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Evaluating Real-World Fuel Economy on Heavy Duty Vehicles using a Portable Emissions Measurement System

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ABSTRACT

Current SAE practices for evaluating potential improvements in fuel economy on heavy-duty vehicles rely on gravimetric measurements of fuel tanks. However, the recent evolution of portable emissions measurement systems (PEMS) offers an alternative means of evaluating real-world fuel economy that may be faster and more cost effective. This paper provides a direct comparison of these two methods based on a recent EPA study conducted at Southwest Research Institute. More than 228 on-road tests were performed on two pairs of class 8 tractor-trailers according to SAE test procedure J1321 in an assessment of various chassis components designed to reduce drag losses on the vehicle. During these tests, SEMTECH-D™ portable emissions measurement systems from Sensor's, Incorporated were operating in each of the vehicles to evaluate emissions and to provide a redundant measure of fuel economy. These measurements showed excellent correlation to the gravimetric results with a coefficient of determination greater than 0.98 and nearly identical regression slopes for three of the four trucks. One truck had a series of suspect data toward the end of the study that biased the regression slope higher by 4%. Measurement variability also compared favorably between the two test methods. The average coefficient of variation based on the three repeat laps performed on every test segment was 2.98% for the gravimetric measurements and 3.26% for the SEMTECH-D measurements at a 95% confidence interval. These results all support the use of SEMTECH-D as a viable alternative to the gravimetric measurements for heavy-duty in-use fuel economy determination.

INTRODUCTION

BACKGROUND

Fuel economy is of high importance in the trucking industry, but the inherent difficulty in measuring real-world fuel economy and fuel consumption on heavy-duty trucks is prohibitive for evaluating fuel-saving technologies. The recent availability of Portable Emissions Measurement Systems (PEMS) may offer some relief in this area, provided it can be demonstrated that measurements are comparable to current practices which rely on gravimetric measurement of removable fuel tanks. That is the topic of this paper.

PEMS have undergone significant development over the past several years, largely due to new regulatory requirements to use such devices for evaluation of in-use emissions as part of a manufacturer-run, in-use emissions testing program for 2007 and later model year heavy-duty diesel vehicles. [3] The U.S EPA has already established design and performance standards for PEMS, requiring them to use the same measurement technologies and meet the same audit criteria as laboratory instrumentation under CFR40 Part 1065 Subpart D. [2] The determination of in-use fuel consumption based on a carbon balance of gaseous emissions is a natural extension of the technology. Determining fuel economy using the carbon-balance method has been a standard in the automotive industry for decades. EPA's regulations on how to test vehicles, measure, calculate and report fuel economy using the carbon-balance method are found in the Code of Federal Regulations, CFR Part 600.

PURPOSE AND SCOPE

The U.S. EPA conducted a 6 month fuel economy study at Southwest Research Institute in support of the SmartWay® Transport Partnership. Details about the scope of the overall study and results can be found in SAE publication 2006-01-3474. In general, strategies used by SmartWay partners include retrofitting existing trucks with more fuel efficient tires and aerodynamic fairings. The primary goals of the program were to assess the potential benefit of tires with low rolling resistance and aerodynamic fairings in regards to fuel consumption and NOx emissions. The comparison of fuel consumption measurements based on gravimetric and carbon-balance methods was a secondary benefit of the program, which is why this topic is being addressed separately in this paper.

METHODS

OVERVIEW

To determine the fuel economy benefits of the special tires and aerodynamic fairings, a test matrix was completed using procedures from the SAE J1321, “Joint TMC/SAE Fuel Consumption Test Procedure Type II” [1]. This procedure was modified in order to simultaneously collect emissions data as well as fuel economy.

Under this procedure, a control vehicle (C) was run simultaneously with a test vehicle (T) to provide a baseline reference. Ratios of the test and control truck (T:C ratios) were used to evaluate the effect of the vehicle modifications on fuel consumption and emissions. Southwest Research Institute conducted the tests on an 8.5-mile oval track at the Continental General Proving Grounds in Uvalde, Texas.

Each pair of vehicles was tested over four drive cycles (Figure 1). For the purposes of this paper, we are only interested in the direct comparisons of fuel economy results base on the simultaneous gravimetric and carbon-balance measurements. Each test on each of the four trucks used in this study provides a paired set of data used in a linear regression analysis. There were 20 configurations tested on the Kenworth trucks, and 18 configurations on the Freightliner trucks. Each configuration was tested three times each, providing 60 paired data points for each Kenworth truck and 54 paired data points for each Freightliner truck. The paired data points are also evaluated qualitatively on a time scale, comparing trends over the course of the study.

Measurement variability of in-use fuel economy testing is evaluated for each method, and provides a basis by which one can determine thec significance of any differences in fuel economy measurements. Because each vehicle configuration was tested three times, we can compare the variability between the gravimetric and carbon-balance method for 76 different data sets. In addition, the unchanging control trucks provide longer term test variability that encompasses changing environmental conditions in addition to driver repeatability.

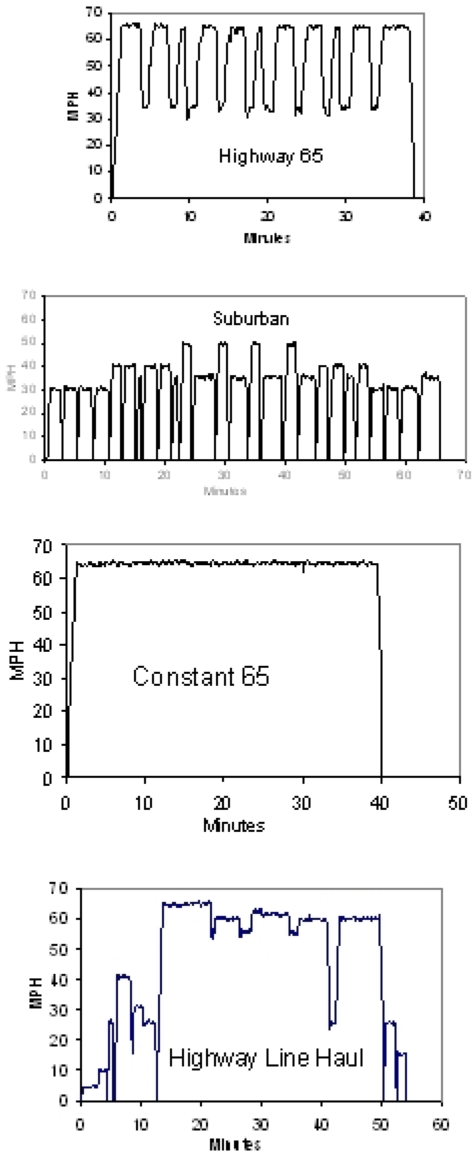

Figure 1: Typical Speed traces of drive cycles tested

DATA COLLECTION

Fuel consumption was measured using the gravimetric method described in SAE J1321 [1]. Detachable fuel tanks installed on each truck were weighed before and after each lap to determine the fuel consumed. Fuel economy was also computed for the gravimetric method using distance determined from a global positioning system (GPS) receiver in the PEMS.

Fuel consumption and fuel economy were also measured using a SEMTECH-D™ portable emissions measurement system (PEMS) installed onboard each truck. SEMTECH-D is manufactured by Sensors, Inc., and determines fuel consumption based on a carbon balance of measured emissions. Emissions measured and recorded include THC, NO, NO2, CO, CO2, and O2. In addition, engine data from the vehicle’s diagnostic port, weather conditions, and GPS data are all recorded on a real-time basis. Based on the emissions, speed and distance data computed the GPS, carbon balance fuel economy was calculated using the method outlined in SAE Standard J1094a. [4]

SEMTECH-D instruments measure CO2 and CO using non-dispersive infra-red spectroscopy, and simultaneous NO and NO2 using non-dispersive ultra-violet spectroscopy. These analyzers are designed and manufactured by Sensors, Inc. A heated flame ionization detector measures total hydrocarbons, and an electrochemical sensor provides oxygen measurements. Raw exhaust is sampled through heated transport tubing and particulate filtration. Ambient pressure, temperature and humidity measurements are used for NOx humidity correction. Sensor's SEMTECH EFM exhaust mass flowmeter, based on differential pressure across an averaging pitot tube, provides a means for mass emissions computations. The SEMTECH EFM utilizes four separate differential pressure sensors with auto-zeroing functions to achieve the necessary dynamic range. Calculated emissions rates based on the various inputs are updated and displayed real-time using the LabView™ user interface. All raw data are also logged to on-board removable storage media for later analysis using a post-processing utility.

All gas analyzers were calibrated and audited daily with NIST traceable standards. Routine maintenance of the equipment was performed per the manufacturer's recommendations.

Vehicle selection

Two pairs of class 8 trucks were tested in this program (Tables 1 and 2). The two trucks in each pair were identical model year, engine model, drive train components, and emission controls. All four trucks and the two trailers underwent inspections and up-to-date maintenance to ensure proper function and operation of mechanical components. Engine, transmission, and axle lubricants were changed prior to test. Type 2-D highway diesel fuel meeting the fuel specifications of 40 CFR 86.113-94 was used for all warm-up and testing operations.

The Detroit Diesel engines on the Freightliner trucks were equipped with a crankcase breather tube (open crankcase) that vents blow-by gases to the atmosphere. It was noted that the Freightliner control truck had significant blow-by at the beginning of the testing based on visual observation of smoke emitting from the vent. There is no way of quantifying the amount of blow-by, or if it remained constant during the testing. It is undesirable to conduct PEMS testing when blow-by is present, because the PEMS relies on full exhaust flow measurements. If some exhaust escapes from the crankcase, the PEMS will have a low bias in exhaust flow measurement and a correspondingly high bias in fuel economy. If the blow-by actually increased during the course of the study, it would explain some anomalous results on this vehicle.

The experiments involved the use of three experimental modifications of the test vehicle: Single wide tires, trailer aerodynamic devices, and both in combination. Conventional dual tires on the drive and trailer axles were replaced with 17-inch single wide tires mounted on aluminum wheels. The tires improve fuel economy through lower rolling resistance and decreased mass.

The trailer aerodynamic devices include a gap reducer, skirt fairings attached to the lower edge of each trailer side between the axles and a boat-tail. A single gap fairing design was used for all the tests. The gap fairing was attached to the top and side edges of the trailer face. Two different designs of "skirt" fairings were used, the "composite skirt" and the "aluminum skirt" (The terms are based on the material used for each.) Two types of boat tail fairings were tested. One was designated the "inflatable boat tail" fairing and the other was designated the "folding boat tail". The skirt fairings reduce crosswind and underside drag, the gap fairing reduces turbulent drag between the tractor and the trailer and reduces drag on the front of the trailer, and the boat tail reduces turbulence at the rear of the trailer, maintaining laminar flow over the trailer.

Table 1: **Kenworth Truck**, Engine & Trailer Descriptions. Hp: horsepower; lbs: pounds; VIN: Vehicle Identification Number; GVWR: Gross vehicle weight rating

Description	Control Truck	Test Truck
Test ID # VIN	989 1XKADB9X96R135622	986 1XKADB9X96R135619
Manufacturer / Model / Year	Kenworth T600 2005	Kenworth T600 2005
Engine Family	5CPXH0928EBK	5CPXH0928EBK
Engine Model	Caterpillar C15 ACERT	Caterpillar C15 ACERT
Rated Hp and engine displacement	625 hp 15.2 liter	625 hp 15.2 liter
Emission Control	Electronic Control & Engine Modification	Electronic Control & Engine Modification
GVWR(lbs)/Base-line Wgt (lbs)	80,000/ 66,389	80,000/ 66,054
Mileage at SOT	32,608	14,717
Trailer	53' Wabash box van	53' Wabash box van

Table 2: **Freightliner Truck**, Engine & Trailer Descriptions. Hp: horsepower; lbs: pounds; VIN: Vehicle Identification Number; GVWR: Gross vehicle weight rating

Description	Control Truck	Test Truck
Test ID # VIN	4923 1FUYDSZB3YPB03001	4924 1FUYDSZB5YPB03002
Manufacturer / Model / Year	Freightliner FLD120 2000	Freightliner FLD120 2000
Engine Family	XVVXH12.7EGL	XVVXH12.7EGL
Engine Model	Detroit Diesel Series 60	Detroit Diesel Series 60
Rated Hp and engine displacement	500 hp 12.1 liter	500 hp 12.1 liter
Emission Control	Electronic Control Low NO$_X$ Kit	Electronic Control Low NO$_X$ Kit
GVWR(lbs)/Base-line Wgt (lbs)	80,000/ 65,103	80,000/ 65,352
Mileage at SOT	788,407	723,210
Trailer	53' Wabash box van	53' Wabash box van

DATA ANALYSIS

The paired data points generated from the gravimetric fuel economy and PEMS carbon-balance fuel economy were examined in several ways. First, a least-squares linear regression analysis was performed on data sets from each truck using MINITAB® statistical software. Because there was a relatively narrow range of fuel economy results, this analysis produced unrealistic y-intercepts. In order to provide more meaningful results, the intercepts of the regression lines were forced through zero. There is in fact a physical relationship that requires both measurement methods to always report zero fuel economy at the same time. Any test resulting in zero fuel economy requires a zero distance in the numerator, and both methods rely on the same GPS data to estimate distance traveled. It would be trivial to generate such test data.

Next, measurement variability was compared for the two test methods. Each test segment consisted of three laps, so a coefficient of variation (COV) was determined for each segment on each truck for both methods. Low measurement variability is more critical than overall accuracy in fuel economy testing when using the SAE J1321 method. Test ratios cancel out any systematic errors, so only measurement variability remains as a source of error. This analysis was only performed on the Kenworth truck.

Because the control trucks always were tested in exactly the same configuration, it was also possible to determine measurement variability over long periods of time. All tests were grouped by test cycle and analyzed for variability within each cycle. There were multiple test segments over significant time periods included in the variability analysis.

Finally, the fuel economy T:C ratio results were compared for the two measurement methods.

RESULTS

Table 3 summarizes the linear regression of the paired data points on both the Kenworth control truck and test truck. Figure 2 shows these results graphically. The regression lines are forced through zero because of the relatively narrow band of fuel economy data. It is also arguable that a test resulting in zero miles per gallon would always occur on both the gravimetric and carbon-balance method, since this requires a zero distance in the numerator and both methods rely on the same GPS data to estimate distance traveled.

Results are very similar between the two trucks. Slopes are 0.9695 and 0.9588 for the test and control trucks respectively. The coefficient of determination was 0.9825 on both trucks, indicating very little scatter in the data. The standard error was also very similar at 0.0838 mpg and 0.0785 mpg respectively. For the Control truck, one lap did not contain PEMS data so there is one less data point than the test truck.

Table 3: Linear regression statistics for Kenworth test and control trucks.

Statistic	Test Truck	Control Truck
n	60	59
r^2	0.9825	0.9825
SEE (mpg)	0.0838	0.0785
Slope	0.9695	0.9588

Table 4 shows the linear regression of the paired data points on both Freightliner trucks. The results for the test truck were nearly identical to those of both Kenworth trucks. However, the control truck had a significantly higher slope and standard error. Investigation into this result revealed an increasing high bias in the PEMS relative to the gravimetric results beginning about halfway into the testing. This is shown in Figure 4. There were no indications of malfunctions in the PEMS equipment; it continued to pass the standard daily quality assurance checks. One possibility that could explain this result would be an increase in the blow-by for this vehicle. As discussed above, this vehicle was not an ideal candidate for this study because it had significant blow-by at the start of the test. Unfortunately, no pressure measurements were made at the crankcase to verify if the blow-by did increase toward the end of the testing. When analyzed with the last 5 segments omitted, the regression slope of the Freightliner control truck was 0.972, which is consistent with the other three trucks.

Table 4: Linear regression statistics for Freightliner test and control trucks.

Statistic	Test Truck	Control Truck
n	53	53
r^2	0.9741	0.9792
SEE (mpg)	0.1075	0.2214
Slope	0.9590	1.001

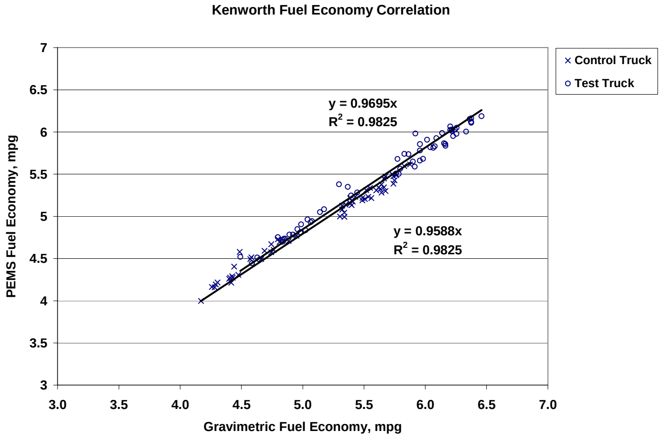

Figure 2: Linear regression analysis of fuel economy based on gravimetric method versus PEMS carbon balance method, for all data collected on the two Kenworth trucks. Regression lines are forced through zero.

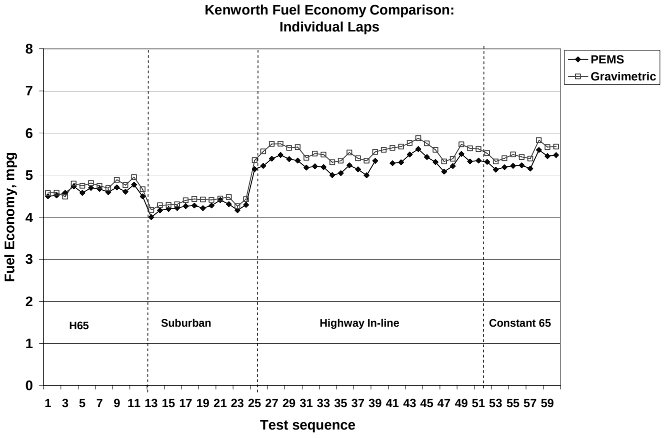

Figure 3: Comparison of fuel economy measurements for each test lap of the Kenworth control truck.

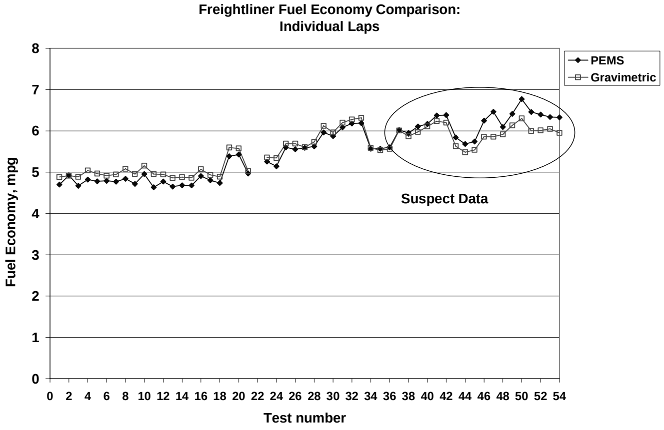

Figure 4: Comparison of fuel economy measurements for each test lap of the Freightliner control truck. There is a clear crossover in the relationship between the PEMS and gravimetric data.

Figure 5 shows the relative variability of the gravimetric fuel economy measurements compared to the PEMS carbon balance measurements for each segment on the Kenworth control truck. The test segments consist of three laps that were typically performed in the same day. The chart is divided by the four test cycles. The error bars are based on the three laps in each segment, and represent 95% confidence limits. The error bars are similar between the two test methods, and in general, correlate between the two methods. This suggests that sources of variability are primarily systematic (i.e. driver or test conditions) rather than the measurement instruments.

Table 5 quantifies this variability of the two measurement methods in terms of coefficient of variation (COV). A COV was computed based on the three laps for each segment. The COVs were then averaged for each truck and compared. This analysis shows the PEMS measurements have slightly higher variability than the gravimetric method, but still very comparable.

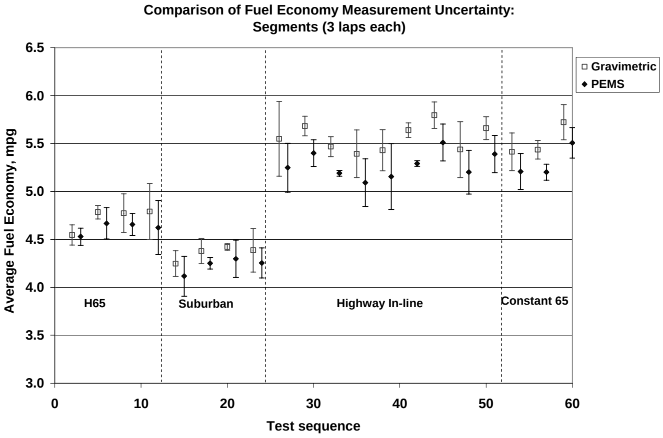

Figure 5: Comparison of fuel economy measurement uncertainty for each test segment of the Kenworth control truck. Error bars are at 95% confidence intervals.

Table 5: Variation of fuel economy measurements during each segment on the Kenworth trucks expressed as average coefficient of variation (COV).

	Average Gravimetric COV	Average PEMS COV
Test Truck	2.69%	3.09%
Control truck	3.27%	3.42%
Overall Average	2.98%	3.26%

Figure 6 illustrates long-term measurement variability for the two test methods. In this chart, the variability is computed over all test segments for each test cycle. Note that the error bars are significantly larger than the analysis over individual segments. However, the two test methods are quite comparable.

Table 6 summarizes the variability of the two measurement methods for the Kenworth control truck using all data for each cycle. Variability is expressed in terms of coefficient of variation (COV) computed at a 95% confidence interval. The variation in the PEMS measurements over each cycle is roughly equivalent to the variation using the gravimetric method. Because the various segments for each cycle were conducted over a significant time period, it is believed that variability in both measurement methods is dominated by changing environmental conditions rather than instrumentation.

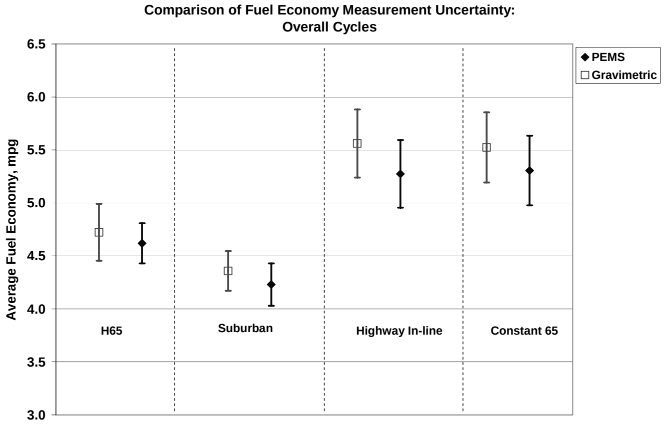

Figure 6: Comparison of long tern fuel economy measurement uncertainty over entire study for each test cycle on Kenworth control truck. Error bars are at 95% confidence intervals.

Table 6: Coefficient of Variation (COV) at 95% confidence interval for all fuel economy measurements at each cycle on the Kenworth control truck.

Cycle	n	Gravimetric	PEMS
H65	12	5.67%	4.10%
Suburban	12	4.29%	4.73%
Highway line haul	27	5.77%	6.03%
Constant 65	9	6.00%	6.19%
Average		5.43%	5.26%

Comparison of T:C ratios

A comparison of T:C ratios for gravimetric and carbon-balance fuel economy are shown in figure 7 for the Kenworth trucks. Variability of these T:C ratios for each segment are shown in figure 8. Given that the measurement variability of the PEMS carbon-balance method has been shown to be comparable to the gravimetric method, it is not surprising that the T:C ratios compare well also. However, there is a noticeably higher variability in the PEMS T:C ratio for some segments. Nevertheless, the average of the three laps in each segment compare favorably with the gravimetric method.

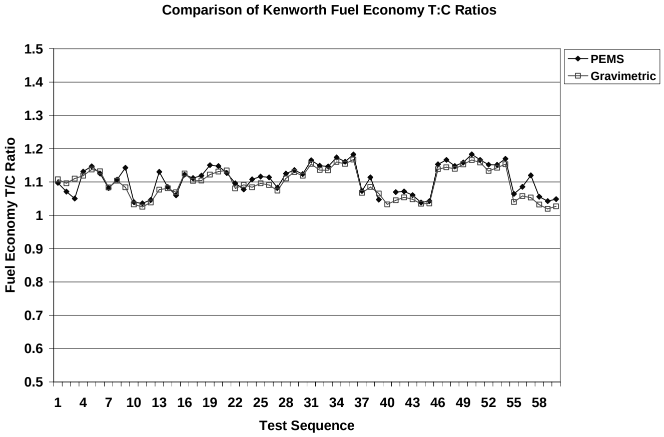

Figure 7: Comparison of T:C ratios for each test lap on Kenworth trucks.

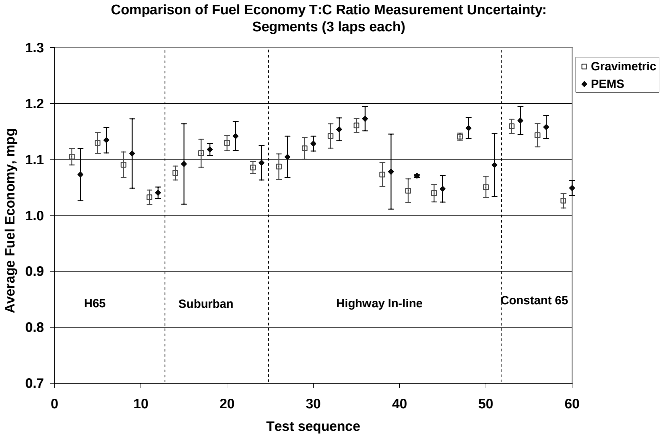

Figure 8: Comparison of T:C ratios and error bars for each test segment on Kenworth trucks. Error bars are at 95% confidence intervals.

DISCUSSION

Aside from the anomalous data on the Freightliner truck toward the end of the study, the linear regression analysis shows excellent consistency on all four trucks with regard to slope and data scatter. With regard to slope, the consistent 3 to 4% low bias on the SEMTECH compared to the gravimetric is indicative of a systematic error, or combination of several systematic errors. Potential sources of systematic errors for the PEMS include tolerances on: calibration gas standards, gas analyzers, exhaust flowmeter, and the flowmeter calibration standard. In addition, there is a tolerance on the gravimetric measurements themselves. These sources of systematic error are well understood, and one of the fundamental reasons why a control test must be performed in every real-world fuel economy test in accordance with SAE J1321. Using this procedure, any biases are factored out of the analysis, because we only consider changes from the baseline condition, not absolute values of fuel economy.

Although systematic errors do not affect the results of fuel economy studies using a control test, nonsystematic errors can produce erroneous results. This is why analysis of the measurement variability is so important. Data from this study shows that the fuel economy measurement variability from the SEMTECH analyzers is comparable to the gravimetric system at a COV of 3.26% vs 2.98%. These can be considered detection limits for fuel economy testing using the two methods, meaning that one cannot discern differences in fuel economy that are smaller than these values. As discussed above, the fact that the size of the error bars on a given test segment seem to correlate between the two methods implies that the variability is due to an external source, such as driver repeatability.

The comparison of T:C ratios for the gravimetric and SEMTECH fuel economies also shows good agreement, as one would expect based on the strong correlation and comparable measurement variability. It is clear from this result that the SEMTECH could be used in place of the gravimetric measurements and produce results that are within the error bands of the latter for the majority of the test segments.

CONCLUSION

The results of this analysis demonstrate that portable emissions measurements systems, such as the SEMTECH-D from Sensors, Inc., can be used in place of gravimetric measurements for SAE J1321 test procedures. They produce very similar results, which are typically within the error band of the gravimetric measurements. The study also demonstrated the benefits of testing in tandem with a control truck to eliminate the significant effects of environmental conditions as well as any systematic errors in the measuring equipment. However, if the test truck can be refitted back to a baseline level within a short enough time period to insure similar environmental conditions, it may be possible to achieve equivalent results with only one truck. Using a PEMS can significantly speed up the test process in several ways. First, the test cycle could be shorter, since the SEMTECH-D measures fuel economy on a real-time basis whereas the gravimetric method requires a minimum driving distance sufficient to consume a measurable quantity of fuel. Secondly, hours can be saved by not having to remove fuel tanks for weighing before and after each lap. Using the SEMTECH, laps can be repeated immediately.

Analysis of the variability of the individual fuel economy measurements demonstrates that it feasible to accurately detect fuel economy changes as low as 3 percent for the gravimetric method with only a slightly higher detection limit for the SEMTECH-D carbon-balance method. Because the variability is so similar for the two test methods, it is believed to be dominated by driver repeatability on the test track rather than measuring equipment.

ACKNOWLEDGMENTS

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