Effect of Single Wide Tires and Trailer Aerodynamics on Fuel Economy and NOx Emissions of Class 8 Line-Haul Tractor-Trailers

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ABSTRACT

We hypothesize that components designed to improve fuel economy by reducing power requirements should also result in a decrease in emissions of oxides of nitrogen (NOx). Fuel economy and NOx emissions of a pair of class 8 tractor-trailers were measured on a test track to evaluate the effects of single wide tires and trailer aerodynamic devices. Fuel economy was measured using a modified version of 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 correlated to fuel meter measurements. Tests were conducted using drive cycles simulating highway operations at 55 mph and 65 mph and suburban stop-and-go traffic. The tests showed a negative correlation (significant at p < 0.05) between fuel economy and NOx emissions. Single wide tires and trailer aerodynamic devices resulted in increased fuel economy and decreased NOx emissions relative to the baseline tests. Decreases in NOx emissions were disproportionately larger than increases in fuel economy; however, this effect may be an artifact of the particular engine being tested. These results demonstrate that emissions reductions can be achieved using strategies that decrease fuel use and save truck operators money.

INTRODUCTION

BACKGROUND

Fuel consumption of heavy-duty vehicles can be reduced by the installation of components that reduce the vehicle's power requirements. A simple load relation equation presented by Clark [1] shows that two important sources of energy loss in vehicles are tire rolling resistance and aerodynamic drag:

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

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. At a steady speed of 65 miles per hour on a flat road, aerodynamic drag and rolling resistance account for 21 percent and 13 percent, respectively, of the total energy used by a class 8 heavy-duty tractor trailer [2]. At lower speeds, rolling resistance assumes a greater fraction of the vehicle's power requirements.

Further, because total vehicle emissions are a function of the power output of the engine, [2] reductions in power requirements should be expected to also result in a corresponding reduction in vehicle emissions. This is more likely the case for emissions of oxides of nitrogen (NOx), as opposed to emissions of particulate matter (PM). NOx is primarily a function of power output, whereas PM is controlled by a more complex set of factors in addition to power output, including fuel composition, and transient engine properties, such as air/fuel ratio, oil leakage through piston rings, and exhaust gas temperature.

Measurements of whole-vehicle emissions from class 8 tractor-trailers are not readily available because historically such measurements involve dynamometer testing in the laboratory, and dynamometers suitable for class 8 tractor trailers are rare. Also, because each model of heavy-duty diesel engine is used on a large number of vehicle types, it is the engine, not the whole vehicle, that is certified by regulatory agencies. In recent years, however, advances in the technology of **O**n-**R**oad **E**missions **M**easurement (OREM; also called "PEMS," **P**ortable **E**missions **M**easurement **S**ystem) allow for the possibility of emissions measurements being conducted in conjunction with on-road fuel-economy measurements, thus permitting the examination of the relation between fuel economy and emissions under "real world" driving conditions.

A number of different PEMS systems were developed during the 1980's and 1990's. [3] While some systems involve the collection of exhaust gases into bags for analysis in the laboratory at a later time, modern commercially-available systems [4] now employ sensors that directly monitor exhaust gases and flow rate and provide real-time data.

Despite the growing interest in on-road emissions measurement, there have been few, if any, studies in which the relation between emissions and fuel economy has been measured on the road. There are reports on the use of PEMS systems to measure the effect of driving conditions on in-use emissions [5].

PURPOSE

The work described in this paper was done in support of the SmartWay® Transport Partnership. This voluntary partnership between shippers, transportation providers, such as truck fleets, and the U.S. Environmental Protection Agency (EPA) is designed to encourage shippers and fleets to reduce air pollution and greenhouse gas emissions through lower fuel consumption. EPA is encouraging the adoption of innovative fuel-saving technologies by truck fleets and is in the process of developing a consistent fuel economy test measurement procedure for technology vendors. EPA would like to identify "retrofit" technologies that transportation providers can use to obtain fuel savings and emission reductions on existing vehicles, which will probably remain in service for many years to come. In addition, if the relation between fuel economy improvement and emissions reduction can be documented and quantified, it may be possible to account for some of these emission reductions in innovative and cost-effective programs to improve air quality in non-attainment areas and comply with transportation conformity rules (Clean Air Act, section 176(c); 42 U.S.C. 7506(c)).

SCOPE

This paper contains a report of an experimental test of the effects of reducing aerodynamic drag and rolling resistance on fuel economy and NOx emissions from class 8 tractor-trailers.

Emissions tests were restricted to hydrocarbons (HC), carbon dioxide (CO_2), carbon monoxide (CO) and NOx. PM was not measured, because the currently available on-board PM measurement devices have not been shown to correlate with the standard EPA method. Data from the HC channel were not analyzed here because (1) HC emissions are usually much lower than applicable standards for diesel engines, and (2) the HC sensing system in the particular PEMS unit used was designed for gasoline engines, and provides an underestimate of HC for diesel engines because of this. (Leo Breton, U.S. Environmental Protection Agency, personal communication). Test and control vehicles were tested on an outdoor track using different drive cycles that approximate actual driving conditions. The results presented here are preliminary, as only one truck engine model was tested. They show a relation between improved fuel economy and decreased NOx, although the exact nature of the relation for other engines may be different than the one tested.

METHODS

OVERVIEW OF TEST METHOD

The effects of the experimental modifications were evaluated using a modification of SAE Test Procedure J1321 [6]. This consisted of operating the test truck and a control truck on a test track using drive cycles approximating real-world operating conditions. Ratios (T:C) of the results of the test (T) and control (C) truck values were computed under "baseline" conditions (test truck equipped the same as the control truck) and using various combinations of the test components (single wide tires and trailer aerodynamic devices).

T:C ratios are calculated separately for fuel economy and NOx emissions. Replicates of baseline test runs or replicates of test runs with a given experimental modification are used to compute an average T:C ratio. The percentage change (PC) in either fuel economy or NOx emissions relative to the baseline is calculated as:

$$PC = \left[\frac{T:C_{\text{mod}ification} - T:C_{baseline}}{T:C_{baseline}} \right] \times 100 \qquad (2)$$

If test component improves fuel economy, then $T:C_{modification}$ will be larger than $T:C_{baseline}$, and PC will be positive. If an experimental modification decreases NOx emissions, then $T:C_{modification}$ will be smaller than $T:C_{baseline}$, and PC will be negative. This equation is similar to those used in the SAE test procedure [6] to calculate percent fuel saved or percent improvement in fuel consumption, but it was adapted to directly determine the percentage change relative to baseline due to the modification of the truck components. SAE test method J1321 [6] also specifies that test results be voided if the T:C ratios for the three replicate test runs are not within 2 percent. We did not do this because we did not want the variability among test runs so constrained. Test runs were voided only in cases of obvious failure of test equipment or components as described below.

The tests were conducted by the U.S. Army Aberdeen Test Center using a test track of the Perryman Test Area at Aberdeen Proving Ground, Aberdeen, Maryland. The track was a 3-mile straightaway with a turning loop at each end. The track configuration required test vehicles operating at highway speeds to slow down to about 35 miles per hour (mph) when turning. Thus, our "Highway"

drive cycles include considerable acceleration and deceleration. Three drive cycles (Figure 1) were devised that were considered representative of line-haul tractor-trailer operations: "Highway" cycles with maximum speeds of 55 mph and 65 mph, respectively, and a "Suburban" stop-and-go cycle with varying maximum speeds typical of operations on suburban and urban arterial roads.
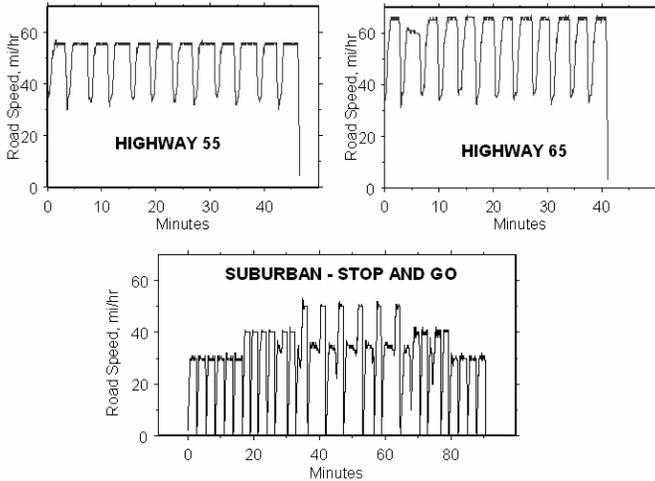

Figure 1: Speed traces of drive cycles tested

DATA COLLECTION

Data was collected directly from each truck using an EPA-developed PEMS system known as "ROVER" (Real-time On-road Vehicle Emissions Reporter). ROVER allows for emission data to be collected simultaneously with vehicle and engine data from the vehicle's diagnostic port. [7]

Fuel economy measurement

Fuel consumption calculations from ROVER data are based on the carbon balance method outlined in the SAE Standard J1094a. [8] Data from the HC channel are included in the carbon mass balance. Although, as described above, the results from the HC channel is an underestimate of total HC, we do not think that this seriously affects the accuracy of the fuel consumption estimate, because the carbon contained in the HC is negligible compared to the total carbon.

Non-dispersive infra-red (NDIR) detector technology was used to analyze for CO and CO_2. [7] Use of the carbon balance method to measure fuel consumption is a modification of SAE Test Method J1321 [6], which specifies either a weighed fuel tank or electronic flow meter. The carbon balance method was compared to an electronic fuel meter prior to the full experiment by means of test runs conducted using both the Rover system and an electronic fuel meter (MAX Machinery, Model No. 710)[1].

During this comparison, the electronic fuel meter was physically plumbed into the fuel delivery system of the vehicle and fuel was supplied through the system via a calibrated level tank to the engine. Any fuel not used by the engine was returned to the level tank as well. Fuel was added to the level tank through a calibrated pump located within the fuel measurement system. The amount of fuel added to the level tank is equal to the volume of fuel used by the engine. That fuel volume is measured knowing the pump displacement and the measured rotational speed of the pump. We found that fuel consumption measurements using the carbon balance method were comparable with those made by the electronic fuel meter. All of the experimental fuel economy results presented here were made on the basis of carbon balance calculations conducted on the output of the ROVER system.

Emissions measurements

ROVER uses a Snap-on MT3505 analyzer to measure HC, CO, CO_2, NOx and oxygen (O_2). HC, CO, and CO2 are measured using NDIR technology. NOx and O_2 are measured by an electrochemical sensor. [7] NOx was also analyzed using a Horiba MEXA 120 zirconia NOX sensor. Because of reported problems with zero-drift error when using the electrochemical sensor [7], we used the NOx data from the MEXA zirconia sensor in the data analysis presented here. The zirconia NOx instrument has a reported calibration range of 4 – 1,500 ppm and an accuracy of ±5% as compared to primary standards. [9] ROVER performs volume flow calculations via differential pressure transducers and absolute pressure in the tunnel, and while correlated to temperature and provided emissions measurements over a one second average.

Vehicle selection and mechanical preconditioning

Two class 8 trucks of identical model year, engine model, drive train components, and emission controls were tested in this program (Table 1). The trucks were equipped with 2004 EPA compliant highway test engines.

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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.

Table 1: Truck, Engine & Trailer Descriptions. Hp: horsepower; rpm: revolutions per minute; lbs: pounds; EGR: Exhaust gas recirculation; VIN: Vehicle Identification Number; GVWR: Gross vehicle weight rating

Test ID # VIN	55518 1M1AE06Y35N021518	55519 1M1AE06Y35N021519
Manufacture / Year	Mack 2004	Mack 2004
Engine Family	4MKXH11.9H70	4MKXH11.9H70
Engine Model	AC-427	AC-427
Rated Hp and engine displacement	427 @ 1800 rpm 11.9 liter	427 @ 1800 rpm 11.9 liter
Engine build Date	03-01-04	03-01-04
Emission Control	Cooled EGR, Electronic Control & Engine Modification	Cooled EGR, Electronic Control & Engine Modification
GVWR(lbs)/Test Wgt (lbs)	80,000/ 63,360	80,000/ 63,360
Mileage	36,628	43,715
Trailer	1999 Fruehauf	1999 Fruehauf

Both tractors were identical model Mack 2004 Vision CX613 models. Both vehicles were modified to include a factory approved roof fairing which was added to prior to testing. Both vehicles underwent inspections and up-to-date maintenance to ensure proper function and operation of mechanical components. Lubricants and coolants were replaced according to manufacturer specifications. New tires were placed on both tractors (steer and drive) as well as all trailer positions prior to baseline testing. Cold tire pressure was set at 95 psi and checked daily prior to testing. Vehicles were warmed up for a 1 hour period on the test track immediately before the start of testing each day. Daily pre-test checks were performed on vehicles and test equipment. Test weights were established at 65% of GVWR. 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 were 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 wide single wide tires mounted on aluminum wheels. These tires are the most advanced of their type commercially available. The tires improve fuel economy through lower rolling resistance and decreased mass.

The trailer aerodynamic devices include a "skirt" fairing attached to the lower edge of each trailer side between the axles, gap fairings attached to the top and side edges of the trailer face, and an inflatable "boat tail"

fairing affixed to the rear door of the trailer. 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.

In order to test the technology and not particular products, the components were sourced from multiple manufacturers. Two brands of single wide tires were used, one on the tractor, the other on the trailer. The vendor for the boat tail was different from the vendor for the skirt and gap fairings. 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. On installation of single wide tires, the electronic control module of the test truck was reprogrammed according to the manufacturer's recommendation to account for the change in tire diameter.

DATA ANALYSIS

A three-factor experimental design (Figure 2) allowed for testing the experimental modifications. The three replicates run for each combination of factors were used to calculate measurement variability. Because of occasional voided tests, meaningful analysis of variance could not be run on the full factorial data set. Data were analyzed for fuel economy and emissions as well as changes in both due to the experimental modifications. Because of the preliminary nature of the data (i.e., it was collected from tests on only one engine type and a limited number of drive cycles), improvements in fuel economy and reductions in emissions presented here may not be applicable in general to class 8 tractor-trailers under all driving conditions.
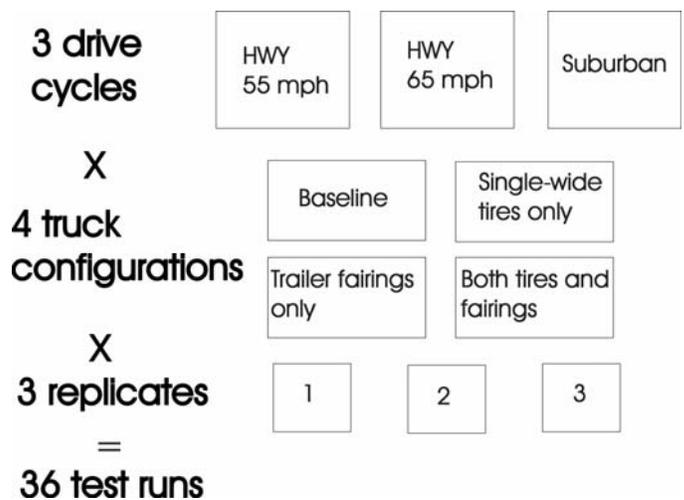

Figure 2: Experimental design showing experimental modifications and replication

RESULTS

Results from all test runs are shown in Table 2 and a summary of the percent changes due to the test modifications is shown in Table 3. Four test runs were voided because of deflation of the boat tail during the test run. A NOx value from one test run was voided because of equipment failure in the PEMS.

We observed improvements in fuel economy in all valid tests, and we observed decreases in NOx emissions in all valid tests, but one. Day to day variations in ambient environmental conditions (e.g. temperature, wind speed, wind direction, humidity) may have contributed to the relatively large confidence limits shown in some cases in Table 3 and Figures 4 and 6. These confidence intervals make it difficult to determine the effect of the drive cycles on fuel economy or NOx emissions.

Table 2: Summary statistics of measured data for all test runs.

	Fuel Economy (miles per gallon)			NOx Emissions (grams per mile)		
	Test	Control	T:C ratio	Test	Control	T:C ratio
Number of test runs	30	30	30	29	30	29
Minimum	3.9	4.1	0.88	2.73	7.35	0.34
25th Percentile	4.8	4.8	0.96	7.30	10.50	0.68
Median	5.0	5.0	1.0	8.70	11.91	0.74
75th Percentile	5.5	5.4	1.03	10.48	12.96	0.81
Maximum	7.0	6.3	1.35	15.74	14.58	1.36

FUEL ECONOMY

We observed improvements in fuel economy in all valid tests. A few test failures, resulting in voided tests, are noted in Table 3. In one case, combined modifications at the "Highway 55" cycle, all test runs were voided. The variability of T:C ratios for all tests are shown in Figure 3, and that of the percent change in fuel economy relative to the baseline is shown in Figure 4. It should be noted that under baseline conditions, the T:C ratio is slightly less than 1.0, which means that the test truck tends to have a slightly lower fuel economy than the control truck.

Table 3: Percentage change in fuel economy and NOx emissions due to drive cycles and experimental modifications.

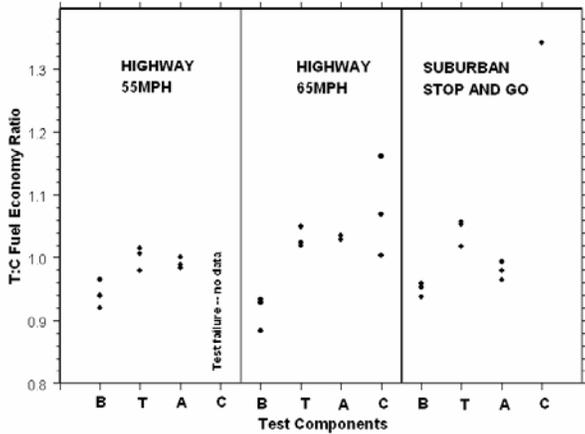| Experimental modification	Drive Cycle	Percentage change relative to baseline, with 95 percent confidence limits. Values without confidence limits were based on less than 3 replicates.		Notes
		Fuel Economy	NOx Emissions	
Single wide tires	Highway 55 mph	6.04±4.23	-36.9	Equipment malfunction; only 2 NOx replicates
	Highway 65 mph	12.6±6.74	-30.5 ±0.27	
	Suburban	10.0±2.27	-13.9 ±21	
Trailer aerodynamic devices (fairings)	Highway 55 mph	5.00±5.92	18.7±111	One possible outlier NOx measurement
	Highway 65 mph	12.6	-33.5	Only 2 replicates measured; no confidence limits
	Suburban	3.21±1.24	-10.3 ±14.0	
Combined modifications: Single wide tires and trailer aerodynamic devices	Highway 55 mph	No data	No data	Test voided; Boat tail deflated during test
	Highway 65 mph	17.9±13.7	-44.6 ±0.39	
	Suburban	41.1	-25.1	Only 1 replicate; boat tail deflated during test; engine fan running 100% of time

Figure 3: Fuel economy test results grouped by drive cycle and experimental modification, labeled as follows: B – baseline; T – single wide tires only; A – trailer aerodynamics (fairings) only; C– both single wide tires and trailer aerodynamics.
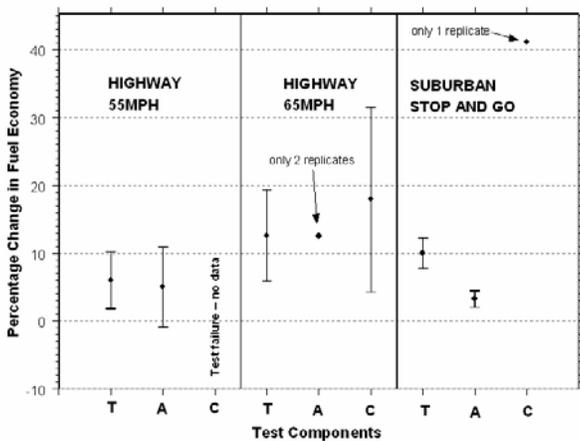

Figure 4: Percentage change in fuel economy (with 95 percent confidence intervals) as a result of the experimental modification, labeled as follows: T – single wide tires only; A – trailer aerodynamics (fairings) only; C – both single wide tires and trailer aerodynamics.

The addition of single wide tires increased fuel economy in all of the drive cycles and there appeared to be no significant differences between the drive cycles. (Figure 4) Any effect of the different driving cycles was apparently obscured by the similarity of the drive cycles (Figure 1), which is an artifact of using a straightaway test track with sharp turn-around loops that require numerous decelerations and accelerations.

Trailer aerodynamic devices also appeared to consistently improve fuel economy. The improvements were similar to those from the single wide tires for both "highway" drive cycles, but were significantly less than those for single wide tires in the "Suburban" stop-and-go cycle. (Figure 4) This is consistent with what would be expected from Equation 1, as the "Suburban" cycle operates at lower speeds than the highway cycle, and

thus tire rolling resistance would comprise a greater fraction of the total power requirements of the vehicle.

The combined effects of the test components are difficult to evaluate using these results. During the combined test at the "Highway 55" and "Suburban" drive cycles, the boat tail deflated and resulted in decreased fuel economy. The combined test at the "Highway 65" cycle did show an improvement in average fuel economy, but the replicates were highly variable, and the fuel economy change was indistinguishable from other tests at the "Highway 65" cycle. (Figure 4)

NOx EMISSIONS

Reductions in NOx emissions were consistently observed. However, the results were not as clear as the improvements in fuel economy. This may be due to the greater sensitivity of the NOx analyzer as compared to the CO_2 analyzer used to calculate fuel consumption and to changes in engine parameters and ambient environmental conditions.
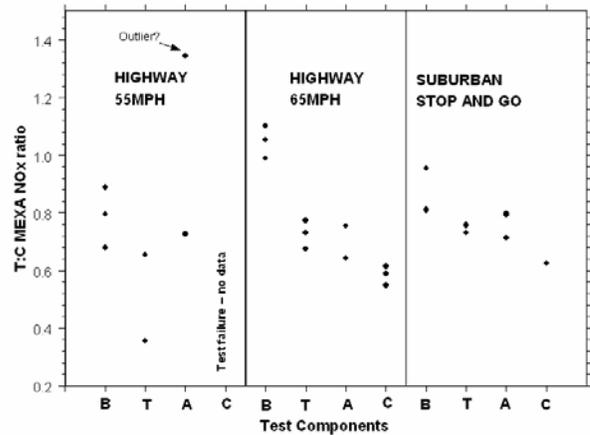

Figure 5: NOx test results grouped by drive cycle and experimental modifications, labeled as follows: B – baseline; T – single wide tires only; A – trailer aerodynamics (fairings) only; C – both single wide tires and trailer aerodynamics.
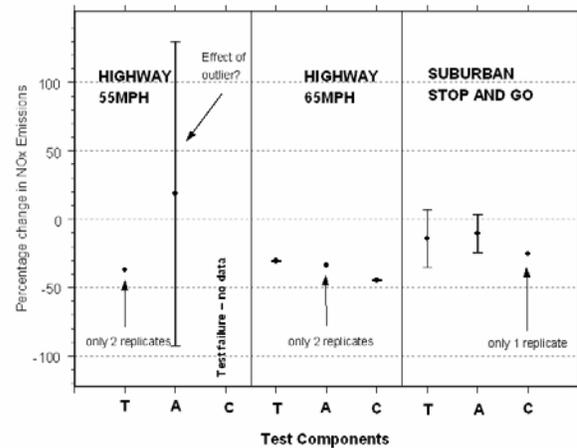

Figure 6: Percentage change in NOx emissions as a result of the experimental modifications, labeled as follows: T – single wide tires only; A – trailer aerodynamics (fairings) only; C – both single wide tires and trailer aerodynamics.

The most striking reduction in NOx emissions can be seen from the tests run at the "Highway 65" drive cycle (Figures 5 and 6). All replicates under all of the experimental condition show a NOx ratio less than those reported at baseline (Figure 5) and all percentage changes of NOx have confidence limits in an entirely negative range (Figure 6).

Tests run under the "Suburban" cycle also show a consistent decrease in NOx as compared to baseline. However the percentage change calculated for tests run with single wide tires and tests run with aerodynamic devices have confidence intervals whose range is partially positive, which may suggest that under some conditions (which would be expected to occur with a low probability), the experimental modifications might not result in NOx emissions. It is also possible that the large confidence interval is merely a function of the small number (3) of replicates. The test of combined treatments was also compromised by the deflation of the boat tail and by continuous operation of the engine fan during the test runs.

Tests run under the "Highway 55" cycle were compromised by a NOx analyzer malfunction on one of the tests using single wide tires, so only 2 replicates are usable. One test run involving a trailer aerodynamic device appeared to have uncharacteristically high NOx (Figure 5), which resulted in the percent change in NOx having a higher value than would otherwise be the case (Figure 6). Finally, as described in the previous section on fuel economy, a boat tail deflation during the test of the combined treatments may have adversely affected those results (Figures 5 and 6).

Despite some of the problems with the NOx testing, the overall data show a clear relation between fuel economy and NOx emissions. The scatter plot in Figure 7 shows a statistically significant correlation between the two, and a line of regression of NOx against fuel economy with a slope of -2.9. These data are for measurements of the test vehicle, for which runs were done using all of the experimental modifications and drive cycles.
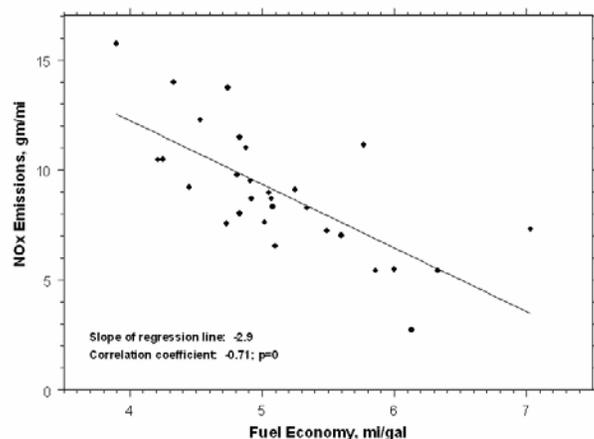

Figure 7: Relation between fuel economy and NOx emissions as measured in the test vehicle.

DISCUSSION

The test data suggest that the experimental modifications result in a decrease in NOx disproportionately greater than the improvement in fuel economy. Improvements in fuel economy range from 3 to 18 percent, whereas decreases in NOx emissions range from 9 to 45 percent. This is unexpected under an assumption that fuel economy and NOx emissions are both a simple function of power output.

ROVER collects data on the power output of the engine as well as exhaust emissions, and some of these data are summarized in Table 4. Output from one replicate of a baseline test is compared to output from one replicate of a test of combined experimental modifications run under the "Highway 65" drive cycle. Under baseline conditions, the median power output and median NOx emissions in the test and control vehicles are very close to being identical. Under the combined experimental modifications, however, median NOx emissions from the test vehicle are 67 percent of those from the control vehicle, whereas whereas the median power output of the test vehicle is 84 percent of the control vehicle.

Table 4: Comparison of NOx emissions and power output as a result of the combined experimental modifications.		
	Median values of 2,490 measurements	
	NOx, in grams per brake-horsepower hour (gm/bhp-hr)	Power output, in horsepower (Hp)
Test Vehicle, baseline	2.1	255
Control Vehicle, baseline	2.2	260
Test vehicle combined treatments (single wide tires and trailer aerodynamics)	1.8	220
Control vehicle, combined treatments	2.7	261

The effect of the experimental modifications on the relation between NOx and power output is further illustrated in data from the test truck, as shown in Figure 8. Under baseline conditions (Figure 8A), elevated NOx emissions(>2.5 grams per brake-horsepower hour [gm/bhp-hr]) were observed at all levels of power output. Under the experimental modifications (Figure 8B) however, such NOx "spikes" tend to occur at only at lower power outputs. There are also a larger number of low NOx readings (<1.0 gm/bhp-hr) than there are under baseline conditions. (It should be noted that the "NOx spikes" were occasional and scattered through the test run, and that the engines of both vehicles have been tested and are fully compliant with the certification standards.)
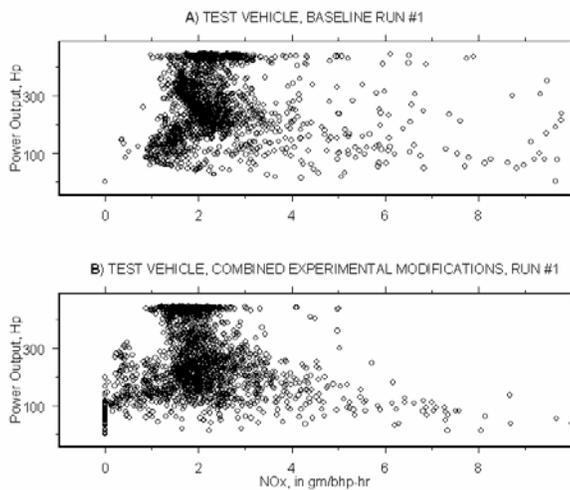
Figure 8: Comparison of NOx-power relationship of the test vehicles under (A) Baseline conditions (no experimental modifications) and (B) the combined experimental modifications (single wide tires and trailer aerodynamics).

Because of the large number (over 2,400) number of data points measured during each test, low NOx values may be more significant than the relative lack of "NOx spikes" in explaining the disproportionately lower NOx emissions under the full experimental modifications. It is unclear whether the observed response to the experimental modifications is a universal property of diesel engines or is an artifact of the particular design of the engine used for this test program. Testing of a wider variety of engine designs would prove useful in further understanding of the general relations between power output and engine emissions.

CONCLUSION

Experimental track testing of class 8 tractor-trailers demonstrates that it is possible to simultaneously measure fuel use, engine performance, and NOx emissions in a simulation of real world operating conditions. The tests show that components designed to reduce power load not only reduce power load and improve fuel economy, but they also reduce NOx emissions. In some cases, NOx reductions may be disproportionately greater than improvements in fuel economy, although this may be an artifact of the particular engine design that was tested. Additional testing of other engine designs is necessary to quantify the relation between NOx reduction and improvements in fuel economy. In addition, when on-board measurement technology becomes practical, a similar series of experiments should be conducted to evaluate the relation between fuel economy and PM emissions.

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. The simple, cost-effective components tested here not only have the potential to reduce fuel costs, they may also provide a method of NOx control "retrofit" that pays for itself.

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