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Fuel Economy Improvements and NOx Reduction By Reduction of Parasitic Losses: Effect of Engine Design

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ABSTRACT

Reducing aerodynamic drag and tire rolling resistance in trucks using cooled EGR engines meeting EPA 2004 emissions standards has been observed to result in increases in fuel economy and decreases in NOx emissions. We report here on tests conducted using vehicles equipped a non-EGR engine meeting EPA 2004 emission standards and an electronically-controlled engine meeting EPA 1998 emissions standards. The effects of trailer fairings and single-wide tires on fuel economy and NOx emissions were tested using SAE test procedure J1321. NOx emissions were measured using a portable emissions monitoring system (PEMS). Fuel consumption was estimated by a carbon balance on PEMS output and by the gravimetric method specified by test procedure J1321. Fuel consumption decreased and fuel economy increased by a maximum of about 10 percent, and NOx emissions decreased by a maximum of 20 percent relative to baseline. This compares with NOx reductions of up to 45 percent reported in the earlier test on the cooled EGR engine. The reduction in power requirements in the current test did not result in a corresponding reduction in brake specific NOx emissions, as it did in the earlier test. These results provide further evidence that reducing parasitic losses in heavy-duty highway vehicles will not only reduce fuel consumption and greenhouse gas emissions, but will also provide NOx reductions that pay for themselves through reduced fuel use.

INTRODUCTION

BACKGROUND

Aerodynamic drag and tire rolling resistance losses account, after engine losses, for most of the fuel consumption of heavy duty vehicles operating on the highway. Aerodynamic drag accounts for 21 percent of the power requirement of such a vehicle, and rolling resistance accounts for 13 percent [1]. A load reduction equation presented by Clark et. al. [2] provides further details of the relative effect of tire rolling resistance and aerodynamic drag on vehicle power requirements:

$$P = 1/2\rho_a C_d A V^3 + \mu M g V + M g V \sin\theta \qquad (1)$$

Where P is the power needed to maintain a steady speed, ρ_a is the density of air, C_d is the aerodynamic drag coefficient of the vehicle, A is the frontal area of the vehicle, V is the vehicle speed, μ is the tire rolling resistance coefficient, M is the mass of the vehicle, g is gravitational acceleration, and θ is the angle of inclination of the road grade. The equation shows that as speed increases, aerodynamic drag increases power needs exponentially, whereas the power required to overcome rolling resistance increases in only a linear manner.

Simple components that reduce aerodynamic drag and tire rolling resistance can be a cost-effective way to increase the fuel economy of existing, as well as new heavy-duty highway trucks. Because most heavy-duty tractor-trailer trucks remain in service for many decades, and these trucks are also responsible for the majority of fuel used in the trucking industry, approaches that save fuel for the legacy on-highway heavy truck fleet can have a substantial impact on the total fuel consumption of the commercial trucking industry.

In addition, engine-out vehicle emissions are a function of power output of the engine, so reductions in power requirements should result in a reduction in those emissions. This is of more significance for NOx emissions than particulate matter (PM), because aftertreatment devices capable of reducing NOx emissions are not commercially available for retrofit on existing trucks whereas devices (such as oxidation catalysts and particulate filters) are available for PM. Such hypothesized relations among reduced power output, increased fuel economy and reduced engine-out distance-specific NOX emissions were reported by

Bachman et. al. [3] for a model year 2004 Mack[1] class 8 tractor using a cooled EGR engine. The test was conducted over several different drive cycles, using a modified version of SAE J1321 Fuel Consumption Test Procedure, with the addition of a portable emissions monitoring system. [4] Vehicle power need was reduced using single wide tires to reduce rolling resistance, and trailer fairings to reduce aerodynamic drag. Improvements in fuel economy ranged from 3 to 18 percent (relative to the baseline truck); corresponding decreases in NOx emissions relative to baseline ranged from 9 to 45 percent [3].

Emission reductions were considered to be out of proportion to the magnitude of the fuel economy improvements. Examination of some of the power-specific NOx emissions data suggested that the test components were somehow reducing the power-specific emissions as well as reducing the total power output. Discussion with the engine manufacturer suggested that this phenomenon might be common in cooled EGR engines, and that testing of other engine types would provide useful data to evaluate this possibility. In this paper, we present the results of similar testing of two other engine types for comparison.

PURPOSE AND SCOPE

The testing described in this paper was done in support of the SmartWay® Transport Partnership. SmartWay is a voluntary partnership among shippers, transportation providers, such as truck fleets, and the U.S. Environmental Protection Agency (EPA), designed to improve air quality and reduce greenhouse gas emissions through the use of cleaner, more efficient freight transport practices and equipment. Strategies used by SmartWay partners include retrofitting existing trucks with more fuel efficient tires and aerodynamic fairings.

The test results presented here will further the EPA's understanding of the fuel-saving benefit of these strategies, and provide additional quantification of the associated NOx impacts, so that it may be possible to account for emission reductions in innovative, cost-effective programs to improve air quality, especially in areas seeking NOx reductions.

The work described here also supports the EPA's regulatory program for heavy-duty diesel vehicles by providing an opportunity to gather data on the use and performance of portable emissions monitoring systems. EPA is requiring the use of portable emissions monitoring systems in its regulatory program for heavy-duty diesel engines, as part of a manufacturer-run, in-use emissions testing program for 2007 and later model year heavy-duty diesel vehicles. [5] The information generated in this test will also support the activities of States, academic institutions, and other organizations interested in using portable emissions monitoring systems to examine the relation between fuel economy and emissions under "real world" driving conditions.

Emissions tested were total hydrocarbons (HC), carbon dioxide (CO2), carbon monoxide (CO) and NOx. PM was not measured. Although the state of on-board PM measurement devices is rapidly evolving, at the time of this test, commercially available devices had not yet demonstrated sufficient accuracy and precision to meet the test objectives. [6] Results for NMHC and CO are not presented because they are very small in relation to NOx, and emissions from heavy-duty diesel account for a small percentage of the total NMHC and CO emission inventory.

Test and control vehicles were tested on an outdoor track using different drive cycles that approximate actual driving conditions. Two truck engine models were tested. Taken together with the engine tested previously [3], these three engine types represent the majority of engine types used by class 8 tractor-trailer combination trucks in highway operation in the United States. The results of all of these tests show a strong relation between improved fuel economy and decreased NOx.

METHODS

OVERVIEW OF TEST METHOD

The effects of the experimental modifications on fuel economy improvement and NO_X emissions reduction were evaluated using the SAE J1321, "Joint TMC/SAE Fuel Consumption Test Procedure Type II" [4] modified to provide information on emissions as well as fuel economy. An unchanging control vehicle (C) is run through a drive cycle in tandem with a test vehicle (T) to provide reference data. Each run through the drive cycle by the pair of trucks is referred to as a "lap."

T:C ratios are computed on results from a baseline where T is equipped the same as C and under test conditions, where T is equipped with the components being tested. The percent difference (PD) between the T:C ratios at baseline and test represent the percent difference due to the test component:

$$PD = \left[\frac{T:C_{test} - T:C_{baseline}}{T:C_{baseline}} \right] \times 100 \qquad (2)$$

The T:C ratios used here are actually averages of a minimum of 3 laps. In accordance with the SAE J1321 procedure, a "test segment" consists of three laps in which the T:C ratios of fuel consumption are within 2 percent.

The equation used here is very similar to the equation in SAE J1321 for "percent fuel saved" (equation A.2.3 in

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[1] Names of commercial products are mentioned for identification purposes only, and such identification does not constitute an endorsement by EPA.

ref. [4]) with the exception that the terms in the numerator are reversed. This was done for consistency with our earlier study [3]. All results are thus presented in terms of “percent difference relative to baseline.” Negative values indicate a decrease relative to baseline and are a desirable outcome for fuel consumption and NOx emissions. The fuel consumption results could be applied directly to estimate the cost savings from improved fuel economy. However, the main objective of this paper is to evaluate the relations among engine types, fuel-saving components, fuel economy, and emissions, so caution should be exercised if these data are used to compute actual cost savings.

Southwest Research Institute conducted the tests on the oval track at the Continental General Proving Grounds in Uvalde, Texas. The 8.5-mile oval road surface is asphalt and generally flat with a few rolling hills.

Four drive cycles (figure 1) were conducted that were considered representative of potential class 8 tractor-trailer operations: The “Highway 65” cycle [3] was a simulation of the drive cycle previously conducted in a modified SAE J1321 program at the Aberdeen Proving Ground in Aberdeen, Maryland**.** The “Suburban” cycle, also used at Aberdeen, [3] was predominately stop and go driving with an average speed of about 30.4 mph. A “Constant 65” cycle involved acceleration to 65 mph, constant speed of 65 mph, and a deceleration to stop. The “Highway Line Haul” cycle was modified from the California Heavy-Duty Diesel truck test schedule derived from statistical analyses of on-road truck operations [7]. This cycle includes extended idle and off idle operation to simulate a line haul truck exiting an arterial road, including traffic lights, and proceeding to a loading/unloading location.

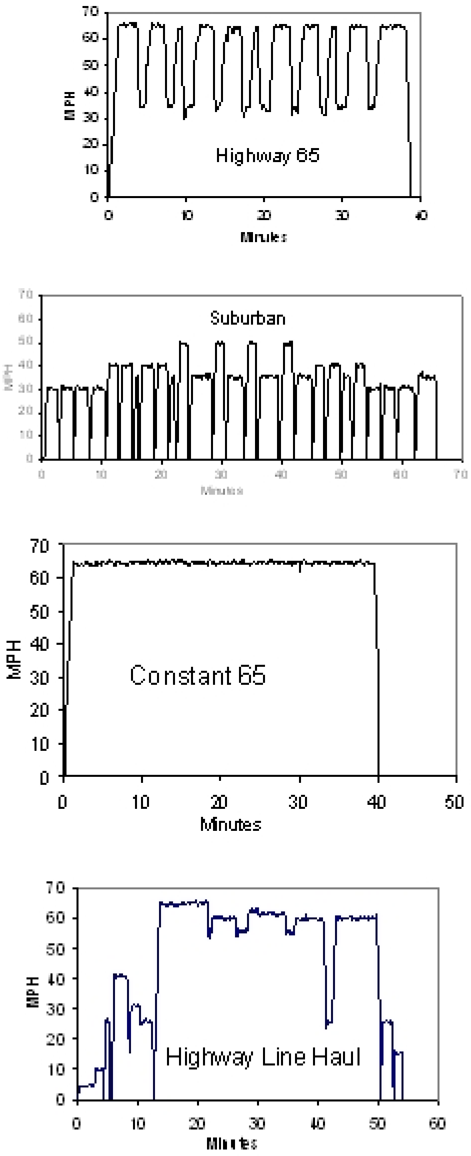

Figure 1: Typical Speed traces of drive cycles tested

DATA COLLECTION

Fuel consumption was measured directly using the gravimetric method described in SAE J1321 [4]. This involved a detachable auxiliary fuel tank installed on each truck, which was weighed before and after each lap to determine the fuel consumed. These gravimetric results were used to calculate the T:C ratios to determine the three valid laps for an SAE J1321 segment.

Tail pipe emissions data were collected with a SEMTECH-D™, a Portable Emissions Monitoring System (PEMS) manufactured by Sensors, Inc., installed onboard each truck. These units measured HC, NOx, CO, and CO2, and recorded engine data from the vehicle’s diagnostic port. Based on the emissions, speed and distance data computed by a global positioning system (GPS) receiver in the PEMS, a carbon balance fuel economy was calculated using the method outlined in SAE Standard J1094a. [8]

Emissions measurements

SEMTECH-D™ instruments measure CO2 and CO using non-dispersive infra-red spectroscopy, and simultaneous NO and NO2 using non-dispersive ultra-violet spectroscopy. A heated flame ionization detector measures total hydrocarbons, and an electrochemical sensor provides oxygen measurements. Raw exhaust is sampled through heated transport tubing and filtration. Ambient pressure, temperature and humidity measurements are used for NOx humidity correction. Sensor's EFM exhaust mass flow meter, based on differential pressure across an averaging pitot tube, provides a means for mass emissions computations. The 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 and mechanical preconditioning

Two pairs of class 8 trucks were tested in this program (Tables 1 and 2). The trucks were selected because they contained two widely-used engine types – The Kenworth truck was equipped with a Caterpillar C15 ACERT engine certified to the 2004-2006 emissions standards [9], and the Freightliner truck was equipped with a Detroit Diesel Series 60 engine compliant with the 1998-2003 emission standards [10]. The two trucks in each pair were identical in model year, engine model, drive train components, and emission controls.

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

Both pairs of tractors were equipped with a factory approved roof fairing. All four trucks and the two trailers underwent inspections and up-to-date maintenance to ensure proper function and operation of mechanical components. Fresh engine, transmission, and synthetic axle lubricants were installed prior to test. As recommended by EPA, a low-NOx rebuild kit available from the engine manufacturer was installed on each of the Freightliner trucks

The tires used in the testing were the ones used during the previous testing at Aberdeen [3]: two complete sets of baseline tires (18 tires in each set) provided by EPA and one set of single wide test tires (8 single wide tires mounted on wheels) provided by the tire manufacturers. Manufacturers of aerodynamic devices for box van trailers supplied the aerodynamic devices.

The baseline tires were placed on both tractors (steer and drive) as well as all trailer positions prior to baseline testing. Cold tire pressure was set to 100 psi daily prior to testing. Vehicles were warmed up at 65 mph for 34 miles on the test track immediately before the start of testing each day. EPA, Sensors, Inc., and Southwest Research Institute personnel developed a PEMS pre-test checklist, which was performed daily prior to conducting SAE J1321 evaluations. Test baseline weights were established at 65% of the gross vehicle weight rating (GVWR). The individual weights of the single wide tires versus the baseline tires and weights of the aerodynamic devices changed the weight of the test truck and trailer rig when these devices were tested. Drivers were thoroughly trained in performing the cycles and monitored to ensure that the cycles were driven as intended. 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.

TEST COMPONENTS

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 included a gap reducer, skirt fairings attached to the lower edge of each trailer side between the axles and a boat-tail. A single gap reducer design was used for all the tests. The gap reducer 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.

The components were sourced from multiple manufacturers in order to test the technology and not particular products. Two brands of single wide tires were used, one on the tractor and the other on the trailer. Four different vendors supplied the trailer aerodynamic improving devices. All components were installed according to manufacturer’s specifications. In some cases, a manufacturer’s representative was on hand to observe the installation, the testing, or both.

Distance was measured with the GPS receiver in the PEMS unit and was checked knowing the total distance of the lanes on the oval track.

DATA ANALYSIS

A three-factor experimental design allowed for testing the experimental modifications. The factors were: drive cycles, test components, and replicates. The three replicates run for each combination of factors were used to calculate measurement variability. The full factorial test was performed only on the Kenworth truck because of time and resource limitations. The exact combinations of drive cycles and components tested are listed in the results section, below. Because of occasional voided tests, meaningful analysis of variance could not be run on the full factorial data set, but subsets of meaningful data could be analyzed. Data were analyzed for fuel consumption by the gravimetric method, fuel economy by the carbon-balance method, and NOx emissions. In addition, percent changes in these values due to the test components were also calculated. Statistics were calculated using S-Plus (version 6.0) Statistical software [11].

RESULTS

Results from all test runs are shown in Tables 3 and 4 and a summary of the percent changes due to the test modifications is shown in Tables 5 and 6. Equipment malfunctions resulted in loss of carbon-balance fuel economy and NOx emission data in one test lap of the Kenworth truck and two test laps of the Freightliner trucks. The Kenworth data loss occurred during a baseline lap, and thus confidence limits could not be calculated around the percent change calculated for the 4 tests using that baseline.

Table 3: Summary statistics for all test runs of the Kenworth trucks

	Minimum	Maximum	Median	Mean	Standard Deviation	Coefficient of variation (%)
Test Fuel consumption, lbs. N=60	44	53.3	48.7	48.84	2.0	4.1
Control Fuel Consumption, lbs N=60	48.4	57.4	53.5	53.5	2.1	3.9
Test Fuel Economy, mpg N=60	4.44	6.18	5.67	5.47	0.54	9.9
Control Fuel Economy, mpg N=59	4.00	5.61	5.13	4.93	0.46	9.3
Test NOX, gm/mi N=60	8.99	13.02	10.05	10.61	1.38	13
Control NOX, gm/mi N=59	9.07	12.85	10.25	10.71	1.14	11

Table 4: Summary statistics for all test runs of the Freightliner trucks.

	Minimum	Maximum	Median	Mean	Standard Deviation	Coefficient of variation (%)
Test Fuel consumption, lbs. N=54	41.9	56.8	47.6	47.7	2.77	5.8
Control Fuel Consumption, lbs. N=54	46.4	59.5	49.4	50.4	2.79	5.5
Test Fuel Economy, mpg N=53	4.61	6.79	5.66	5.61	0.67	12
Control Fuel Economy, mpg N=53	4.63	6.77	5.58	5.53	0.66	12
Test NOX, gm/mi N=53	12.22	19.81	15.88	15.76	1.83	12
Control NOX, gm/mi N=53	13.11	19.30	16.14	15.47	1.29	8.1

Fuel economy (carbon balance method) and NOx data from several tests (marked “*” in table 6) may be in error due to anomalies in data from the SEMTECH-D on the Freightliner control truck. In general, the the fuel economy computed by the gravimetric method had a fairly stable relationship with that computed by the carbon-balance method. However, in the tests marked with “*” in table 6, carbon-balance fuel economy was significantly higher than gravimetric. This would suggest that exhaust volume was somehow decreasing (with resulting decrease of mass emissions of CO, CO_2, and HC and thus an increase of apparent fuel economy.) This could be due to either mechanical problems that increased crankcase blow-by (The Freightliner engine has a ventilated crankcase), a leak in the exhaust system upstream of the flow meter and analyzers, or a malfunction in the flow meter or SEMTECH system. Unfortunately, there is no good evidence to permit determination of the cause of the anomaly. There was no indication of malfunctions in the SEMTECH units, and they passed their daily quality assurance tests. In addition, no pressure measurements were made at the crankcase to determine whether blow-by was increasing

FUEL ECONOMY

Fuel economy is strongly influenced by the drive cycle (figure 2). These data are from the respective control trucks, which were not modified over the course of the test program. One-way analysis of variance (ANOVA) indicates a significant difference (P<0.01) among drive cycles for both trucks. Tukey HSD analysis of pairwise comparisons indicates significant differences at p=0.05 between all cycles for each truck, except that no significant difference was found between fuel economy for the Kenworth truck using the “constant 65” cycle and the “highway line haul” cycle. Similar patterns were observed for the fuel consumption (expressed as pounds per mile) measured by the gravimetric method.

Table 5: Percentage change in fuel economy and NOx emissions due to drive cycles and test components – Kenworth truck.

Test components	Drive Cycle	Percentage change relative to baseline, with error computed from the 95 percent confidence limits of the T:C ratios. Values without confidence limits were based on less than 3 replicates in either the test or baseline segment.		
		Fuel consumption (gravimetric)	Fuel economy (carbon balance)	Distance specific NOx
Single wide tires	Highway 65 mph	-5.3±1.0	6.7±6.2	-9.3±3.4
	Suburban	-2.9±1.5	2.4±7.8	0.6±2.4
	Highway Line Haul	-2.7±.05	0.7±6.7	-2.4
Trailer aerodynamic devices (fairings) using composite skirt	Highway 65 mph	-6.6±0.1	3.1±4.4	-6.3±5.4
	Suburban	-0.6±.01	0.2±5.1	1.9±5.6
	Highway Line Haul	-4.0±0.1	3.2±3.1	1.0
Combined modifications: Single wide tires and trailer aerodynamic devices using composite skirt	Highway 65 mph	-8.6±0.5	9.0 ± 1.4	-10.5±0.8
	Suburban	-4.4±0.2	4.6±6.1	-3.6±1.2
	Highway Line haul	-6.8±0.4	5.4±0.3	-3.1
Combined modifications: Using aluminum skirt	Highway Line Haul	-8.6±0.2	7.7±1.1	-7.9
	Constant 65 mph	-10.4±0.4	12.0±0.6	-10.3±1.7
Combined modifications: Using aluminum skirt REPLICATE TEST	Highway Line Haul	-7.9±1.4	6.1±4.9	-4.0±1.5
	Constant 65 mph	-11.5±0.2	11.5±1.3	-12.3±3.1
Combined fairings using aluminum skirt and omitting boat-tail	Constant 65 mph	-10.2±0.6	10.4±0.7	-10.1±4.1

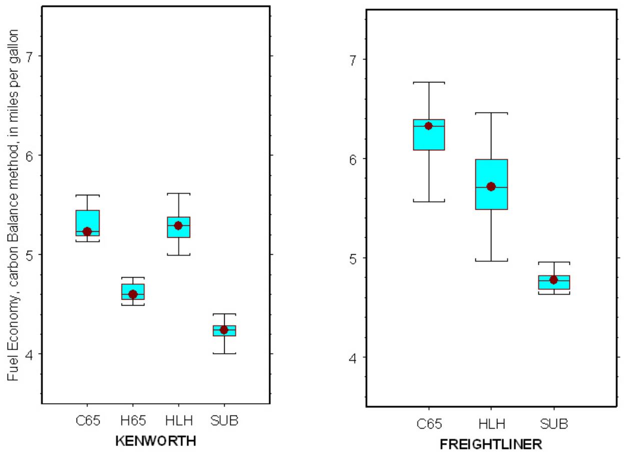

Figure 2: Comparison showing the relation between drive cycle and fuel economy. Central point is median. Box limits are 25th and 75th percentiles. Whisker limits are minimum and maximum. Drive cycles are as follows: **C65** – "constant 65; **H65** – "highway 65: **HLH** – "highway line haul"; **SUB** – "suburban"

All of the components had some effect on reducing fuel consumption and increasing fuel economy(tables 5 and 6, figure 3), with the maximum improvements being about 10 percent for the "combined modifications" run on the "highway line haul" or "constant 65" test cycles. In some tests, particularly the "suburban" cycle run with only one component (either tires or trailer fairings), the test-to-test variability suggested that there would be a reasonable chance of not achieving fuel economy improvements under those conditions.

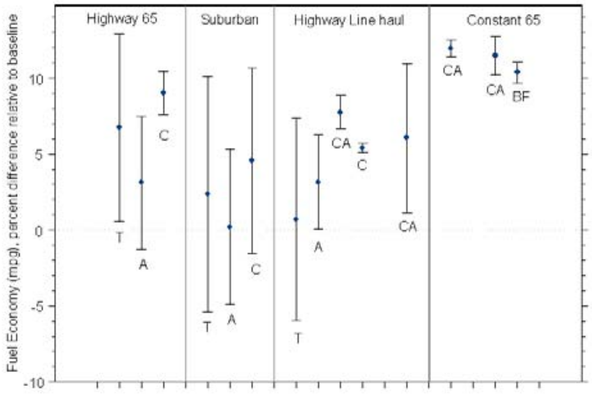

Figure 3: Percentage change in fuel economy based on carbon balance method for the Kenworth truck relative to baseline. Error bars were calculated from the 95 percent confidence limits of the T:C ratios. Test components are as follows: **T** –single wide tires; **A** – trailer fairings with composite skirt; **C** – Combined components with composite skirt; **CA** – combined with aluminum skirt; **BF** – Combined aluminum skirt, no boat-tail

Table 6: Percentage change in fuel economy and NOx emissions due to drive cycles and test components – Freightliner truck.

Test components	Drive Cycle	Percentage change relative to baseline, with error computed from the 95 percent confidence limits of the T:C ratios. Values without confidence limits were based on less than 3 replicates in either the test or baseline segment.		
		Fuel consumption (gravimetric)	Fuel economy (carbon balance)	Distance specific NOx
Combined modifications: Using aluminum skirt and inflatable boat-tail	Suburban	-5.0±.6	4.3±6.6	-11.2±0.9
	Suburban (replicate)	-2.4±1.3	5.0±0.1	-1.2±10.6
	Highway Line Haul	-8.7±0.6	9.4	-13.3
	Constant 65 mph*	-7.1±0.6	3.6±1.3*	-7.2±1.3*
	Constant 65 mph (boat-tail omitted)*	-8.8±0.05	5.2±0.7*	-6.3±1.7*
Trailer aerodynamic devices (fairings) using aluminum skirt and inflatable boat-tail	Suburban	-1.7±0.1	3.5±2.3	-5.8±5.3
	Highway Line Haul*	-4.6±0.5	2.5*	0.22*
Combined modifications using aluminum skirt, inflatable boat-tail and Diesel Oxidation catalyst	Suburban	-4.5±0.9	4.5±3.0	-7.9±9.4
	Highway Line haul*	-6.7±2.2	4.4±6.2*	-3.5±0.4*
Combined modifications using aluminum skirt and folding boat-tail	Highway Line haul	-5.3±0.5	5.2±1.2	-19.0±4.4
	Highway Line haul using Diesel oxidation catalyst	-2.4±0.9	8.4±0.5	-19.6±2.6
	Constant 65 mph	-10.02±1.3	10.3±0.3	-15.71±4.4

* Results for carbon-balance fuel economy and NOx should be interpreted with caution due to data anomalies from SEMTECH unit on control truck.

NOX EMISSIONS

NOx emissions from the control trucks are also strongly influenced by the drive cycle used (figure 4). As with fuel economy, ANOVA disclosed significant differences (P<0.01) among drive cycle for both trucks, and Tukey HSD analysis of pairwise comparisons found no significant difference (at P=0.05) between the Kenworth truck operating at the "constant 65" and "Highway line haul" cycles. NOx values were highest for the suburban cycle on the Kenworth, which makes sense, as emission peaks are associated with engine transients. However, for the Freightliner, the suburban cycle had the lowest NOx values This may be related to the data anomalies associated with the SEMTECH units of the control truck described previously.

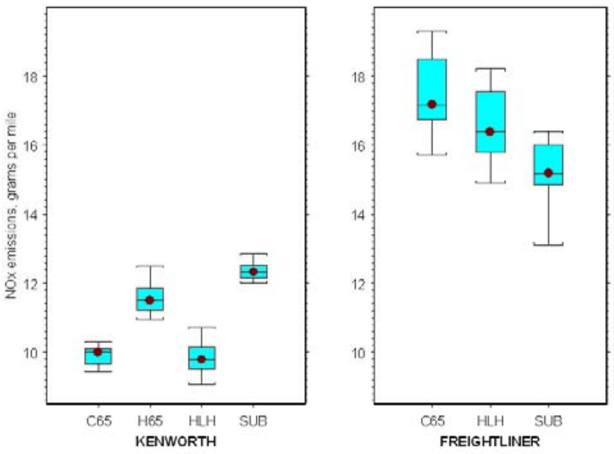

Figure 4: Comparison showing the relation between drive cycle and NOx emissions. Central point is median. Box limits are 25th and 75th percentiles. Whisker limits are minimum and maximum. Drive cycles are as follows: **C65** – "constant 65; **H65** – "highway 65: **HLH** – "highway line haul"; **SUB** – "suburban"

All components had some effect on reducing NOx emissions, except for tires and fairings alone run under the suburban cycle with the Kenworth. In some other tests (tables 5 and 6), the test-to-test variability suggested a reasonable chance that no NOx reduction was achieved under those conditions. The largest NOX reductions (of 10 to 19 percent relative to baseline) were observed with both tires and fairings run under the highway line haul or constant 65 cycles.

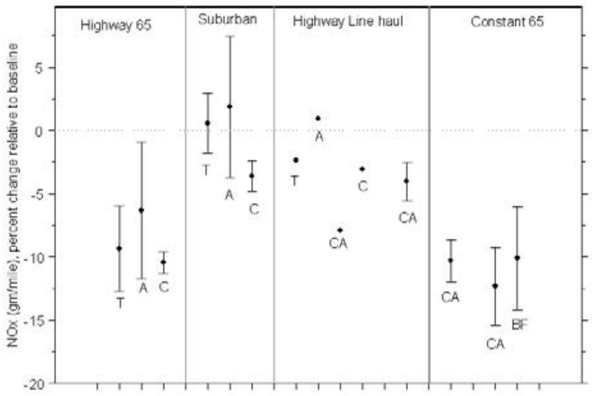

Figure 5: Percentage change in NOx for the Kenworth truck relative to baseline. Error bars were calculated from the 95 percent confidence limits of the T:C ratios. Test components are as follows: **T** –single wide tires; **A** – trailer fairings with composite skirt; **C** – Combined components with composite skirt; **CA** – combined with aluminum skirt; **BF –** Combined aluminum skirt, no boat-tail

DISCUSSION

The maximum percentage in fuel economy improvements (10 percent) and NOx reductions (19 percent) were lower than the maximum values (18 and 45 percent, respectively) reported from the cooled EGR truck tested previously [3]. This may be due in part to improvements made in conducting the test procedure – In the current test, replicate laps were not accepted until they met the 2 percent repeatability requirement of SAE J1321. This was not done during the previous test. Also, differences between local conditions at the test track may have affected results. The current test was run on an oval track where trucks could maintain highway speeds for the entire drive cycle, whereas the previous test was conducted on a 3-mile straightaway track with a reduced-speed turnaround at each end. In addition, resource constraints and equipment malfunctions during the previous test resulted in some segments with measurements that could be outliers, or only one measurement for which confidence limits could not be calculated [3]. This only occurred in three segments during the current test. However, there is evidence that most of the difference in performance between the tests is that the cooled EGR engine used in the previous test somehow responds differently to a decrease in power needs than the two engines tested here. Further investigation of the relationship between EGR engines, fuel efficiency, and NOx reductions would be helpful to determine whether this observation is a product of EGR in general or an artifact of this particular engine.

RELATION TO CHANGES IN ENGINE POWER OUTPUT

The SEMTECH-D unit records an estimate of engine torque, as estimated by the trucks on-board computer. If that estimate is not available, the SEMTECH post-processing software can calculate engine torque using engine speed and a torque curve supplied by the engine manufacturer. The torque data can be converted into distance-specific work for the test run, in brake-horsepower per mile. A work estimate can be analyzed using the J1321 method, just as fuel consumption, fuel economy from the carbon balance, and NOx are. The results are shown in figure 6. It is clear that in nearly all cases, the distance specific work of a truck equipped with one or more test component decreases relative to baseline.

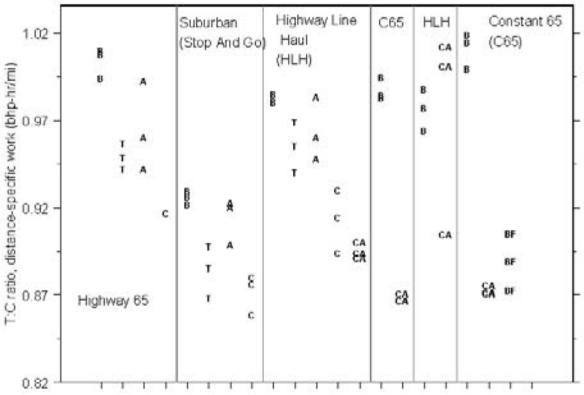

Figure 6: Variation of T:C ratios of distance specific work grouped by drive cycle and test component for the Kenworth truck. Test components are as follows: **T** –single wide tires; **A** – trailer fairings with composite skirt; **C** – Combined components with composite skirt; **CA** – combined with aluminum skirt; **BF –** Combined aluminum skirt, no boat-tail

Total work and brake-specific NOx were calculated for data from the cooled EGR engine tested in our previous study [3] and compared to work and brake specific NOx values for the Kenworth and Freightliner trucks run on equivalent drive cycles. (Table 7) These results clearly show that while test components do not result in a significant change in brake specific NOx in the Freightliner and Kenworth trucks, they result in significant decreases in the Mack cooled EGR truck.

Table 7: Comparison of changes in engine output, brake specific NOx emissions, Fuel Economy, and Distance specific NOx emissions for different engine types. NOTE: Data for the cooled EGR (Mack) engine were collected previously [3] at Aberdeen Proving ground, Aberdeen Maryland. Trucks equipped with “combined” (single-wide tires and full trailer fairing set.)

	Percent difference, relative to baseline			
	Total Work (bhp-hr)	NOx (gm/ bhp-hr)	Fuel economy, carbon balance (mpg)	Distance-specific NOx (gm/mi)
	Aberdeen Highway 65 cycle			
Cooled EGR (Mack)	-8.5	**-52.4**	17.9	**-44.6**
Kenworth (CAT ACERT)	-12.3	0.1	9.0	-10.5
	Suburban Stop and Go Cycle			
Cooled EGR (Mack) (only one valid lap)	-6.1	**-19.5**	41.1	**-25.1**
Kenworth (CAT ACERT)	-8.0	2.7	4.6	-3.6
Freightliner (DDC 60)	-10.8	-0.9	4.3	-11.2
Freightliner (DDC 60 with Diesel Oxycat	-8.9	0.6	4.5	-7.9

CONCLUSION

Experimental track testing of two distinct class 8 tractor-trailers demonstrates simultaneous measurement of fuel use, engine performance and NOx emissions in a simulation of real world operating conditions. Tests were conducted on two tractor-trailer truck combinations having different emission control systems that varied based on the model year and the associated emission standards. The test results show that components designed to reduce power load not only reduce power load and improve fuel economy, but they also provide a proportional reduction in NOx emissions. These reductions were not as large as they were in our previous test using a cooled EGR engine, where emission reductions were much greater than fuel economy improvements. (The apparent exception, where a cooled EGR engine running a suburban cycle had greater fuel economy improvements than emissions reductions (table 7) may be a non-representative outlier – equipment malfunctions resulted in only one valid lap for that segment.) Further examination of the data showed that the cooled EGR engine responded to the test components with greatly reduced brake-specific NOx emissions, whereas the other engines did not. Thus, NOx emission reductions from vehicle components that reduce parasitic losses may be greatest in trucks that use cooled EGR engines, although trucks with other engine types will see significant (~10 percent) reductions.

These test results should be of particular interest to the freight industry, because most fleets and operators will be using existing heavy-duty trucks for many years or even decades to come. As the payback period due to fuel savings is generally 18 months or less, the addition of these devices will pay for themselves many times over during the life of the truck. The simple, cost-effective components tested here not only have the potential to reduce fuel consumption and related costs, they may also provide a method of NOx control “retrofit” that pays for itself. The results of this testing will be used in the design concept of the “SmartWay Upgrade

Kit" that is being developed by EPA's SmartWay Transport Partnership™. These results provide further evidence that reducing parasitic losses in heavy-duty highway vehicles will not only reduce fuel consumption and greenhouse gas emissions, but will also provide NOx reductions that pay for themselves through reduced fuel use.

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