the Navistar aging split exhaust system are shown in Figure 3.9. Similar calibration curves were produced for the Cummins aging orifices.

Figure 3.9: Calibrations of orifices for the Navistar aging set-up.

3.8.2 Procedure for balancing evaluation split exhaust configuration.

Having the same exhaust flow in each leg was essential considering the active catalyst was designed for half the engine exhaust flow and catalyst performance was being evaluated. Instead of orifices as a means of balancing the flow, CO₂ concentration was used

to balance the split exhaust system. The first step in balancing the exhaust system was to determine the amount of CO₂ generated by the diesel engine. This was the full flow part of the engine testing in the testing series. All full flow tests were conducted at the same engine back pressure of roughly 32 inches of water for the Navistar and 41 inches of water for the Cummins at rated speed (1800rpm for the Cummins, 2300rpm for the Navistar), and full load. Engine backpressure was controlled with a throttling valve in the full exhaust and measured with Smar LD301 pressure transmitter. The primary purpose of the full flow testing was to obtain the CO₂ concentration produced by the engine so that half of that value was flowing through the catalyst during evaluation.

The engine's exhaust was then connected to the split exhaust system with the dilution tunnel operating at the same nominal flow rate as the full flow case. The engine was then brought up to a selected operating condition (1888 rpm, 998 ft-lb for Cummins and 2200 rpm, 406 ft-lb for Navistar) of the steady-state cycle that the engine performed in the full flow exhaust configuration. The throttling valves in each exhaust branch were positioned so the exhaust backpressure was specified by the manufacturer while the CO₂ concentration was approximately half that of the full flow case. Refer to Figure 3.8 for a schematic of the split exhaust set-up.

The split ratio, Equation 3.6, was defined as the CO₂ concentration for the split exhaust case divided by the CO₂ concentration for the full flow case. For example, an emission test with an average split ratio of .50 would be a perfect split, the split exhaust flow was exactly half of the full exhaust flow based upon CO₂. This split ratio was used to correct all split exhaust gaseous emissions to reflect full flow levels. During the duration of the DECSE program, the split ratio was kept as close to .50 as possible. For transient testing, an

average split ratio was calculated over the entire cycle and applied to the integrated split flow results. During steady-state testing, a modal split ratio was determined for each set point and applied to each mode. These modal results were then combined to generate a weighted result for the entire test. Annubar split ratios were calculated in a similar manner. The calculated split ratio for the Annubar exhaust flow measurements, Equation 3.7, was flow measured in catalyst branch divided by the total flow in both branches. Refer to Figure 3.10 for a set of typical split ratios for the Cummins testing.

$$CO_2 SR = \frac{CO_{2(SplitExhaust)}}{CO_{2(FullFlow)}} \quad (3.6)$$

$$AnnubarFR = \frac{Flow_{(CatalystBranch)}}{Flow_{(Catalyst+BypassBranch)}} \quad (3.7)$$

Figure 3.10: Typical split ratios for Cummins ISM370.

3.8.3 Procedure for balancing split exhaust validation set-up.

Balancing the split exhaust system was completed in the same manner as described in Section 3.8.2 for catalyst evaluation. Additional balancing was required because the split exhaust validation not only examines flow rates that correspond to a .50 split ratio, but also examines exhaust flow rates that correspond to split ratios of approximately .30 and .60 respectively. It should be noted that a .30 split ratio has a lower flow rate in the catalyst branch of the split exhaust system than the bypass branch and vice versa for the .60 split ratio. When conducting the .30 and .60 split ratios test runs, the same procedure described in Section 3.8.2 were followed except only 30% or 60% of the full flow CO₂ concentration was set with the throttling valve positions while maintaining the specified backpressure.

4. Results and Discussion

The experimental results for the split exhaust validation are presented at the beginning of this chapter. Sections of this chapter are divided into tests performed with the different exhaust configurations described in Chapter 3 namely full flow tests and split flow tests with split ratios of 50/50, 60/40, and 30/70. Catalyst performance data from the DECSE program will be discussed at the end of this chapter. Only data taken from a Cummins ISM370 ESP are presented.

$$\% difference = \frac{measured - reference}{reference} * 100 \quad (4.1)$$

Equation 4.1 was applied when discussing error, percent difference, between two quantities. Measured full flow values were used as the reference in the calculation of errors between the split exhaust and full exhaust systems.

4.1 Full flow results

The first part of all split flow testing was to perform an engine baseline with the entire engine's exhaust directed to the dilution tunnel as prescribed by the CFR 40. The engine exercised the FTP and SSC cycles described in Section 3.6. Data was taken and reduced as described in Chapter 3. Results of these full flow tests are presented in Table 4.1 for the transient cycles and Table 4.2 for the steady-state cycles. All values presented in both tables are either measured as full flow or corrected to full flow as described in Section 3.5.5 except for the column labeled CO_2 (split flow) which contains uncorrected CO_2 concentration recorded during each split flow test run. This uncorrected quantity was compared to the full flow CO_2 concentration and created the split ratio described in Section 3.8.2 for that particular test. This ratio was used to correct all other gaseous emissions to full flow levels.

Table 4.1 and Table 4.2 also contain split flow exhaust data that will be discussed in each respective section. For example, the 50/50 result are presented with the full flow test results but will be explained in the 50/50 results section. Please note that the FTP full flow emissions levels of this 1999 model year engine are below the standards presented in Table 4.1.

Table 4.1: Split exhaust validation transient results.

FTP Cycle							
** units are g/bhp-hr	Test	HC	CO	CO ₂ (Full Flow)	CO ₂ (Split Flow)	NOx	PM
Full Flow	Ftp5	0.172	0.765	538.84	NA	3.998	0.05876
	Ftp6	0.181	0.757	541.76	NA	3.95	0.05584
	Ftp7	0.168	0.758	542.95	NA	3.924	0.05715
<i>Average</i>		<i>0.174</i>	<i>0.760</i>	<i>541.18</i>		<i>3.957</i>	<i>0.05725</i>
Split Flow	Ftp10	0.182	0.859	(546.91)	278.92	3.933	0.05725
50 / 50	Ftp11	0.153	0.83	(546.91)	273.46	4.056	0.0644
	Ftp12	0.182	0.831	(542.9)	271.45	4.192	0.06074
<i>Average</i>		<i>0.172</i>	<i>0.840</i>	<i>545.57</i>		<i>4.060</i>	<i>0.06080</i>
<i>Percent Difference</i>		<i>0.8</i>	<i>10.5</i>	<i>0.8</i>		<i>2.6</i>	<i>6.2</i>

Table 4.2: Split exhaust validation steady-state results.

Steady State Cycle						
** units are g/bhp-hr		HC	CO	CO ₂ (Full Flow)	CO ₂ (Split Flow)	NOx
Full Flow	SSC3	0.103	0.207	476.24	NA	5.66
	SSC4	0.105	0.208	476.94	NA	5.621
	SSC5	0.103	0.206	477.38	NA	5.616
<i>Average</i>		<i>0.104</i>	<i>0.207</i>	<i>476.85</i>		<i>5.632</i>
Split Flow	SSC13	0.102	0.231	(476.3)	244.10	5.96
50 / 50	SSC14	0.108	0.236	(476.31)	245.53	5.917
	SSC15	0.108	0.235	(476.32)	248.40	5.899
<i>Average</i>		<i>0.106</i>	<i>0.234</i>	<i>476.32</i>		<i>5.925</i>
<i>Percent Difference</i>		<i>2.3</i>	<i>13.0</i>	<i>0.1</i>		<i>5.2</i>
Split Flow	SSC18	0.101	0.231	(476.31)	285.31	6.535
60 / 40	SSC19	0.101	0.231	(476.3)	292.33	6.186
	SSC20	0.104	0.243	(476.3)	291.14	6.238
<i>Average</i>		<i>0.102</i>	<i>0.235</i>	<i>476.30</i>		<i>6.320</i>
<i>Percent Difference</i>		<i>1.6</i>	<i>13.5</i>	<i>0.1</i>		<i>12.2</i>
Split Flow	SSC21	0.071	0.234	(476.31)	143.96	5.965
30 / 70	SSC22	0.082	0.24	(476.3)	142.18	6.039
	SSC23	0.077	0.234	(476.3)	141.70	6.072
<i>Average</i>		<i>0.077</i>	<i>0.236</i>	<i>476.30</i>		<i>6.025</i>
<i>Percent Difference</i>		<i>26.0</i>	<i>14.0</i>	<i>0.1</i>		<i>7.0</i>

4.2 50/50 split flow results

The split exhaust system was connected to the Cummins engine. Balancing procedures were performed as described in Section 3.7.2. CO₂ concentration was approximately half that of the full flow case upon the completion of the flow balancing process.

4.2.1 FTP results

The engine exercised three successive FTP cycles. Data was corrected as described in Section 3.5.5 yielding results presented in Table 4.1. Average values of emissions for the three test runs were determined and compared to the average of the three full flow test runs. Results from this comparison showed that corrected HC was within 1% of its corresponding full flow value, CO was within 11% of its respective full flow total, NO_x was within 3% of the full flow level, and PM collected through the entire test was within 7% of the full flow PM quantity. Figures 4.1 through 4.4 provide CO₂, NO_x, CO, and HC with units of grams per second for a full flow FTP and a 50/50 split flow FTP. Please observe that the split flow curve for all four graphs is approximately half the respective full flow curve. An integrated CO₂ split ratio was determined to be 0.51 which was used for split flow data correction. Figure 4.4 initially provides negative HC values. This was attributed to minimal HC produced by modern diesel engines, especially at idle which was where the negative values were measured.

Figure 4.1: Continuous FTP CO₂ for full flow and 50/50 split flow exhaust configurations.

Figure 4.2: Continuous FTP NO_x for full flow and 50/50 split flow exhaust configurations.

Figure 4.3: Continuous FTP CO for full flow and 50/50 split flow exhaust configurations.

Figure 4.4: Continuous FTP HC for full flow and 50/50 split flow exhaust configurations.

Data obtained from one full flow and one 50/50 split flow FTP test were reduced and emissions are presented on an accumulation basis. The split flow test run data were corrected with the CO_2 split ratio described in Section 3.8.2. This corrected result was compared to the full flow result and illustrated in Figure 4.5 for HC. The calculated split ratio applied was 0.51 which caused the corrected data to be approximately 8% larger than the amassed full flow data. A similar correlation was created for CO and is illustrated in Figure 4.6. The corrected CO demonstrated a 6% difference between the accumulated split flow and full flow data. Figure 4.7 shows a 6% difference in NO_x between the accumulated split flow and full flow data.

Figure 4.5: Accumulated HC during the FTP full flow and CO_2 corrected 50/50 split flow.

Figure 4.6: Accumulated CO during the FTP for full flow and CO₂ corrected 50/50 split flow.

Figure 4.7: Accumulated NO_x during the FTP for full flow and CO₂ corrected 50/50 split flow.

4.2.2 Steady-state results

The engine performed three successive SSC cycles. Data were collected only at the end of each mode as mentioned in Section 3.6 and corrected as described in Section 3.5.5. These corrected results are presented in Table 4.1. Average values of emissions for the three test runs were determined and compared to the average of the three full flow test runs. Results from this comparison showed that corrected HC was within 3% of its corresponding full flow value, CO was within 13% of its respective full flow total, and NO_x was within 6%

of the full flow level. These errors are similar to the errors observed during transient engine operation. PM was not collected during the steady-state test runs.

Figure 4.8 provides a comparison between full flow CO₂ and 50/50 split flow CO₂. Modal split ratios which range from 0.51 to 0.53 were calculated as discussed in Section 3.8.2. It is clear from Figure 4.8 that the split flow works successfully at high exhaust flow rates. This is because the split flow was adjusted to the desired ratio under similar conditions. However, at low flow rates, in particular at idle, deviation from the desired ratio is substantial. When determining an integrated split ratio for the entire test run, the idle conditions were omitted from the calculation.

The annubar flow measurement data show that the catalyst leg allowed 50% to 54% of the flow at high exhaust flow rates for the nominal 50/50 split as seen in Figure 4.9. However, at idle, the annubar data show 63% to 64% exhaust flow leaving via the catalyst leg. The CO₂ data agree for the higher flow rates, but clearly show that almost all the flow is through the bypass leg during idle, in clear contradiction of the annubar data. Deviations from the desired split at low flow rates may arise due to the small differential pressures available to control the flow split. However, the measurement techniques used are also challenged at low flow rates. Differential pressures across the Annubar will decrease by about two orders of magnitude between full and idle flow conditions, so the differential pressure transducer errors become significant. In this study, the CO₂ errors were certainly greater at idle than the annubar errors because dilution in the full-scale tunnel is high so that background (dilution air) CO₂ mass flow can mask engine CO₂ mass flow. It is therefore speculated that the annubar values of 63% to 64% catalyst flow are far more realistic than the CO₂ split data for idle conditions, and that split ratios remain acceptable at idle. Since idle

operation contributes only a small fraction of NO_x and PM emissions, deviations at idle during test procedures will usually be acceptable.

An integrated flow ratio across the cycle of 0.53 was observed with the omission of the data collected at the idle conditions. This ratio, similar to the CO_2 split ratio, was determined by Equation 3.7 given in Section 3.8.2. A 1% difference between CO_2 ratio and flow ratio provides a accurate means of correcting partial flow exhaust streams to full flow exhaust levels without measuring the flow rate.

Figure 4.8: Comparison between full flow CO_2 and 50/50 split flow CO_2 .

Figure 4.9: Measured exhaust flow during 50/50 SSC cycle.

4.3 60/40 split flow results

The split exhaust system was connected to the Cummins engine. Balancing procedures were performed as described in Section 3.7.2. CO₂ concentration was approximately 60% of the full flow case upon the completion of the flow balancing process.

The engine performed three successive SSC cycles. Data were collected only at the end of each mode as mentioned in Section 3.6 and corrected as described in Section 3.5.5. These corrected results are presented in Table 4.1. Average values of emissions for the three test runs were determined and compared to the average of the three full flow test runs. Results from this comparison showed that corrected HC was within 2% of its corresponding full flow value, CO was within 14% of its respective full flow total, and NO_x was within 13% of the full flow level. PM was not collected during the steady-state test runs.

Figure 4.10 provides a comparison between full flow CO₂ and 60/40 split flow CO₂. Modal split ratios range from 0.61 to 0.62 (0.61 integrated) were calculated as discussed in Section 3.8.2. The deviations that occurred at the idle condition were discussed in Section 4.2.2. The section will only compare the CO₂ split ratios and the calculated Annubar flow ratios, described in Section 3.8.2, for the middle four modes of the cycle. Calculated Annubar flow ratios varied from 0.61 to 0.65 (0.64 integrated) as presented in Figure 4.11. These results are consistent with the 50/50 results in that Annubar ratios are slightly larger than the CO₂ ratios.

Figure 4.10: Comparison between full flow CO₂ and 60/40 split flow CO₂.

Figure 4.11: Measured exhaust flow during 60/40 SSC cycle.

4.4 30/70 split flow results

The split exhaust system was connected to the Cummins engine. Balancing procedures were performed as described in Section 3.7.2. CO₂ concentration was approximately 30% that of the full flow case upon the completion of the flow balancing process.

The engine performed three successive SSC cycles. Data were collected only at the end of each mode as mentioned in Section 3.6 and corrected as described in Section 3.5.5. These corrected results are presented in Table 4.1. Average values of emissions for the three test runs were determined and compared to the average of the three full flow test runs. Results from this comparison showed that corrected HC was within 26% of its corresponding

full flow value, CO was within 14% of its respective full flow total, and NO_x was within 7% of the full flow level. PM was not collected during the steady-state test runs.

Figure 4.12 provides a comparison between full flow CO₂ and 30/70 split flow CO₂. Modal split ratios range from 0.27 to 0.31 (0.29 integrated) were calculated as discussed in Section 3.8.2. The deviations that occurred at the idle condition were discussed in Section 4.2.2. The section will only compare the CO₂ split ratios and the calculated Annubar flow ratios, described in Section 3.8.2, for the middle four modes of the cycle. Calculated Annubar flow ratios varied from 0.33 to 0.34 (0.34 integrated) as presented in Figure 4.13. These results are consistent with pervious 50/50 and 60/40 results in that Annubar flow ratios are slightly larger than the CO₂ split ratios. Also, the differences between the CO₂ split ratios and the Annubar flow ratios increases as the difference in flows between the branches increase. Figure 4.14 provides modal split ratios results for all three of the split flow balanced conditions of the validation study.

Figure 4.12: Comparison between full flow CO₂ and 30/70 split flow CO₂.

Figure 4.13: Measured exhaust flow during 30/70 SSC cycle.

Figure 4.14: Modal split ratios for validation study.

4.5 Oxidation catalyst results

This section is divided up into four sub-sections to present results from the high-temperature diesel oxidation catalyst for the four different fuel sulfur levels used in the DECSE program. Both FTP and ESC4 results are presented by the accumulation of the constituents, HC, CO, CO₂, and NO_x, throughout the cycle according to CFR40 and European regulations [1,18]. PM is presented on a continuous basis via TEOM and also

presented as total PM mass collected from 70-mm filters. Gaseous emissions results are provided as engine-out split flow test with no aftertreatment and as catalyst out emissions recorded at various stages of catalyst aging. The oxidation of HC and CO during catalyst tests is presented as a percent reduction from the engine-out test. Figure 4.15 provides a temperature measured 6 inches before the oxidation catalyst termed precat and temperature measured 6 inches downstream of the catalyst called the postcat. Temperatures ranged between ± 25 °C of the two temperature traces provided in Figure 4.15 for the DECSE catalyst testing.

Figure 4.15: Oxidation catalyst temperatures.

4.5.1 3ppm gaseous results

Results were obtained from the Cummins ISM370 engine operating on 3ppm sulfur diesel fuel described in Section 3.2. Figure 4.16 shows the accumulated results of HC measured during the FTP cycle. This figure demonstrated that the catalyst oxidizes the majority of HC and 80 percent HC reduction is illustrated in Figure 4.17. Approximately 3 grams of HC amassed throughout the cycle without aftertreatment is small and hard to

quantify. Thus, measurement difficulties occurred when catalyst evaluation was completed because the measured values were close to zero. The 0 and 150 hour data demonstrate a negative accumulation of HC across the cycle which is obviously measurement error because burning of a hydrocarbon fuel will generate gaseous HC, not clean the atmosphere. The HC reductions greater than 100% seen in Figure 4.17 can be attributed to these measurement errors. Catalyst aging provided no significant effect on HC oxidation.

Figure 4.18 presents the amassed CO throughout the transient cycle. The catalyst appears to reach its “light-off” temperature and start functioning approximately halfway through the cycle. Light-off temperature is defined as the temperature required to initiate the catalytic reaction. At the beginning of the aging period, CO reduction is 50% and decreases over aging to roughly 30% as seen in Figure 4.19. The spike that occurs at the beginning of Figure 4.19 is attributed to a small difference in two small numbers, namely the engine-out accumulated value and the 250 hours accumulated value, that cause a large percentage difference (Refer to Equation 4.1). The catalyst has no effect on CO₂ and NO_x which is verified in Figure 4.20 and Figure 4.21.

Figure 4.16: FTP accumulated HC for 3ppm oxidation catalyst through the aging period.

Figure 4.17: Percent reduction of HC for 3ppm oxidation catalyst.

Figure 4.18: FTP accumulated CO for 3ppm oxidation catalyst through the aging period.

Figure 4.19: Percent reduction of CO for 3ppm oxidation catalyst.

Figure 4.20: FTP accumulated CO₂ for 3ppm oxidation catalyst through the aging period.

Figure 4.21: FTP accumulated NO_x for 3ppm oxidation catalyst through the aging period.

4.5.2 30ppm gaseous results

Results were obtained from the Cummins ISM370 engine operating on 30ppm sulfur diesel fuel as described in Section 3.2. Figure 4.22 shows the accumulated results of HC measured during the FTP cycle. Similar to the results obtained from the 3ppm oxidation catalyst, the 30ppm catalyst oxidizes approximately 75% of HC which is illustrated in Figure 4.23. Please observe that both the 3 and 30ppm oxidation catalysts seem to initially oxidize above 90% of the HC. After the first aging period, HC oxidation average reduction is 75%.

Figure 4.24 presents the amassed CO throughout the transient cycle for the four aging points. The same phenomenon that occurred with the 3ppm oxidation catalyst of the catalyst

not oxidizing CO until halfway through the cycle occurs with the 30ppm catalyst. CO reduction increases from 20% initially to 30% for the remaining amount of aging. The 20% CO reduction with no aging must be anomalous due to a significant increase initially in CO over the engine-out case. The 30% CO reduction observed for the remaining aging hours corresponds to the results from the 3ppm oxidation catalyst. Figure 4.26 and Figure 4.27 support the same observation for the 30ppm oxidation catalyst that was made with the 3ppm oxidation catalyst which was the catalyst has no effect on CO₂ and NO_x.

Figure 4.22: FTP accumulated HC for 30ppm oxidation catalyst through the aging period.

Figure 4.23: Percent reduction of HC for 30ppm oxidation catalyst.

Figure 4.24: FTP accumulated CO for 30ppm oxidation catalyst through the aging period.

Figure 4.25: Percent reduction of CO for 30ppm oxidation catalyst.

Figure 4.26: FTP accumulated CO₂ for 30ppm oxidation catalyst through the aging period.

Figure 4.27: FTP accumulated NO_x for 30ppm oxidation catalyst through the aging period.

4.5.3 150ppm gaseous results

Results were obtained from the Cummins ISM370 engine operating on 150ppm sulfur diesel fuel described in Section 3.2. Figure 4.28 shows the accumulated results of HC measured during the FTP cycle. Please disregard the 250 hour trace in Figure 4.28 due to measurement error as described in Section 4.5.1. 150ppm HC oxidation results are consistent with the 3 and 30ppm oxidation catalysts results of a large initial HC reduction and a decrease in performance after the first aging period. Figure 4.29 illustrates this decrease in performance that was more severe than the 3 and 30ppm results. The HC reduction was only 40% after the first 50 and 150 hours of aging. The 250 hour data could not support the loss in performance due to increased sulfur concentration in the diesel fuel because of below zero results.

Figure 4.30 presents the amassed CO throughout the transient cycle for the four aging points. The 150ppm catalyst does not function until halfway through the cycle consistent with the 3 and 30ppm results. A 33% CO reduction for the first 150 aging hours is illustrated in Figure 4.31, which is a slight increase from the 3 and 30ppm results. In the last 100 hours of aging, CO reduction by the oxidation catalyst decreases to 20%. This may be attributed to

either thermal effects or catalyst poisoning from the increase in diesel fuel sulfur concentration. There was no decline in performance between the 150 and 250 hour evaluations in the 3ppm or 30ppm results, so it is speculated that the decline is due to fuel sulfur concentration. No effect on CO₂ and NO_x was observed from the oxidation catalyst or the increase in diesel fuel sulfur concentration as illustrated with Figure 4.32 and Figure 4.33.

Figure 4.28: FTP accumulated HC for 150ppm oxidation catalyst through the aging period.

Figure 4.29: Percent reduction of HC for 150ppm oxidation catalyst.

Figure 4.30: FTP accumulated CO for 150ppm oxidation catalyst through the aging period.

Figure 4.31: Percent reduction of CO for 150ppm oxidation catalyst.

Figure 4.32: FTP accumulated CO₂ for 150ppm oxidation catalyst through the aging period.

Figure 4.33: FTP accumulated NO_x for 150ppm oxidation catalyst through the aging period.

4.5.4 350ppm gaseous results

Results were obtained from the Cummins ISM370 engine operating on 350ppm sulfur diesel fuel described in Section 3.2. Figure 4.34 shows the accumulated results of HC measured during the FTP cycle. The 350ppm HC oxidation results are at the 80% reduction level observed with the 3 and 30ppm oxidation catalysts which is displayed in Figure 4.35. Diesel fuel sulfur concentration has no significant effect on the reduction of HC with an oxidation catalyst as speculated in the 150ppm results.

Figure 4.36 presents the amassed CO throughout the transient cycle for the four aging points. All four sulfur fuel levels were consistent that CO oxidation does not initiate until halfway through the FTP cycle. A 40% CO reduction was observed at the beginning and after 50 aging hours which is 10% increase from the 3 and 30ppm results and a 7% increase from the 150ppm results. A decline of 10% in CO reduction was observed earlier in the catalyst life due to catalyst poisoning from the high sulfur levels in the diesel fuel. After this 10% decline illustrated in Figure 4.37, the oxidation catalyst still reduced CO by 30% which was at the level of the other three oxidation catalysts. No effect on CO₂ and NO_x was

observed from the 350ppm oxidation catalyst as displayed in Figure 4.38 and Figure 4.39 which was consistent in the other fuel level results.

Figure 4.34: FTP accumulated HC for 350ppm oxidation catalyst through the aging period.

Figure 4.35: Percent reduction of HC for 350ppm oxidation catalyst.

Figure 4.36: FTP accumulated CO for 350ppm oxidation catalyst through the aging period.

Figure 4.37: Percent reduction of CO for 350ppm oxidation catalyst.

Figure 4.38: FTP accumulated CO₂ for 350ppm oxidation catalyst through the aging period.

Figure 4.39: FTP accumulated NO_x for 350ppm oxidation catalyst through the aging period.

4.5.5 PM results

Total particulate matter is presented on a brake-specific basis and on a continuous basis. PM was collected on filters as required by the CFR [1]. The process used to collect PM was described in Section 3.4.2. Measured PM was converted to units of g/bhp-hr for each catalyst evaluation. PM results of the oxidation catalysts for the four sulfur fuel levels are presented in Figure 4.40. Equation 4.1 was used to determine the difference between initial and final measured PM during the aging process with initial data used as the reference. The 3ppm fuel provided a 7% increase in PM over the aging process. This was the only fuel for which an increase in PM was observed. The remaining 30ppm, 150ppm, and 350ppm fuels demonstrated PM reductions of 16%, 4%, and 21% respectively.

Figure 4.41 presents continuous PM measured with the TEOM for the four different fuels. An increase in sulfur in the diesel fuel increases the amount of sulfate present in the exhaust. These sulfates attach to particles which affect the weight of total particulate matter. Therefore, an increased concentration of sulfur in the diesel fuel should increase the measured PM. This was not the case for both the PM collected on filter and PM collected by the TEOM. The highest sulfur fuel produced the least amount of PM and the smallest quantity of sulfur in the fuel provided the most PM by both methods of measurement.

Figure 4.40: Total PM collected during oxidation catalyst evaluations.

Figure 4.41: Continuous accumulated PM from TEOM for the oxidation catalysts.

4.6 Lean-NO_x catalyst results

This section is divided up into four subsections to present the results from the high-temperature lean-NO_x catalyst for the four different sulfur fuel levels. The results are presented by the accumulation of the constituents, HC, CO, CO₂, and NO_x, throughout the steady-state cycle. This lean-NO_x catalyst required a reductant injected upstream of the device for NO_x reduction. Reductant was only injection in modes 4 and 5 of the ESC4 cycle because injection in modes 2 and 3 provided minimal NO_x reduction. Gaseous emissions results are provided as engine-out split flow test with no aftertreatment and as catalyst out emissions recorded at various stages of catalyst aging. Equation 4.1 was used to determine % increase of HC and CO with the engine-out value used as the reference value. Figure 4.42 provides a temperature measured 6 inches before the oxidation catalyst termed precat and temperature measured 6 inches downstream of the catalyst called the postcat. Temperatures ranged between ± 20 °C of the two temperature traces provided in Figure 4.42 for the DECSE catalyst testing.

Figure 4.42: Lean-NO_x catalyst temperatures.

4.6.1 3ppm gaseous results

Results were obtained from the Cummins ISM370 engine operating on 3ppm sulfur diesel fuel described in Section 3.2. Figure 4.43 presents the accumulated results of HC measured during the ESC4 cycle, which was described in Section 3.6. This figure illustrates that a large increase of HC was reported during the last two modes from the reductant injection. Figure 4.44 shows an 800% increase in HC from reductant injection at the final aging evaluation. The percent HC increase due to the reductant injection seems to increase as the catalyst ages.

CO accumulated throughout the ESC4 is shown in Figure 4.45. CO, just like HC, was generated during the reductant injection. Figure 4.46 provides CO generated from the reductant injection as a percentage of the engine-out CO with no reductant injection. The catalyst had minimal effect on CO₂ as seen in Figure 4.47.

Accumulated NO_x from the steady-state cycle is illustrated in Figure 4.48. Some NO_x reduction occurred before the reductant injection as seen in Figure 4.49. This reduction

could be attributed to the presence of HC introduced from the diesel combustion, not the injection system. The catalyst initially reduces NO_x by approximately 12% which decreases to 7% after the first aging period. The 150 hours evaluation provided a 4% NO_x reduction and increased back up to 7% after the final aging was completed. It seems that the reductant injection system was not working properly during the 150 hour evaluation.

Figure 4.43: *ESC4 accumulated HC for 3ppm lean- NO_x catalyst through the aging period.*

Figure 4.44: *Percent increase of HC for 3ppm lean- NO_x catalyst.*

Figure 4.45: ESC4 accumulated CO for 3ppm lean-NO_x catalyst through the aging period.

Figure 4.46: Percent increase of CO for 3ppm lean-NO_x catalyst.

Figure 4.47: ESC4 accumulated CO₂ for 3ppm lean-NO_x catalyst through the aging period.

Figure 4.48: ESC4 accumulated NO_x for 3ppm lean-NO_x catalyst through the aging period.

Figure 4.49: Percent reduction of NO_x for 3ppm lean-NO_x catalyst.

4.6.2 30ppm gaseous results

Results were obtained from the Cummins ISM370 engine operating on 30ppm sulfur diesel fuel described in Section 3.2. Figure 4.50 presents accumulated results of HC measured during the ESC4 cycle. A large increase of HC was observed during the last two modes consistent with the 3ppm lean-NO_x results. Figure 4.51 showed approximately a 700% increase in HC at the final aging evaluation. As speculated in the 3ppm results, HC increased from the reductant injection increased as the catalyst aged.

CO accumulated throughout the ESC4 is shown in Figure 4.52. Figure 4.53 illustrates approximately 800% CO generation from the reductant injection. The CO increase from the reductant increased as the catalyst was aged. Figure 4.54 shows that the catalyst had no effect on CO₂ which is consistent with the 3ppm results.

Accumulated NO_x from the steady-state cycle is illustrated in Figure 4.55. As was the case with the 3ppm results, some NO_x reduction occurred before the reductant was injected. Figure 4.56 provides percent NO_x reduction for the cycles executed during the four aging points. The data shows that NO_x reduction increased to 12% for the 250 hour evaluation. 3ppm results do not support this result of increased catalyst performance while aged.

Please note that the 50 hour evaluation experienced lower increases in HC and CO with less NO_x reduction. This may be attributed to a reductant injection malfunction introducing not enough reductant.

Figure 4.50: ESC4 accumulated HC for 30ppm lean-NO_x catalyst through the aging period.

Figure 4.51: Percent increase of HC for 30ppm lean- NO_x catalyst.

Figure 4.52: ESC4 accumulated CO for 30ppm lean- NO_x catalyst through the aging period.

Figure 4.53: Percent increase of CO for 30ppm lean- NO_x catalyst.

Figure 4.54: ESC4 accumulated CO₂ for 30ppm lean-NO_x catalyst through the aging period.

Figure 4.55: ESC4 accumulated NO_x for 30ppm lean-NO_x catalyst through the aging period.

Figure 4.56: Percent reduction of NO_x for 30ppm lean-NO_x catalyst.

4.6.3 150ppm gaseous results

Results were obtained from the Cummins ISM370 engine operating on 150ppm sulfur diesel fuel described in Section 3.2. Figure 4.57 presents accumulated results of HC measured during the ESC4 cycle. A 1000% increase in HC was observed at the final aging evaluation as illustrated in Figure 4.58. This increase in HC was larger than the increase observed in the 3 and 30ppm results but the 150ppm results supported the previous results that HC increase from the reductant injection increase as the catalyst aged.

CO accumulated throughout the ESC4 is shown in Figure 4.59 which illustrates a CO generation of approximately 1200% from the reductant injection which is a significant increase from the 3ppm and 30ppm results. The CO increase from the reductant injection increased as the catalyst was aged except for the 250 hours result. Figure 4.61 shows that the catalyst had no effect on CO₂ which is consistent with the 3ppm and 30ppm results.

Accumulated NO_x from the steady-state cycle is illustrated in Figure 4.62. Figure 4.63 provides percent NO_x reduction for the cycles executed during the four aging points. The data shows initial NO_x reduction of 17% but declines to 5% for the 250 hour evaluation. No NO_x reduction was observed for the evaluations of 50 and 150 aging hours. The 3ppm results are consistent with the result that NO_x reduction decreases as the catalyst ages but the 30ppm results do not support this outcome.

Figure 4.57: ESC4 accumulated HC for 150ppm lean-NO_x catalyst through the aging period.

Figure 4.58: Percent increase of HC for 150ppm lean-NO_x catalyst.

Figure 4.59: ESC4 accumulated CO for 150ppm lean-NO_x catalyst through the aging period.

Figure 4.60: Percent increase of CO for 150ppm lean-NO_x catalyst.

Figure 4.61: ESC4 accumulated CO₂ for 150ppm lean-NO_x catalyst through the aging period.

Figure 4.62: ESC4 accumulated NO_x for 150ppm lean-NO_x catalyst through the aging period.

Figure 4.63: Percent reduction of NO_x for 150ppm lean-NO_x catalyst.

4.6.4 350ppm gaseous results

Results were obtained from the Cummins ISM370 engine operating on 350ppm sulfur diesel fuel described in Section 3.2. Figure 4.64 presents the accumulated results of HC measured during the ESC4 cycle. As was the case with the 3ppm, 30ppm, and 150ppm results, HC increased during the last two modes from the reductant injection. Figure 4.65 shows approximately an 700% increase in HC from reductant injection at the final aging evaluation. The HC increase from the reductant injection increased as the catalyst aged which was consistent with the pervious three sets of results. Fuel sulfur concentration had no effect on the amount of increase that occurred.

CO accumulated throughout the ESC4 is shown in Figure 4.66. Figure 4.67 provides CO generated from the reductant injection as percent of the engine-out test with no reductant injection. The final 250 hour evaluation experienced an 1000% increase of CO compared to the engine-out test run with no reductant injection. The CO increase from the reductant injection increased as the catalyst was aged which supports the pervious results. Fuel sulfur concentration caused a increase in the amount of CO increase. The catalyst had negligible effect on CO₂ which was consistent with the pervious results.

Accumulated NO_x from the steady-state cycle is illustrated in Figure 4.69. NO_x demonstrated minimal affect by the catalyst until reductant injection but Figure 4.70 shows some reduction occurring before reductant injection for two aging periods. The catalyst initially reduced NO_x by approximately 9% which increased to 10% after all aging was completed. The 150 hours evaluation provided a 5% NO_x reduction. A increase in NO_x reduction from 150 hours evaluation to the 250 hours evaluation was observed with all four fuel sulfur concentrations without any explanation. Perhaps catalysts were not fully degreened in the first 250 hours.

Figure 4.64: ESC4 accumulated HC for 350ppm lean- NO_x catalyst through the aging period.

Figure 4.65: Percent increase of HC for 350ppm lean- NO_x catalyst.

Figure 4.66: ESC4 accumulated CO for 350ppm lean-NO_x catalyst through the aging period.

Figure 4.67: Percent increase of CO for 350ppm lean-NO_x catalyst.

Figure 4.68: ESC4 accumulated CO₂ for 350ppm lean-NO_x catalyst through the aging period.

Figure 4.69: ESC4 accumulated NO_x for 350ppm lean- NO_x catalyst through the aging period.

Figure 4.70: Percent reduction of NO_x for 350ppm lean- NO_x catalyst.

4.6.5 PM results

Total particulate matter is presented on a brake-specific basis and on a continuous basis. PM was collected on filters as required by the CFR [1]. The process used to collect PM was described in Section 3.4.2. Measured PM was converted to units of g/bhp-hr for each catalyst evaluation. PM results of the lean- NO_x catalysts as aging occurred for all four-fuel levels are presented in Figure 4.71. Equation 4.1 was used to determine the difference between initial and final measured PM during the aging process with initial data used as the reference. The 3ppm fuel provided a 70% increase in PM over the aging process. The

remaining 30ppm, 150ppm, and 350ppm fuels demonstrated an increase in PM of 27%, 81%, and 18% respectively.

Figure 4.72 presented continuous PM measured with TEOM for the four different fuels. As described in Chapter 3, the lean- NO_x catalyst was only evaluated under steady-state conditions and data was collected at the end of each mode. That explains the step changes in Figure 4.72. The TEOM reported that all four fuels generated the same amount of PM under steady-state operations.

Figure 4.71: Total PM collected during lean- NO_x catalyst evaluations.

Figure 4.72: Continuous accumulated PM from TEOM for the lean- NO_x catalysts.

5. Conclusions

The split exhaust system was balanced at three different exhaust flow rates entering the dilution tunnel during the system validation. Gaseous emissions were corrected based on a calculated CO₂ ratio between the full exhaust stream and the partial stream. This ratio related split flow data back to full flow data within 1% for HC, within 11% for CO, within 3% for NO_x, and within 7% for PM on a brake-specific basis under transient engine operation. On an accumulated basis, gaseous emissions levels were within 8% of the full flow levels. With the engine operating under steady conditions, corrected data from the different flow rates was within 26% for HC, within 14% for CO, and within 13% for NO_x. Please note that these are maximum differences and the majority of corrected data was within 7% of the full flow values. No PM was collected during steady-state testing. It is concluded that the modest deviations in flow that may arise from split flow considerations are more than offset by the reduction in engine hours needed for aging by splitting the flow.

The four oxidation catalysts evaluated by the DECSE program initially demonstrated 80% or above reduction of HC with a slight decline in performance after the first aging period. HC reduction was then maintained for the remaining 200 hours of aging. The catalyst oxidized HC across the entire FTP cycle but CO was only oxidized during the second half of the cycle. Both 3ppm and 350ppm fuels experienced a decline from 40% to 30% CO reduction during aging while 30ppm and 150ppm fuels began and maintained a 30% CO reduction. No effect on CO₂ and NO_x was observed from the catalysts or from the increase in fuel sulfur concentrations during the testing of the oxidation catalysts.

The four lean-NO_x catalysts evaluated by the DECSE program experienced HC increase from the reductant injection of initially 300% and increased to approximately 700%

after the 250 aging hours. Fuel sulfur concentration had little effect on the break-through of HC but the different fuels effected CO increase. A 700% increase in CO for the low-sulfur 3ppm and 30ppm fuels was observed at the last catalyst evaluation but over 1000% increase for the high-sulfur 150ppm and 350ppm fuels. Initially, CO increase was approximately 500% for the low-sulfur fuels and 700% for the high sulfur fuels. The lean-NO_x catalysts demonstrated no effect on CO₂ during the steady-state testing. Initial NO_x reductions of approximately 10% were observed but decrease to 8% after 250 hours of aging. Some NO_x reduction was observed on steady-state modes with no reductant injection. This was attributed to HC produced from the combustion serving as the catalyst reductant.

6. Recommendations

Some research needs to be completed to examine the limits of the split exhaust system. For example, this thesis presented a maximum flow bias of 40%, the 30/70 case. Would testing be possible with a 50% bias such as a 25/75 split? What is the maximum bias that can be achieved? Investigating using Annubars in each branch of the exhaust split using computer-controlled throttling valves to maintain the split ratio might yield interesting results.

The lean- NO_x catalysts demonstrated an 8% reduction in NO_x with a 700% increase of HC and 1000% increase of CO. An 80% reduction of HC and a 30% reduction of CO were observed during the oxidation catalyst testing. Further testing needs to be performed with the lean- NO_x and the oxidation catalyst in series to determine if the 8% NO_x reduction is achievable without any increase in HC or CO.

Lean- NO_x catalyst evaluations under transient engine operation might generate favorable results. The development of an interface between the engine and the injection system could be used to control reductant injection. This analysis would be beneficial if similar NO_x reduction results observed by the steady-state DECSE results were achieved. Some time spend examining another means of NO_x reduction such as urea injection with a selective catalytic reduction or a NO_x adsorber might yield a larger NO_x reduction the provided by the Lean NO_x catalyst.

7. References

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**Appendix A: Certificates of Analysis of the Diesel Fuel Formulations with
Four Different Sulfur Levels**

3ppm Fuel Analysis

Certificate of Analysis

PHILLIPS CHEMICAL COMPANY
A DIVISION OF PHILLIPS PETROLEUM COMPANY

SPECIALTY CHEMICALS
P.O. BOX 968
BORGER, TX 79008-0968

DATE OF SHIPMENT
09-01-2000

CUSTOMER ORDER NO.
JCO-9-29021-01

INV./REQN. NO.
5272138

CONTAINER NO.
TRLR # 350

MFG. DATE: 04/99

DIESEL UL SULFUR TYPE 2 9DP05L01

TESTS	RESULTS	SPECIFICATIONS	METHOD
Specific Gravity, 60/60	.826	0.82 - 0.85	ASTM D-4052
API Gravity	39.8	35.0 - 41.0	ASTM D-1298
Sulfur, PPM	3.3	<10	ASTM D-4294
Flash Point, °F, PM	157.5	>125	ASTM D-93
Pour Point, °F	-5	Report	ASTM D-97
Cloud Point, °F	-5	Report	ASTM D-2500
Viscosity, cs 40C	2.5	>2.0	ASTM D-445
Hydrogen, wt%	13.4	Report	Phillips
Carbon, wt%	86.6	Report	Phillips
Molecular weight	to be reported	Report	ASTM D-524
Net Heat of Combustion, btu/lb	18593	Report	ASTM D-3338
Gross Heat of Combustion, btu/lb	19838		
Cetane Index	53.5	Report	ASTM D-976
Cetane Number	44.4	42-48	ASTM D-613
			ASTM D-86
<u>DISTILLATION, °F</u>			
IBP	364.5		
5%	387.1		
10%	402.9		
15%	413.0		
20%	430.6		
30%	460.0		
40%	483.0		
50%	497.6		
60%	509.9		
70%	524.0		
80%	547.4		
90%	598.5		
95%	643.3		
EP	661.7		
Loss	0.45		
Residue	1.2		
<u>HYDROCARBON TYPE, VOL %</u>			
Aromatics	26.9	25 - 32	ASTM D-1319
Olefins	2.3	1 - 3	
Saturates	70.8	55 - 70	
Polynuclear Aromatics, wt%	9.8	3 - 10	

DGD:jam
09/01/00
1024290

30ppm Fuel Analysis

Certificate of Analysis

PHILLIPS CHEMICAL COMPANY
A DIVISION OF PHILLIPS PETROLEUM COMPANY

SPECIALTY CHEMICALS
P.O. BOX 968
BORGER, TX 79008-0968

DATE OF SHIPMENT
11-13-99

CUSTOMER ORDER NO.
JC0-9-29021-01

INV./REQN. NO.
3648897

CONTAINER NO.
TRLR #380

MFG. DATE: 11/99

DIESEL UL SULFUR TYPE 2 (30 PPM) 9KP05L01

<u>TESTS</u>	<u>RESULTS</u>	<u>SPECIFICATIONS</u>	<u>METHOD</u>
Specific Gravity, 60/60	.8266	Report	ASTM D-4052
API Gravity	39.68	40 Max	ASTM D-1298
Sulfur, PPM	25	Report	ASTM D-4045
Flash Point, °F, PM	157	Report	ASTM D-93
Pour Point, °F	-5	Report	ASTM D-97
Cloud Point, °F	-5	Report	ASTM D-2500
Viscosity, cs 40C	2.50	Report	ASTM D-445
Carbon, wt%	86.2	Report	Phillips
Hydrogen, wt%	13.8	Report	Phillips
Net Heat of Combustion BTU/LB	18540	Report	ASTM D-3338
Cetane Index	53.4	Report	ASTM D-976
Cetane Number	43.8	40 Min	ASTM D-613
<u>DISTILLATION, °F</u>			
IBP	361.6		ASTM D-86
5%	389.2		
10%	401.7		
20%	427.8		
30%	457.9		
40%	481.9		
50%	496.8		
60%	508.8		
70%	522.9		
80%	546.3		
90%	598.6		
95%	641.6		
EP	664.0		
Loss	0.8		
Residue	1.1		
<u>HYDROCARBON TYPE, VOL%</u>			
Aromatics	26.2	Report	ASTM D-1319
Olefins	2.6		
Saturates	76.2		
Aromatics, wt%	29.8		
Polynuclear Aromatics, wt%	10.2		

DGD:teh
11/13/99
1024309

150ppm Fuel Analysis

Certificate of Analysis

PHILLIPS CHEMICAL COMPANY
A DIVISION OF PHILLIPS PETROLEUM COMPANY

SPECIALTY CHEMICALS
P.O. BOX 968
BORGER, TX 79008-0968

DATE OF SHIPMENT

CUSTOMER ORDER NO.

INV./REQN. NO.

CONTAINER NO.

MFG. DATE: 08/00

ULTRA-LOW SULFUR DIESEL QHPULD01

<u>TESTS</u>	<u>RESULTS</u>	<u>SPECIFICATIONS</u>	<u>METHOD</u>
Specific Gravity, 60/60	8264	0.82 - 0.85	ASTM D-4052
API Gravity	39.72	35 - 41	ASTM D-1298
Sulfur, PPM (HOUSTON-ATLAS)	152	130 - 170	ASTM D-4045
Flash Point, °F, PM	157.5	>125	ASTM D-93
Pour Point, °F	-5	Report	ASTM D-97
Cloud Point, °F	-5	Report	ASTM D-2500
Viscosity, cs 40C	2.5	>2.0	ASTM D-445
Carbon Wt%	86.01	Report	Phillips
Hydrogen wt%	13.99	Report	Phillips
Net Heat of Combustion, btu/lb.	18550	Report	ASTM D-3338
Cetane Index	53.51	Report	ASTM D-976
Cetane Number	44.4	Report	ASTM D-613
<u>DISTILLATION, °F</u>			ASTM D-86
IBP	355.9		
5%	390.3		
10%	402.6		
20%	430.7		
30%	460.7		
40%	483.3		
50%	497.6		
60%	509.3		
70%	523.6		
80%	546.3		
90%	595.3		
95%	638.2		
EP	663.9		
Loss	0.6		
Residue	1.0		
<u>HYDROCARBON TYPE, VOL%</u>			ASTM D-1319
Aromatics	26.9	Report	
Olefins	2.3	Report	
Saturates	70.8	Report	

BJS:jam
09/05/00
1024307

350ppm Fuel Analysis

Certificate of Analysis

PHILLIPS CHEMICAL COMPANY
A DIVISION OF PHILLIPS PETROLEUM COMPANY

SPECIALTY CHEMICALS
P.O. BOX 968
BORGER, TX 79008-0968

DATE OF SHIPMENT
11-13-99

CUSTOMER ORDER NO.
JCO-9-29021-01

INV./REQN. NO.
3648897

CONTAINER NO.
TRLR #380

MFG. DATE: 11/99

DIESEL UL SULFUR TYPE 2 (350 PPM) 9KP05L02

<u>TESTS</u>	<u>RESULTS</u>	<u>SPECIFICATIONS</u>	<u>METHOD</u>
Specific Gravity, 60/60	8266	Report	ASTM D-4052
API Gravity	39.68	40 Max	ASTM D-1298
Sulfur, PPM	361	Report	ASTM D-4045
Flash Point, °F, PM	157	Report	ASTM D-93
Pour Point, °F	-5	Report	ASTM D-97
Cloud Point, °F	-5	Report	ASTM D-2500
Viscosity, cs 40C	2.50	Report	ASTM D-445
Carbon, wt%	86.2	Report	Phillips
Hydrogen, wt%	13.8	Report	Phillips
Net Heat of Combustion BTU/LB	18540	Report	ASTM D-3338
Cetane Index	53.4	Report	ASTM D-976
Cetane Number	43.8	40 Min	ASTM D-613
<u>DISTILLATION, °F</u>			
IBP	361.6		ASTM D-86
5%	389.2		
10%	401.7		
20%	427.8		
30%	457.9		
40%	481.9		
50%	496.8		
60%	508.8		
70%	522.9		
80%	546.3		
90%	598.6		
95%	641.6		
EP	664.0		
Loss	0.8		
Residue	1.1		
<u>HYDROCARBON TYPE, VOL%</u>			
Aromatics	26.2	Report	ASTM D-1319
Olefins	2.6		
Saturates	76.2		
Aromatics, wt%	29.8		
Polynuclear Aromatics, wt%	10.2		

DGD:teh
11/13/99
1024309