Program for Advanced Vehicle Evaluation

PAVE

at AUBURN UNIVERSITY

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Report on

Strataclear™ CO_2 Reducer Removal Efficiency and Fuel Economy Impact

Conducted for

RYNCOSMOS, LLC
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ABSTRACT

The Program for Advanced Vehicle Evaluation (PAVE) was established at Auburn University as a complementary research activity at the Pavement Test Track (www.pavetrack.com). In order to damage experimental pavements on the 1.7-mile test oval, it is necessary to run a fleet of heavy diesel trucks more than ¾ million miles per year. Closed operations at the Track provide a unique opportunity to study important vehicle research issues in a highly controlled and cost-effective manner. The purpose of this series of tests was to measure the effectiveness of a Strataclear™ CO_2 removal system installed in a diesel powered passenger car that was provided by the company that owns the patented technology (RYNCOSMOS, LLC).

The test vehicle was a 2006 Volkswagen Jetta equipped with a 1.9L turbo diesel engine. The odometer reading at the time of testing was approximately 79,000 miles. Except for the addition of the prototype exhaust treatment system, the car did not appear to be modified in any way. A prototype Strataclear™ CO_2 Reducer system was installed in the trunk of the vehicle prior to its delivery to Auburn University. Two Autologic exhaust gas analyzers were provided to allow for the measurement of CO_2 concentration before and after treatment, complete with a switching system that allowed exhaust gases to be diverted around the experimental treatment system. Two computers were installed in the back seat of the vehicle to collect real time data from the exhaust gas analyzers while the vehicle was being operated. Additionally, one of these same computers was used to simultaneously log data from a Ross Tech OBD-II interface for the purpose of estimating fuel consumption. The amount of fuel needed to facilitate the first series of test was weighed in order to calibrate OBD-II estimates.

The duty cycle on the Pavement Test Track provides a significant amount of variability that can be used to generate meaningful performance data. The due east-west straight sections are precisely 2600 feet long, connected with spiral-curve-spiral sections approximately 1900 feet in length. The east curve profile travels down a –0.5 percent grade, while the west curve profile travels up a +0.5 percent grade. The maximum side slope (i.e., super elevation) of both curves is 15 percent, which supports a design speed for the Track's heavy diesel trucks of approximately 46½ mph. Significantly higher speeds were possible with the test vehicle in this experiment. In order to measure CO_2 removal efficiencies over a broad range of operating speeds, the test vehicle used for this study was operated over a range of speeds with the cruise control engaged in 30 minute duty cycles.

After a one hour warm up period and a sensor reversal to ensure pre- and post-treatment emissions data were not biased, 30 minutes of emissions and OBD-II fuel economy data were logged at four different speeds (55 mph, 40 mph, 25 mph, and 0 mph) with one cartridge engaged. Following another warm up period, OBD-II data was collected again at 55 mph with the unit bypassed completely to determine fuel economy with no back pressure. Afterward, 55 mph data collection was repeated with two then four cartridges engaged to investigate the relationship between fuel economy and any back pressure that might be created by the CO_2 removal process. Finally, 55 mph testing was repeated, with treatment cartridges weighed before and after testing to gravimetrically verify that mass had been transferred from exhaust gases to the filter cartridges. Emissions data was collected during each phase of testing to provide for the calculation of CO_2 removal efficiency for all vehicle speeds and modes of operation.

Removal efficiency was calculated by dividing post-treatment CO_2 concentration by pretreatment concentration, subtracting the result from one, and multiplying by one hundred to express the final value as a percentage. In this manner, removal efficiency was calculated for the entire period of time the test vehicle was operated. This process was repeated at all speeds of vehicle operation. Removal efficiencies at the start of each run were observed to consistently exceed 95 percent, with performance declining over time. Rates of decline in removal efficiencies were observed to increase with speed, meaning the life of the cartridges was much shorter at higher speeds. Individual fuel economy measurements for each OBD-II measurement interval were combined to determine the average fuel economy for each lap of operation on the Pavement Test Track. The Minitab computer program (version 16) was used to perform a one-way analysis of variance (ANOVA) for the purpose of determining statistical differences in fuel economy for the various operational scenarios. Test runs made with the Strataclear™ CO_2 Reducer engaged and flow passing through two or more cartridges, as well as the run made with the system set for full bypass, were not found to be statistically different; however, the run made with the unit engaged and flow passing through only one cartridge did produce significantly lower fuel economy ($\alpha = 0.05$).

These data indicate that the prototype Strataclear™ CO_2 Reducer did effectively remove CO_2 from the exhaust of the test vehicle in a manner that did not have a negative impact on fuel economy, provided flow was passed through at least two cartridges. Additional testing using more rigorous methods may be used to improve the statistical significance of these conclusions. Future versions of the prototype system should be improved to provide sustained removal efficiency levels over longer duty cycles, especially at higher speeds. In order to facilitate commercial deployment, the technology will need to be packaged in a consumer friendly design and an infrastructure will need to be developed to support CO_2 recycling and cartridge reuse.

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INTRODUCTION

Concerns about climate change have made reductions in greenhouse gases a top international priority. Carbon dioxide (CO_2) is a greenhouse gas that is produced by human activity. At the request of RYNCOSMOS, LLC, the PAVE research program at Auburn University recently conducted a test of a prototype device that is designed to remove CO_2 from the exhaust gases of combustion vehicles. The purpose of the testing program described herein was to measure the effectiveness of the Strataclear™ CO_2 Reducer in treating exhaust gases from a vehicle that had been retrofitted with a prototype device. In addition to the primary objective of measuring the CO_2 removal efficiency at different speeds, a secondary objective was to determine if the use of the device had a negative effect on fuel economy.

TEST PROCEDURE

Research Vehicle

Because the test vehicle was retrofitted with an exhaust switching system that allowed the treatment CO_2 removal system to be turned off and on without stopping, it was possible to collect both control and treatment data with only one vehicle. The test vehicle, shown in Figure 1, was a 2006 Volkswagen Jetta equipped with a 1.9L turbo diesel engine. The odometer reading at the time of testing was approximately 79,000 miles. Except for the addition of the prototype exhaust treatment system, the car did not appear to be modified in any way.

Figure 1 – 2006 Volkswagen Jetta Test Vehicle with 1.9L Turbo Diesel Engine

A prototype Strataclear™ CO_2 Reducer system was installed in the trunk of the vehicle prior to its delivery at Auburn University. As seen in Figure 2, two Autologic exhaust gas analyzers were provided to allow for the measurement of CO_2 concentration before and after treatment. A switching system was also installed in the trunk that allowed exhaust gases to either be run through the Strataclear™ CO_2 Reducer system (for treatment data collection) or diverted without treatment (for control data collection).

Figure 2 – Prototype Strataclear™ CO_2 Reducer System Installed in Trunk

Two computers were installed in the back seat of the vehicle to collect real time data from the Autologic exhaust gas analyzers while the vehicle was being operated. Additionally, one of these same computers was used to simultaneously log data from a Ross Tech OBD-II interface. As seen in Figure 3, the upper computer was used to monitor data from a single Autologic exhaust gas analyzer, while the lower computer was used to log data from the other Autologic exhaust gas analyzer as well as the Ross Tech OBD-II interface. Prior to the collection of actual test data, the plumbing for the exhaust gas analyzers were reversed with the Strataclear™ CO_2 Reducer system engaged then bypassed in order to ensure that the system had not been tampered with to produce false positive results. The standard gas used to calibrate both exhaust gas analyzers prior to the test is shown in Figure 4.

Figure 3 – Onboard OBD-II and Emission Monitoring Computers

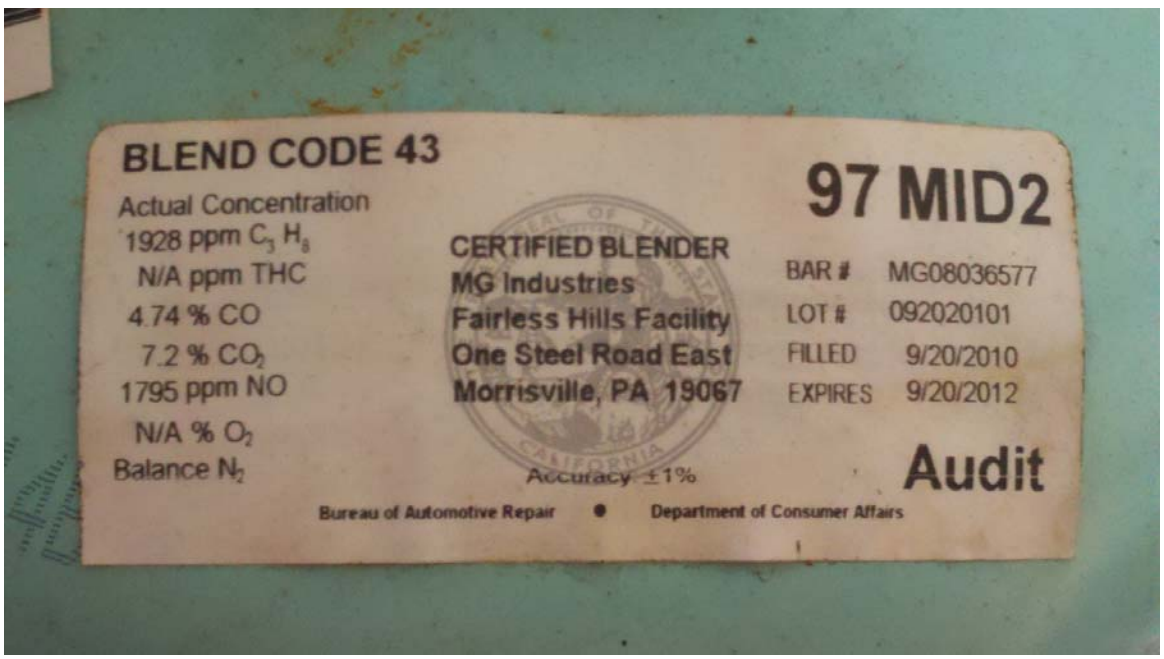

Figure 4 – Calibration Standard Gas for Autologic Exhaust Gas Analyzers

In order to improve the statistical value of inherently unreliable fuel consumption measurements derived from OBD-II data, the actual amount of fuel consumed on the first test run was weighed on a calibrated scale accurate to within 0.1 pounds. As seen in Figure 5, the exact volume of fuel needed to make this gravimetric measurement was determined with a sight tube that was installed at the bottom of the fuel tank.

Figure 5 – Sight Tube Installed in Fuel Tank to Measure Volume of Fuel Consumed

Test Route

As seen in Figure 6, the test route consisted of a 1.7-mile closed loop oval adjacent to a research staging area. The Pavement Test Track at Auburn University is a controlled-access facility on which a fleet of five heavy triple trucks each run over 3,000 miles a week in order to damage experimental pavements. Interest in the Track is not limited to pavements, and the operation of vehicles on the closed loop oval provides an excellent opportunity to study experimental technologies in a highly controlled manner.

The due east-west straight sections on the Pavement Test Track are precisely 2600 feet long, connected with spiral-curve-spiral sections approximately 1900 feet in length. The east curve profile travels down a –0.5 percent grade, while the west curve profile travels up a +0.5 percent grade. The resulting duty cycle provides a significant amount of variability that can be used to generate meaningful performance data. The maximum side slope (i.e., super elevation) of both curves is 15 percent, which supports a design speed for the Track's heavy diesel trucks of approximately 46½ mph. Significantly higher speeds were possible with the test vehicle in this experiment. In order to provide CO_2 removal efficiencies over a broad range of operating speeds, the test vehicle used for this study was operated at 55 mph, 40 mph, 25 mph, and at idle in 30 minute duty cycles.

Figure 6 – Pavement Test Track at Auburn University

Research Methodology

A research plan was developed and executed to satisfy the primary and secondary objectives laid out for the experiment. After a one hour warm up period and a sensor reversal to ensure that pre- and post-treatment emissions data was not biased in any way, 30 minutes of emissions and fuel economy data was logged at 4 different speeds (55 mph, 40 mph, 25 mph, and 0 mph). Data was collected for this phase of testing between 10:48 AM and 12:55 PM on June 6, 2011. The fuel level in the tank was precisely noted in the sight tube at 10:35 before the data collection process was initiated. At 1:00 PM, 14.9 pounds of fuel was needed to restore the sight tube to the noted pretest level at a blended temperature of 118F. No volumetric correction was required because this was also the fuel temperature at the time the warm up period was completed. An Ohaus Champ II Model CH300R digital scale with a 650-pound capacity was used (shown in Figure 7), with the calibration verified before and after testing. This known quantity of consumed fuel was then used to improve the accuracy of OBD-II based fuel economy estimates.

Figure 7 – Gravimetric Measurement of Fuel Consumption

Following another warm up period (shortened to 30 minutes because the vehicle was not allowed to cool down fully from the earlier tests), OBD-II data was collected again at 55 mph with the Strataclear™ CO_2 Reducer bypassed completely to determine fuel economy with no back pressure. Afterward, 55 mph data collection was repeated with two then four cartridges engaged to investigate the relationship between fuel economy and any back pressure that might be created by the CO_2 removal process. Finally, 55 mph testing was repeated on June 7th, with treatment cartridges weighed before and after testing to quantify the total mass of material removed from exhaust gases as a result of treatment with the Strataclear™ CO_2 Reducer. Emissions data was also collected during each phase of testing to provide for the calculation of CO_2 removal efficiency for all vehicle speeds and modes of operation.

In summary, the following test runs were made over the course of the two day study:

1. 55 mph with the unit bypassed (the experimental control);
2. 55 mph with one cartridge engaged;
3. 55 mph with two cartridges engaged;
4. 55 mph with four cartridges engaged;
5. 55 mph with two cartridges engaged (repeat on second day);
6. 40 mph with one cartridge engaged;
7. 25 mph with one cartridge engaged; and
8. 0 mph with one cartridge engaged.

Test Data

Emissions and fuel economy data were collected between 9:00 AM and 5:00 PM on June 6, 2011, and between 10:00 AM and noon on June 7, 2011. Temperatures on June 6th increased from 82F at 9:00 AM to 99F at around 4:00 PM, falling back to 97 degrees by the time testing was completed at 5:00 PM. Temperatures on June 7th increased steadily from 80F at 10:00 AM to 90F at noon. All times reported relate to the central time zone, which is the local time zone for Auburn, Alabama. Plots that graphically describe the changing temperature, barometric pressure, wind speed, and wind direction for the two test dates were obtained from the Weather Underground web (wunderground.com) for inclusion in Figures 9 (June 6th) and 10 (June 7th). Times during which test data were collected are shown enclosed within red boxes.

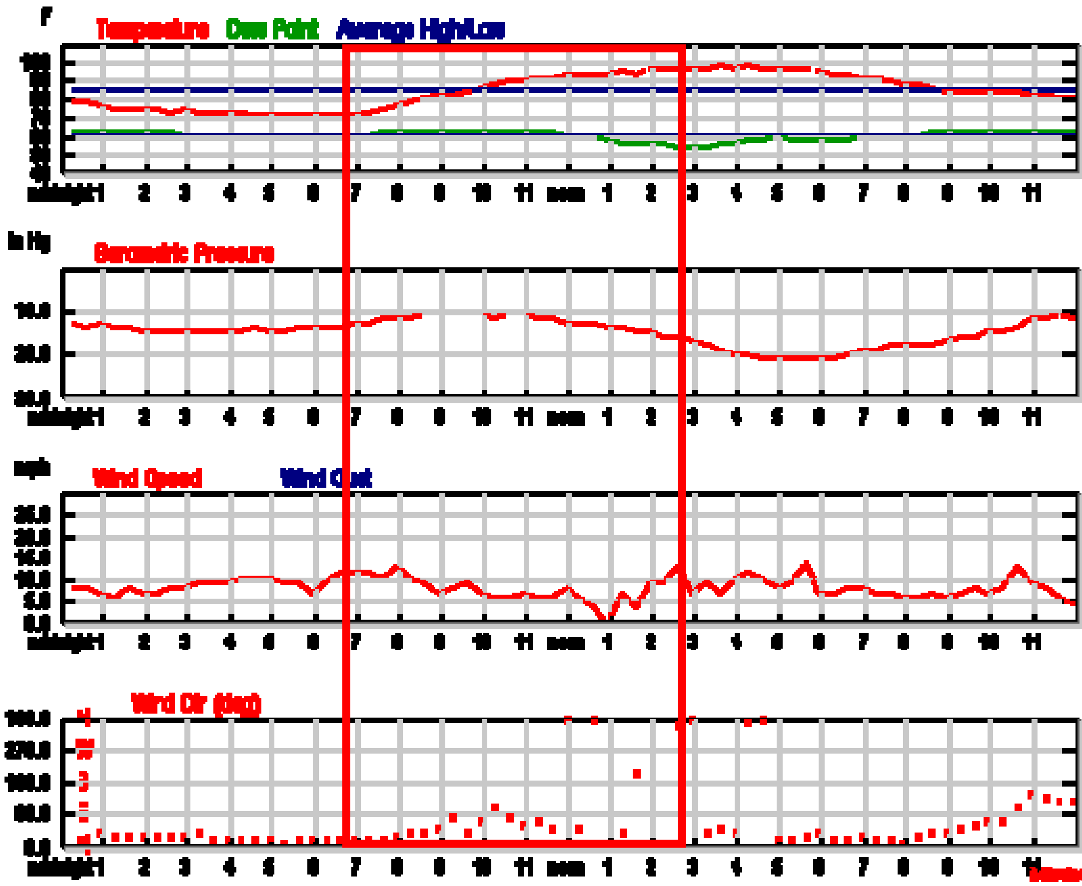

Figure 9 – Hourly Weather Summary for June 6, 2011 (wunderground.com)

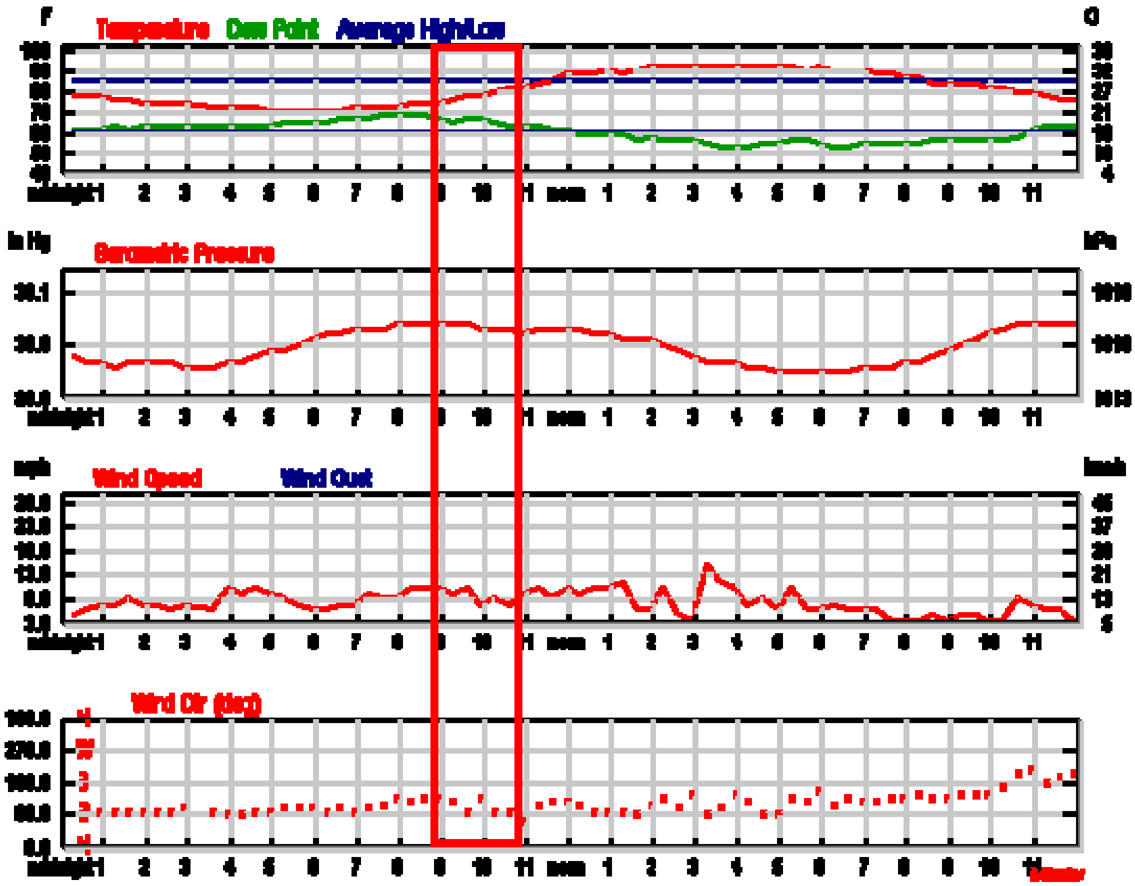

Figure 10 – Hourly Weather Summary for June 7, 2011 (wunderground.com)

Data was continuously logged from both exhaust gas analyzers and the OBD-II interface using the onboard computers shown in Figure 3. Emissions data from the exhaust gas analyzers was sampled at an average rate of 0.25 hertz, while fuel economy data from the OBD-II interface was sampled at a rate of 1.23 hertz. Sample data from one of the exhaust gas analyzers is shown in Table 1, while sample data from the OBD-II interface is shown in Table 2. A tremendous amount of raw data was collected over the course of this testing program. In the interest of space in this report, a complete set of raw data is available for download at www.pavetrack.com/strataclear.

CO	CO2	HC	O2	TimeString
0.051	9.74	353	7.49	15:33:02.870
0.051	9.43	348	7.90	15:33:05.955
0.051	9.38	346	7.86	15:33:09.918
0.051	9.36	346	7.79	15:33:14.830
0.051	9.38	345	7.61	15:33:17.936
0.051	9.44	343	7.52	15:33:21.914
0.050	9.48	341	7.63	15:33:26.800
0.050	9.50	339	7.67	15:33:29.933
0.050	9.49	338	7.70	15:33:33.895
0.050	9.51	337	7.67	15:33:38.760
0.050	9.52	335	7.52	15:33:41.929
0.049	9.51	333	7.77	15:33:46.313
0.049	9.49	330	7.93	15:33:50.720
0.049	9.44	328	7.92	15:33:53.926
0.049	9.42	325	7.93	15:33:58.309
0.050	9.44	316	7.51	15:34:02.530
0.051	9.43	314	7.73	15:34:05.922
0.050	9.42	312	7.71	15:34:10.306
0.050	9.41	310	7.72	15:34:14.500
0.050	9.40	308	7.83	15:34:17.903

Table 1 – Sample Data from Exhaust Gas Analyzers

Monday	6 June		2011	15:33:02.556 VCDS Ve		Data version: 20101206		
Marker	TIME STAMP	PID A - 012 Engine RPM (/min)	TIME STAMP	PID B - 013 Vehicle speed (km/h)	TIME STAMP	PID C - 016 Mass Air Flow (g/s)	TIME STAMP	PID D - 036 Lambda
	510.15	1794	510.35	83	509.74	22.77	509.95	0.103
	510.96	1798	511.16	83	510.55	22.58	510.76	0.100
	511.77	1789	511.97	83	511.36	23.63	511.57	0.103
	512.58	1791	512.78	83	512.17	22.02	512.38	0.104
	513.39	1793	513.59	83	512.99	21.72	513.19	0.104
	514.20	1790	514.40	83	513.80	21.80	514.00	0.102
	515.01	1790	515.22	83	514.61	22.66	514.81	0.103
	515.83	1787	516.03	83	515.42	23.02	515.62	0.102
	516.64	1790	516.84	83	516.23	23.27	516.44	0.101
	517.45	1784	517.65	83	517.04	23.30	517.25	0.101
	518.26	1789	518.46	83	517.85	23.08	518.06	0.100
	519.07	1785	519.27	82	518.66	23.66	518.87	0.101
	519.88	1786	520.08	83	519.48	25.58	519.68	0.101
	520.69	1790	520.89	83	520.29	24.97	520.49	0.102
	521.50	1787	521.70	83	521.10	24.22	521.30	0.101
	522.31	1784	522.52	83	521.91	24.44	522.11	0.099
	523.13	1783	523.33	83	522.72	25.55	522.93	0.101
	523.94	1789	524.14	83	523.53	25.44	523.73	0.103
	524.75	1787	524.95	83	524.34	23.83	524.55	0.102
	525.56	1786	525.76	83	525.15	23.97	525.36	0.100

Table 2 – Sample Data from OBD-II Interface

Calculations

As previously stated, the primary objective of the study was to determine CO_2 removal efficiency at various speeds. Removal efficiency was calculated by dividing post treatment CO_2 concentration by pretreatment concentration, subtracting the result from one, and multiplying by one hundred to express the final value as a percentage. In this manner, removal efficiency was calculated for the entire period of time the test vehicle was operated. Figure 11 is provided to illustrate how efficiency was calculated throughout the testing process. This process was repeated as described above with the test vehicle operating at different speeds. As seen in Figures 12 and 13, efficiency was observed to drop off more rapidly as speed was increased.

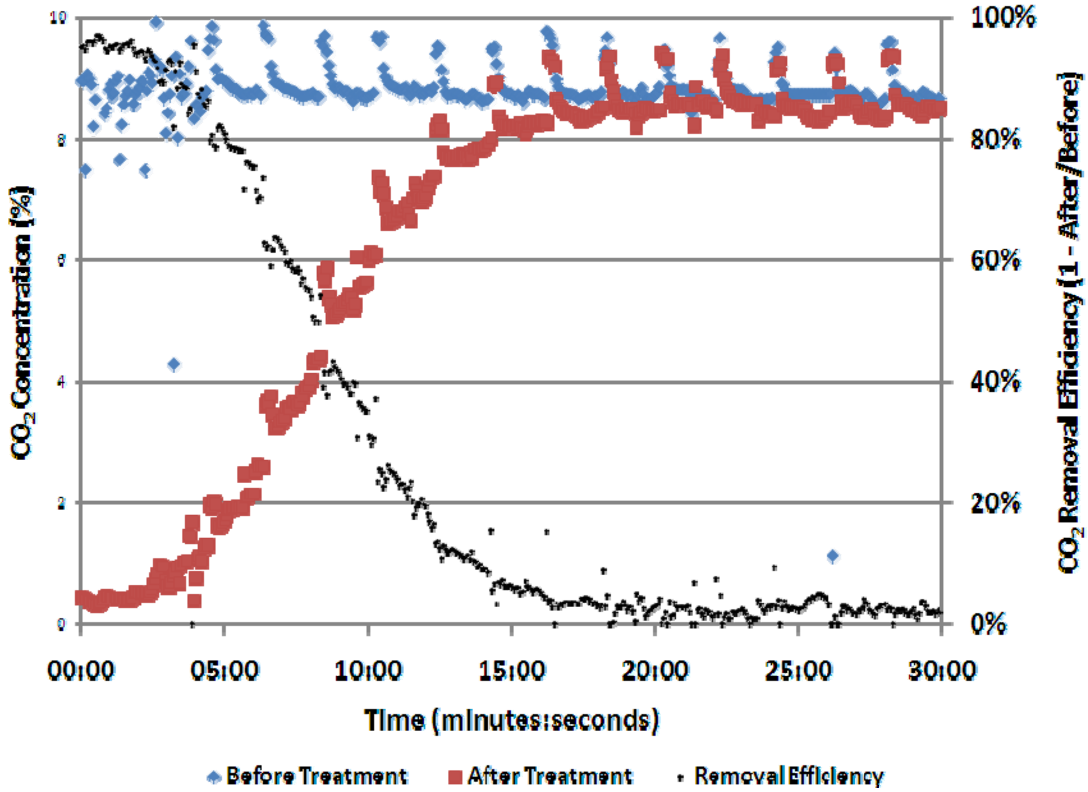

Figure 11 – Plot Showing Efficiency Calculation and Loss with Time

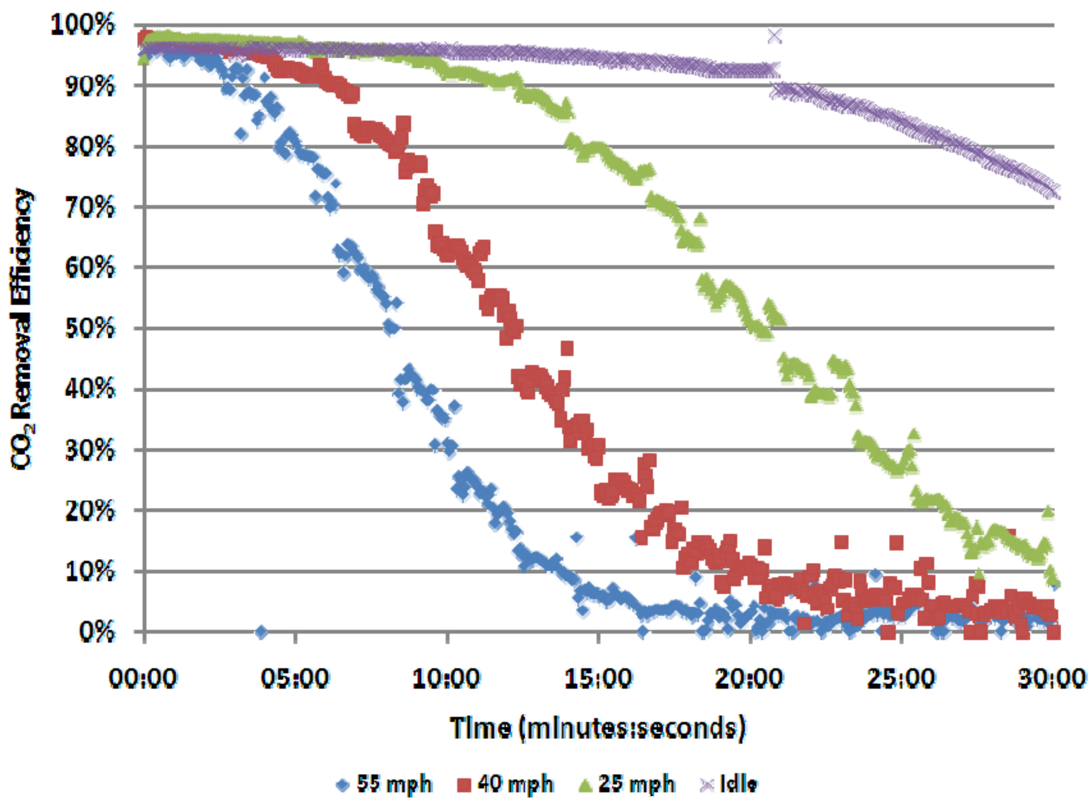

Figure 12 – Plot Showing Changing Efficiency versus Time

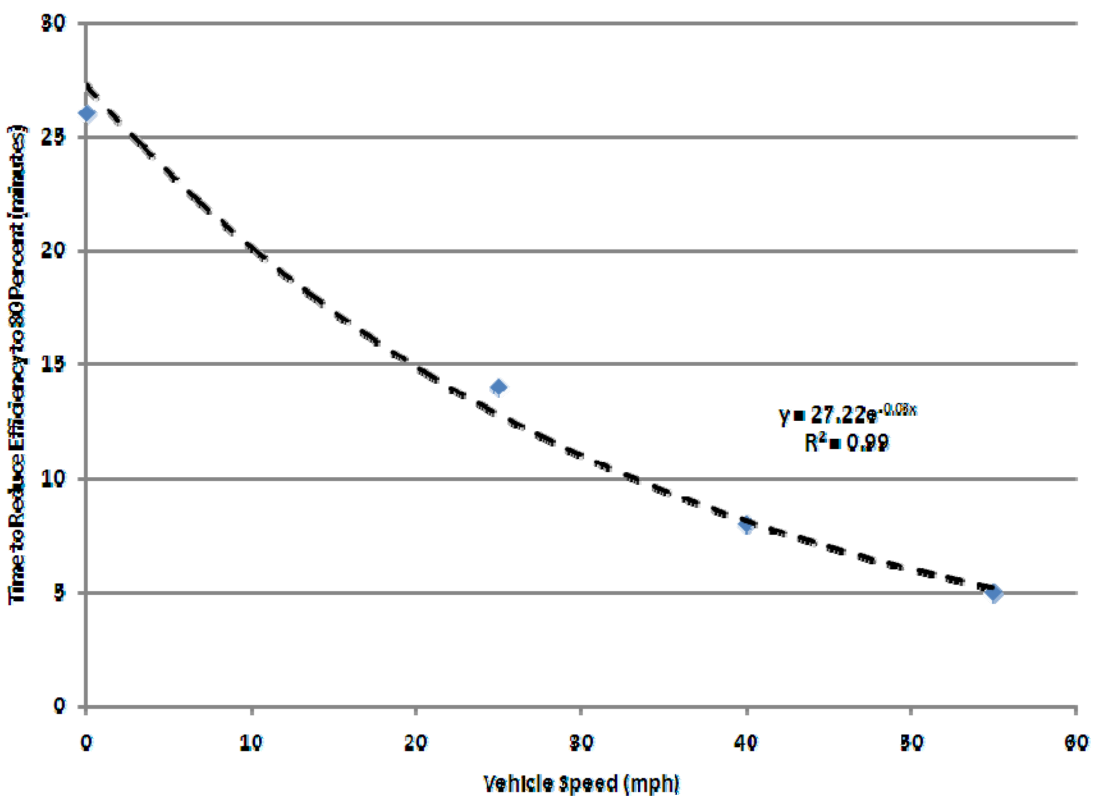

Figure 13 – Relationship Between Time to Drop to 80 Percent Efficiency and Speed

The secondary objective of the experiment was to study the effect of the operation of the Strataclear™ CO_2 Reducer on fuel economy. Individual fuel economy measurements for each 0.81 second OBD-II measurement interval were combined to determine the average fuel economy for each lap of operation on the Pavement Test Track. Because the vehicle was operated for a fixed amount of time at each test speed, the number of laps was reduced as speed was decreased. Fuel economy was calculated for each 0.81 second data interval using the following equation:

$$\text{mpg} = (\text{vehicle speed x Lambda x scale factor}) / \text{mass air flow}$$

The Minitab computer program (version 16) was used to perform a one-way analysis of variance (ANOVA) for the purpose of determining statistical differences. In Table 3, the “Level” column refers to the number of the test run. Because fuel economy varies significantly on the Pavement Test Track as a function of pavement condition and grade, the study parameter in the analysis was the gravimetrically calibrated average fuel economy for each 55 mph lap as measured in the vehicle via the OBD-II interface. Thus, the “N” column refers to both the number of data points included in the analysis for each test run and the number of laps.

One-way ANOVA: MPG versus Run

```
Source  DF      SS     MS      F      P
Run      4  38.538  9.635  71.84  0.000
Error   59   7.913  0.134
Total   63  46.451

S = 0.3662   R-Sq = 82.97%   R-Sq(adj) = 81.81%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  -------+---------+---------+---------+--
1      16  34.365  0.322                         (--*--)
2      13  32.640  0.248  (--*--)
3      15  34.653  0.454                             (--*--)
4       4  34.863  0.256                              (----*----)
5      16  34.532  0.411                            (-*--)
                          -------+---------+---------+---------+--
                             32.90     33.60     34.30     35.00

Pooled StDev = 0.366
```

Table 3 – Statistical Analysis of Fuel Economy Data (N=Number of Laps)

The test run described as Level 1 is the run with the system set to full bypass (i.e., no possibility of restricted flow). The test run described as Level 2 is the run with the system engaged and flow passing through a single cartridge. Likewise, the test runs described as Levels 3 and 4 were made with the system engaged and flow passing though two and four cartridges, respectively. Finally, the test run described as Level 5 was a repeat run with two cartridges engaged in which the mass of the cartridges was measured before and after testing to verify removal of CO_2. This same numbering system for test runs was used to compile the numbered bullet list on page 10. All test runs included in Table 3 were made with the cruise control engaged at a speed of 55 mph. The sample size is slightly smaller in the Level 2 data set because the cruise control was not properly engaged when the data collection process was initiated.

Significant differences in the means of the fuel economy data sets are apparent in Table 3 ($\alpha = 0.05$); however, the data fall into only two statistically distinct groups. Test runs referred to as Levels one, three, four, and five (made with the Strataclear™ CO_2 Reducer engaged and flow passing through two or more cartridges) are not statistically different. The first test run was made with the system set for full bypass. The second run (which was the only one found to produce statistically different results) was made with the Strataclear™ CO_2 Reducer engaged and flow passing through only one cartridge. Consequently, the operation of the Strataclear™ CO_2 Reducer would not be expected to have a negative effect on fuel economy as long as exhaust gases are passing through two or more cartridges. Operation of the unit with only one cartridge is not recommended because it would be expected to have a negative effect on fuel economy, presumably as a result of restricted flow.

CONCLUSIONS AND RECOMMENDATIONS

Based on an analysis of the data collected during this testing program, the following conclusions were made regarding the performance of the Strataclear™ CO_2 Reducer:

- The unit was very efficient at CO_2 removal when it was first engaged at any speed, with a starting value of over 95 percent;
- Removal efficiency in the current design reduces rapidly at higher speeds. As seen in Figures 12 and 13, it took only 5 minutes to drop to approximately 80 percent efficiency at 55 mph. It took approximately 8, 14, and 26 minutes to drop to the same 80 percent efficiency level at 40 mph, 25 mph, and 0 mph, respectively;

- Operation of the unit did not have a negative effect on gravimetrically calibrated OBD-II fuel economy measurements as long as more than one filter cartridge was engaged;
- A statistically significant drop in gravimetrically calibrated OBD-II fuel economy measurements did occur when only one filter cartridge was engaged, presumably as a result of an increase in exhaust back pressure. The suspected relationship between mode of operation, a decrease in fuel economy, and exhaust back pressure could be verified with additional testing;
- More rigorous testing methodologies may be used to improve the statistical significance of conclusions regarding CO_2 removal efficiencies and the impact on vehicle fuel economy of various modes of operation. More precise fuel economy measurements could be obtained by adding a control vehicle and by outfitting both the control and treatment vehicles with removable weigh tanks. More precise emissions data could be obtained by using laboratory grade equipment for exhaust gas analysis. These improvements would be expected to reinforce, rather than contradict, the conclusions previously stated;
- Before the Strataclear™ CO_2 Reducer can become a commercially viable product, the design of the unit will need to be optimized for practical deployment with a focus on size, cost, reliability, maintenance, recyclability, and performance that is sustainable for realistically long duty cycles;
- A system will likely be needed that will allow users to recharge, recycle, recover, and/or reuse cartridges that have exhausted their potential to absorb CO_2. Ideally, the infrastructure that supports this critical activity should be designed to convert absorbed CO_2 into a valuable commodity (e.g., combustible fuels produced directly by genetically modified, light wavelength optimized algae using absorbed CO_2); and
- Applied research is needed to improve the prototype design and envision the needed CO_2 recovery infrastructure. An institution like Auburn University with an international reputation for partnering with industry to take proof-of-concept research to the marketplace (especially with multidisciplinary technologies that require expertise in transportation, energy, the environment, and supply chain management) could play a key role in a successful effort.