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Final Report

Chassis Dynamometer Evaluation of the “Cartential®” Effect

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1. OBJECTIVE

The objective of this study is to evaluate the impact that "Cartential®" cooling system additive had on the emissions and fuel economy of a class 8 tractor, using a heavy duty chassis dynamometer. A series of three widely accepted heavy-duty chassis dynamometer test cycles were used to exercise a WVU fleet vehicle in its baseline configuration, as well as with the "Cartential®" cooling system additive. The chassis dynamometer tests were conducted on-site in Riverside, CA using the WVU Transportable Emissions Measurement System (TEMS). Engine emissions of total oxides of nitrogen (NOx), carbon monoxide (CO), total hydrocarbons (THC), carbon dioxide (CO2), and particulate matter (PM) were measured and reported on a distance-specific basis. In addition, gravimetric fuel consumption was reported for each test conducted. Four repeat tests, comprised of one warm-up and three hot-start repeats, were performed on each cycle for the baseline configuration and with the "Cartential®" cooling system additive. Hot-Start repeats are performed to establish data repeatability of fuel consumption.

2. EXPERIMENTAL SETUP

2.1. Vehicle emissions testing laboratory

The West Virginia University Transportable Emissions Measurement System (TEMS) consists of transportable heavy-duty chassis dynamometer and a transportable emissions measurement container built and operated to CFR 40 Part 1065 specifications.

2.1.1. Chassis Dynamometer

The chassis dynamometer test bed consists of load simulation system, which includes flywheel assembly system to simulate inertial load and eddy current power absorbers to imitate road load and wind drag experienced by the vehicle when driven on the road, rollers, hub adapter, torque and speed transducer built onto a tandem axle semi trailer. The hydraulic jack on the chassis dynamometer test bed is functional in setting the test bed on the ground and onto the trailer. The various components of the chassis dynamometer are discussed in detail below.

- Load Simulation System: The load simulation system consists of a flywheel assembly, an eddy current power absorber, a speed and torque transducer, double differentials and universal couplings on either side of the vehicle to be tested as shown in the figure below. The power from the vehicle's drive axle is transmitted to the flywheel assembly and power absorbers by a hub adapter which is connected to a 24 inch (61 mm) long spline shaft running into a pillow block. The spline shaft is connected to the speed and torque transducer by a universal coupling which can withstand torque up to 16,415 lb-ft (222,256 N-m) on either side. The speed and torque transducer streams data at a rate of 10 Hz, which is recorded on a data logging computer. The torque transducer drives a second shaft via companion flange. This shaft transfers power to a right-angle speed increasing drive, a double reduction differential with a ratio of 1:3.65, which drives the flywheel assembly and a second differential. The second differential with a ratio of 1:5.73 drives the eddy current power absorbers.
- Flywheel Assembly: The flywheel assembly is designed to simulate vehicle gross weights of 40,000 to 66,000 lb. With the maximum being 40,000 lb (18,144 kg) at a wheel diameter of 4 ft (1.22 m) and 66,000 lb (30,000 Kg) at a wheel diameter of 3.25 ft (1 m). The flywheel assembly consists of a drive shaft with four drive rotors running in two pillow blocks. Each drive shaft supports eight flywheels of different sizes with bearings resting on the shaft. By selectively engaging the flywheels to the drive rotors, vehicle mass can be simulated in 250 lb (113 kg) increments.
- Eddy Current Power Absorbers: A Mustang model CC300 air cooled eddy current dynamometer mounted on two bearings is used as power absorbers. The power absorbers are used to simulate load due to rolling friction of the tires and the aerodynamic drag resistance. The eddy current dynamometer has the capability of absorbing 300 hp (224 kW) continuously and 1000 hp (745.7 kW) intermittently during peak operation. Dynamometer load at any speed is controlled by the direct current supplied to the coils and the power absorbed is measured by the torque arm force transducer (load cell).
- Rollers: The chassis dynamometer consists of a set of two paired rollers in the front which supports the single or forward drive axle and a set of single roller at the back in order to support the rear axle of tandem axle vehicles. The rear pair of rollers can be placed in three different positions to accommodate tandem spacing of 4 to 5 ft (1.22 – 1.52m) and each roller is 12.6 inch (32 cm) in diameter with their axis along the length of the test bed. Each pair of

rollers is linked by a flexible coupling to have uniform rotational speed on either side of the vehicle and the coupling was designed to accept 20% of the wheel torque in case of any imbalance due to uneven surface at the test location.

- Hub Adapters: The hub adapters are used to couple the engine drive axle with the flywheel assembly and eddy current power absorber via torque and speed transducer. The adapter is made of a 0.5 inch (13 mm) thick aluminum plate of diameter 1.8 ft (0.55 m).

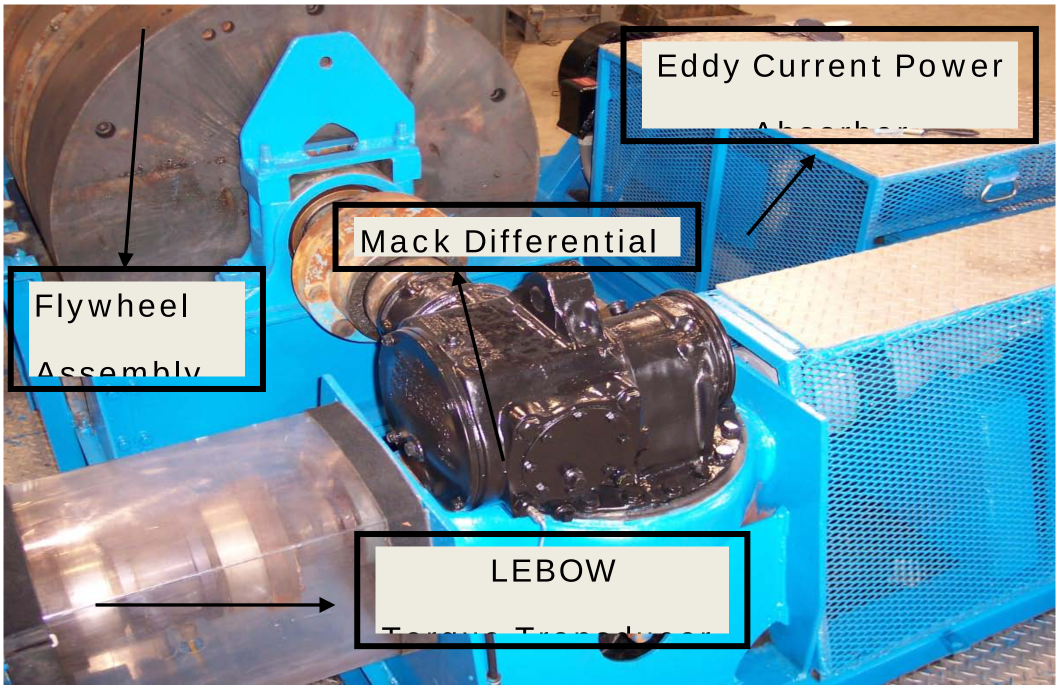

Figure 1 Components of a Chassis Dynamometer

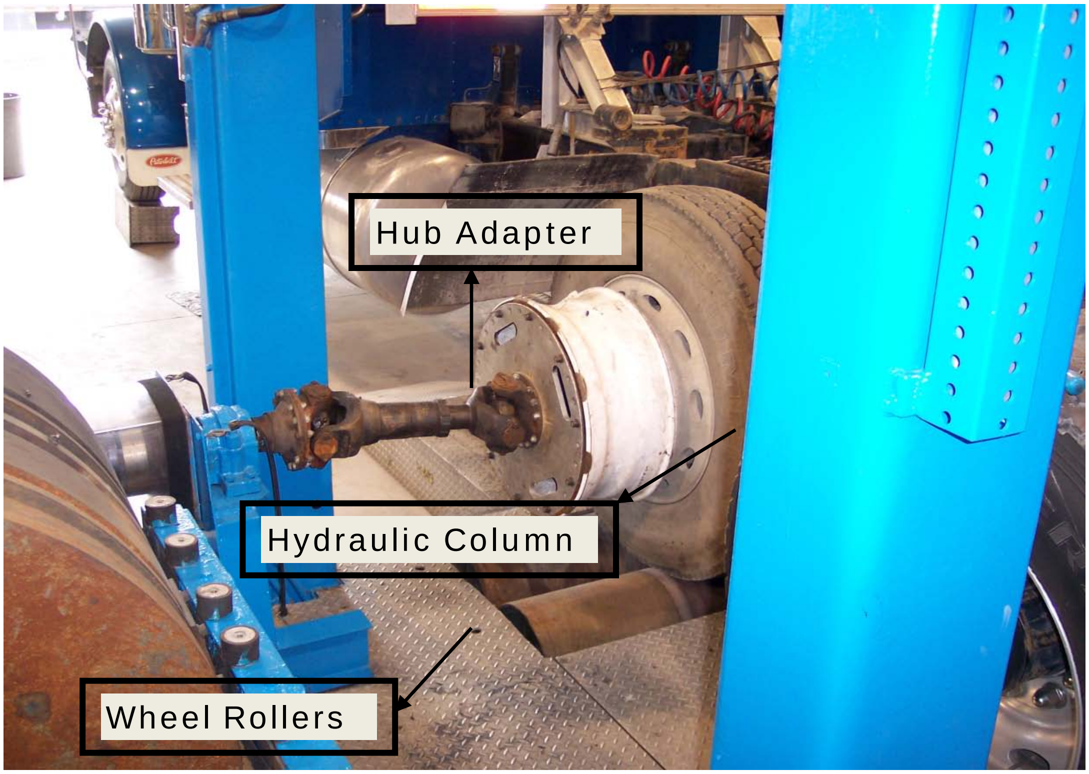

Figure 2 Connecting and supporting structure of chassis dynamometer

While the driver is responsible for the control of the speed, the transient torque must be controlled by an automated system. The load supplied by the flywheels simulates the inertial weight on the engine and is controlled by their rotational speed, while the load due to rolling friction and wind drag is simulated by the eddy current dynamometer. The eddy current dynamometer is controlled using a Dyn-Loc IV control system provided by Dyne-Systems. The Dyn-Loc IV control system operates on a PID control loop where “P” stands for proportional control in which the controller calculates error between the actual and the desired output resulting in a restoration signal linearly proportional to the error. “I” stands for integral control in which the controller calculates the average error over a time and provides a restoring signal which is the product of the error and the time the error persisted. It is used to restore the original set point. D stands for differential control in which the controller calculates the rate at which the set point is changed and produces a corrective signal to reach the set point quickly. Hence, PID controller provides a fast and smooth response in controlling the transient set points. During the test, the power absorbers receive the torque set point, a function of vehicle speed, from the dyne-loc controller. The set point is equal to the road load power and it is calculated using the following equation

$$P_r = (C_r Mg + \frac{1}{2}\rho_a C_D AV^2)V$$

Where

P_r = Road load power

C_r = Coefficient of rolling resistance

M = Vehicle gravitational mass

ρ_a = Air density

A = Frontal area of vehicle

C_D = Coefficient of drag

V = Vehicle speed

The set point is updated every 100 milliseconds. The actual speed and torque values are logged at a frequency of 10 Hz and compared with set speed trace through regression analysis.

2.1.2. Emissions Measurement Container

The housing for the new transportable laboratory is a reconstructed 9.1m (thirty-foot) long cargo container which houses a HEPA filtered primary dilution unit, two full-flow primary dilution tunnels, a subsonic venturi, a secondary particulate matter sampling system, an analytical bench for gaseous emissions measurement, a computer-based DAQ and control system, a heating, ventilating and air conditioning (HVAC) system, and chassis dynamometer control systems. Figure 3 shows the schematic of the transportable laboratory container. The two primary dilution tunnels inside the container, of 0.46 m (18 inches) ID and 6.1 m (20 feet) long, were designed to provide dedicated measurement capability for both low PM emissions ("clean") vehicles (with the upper tunnel referred as the "clean tunnel"), as well as traditional diesel-fueled vehicles with high PM levels (lower tunnel referred as "dirty tunnel"). This provision reduces tunnel history effects between test programs of differing exhaust emission composition. A stainless steel plenum box houses two HEPA filters for filtering primary dilution air, along with twin dual-wall exhaust transfer inlet tubes dedicated as exhaust inlets for the upper and lower tunnels. The HEPA plenum is connected into the main dilution tunnels, which are selectively connected to the subsonic venturi via stainless elbow sections. The air compressor and two vacuum pumps are installed inside a noise isolating overhead unit. An air tank stores compressed air and provides shop air to the zero air generator (a device which removes PM and THC) for use in emissions measuring system. A PM sampling box with secondary dilution tunnels is located alongside the primary tunnels, downstream of tunnels' sample zones. The secondary PM dilution tunnel of either the dirty or clean tunnel is connected to the PM sampling box for PM measurement. Figure 4 shows the transportable laboratory container on the transportation Landoll 435 trailer.

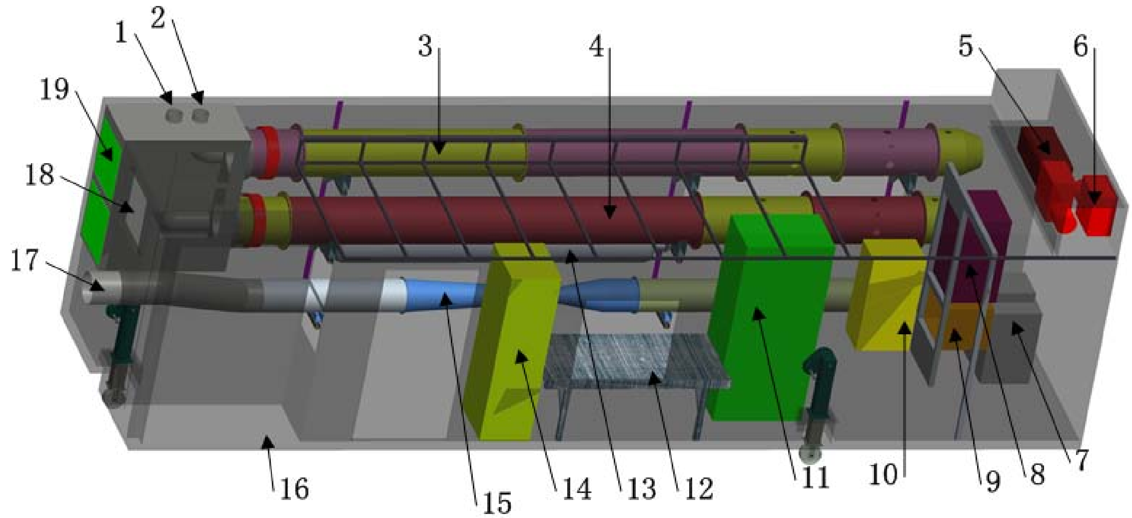

Figure 3 Schematic of the transportable laboratory container

1- Exhaust inlet of dirty tunnel; 2- Exhaust inlet of clean tunnel; 3- Clean tunnel; 4- Dirty tunnel; 5- Air compressor; 6- Vacuum pumps; 7- Oven; 8- PM sampling box; 9- Glove box; 10- Zero air generator; 11- MEXA-7200D motor exhaust gas analyzer; 12- Computer table; 13- Air tank; 14- DAQ rack; 15- Subsonic venturi; 16- Air conditioner deck; 17- Outlet to blower; 18- Ventilation fan; 19- HEPA filters

Figure 4 View of the transportable laboratory container

2.1.2.1. ***Gaseous Emissions Sampling System.***

The gaseous emissions measurement system is designed to be capable of measuring raw as well as diluted exhaust sample continuously as the test vehicle is operated over a prescribed duty cycle. Final emissions value for diluted sample is reported with corrections for background level. The background/dilution air is sampled immediately after the HEPA filters inside the plenum box. Additionally diluted exhaust is sampled into a bag from a sample probe installed at the primary sample zone, which is analyzed along with the background bag. While the purpose of the background batch sampling is to correct for background gaseous emission levels, whereas the diluted batch sampling serves in verifying integrated continuous measurement values for quality control purposes. In some cases, where the emissions vary over a wide concentration range over a cycle, a dilute bag analysis will provide a more accurate assessment of those species than can be obtained by integration. This is often the case for CO from legacy diesel vehicles over severe transient cycles.

The container is equipped with Horiba MEXA 7200D motor exhaust gas analyzer for gaseous measurements from the dilution tunnel. The MEXA7200D is capable of measuring all regulated emission species that include THC, CO, CO_2, NOx and methane through a non-methane cutter equipped secondary hydrocarbon channel. The unit can be fitted with various analyzer modules, and the current configuration consists of AIA-721A CO analyzer, an AIA-722 CO/ CO_2 analyzer and a CLA-720 “cold” NO_x analyzer part of the cold sample stream and the FIA-725A THC analyzer and CLA-720MA NO_x analyzer part of the heated sample stream.

2.1.2.2. ***PM Sampling and Measurement System***

The measurement container houses the PM sampling system for the transportable laboratory. However, the gravimetric analysis (pre- and post weighing) of the PM filters are carried out in a class 1000 clean room, with controlled environment for accurate weighing of the filters, located at WVU. The measurement system is operated with in-house developed software to calibrate the scales, perform measurements, and also to monitor the filters history. The schematic of the on-board PM sampling system is as shown in Figure 5.

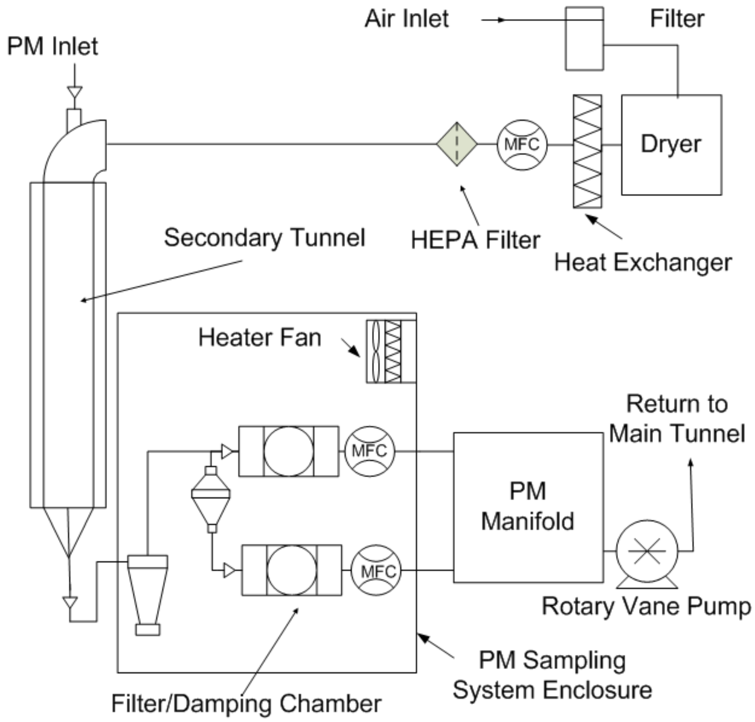

Figure 5: Schematic of the PM sampling system

Figure 6 shows the view of the temperature controlled PM sampling system with two independent streams for the clean tunnel and the dirty tunnel.

Figure 6: 1065 compliant PM sampling system on-board the transportable laboratory container

The sampling system consists of the dilution air stream, which is filtered and cooled to remove moisture. The dry dilution air is then heated to 25±5°C as per regulations prescribed in CFR 1065. The conditioned secondary dilution flow is subsequently introduced to the main PM flow drawn from the primary dilution tunnel and allowed to mix in the secondary dilution tunnel. The secondary dilution tunnel is designed based on Simulink modeling [ref]. The secondary tunnel wall is maintained at 47 Deg C. The flow from the secondary tunnel is passed through a PM_{10} cut-point cyclone, to trap any bigger particle considered to be a tunnel artifact, before collecting the PM on a 47mm filter. The PM system consists of two streams with two separate cyclones and filter holders, connected to the two different primary dilution tunnels. The PM box is also maintained at 47 Deg C. All flows are controlled by calibrated mass flow controllers.

2.1.2.3. ***CVS Flow Control***

The laboratory's CVS flow control is achieved through a sub-sonic venturi (SSV). The SSV installed on the transportable laboratory was supplied with 300 series Schedule 5 stainless steel pipe sections, with a nominal internal diameter of 12", and a throat diameter of 6.26". To ensure the accuracy and repeatability of SSV flow rate measurement, a straight section of Schedule 5 pipe, ten feet in length, was flanged and attached to each end of the subsonic venturi to minimize the flow wakes, or eddies, or flow circulation which might be induced by pipe bends or coarse inside walls. This particular SSV was calibrated using a reference SSV for flow ranging from 400 scfm to 4000 scfm per 40 CFR Part 1065.340. The flow rate of the SSV is calculated, in real time, using the equations prescribed in 40 CFR Part 1065.640 and 40 CFR Part 1065.642.

2.2. **Test Vehicle and Engine Specifications**

At the approval of the the sponsor, ICT GmbH, WVU utilized a 1994 Freightliner series 60, 12.7L tractor as the test vehicle. The vehicle was tested at a simulated GVW of 66,488 lbs. Test vehicle and engine information is shown in Table 1 and Table 2, respectively. Accessory loads such as air-conditioner, and other hotel services was deactivated during cycle evaluation testing.

Table 1 Test Vehicle Specifications

Vehicle (VIN)	Chassis Manufacturer	CGVWR [LB]	Odometer Reading	Vehicle MY	Aftertreatment System
2FUYDSEB8SA562533	Freightliner of Canada, Ltd	80000	327442	1995	None

Table 2: Test Engine specifications

Engine Manufacturer	Engine Model	Engine MY	Displacement/Power [L/HP@rpm]	Engine Serial Number	Fuel	NOx/PM (gm/bhp-hr) *
Detroit Diesel	Series 60	1994	12.8/445@1500	06R020214	ULSD	4.0/0.1

** Values indicate the USEPA emissions standard compliance of the engine*

2.3. Test Cycles

WVU is utilized three widely used chassis dynamometer test cycles for the "Cartential®" Effect evaluation. The UDDS, HHDDT Cruise Mode and the WVU 5-Peak cycles, described below, were used to exercise the test vehicle in its baseline configuration and with the "Cartential®" cooling system additive. Baseline tests for all three cycles were conducted over a 1-day period (11/16/2011). The test activity log for this period is included as Table 9 in Appendix A. The tests with the "Cartential®" cooling system additive (test configuration) for all three cycles were conducted over a 1-day period (11/17/2011). The test activity log for this period is included as Table 10 in Appendix A. Tests for each of the test cycles are separated by 20-minute soak periods, for vehicle and test system conditioning, as well as sample media exchange. Per the sponsoring agency's directive, the “Cartential” cooling system additive, which requires 15 to 20 minutes of operation to become active, was added prior to the warm start HHDDT Cruise Mode (34.7 min.) to serve as the initialization time period for the “Cartential” effect.

2.3.1. UDDS Test Cycle Description

The Code of Federal Regulations describes a test schedule to simulate gasoline-fueled heavy-duty vehicle operation in urban areas termed as the Urban Dynamometer Driving Schedule and it is listed as section (d) in Appendix I (CFR Title 40, Part 86, Subpart N). WVU researchers term this test schedule as Test-D. It has recently been used to provide a realistic emissions test schedule for heavy-duty vehicles. The UDDS cycle simulates the freeway and non-freeway operation of a heavy-duty vehicle. The UDDS was also use as the basis to develop the Federal Test Procedure (FTP) engine dynamometer cycle.

The cycle is of 1060 seconds in duration with a maximum speed of 58 MPH. The vehicle is exercised over 5.5 miles over the entire test cycle.

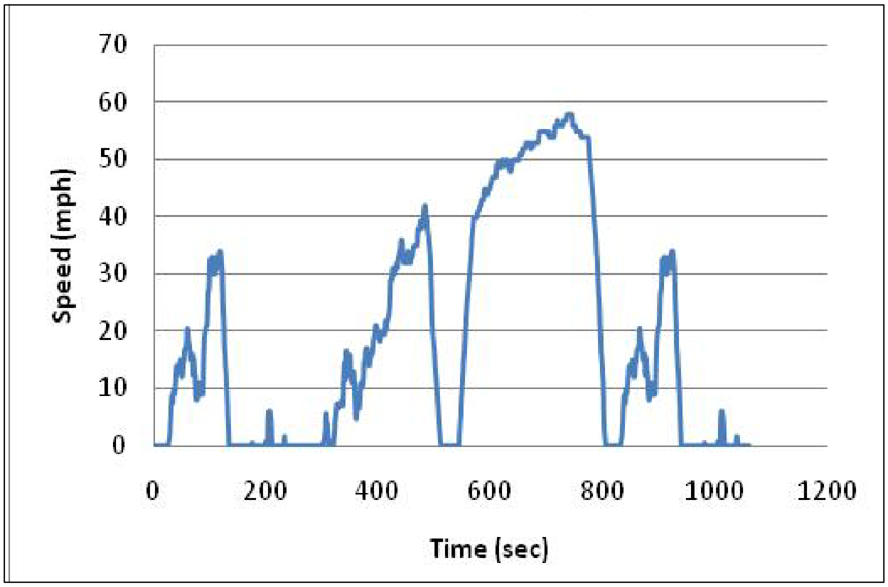

Figure 7 Graphical Representation of the UDDS Test Cycle (Speed vs. Time)

2.3.2. Heavy-Heavy Duty Diesel Truck (HHDDT) Cruise Mode Test Cycle Description

The Heavy Heavy Duty Diesel Truck Cycle was developed for the California Air Resources Board by West Virginia University. The cycle was developed with the aid of GPS data logging which tracked vehicle operation during two ARB funded projects from 1997 to 2000. The HHDDT cycle is divided into four segments, but, for the proposed study, only the cruise cycle will be utilized. The cruise cycle is designed to simulate freeway driving through populated areas. It characterizes vehicles traveling along Highway 99 and Interstate 5 while also accounting for the more congested parts of the highways in the Bay Area and South Coast Basin. The cycle duration is 2083 seconds, with a distance of 23 miles. The average speed throughout the cycle is approximately 40 MPH, with maximum vehicle speeds reaching 60 MPH.

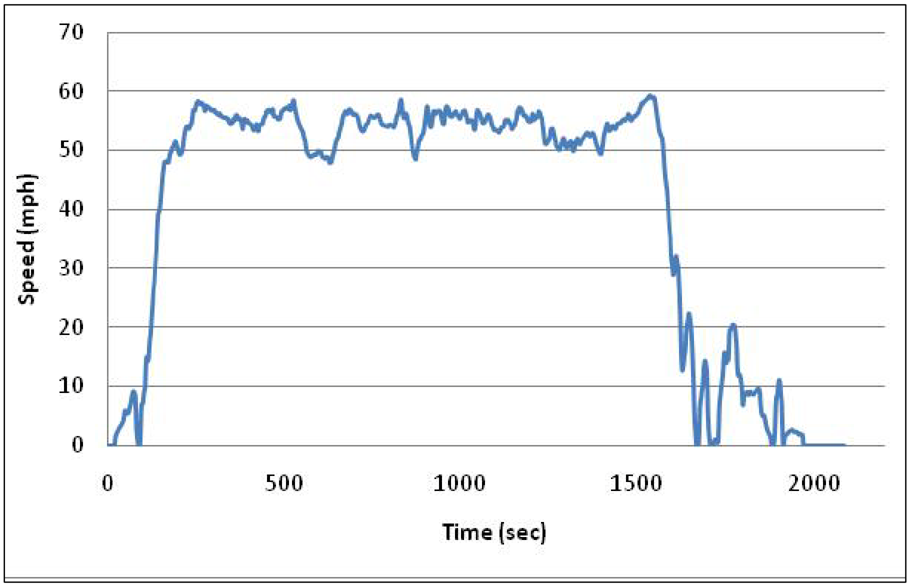

Figure 8 Graphical Representation of the HHDDT Cruise Mode Test Cycle (Speed vs. Time)

2.3.3. WVU 5-Peak Test Cycle Description

The West Virginia University 5-Peak test cycle was developed in 1994. The cycle consists of five short steady-state periods with subsequent increments by 5 MPH. The first steady-state period begins with 20 MPH and continuous incrementing until 40 mph. Each increment is preceded by a brief idle time. The cycle covers a simulated five mile stretch, and for a duration of 900 seconds. This was designed specifically to study the relationship between engine speed load and emissions of various pollutants.

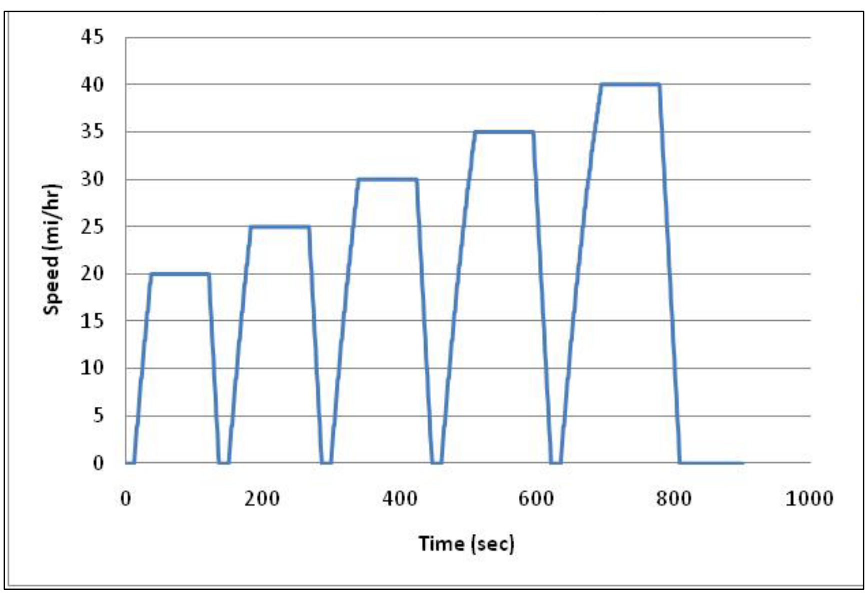

Figure 9 Graphical Representation of the 5 Mile WVU Test Cycle (Speed vs. Time)

3. Emissions Testing Procedure

3.1. Set-up

The chassis dynamometer, which is built onto a flat bed trailer is set-up on a flat surface and leveled to prevent variation in the vehicle's inertial loading which is simulated using rotating flywheels. The emissions measurement container which houses the analyzers, dilution tunnel, dynamometer control and signal conditioning devices was placed close to the chassis dynamometer. This reduced the length of exhaust tubing between the tail pipe and the dilution tunnel, and the transfer pipe was insulated to reduce thermophoretic and other losses of particulate matter in the transfer tube. The blower was placed at the end of the dilution tunnel and a flexible air duct was used in connecting the tunnel to the blower. HEPA filters were installed to the inlet manifold of the dilution tunnel. After all the connections were made to the dilution tunnel the instrument trailer was prepared for testing.

3.2. Laboratory Checks

Initial laboratory set-up procedures include complete measurement system verification followed by calibration. All required system verifications are performed as per requirements stated in 40 CFR 1065 Subpart D. The measurement container is equipped with the Horiba Mexa 7200 Motor Exhaust Gas Analyzer, which is capable of automatically performing the required analyzer verification tests. The verification procedure and pass criteria of the tests were in accordance to the provisions described in 40 CFR 1065 Subpart D. Table 3 lists the complete set of analyzer verification checks performed before commencement of the testing. Table 4 lists the complete set of leak checks performed on the gaseous and PM measurement systems.

Table 3: Analyzer verification checks

Analyzer Checks	Pass Criteria
THC1 Hang-up	
THC2 Hang-up	
CO(L) CO2 Interference Check	Within ±1%
THC O2 Interference Check	Within ± 2%
CO2 Quench NOx1	Within ±1%
CO2 Quench NOx2	Within ±1%
H2O Quench NOx1	Within ±1%
H2O Quench NOx2	Within ±1%
Non-Methane Cutter Efficiency	PFCH4>0.85 and PFC2H6<0.02

Table 4: Gaseous and PM measurement system verification checks

Leak Checks	Pass Criteria
Leak and Delay Time Check (all analyzers)	Within ± 5% over 30 sec interval
PM System 1 Leak Check	
PM System 2 Leak Check	

3.3. Mass Flow Controller Calibration

Mass flow controllers were used in controlling the flow through cyclonic particle classifier, TPM flow through the filter and various other unregulated emissions sampling systems. The calibration was performed against a Laminar Flow Element supplied by Meriam Flow Measurement Devices. Meriam provides a calibration equation and co-efficient for each LFE which is obtained through calibration involving a flow meter that is traceable to NIST standards. A five point calibration was performed on the MFCs between fully open and fully closed position. The flow through the LFE was calculated using the following equation

$$\dot{V}_{actual} = [B \times (\Delta P) + C \times (\Delta P)] \times \frac{\mu_{std}}{\mu_{flow}}$$

Where

B & C = LFE specific co-efficient

ΔP = Pressure differential measured across LFE

$\frac{\mu_{std}}{\mu_{flow}}$ = Viscosity correction factor

The viscosity variations was calculated using the correction factor given in the following equations

$$\text{Correctionfactor} = \left(\frac{529.67}{459.67 + T(\text{in}\,^{o}F)} \right) \times \left(\frac{181.87}{\mu_g} \right)$$

$$\mu_g = \frac{14.58 + \left(\frac{459.67 + T\left(\text{in}^{o}F\right)}{1.8} \right)}{110.4 + \left(\frac{459.67 + T\left(\text{in}^{o}F\right)}{1.8} \right)}$$

Differential pressure across the LFE and absolute pressure was measured using a Heise pressure reader and the temperature was measured using a Fluke Temperature calibrator. The actual flow measured through the LFE was converted to standard flow by CFR 40 specified standard condition of 20 ^{o}C and 101.1 kPa.

3.4. CVS-SSV Dilution Tunnel Verification

The CVS system was verified by injecting a known quantity of propane into the primary dilution tunnel while CVS-SSV system operating. The concentration of the propane was determined using a pre-calibrated HFID analyzer and the mass of propane injected was measured by the flow data and the density of propane. The propane injection test helped in determining leak in the tunnel and any discrepancy in the flow measuring device (CVS-SSV system).

The method uses a propane injection kit with a critical flow orifice meter to accurately measure the amount of propane injected into the tunnel. The flow rate of propane through the orifice meter is determined by measuring the inlet temperature and pressure using the following equation.

$$q = \frac{A + (B \times P) + (C \times P^2)}{\sqrt{460 + T}}$$

Where

q = flow rate through orifice in scfm at standard condition (20 ^{o}C and 101.1 kPa)

A, B and C = calibration co-efficients provided by the orifice manufacturer

P = absolute orifice inlet pressure, in psia (guage pressure + atmospheric pressure)

T = orifice inlet temperature in ^{o}F

The total flow through CVS is given by the following equation

$$Q = \frac{V}{t} \times 60$$

Where

Q = total volume in scf

V = flow rate in scfm measured by CVS

T = time interval in seconds, usually 300 seconds

The calculated sample concentration was determined by the following equation

$$C_{calc} = \left(\frac{q}{Q} \times 10^{6} \right) \times 3$$

The system error was then given by

$$Error = \left(\frac{C_{obs}}{C_{calc}} - 1 \right) \times 100$$

Where

C_{obs} = measured concentration of the injected propane by HFID analyzer

If the error is greater than ± 2 %, then the cause for discrepancy was found and corrected. The error could be due to various reasons such as leaks before the sampling plane, leaks after the sampling plane and improper analyzer calibration. 3 repeatable propane injections within a difference 0.5% of each other is required pass the dilution tunnel verification test.

3.5. Test Procedure

Before mounting the vehicle on the chassis dynamometer the appropriate flywheel combination was determined and locked in place to simulate the inertial load of the vehicle. The inertia setting for the truck was equal to 66,488 lbs. The outer rear wheel on the drive axle was removed and fitted with hub adapters that are later connected to a drive plate. The vehicle was backed onto the dynamometer and the vehicle drive axle was connected to the flywheel assembly and power absorbers through a the hub adapter drive plate. The vehicle was leveled with the drive axle and the tires were checked for any distortion as it would add to the vehicle loading. The vehicle exhaust was then connected to the dilution tunnel using insulated transfer tubes. To complete installation on the chassis dynamometer test bed, the vehicle was chained down to limit position change.

The vehicle was operated at a high speed after being mounted on the dynamometer in order to warm the lubricating oil to operating temperature. During this warm up activity, gas analyzers were zeroed and spanned with the dilution tunnel operating at its target test set-point. The driver interface speed monitor and communication head sets were installed to aid the driver in following the scheduled drive cycle. Coast-down procedures were run to determine the aerodynamic drag co-efficient, C_D, and tire rolling resistance, μ, that would be used to determine the road load factor used in simulating the energy output for a given speed and acceleration as if the vehicle would have experienced while operating on the road [SAE920252]. After coast-down procedures, a preliminary "dummy" test was conducted by making vehicle to run over the scheduled drive cycle with "dummy" media loaded in the tunnel to verify optimal gas analyzer measurement ranges and to verify adequate sample flow rate control via mass flow controllers. In the event that analyzer ranges were determined to be inadequate, they were recalibrated with appropriate span gas and the mass flow controllers were again verified. After the warm-up run the vehicle was shut down and allowed to soak for twenty minutes. During the soak time the PM filter media were loaded and analyzer zero-span activities were performed while adjusting for the analyzer drift, per manufacturer specifications. Sample media loading was carried out in the controlled chamber to avoid accumulation of contaminants.

3.5.1. **Addition of "Cartential®" Cooling System Additive**

After the baseline testing was performed, the test vehicle was prepared for addition of the "Cartential®" cooling system additive. "Cartential®" representatives provided recommended procedures for adding their product to the cooling system of the 1994 Freightliner test vehicle. Specifically, the introduction technique used is included as Table 5.

Table 5 Manufacturer Instructions for Introduction of "Cartential®" Cooling System Additive

1) As recommended by the sponsoring agency, WVU will remove just over 2,000 ML of existing coolant fluid in the 1994 Freightliner and store as the baseline coolant fluid sample.
2) WVU will follow the instructions on the bottle of Cartential as well as the additional instructions provided in this table and document each step of the process.
3) Shake each bottle of Cartential well immediately prior to introducing the Cartential into the coolant reservoir, introduce the entire contents of each bottle of Cartential.
4) Make certain that there is enough room in the coolant system to accept the 2,000ML (5 Bottles) of Cartential without exceeding the factory recommended capacity limit for the amount of fluid in the coolant reservoir. Do not fill coolant reservoir past the full marker after the Cartential has been introduced.
5) 5 bottles of Cartential per Coolant Capacity in the Freightliner 1994 Series 60; 12.7L
6) Upon completion of the testing, WVU will remove approximately 2,000 ML of the Cartential coolant fluid mixture and store as the "Cartential" effect sample.
7) The sponsoring agency will provide WVU with at least 1 additional bottle of Cartential to be stored as the pure Cartential sample.

4. Results and Discussions

Regulated emissions of THC, CO, NOx, and PM were measured and are reported herein in distance-specific mass units along with distance-specific results for mass fuel consumption and CO_2 mass emissions for each test and as an average for each sequence of the same test configuration and cycle. These results will be presented, subdivided according to test cycle. The specific log of testing activities for the two days of testing, namely baseline tests and those tests with "Cartential®" cooling system additive, are included in Table 9 and Table 10of Appendix A. WVU maintains a chain of custody logs for the baseline coolant fluid sample, Cartential effect coolant mixture sample, pure Cartential sample, fuel supplied, fuel samples retained at WVU, and TPM filters. These will be made available to the sponsor, ICT GmbH, upon request. Similarly, continuous data traces, such as regulated emissions, ambient conditions, tunnel conditions, or vehicle performance, could be prepared for the sponsor upon request.

The difference between the baseline test and the tests with Cartential® cooling system were analyzed for statistical significance using Student t-Test assuming unequal variances, at a confidence interval of 95%. A single tail t-test is used here to the advantage of new technology, which is employed towards reducing emissions and to improve fuel economy. Difference between the two test configurations is considered statistically significant when the P-value of student t-Test is less than 0.05, which is indicated by an asterisk next to the P-value in the test results table. If the difference between the two test configurations is statistically significant, then the results of those tests are analyzed in detail to quantitate the decrease or increase of emissions and fuel economy.

4.1. **HHDDT Test Cycle Results:**

A summary of the distance-specific emissions and fuel consumption for the baseline and test configurations are presented in tabular form as Table 6, and graphically in Figure 10 for chassis dynamometer tests involving the HHDDT test cycle.

The total NOx emission from baseline HHDDT test cycle operation was measured to be 23.19 g/mile, an average of three repeats, while the total NOx emission from test configuration ("Cartential®" cooling system additive) HHDDT test cycle operation was measured to be 21.01 g/mile. The difference in NOx emissions between the baseline and test configuration was 9.4% of decrease compared to baseline. The total hydrocarbon (THC) emissions from baseline HHDDT test cycle operation was measured to be 0.28 g/mile while the total hydrocarbon (THC) emissions from test configuration ("Cartential®" cooling system additive) HHDDT test cycle operation was measured to be 0.28 g/mile. The difference in THC emissions between the baseline and test configuration was negligible. The total CO emissions from baseline HHDDT test cycle operation was measured to be 2.93 g/mile while the total CO emissions from test configuration ("Cartential®" cooling system additive) HHDDT test cycle operation was measured to be 3.19 g/mile. The difference in CO emissions between the baseline and test configuration was 8.9% increase compared to baseline. The total CO_2 emission from baseline HHDDT test cycle operation was measured to be 1364.33 g/mile while the total CO_2 emission from test configuration ("Cartential®" cooling system additive) HHDDT test cycle operation was measured to be 1279.67 g/mile. The difference in CO_2 emissions between the baseline and test configuration was 6.21% decrease compared to baseline. As total CO_2 emissions for tests involving a common fuel are the majority of the carbon resultant of the combustion process - these results should be quite comparable to fuel consumption. As shown, fuel consumption from baseline HHDDT test cycle operation was measured to be 424.29 g/mile, based on carbon balance method, while the fuel consumption from test configuration ("Cartential®" cooling system additive) HHDDT test cycle operation was measured to be 398.54 g/mile. The difference in fuel consumption between the baseline and test configuration was 6.07% decrease compared to baseline.

Table 6: CARB HHDDT Test Cycle Emissions and Fuel Consumption Results

CARB HHDDT		NOx [g/mi]	THC [g/mi]	CO [g/mi]	CO2 [g/mi]	TPM [g/mi]	Fuel Mass CB [g/mi]	Fuel Mass Gravimetric [g/mi]	Axle Work [Hp-hr]
Baseline	1	23.66	0.27	2.94	1387.00	0.13	431.27	434.82	37.00
	2	23.12	0.25	3.14	1375.00	0.13	427.77	438.47	37.42
	3	22.78	0.31	2.69	1331.00	0.12	413.82	426.34	36.59
	Average	23.19	0.28	2.93	1364.33	0.13	424.29	433.21	37.00
	Std Dev	0.44	0.03	0.23	29.48	0.005	9.23	6.22	0.42
	COV†	2%	10%	8%	2%	4%	2%	1%	1%
Cartential® Coolant Additive	1	21.37	0.28	3.09	1285.00	0.13	400.26	410.57	36.64
	2	21.11	0.28	3.37	1277.00	0.14	397.79	407.79	36.94
	3	20.54	0.27	3.10	1277.00	0.13	397.57	407.10	36.56
	Average	21.01	0.28	3.19	1279.67	0.14	398.54	408.49	36.71
	Std Dev	0.42	0.00	0.16	4.62	0.004	1.49	1.83	0.20
	COV†	2%	1%	5%	0.4%	3%	0.4%	0.4%	0.5%
Baseline vs. Cartential		**-9.40%**	**-0.16%**	**8.90%**	**-6.21%**	**5.38%**	**-6.07%**	**-5.71%**	**-0.78%**
Student t-test P value		**0.002***	**0.491**	**0.088**	**0.02***	**0.058**	**0.021***	**0.011***	**0.179**

Note: negative sign indicates improvement whereas positive sign indicates deterioration in respective values due to the use of Cartential® coolant additive in comparison to the baseline results.

* indicates statistically significant difference

† is Coefficient of Variation, which gives a measure of variability in a given data set and it is defined as the ratio of standard deviation to average. Lower the COV higher the repeatability.

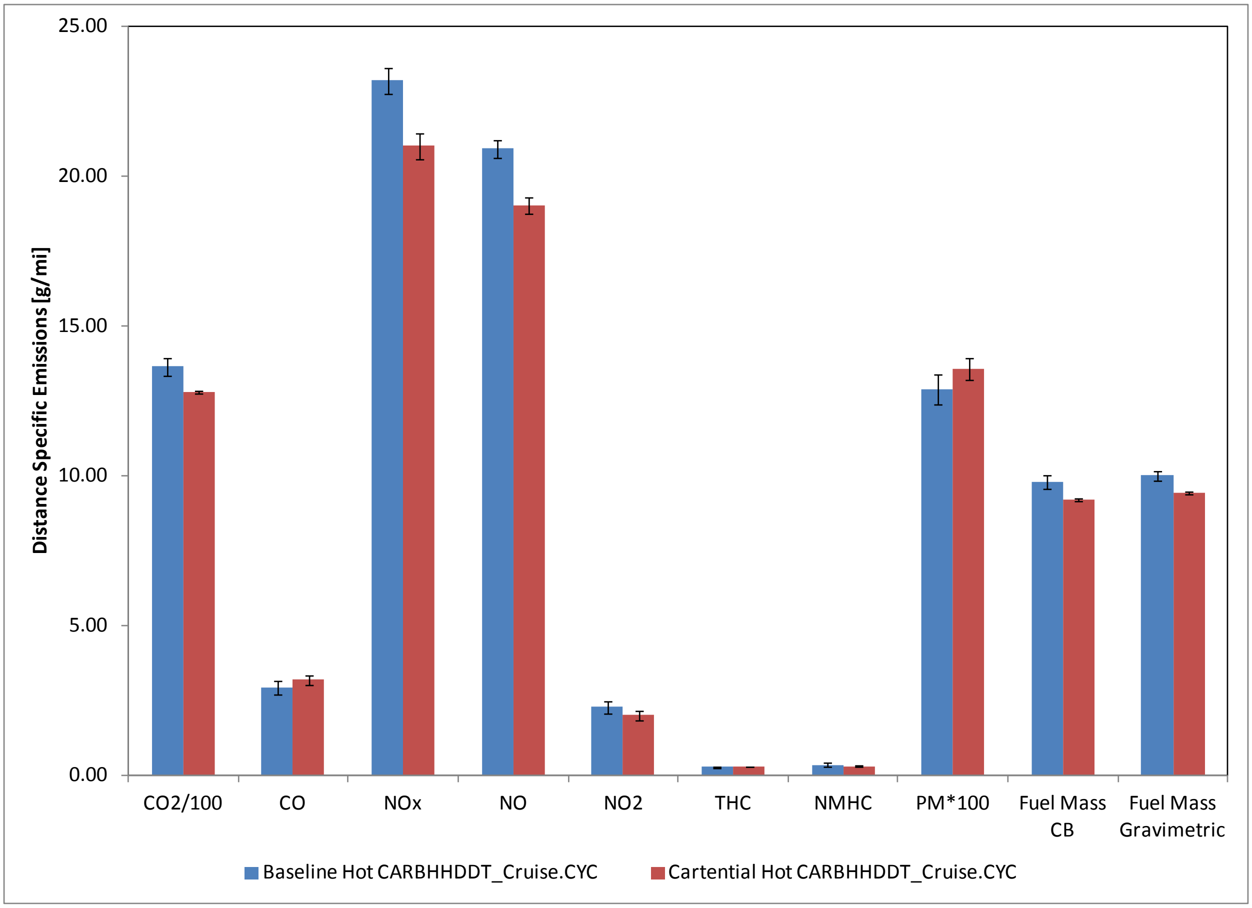

Figure 10: Emissions and Fuel Economy Results for HHDDT Test Cycle

5. Conclusion

Preliminary evaluative testing of the "Cartential®" cooling system additive was performed by WVU CAFEE, utilizing its TEMS and transportable heavy duty vehicle chassis dynamometer. The evaluation was performed by quantifying emissions and fuel consumption changes between baseline operation of a class 8 tractor of MY 1995, powered by a 1994 DDC Series 60 heavy duty diesel engine and the test configuration of the same vehicle that involved addition of the sponsor-recommended dosing and introduction of the "Cartential®" cooling system additive into the vehicle's cooling system. Following are the findings of the evaluation exercise.

In reviewing the data in terms of validity and statistical significance, Student's t-Test values were calculated. Student's t-Test is one of the most commonly used statistical significance testing methods to measure the difference between two groups of independent measurements, of which one serves as a reference or baseline. The significance of the difference between two set of observation is qualitatively determined using a confidence interval 95% of the test variability, in other words it is two times the standard deviation of the sample. A P-value called as probability value is used to indicate the statistical significance between the two test groups. The difference between the observations of the two groups is considered statistically significant when the p-value is less than 0.05 for 95% CI, that is the probability of obtaining the same set of measurements between the two test groups is less than 5% due to chance. In other words, the difference caused by the treatment other than baseline is considered statistically significant. Student's t-test follows a t-distribution which is symmetric with mean of zero and it is bell shaped similar to the Gaussian or normal distribution curve, but the t-distribution curve has larger tail area than normal curve for small degrees of freedom and approach normal distribution for higher degrees of freedom. There are several t-distribution curves based on the degree of freedom, which is a number of independent observations in a set of data. The t-distributions are used for small number of samples derived from population that approximately follows normal distribution. With only three repeats being conducted for both baseline and test configurations, it is not guaranteed that this smaller sample is a subset of a larger, Gaussian distributed sample population, however, the Student's t-test is one of the approved and highly recommended statistical significance testing prescribed by the CFR followed in emissions testing.

Considering the above explanation of the validity concerning the use of the Student t-Test, one could also compare the COVs obtained during this study with past chassis dynamometer test campaigns, which was another evaluative measure that comprises standard internal data quality control/quality assurance activities (QC/QA). In support of the T-test figures, the internal QC/QA review resulted in no significant errors being identified with the test data. With these points being considered, the results proved to be quite contradictory in that a reduction in three-test average NOx emissions was realized for the HHDDT cycle tests, but a similar magnitude increase in three-test average NOx emissions was realized for the WVU 5-Peak cycle tests. The UDDS, showed minimal (~2%) change in NOx emissions.

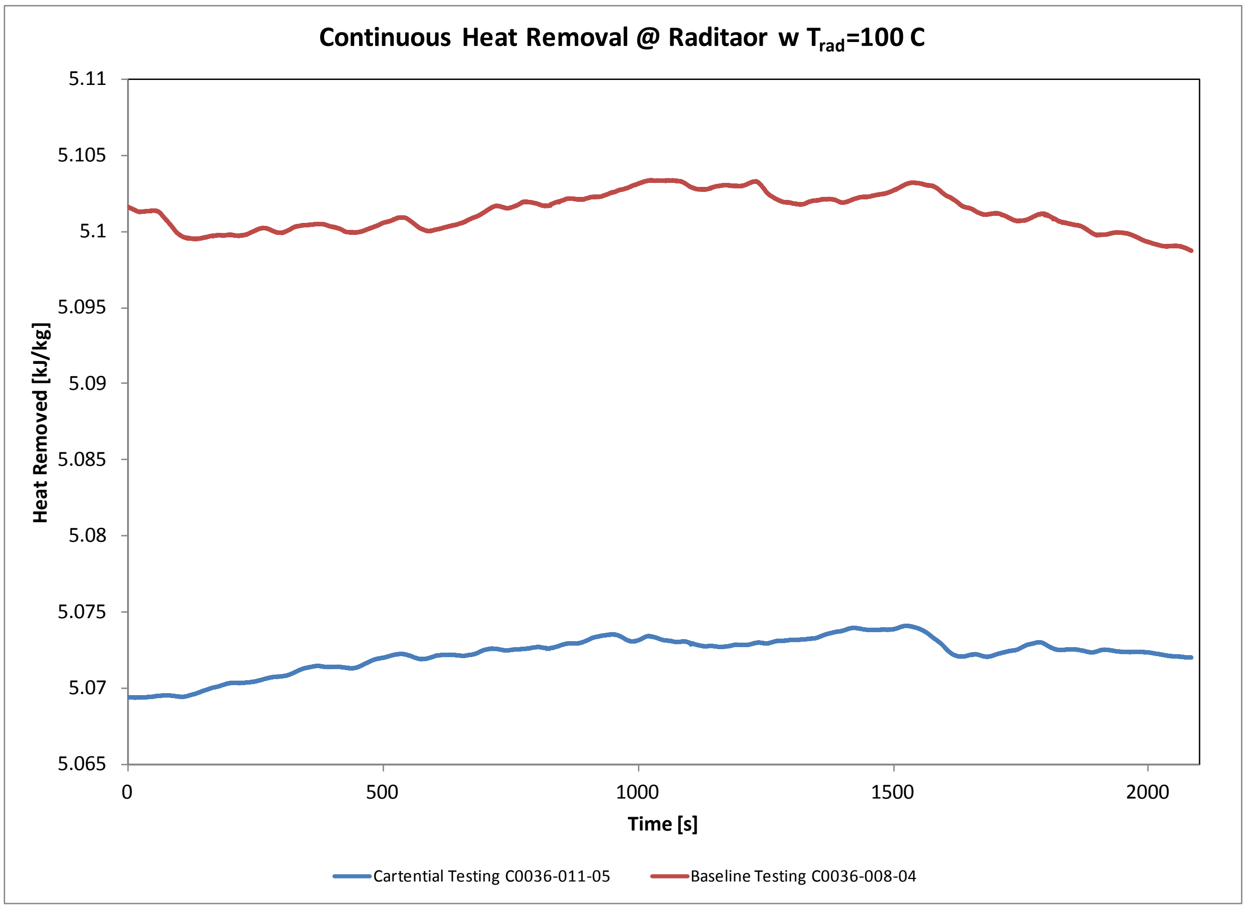

Figure 13 Heat Removal Capacity of Ambient Air

Considering that the "Cartential®" additive is a cooling system agent, data analysis was focused on the potential gains that could be made available as a result of cooling system efficiency enhancements. To explain, if standard coolant was replaced by a liquid with higher heat removal capacity, a reduction in engine cooling fan engagement would likely result, all other conditions being equal. This would tend to exhibit itself as a disproportion in changes in three-test average shaft work as compared to changes in three-test averages of fuel consumption, as fan operation is accounted for in fuel consumption, but not for shaft work. Figure 13 illustrates comparison of single tests of baseline and "Cartential®" additive over the HHDDT test schedule. This data indicates that, even with reduced heat removal capacity, the "Cartential®" additive test case exhibited less NOx and fuel consumption than its baseline counterpart. The research team is currently evaluating the plausibility of this explanation by equating the reduced amount of fan operating time that would be necessary to effect a 5-6% reduction in fuel consumption. However, the WVU 5-Peak results do not support such an explanation, thus additional analysis is forthcoming.

In order to explain the difference in the fuel consumption values between baseline and "Cartential®" additive tests over the HHDDT test schedule, it is considered that in a traditional heavy duty diesel engine, wherein all the accessories are run by the engine crank shaft the fuel energy is dissipated approximately equally as useful work at the axle, heat energy lost to the coolant and ambient across different heat exchangers, and the remaining being lost as waste heat through exhaust. The useful work at the wheels is determined by the chassis dynamometer measurement as axle work, the heat lost through the coolant is determined by measuring the coolant flow rate, and the temperature difference between the radiator inlet and outlet, similarly for other heat exchangers, and finally the energy lost in the exhaust is determined by the species concentrations and thermal energy. With the above argument of energy distribution in a diesel engine, single test data from baseline and from the Cartential® additive test, which resulted in maximum reduction of NOx emissions as well as fuel consumption over HHDDT test cycle, is considered to explain the plausibility of enhanced heat removal capability of Cartential® additive.

Since the test vehicle did not have the capability of broadcasting temperature and flow related information of the coolant circuit, and with the shaft power being the same between baseline and Cartential® additive testing and negligible exhaust energy difference one could explain that the 6% fuel economy is largely due to energy lost to the cooling system. Models have estimated that one third of the total fuel energy lost in the coolant system can be further divided into 11% of energy being lost in the coolant system, 5% to the charge air cooler and the remaining to EGR cooling system at rated power. As it was suggested that the fuel economy improvement is due to the radiator fan operation, which is not accounted for the shaft work. The average fan power of 36” diameter fan is assumed to be 22kW and with inefficiencies it is estimated to be consuming approximately 28kW of power. If 11% of the fuel consumption difference between baseline and Cartential® additive test is considered to be due to fan operation time, this would result in reduced fan operation time by 394 seconds. Although, this time difference is within the total test time it would seem to be a disproportionately high amount of fan de-activation compared to baseline, perhaps suggesting other factors could be contributing towards reduction in fuel consumption.

It is noted that these are rudimentary estimates of fuel energy proportioning, without data from coolant system and fan operation absolute values cannot be determined. As a result it is recommended that additional tests be performed in an engine dynamometer test cell that provides for higher resolution and additional combustion performance information. Engine test cell could also provide de-coupling of the fan from the engine system further enabling to draw conclusions regarding factors that may attribute to reduction in fuel consumption.

6. Recommendations

WVU had originally proposed the workplan, with a limited number of tests, in order to reduce sponsor's costs for preliminary data. In light of the results obtained, the research team would recommend that additional tests be performed in order to further enhance these preliminary findings. For instance, day-to-day variability, resultant from a variety of factors including, but not limited to, ambient temperature, barometric pressure, and ambient humidity, should be addressed. WVU follows CFR standards for humidity correction, however these singular corrective measures will likely not account for all variability. Revisiting baseline performance data at the conclusion of the test configuration tests, would have perhaps offered some clarification to these data. It is recommended that, in light of the limited number of tests, and that additive test data was collected from only a single test vehicle, additional test data be collected on a variety of vehicles in order to clarify the results afforded by this study.

In addition, engine test cell research could be conducted with an equivalent vehicle cooling system by having a liquid to liquid heat exchanger consisting of equal volume of coolant as in the real world engine operation and thereby, de-coupling the fan and radiator system. Ambient air temperatures could be controlled more accurately, and test-to-test repeatability is significantly improved due to elimination of driver performance as well as combustion air quality.