PROCEEDINGS OF THE

1995 DIESEL ENGINE EMISSIONS

REDUCTION WORKSHOP

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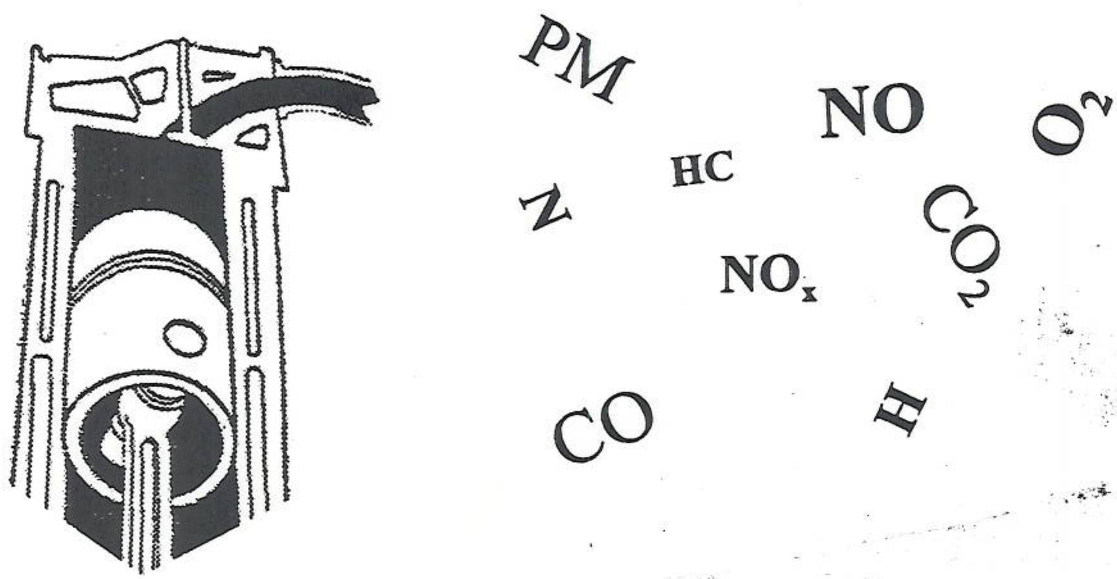

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Development of On-Road Emission Factors for Heavy-Duty Vehicles

by

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INTRODUCTION

Ambient air ozone levels have not responded to control strategies used in the U.S. as have the other criteria pollutants. (1,2) Sulfur oxides and carbon monoxide have been markedly reduced by strict emission standards for mobile and stationary sources. The formation of ambient ozone is created in the urban atmosphere with either volatile organic chemicals (VOCs) or nitrogen oxides (NOx) being the rate controlling species depending upon the relative ratio present. Much of the ozone reduction effort has been focused on VOCs through hydrocarbon emission limits from the same sources. NOx control has been centered on spark ignition vehicles using engine modifications and catalytic tailpipe treatment. Modifications to compression ignition engines have started to reduce these emissions, but work is ongoing to make similar emissions reductions from compression ignition engines.

Current airshed models rely upon emission inventories for accurate data to estimate effects that control strategies could have on future pollutant reduction scenarios. Most of the inventory data are from samples taken from the sources during normal operations. Mobile inventory data have relied upon laboratory dynamometer data using a variety of fundamentally and experimentally derived conversion factors to estimate in-use emissions. This link has not been extensively confirmed due to problems sampling emissions from in-use cars and trucks. This study endeavors to confirm or modify those conversion factors by building a facility which will allow sampling from heavy-duty diesel vehicles (HDDVs) and the development of appropriate models for operations related emission factors.

STUDY DESIGN

The objectives of this project are to: 1) define on-road emissions from HDDVs; 2) assess agreement among engine and chassis dynamometers and on-road emission factors; 3) evaluate current conversion factors for dynamometer data and develop appropriate ones if needed; and 4) develop a modal emissions model. The on-road test component uses an instrumented 45-foot* cargo van trailer to test various tractors during on-road operation according to a modal matrix. These results are compared to those obtained during actual runs over selected routes. A separate road version of a certification cycle is used to provide a link back to the dynamometer data. The tractors will be tested using a chassis dynamometer to check agreement with that testing method using urban driving cycles, modal cycles, and an adaptation of the certification cycle. The engine from the road and chassis dynamometer tested truck will be shipped to EPA's Office of Mobile Sources for testing on their engine dynamometer to directly compare with the on-road data for the adapted certification cycle and to check against the original Federal Test Procedure (FTP) certification data.

Our experimental approach involves on-road testing according to the test matrix shown in table 1. This test sequence develops the modal data necessary to model the emissions as a function of speed, load, grade, and acceleration. These data are fitted to each of three routes representing: 1) trans-urban interstate travel, 2) terminal entry/exit, and 3) urban delivery. The actual routes are run, and the emission factors generated are compared to the modal model results. A final test sequence utilizes a certification cycle that has been adapted to suit actual truck operational capability to develop data for direct comparison with the dynamometer data.

The modal experimental design utilizes four-lane limited access highways with long and relatively straight sections at three grades. These

* Metric equivalents appear at the end of this paper.

Table 1: General Test Matrix (Each Tractor)

Speed	Slow	15 MPH	(constant speed)
	Medium	35 MPH	(constant speed)
	Fast	55 MPH	(constant speed)
Accleration 0 to 55 MPH	Normal		Shift gears as governed
	Short Shift		Shift @ 80-90% governed engine speed
Grade	Level	0%	U.S. 70 near New Bern, NC
	Moderate	2-3%	I-26 near Hendersonville
	Steep	5-7%	I-26 near Hendersonville
Downhill	Steep	5-7%	Load variation only
Load (GCW)	Light	Empty Trailer	(25000 - 30000 lb GCW)
	Medium	½ Max Cargo Load	(up to 55000 lb GCW)
	Heavy	Max Cargo Load	(up to 80000 lb GCW)

(3 Speeds + 2 Accelerations)•(3 Grades • 3 Loads) + Downhill = 46 Triplicate Tests Maximum

highways provide a safe operating area for sometimes very slow moving vehicles when testing is confined to low traffic load times. The extent to which the matrix is completed depends upon the vehicle power available to pull some loads up grades as steep as 7%. A coast-down test per White and Korst (3) is run for each vehicle to develop the power requirements for each configuration.

SYSTEM DEVELOPMENT

Two preliminary test sequences were conducted to develop familiarity with diesel engine testing and specific test procedures. A diesel powered generator set was tested to familiarize personnel with the effects of load on monitored parameters and establish the ranges of these parameters. A bank of resistive loads could be switched to simulate the load-based test procedure. A more complete development phase was conducted using a diesel powered pickup truck and a horse trailer to simulate the HDDV tractor-trailer.

The first step was to identify the appropriate road sections to conduct the test matrix. The North Carolina Department of Transportation (NCDOT) provided detailed site plans of sections which met our grade and distance requirements as well as practical recommendations to guide our selection. Level grades were easy to find near the Atlantic coast of North Carolina, and a 0.0%, 20-mile long section of U.S. 70 near New Bern was selected. This has the added advantage of including a large rest area which we could use for short term staging. The 3 and 7% grades are numerous but usually too short to meet our requirement for at least 60 seconds of continuous data acquisition. The NCDOT located a stretch of Interstate 26 south of Hendersonville which includes both slopes. It too has a rest area nearby for staging.

The development of the sampling and analysis system was based upon designs used by the authors during stationary source monitoring projects. A continuous emission monitoring (CEM) bench was assembled from backup units available from ongoing laboratory projects. This short rack-mounted unit was set into the horse trailer on instrument shock mounts. A computer-based data acquisition system operating Labtech

Notebook software was mounted on the instrument rack with added shock padding. The pickup was wired with sensors, and a heated sampling line connected the tailpipe to the sample conditioning system in the trailer storage bay. Since these instruments operate on 110 volt AC, a gasoline-powered generator was mounted in the pickup bed. The monitored parameters,

Table 2: Monitored Parameters

Emissions Measurements	Operational Parameters
O_2 (%)	Vehicle Speed (mph)
CO_2 (%)	Acceleration (mph/sec)
CO (ppm)	Engine Speed (rpm)
NO_x (ppm)	Net G-Force (lb)
THC (ppm)	Engine Temperature (°F)
Exhaust Flow (scfm)	Exhaust Opacity (%)

shown in table 2, were measured 10 to 30 times per second, averaged for 0.1 and 1 second, and stored in the computer file. The assembled system is shown schematically in figure 1. The load was varied using concrete blocks placed in the pickup. This system completed the matrix successfully allowing the basic design to be transferred to the HDDV.

The CEM system from the pickup forms the basis for the two rack system installed in the new 45-foot cargo van trailer. The facility schematic is shown in figure 2. The rack and the calibration gas cylinders are mounted in the front of the trailer to minimize sample line length. This also provides a small space for the refrigeration unit to keep cool when the cargo divider is installed. The rest of the trailer is available for positioning the concrete weights that comprise the test load. The layout of the trailer is shown in figure 3. All operational electric power is provided by an 8.5 kW generator mounted under the trailer.

Exhaust stack measurements and samples are collected from a modified section of exhaust pipe which replaces the section above the vertical muffler. Included in this section is an Annubar-averaging pitot tube for flow measurement, a sample port for extracting the gas sample, and an optical transmissometer

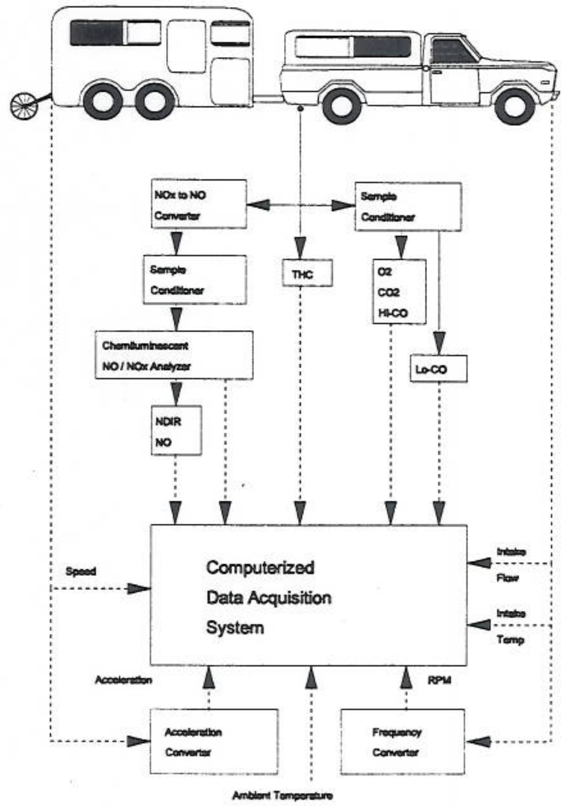

Figure 1: Pickup Test Facility Schematic

(smoke meter) at the end. A sheath air system was added to the smoke meter to limit contamination on the lenses. The sample port is closely coupled to an electrically controlled ball valve which allows either exhaust or calibration gas to flow through the entire sampling system. This provides total system quality assurance

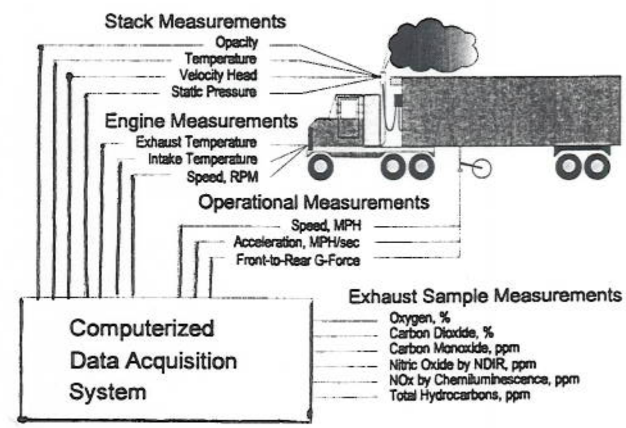

Figure 2: HDDV Facility Schematic

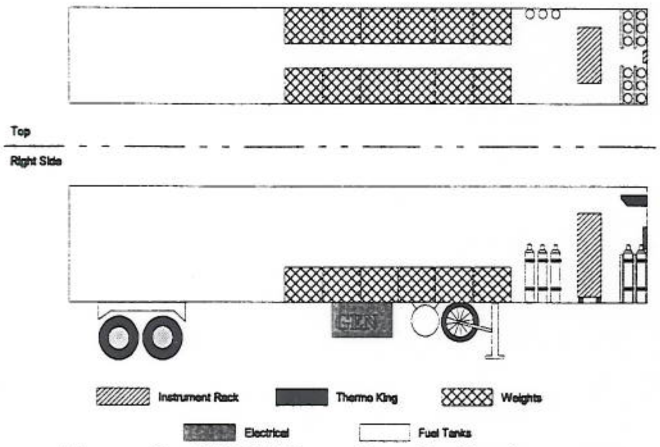

Figure 3: HDDV Sampling Trailer Layout

(QA) checks in addition to the individual CEM calibration and QA tests. A heated Teflon-lined sampling line connects the sample port to a heated filter and pump mounted on the front of the trailer. A short, heated line connects to the instrument rack, and the sample remains heated to the total hydrocarbon and chemiluminescent NOx analyzers, while a parallel sample is cooled and dried using a PermaPure dryer for the non-dispersive infrared (NDIR) analyzers.

The rack-mounted industrial computer data acquisition system uses Labtech Notebook and Lotus 1-2-3 to record calibration and measurement data. Some time alignment of the data from the individual analyzers is done manually due to differing response times of the instruments. The computer was recently upgraded to a Pentium chip to handle the large quantities of data generated by the test facility.

A second trailer is used as a support facility. It contains a small office/laboratory area and an area for storing the weights not being used in the test facility. The two trailers are parked back to back in the staging area, and an electric pallet jack is used to move the weights between the two trailers. Permanent staging areas have been set up near the remote test sites with electric power to operate the facilities.

INITIAL RESULTS

The first tractor being tested is a 1989 Ford L9000 Cab-over with a 315 HP Cummins NTC engine. Modal testing has been completed. The results for the NOx emissions for each constant speed, load, and grade condition are presented in figure 4. Little effect is noticed except for the low speed runs where significantly elevated levels are found. The grams/brake horsepower-hour (g/BHP-hr) data are plotted in figure 5 as a function of the estimated engine

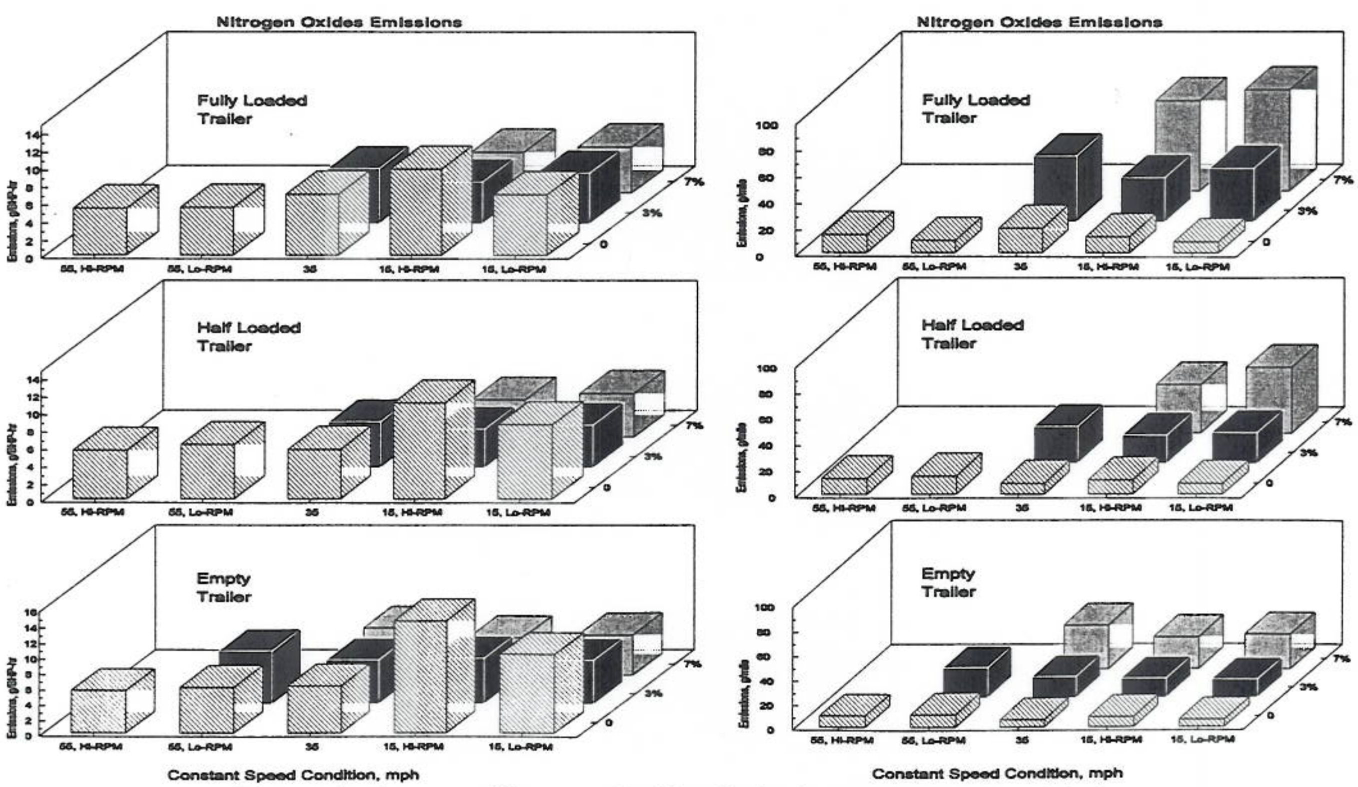

Figure 4: Average Nitrogen Oxides Emissions by Operating Mode

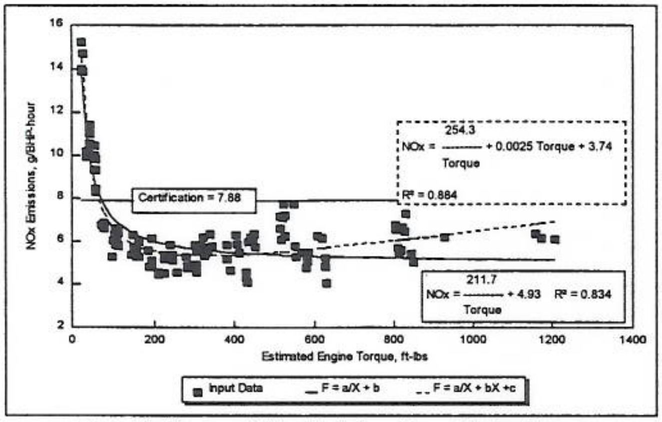

Figure 5: Nitrogen Oxides Emissions Versus Engine Torque

torque required by the truck. The federal certification level of 7.88 g/BHP-hr for this engine is indicated on this figure with most of the data below that level except for the low torque operating conditions. Analysis of these data is continuing and will be reported in a later paper.

As part of a cooperative agreement with the North Carolina Truck Driver Training Program at Johnston Community College (JCC), we have conducted acceleration studies to determine the effect, if any, progressive shifting has on vehicle emissions. Progressive shifting limits the maximum engine speed (in revolutions per minute, rpm) reached in each gear constant before shifting to the next successive gear. The normal procedure, acceleration to maximum governed rpm in each gear, is compared to the progressive method in figure 6. No definite trend can be identified in this initial test sequence. The small circle plotted on this graph represents the total emissions from that vehicle at a constant 55 mph for the distance it took to accelerate it to 55 mph. This suggests that limited access bypasses reduce emissions when compared to a bypass with stoplight traffic controls.

Figures 7 and 8 present examples of the data traces from actual runs. The acceleration run in figure 7 shows that the CEMs and engine sensors readily follow the changes in engine operating conditions as the vehicle goes through the gears. A section of urban delivery route is shown in figure 8. The bottom line displays the total g-load which is the sum of the forward acceleration vectors due to gravity and velocity change. This line shows the spikes as the vehicle accelerates in each gear, and the corresponding

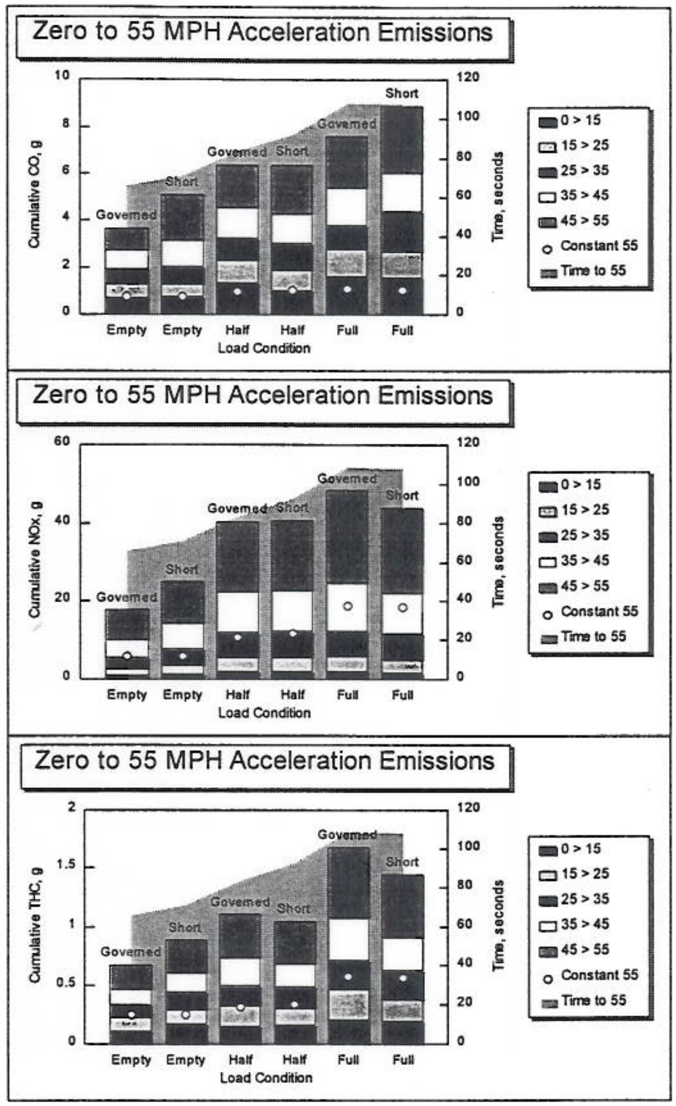

Figure 6: Effect of Shifting Patterns on Emissions During Acceleration

increases in vehicle speed and NOx can be seen in the curves above it. The slight dips in these curves are from the small time it takes the operator to shift gears and for the engine to reduce speed for the next gear.

The next tasks for this vehicle are to complete the route testing and the certification simulation sequence. These data will provide the measure by which the capability of the modal model will be tested. Analysis of these results will provide guidance to develop any changes needed in the test program. Early indications suggest a need to increase the number of constant speed points to improve the data fits to the modal models.

These results are for the first of at least seven tractors from the JCC fleet to be tested by

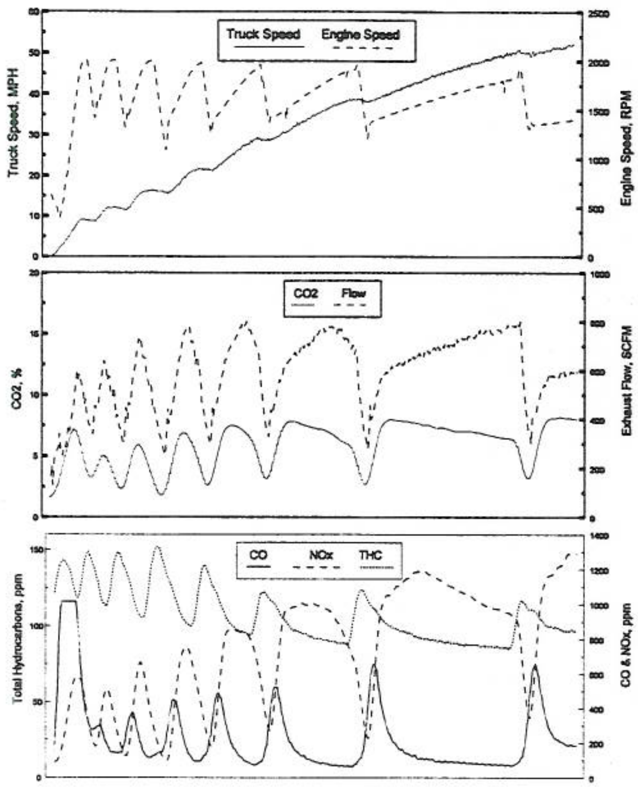

Figure 7: Fully Loaded Truck Acceleration

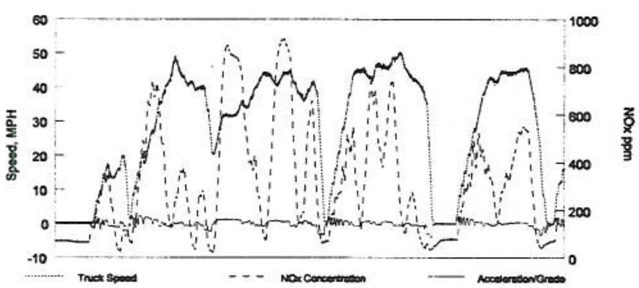

Figure 8: Test Data from Section of Urban Delivery Route

this program. The results presented are specific to the engine/tractor combination that was tested, and may not be typical of the fleet as a whole. Nonetheless, the remaining units will cover all major engine manufacturers as well as represent the range of emission standards the engines were designed to meet through the 1994 standard. This project is expected to continue for 2 more years.

REFERENCES

1. National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution,* National Academy Press, Washington, DC, 1991.

2. Southern Oxidants Study 1995. The State of The Southern Oxidants Study: Policy-Relevant Findings in Ozone Pollution Research, 1988-1994. Prepared by the Southern Oxidants Study, North Carolina State University, Raleigh, NC. April 1995.

3. White, R. A., Korst, H. H., "The Determination of Vehicle Drag Contributions from Coast-Down Tests," SAE 720099, Society of Automotive Engineers, Warrendale, PA, 1992.

METRIC EQUIVALENTS

Readers more familiar with the metric system may use the following equivalents to convert to those units:

5/9(°F-32) = 1°C
0.305 ft = 1 m
0.0283 ft^3 = 1 m^3
746 hp = 1 W
0.454 lb = 1 kg
1.609 mi = 1 km