

ICAT Grant No. 06-02: FINAL REPORT

CORRELATION OF the REAL-TIME PARTICULATE MATTER EMISSIONS MEASUREMENTS of a ESP REMOTE SENSING DEVICE (RSD) and a DEKATI ELECTRONIC TAILPIPE SENSOR (ETaPS) with GRAVIMETRICALLY MEASURED PM from a TOTAL EXHAUST DILUTION TUNNEL SYSTEM

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Abstract

The University of Denver spent six weeks in West Virginia measuring diesel particles from 15 heavy duty diesel trucks with an Electrical Tailpipe Particle Sensor (ETaPS) and correlating the results with a RSD 4600 (supplied by ESP) and a gravimetric filter from a chassis dynamometer. The ETaPS is an electrical charger, placed directly in raw exhaust, and measures particles based on their active surface area. The use of a diesel particle filter (DPF) was implemented in three different ways. Five trucks were installed with a functioning DPF, five trucks were installed with bypassed DPF to simulate a failing DPF, and the last five trucks had no DPF. The University of Denver found that ETaPS (volt*sec/mile also Vs/mi) correlates well with to gravimetric readings (gm/mile) except for one truck. Probably the expected disagreement with semi-volatiles indicated by high HC readings from said truck. Functioning DPFs produce typical ETaPS readings of 2volt*sec/mile while readings of 20volt*sec/mile, or more, indicate either a failing DPF or an absent DPF. An ETaPS can be mounted on a real truck and be ready to drive in real-world conditions in ten minutes or less. Any outdoors testing with an ETaPS must be in a shielded environment as there is significant interference from other power sources (i.e. power lines, and transformers). RSD smoke factor readings above 0.15 (1.5gm of soot/kg of fuel) certainly indicate a malfunctioning DPF.

Introduction

This is the final submission providing the results and conclusions towards ICAT grant number 06-02. The sections herein describe the testing process of the ETaPS as an in-use diesel inspection technology and its correlations are determined to RSD and gravimetric tests. The sensitivity of the instrument was found to be adequate to distinguish DPF from even minor DPF failures. Interference problems are also discussed.

Innovative Technology

The Electric Tailpipe Particle Sensor (ETaPS) measures particulate matter in raw exhaust by measuring the current loss in a corona as the particles pass through. The ETaPS reports an analog signal (0-10V) proportional to the surface area of the particles. This technology has unique applications in the field of detection and classification of high emitting PM HDDVs. Since the ETaPS is placed in the raw exhaust, no additional equipment is needed. It is small, light-weight and inexpensive compared to the standard methods of emission testing for HDDVs (i.e. dynamometer testing). This study shows that, under optimum conditions, the ETaPS can fully discriminate between HDDVs with functioning DPF systems and HDDVs with simulated failed DPF systems where the gravimetric tests could not fully discriminate.

ICAT Project

Summary

This ICAT project involved comparing particle mass (PM) emission measurements from a commercially available Remote Sensing Device (RSD; Environmental Systems Products RSD4600), a commercially available Exhaust Tailpipe Particle Sensor (ETaPS; Dekati Finland), and a federal reference method gravimetric filter measurements on Heavy Duty Diesel Vehicles (HDDV). A system was developed to easily field mount and dismount a wide range oxygen sensor and the ETaPS together with its air pump, power supply, 110V generator and data acquisition system. The oxygen sensor provides an indirect measure of load/fuel use, and the ETaPS provides a measure of PM. The ETaPS was mounted directly in the exhaust flow without tailpipe connections or shielding because this “open” arrangement provides the most rapid mounting capability. Preliminary tests conducted at University of Denver were promising. The ETaPS system and the RSD4600 were moved to the West Virginia University’s (WVU) HDDV dynamometer facility in Westover WV for collection of gravimetric filter measurements.

Testing at WVU was conducted in two phases. Phase 1 involved five HDDV vehicles without diesel Particulate Filters (DPF): four truck tractors and one bus. The ETaPS system and oxygen sensor were easily mounted on each test vehicles and the vehicles were driven past the RSD just outside the dynamometer facility using several different driving modes, speeds and loads. The ETaPS gave generally large signals, as expected since these were not DPF-equipped vehicles, but the signals were more variable than expected. These vehicles were next tested on the dynamometer over several different cycles (three UDDS, three cruises and one acceleration cycle each) with the ETaPS monitoring the exhaust stream just upstream of the dilution tunnel entrance. Complete exhaust gas measurements, a gravimetric result and continuous Tapered Element Oscillating Microbalance (TEOM) data were obtained by WVU. In Phase 2, ten additional vehicle configurations were subjected to the same test program described above. The ten configurations included five DPF-equipped, modern HDDV (four tractors and one bus), and the same five HDDV equipped with a partial DPF bypass to simulate a partial DPF failure.

Investigation of the variability in outdoor ETaPS signals showed that overhead power lines were interfering with the ETaPS in its truck-mounted, open configuration. The data from outdoor ETaPS comparisons with RSD had to be discarded. When the ETaPS is installed inside the pipe connector supplied by Dekati, the interference is prevented. However, this was not discovered until after outdoor tests were completed. The available data to analyze consisted of the dynamometer ETaPS, oxygen and gravimetric data and the outdoor RSD readings, but no outdoor ETaPS.

The ETaPS-gravimetric comparison shows that all cycles for DPF equipped trucks average about 1Vs/mi. ETaPS readings for bypassed and older truck cycles vary with truck and driving mode, ranging from 8 to 390 Vs/mi, typically about 100Vs/mi. The ETaPS results correlate with the HDDV gravimetric results. Regression of dynamometer ETaPS data against gravimetric mass gave a correlation r^2 of 0.64 with intercept forced through zero. A correlation of 0.80 was obtained (97 data points) when one outlier truck was removed. ETaPS readings showed a difference in signal by a factor of 5 between DPF equipped trucks and non-DPF trucks, demonstrating that ETaPS can detect DPF failure. The outlier truck that did not fit this

correlation was a 2008 Volvo (8gm/mi gravimetric) with DPF bypassed, which based on its relatively high HC emissions, emitted a high fraction of semi-volatile mass. The ETaPS does not see this semi-volatile material at exhaust temperature, but it is captured on the gravimetric filter which is collecting sample at much lower temperature. The ETaPS and TEOM results were reasonably well correlated with each other, and the CO₂/load reading derived from the oxygen sensor was in reasonable agreement with the dynamometer results.

We directly compared the average RSD readings with the gravimetric readings from these vehicles. On average, the RSD differentiates between the working DPF equipped vehicles and those that are either bypassed, or pre-control vehicles, with the exception of the outlier vehicle. As with the ETaPS, the RSD is sensing hot exhaust and would not detect semi-volatiles. The DPF equipped vehicles showed 0% of their RSD readings above 0.10 and only 4% above 0.05 UV smoke factors. There is some overlap in RSD response between the DPF and non-DPF equipped vehicles. Figure 1.1 shows a fitted distribution of RSD response for both the DPF and non-DPF trucks. Measuring smoke close to zero accurately is difficult, and the focus of using RSD should be to detect failing or missing DPFs with high confidence. Using an RSD smoke factor limit of 0.1 (1 gsmoke/kg of fuel +2 s.d.) for this data set will yield a 2.5% chance of false positives (trucks falsely flagged as having a failing DPF), and a using a limit of 0.15 (1.5 gsmoke/kg fuel) yields less than 0.15% of false positives regardless of driving mode.

In summary, the RSD system is capable of flagging DPF failures. The ETaPS system is also capable of flagging DPF failures if installed in a shielded configuration, but a system to field mount the ETaPS in such as configuration was not demonstrated. While the integrated ETaPS signal demonstrated correlation with gravimetric filter measurements, the precision was not sufficient to allow replacement of gravimetric filters with ETaPS measurements.

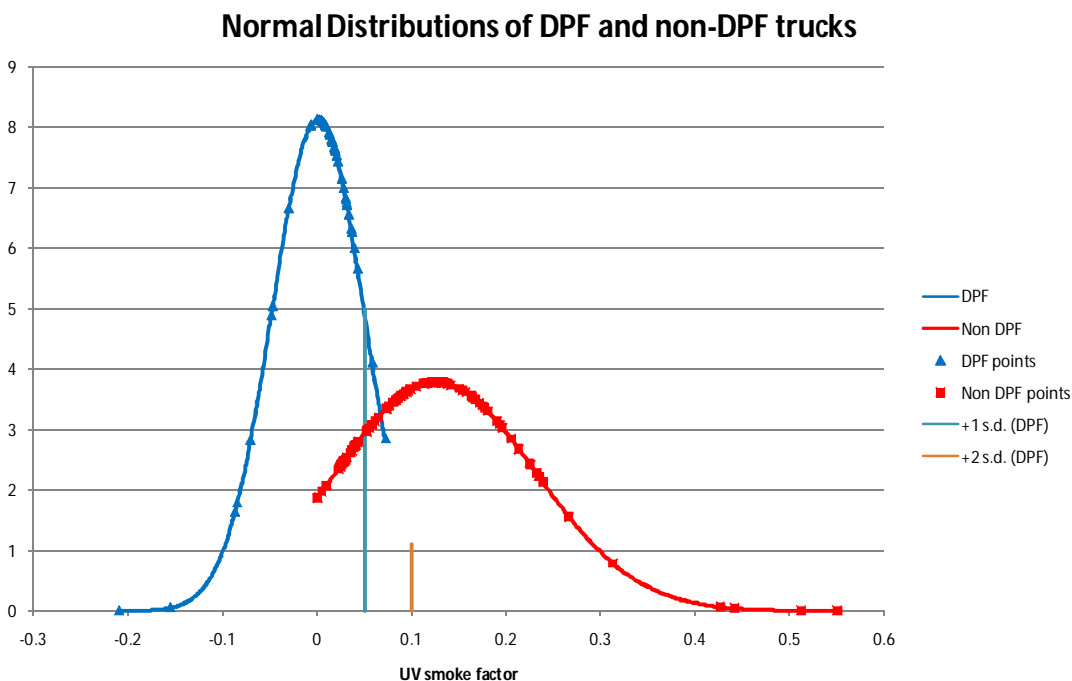


Figure 1.1

1. Introduction and Experimental

Project Goal: Demonstrate In-Use Diesel PM Inspection Technologies Correlation to Gravimetric PM.

According to the original ETaPS ICAT project proposal, the goal statement was:

“Trucks with particle emissions which are significantly higher than they should be, need to be identified and repaired. If the outcome of the ICAT experiment is as positive as we hope, then we can imagine determination of “probable cause” using RSD, for instance as the vehicle accelerates from a stop at a weigh station. The trucks so identified could then be quickly instrumented and subjected to a road load ETAPS investigation, the outcome of which could be used to trigger enforcement action and calculate mass emission credits upon repair.”

The details of the ETaPS, how it works and the model equations are in the literature (1,2). Basically the device is a corona charger with a feedback loop determining the current necessary to maintain the corona. More particle flux, more charge removal from the corona, thus more current signal which is converted to voltage by the ETaPS electronics. The ETaPS literature indicates that the ETaPS voltage response is remarkably linear versus the product of particle concentration and flow rate. The observed linearity is actually better than the model equations suggest. Thus, the ETaPS signal can be considered as a monitor of particle flux, with the caveat that the constant of proportionality is probably dependent upon size distribution. If the ETaPS is hot and the particle measurement device for comparison is colder, then the ETaPS can not be expected to monitor semivolatile materials which are in the gas phase at high temperatures and particles only at a lower collection temperature.

In the previous studies, the ETaPS was mounted perpendicular to the exhaust flow, directly coupled to the vehicle tailpipe together with an exhaust flow meter system. We believed that coupling this much hardware to a realistic truck in a field situation would take more time and effort than the driver or the system user would tolerate. We therefore decided to use the fast response and direct reading capability of the ETaPS in a simpler mode by directly mounting the ETaPS roughly perpendicular to the exhaust stream as it exits the truck. In view of the fact that the ETaPS monitors particle flux and HDDV engine standards are in units of emissions per power (gm/bhp-hr) we added a wide-range oxygen sensor system (OXY6200, ECM, Sunnyvale CA) to the ETaPS mount with the goal of determination of the exhaust CO₂, and thus power, using the fact that modern diesel engines use about 0.15 kg of fuel per bhp-hr under most loaded modes, or most operating conditions. Private Communication (Cummins Diesel).

Two ETaPS units were received from Dekati (Finland). The necessary power supplies and wiring were provided by ESP (Tucson) and the University of Denver. An RSD 4600 unit was supplied by ESP (Tucson) and was used mounted on scaffolding as described in previous on-road remote sensing truck studies (3).

An important parameter of the RSD 4600 is the UV smoke response which monitors UV opacity at 230 nm in ratio to CO₂ absorption from the exhaust. The system has been set up in such a way that a soot emission of 10g/kg of fuel (1% by mass) gives rise to a UV smoke factor reading of 1.0. Recent on-road RSD studies in California (4) have shown that the RSD 4600 reported IR smoke readings (IR opacity at 3.9 microns relative to exhaust CO₂) are on average about 1.7 times larger than the UV smoke factor reported when observing a realistic fleet of HDDV.

1.1. Mounting an ETaPS on a Modern Truck

Figures 1.2 and 1.3 shows typical ETaPS mounts on an older and on a modern DPF equipped truck.

Make: PETE
Model: 385
Year: 2000

This is a 5 inch diameter exhaust pipe curved back and to the right side of the cab of the truck. The ETaPS is connected to a rotatable hinge allowing for multiple angles ranging from vertical to horizontal alignment. The orange padding is a vest so the exhaust pipe would not get scratched. This protection is used because the trucks are new vehicles in a showroom lot. Suitable insulated padding is on order for on-road use. There is a supporting telescopic pole to accommodate for varying distances.



Figure 1.2 shows the ETaPS mounted on the tailpipe of a 2000 MY Peterbilt tractor. The orange cloth was used to protect the vehicle (for sale in a dealer lot) from scratches.

Make: PETE
Model: 379 EXHD
Year: 2006

This is a 7 inch diameter exhaust pipe with the ETaPS unit in the horizontal alignment. All the same connections are in place from the previous truck.



Figure 1.3 shows the same ETaPS on a 7" exhaust stack from a DPF equipped 2006 MY Peterbilt

The first studies in this program were carried out in Denver and showed that indeed an ETaPS could be successfully mounted and demounted from various trucks in various configurations and that the ETaPS, oxygen sensor, power supplies, laptop data acquisition system and generator gave reasonable looking results. Examples of other mounting configurations are shown in the next section.

1.2. Experiments at the WVU facility in WV

The major experimental aspect of this project was to compare RSD and ETaPS readings to readings obtained using the HDDV dynamometer facility in Westover WV. The facility itself and its capabilities are described elsewhere (5). The experimental design was a two step process. In the first step, a tractor/trailer combination was to be equipped with an ETaPS and driven at various speeds and loads past the outdoor RSD system. In the second step, the same truck was to be taken into the facility and subjected to various dynamometer cycles at a comparable load while simultaneously the ETaPS signals and the pollutant gas concentrations and gravimetric filter data were obtained. In the outdoor RSD experiments, the ETaPS was mounted as described previously. In the dynamometer experiments the ETaPS was mounted in the exhaust flow just before the dilution tunnel. In this case the truck exhaust had generally been through a heated transfer line about 20 ft before meeting the ETaPS. There were cases when the ETaPS electronics overheated in this configuration and the ETaPS automatically shut itself off. A strong fan mounted close by solved this experimental problem for later truck measurements.

In order to provide tests simulating failed DPF systems, and in order to provide a range of experimental data, five pre-DPF vehicles were tested and five post DPF vehicles were tested as is, and then were equipped with a DPF bypass with the intent of showing increased emissions and, in a way, simulating a failed DPF system.

A complete list of the vehicles measured is given in Appendix A. The UWV results for these vehicles are available to be downloaded from <http://diesel.mae.wvu.edu/~icat/> with the user name icat and the password ETaPSicat.

Figure 1.4 shows a satellite image of the Westover Facility and surroundings.

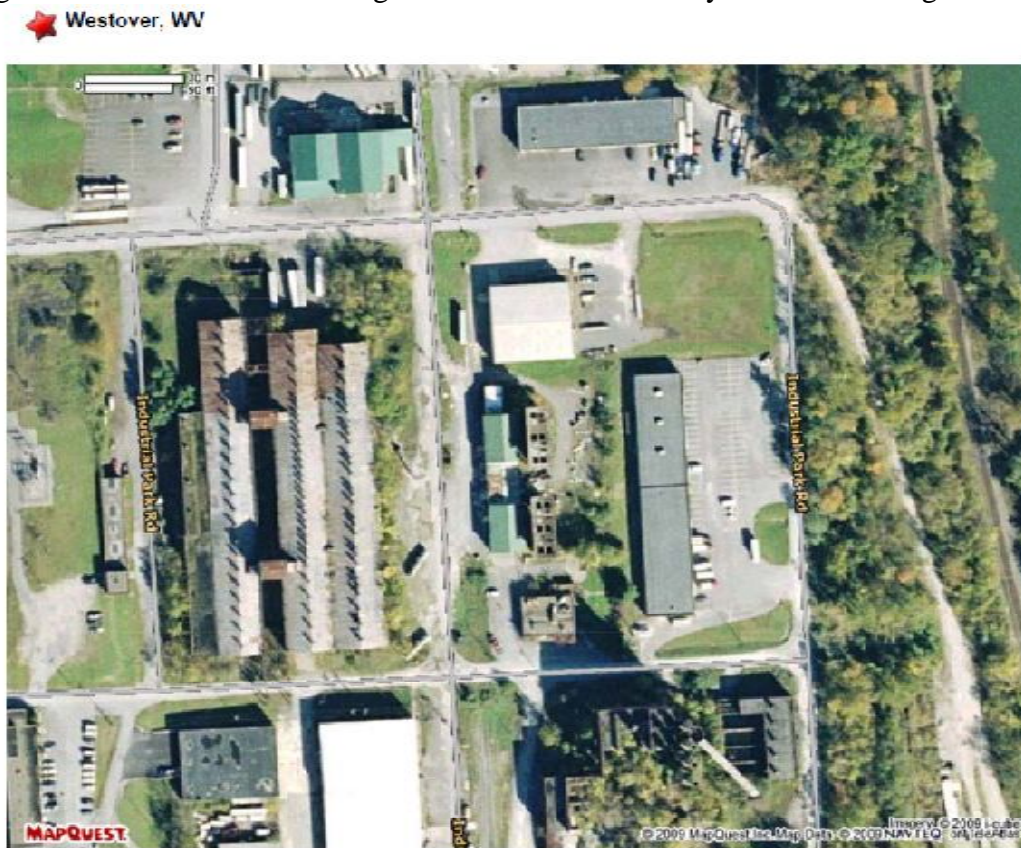


Figure 1.4. Map and image of the Westover WVU facility. The building at the top center, with the trucks visible to the east, houses the dynamometer facility. The RSD measurement system was set up with the detector and scaffolding on the black spot just north of the roadway looking across the road. The trucks being measured were driving uphill (two degrees gradient) westbound. Sometimes the tractor backed down for a rerun, most often the vehicle drove anticlockwise around the rectangle of roadways the east most being labeled “Industrial Park Road.”

References:

- 1) “Evaluation of a Prototype Tailpipe PM Sensor”, M. M. Maricq, N. Xu, R.E. Chase and S.D. Shah, Personal Communication, Maricq, Ford Unpublished.
- 2) “Operation of Electrical Sensor for Vehicle Particle Emission Measurement” A. Rostedt, M. Marjamäki, J. Keskinen, V. Niemelä, K. Janka, 19th CRC On-Road Vehicle Emissions Workshop, San Diego CA, March 23-25, 2009.
- 3) “Remote Sensing of In-Use Heavy-duty Diesel Trucks” D.A. Burgard, G.A. Bishop, D.H. Stedman, V.H. Gessner and C. Daeschlein, **Environ. Sci. Technol.**, **40**:6938-6942, 2006.
- 4) “Remote Measurements of On-Road Emissions from Heavy-Duty Diesel Vehicles” Draft Final Report
- 5) <http://www.cemr.wvu.edu/research/center-details.php?&id=32&type=center>

2. Preliminary ETaPS Results from Denver

Prior to the trip to West Virginia the ETaPS was attached to a Caterpillar Diesel front loader and gasoline powered Winnebago to verify functionality and test the data acquisition system. The Caterpillar was measured before the data recording program was finalized. Samples were taken every second but they were the final value for a data stream acquired at 100Hz. The Winnebago and all later results again monitored at 100Hz but stored the average every second. Both tests, as expected, demonstrate the ETaPS measuring at zero volts when there were few particles in the exhaust, thus demonstrating that simply placing the ETaPS where it intercepts the exhaust did not eliminate its potential usefulness. Close to zero readings of order 5 mV gave rise to the expectation that small amounts of particles causing only a few mV more signal should have been easily observable in WV.



Figure 2.1 shows the ETaPS mounted on a diesel Caterpillar front loader. As in all installations power was provided from an on-board 110V generator grounded to the vehicle

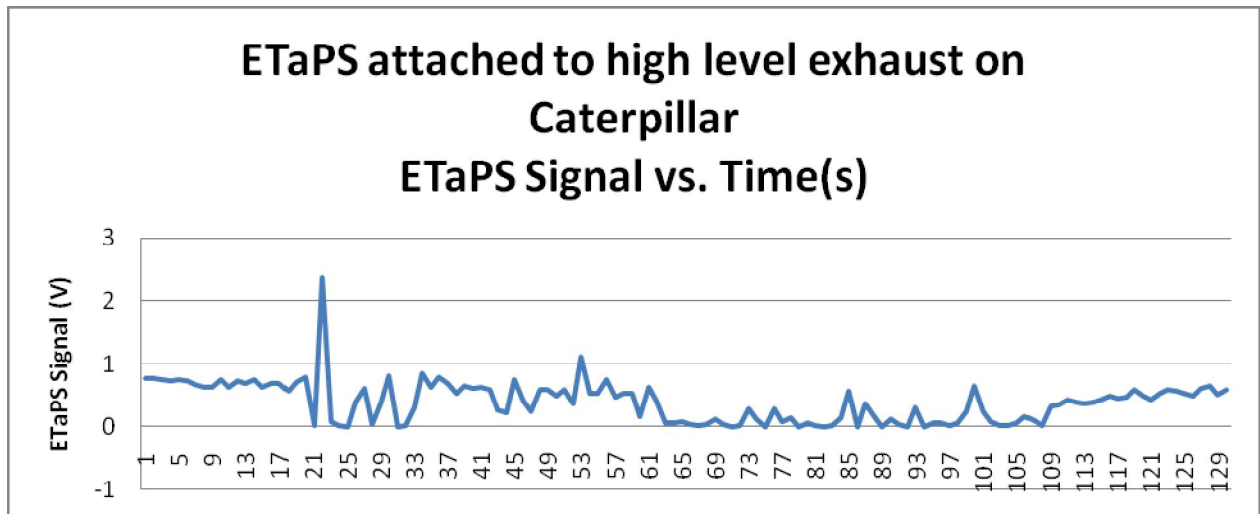


Figure 2.2. ETaPS signal results versus time showing the expected particle response upon startup and upon higher power towards the end with closer to zero when the engine was warmed up and under low load in the 60-85 second time frame.



Figure 2.3 ETaPS mounted so as to observe the particles exiting the exhaust of a gasoline powered 1996 Winnebago Itasca motor home powered by a GM 454 cu.in. V8 engine.



Figure 2.4 Side view of Figure 2.3

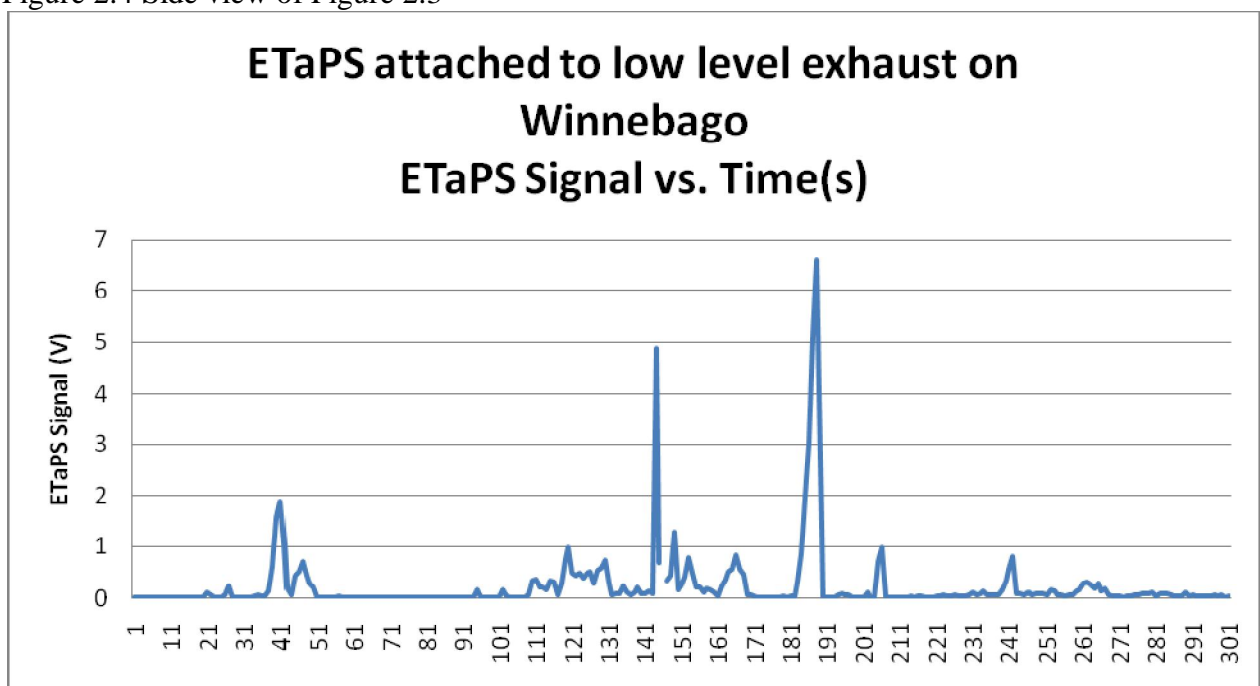


Figure 2.5. Typical on-road ETaPS trace versus time for the gasoline powered motor home showing peaks for each acceleration event and readings indistinguishable from zero under cruise conditions.

These results gave us reason to believe that the outdoor mounting of the ETaPS could be expected to provide useful particle information upon exposure to realistic truck exhaust in Westover. We also discovered in the process of this testing that testing a gross emitting smoking vehicle in a cold start mode is a mistake because the soot coats the ETaPS and turns off the corona, requiring disassembly and ultrasonic cleaning.

2.1. Power line Interference

In the first quarterly report we attempted to draw a correlation between the five older truck exhaust ETaPS measurements and their RSD results. This effort was based on the successful preliminary observations in Denver and also based on the observation that when the ETaPS was placed on the trucks close to the dynamometer facility and the trucks were not operating, the ETaPS signal was essentially zero (as expected). The efforts in the quarterly report were made to correct for any time difference between the ETaPS and RSD measurements. ETaPS data points from a five second timeframe around the RSD measurement time were checked for large deviations. Data with too large of a deviation over the five second time frame were discarded. An effort was made on the second trip to West Virginia to make sure that runs were repeated until this condition was satisfied. This was done so that no runs would have to be discarded. In doing this, it was discovered that an unexpected and undesirable repeatable pattern appeared for every run. A DPF equipped bus was used to map out this pattern. The bus was stopped 200ft away from the RSD platform. For every ten feet, the bus was allowed to idle and ten seconds of data were recorded. Each point on the graph (Figure 2.6) represents the average of the ten data points at each ten foot stop. The peak corresponds to the point directly beneath a power line crossing over the street. These are large signals compared to the zeros which we expected based upon our preliminary measurements in Denver.

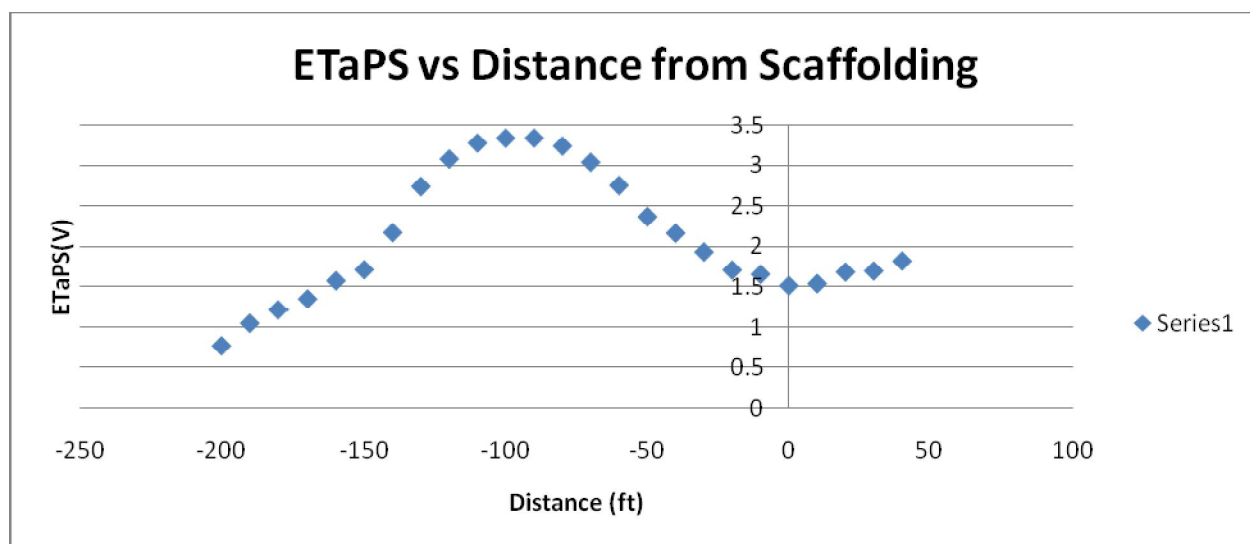


Figure 2.6. ETaPS readings as a function of distance from the RSD location showing a large signal peak when the ETaPS was under the power line crossing the roadway.

Three, same speed runs for a DPF equipped and DPF bypassed vehicle taken within minutes of each other were graphed in Figure 2.7. The x-axis shows a time window of 15 seconds around the time of RSD measurement. Both graphs show a consistent pattern matching the power line interference. It should also be noted in this case that when the vehicle is DPF bypassed, there is approximately a 0.25V increase from the non-bypassed runs. Unfortunately, this expected increase is also within the differences seen between various runs with the DPF installed and operating. We interpret these differences as arising from different values of the current drain in the overhead power lines which look to be at least at several thousand volts because they are equipped with about 15 cm long insulators.

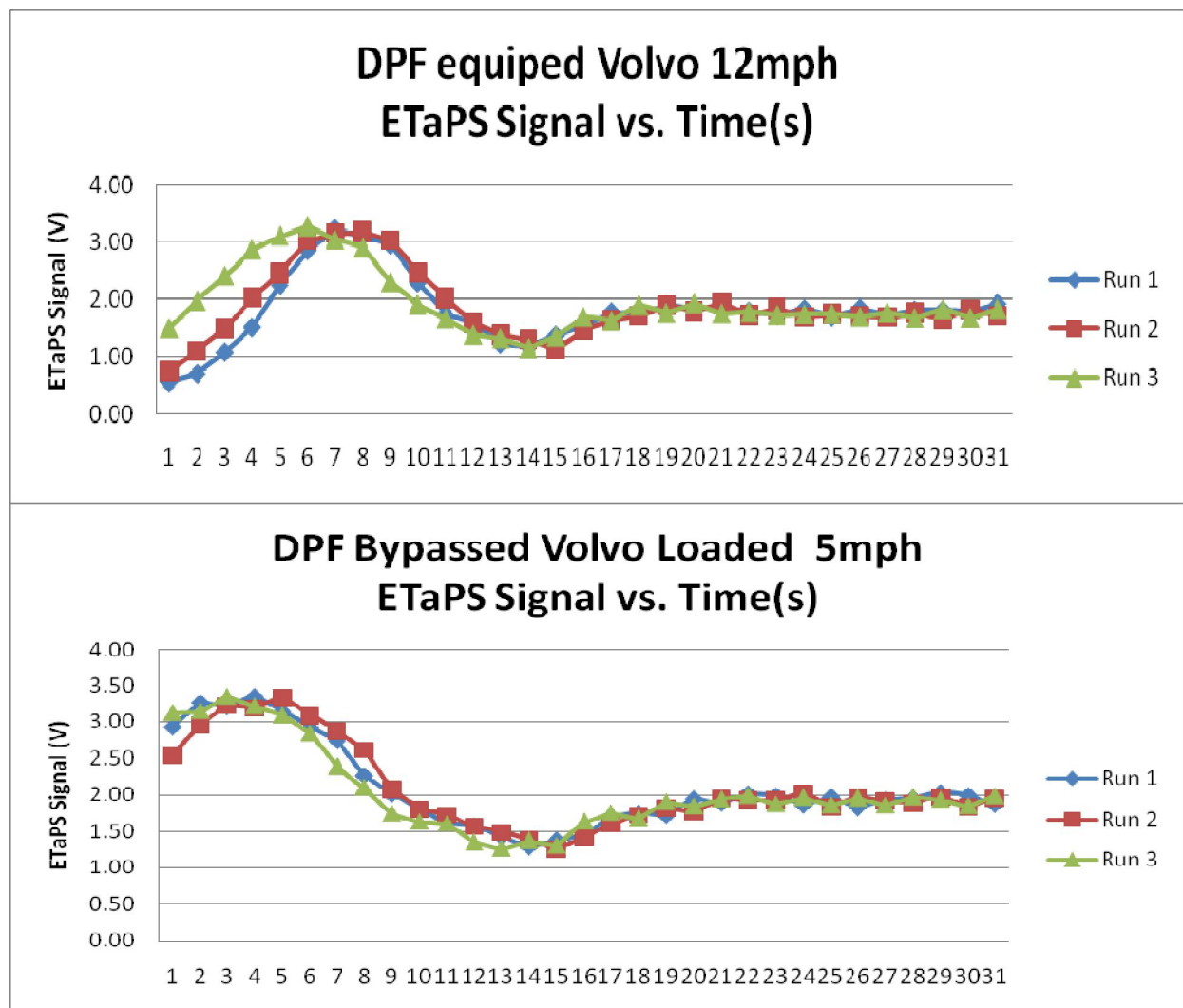


Figure 2.7a (top) b (bottom). ETaPS signals versus time in seconds for three runs of a DPF equipped Volvo (top) and three runs of the same vehicle with a bypass (bottom).

Because power line interference with the ETaPS may vary over time, for the reason discussed above, measurement signals from all DPF equipped modern trucks were compared over time in Figure 2.8.

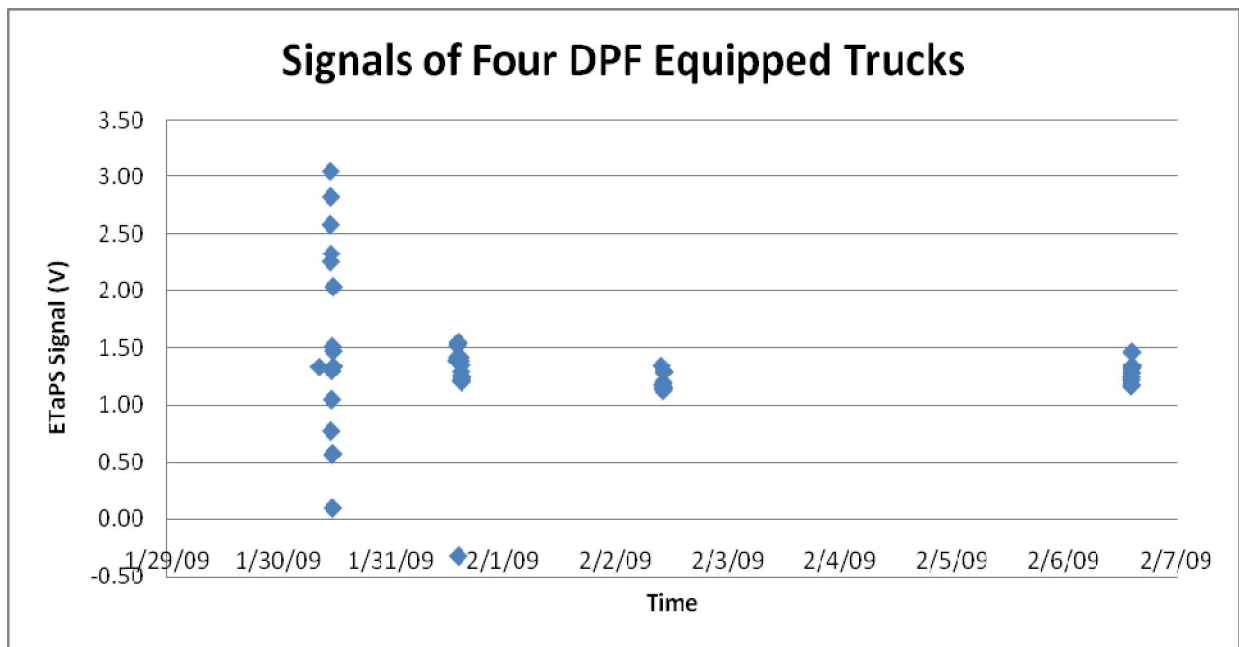


Figure 2.8. Two second average ETaPS readings from four DPF equipped trucks as they passed the RSD location. The tightest cluster of points belonged to the DPF equipped Penske truck. This set of data is shown expanded versus time in Fig. 2.9. The observed signal had a range of about 0.25V for the least variable readings. The others were more variable.

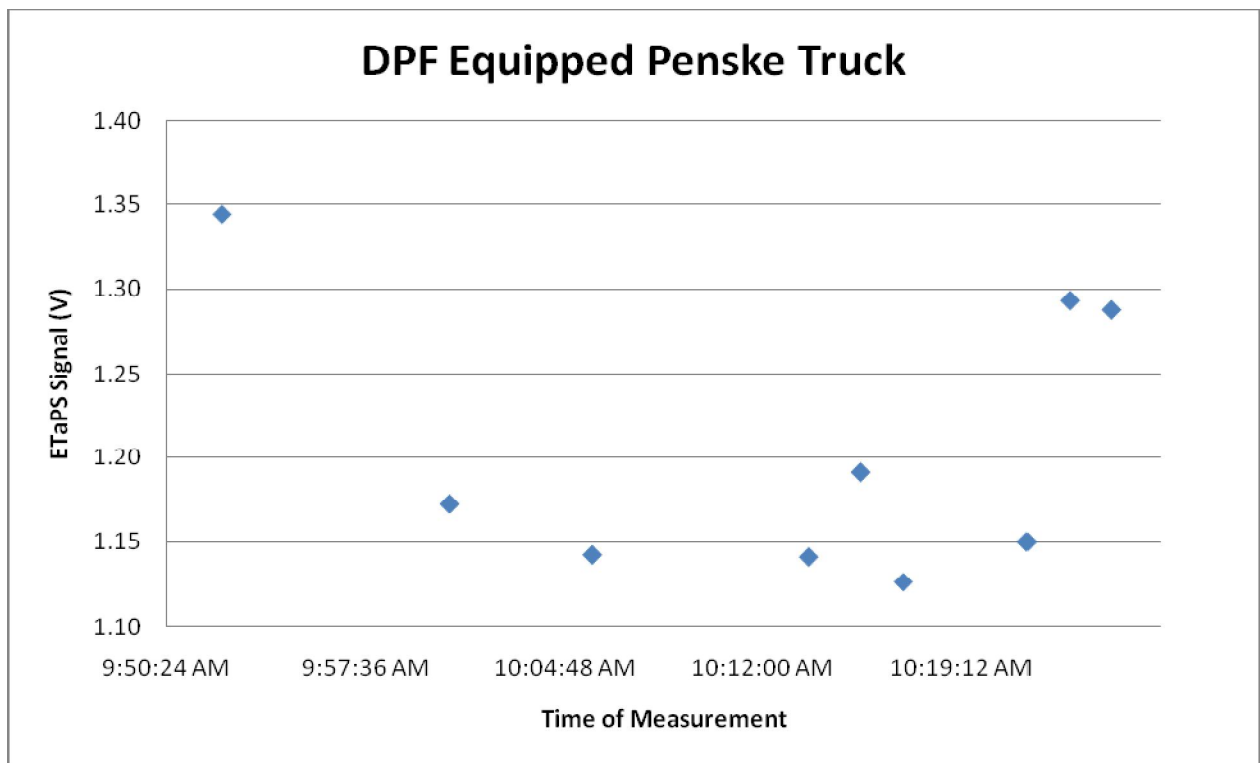


Figure 2.9. Two second average ETaPS voltage readings graphed versus the time at which this vehicle passed the RSD location for the least variable DPF equipped vehicle monitored at Westover.

The dynamometer testing, expected to show no power line interference, only showed a signal range of about 0.0275V and an average of 0.01V for approximately 2000 one-second data points for both the cruise and step test. These results are shown in Figures 2.10 and 2.11.

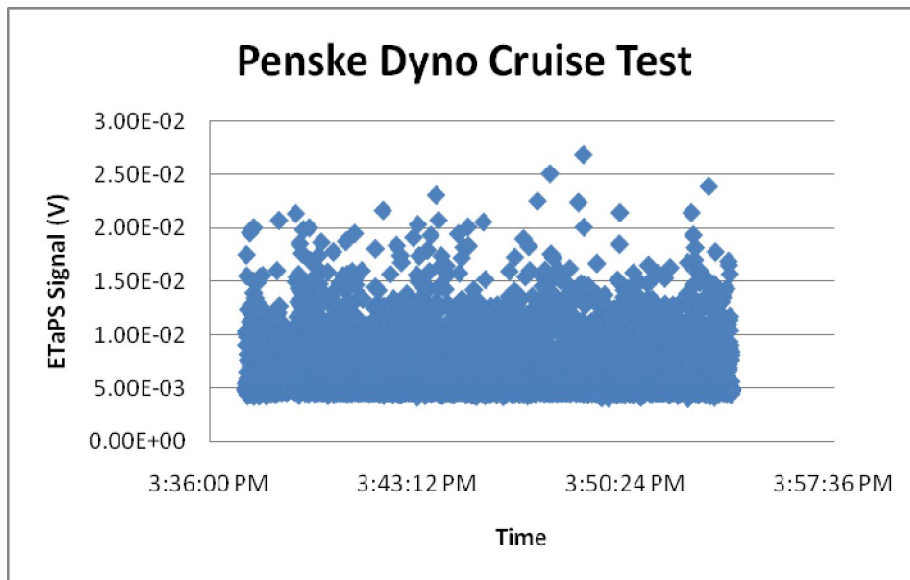


Figure 2.10. More than 2000, one second ETaPS readings from a DPF vehicle on the dynamometer.

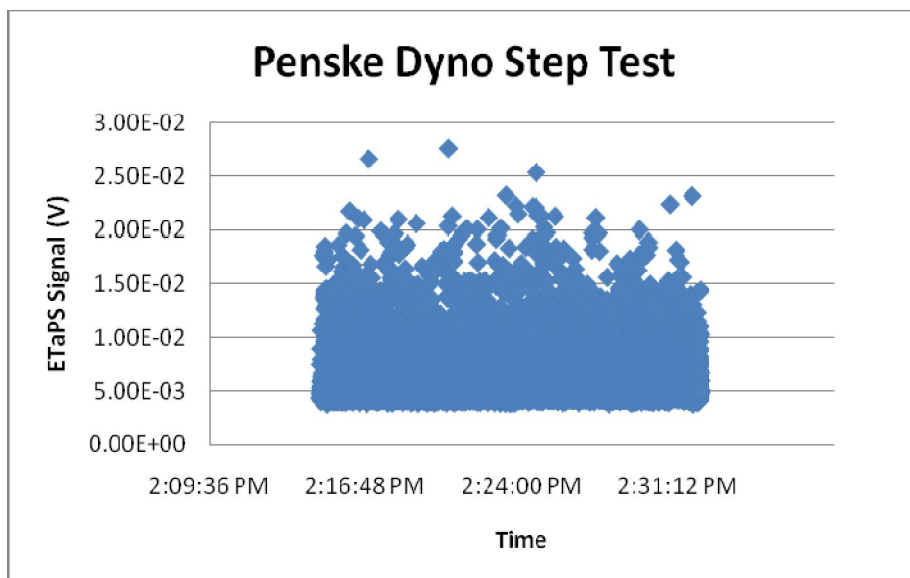


Figure 2.11. More than 2000, one second ETaPS readings from a DPF vehicle on the dynamometer.

In the best case scenario, the variability with time of ETaPS signals under the power line is more than an order of magnitude larger than the variability on the dynamometer. The observed variability is also equal in magnitude to the signal difference between a DPF bypassed and non-bypassed Volvo truck. In the worst case scenario, the fluctuation of ETaPS signals under the power line ranged from 0 to 3V in a single day. Not only is this variability a problem but also the average ETaPS signal is over 1V while it should be less than 0.01 V for these vehicles which all other measurements indicate are not emitting a significant quantity of particles.

In retrospect we have looked at the ETaPS readings from the later round of vehicle testing when the truck engine was turned off. These readings varied from the expected zero to as high as 3.7V, presumably depending on where the driver chose to park the tractor relative to the overhead power lines. We did not attempt to control where this event occurred. See Section 3.9 for results on ETaPS precision and variability for the “open” configuration.

Findings 2.1:

- The ETaPS response to the power line interference, when compared to its dynamometer tests, showed its variability to outside influences in its “open” configuration.

2.2. ETaPS versus RSD Data

As discussed in the previous section, we are now certain that the ETaPS data in Westover are highly compromised by the effect of the local overhead power lines. We did not know if this interference was with the ETaPS corona itself or with the data lines which bring the data to the data acquisition system. We have now proven the former, because the same open data lines were used in the preliminary studies in Denver in which the (shielded) ETaPS baseline readings were reasonably close to zero volts.

In case there was any useful residual information in the outdoors ETaPS readings, PM measurement by ETaPS was calculated in ratio to CO₂ to compare to the RSD readings which are all ratio to CO₂. The ETaPS readings were averaged over two seconds when the vehicle was passing the RSD unit. CO₂ was determined by calculation from the measurement of percent O₂ in the exhaust stream averaged over the two seconds when the vehicle was passing the RSD unit. This ETaPS ratio was plotted vs. UV smoke signal from the RSD 4600 in Figure 2.12.

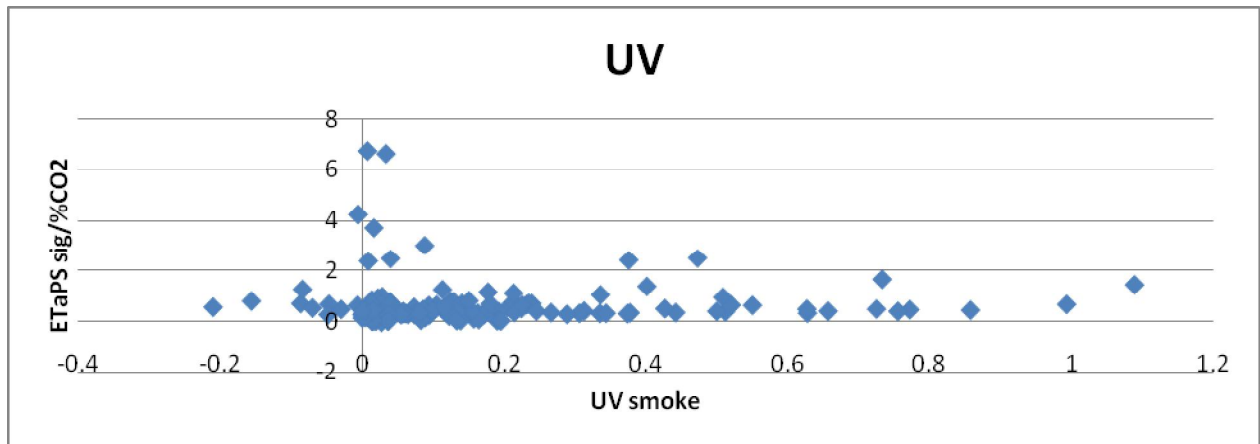


Figure 2.12. ETaPS divided by CO₂ versus UV smoke reading.

There is very significant scatter in the data, although there does appear to be a large clump of data close to zero (mostly provided by the DPF equipped vehicles) and a general tendency of the ETaPS/CO₂ readings to increase as the UV smoke reading increases. This correlation was not studied further in view of the conclusions above regarding the unreliability of the Westover ETaPS readings.

With the good looking outdoor ETaPS results in Denver we were expecting equally good ETaPS readings at Westover. The first five trucks gave the expected zero readings when the truck was parked with the engine off, away from the power lines and relatively high readings when passing the RSD which we (incorrectly as it turned out) ascribed to particles. The second visit we did manage to find and obtain some quantitative readings on the power line interference, however, we were not able to find a means to eliminate this problem. We have now shown that mounting the ETaPS in its small section of exhaust pipe is a solution.

3. ETaPS Data from West Virginia

Five different post 2007 trucks, equipped with a DPF, were tested in two modes (A and B). Mode A tests the ETaPS ability to detect particles in raw exhaust that has been treated with a functional DPF. Mode B tests the ETaPS ability to detect particles in raw exhaust that has been partially bypassed around the DPF, which simulates a failing DPF. A five inch diameter pipe was fixed to the exhaust line right before and after the DPF. Exhaust was diverted through this bypass pipe with a butterfly valve. The butterfly valve was only a quarter of the way open as to not saturate the ETaPS output, which is only 10 volts. For our purposes we consider trucks tested under Mode A to be different than trucks tested under Mode B which means that 10 post 2007 trucks have been tested, not 5 (Table 3.1). Test procedures from Milestone 3 were duplicated for this round of testing. Combining the tests for the pre-2007 trucks, from Milestone 3, with the post-2007 tests, each truck underwent three different testing cycles (UDDS, ETaPS40-cruise, and Accel) on the dynamometer chassis for a total of 44 tests and 104 runs (See Appendix A for details on each cycle). Correlations were also analyzed between ETaPS and inferred CO₂ measurements as well as CO₂ measurements from the dilution chamber and integrated ETaPS measurements against integrated TEOM measurements. Each truck also underwent three or more runs at three different speeds (5mph, 10-15mph, and ~20mph) through the RSD 4600 for a total of 149 tests. RSD is graphed against the gravimetric results to see if RSD can be a reasonable detector of high PM emitting trucks.

Truck	Bypassed?	Test			# Tests	# Runs
		UDDS	Cruise	Accel		
1995 Mack	N/A	3	3	1	3	7
1996 Peterbilt	N/A	3	3	1	3	7
1994 Freightliner	N/A	3	3	1	3	7
1999 Peterbilt	N/A	3	3	1	3	7
2005 Thomas Bus	N/A	3	3	0	2	6
2009 Thomas Bus A*	No	3	3	1	3	7
2008 Volvo A*	No	3	3	1	3	7
2008 Penske A*	No	3	3	1	3	7
2008 Volvo Day Cab A*	No	3	3	1	3	7
2007 Prostar A*	No	3	3	1	3	7
2009 Thomas Bus B*	Yes	3	3	1	3	7
2008 Volvo B*	Yes	3	3	1	3	7
2008 Penske B*	Yes	3	3	1	3	7
2008 Volvo Day Cab B*	Yes	3	3	1	3	7
2007 Prostar B*	Yes	3	3	1	3	7
* denotes DPF equipped					44	104

Table 3.1 shows the number of runs performed for each test listed by vehicle.

Truck	MY	DPF	PM	ES2	UV
Mack	1995	N/A	0.266	84.3	0.258
Peterbilt	1996	N/A	0.449	306	0.213
Freightliner	1994	N/A	0.297	243	0.559
Peterbilt	1999	N/A	0.469	295	0.145
Thomas Bus	2005	N/A	0.350	222	0.200
Thomas Bus A	2009	Non-Bypassed	0.006	1.01	N/A
Volvo A	2008	Non-Bypassed	0.008	1.37	0.018
Penske A	2008	Non-Bypassed	0.007	0.94	0.021
Volvo Day Cab A	2008	Non-Bypassed	0.007	0.80	0.017
Prostar A	2007	Non-Bypassed	0.012	0.85	-0.081
Thomas Bus B	2009	Bypassed	0.150	133	N/A
Volvo B	2008	Bypassed	1.106	92.6	0.037
Penske B	2008	Bypassed	0.070	118.	0.080
Volvo Day Cab B	2008	Bypassed	0.074	47.00	0.031
Prostar B	2007	Bypassed	0.168	105	0.132

PM- PM (g/mile)

ES2- ETaPS Signal (volt sec/mile)

UV- UV smoke factor (Sec. 1)

Table 3.2 lists averaged data for each truck tested. Each average (PM, integral volts, and UV smoke) includes all runs of all tests for one truck. The UV results for the 2009 Thomas bus are listed as N/A because RSD testing on this vehicle was cut short due to weather and we are unable to determine if the few runs that were recorded were bypassed. For a full list of individual truck emissions see Appendix A, Table 2.



ETaPS in hot, raw exhaust before CVS dilution tunnel.



Current setup of ETaPS on an elevated exhaust pipe.



RSD setup outside WVU testing facility.



2008 Volvo day cab on dynamometer with insulated pipe.

Figure 3.1 Pictures of the ETaPS in various configurations

These four pictures in Figure 3.1 show the current setups for the ETaPS, RSD and Dynamometer instruments. As discussed in previous sections, the ETaPS responds very differently if it is not put in an enclosed, shielded pipe as in the CVS test. The top right picture shows just one possible conformation of the ETaPS in an open environment with long, running cables traveling to the bed of the truck and to the passenger seat. The time required to decorate an ETaPS on a truck can be as little as 5 minutes. We used a large plastic storage bin, purchased from Office Depot, to store the necessary operational components. These included: a 15 volt power supply, an air pump with two outputs of 30 lpm to keep the ETaPS clean and cool, a 15 volt power supply for the oxygen sensor, and a NI USB-6009 data acquisition box. A portable 1 kilowatt generator provides sufficient power for the bin. Both the generator and storage bin can be easily fastened to the bed of the truck with bungee cords. In some instances there was no room on the bed and the generator was fastened to the passenger side steps and the storage bin was placed in the cab of the truck. The lower right picture shows the insulated piping of the exhaust to reach the CVS dilution tunnel. Distances varied depending on the location of the exhaust pipe. The top left picture shows the successful horizontal conformation, accompanied with a large blue floor fan to help cool the ETaPS circuitry. The original vertical conformation was too favorable for overheating issues in the ETaPS circuitry.

3.1. Post 2007 Results

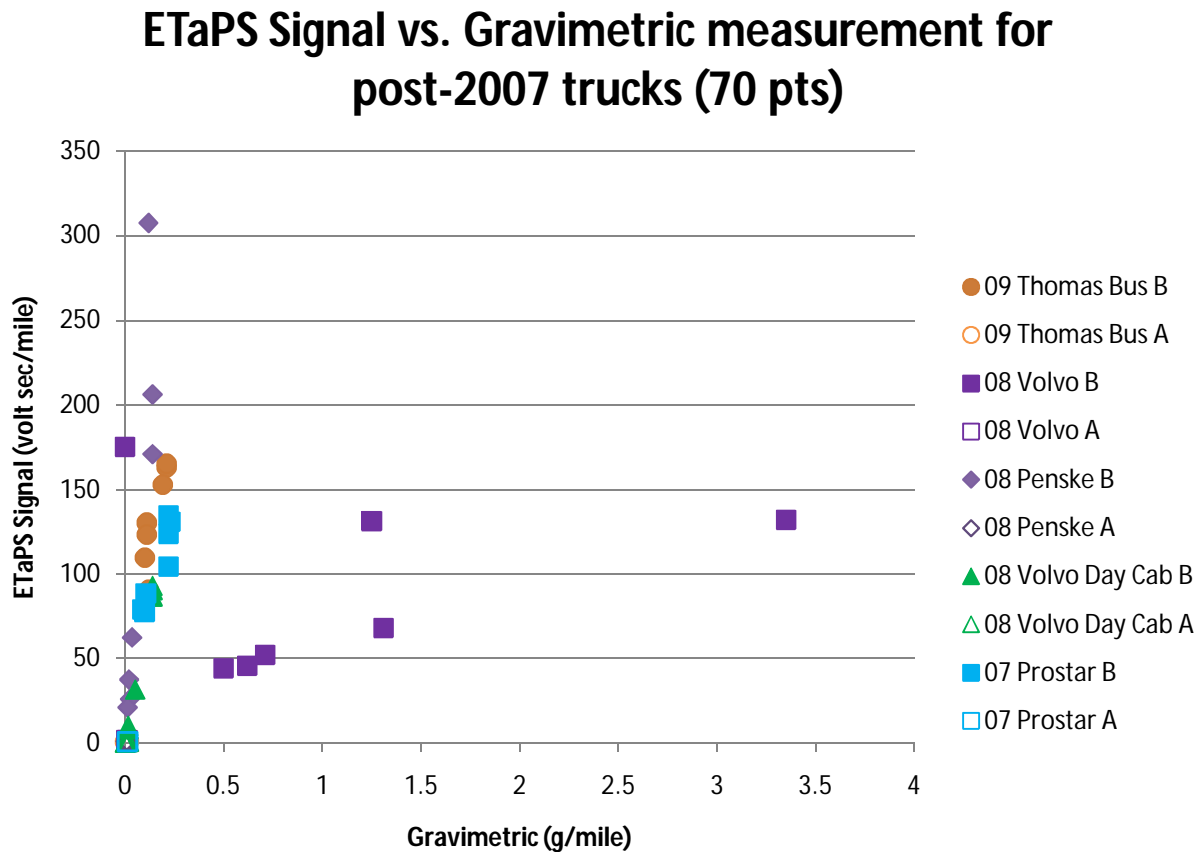


Figure 3.2 shows all runs for post-2007 vehicles categorized by individual vehicle. Notice what seems to be a nice correlation of points that produce less than 0.5 g/mile. Tests that produce >0.5 g/mile come from the 2008 Volvo B and are most likely due to semi volatiles in the exhaust that the ETaPS cannot detect (see section 3.3). 35 of the 70 points are at the origin and come from trucks tested in Mode A (see section 3.2).

ETaPS Signal vs. Gravimetric measurement by driving mode for post-2007 trucks (70 pts)

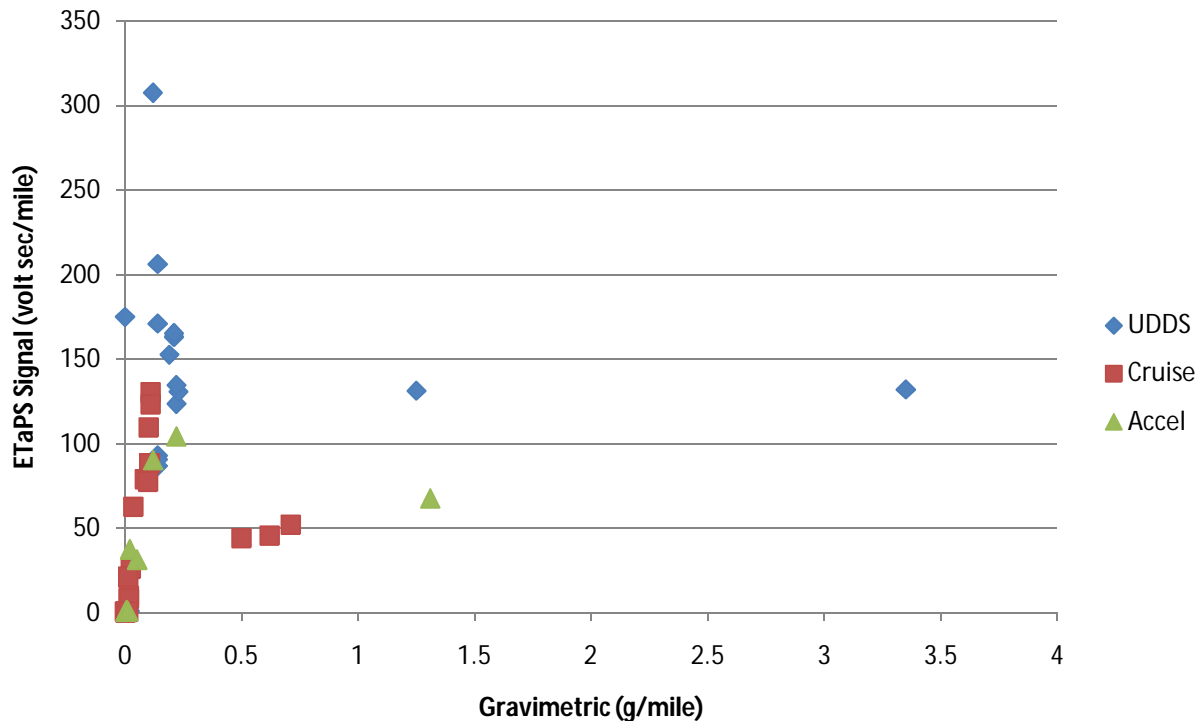


Figure 3.3 shows all runs for post-2007 vehicles categorized by driving mode.

Findings:

- Eight of the ten post-2007 trucks seem to correlate well and relatively clean (<0.5 g/mile)
- 2008 Volvo B is high emitter relative to the nine other trucks (discussed in section 3.3)
- Trucks tested under Mode A produce points at the origin (35 points)

3.2. Post 2007 Results Excluding the 2008 Volvo B

3.2.1. The gross polluting 2008 Volvo B shows just how dependent it is on its DPF. If we assume for a moment that this vehicle is non-representative of the post 2007 fleet of vehicles (or that it is simply failing elsewhere) and exclude it, we will see a fairly good correlation between the remaining four trucks.

ETaPS Signal vs. Gravimetric measurement for post-2007 trucks, no 2008 Volvo B (63 pts)

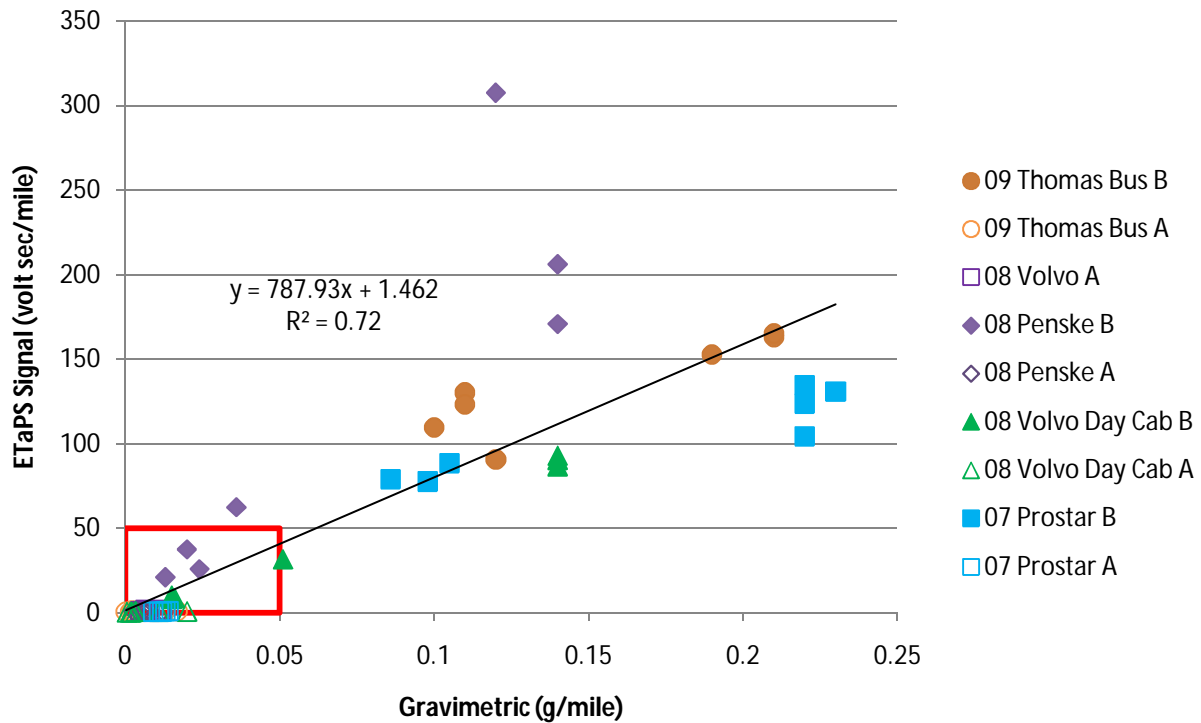


Figure 3.4 shows the overall correlation (R^2 of 0.72) for nine of the ten post-2007 vehicles. Only the 2008 Volvo B truck is excluded. We should point out that the maximum points on the x-axis are all < 0.25 g/mile. Again, the butterfly valve used in the Mode B tests was intentionally set to increase the real-time ETaPS signal independent of any gravimetric data. The red box outlines the dimensions for Fig. 3.4a.

ETaPS Signal vs. Gravimetric measurement for post-2007 trucks, no 2008 Volvo B (41 pts)

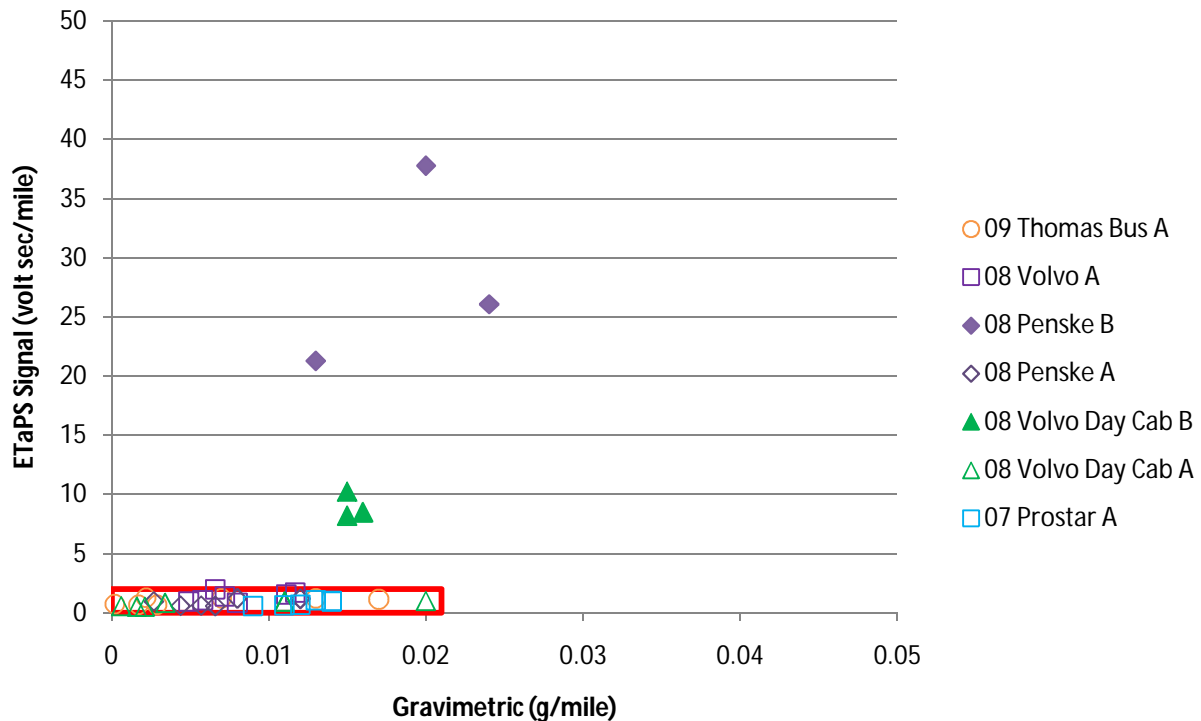


Figure 3.4a is a closer view of points around the origin. All points within the red box are non-bypassed DPF equipped trucks. All points outside box are bypassed DPF equipped trucks. The box dimensions are 0.021 g/mile and 2 Vs/mi.

Even though both axes have been reduced by at least a factor of 5 in Figure 3.4a, the box that separates all the non-bypassed from the rest of the data is very small. All non-bypassed points are less than 2 Vs/mi for the ETaPS and less than 0.021 g/mile for gravimetric. There are however, 5 points that fall below the gravimetric boundary of 0.021 g/mile that are bypassed, but these 5 points read at least 5 times higher on the ETaPS.

ETaPS Signal vs. Gravimetric measurement by driving mode for post 2007 trucks, no 2008 Volvo B (63 pts)

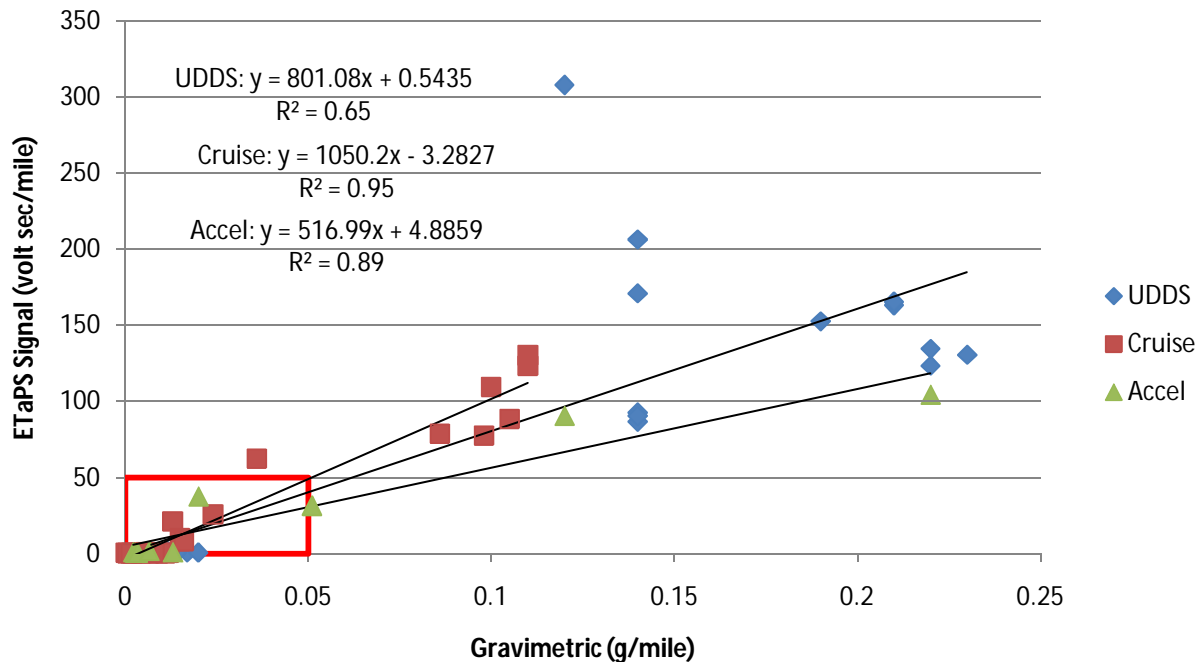


Figure 3.5 shows the individual correlations based on test cycle driven for eight of the ten post-2007 trucks. This is the same data set as shown in Fig. 3.4 except that it has been divided into three subsets and correlations were determined for each subset. In the cases for the Accel cycle and Cruise cycle, the correlations improve 24% and 32%, respectively. The UDDS, however, slightly decreased by 10%. The red box outlines the dimensions for Fig. 3.5a.

One would expect these correlations to be smaller than the original if the original data set is decreased, yet we see larger correlations for two subsets when the data set is decreased by one third. This illustrates to us that these new data subsets are meaningful and that there are correlations among all eight trucks depending on the driving cycle.

ETaPS Signal vs. Gravimetric measurement by driving mode for post 2007 trucks, no 2008 Volvo B (41 pts)

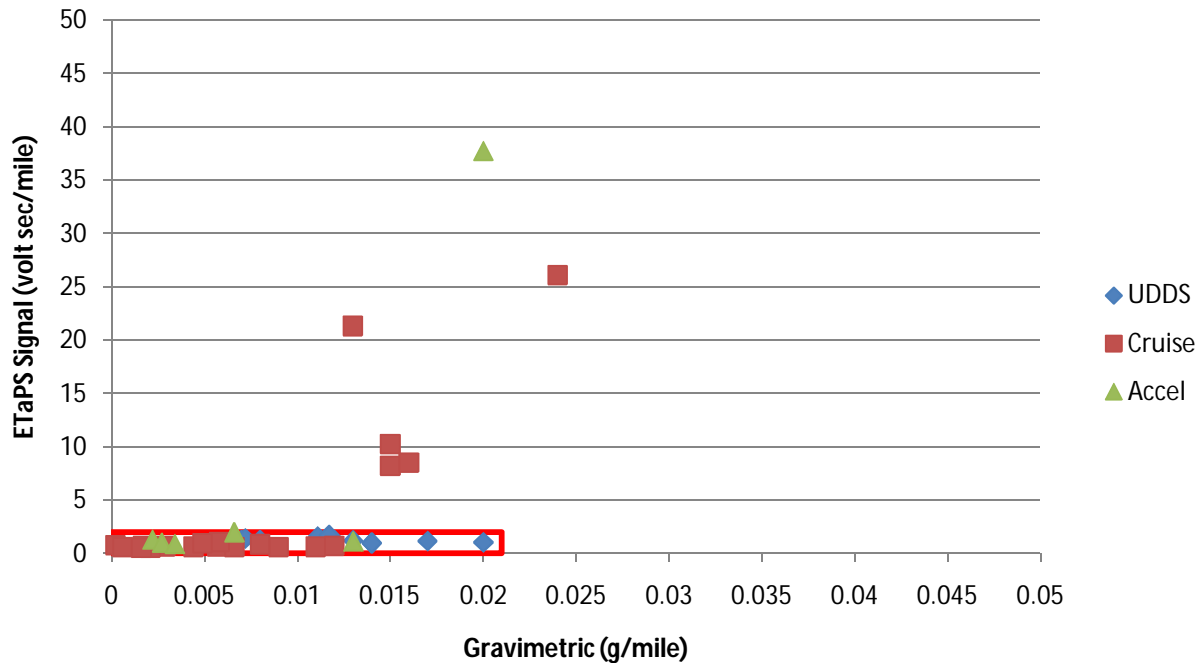


Figure 3.5a is a closer view of points around the origin. All points within the red box are non-bypassed DPF equipped trucks. All points outside the red box are either bypassed DPF equipped trucks or not equipped DPF trucks. The box dimensions are 0.021 g/mile and 2 Vs/mi.

Findings:

- Nine of the ten post-2007 trucks correlate well with each other having an R^2 value of 0.72.
- Classifying all 63 points for the nine trucks by driving cycle drastically improves the correlations for the Accel cycle and Cruise cycle by 24% and 32%, respectively. The UDDS cycle decreased by 10%.
- All trucks tested under Mode A fall near or at the origin with a very distinct separation from trucks tested under Mode B (i.e. 5x lower ETaPS reading)
- ETaPS shows promising ability to indicate whether or not a DPF is operating correctly or failing.

3.3. 2008 Volvo B Outlier

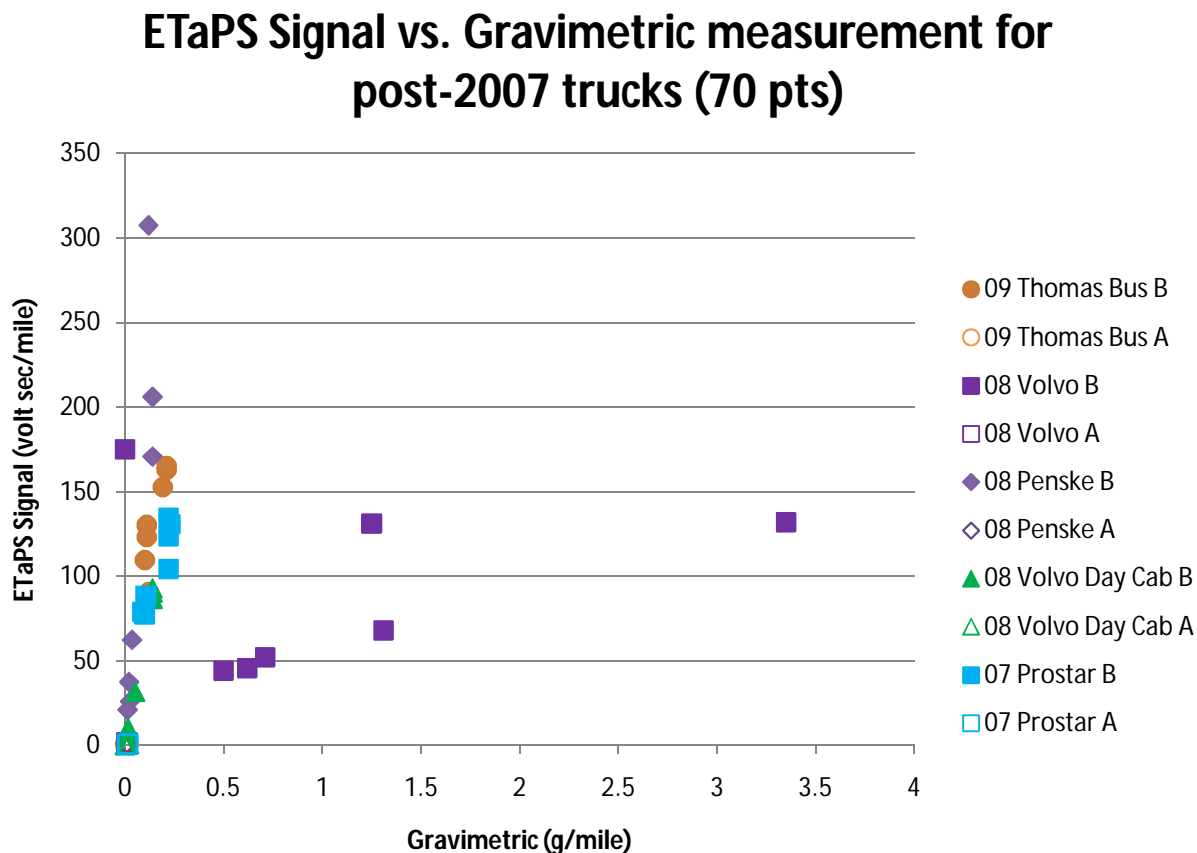


Figure 3.6. All vehicles, all ETaPS Vs/mi integral voltages versus gravimetric readings. The 2008 Volvo B shows a distinct, separate trend from the other eight trucks

One major difference between the ETaPS collection point and the gravimetric filter collection point is temperature. The ETaPS is a real time diffusion charger that is placed in the raw exhaust where, in our case, temperatures can reach as high as 600° F. The temperatures on the filter face were far lower with values around 100° F. At these relative lower temperatures semi-volatiles that are present in the exhaust are allowed to cool and condense on the filters, whilst not registering on the ETaPS readout. Looking at the data for the raw emissions the 2008 Volvo B was the *only* truck that disagreed with the other 14 trucks on hydrocarbon emissions. While the 14 other trucks registered a high of 0.75 g/mile for HC, the 2008 Volvo registered a high of 10 g/mile for HC.

Findings:

- Semi-volatiles in the exhaust will score high on the gravimetric and lower on the ETaPS due to the large temperature difference.
- The 2008 Volvo B was the only truck to register large HC emissions (10 g/mile).

3.4. Pre 2007 and Post 2007 Results 14 of the 15 trucks (excluding 2008 Volvo B)

Combining all points/trucks thus far shows a correlation between a wide variety of vehicles. Figure 3.7 shows all points from the beginning of testing in December 2008 to the end of testing in February 2009. In absence of the aforementioned 2008 Volvo B, there is a reasonable correlation among the rest of the points (Fig 3.8).

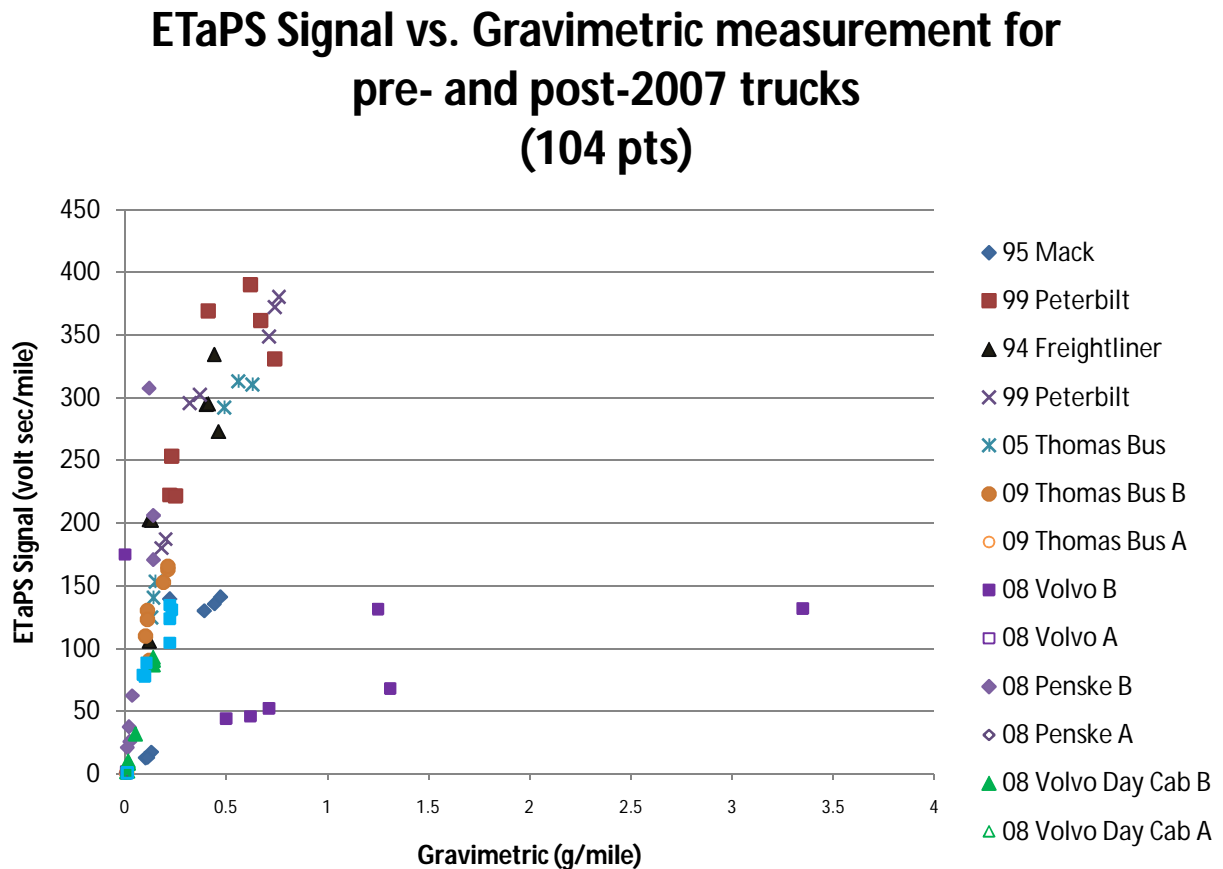


Figure 3.7 shows all points collected from 15 trucks. Y-axis is the ETaPS Signal (Vs/mi). X-axis is Gravimetric (g/mile).

ETaPS Signal vs. Gravimetric measurement for pre- and post-2007 trucks, no 2008 Volvo B (97 pts)

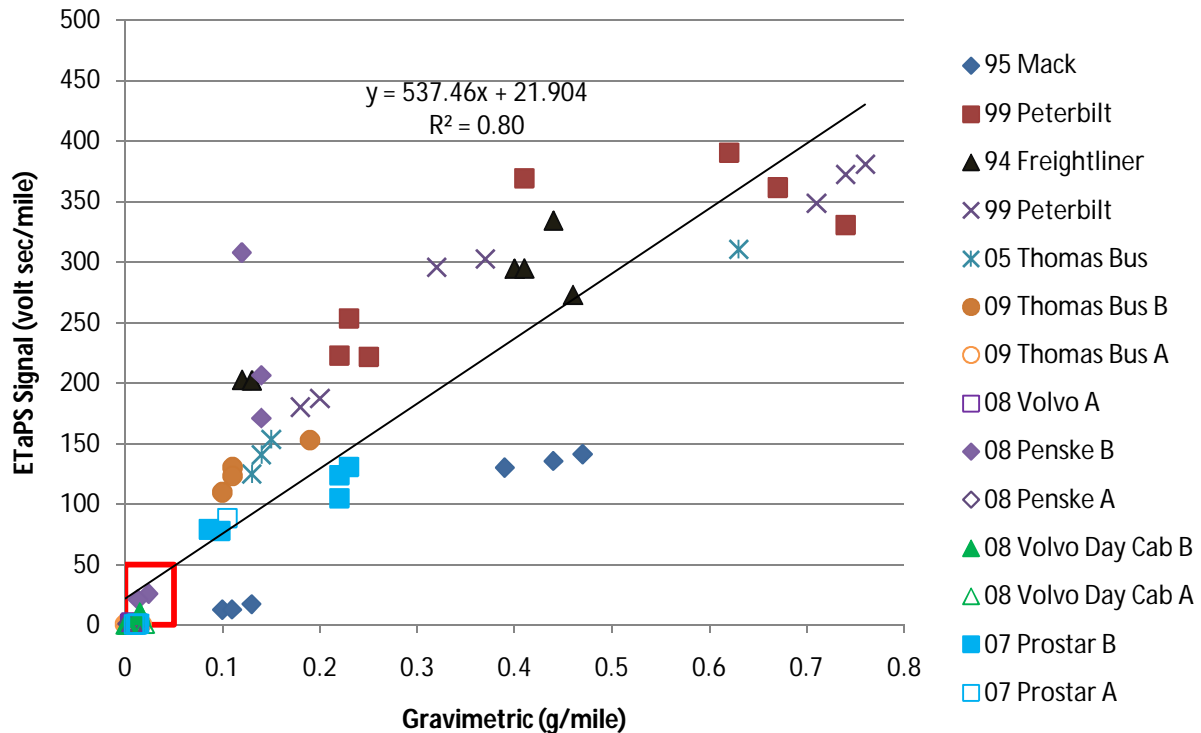


Figure 3.8 shows a decent overall correlation of 0.80 for all tests (excluding the 2008 Volvo B).

There are a total of 97 data points plotted in Figure 3.8. More than one third (41) of these points are located within the red box outlined near the origin. This red box is enlarged in Figure 3.8a to show where exactly any trucks tested under Mode A would fall compared to trucks tested under Mode B. Of the 41 points in the red box all 35 runs corresponding to a functional DPF system fall right at the origin. The remaining 6 points are trucks with bypassed DPF systems that are still burning fairly clean according to the gravimetric results.

ETaPS Signal vs. Gravimetric measurement for post-2007 trucks, no 2008 Volvo B (41 pts)

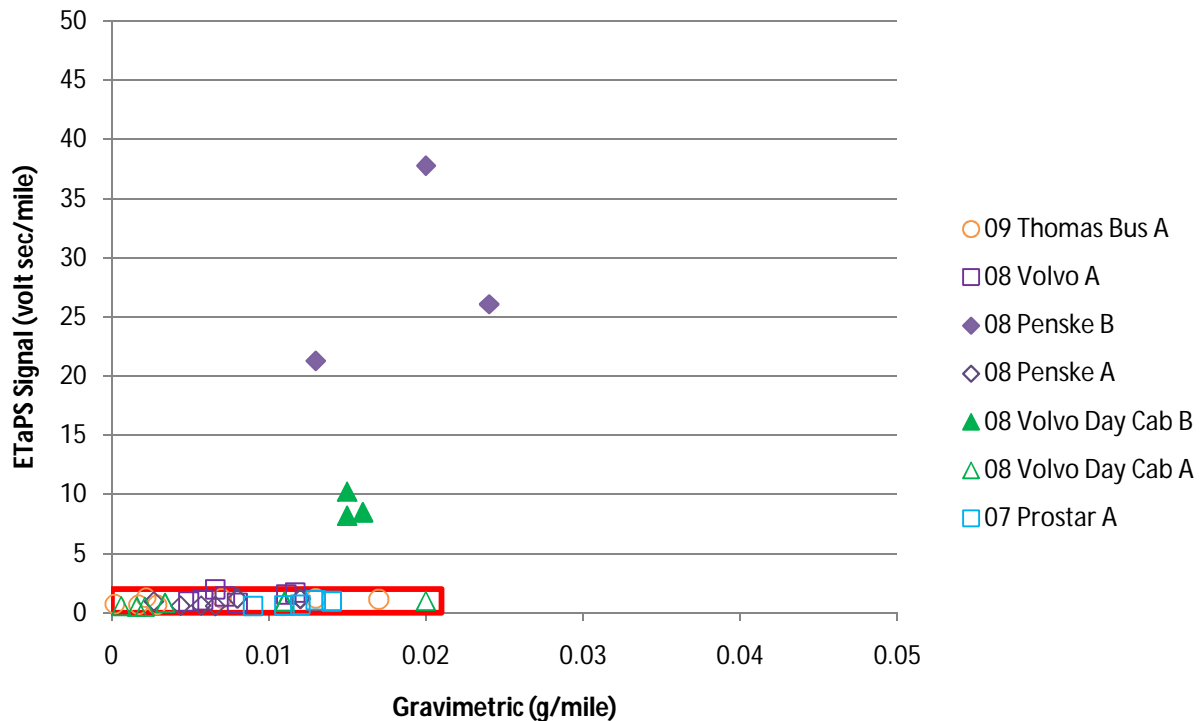


Figure 3.8a is closer view of points around the origin from Figure 3.8. All points within the red box are non-bypassed DPF equipped trucks. All points outside the red box are either bypassed DPF equipped trucks. There are no points from pre-2007 trucks that fall within the parameters of this graph.

Every truck with a DPF system tested under functioning conditions totaled less 2 Vs/mi on the ETaPS and less than 21 mg/mile on the gravimetric scale. The cleanest Mode B trucks (2008 Volvo Day Cab A and 2009 Penske A), according to the gravimetric readings, were just as low emitting as the Mode A trucks but had at least a 5 times higher reading on the ETaPS.

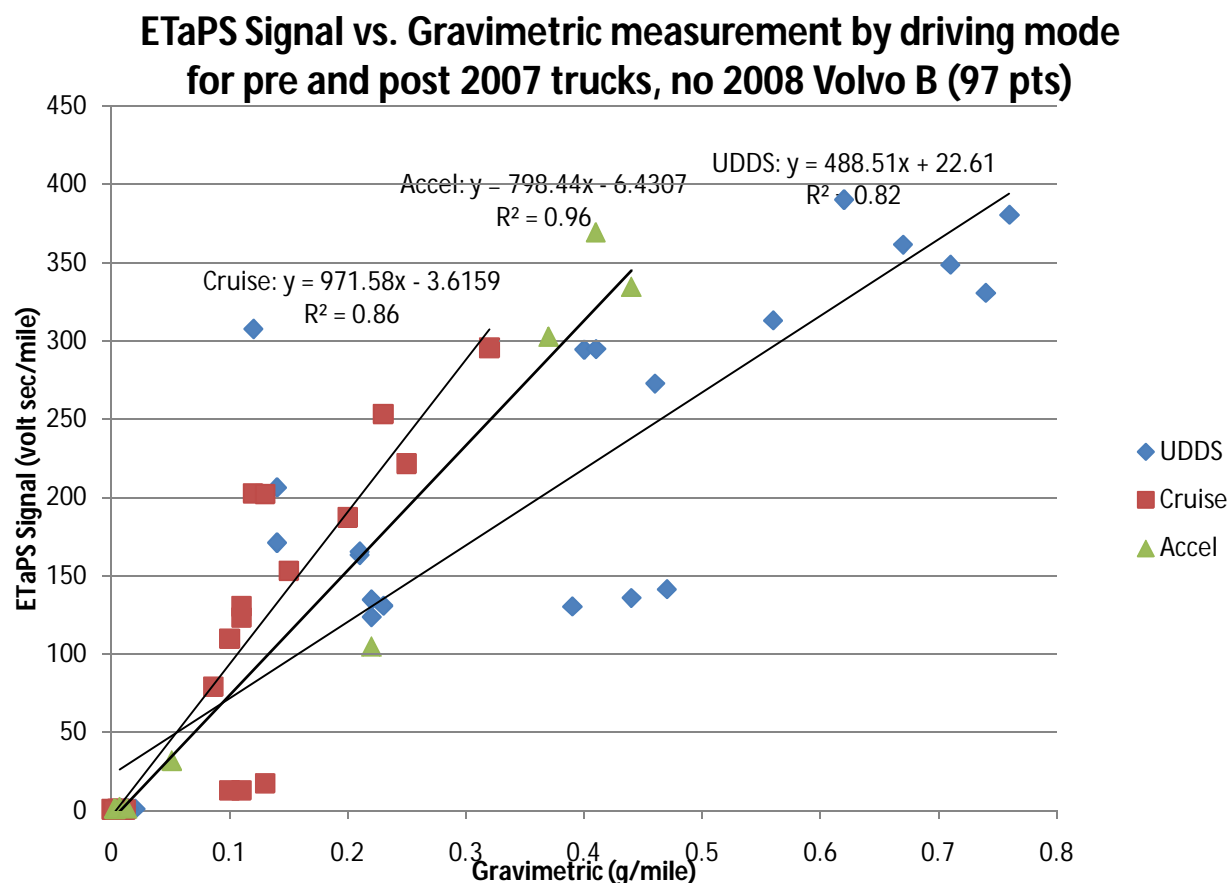


Figure 3.9 separates all those points from Fig. 3.8 by individual test. It is worth noting that even though the data set was divided into smaller groups, by each test, there is a greater R^2 value for each group than the overall trendline.

Looking more closely at the slopes of Figures 3.8 and 3.9, the Cruise cycle and Accel cycle ETaPS results (~500-1000 Vs/g) are close to one Vs/mg within the 95% confidence limit of their slopes. For the UDDS the overall slope is closer to 0.5. The Cruise cycle and Accel cycle show the most agreement with a recent ETaPS study from Maricq et al. (1) comparing the ETaPS response to gasoline, diesel and high-emitting diesel vehicles. They report a slope near one Vs/mg of ETaPS against gravimetric. The Maricq study only tested LDDV and no post-2007 DPF equipped diesel trucks, which they report emit ~80% elemental carbon.

ETaPS Signal vs. Gravimetric measurement by driving mode for post 2007 trucks, no 2008 Volvo B (41 pts)

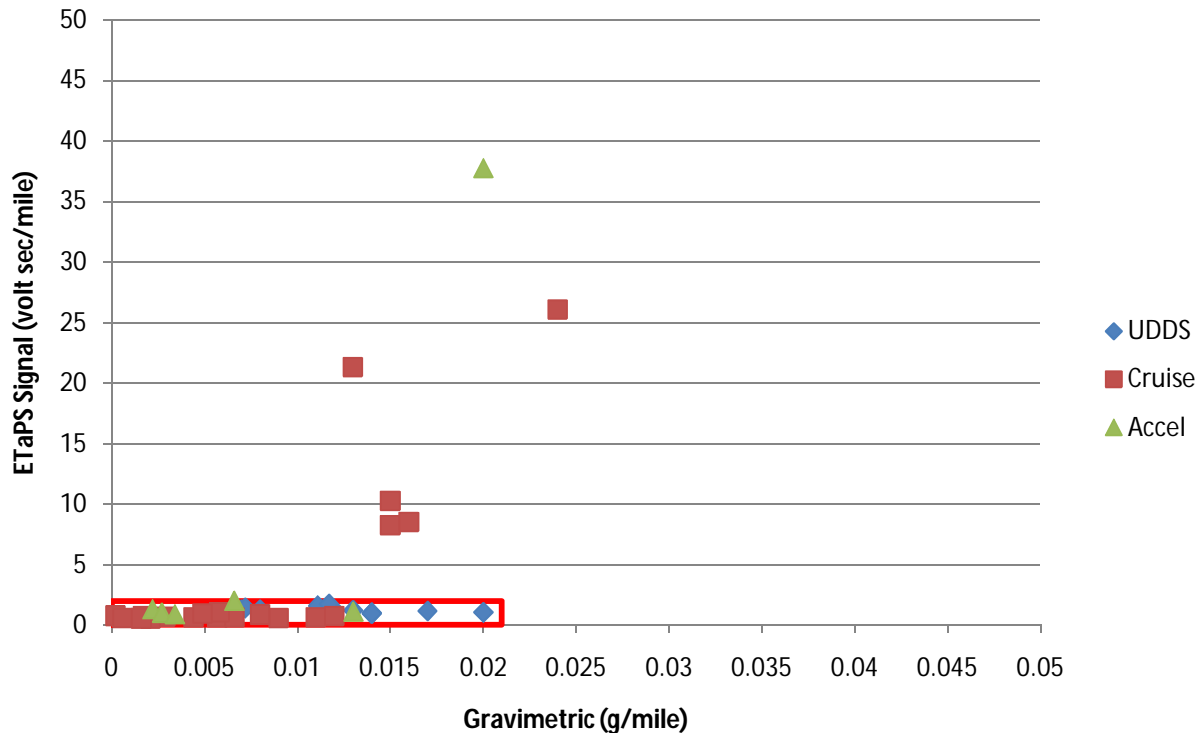


Figure 3.9a is closer view of points around the origin. All points within the red box are trucks tested under Mode A (non-bypassed). All points outside the red box are trucks tested under Mode B (bypassed) and have dimensions of 2 Vs/mi (ETaPS Signal) and 21 mg/mile (Gravimetric). There are no points from pre-2007 trucks that fall within the parameters of this graph.

Summary:

- 3.1 Findings
 - Nine of the ten post-2007 trucks seem to correlate well and relatively clean (<.5 g/mile)
 - 2008 Volvo B is high emitter relative to the nine other trucks (discussed in section 3.3)
 - Trucks tested under Mode A produce points at the origin (35 points)
- 3.2 Findings
 - Nine of the ten post-2007 trucks correlate well with each other having an R^2 value of 0.72.
 - Classifying all 63 points for the eight trucks by driving cycle improves the correlations for the Accel cycle and Cruise cycle by 24% and 32%, respectively. The UDDS cycle decreased by 10%.
 - All trucks tested under Mode A fall near or at the origin with a very distinct separation from trucks tested under Mode B (i.e. 5x lower ETaPS reading)
 - ETaPS shows promising ability to indicate whether or not a DPF is operating correctly or failing.
- 3.3 Findings

- Semi-volatiles in the exhaust will score high on the gravimetric and lower on the ETaPS due to the large temperature difference.
- The 2008 Volvo B was the only truck to register large HC emissions (10 g/mile).
- 3.4 Findings
 - Combining pre-2007 points with post-2007 points increases the overall correlation to 0.80 for 14 of 15 trucks
 - Dividing the data set (97 pts) by test cycle increases the original correlation by 7.5%, 20%, and 2.5% for Cruise, Accel and UDDS, respectively.
 - Good slope agreement of one Vs/mg compared to Maricq study for Cruise and Accel cycles (97 points)

3.5. ETaPS VS CO₂

A wide-range oxygen sensor was placed near the ETaPS corona in raw exhaust to infer CO₂ and was compared to ETaPS response as well as the CO₂ measurements in the dilution chamber. Figure 3.10 shows good agreement between the wide-range oxygen sensor and the CO₂ measurements in the dilution chamber for the 1999 Peterbilt during a cruise cycle. Figure 3.11 shows the inferred CO₂ from the wide-range oxygen sensor versus the CO₂ measurements from the dilution chamber from 200 -875 seconds of the 1000 second cycle. Figure 3.12 shows the ETaPS response versus the inferred CO₂ readings from 200-1000 seconds of the 1999 Peterbilt cruise cycle.

Inferred CO₂ and Gravimetric CO₂ VS Time for 1999 Peterbilt cruise cycle

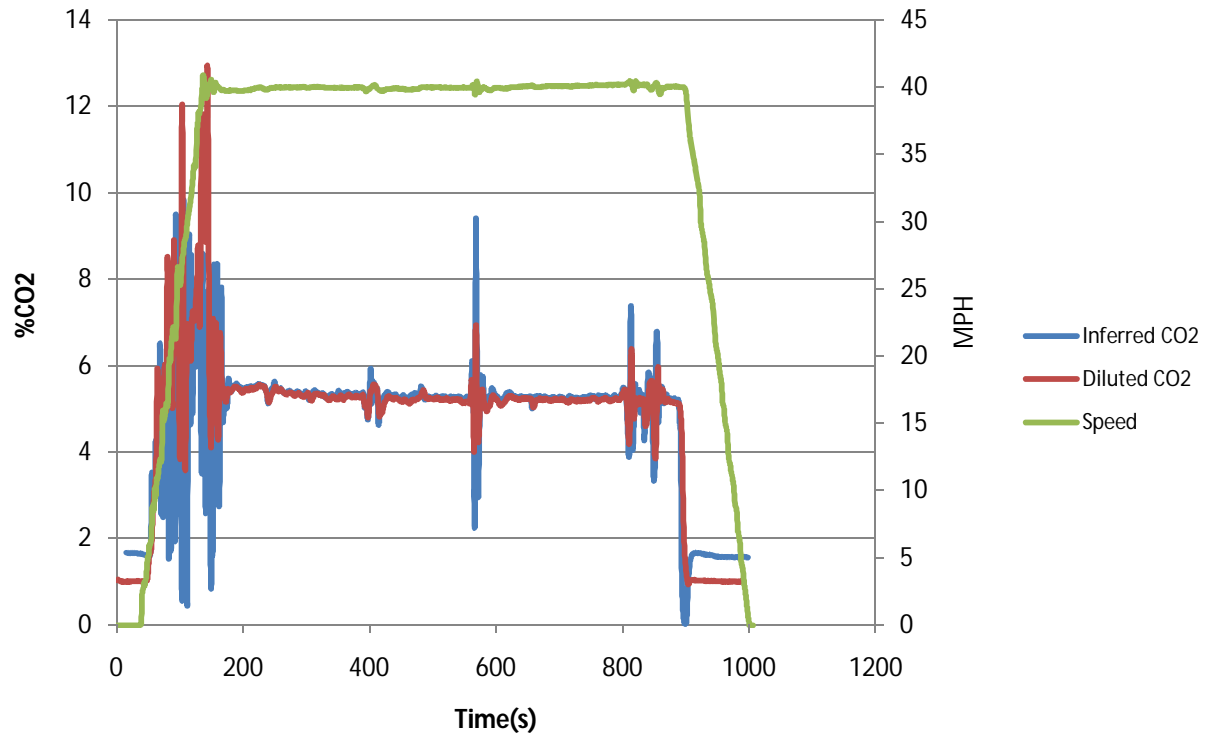


Figure 3.10 shows inferred CO₂ and CO₂ from the dilution chamber vs time. The diluted CO₂ readings have been adjusted by the chambers dilution factor and adjusted for the delay time it takes the exhaust around the ETaPS to reach the dilution chamber. Low values at the beginning of test are idle.

Inferred CO₂ VS Diluted CO₂ (200-875 sec)

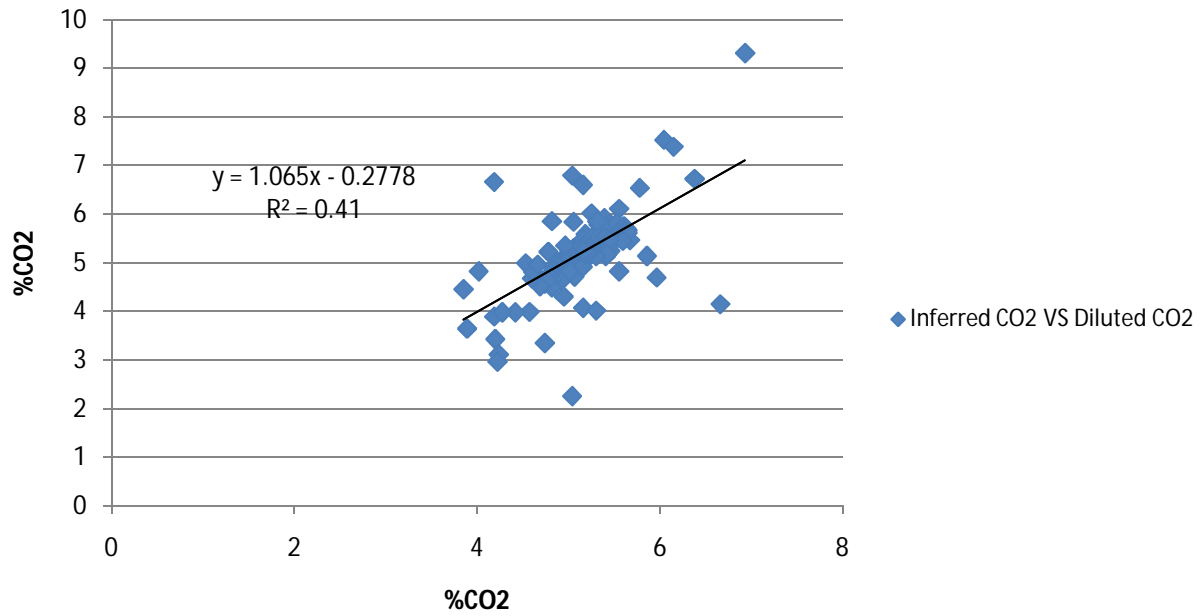


Figure 3.11 the two ends of the cycle were discarded for ratio comparison because of “jerky” accelerations and slowdowns that may have caused “coughs” in the system. Data were taken from the 1999 Peterbilt cruise cycle and the “noise” about the slope of one is expected due to the different time response of the two sensors.

ETaPS VS Inferred CO₂ (200-1000 sec)

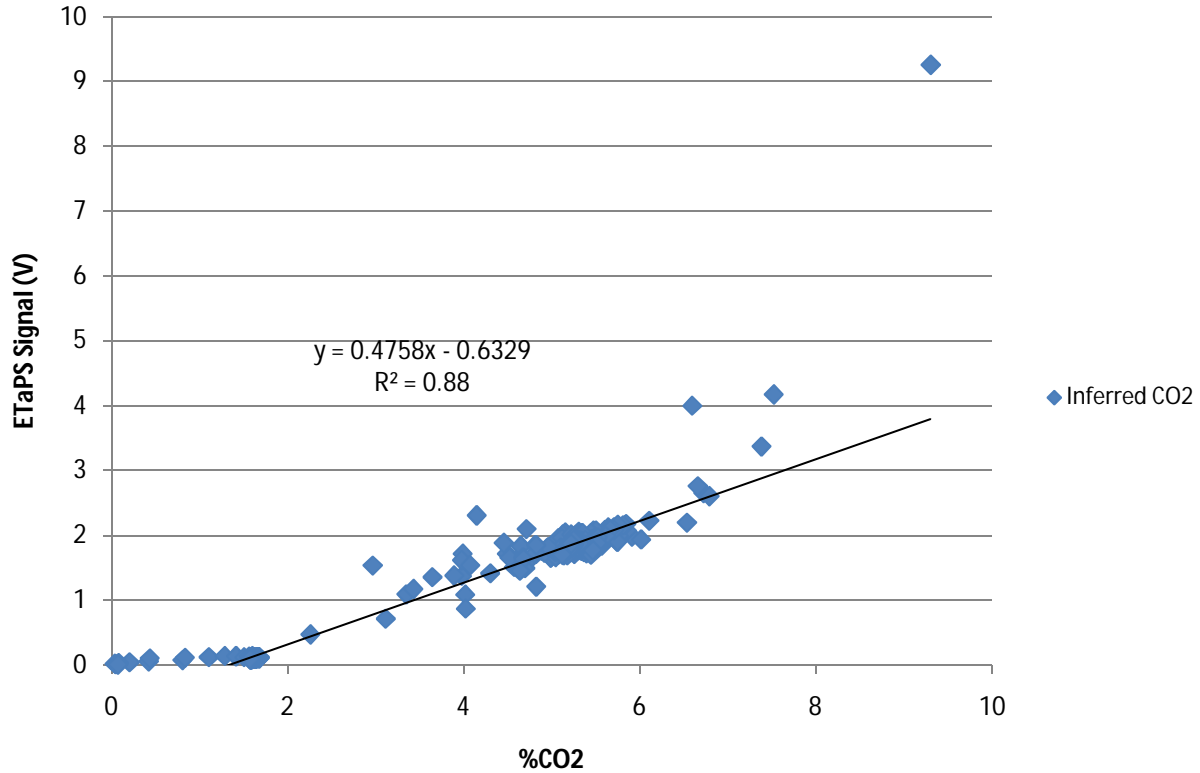


Figure 3.12 shows the same 1999 Peterbilt cruise cycle from 200-1000 seconds. The first 200 seconds were discarded also because of “jerky” accelerations causing “coughs.” For this pre-control vehicle it is apparent that the instantaneous particle emissions as measured by the ETaPS are well correlated with the vehicle load as determined by means of the simultaneous exhaust oxygen measurement. The zero ETaPS points are from the last 100 seconds of the test.

Findings:

- Inferred CO₂ measurements from the wide-range O₂ sensor showed reasonable agreement with the in-house CO₂ analyzer.
- Particle emissions are well correlated with vehicle load as determined by the inferred CO₂ for an individual vehicle.
- Using the inferred CO₂ measurements to weight the ETaPS measurements in hopes that emissions particle emissions rose and fell as a function of vehicle load did not tell us anything new compared to non-weighted ETaPS measurements. No further study was administered after seeing the results.

3.6. Integral ETaPS VS Integral TEOM

Comparing between the integrated ETaPS signal and the integrated TEOM mass shows results similar to the integral ETaPS VS PM mass filters with only a few negative TEOM values. Figure 3.13 shows results for each. Integrated ETaPS did not correlate as well with TEOM results as it did with the gravimetric results. More problems arose with the TEOM's dependence on humidity and temperature. While the R^2 values were only slightly less for the ETaPS/TEOM analysis, large negative and large positive TEOM values were thrown out due to temperature/humidity control problems that either added weight or reduced weight. Not only are the 2008 Volvo A/B results thrown out of this graph because of extremely high TEOM readings (i.e. 8 g/mile) but it also had the most negative points thrown out. That is to say, the 2008 Volvo's exhaust (composition and temperature) registers a decrease in mass according to the TEOM analyzer when the gravimetric filters register large amounts of apparent mass.

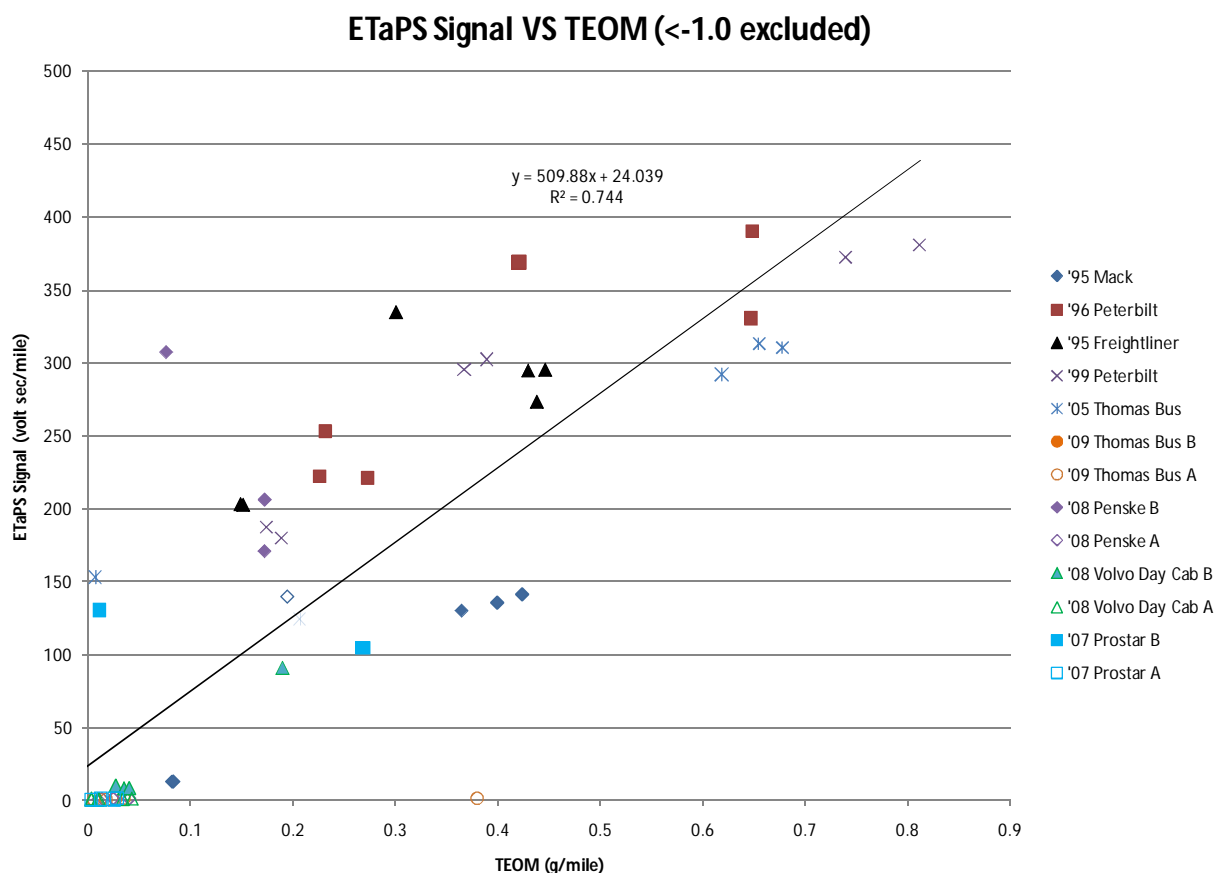


Figure 3.13 excludes points <-1.0 for Int. TEOM and excludes the 2008 Volvo Mode A/B points because Mode A had mostly negative values and Mode B had very large readings. Y-axis is ETaPS Signal (Vs/mi) and X-axis is TEOM (g/mile).

Findings:

- While the TEOM results were erratic in some instances (points not shown), they may provide extra information explaining why the 2008 Volvo is an outlier.

3.7. RSD VS Gravimetric

Figure 3.14 plots RSD averages of either bypassed, non-bypassed, or non-DPF equipped trucks against averages of their gravimetric results.

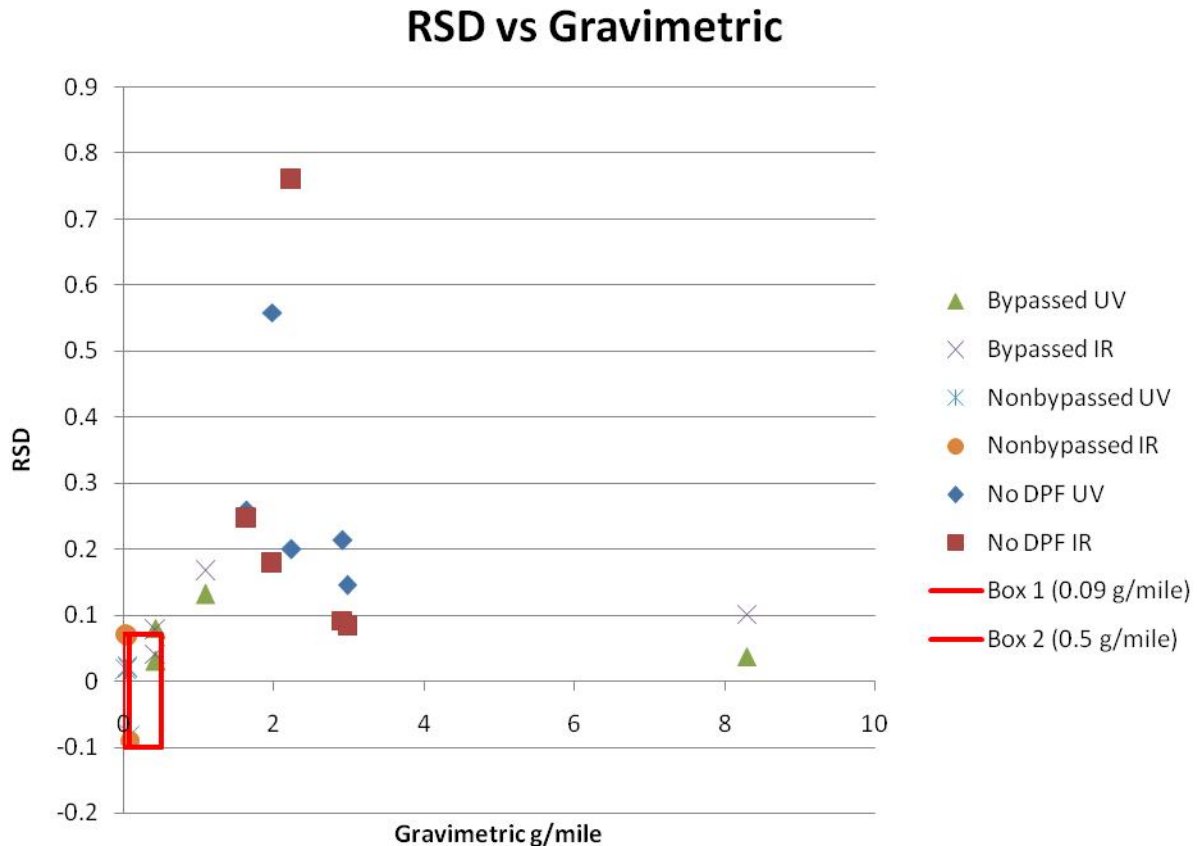


Figure 3.14 shows average RSD results plotted against average gravimetric results. Two boxes are drawn to show the separation of non-bypassed trucks versus bypassed trucks. Fig. 3.14a shows an enlarged emphasizing the points near the origin. The IR readings have been adjusted by a factor of 1.7 to better reflect their UV counterparts. There are a total of 26 points shown here. 8 (4x2) are non-bypassed, 8 (4x2) are bypassed, and 10 (5x2) are non DPF equipped.

Figure 3.14 shows all the RSD readings averaged by truck and then grouped either if that truck was operating in the bypassed mode or non-bypassed mode. A total of 26 data points are plotted from 13 different trucks. Mode A and Mode B were discarded for the 2009 Thomas Bus because of insufficient data. Each truck's RSD reading consisted of two smoke measurements (UV and IR) bringing the total number of points to 26.

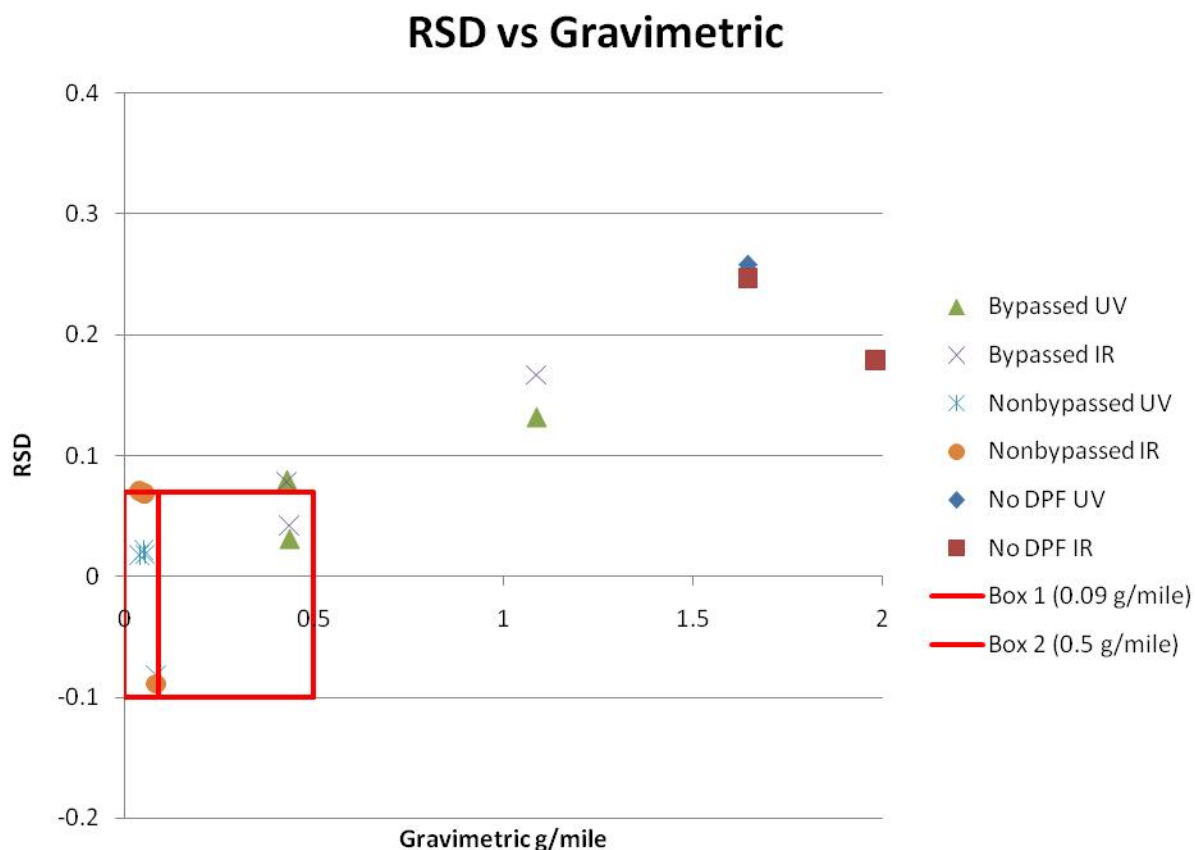


Figure 3.14a. When we choose boundaries of 0.07 for RSD and 0.09 g/mile for gravimetric all 8 the non-bypassed points are captured and all the remaining 18 points would be seen by the RSD as high PM emitters.

If we choose to say that an RSD reading of 0.07 or lower constitutes a low emitting vehicle, then in this case RSD thinks there are 12 of 26 points belonging to low emitters. Two of these points belong to the 2008 Volvo Mode B that gravimetric says is high PM emitting averaging around 8g/mile. Two more points belong to the 2008 Volvo Day Cab which might be considered clean if gravimetric standards declared vehicles emitting less than 0.5g/mile to be clean.

Figure 3.15 is a histogram showing the frequency of all 149 individual UV smoke readings categorized by DPF (non-bypassed) or non DPF (bypassed and not DPF equipped) trucks.

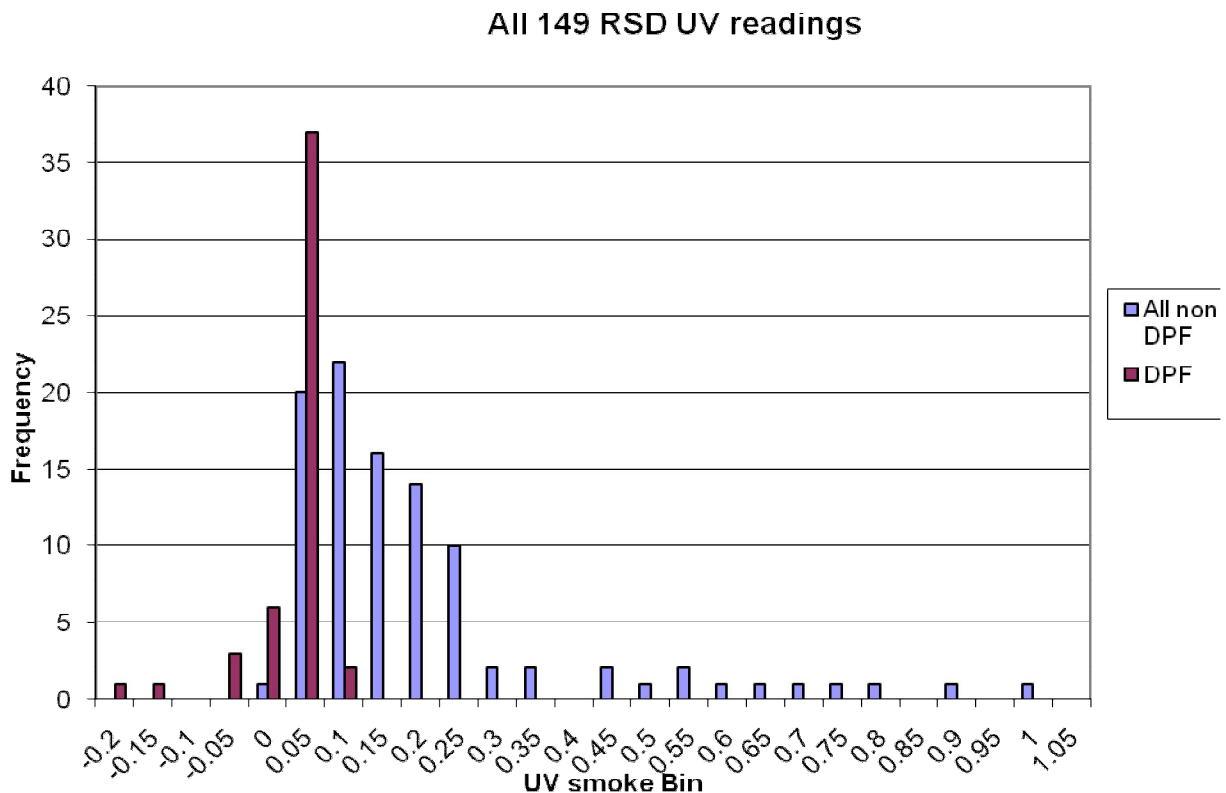


Figure 3.15 Notice the different distribution shapes as well as the position of each group. While there is some overlap between the two groups around 0.05 and 0.1, all the DPF readings abruptly halt going from 0.05 to 0.1 and the bulk of the non DPF readings in those same two bins are our attempts to create a failing DPF. The majority of the non DPF readings were in bins 0.15 and above. There were no DPF smoke readings in these same bins.

It should be noted that the where the DPF and non-DPF distributions seem to overlap there are zero UV readings from trucks with non-equipped DPF systems in the 0.05 bin and only 5 UV readings from trucks with non-equipped DPF systems in the 0.1 bin. These two bins together have 42 UV readings total. The remaining 37 UV readings are from intentionally bypassed post-2007 trucks that are still burning quite clean.

Figure 3.16 shows the normalized histogram distribution for the individual UV smoke readings.

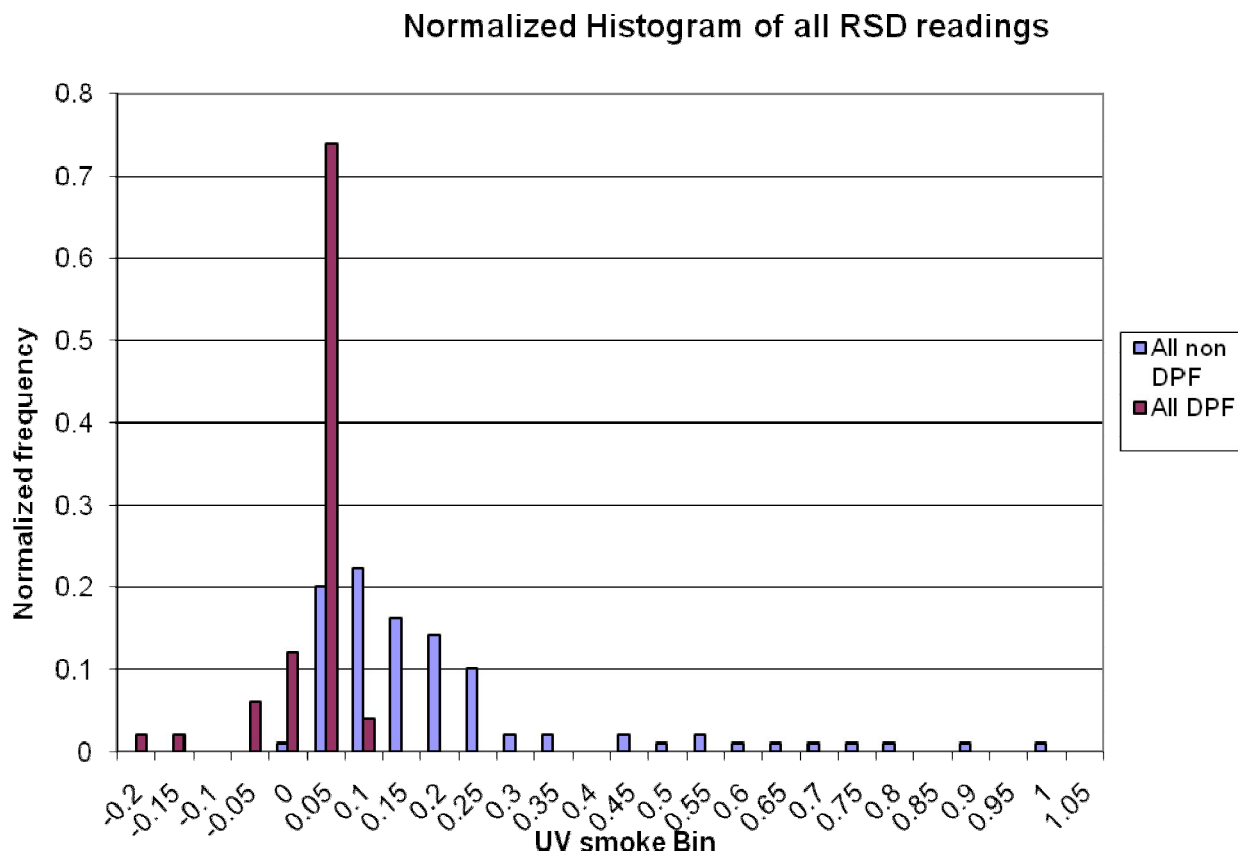


Figure 3.1. The normalized histogram clearly shows that the DPF trucks dominate the lower bins ≤ 0.05 and the non DPF trucks dominate the higher bins ≥ 0.1 .

Figures 3.15 and 3.16 show distinct shapes and positions for the distributions of DPF systems and non-DPF systems. An RSD instrument could certainly be programmed to differentiate between the two and therefore could be used as a first phase instrument to locate probable malfunction in a vehicle which by its license plate is determined to be supposed to be DPF controlled.

Findings:

- The smoke readings for the RSD 4600 are useful indicators of ‘probably’ smoking trucks and could be used as a first pass instrument

3.8. Power line Interference on ETaPS output baseline

The power line interference on the ETaPS is tremendous when the ETaPS configuration is unshielded. We conducted a series of tests to show the range of baseline ETaPS readings in shielded/unshielded forms as well as different distances from local power lines in Denver.

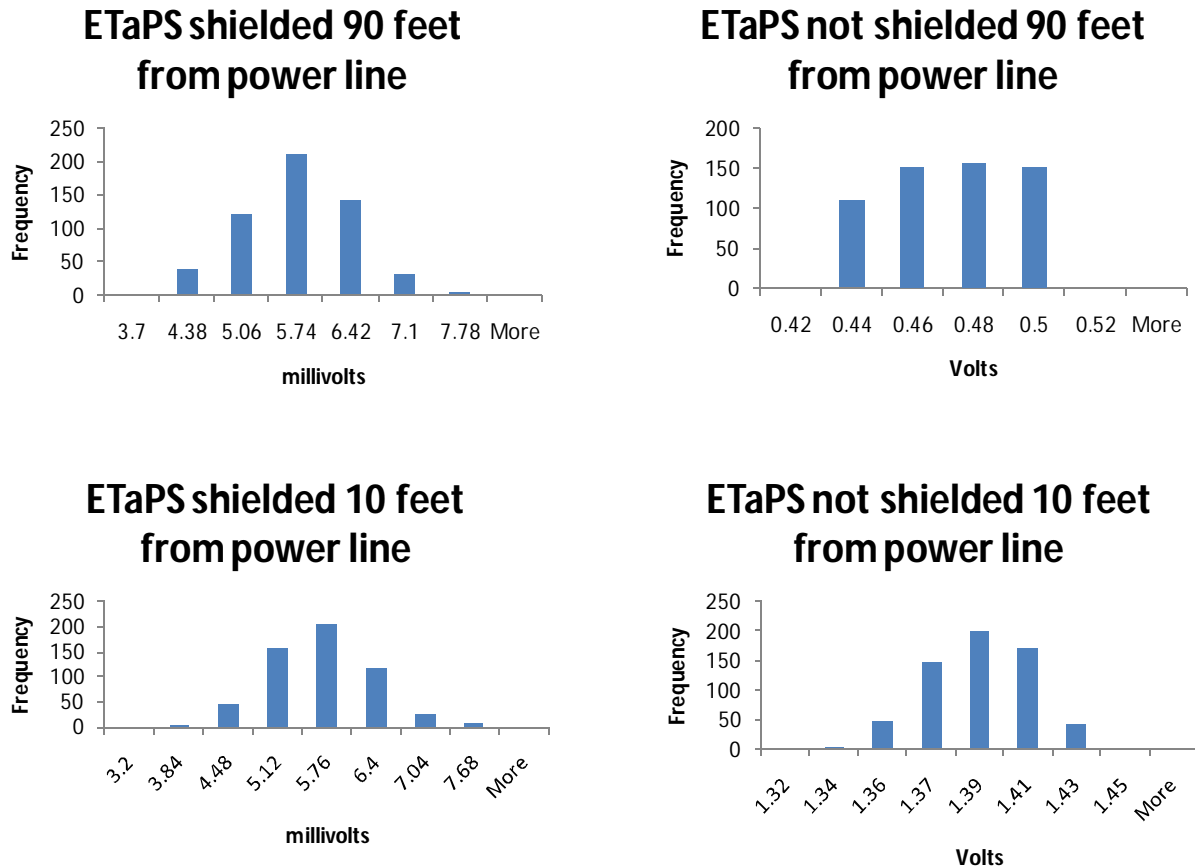


Figure 3.17 shows histograms of 10 minute tests of ETaPS in different configurations. In all cases there was no exhaust present and the ambient wind was calm. The difference between each bin is equal to one standard deviation for each specific test.

The right most graphs are histograms for the most similar conditions we encountered in West Virginia. Notice that in the absence of exhaust particles there is a very noticeable increase in baseline signal as the ETaPS gets closer to a power line. The left most graphs are histograms of the previous tests only in a shielded environment by means of a T-connector pipe supplied by Dekati. Shielding the ETaPS at both distances drastically reduced the baseline signal by a couple of orders of magnitude (Volts to millivolts). It is important to note that in both cases the standard deviations for the non-shielded tests are greater than the entire range of signal for their shielded tests.

3.9. ETaPS, UV and IR Precision

Without a standard, constant emission source the precision of the ETaPS can not be directly determined. However, when the same truck undertakes the same cycle three times, the range of results is a conservative measure of the ETaPS precision because some of the variability certainly arises from the vehicle/driver rather than the instrument. Figures 3.18 – 3.22 are an attempt to show the variability of the ETaPS signal using the standard deviations for the three runs done for each test. The Accel test has only one run and therefore will show no uncertainty bars. The overall correlation increases slightly from 0.80 to 0.83 when runs from the same test are averaged for each truck. Figure 3.19 separates all points by driving mode. No trendline is given for the Accel cycle because it is the same data set as previous graphs and only the points for the UDDS and the Cruise tests have been averaged. The ETaPS instrument noise for the following comparisons has been calculated to be less than or equal to 40 mVs/mi. for a DPF equipped vehicle whose total readings average less than 1 Vs/mi. and are always below 2 Vs/mi in all tests. This precision was determined from a truck tested under Mode A where particles are not present and confirmed with gravimetric results. This is very small compared with the larger uncertainty lines shown for some non-DPF trucks. The uncertainty present, with some points, represents the highly variable nature of the individual runs for each test. Figure 3.20 shows the low variability for the Mode A tested trucks near the origin with clear separation from a few Mode B tested trucks.

Looking at the higher ETaPS readings in these graphs and in Appendix A, from bypassed and older trucks, the average readings vary from 8-390Vs/mi, typically nearer 100 Vs/mi with an instrument precision certainly better than 6% of the reading.

Figure 3.21 shows the same uncertainty for the IR and Figure 3.22 shows uncertainty for UV smoke readings in the RSD vs. Gravimetric comparisons. A clear distinction can be seen as the variability for the IR is very large while the UV uncertainty is smaller.

ETaPS Signal vs. Gravimetric measuerment, by individual truck no 2008 Volvo B

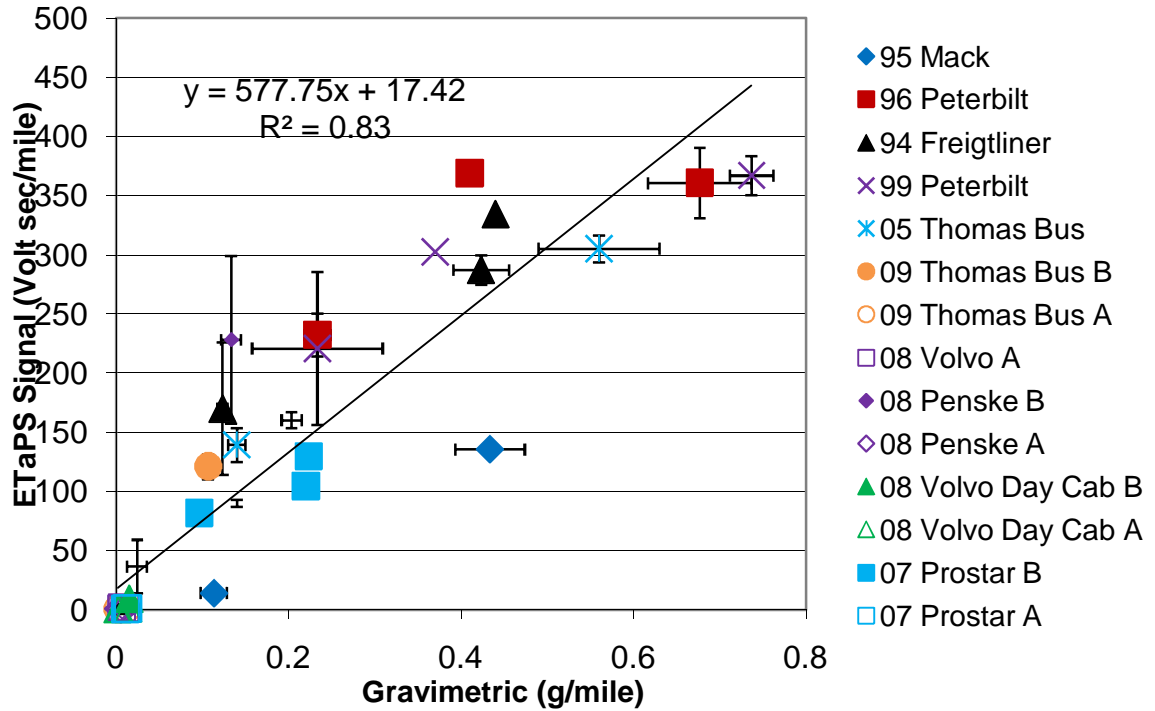


Figure 3.18 ETaPS signal (Vs/mi) against Gravimetric (g/mile). There are now 44 points on this graph after averaging the runs for the same tests for each truck. 15 trucks times 3 tests minus one (the 2005 Thomas Bus did not undergo an Accel test) is 44.

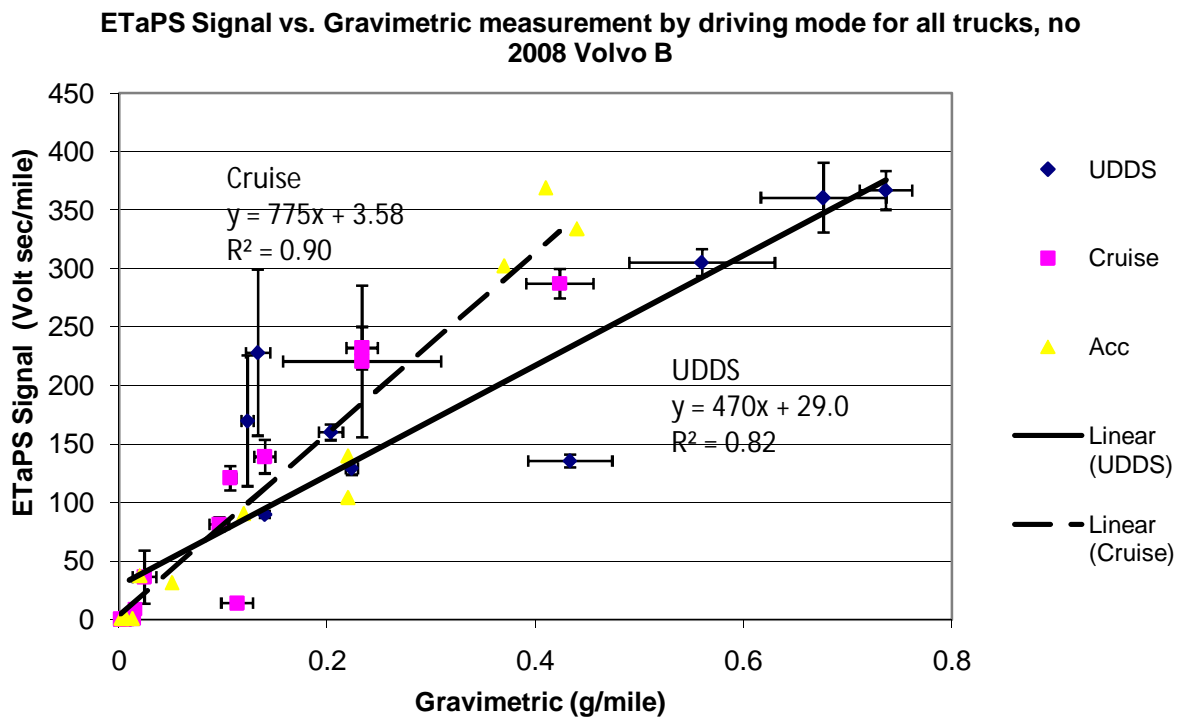


Figure 3.19 shows uncertainty bars for the UDDS and Cruise tests.

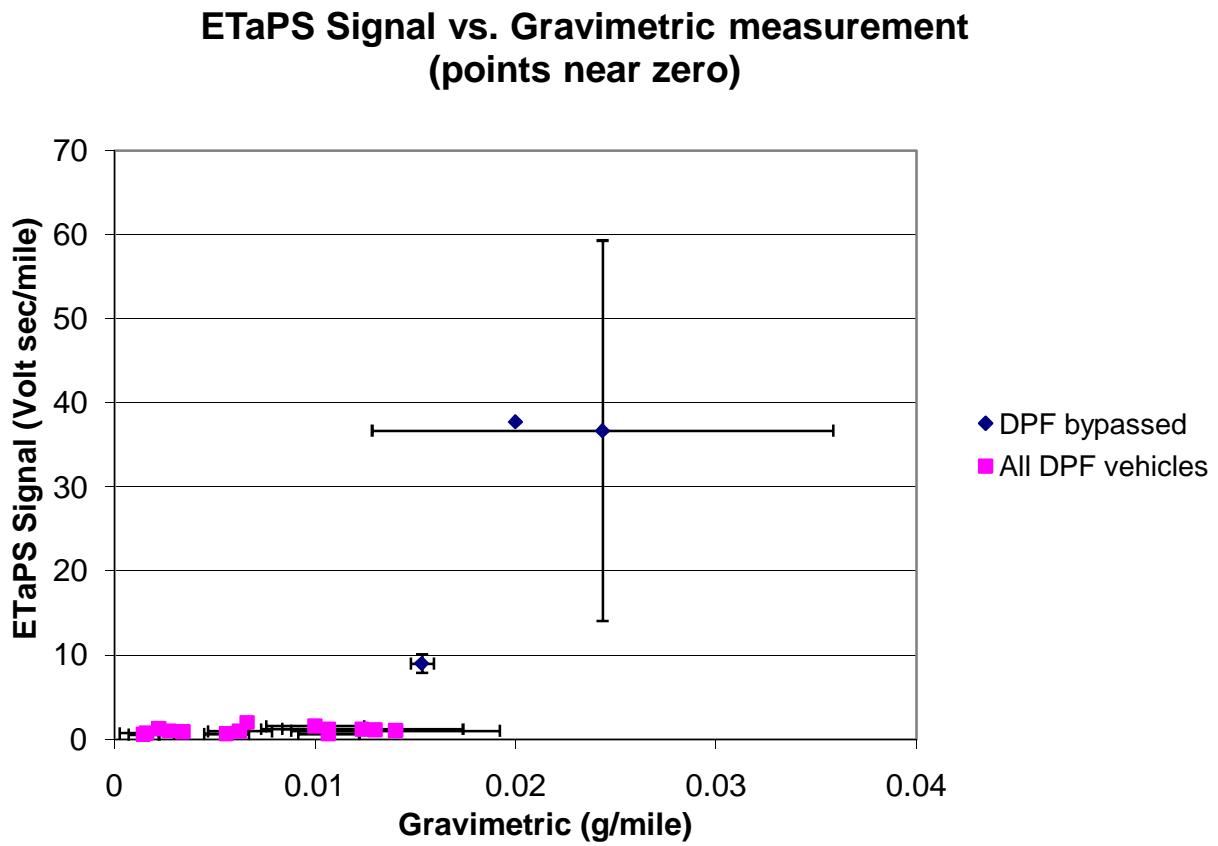


Figure 3.20 shows the low variability of ETaPS signal for DPF equipped trucks (Mode A).

RSD IR vs. Gravimetric

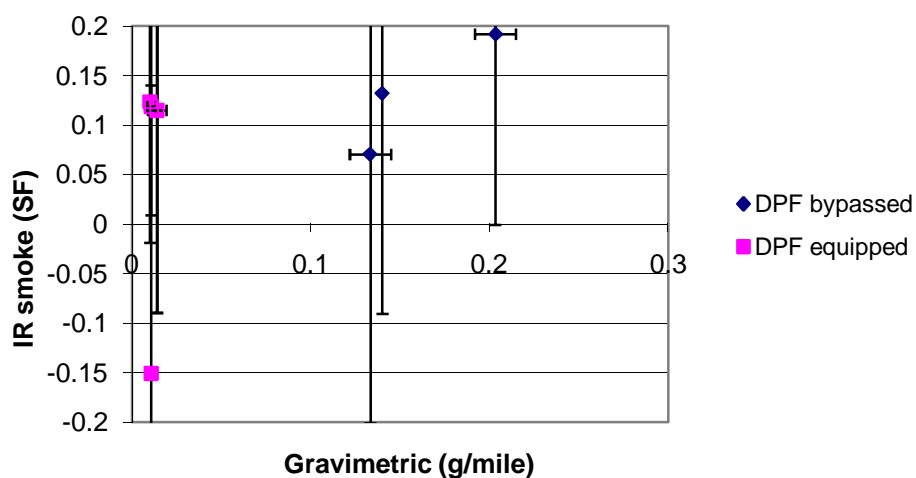


Figure 3.21 shows IR smoke readings with uncertainty bars for the RSD vs. Gravimetric comparison. Notice the many large and overlapping uncertainty ranges.

RSD UV vs. Gravimetric

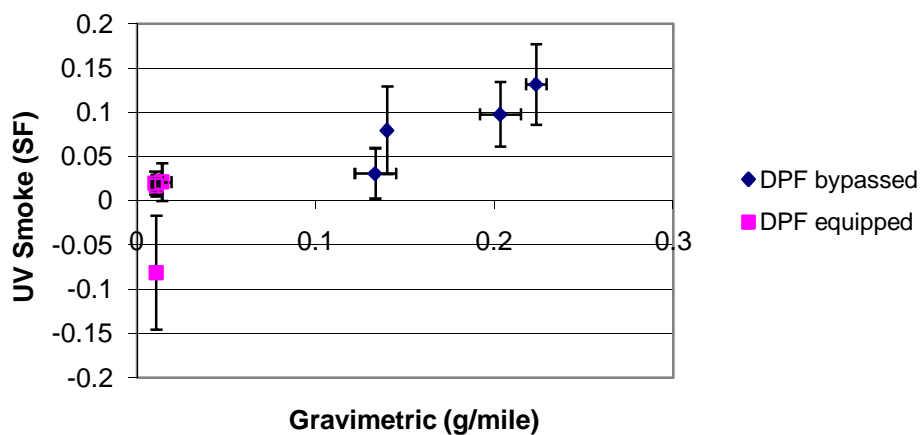


Figure 3.22 shows UV smoke readings with uncertainty bars for the RSD vs. Gravimetric comparison. The uncertainty bars range far less than the IR readings and include many speeds/driving modes.

3.10 Emissions Data Collected

The following emissions data were recorded using WVU's Transportable Heavy-Duty Vehicle Emissions Testing Laboratory:

Total Hydrocarbons
Oxides of Nitrogen
Particulate Matter
Carbon Monoxide
Carbon Dioxide
Continuous Tapered Element Oscillating Membrane (TEOM)

4. Test Vehicles

Information regarding the vehicles tested during this study are tabulated below (Table).

Table 4.1 Vehicle Test Weights

Test Vehicle	Gross Vehicle Weight Rating (GVWR)	Measured Vehicle Curb Weight (lbs.)	Vehicle Test Weights	
			ETaPS/RSD	ETaPS/WVU THDVETL
1995 Mack	52,000	17,360	39,080	42,352
1996 Peterbilt	46,000	20,340	42,160	42,352
1995 Freightliner	51,954	19,160	40,900	42,352
1999 Peterbilt	33,000	14,900	33,580	30,000
2005 Thomas Bus	36,200	22,860	22,860	35,000
2009 Thomas Bus	36,200	22,220	22,220	35,000
2008 Volvo Tractor		18,160	37,060	42,000
2008 International Box Truck	25,500	15,260	15,260	25,600
2008 Volvo Day Cab	50,350	16,600	35,080	42,000
2007 International	52,000			42,000
Note: The GVWR of a tractor is not the same as the Combined GVWR of tractor and trailer (typically 80,000 lbs.)				

Status of Technology

The ETaPS is currently on engineering and sales hold as they focus developments of other products. There are, however, similar products from West Virginia University and Pegasor Oy that operate under the same principle as the ETaPS. The ETaPS can successfully be used to determine if DPF vehicles have malfunctioning emission control systems. Quantitative evaluation of high PM emitting HDDVs shows a reasonable level of correlation with gravimetric results. The operation is simple and maintenance requirement is low. This project determined that any on road testing of ETaPS aboard HDDVs needs to include the use of the shielding element provided for the purpose of surrounding the corona of the ETaPS.

Appendix A

Program Summary

This study has focused on the emissions evaluation of 15 heavy-duty vehicle configurations over four different driving cycles: three dynamometer cycles and one test track cycle. Each vehicle configuration was tested on-road concurrently with RSD and ETaPS, as well as on WVU's chassis dynamometer, with simultaneous ETaPS measurements, in order to correlate PM mass emissions. Per WVU's telecom with ESP (Niranjana Vescio), CARB (John Collins), and University of Denver (Don Stedman) the following test vehicle configurations were selected.

1. Five vehicles (pre-2007 model year) without diesel particulate filters (DPFs) were tested in the initial phase of the study.
2. An additional five vehicles (post-2007 model year) that were equipped with a DPF and/or an oxidation catalyst were tested during the second phase of the study.
3. For each of the post-2007 vehicles (five), the exhaust system was modified by installing a bypass loop around the aftertreatment system. The amount of bypass was controlled to alter the exhaust stream PM concentration downstream of the aftertreatment system in order to simulate a DPF failure, as well as attempt to quantify the low-level sensitivity/performance of the ETaPS.
4. Each vehicle was tested on the following dynamometer driving cycles:
 - a. UDDS (three replicates) – 15 trucks, 45 runs
 - b. Steady State (three replicates) called the ETaPS 40 cycle – 15 trucks, 45 runs
 - c. ETaPS acceleration cycle – 15 trucks, 14 runs (no Accel data for 2005 Thomas Bus).
5. In addition, 15 vehicles were tested by driving them on a test track through a RSD 4600 (ESP device)
 - a. Acceleration cycle (Loaded/Unloaded, 3-4 different speeds, Mode A/B) – 15 trucks, 149 runs

The above test plan resulted in a total of 44 test configurations. WVU conducted chassis dynamometer tests on three different cycles instead of only one. We found that evaluating multiple post-2007 vehicles did not yield significantly different exhaust characteristics, in particular the PM emissions; hence, the correlation study between ETaPS and the chassis dynamometer data would have been rather futile. However, running a vehicle on different cycles produced exhaust streams of relatively different characteristics, thereby providing for a meaningful demonstration study of the ETaPS and its comparison against the gravimetric measurements and the TEOM.

A summary of the vehicle tests is included as Table A1. A complete list of results is included in Table A2.

Table A1 Summary of tested ICAT Vehicles

Test	Test Cycle	Measurement Systems	Tests Completed	Test Description	Vehicle Model Year
1	UDDS (Test D)	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	1995
2	UDDS (Test D)	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	1996
3	UDDS (Test D)	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	1995
4	UDDS (Test D)	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	1999
5	UDDS (Test D)	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	2005
6	UDDS (Test D)	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2009
7	UDDS (Test D)	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2008
8	UDDS (Test D)	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2008
9	UDDS (Test D)	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2008
10	UDDS (Test D)	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2007
11	UDDS (Test D)	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2009
12	UDDS (Test D)	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2008
13	UDDS (Test D)	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2008
14	UDDS (Test D)	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2008
15	UDDS (Test D)	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2007
16	ETAPS_40	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	1995
17	ETAPS_40	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	1996
18	ETAPS_40	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	1995
19	ETAPS_40	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	1999
20	ETAPS_40	WVU THDVETL/ETaPs	3	Pre 2007 Exhaust Concentration	2005
21	ETAPS_40	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2009
22	ETAPS_40	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2008
23	ETAPS_40	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2008
24	ETAPS_40	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2008
25	ETAPS_40	WVU THDVETL/ETaPs	3	Post 2007 Exhaust Concentration (DPF-Equipped)	2007
26	ETAPS_40	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2009
27	ETAPS_40	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2008
28	ETAPS_40	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2008
29	ETAPS_40	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2008
30	ETAPS_40	WVU THDVETL/ETaPs	3	Simulated DPF Failure (DPF-Bypass)	2007
31	ETAPS_acc	WVU THDVETL/ETaPs	1	Pre 2007 Exhaust Concentration	1995
32	ETAPS_acc	WVU THDVETL/ETaPs	1	Pre 2007 Exhaust Concentration	1996
33	ETAPS_acc	WVU THDVETL/ETaPs	1	Pre 2007 Exhaust Concentration	1995
34	ETAPS_acc	WVU THDVETL/ETaPs	1	Pre 2007 Exhaust Concentration	1999
35	ETAPS_acc	WVU THDVETL/ETaPs	1	Post 2007 Exhaust Concentration (DPF-Equipped)	2009
36	ETAPS_acc	WVU THDVETL/ETaPs	1	Post 2007 Exhaust Concentration (DPF-Equipped)	2008
37	ETAPS_acc	WVU THDVETL/ETaPs	1	Post 2007 Exhaust Concentration (DPF-Equipped)	2008
38	ETAPS_acc	WVU THDVETL/ETaPs	1	Post 2007 Exhaust Concentration (DPF-Equipped)	2008
39	ETAPS_acc	WVU THDVETL/ETaPs	1	Post 2007 Exhaust Concentration (DPF-Equipped)	2007
40	ETAPS_acc	WVU THDVETL/ETaPs	1	Simulated DPF Failure (DPF-Bypass)	2009
41	ETAPS_acc	WVU THDVETL/ETaPs	1	Simulated DPF Failure (DPF-Bypass)	2008
42	ETAPS_acc	WVU THDVETL/ETaPs	1	Simulated DPF Failure (DPF-Bypass)	2008
43	ETAPS_acc	WVU THDVETL/ETaPs	1	Simulated DPF Failure (DPF-Bypass)	2008
44	ETAPS_acc	WVU THDVETL/ETaPs	1	Simulated DPF Failure (DPF-Bypass)	2007

Table A2 Complete Emissions Table for all trucks (Abbr. at end of table, ignore bold lines)

Truck	Date	TN	TT	TL	PM	ES1	ES2	GPM	TPM	CO	NOx	HC	CO ₂
95 Mack	12/9/2008	5411-1	UDDS	5.44	0.44	738.35	135.73	2.39	2.17	2.74	25.26	0.4	2144
	12/9/2008	5411-2	UDDS	5.51	0.47	778.77	141.34	2.59	2.33	2.78	21.4	0.35	2082
	12/9/2008	5411-3	UDDS	5.49	0.39	715.11	130.26	2.14	2.00	2.09	22.45	0.4	2062
	12/10/2008	5414-1	Cruise	9.63	0.13	167.59	17.40	1.25	-13.60	0.6	22.21	0.3	1100
	12/10/2008	5414-2	Cruise	9.61	0.1	123.08	12.81	0.96	0.79	0.66	21.23	0.29	1039
	12/10/2008	5414-3	Cruise	9.62	0.11	123.88	12.88	1.06	0.80	0.69	20.73	0.31	1019
	12/10/2008	5415-1	Acc	5.04	0.22	704.67	139.82	1.11	0.98	1.56	15.73	0.53	1374
96 Peterbilt	12/12/2008	5418-2	UDDS	5.67	0.74	1875.05	330.70	4.20	3.67	5.01	17.71	0.55	2222
	12/12/2008	5418-3	UDDS	5.64	0.67	2038.39	361.42	3.78	3.45	4.62	17.13	0.57	2097
	12/12/2008	5418-4	UDDS	5.62	0.62	2192.86	390.19	3.48	3.65	4.79	15.47	0.59	2091
	12/12/2008	5419-1	Cruise	9.79	0.22	2177.46	222.42	2.15	2.21	2.2	8.21	0.38	1041
	12/12/2008	5419-2	Cruise	9.79	0.23	2478.55	253.17	2.25	2.26	2.27	8.07	0.4	1018
	12/12/2008	5419-3	Cruise	9.83	0.25	2177.84	221.55	2.46	2.68	2.38	8.48	0.4	1117
	12/12/2008	5420-1	Acc	5.14	0.41	1897.42	369.15	2.11	2.16	4.16	11.64	0.59	1512
94 Freight liner	12/16/2008	5423-1	Cruise	9.9	0.12	1045.41	105.60	1.19	-37.72	1.58	20.55	0.27	1010
	12/16/2008	5423-2	Cruise	9.95	0.12	2016.33	202.65	1.19	1.48	1.39	22.18	0.29	1058
	12/16/2008	5423-3	Cruise	9.79	0.13	1978.52	202.10	1.27	1.48	1.54	21.73	0.32	1034
	12/15/2008	5427-1	UDDS	6.28	0.4	1848.92	294.41	2.51	2.69	6.65	26.87	0.59	1754
	12/15/2008	5427-2	UDDS	6.25	0.46	1704.83	272.77	2.88	2.73	7.11	25.87	0.44	1731
	12/15/2008	5427-3	UDDS	6.01	0.41	1771.67	294.79	2.46	2.68	8.31	27.78	0.44	1729
	12/16/2008	5428-1	Acc	5.4	0.44	1805.09	334.28	2.38	1.62	5.48	24.76	0.42	1481
99 Peterbilt	12/17/2008	5431-1	UDDS	5.57	0.71	1941.86	348.63	3.95	3.60	6.32	13.71	0.75	1665
	12/17/2008	5431-2	UDDS	5.56	0.74	2068.94	372.11	4.11	4.11	6.82	14	0.63	1691
	12/17/2008	5431-3	UDDS	5.54	0.76	2108.19	380.54	4.21	4.50	7.38	13.91	0.58	1706
	12/17/2008	5432-1	Cruise	9.61	0.2	1798.87	187.19	1.92	1.67	1.86	16.8	0.42	920
	12/17/2008	5432-2	Cruise	9.59	0.18	1726.83	180.07	1.73	1.80	1.83	16.24	0.48	891
	12/17/2008	5432-3	Cruise	9.6	0.32	2836.73	295.49	3.07	3.52	2.76	7.86	0.43	890
	12/17/2008	5433-1	Acc	4.99	0.37	1509.33	302.47	1.85	1.94	4.72	16.62	0.68	1252
05 Thomas Bus	12/19/2008	5436-1	UDDS	5.61	0.56	1756.16	313.04	3.14	3.67	4.35	7.63	0.2	1824
	12/19/2008	5436-2	UDDS	5.61	0.49	1639.42	292.23	2.75	3.47	3.75	7.43	0.21	1772
	12/19/2008	5436-3	UDDS	5.61	0.63	1742.61	310.63	3.53	3.80	4.03	8.05	0.16	1836
	12/19/2008	5437-1	Cruise	9.6	0.14	1348.22	140.44	1.34	13.97	1.12	3.54	0.17	1040
	12/19/2008	5437-2	Cruise	9.61	0.15	1471.75	153.15	1.44	0.06	1.09	3.75	0.18	1030
	12/19/2008	5437-3	Cruise	9.59	0.13	1196.14	124.73	1.25	1.97	1.01	3.62	0.2	1042
09 Thomas Bus B*	1/22/2009	5442-1	UDDS	5.53	0.21	902.28	163.16	1.16	1.17	1.99	5.35	0.33	2291
	1/22/2009	5442-2	UDDS	5.52	0.21	912.99	165.40	1.16	1.30	1.98	5.25	0.39	2373
	1/22/2009	5442-3	UDDS	5.52	0.19	842.90	152.70	1.05	1.21	2.16	5.27	0.34	2268
	1/23/2009	5447-1	Cruise	9.65	0.11	1257.65	130.33	1.06	N/A	0.77	2.47	0.23	1180
	1/23/2009	5447-2	Cruise	9.44	0.11	1164.57	123.37	1.04	N/A	0.85	2.54	0.22	1280
	1/23/2009	5447-3	Cruise	9.69	0.1	1063.28	109.73	0.97	1.07	0.79	2.38	0.22	1168
	1/23/2009	5448-1	Acc	4.98	0.12	451.55	90.67	0.60	0.82	1.03	4.32	0.29	1414
09 Thomas Bus A*	1/22/2009	5439-1	UDDS	5.53	0.017	6.42	1.16	0.09	0.19	0.57	5.08	0.091	2300
	1/22/2009	5439-2	UDDS	5.51	0.013	6.72	1.22	0.07	0.15	0.48	5.12	0.018	2244
	1/22/2009	5439-3	UDDS	5.52	0.007	6.94	1.26	0.04	0.19	0.46	5.27	0.014	2172
	1/22/2009	5440-1	Cruise	9.6	2.E-04	7.31	0.76	0.00	0.05	0.23	2.44	0.016	1020
	1/22/2009	5440-2	Cruise	9.63	2.E-03	6.89	0.72	0.02	0.16	0.23	2.47	0.006	1008

	Date	TN	TT	TL	PM	ES1	ES2	GPM	TPM	CO	NOx	HC	CO ₂
09 Thomas Bus A*	1/22/2009	5440-3	Cruise	9.62	3.E-03	6.58	0.68	0.03	0.11	0.22	2.49	X	1029
	1/22/2009	5441-1	Acc	4.98	2.E-03	6.41	1.29	0.01	1.89	0.4	4.37	0.027	1257
08 Volvo B*	1/28/2009	5457-1	UDDS	5.57	1.25	731.39	131.31	6.96	5.26	4.39	15.32	1.59	2132
	1/28/2009	5457-2	UDDS	5.55	3.35	732.62	132.00	18.59	14.31	5.08	15.22	3.98	2127
	1/28/2009	5457-3	UDDS	5.53	0	968.02	175.05	N/A	45.82	7.2	14.82	10.01	2167
	1/28/2009	5458-1	Cruise	9.62	0.71	501.83	52.17	6.83	4.04	1.65	6.37	2.45	1234
	1/28/2009	5458-2	Cruise	9.64	0.5	426.26	44.22	4.82	2.81	1.49	6.76	2.21	1215
	1/28/2009	5458-3	Cruise	9.62	0.62	441.32	45.88	5.96	3.58	1.2	6.89	2.5	1199
	1/28/2009	5459-1	Acc	5.03	1.31	341.91	67.97	6.59	3.83	1.84	11.71	3.9	1658
	1/27/2009	5451-1	UDDS	5.56	0.0111	8.82	1.59	0.06	-7.30	4	12.77	X	2110
08 Volvo A*	1/27/2009	5451-2	UDDS	5.54	0.0072	7.76	1.40	0.04	-0.43	1.77	12.44	X	2084
	1/27/2009	5451-3	UDDS	5.52	0.0117	9.45	1.71	0.06	0.16	2.29	12.71	X	2108
	1/27/2009	5452-1	Cruise	9.63	0.008	8.37	0.87	0.08	-0.01	0.32	3.46	X	1108
	1/27/2009	5452-2	Cruise	9.66	0.0058	10.31	1.07	0.06	0.04	0.29	3.02	X	1112
	1/27/2009	5452-3	Cruise	9.66	0.0049	9.28	0.96	0.05	0.07	0.35	3.79	X	1078
	1/27/2009	5453-1	Acc	5.18	0.0066	10.24	1.98	0.03	0.26	0.5	7.37	X	1390
	1/31/2009	5467-1	UDDS	5.51	0.12	1694.85	307.60	0.66	0.42	0.38	3.71	X	1732
08 Penske B*	1/31/2009	5467-2	UDDS	5.54	0.14	1142.91	206.30	0.78	0.95	0.48	3.6	X	1760
	1/31/2009	5467-3	UDDS	5.52	0.14	944.02	171.02	0.77	0.95	0.5	3.61	X	1733
	1/31/2009	5468-1	Cruise	9.62	0.036	602.98	62.68	0.35	0.59	0.2	1.36	X	822
	1/31/2009	5468-2	Cruise	9.87	0.024	257.46	26.09	0.24	0.19	0.17	2.65	X	808
	1/31/2009	5468-3	Cruise	9.55	0.013	203.63	21.32	0.12	0.07	0.21	2.78	X	788
	1/31/2009	5469-1	Acc	4.98	0.02	187.99	37.75	0.10	0.25	0.43	2.85	X	936
	1/30/2009	5462-4	UDDS	5.51	0.012	6.82	1.24	0.07	0.22	0.34	3.67	X	1813
08 Penske A*	1/30/2009	5462-5	UDDS	5.54	0.008	6.89	1.24	0.04	0.13	0.38	3.88	0.064	1824
	1/30/2009	5462-6	UDDS	5.52	0.012	6.62	1.20	0.07	0.00	0.34	3.91	X	1784
	1/30/2009	5463-1	Cruise	9.63	0.0057	6.25	0.65	0.05	0.09	0.19	2.74	X	814
	1/30/2009	5463-2	Cruise	9.62	0.0066	5.96	0.62	0.06	-0.02	0.2	2.78	X	791
	1/30/2009	5463-3	Cruise	9.61	0.0044	6.02	0.63	0.04	-0.06	0.25	2.72	X	778
	1/30/2009	5464-1	Acc	5.04	0.0027	5.03	1.00	0.01	0.07	0.3	2.76	X	950
	2/3/2009	5477-1	UDDS	5.59	0.14	519.83	92.99	0.78	0.80	3.38	11.51	0.21	1968
08 Volvo Day Cab B*	2/3/2009	5477-2	UDDS	5.59	0.14	485.06	86.77	0.78	0.84	3.27	11.77	0.27	1931
	2/3/2009	5477-3	UDDS	5.61	0.14	508.08	90.57	0.79	1.06	3.34	11.93	0.31	1950
	2/3/2009	5478-1	Cruise	9.71	0.015	99.51	10.25	0.15	0.27	1.04	2.58	0.27	848
	2/3/2009	5478-2	Cruise	9.67	0.015	79.64	8.24	0.15	0.34	0.7	2.75	0.19	811
	2/3/2009	5478-3	Cruise	9.68	0.016	82.50	8.52	0.15	0.39	0.97	2.88	0.24	807
	2/3/2009	5479-1	Acc	5.05	0.051	160.04	31.69	0.26	0.37	1.62	5.74	0.33	1160
	2/2/2009	5472-1	UDDS	5.56	0.02	5.81	1.04	0.11	-0.01	0.73	10.01	X	2038
08 Volvo Day Cab A*	2/2/2009	5472-2	UDDS	5.59	0.011	5.48	0.98	0.06	0.02	0.78	9.98	X	1932
	2/2/2009	5472-3	UDDS	5.58	0.011	5.59	1.00	0.06	0.24	0.51	9.65	X	1827
	2/2/2009	5473-1	Cruise	9.68	0.0021	5.31	0.55	0.02	0.02	0.22	2.7	0.022	804
	2/2/2009	5473-2	Cruise	9.7	0.0006	5.73	0.59	0.01	0.10	0.21	2.68	0.009	833
	2/2/2009	5473-3	Cruise	9.69	0.0016	5.37	0.55	0.02	0.09	0.2	2.7	X	818
	2/2/2009	5474-1	Acc	5.04	0.0034	4.44	0.88	0.02	0.17	0.36	5.83	X	1135

	Date	TN	TT	TL	PM	ES1	ES2	GPM	TPM	CO	NOx	HC	CO ₂
07 Prostar B*	2/6/2009	5491-1	UDDS	5.47	0.22	676.17	123.61	1.20	-30.89	2.8	8.99	0.45	3252
	2/6/2009	5491-2	UDDS	5.52	0.23	721.72	130.75	1.27	0.06	3.13	9.47	0.39	3293
	2/6/2009	5491-3	UDDS	5.48	0.22	737.93	134.66	1.21	1.53	2.86	8.87	0.37	3464
	2/6/2009	5492-1	Cruise	9.82	0.086	776.39	79.06	0.84	1.09	1	5.29	0.19	2537
	2/6/2009	5492-2	Cruise	9.63	0.105	851.33	88.40	1.01	1.19	1.18	4.87	0.16	2517
	2/6/2009	5492-3	Cruise	9.83	0.098	763.80	77.70	0.96	1.11	1.22	5.29	0.17	2423
	2/6/2009	5493-1	Acc	5.08	0.22	531.02	104.53	1.12	1.36	2.12	6.97	0.35	2919
07 Prostar A*	2/5/2009	5485-1	Cruise	9.75	0.009	5.69	0.58	0.09	0.00	0.19	5.18	X	2533
	2/5/2009	5485-2	Cruise	9.69	0.011	6.10	0.63	0.11	0.03	0.23	5.01	X	2580
	2/5/2009	5485-3	Cruise	9.72	0.012	6.96	0.72	0.12	0.25	0.33	4.93	X	2514
	2/5/2009	5487-1	UDDS	5.49	0.014	5.57	1.02	0.08	-0.06	0.54	9.05	0.029	3410
	2/5/2009	5487-2	UDDS	5.5	0.014	5.38	0.98	0.08	-0.11	0.4	8.86	0.032	3461
	2/5/2009	5487-3	UDDS	5.55	0.014	5.39	0.97	0.08	0.07	0.6	8.74	0.039	3456
	2/5/2009	5488-1	Acc	5.08	0.013	5.54	1.09	0.07	0.14	0.34	5.95	0.058	3328

TN- Test Number

TT- Test Type

TL- Test Length

PM- PM (g/mile)

ES1- ETaPS Signal (volt sec)

ES2- ETaPS Signal (volt sec/mile)

GPM- Gravimetric PM (total gm)

TPM- TEOM PM (total gm)

CO- CO (gm/mile)

NOx- NOx (gm/mile)

HC- HC (gm/mile)

CO₂- CO₂ (gm/mile)

* denotes DPF equipped

Denotes a bypassed DPF

(Truck) A- not bypassed

(Truck) B- bypassed

Table A3 All RSD UV/IR readings

Make/Model	uvSmoke	irSmoke
95 Mack	0.5121	0.9173
95 Mack	0.442	0.5213
95 Mack	0.2052	0.4031
95 Mack	0.1629	0.1599
95 Mack	0.136	0.1322
95 Mack	0.1716	0.5347
95 Mack	0.3129	0.525
95 Mack	0.1207	0.1531
96 Peterbilt	0.2243	0.2412
96 Peterbilt	0.2133	0.0434
96 Peterbilt	0.4268	0.1123
96 Peterbilt	0.2319	0.2149
96 Peterbilt	0.239	0.2103
96 Peterbilt	0.1223	0.2555
96 Peterbilt	0.1048	-0.0388
96 Peterbilt	0.2347	0.2233
96 Peterbilt	0.1243	0.1464
99 Peterbilt	0.1572	0.1071
99 Peterbilt	0.1327	0.3184
99 Peterbilt	0.1672	-0.3715
99 Peterbilt	0.0944	0.0627
99 Peterbilt	0.0645	0.2719
99 Peterbilt	0.0888	0.1903
99 Peterbilt	0.1227	-0.2374
99 Peterbilt	0.2664	0.6342
05 Thomas	0.1749	1.2808
05 Thomas	0.5504	1.5228
05 Thomas	0.0521	0.3668
05 Thomas	0.1642	2.0089
05 Thomas	0.1902	1.446
05 Thomas	0.1931	1.4489
05 Thomas	0.0731	0.9716
09 Thomas Bus	0.0724	0.176
09 Thomas Bus	0.0922	0.2626
09 Thomas Bus	0.1289	0.2791
09 Thomas Bus	0.1404	0.3723
09 Thomas Bus	0.0546	-0.1294
08 Volvo A	0.0301	0.2156
08 Volvo A	0.022	0.222
08 Volvo A	0.0395	-0.0181
08 Volvo A	0.0134	0.126
08 Volvo A	0.0184	0.2063
08 Volvo A	0.0281	0.1131
08 Volvo A	0.0083	0.2074
08 Volvo A	0.0088	0.1352
08 Volvo A	0.0261	0.25

Make/Model	uvSmoke	irSmoke
08 Volvo A	0.0334	0.0281
08 Volvo A	-0.0061	-0.3286
08 Volvo A	0.0179	0.1275
08 Volvo A	0.0071	0.1019
08 Volvo A	0.0163	0.1833
08 Volvo A	0.0126	0.1591
08 Volvo B	0.073	0.2735
08 Volvo B	0.0527	0.2134
08 Volvo B	0.0293	0.128
08 Volvo B	0.0286	0.1257
08 Volvo B	0.0259	0.1493
08 Volvo B	0.0409	0.143
08 Volvo B	0.0223	0.4233
08 Volvo B	0.0271	0.0917
08 Volvo B	0.0352	0.052
08 Volvo B	0.0282	0.0506
08 Volvo B	0.0429	0.249
08 Volvo Day Cab A	0.0586	0.042
08 Volvo Day Cab A	-0.0068	0.1115
08 Volvo Day Cab A	0.0305	0.5102
08 Volvo Day Cab A	0.0003	0.1963
08 Volvo Day Cab A	0.0316	-0.4165
08 Volvo Day Cab A	0.0723	0.0327
08 Volvo Day Cab A	0.0187	0.0351
08 Volvo Day Cab A	0.0057	0.2523
08 Volvo Day Cab A	0.0204	0.1021
08 Volvo Day Cab A	0.0311	0.4271
08 Volvo Day Cab A	0.0161	-0.0045
08 Volvo Day Cab A	-0.0003	0.1772
08 Volvo Day Cab A	0.0159	-0.0964
08 Volvo Day Cab A	0.0095	0.076
08 Volvo Day Cab A	0.0027	0.0839
08 Volvo Day Cab A	0.0094	0.1697
08 Volvo Day Cab A	0.043	0.2591
08 Volvo Day Cab B	0.2255	-0.6066
08 Volvo Day Cab B	0.094	0.1617
08 Volvo Day Cab B	0.039	0.2065
08 Volvo Day Cab B	0.0959	0.1363
08 Volvo Day Cab B	0.1233	0.1775
08 Volvo Day Cab B	0.0837	0.1571
08 Volvo Day Cab B	0.1171	0.4386
08 Volvo Day Cab B	0.0438	0.1367
08 Volvo Day Cab B	0.0579	0.032
08 Volvo Day Cab B	0.0738	0.2158
08 Volvo Day Cab B	0.0761	0.1046
08 Volvo Day Cab B	0.123	0.117

Table A3 continued

Make/Model	uvSmoke	irSmoke
08 Volvo Day Cab B	0.0008	0.4458
08 Volvo Day Cab B	0.0306	0.2252
08 Volvo Day Cab B	0.0911	0.1186
08 Volvo Day Cab B	0.0613	0.0237
08 Volvo Day Cab B	0.0402	-0.02
08 Volvo Day Cab B	0.0578	0.3072
09 Penske B	0.0547	-0.0136
09 Penske B	0.0312	0.028
09 Penske B	0.0242	-0.2429
09 Penske B	0.0369	-0.0195
09 Penske B	0.0097	0.2473
09 Penske B	-0.0001	0.1966
09 Penske B	0.0857	-0.2206
09 Penske B	0.0052	0.5893
09 Penske A	0.0086	-0.0107
09 Penske A	0.0191	0.0691
09 Penske A	0.0135	0.2209
09 Penske A	0.0366	0.1087
09 Penske A	0.036	0.2924
09 Penske A	0.0153	0.2392
09 Penske A	0.0043	0.1051
09 Penske A	0.0044	0.0583
09 Penske A	0.0155	-0.0134
07 Prostar B	0.0398	0.0855
07 Prostar B	0.0879	0.1441
07 Prostar B	0.1131	0.2229
07 Prostar B	0.0987	0.22
07 Prostar B	0.1413	0.3233
07 Prostar B	0.1537	0.2708
07 Prostar B	0.0827	0.0899
07 Prostar B	0.1958	0.3473
07 Prostar B	0.1386	0.8712
07 Prostar B	0.1773	0.1276
07 Prostar B	0.1804	0.2908
07 Prostar B	0.2134	0.2366
07 Prostar B	0.1345	0.2754
07 Prostar B	0.1158	0.2271
07 Prostar B	0.1504	0.2814
07 Prostar B	0.0807	0.3828
07 Prostar B	0.1333	0.4333
07 Prostar A	0.0002	0.0847
07 Prostar A	-0.2088	-0.3721
07 Prostar A	-0.0869	-0.1283
07 Prostar A	-0.0299	-0.072
07 Prostar A	-0.0469	-0.0031
07 Prostar A	-0.0843	0.0144

Make/Model	uvSmoke	irSmoke
07 Prostar A	-0.1546	-0.8282
07 Prostar A	-0.0484	0.0921
07 Prostar A	-0.0703	-0.1457

The following test schedules were employed for correlation of PM data collected using ETaPS and the WVU HDTVETL:

1. UDDS (Test D):

The USEPA Urban Dynamometer Driving Schedule (UDDS), often referred to as “Test D”, with an average speed of 18.8 mph and a maximum speed of 58 mph over 5.5 miles was used as the primary chassis test schedule [Figure 2].

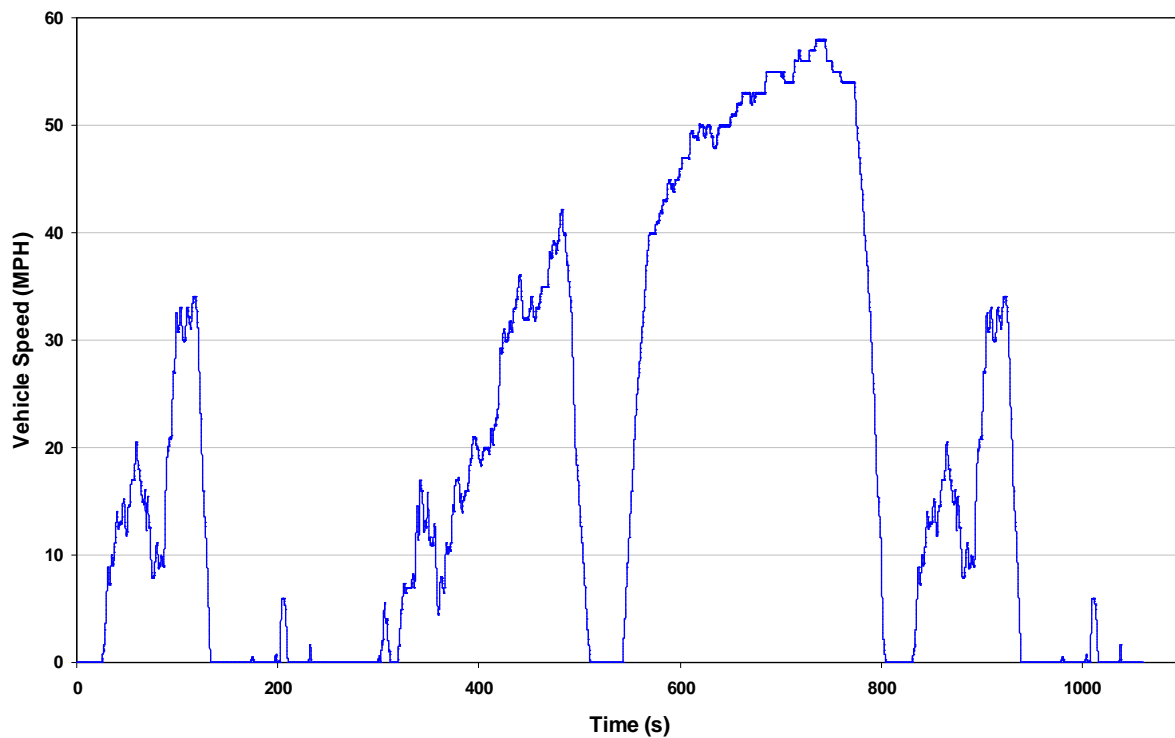


Figure 2 UDDS Chassis Dynamometer Test Cycle.

2. Steady-State Cruise Cycle (ETAPS_40):

A steady-state cycle, at a sustained cruise speed at 40mph over 9.5 miles, was created to simulate steady highway operation [Figure 3]. In addition, stability of signal and, more importantly, inference of aerosol concentration from the ETaPS signal could be more directly.

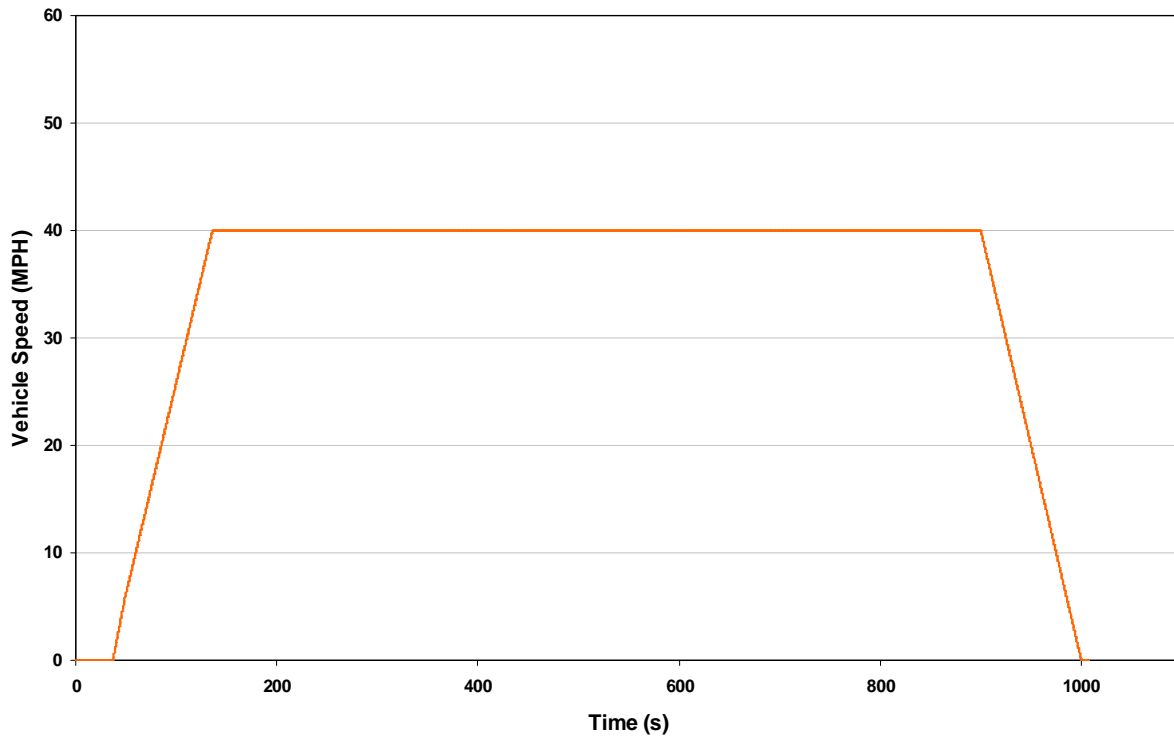


Figure 3 Steady-state Cruise Chassis Dynamometer Test Cycle (ETAPS_40).

3. Acceleration Ramps (ETaPS_acc):

A test cycle, averaging 30 mph and a maximum of 40 mph, derived from the WVU 5-mile schedule, was utilized to evaluate correlation of ETaPS signal with gravimetric PM during vehicle acceleration [Figure 4].

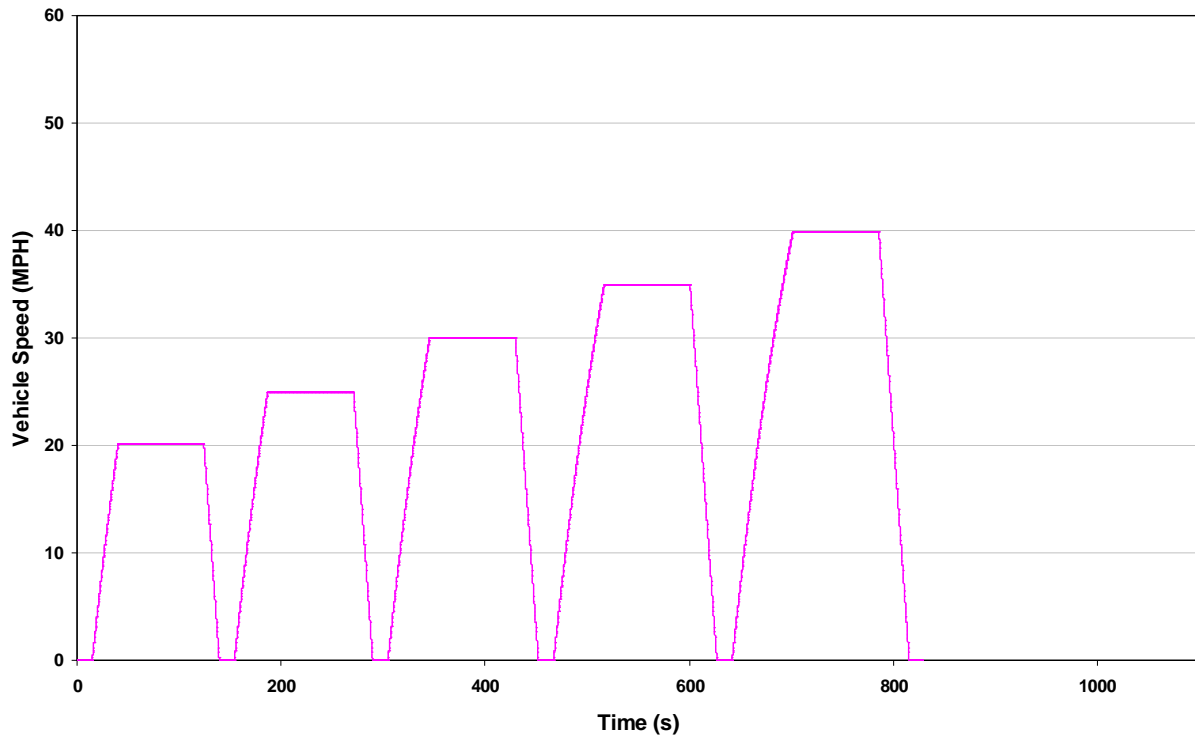


Figure 4 UDDS Chassis Dynamometer Test Cycle.