Fuel Consumption and Emissions Report
for
CARBON CHAIN TECHNOLOGIES LIMITED

Testing 2ct Treated Diesel Fuel

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
COLLEGE STATION, TEXAS

June 2010

Fuel Consumption and Emissions Report for CARBON CHAIN TECHNOLOGIES LIMITED

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Prepared by

Texas Transportation Institute

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INTRODUCTION

Recent increases in the cost of petroleum-based fuels have resulted in an unprecedented interest in products that have the potential to improve fuel economy. At the request of Carbon Chain Technologies Limited (CCT), the Texas Transportation Institute (TTI) in conjunction with Sensors Inc. (the research team) conducted a series of fuel economy and in-use emissions tests of class 8b Heavy-Duty Diesel Vehicle (HDDV-8b). The purpose of this testing program was to evaluate the performance of the CCT combustion enhancer[1], known as 2ct on a HDDV-8b truck.

A test procedure based on the TMC[2]/SAE[3] Type II test procedure (SAE J-1321) was developed and used to evaluate the product's effectiveness in improving the fuel economy of HDDV-8b trucks. A similar procedure was developed and utilized to evaluate the impact of 2ct on the exhaust emissions.

To facilitate the tests, fuel consumption in a test vehicle was compared to fuel consumption in an identical control vehicle before and after 2ct combustion enhancer treatment at the recommended dose rate of 1:500 vol/vol. The manufacturer claims that the product will improve fuel economy and reduce exhaust emissions after two tanks full of treated fuel. For this test, the research team ran the test vehicle for a notional 1,000 miles to ensure that there was no question of conditioning not having been achieved. This report deals with the two pertinent test segments according to SAE J-1321: – untreated baseline testing, and – post treatment. Each segment of testing consisted of gravimetric fuel consumption testing followed by emissions testing using SEMTECH-DS manufactured by Sensors Inc. and Axion manufactured by Clean Air Technology International Inc. (CATI) portable emissions measurement units (PEMS).

TEST PROTOCOL

Fuel Consumption Testing

SAE J-1321 is currently the only approved standardized testing procedure in the U.S. for comparing the in-service fuel consumption of two conditions of a test vehicle when the tested component (in this case a fuel technology) requires a period of time for replacement or modification (e.g. on-road conditioning). Based on SAE J-1321, fuel consumption can be measured by using a portable weigh tank method (gravimetric method) or utilizing a fuel flow meter (flow meter method).

The fuel consumption method determines the overall accuracy achievable with this procedure. The gravimetric method provides an accuracy of ±1% (i.e. the actual improvement is within ±1% of what is observed). The gravimetric method is by far the most widely used fuel consumption measurement method because of its relative simplicity, accuracy, and consistency.

To insure the validity of test results, the following four basic rules must be applied in conducting tests as well as interpreting the results:

[1] The client defines its 2ct combustion enhancer as a petroleum fuels technology comprising hydrocarbon components that is mixed with fuel to improve the combustion burn, of all grades of petroleum fuel.
[2] Technology and Maintenance Council (TMC) of American Trucking Association (ATA).
[3] Society of Automotive Engineers (SAE).

1. "The test routes and cargo weight should be representative of actual operation."
2. "A single test is inconclusive regardless of the results. A single test should be taken as an indicator. Test results must be repeatable to have validity."
3. "The more variables controlled, the more conclusive the results."
4. "All test procedures or methods are accurate within prescribed limits."

The research team used the SAE J-1321 gravimetric method for this study.

SAE J-1321[4]

The Joint TMC/SAE fuel consumption test procedure – Type II – SAE J-1321 is the proposed test protocol for this vehicle class. The procedure includes the following elements. A more detailed description of this testing procedure is provided in Appendix A.

- Two vehicles are used for the test — a control vehicle ("Vehicle C") and a test vehicle ("Vehicle T"). Vehicle C is the control vehicle and is not modified in any way during the entire test and is dedicated to the test until the entire test process is complete. This includes load, trailer, and driver.
- The gravimetric method uses a portable auxiliary tank of at least 16 gallons to measure the fuel consumption. The tank is topped off and weighed before the test run and weighed again after the completion of the test run during which the vehicles perform the same driving pattern.
- The fuel consumption calculations are based on T/C ([vehicle T]/[Vehicle C]) ratios. A T/C ratio is the ratio of the quantity of fuel consumed by the test vehicle (vehicle T) to the quantity of fuel consumed by the control vehicle (vehicle C) during one test run.
- The testing consists of two sets of tests — baseline and treatment. Each set is composed of a minimum of three valid T/C ratios according to SAE J-1321.
    - Baseline: to establish baseline fuel consumption of the test vehicle running on untreated fuel (vehicle T); and
    - Treatment: to establish the fuel consumption of the test vehicle after modification.
- Valid T/C ratios must fit within a 2% band. This means that the lowest T/C ratio cannot be more than 2% below the highest.
- For each test run weather data is recorded. This includes wind velocity, wind direction, temperature, and humidity.
- Both vehicles must follow the warm-up process according to J-1321.
- Vehicle "T" begins the test first and vehicle "C" follows after five minutes.
- Observers are assigned to each vehicle to monitor and record the progress of the test vehicles at assigned points along the track to ensure that the vehicles complete the runs within the set tolerances. Time duration for all test runs must be repeated within ±0.5 percent. During the test run, which requires one hour to complete, repeatability must be within 18 seconds.

The test protocol for this testing effort was according to SAE J-1321 as described above. It must be noted that under SAE J-1321 test procedure, it is not required to go back to baseline condition after the treatment testing is done. SAE J-1321 requires using a portable tank of at least 16

[4] SAE International, Joint TMC/SAE Fuel Consumption Test Procedure – Type II, SAE Surface Vehicle Recommended Practice J-1321, 1986.

gallons. Four 19-gallon auxiliary tanks (two for each vehicle) were used for this purpose. This enabled the research team to minimize the time required for refueling between each run. The tanks were equipped with filters to minimize the possibility of fuel and 2ct evaporation from the tanks (Figure 1).

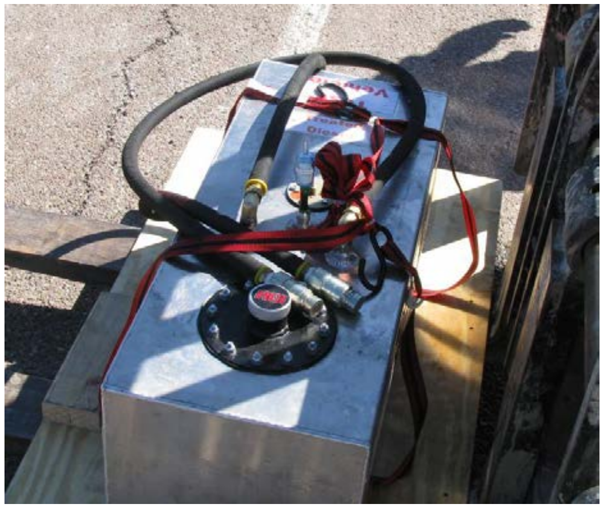

Figure 1. Auxiliary Tank Used in the Gravimetric Fuel Consumption Measurement.

After the baseline tests were completed, the test vehicle was subjected to a period of approximately 1,000 miles running on the treated fuel. CCT representatives monitored the conditioning after this period and confirmed the completion of conditioning.

Test Procedure for Emissions Testing

Emissions of total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NOx), and particulate matter (PM) were measured using two Portable Emissions Measurement System (PEMS) units. The SEMTECH-DS was used to measure THC, CO, CO_2, and NOx emissions, and PM emissions were measured using the Axion system.

The SEMTECH-DS unit includes a set of gas analyzers, an engine diagnostic scanner, a Global Position System (GPS), an exhaust flow meter (EFM), and embedded software. The gas analyzers measure the concentrations of NOx (nitric oxide [NO] and nitrogen dioxide [NO_2]), THC, CO, CO_2, and oxygen (O_2) in the vehicle exhaust. By using the electronic vehicle EFMs for measuring exhaust mass flow, the SEMTECH post-processor application software uses the measured exhaust mass flow information to calculate exhaust mass emissions for all measured exhaust gases.

The Axion system has a laser light scattering detector and a sample conditioning system to measure PM concentration in the exhaust. The PM concentrations were converted to PM mass emissions using concentration rates produced by the CATI unit and the exhaust flow rates produced by the SEMETCH-DS unit.

The test procedure developed for this investigation follows the preparation and calculation methods of SAE J-1321. The following describes this testing method. The emissions testing was performed after completing the fuel efficiency testing. Both the control vehicle (Vehicle C) and the test vehicle (Vehicle T) were used for testing similar to fuel consumption testing. Both vehicles followed the warm-up process according to SAE J-1321. Vehicle “T” began the test first and vehicle "C" followed after five minutes; both vehicles were driven at least four times according to the following driving pattern – drivers were asked to accelerate from 0 mph to 68 mph and maintain their speed for one lap around the track and then stop.

For both vehicles, the emissions rates (g/s) at 68 mph were cleaned and used to build a virtual drive cycle consisting at least 250 seconds readings of emissions. The average grams of emissions (g/h) for this synthetic drive cycle were used to calculate the changes in emissions of the test vehicle. The CO_2 results were calculated according to the calculation procedure of SAE J-1321 (i.e., T/C ratios were the base of the calculations). For other pollutants, only the readings from the test vehicle were used to calculate the changes. The results are presented as the percent difference of emissions rates.

Two sets of tests were performed: baseline and treatment. Each set was composed of a minimum of three runs: – Baseline: to establish baseline emissions rates of the test vehicle running on untreated fuel (vehicle T); and – Treatment: to establish the emissions rate of the test vehicle after treatment.

TESTING INFORMATION

Test Facility

The test was conducted at the Pecos Research and Testing Center (RTC) outside Pecos, Texas. The city of Pecos is located on the Pecos River at the northern border of the Chihuahua Desert. It is 208 miles east of El Paso, 392 miles west of Fort Worth on I-20, and about 80 miles from the Midland-Odessa International airport. The dry, seasonable climate of Pecos enables year-round research and testing. The Pecos RTC operates as an academic-industry collaboration among the TTI, Applied Research Associates (ARA), and the Pecos Economic Development Corporation (PEDC).[5]

The total size of the facility is 5,800-acres and is comprised of a nine-mile, three-lane circular high speed track for speeds up to 200 mph, an El Camino road course, serpentine track, skid pad, flint stone road, cobblestone road, and gravel road. For this high-speed study, the nine-mile circular track was used. Figure 2 shows the location of the Pecos facility as well as an aerial view of the test tracks.

[5] Pecos Economic Development Corporation. http://www.pecos.net/news/pedc/whoweare.htm, accessed June 2008.

Figure 2. Location and Layout of the Test Track.

Test Fuels

Regular diesel fuel was purchased and stored in the Pecos facility prior to the testing. This fuel was used as "base fuel." A specific portion of this fuel was mixed with 2ct combustion enhancer at the recommended ratio of 1:500 (volume-to-volume) and was used as "treated fuel." The mixing was performed by representatives of TTI under supervision of CCT. Treated fuel was used for conditioning and treatment testing.

Test Vehicles

Two 2008 model year class 8b diesel trucks were selected for testing. Table 1 shows the information for these vehicles. Figure 3 shows both vehicles with SEMTECH electronic flowmeter (EFM) installed on them.

Table 1. Test and Control Vehicle Information.

	Control Vehicle (C)	**Test Vehicle (T)**
Make / Model	International / ProStar 1351	International / ProStar 1351
Model Year	2008	2008
Type	Class 8b Diesel Truck	Class 8b Diesel Truck
Trailer	flatbed	flatbed
Transmission	Eaton – 10 Speed	Eaton – 10 Speed
Measured G.V.W.	68,000	68,000
Engine	Cummins ISX 400 ST	Cummins ISX 400 ST
Power / Torque	400(hp) / 1450 (lb.ft)	400(hp) / 1450 (lb.ft)

Both vehicles were equipped with Exhaust Gas Recirculation (EGR) and Diesel Particulate Filters (DPF). EGR is a NOx emissions control device working by re-circulating a portion of exhaust gas back to the engine cylinders. EGR can reduce NOx emissions as high as 50 percent. DPF is a device developed to reduce PM emissions in diesel engines' exhaust gases. DPF works by trapping and collecting PM emissions and burning them. DPF can achieve PM removal efficiencies higher than 90 percent[6].

Figure 3. SEMTECH Electronic Flowmeter Installed on Tested Vehicles.

Test Cargo

According to SAE J-1321, the vehicles under test should have a cargo with weights representative of the fleet operations and within the capability of the vehicles. To comply with this criterion, both control and test vehicles were loaded with concrete barriers to reach the gross vehicle weight of 68,000 lbs. Weight Certificates for both vehicles were obtained at the Flying J Weighbridge in Pecos, Texas.

Drive Cycles

Both control and test vehicles were tested according to the explained test procedures. In order to maintain the consistency between test runs, the vehicles were driven according to the following drive cycles. Prior to testing, a warm-up driving period of 45 miles was executed for both vehicles.

Test Drive Cycles

The proposed drive cycle for the SAE J-1321 fuel consumption portion of the study consisted of the following four basic elements for both vehicles:

- normal acceleration from stop-to-68 mph;

[6] Lee, D. W., Zietsman, J., Farzaneh, M., Protopapas, A., and Overman, J. (2008). "Characterization of In-Use Emissions from TxDOT's Non-Road Equipment Fleet – Phase 1 Report." Texas Transportation Institute, Texas A&M University System, College Station, Texas.

- maintaining the 68 mph speed and driving around the track for five laps (45 miles);
- at the end of the fifth lap, stop at the same spot that the test had began; and
- keep the engine running at idle for one minute, and then shutting down the engine.

A separate drive cycle was developed for emissions measurement components. The drive cycle consisted of intervals of 68-mph steady-state speed. The drive cycle consisted of the following elements:

- accelerate from stop-to-68 mph;
- maintain 68 mph for one lap;
- at the end of lap, decelerate and stop.

Analysis Drive Cycle

A synthetic drive cycle was used for data analysis. The drive cycle consists of normalized (to speed) emissions data for a pre-selected section of the track at speed of 68 mph. The pre-selected section included the most stable portion of driving around the track. The GPS coordinates for boundaries of this section were determined and only data points that were in between them were used in the analysis. In general, these selected data points exclude the first two minutes and last one minute of driving at 68 mph. Emissions of PM and NOx tend to be stabilizing during the first couple of minutes of driving at a steady-state speed. By excluding this period from the data, only the most stabilized portion of data was used for analysis.

The selected emissions rates data were normalized based on that target speed according to the following equation:

$$nE_{ij} = oE_{ij} \times \frac{u_j^T}{u_j^O} \quad [1]$$

Where:

nE_{ij} = normalized emissions rates for pollutant i at speed u_j;

oE_{ij} = observed emissions rates for pollutant i at speed u_j;

u_j^T = target speed (68mph); and

u_j^O = observed speed.

RESULTS

Data Quality Control

The collected data for both sets of tests (SAE J-1321 and emissions measurement) were reviewed by the research team to identify any possible problem within the data. The vehicles, fuel tanks, and data collection sheets were marked clearly to prevent switching fuel and testing equipment between the control and test vehicle. TTI and Sensors both checked the emissions independently to make sure that the serial numbers of PEMS units and their components recorded in the data files match the vehicles for all cases. In addition to routine quality check of data (data time alignment, calibration records, and engine performance record), Sensors Inc. staff conducted a comprehensive quality check on their PEMS unit in the factory to make sure that all the analyzers were working correctly and the collected data are valid.

Fuel Consumption

A work plan was developed based upon the SAE J-1321 Recommended Practice (*In-Service Fuel Consumption Test Procedure – Type II*). In this procedure, fuel consumption measurements in a test vehicle (Vehicle T) are compared to measurements from a control vehicle (Vehicle C) before and after treatment. The difference between the T/C ratios of before and after treatment cases are used to calculate a fuel savings percentage presumably resulting from the treatment.

A test run was defined as five laps (45 miles) of continuous driving on the high speed test track at constant speed of 68 mph. Vehicle operation was synchronized to ensure identical duty cycles. Both vehicles were outfitted with removable fuel tanks (shown in Figure 1) that were weighed before and after each test run to determine the amount of fuel consumed. The temperature of fuel was also measured during weight measurements. The T/C ratios for all test runs were calculated, and the first three ratios that fell within SAE J-1321 prescribed 2 percent filtering band were used to compute an average value representing each segment of testing.

Table 2 shows the data for the three T/C ratios that were used in the calculations. Baseline testing was performed on November 3, 2008. Treatment testing was conducted on November 7, 2008.

Table 2. Gravimetric Fuel Consumption Results.

	Base Condition (11/03/2008)					
	RUN 1		RUN 2		RUN 3	
	Control Veh.	Test Veh.	Control Veh.	Test Veh.	Control Veh.	Test Veh.
Fuel Used (lb)	41.86	43.64	41.8	44	42.49	43.92
Distance (mi)	45	45	45	45	45	45
T/C Ratio	1.043		1.053		1.034	
Min Acceptable T/C Ratio	1.022					
Average T/C Ratio	1.043					
	After Treatment (11/07/2008)					
	RUN 1		RUN 2		RUN 3	
	Control Veh.	Test Veh.	Control Veh.	Test Veh.	Control Veh.	Test Veh.
Fuel Used (lb)	50.34	46.14	49.61	45.62	50.32	45.93
Distance (mi)	45	45	45	45	45	45
T/C Ratio	0.917		0.92		0.913	
Min Acceptable T/C Ratio	0.895					
Average T/C Ratio	0.917					
Fuel Saved (%)	**12.1%**					
Improvement (%)	**13.7%**					

Results in Table 2 show that based on the T/C ratios, the addition of 2ct combustion enhancer to diesel fuel produced an improvement of 13.7 percent under the SAE J-1321 test procedure. The *fuel saved* and *improvement* values in Table 2 are calculated according to SAE J-1321 as following:

% Fuel Saved = (Ave. Baseline T/C – Ave. Treatment T/C) ÷ Ave. Baseline T/C [2]

% Improvement = (Ave. Baseline T/C – Ave. Treatment T/C) ÷ Ave. Treatment T/C [3]

Factors Impacting Fuel Efficiency

The fuel economy of a vehicle is a function of a many factors including the fuel, various vehicle parts including the engine, as well as external conditions, such as weather and wind. The SAE J-1321 testing procedure requires both a test vehicle and a control vehicle so that all external factors are normalized and only the effect of the test product is highlighted. It is however, not unusual to experience significant differences in fuel consumption of the control vehicle between test days if external factors differ between those days.

For this project, base fuel efficiency tests were performed according to SAE J-1321 on 11/3/2008 and after treatment, fuel efficiency tests were conducted four days later on 11/7/2008. Weather and wind conditions differed significantly between these two days as Table 3 demonstrates.

Table 3. Prevailing Conditions during Testing

	Base Condition (11/3/2008)											
	RUN 1				**RUN 2**				**RUN 3**			
	Control Veh. [C]		**Test Veh. [T]**		**Control Veh. [C]**		**Test Veh. [T]**		**Control Veh. [C]**		**Test Veh. [T]**	
	Start	**Finish**	**Start**	**Finish**	**Start**	**Finish**	**Start**	**Finish**	**Start**	**Finish**	**Start**	**Finish**
Temp. (F)	80		80		81		81		82		82	
Humidity (%)	28		28		32		32		31		31	
Barometric Pressure (in)	29.75		29.75		29.74		29.74		29.73		29.73	
Wind Speed	6		6		7		7		6		6	
Wind Direction	E		E		E		E		E		E	

	After Treatment (11/7/2008)											
	RUN 1				**RUN 2**				**RUN 3**			
	Control Veh. [C]		**Test Veh. [T]**		**Control Veh. [C]**		**Test Veh. [T]**		**Control Veh. [C]**		**Test Veh. [T]**	
	Start	**Finish**	**Start**	**Finish**	**Start**	**Finish**	**Start**	**Finish**	**Start**	**Finish**	**Start**	**Finish**
Temp. (F)	55		55		58		58		61		61	
Humidity (%)	18		18		17		17		16		16	
Barometric Pressure (in)	30.21		30.21		30.19		30.19		30.15		30.15	
Wind Speed	10		10		13		13		8		8	
Wind Direction	NW		NW		NW		NW		NW		NW	

Table 3 shows that the temperature during the after treatment testing was much lower, relative humidity was lower, barometric pressure was almost the same, wind speed was higher, and wind direction was quite different than during the base conditions.

Wind Speed

Of all these external factors, wind speed has the most significant effect on fuel efficiency. Even though a circular track was used, Figure 4 illustrates that any wind direction has a detrimental effect on fuel efficiency.

Figure 4. Illustration of the Effect of Wind Speed on a Circular Track

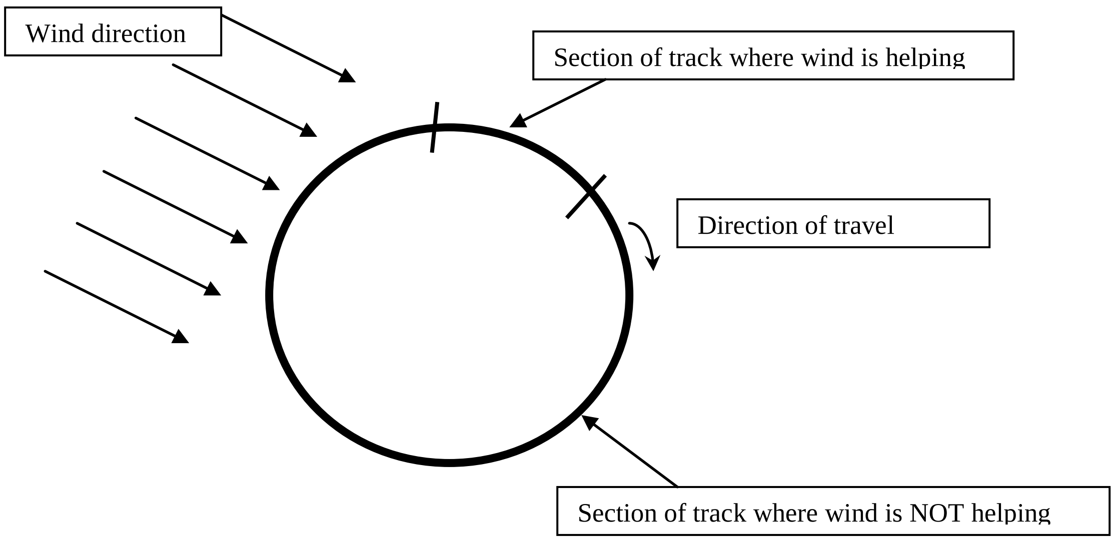

Table 4 shows the significant impact of a headwind on fuel efficiency.[7] For example, the table shows that when a vehicle travels at 70 mph and encounters a headwind of 20 mph, its fuel consumption drops from 40 mpg to 28 mpg.

Table 4. Fuel Economy versus Wind Speed

Vehicle Speed (mph)	**MPG at Selected Headwind Speeds**			
	0 mph wind	**5 mph wind**	**10 mph wind**	**20 mph wind**
40	74	67	60	49
50	60	54	49	41
60	49	45	41	34
70	40	41	37	28
80	34	34	31	24

Temperature

All other things being equal, a vehicle will have slightly better fuel consumption in hot weather. Hot air is less dense than cold air; therefore, the engine breathes less hot air per revolution and requires less fuel. Also, hot air provides less resistance to movement, so the engine does not use

[7] http://pics.tdiclub.com/data/516/Fuel_Economy_2.pdf

as much fuel to maintain motion through the air. It has been documented that in hot weather, the lubricants in the engine and drivetrain run hotter and thinner, again requiring less power or fuel. Finally, tire-rolling resistance is also less in hot weather compared to cold weather.

Barometric Pressure

Lower barometric pressure means less resistance on the vehicle and therefore improved fuel efficiency. Additioinally, barometric pressure affects the density of the air entering the engine and ultimately the air/fuel ratio which can affect fuel consumption.

Relative Humidity

No evidence was found that relative humidity significantly influences fuel economy.

Discussion

Several external factors can affect fuel efficiency. The largest of these factors are wind speed and temperature with wind speed being the largest contributor. Considerable differences in wind speed and temperature were observed and recorded between the base test day and after treatment test day. The difference in fuel consumption of the control vehicle between those days was likely caused by the change in wind speed and temperature. It should be noted that studying effect of external factors on fuel efficiency was outside the scope of this study.

The SAE J-1321 test procedure is designed to have both a test vehicle and a control vehicle to normalize these factors between base conditions and after treatment conditions. Only the effect of the treated fuel is highlighted through the SAE J-1321 test.

Emissions

The emissions testing work plan was developed in a similar manner to the fuel consumption testing. This work plan is explained in detail in the *Analysis Drive Cycle* section. This section also explains the construction of synthetic drive cycles and the data cleaning step. The average emissions of each pollutant were calculated for the synthetic cycle. For CO_2 emissions, these values for a test vehicle (Vehicle T) are compared to measurements from a control vehicle (Vehicle C) before and after treatment. The difference between T/C ratios of before and after treatment cases are used to calculate an improvement percentage presumably resulting from the treatment. For the other pollutants, the differences were calculated based on the test vehicles readings.

A test run was defined as one complete cycle at cruise speed of 68 mph on a pre-selected section of the high-speed test track. Similar to fuel consumption testing, vehicle operation was synchronized to ensure identical duty cycles. PEMS units (SEMTECH-DS and Axion) were installed on both vehicles.

Table 5 and Table 6 show the summary of the emissions results for CO_2, CO, and NOx. Results in Table 5 are based on T/C ratios while results of Table 6 are based on average measured emissions for the analysis drive cycle. Baseline emissions testing was performed on November 4, 2008, after which time the treatment fuel was applied and the process of conditioning was initiated.

Table 5. CO_2 Emissions Results for the class 8b HDD Truck.

	Baseline T/C		Treatment T/C			*t*-test
Pollutant	**Average**	**Coeff. Var.**	**Average**	**Coeff. Var.**	**Improvement**	**p-value[8]**
CO_2	1.061	0.8%	1.004	0.9%	**5.4%**	3.41×10^{-5}

Table 6. CO and NOx Emissions Results for the class 8b HDD Truck.

	Baseline (g/h)		Treatment (g/h)			*t*-test
Pollutant	**Average**	**Coeff. Var.**	**Average**	**Coeff. Var.**	**Improvement**	**p-value[7]**
CO	56.78	6.2%	60.52	6.0%	**-6.6%**	0.1339
NOx	297.50	3.2%	303.68	4.1%	**-2.1%**	0.4161

The improvement percentages in Table 5 and Table 6 are calculated according to the SAE J-1321 calculation method (Equation 3). Positive improvement values mean a decrease in the total emissions for the cycle while a negative value indicates an increase of the pollutant. To test whether the average differences are statistically significant, an unpaired *t*-test was employed. The results of this test are listed in the right-most column of Table 5 and Table 6 and discussed in the Data Quality section.

It was observed that CO_2 comprised more than 99 percent of all the carbon-based emissions of both vehicles. CO_2 is the result of fuel combustion and correlates with fuel consumption. Results in Table 5 show an improvement of 5.4 percent for CO_2 emissions. This improvement is statistically significant at the 95 percent degree of confidence level. The difference between these results and the fuel consumption readings of Table 2 from gravimetric SAE J-1321 may be the result of the following factors:

[8] The results of this column are discussed in the Data Quality section.

- The gravimetric SAE J-1321 testing consisted of three separate test runs each comprising five complete laps, while the emissions measurement test was conducted on less than one complete lap between two points approximately 5.5 miles apart on the track.
- The emissions measurement test was performed at a different time under different environmental conditions; e.g. different temperature, humidity, and wind conditions.

The results of Table 4 indicate a statistically insignificant change in CO and NOx emissions rates at the 95 percent degree of confidence level. For both Control and Test vehicles, CO emissions rates were found to be approximately 25 times less than EPA emissions standards for HDDVs. The PM emissions rates were found to be very low and close to the detection limit of Axion emissions measurement unit. Because of this, the collected data were inconclusive and not reported here.

In the combustion of hydrocarbon fuels, oxides of nitrogen (NOx) are formed from the dissociation of ambient nitrogen above 2000 deg K at a rate that increases with pressure, temperature, and residence time. Increasing these parameters also result in higher combustion efficiency and therefore lower fuel consumption and CO_2 emission level. This trade-off between NOx and carbon emissions is well known and has been a long standing challenge for all industries with emissions regulations[9].

Data Quality

An unpaired *t-test* was employed to determine whether the average differences are statistically significant. A *t-test* is a statistical hypothesis test to test whether the means of two normally distributed populations are equal. Given two data sets, each characterized by its mean, standard deviation and number of data points, one can use a *t-test* to determine whether the means are distinct.

In statistics, a result is called *statistically significant* if it is unlikely to have occurred by chance. A *statistically significant difference* simply means there is statistical evidence that there is a difference. It does not mean the difference is necessarily large, important, or significant in the common meaning of the word. A p-value less than 0.05 in this column indicates a statistically significant difference between baseline and after treatment at the 95 percent degree of confidence level. In contrast, a p-value larger than 0.05 indicates that the difference between the two sets of data is not statistically significant at the 95% degree of confidence level.

ACKNOWLEDGEMENT

A number of organizations and individuals contributed to the success of this investigation. The support of Applied Research Associate (ARA) and Pecos Research and Testing Center (RTC) was critical. Local coordination was provided by Mr. Ben Carrasco of Pecos RTC. Special thanks to Mr. JoJohn Vegas and his colleagues at Mesilla Valley Transportation (MVT) who provided the drivers and trucks. Finally, the authors thank the following TTI staff for their hard

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[9] Payri, F., et al. (2006) Combustion and Exhaust Emissions in a Heavy-Duty Diesel Engine with Increased Premixed Combustion Phase by Means of Injection Retarding, Oil & Gas Science and Technology, Vol. 61, No. 2, 247-258.

work in collecting the data used in this investigation: Lisa Nimocks, Edward Brackin, Tara Ramani and Monica Beard-Raymond.

SUMMARY

In summary, the results presented in this report demonstrate that based on the SAE J-1321 procedure the diesel fuel that was treated with 2ct combustion enhancer improved the fuel consumption of the tested vehicle by 13.7%. The results also show statistically significant changes of carbon dioxide (CO_2). CO_2 was reduced by 5.4%. Changes in carbon monoxide (CO) and oxides of nitrogen (NOx) levels were found to be statistically insignificant. Because the vehicles were equipped with DPF, the PM emissions levels were very low and inconclusive.

Joe Zietsman, Ph.D.
Director, Center for Air Quality Studies
Texas Transportation Institute

APPENDIX A

DESCRIPTION OF SAE J-1321 TESTING PROCEDURE

The following section provides a detailed explanation of SAE J-1321 testing procedure as related to testing of 2CT product

Scope: SAE J-1321 provides a standardized test procedure for comparing the in-service fuel consumption for two conditions of a test vehicle. An unchanging control vehicle is run in tandem with the test vehicle to provide reference fuel consumption data. The test procedure is especially suitable for testing components which require substantial time for removal and replacement, or modification.

The result of a test using SAE J-1321 procedure is the percent difference in fuel consumption between the two test vehicles or the difference in fuel consumption of one vehicle in two different test conditions.

The fuel measurement method is a very important factor in determining the overall accuracy achievable with this procedure. The gravimetric weighing method, provides the best overall test accuracy and, based on test experience, the accuracy will be within +1% (for example, 3% measurement improvement can be from 2-4% actual improvement).

The following four basic rules must be applied to SAE J-1321 test procedure to insure test result validity:

1. “The test routes and cargo weight should be representative of actual operation.”
2. “A single test is inconclusive regardless of the results. A single test should be taken as an indicator. Test results must be repeatable to have validity.”
3. “The more variables controlled, the more conclusive the results.”
4. “All test procedures or methods are accurate within prescribed limits.”

Definitions

Vehicles “C” and “T”: The vehicles being used in testing are identified “C” (for control vehicle) and “T” (for test vehicle). This identification applies to the vehicles and all associated equipment, including the trailer. Vehicle “C” is not modified in any way during the entire test. Control vehicle fuel consumption is used to generate control data. It is required that Vehicle “C” be dedicated to the test and not used for other purposes for the entire testing period. The purpose of Vehicle “C” is to provide a reference for the test route, ambient conditions, and test procedures for each test run. Vehicle “T” is used to evaluate tested components.

Test Run: A test run is defined as a complete circuit of the test route. A test run always starts and ends at the same point. The quantity of fuel consumed by a vehicle on a test run is called a data point.

T/C Ratio: is the ratio of the quantity of fuel consumed by the test vehicle during one test run to the quantity of fuel consumed by the control vehicle during the same test run.

Test Segments: A complete test consists of a baseline and a test segment. A baseline segment is composed of a minimum of three T/C ratios within 2% of each other before modification. A baseline segment establishes baseline fuel consumption of test vehicles. A test segment is also composed of a minimum of three valid T/C ratios within 2% of each other after modifications are made to the test vehicle. A test segment establishes the fuel consumption of the test vehicle after modification. Sufficient information must to be recorded to identify the vehicles under test and the test route.

Test Procedure

Vehicles “C” and ‘T” must follow the same start and warm-up procedures Warm-up speeds should be similar to test speeds. A minimum warm-up period of 1 hour is required and at colder temperature longer warm-up periods may be required. For each run the following data must be recorded: weather, road conditions, traffic conditions, wind velocity, wind direction, temperature, humidity, and barometric pressure. Drivers should remain with their respective vehicles throughout the complete test.

Vehicles “C” and “T” are moved to the starting point and parked with engines stopped. Portable fuel tanks are topped off, weighed, and the weight recorded. To insure consistent fuel grade and quality, vehicles must be fueled from the same designated dispenser for the entire duration of testing.

The driver of Vehicle “T” should start the engine and leave the starting point on the test route. After approximately 5 minutes, the driver of Vehicle “C” should start the engine and leave on the same route. The purpose of this 5-minute interval is to insure that vehicle “T” will not impose an artificial performance limit on the vehicle C and will also allow fueling between runs without disproportionate cooling. Cool-down periods at start of the test and between runs should not exceed 5 minutes.

Observers are used to record time on test runs and accompany each driver. Observers should record a minimum of ten elapsed time recordings on each run. Observers must also record the time the vehicle is stopped at any point on the test route other than at the start and finish point. If required, the observer is to coach the driver, making sure that the vehicle is operated as described in the pre-determined driving cycle.

At the end of each test run, each vehicle must stop at the start point and engines be idled for 1 minute and then shut down. After all data are recorded, the next test run should be started by repeating according to above procedure. All test runs must be repeated within ±0.5% of each other; i.e. for a run which requires 1 hour to complete, all the test runs must be within ±18 seconds.

After the baseline segment is complete, the test vehicle is then modified and a test segment is run according to the above procedure. The test results are calculated from the comparison of baseline and test segments. “A single test is inconclusive regardless of the results. A single test should be taken as an indicator. Test results must be repeatable to have validity.”

The overall accuracy of properly conducted tests using portable tank weigh methods are considered to be within 1%. The same portable scales must be used to weigh all portable tanks. The scale should be protected from winds. A known deadweight should be used for checking scales before each series of readings. The portable scales should stay in the same place between the initial and final weighing of a given test run.