EXPERIMENTAL AND NUMERICAL ASSESSMENT OF ON-ROAD DIESEL AND BIODIESEL EMISSIONS

B.H. West, J.M. Storey, S.A. Lewis, G.L. Devault, J.B. Green - Oak Ridge National Laboratory

C.S. Sluder, J.W. Hodgson, and B.L. Moore - University of Tennessee

INTRODUCTION

The Federal Highway Administration's TRAF-series of models use modal data to estimate fuel consumption and emissions for different traffic scenarios. A process for producing data-based modal models from road and dynamometer measurements has been developed and applied to a number of light-duty gasoline vehicles for the FHWA [1,2].

The resulting models, or lookup tables, provide emissions and fuel consumption as functions of vehicle speed and acceleration. Surface plots of the data provide a valuable visual benchmark of the emissions characteristics of the vehicles. Due to the potential fuel savings in the light-duty sector via introduction of diesels, and the concomitant growing interest in diesel engine emissions, the measurement methodology is been extended under DOE sponsorship to include a diesel pickup truck running a variety of fuels, including number 2 diesel fuel, biodiesel, Fischer-Tropsch, and blends.

EXPERIMENTAL

VEHICLE - The diesel test vehicle is a 1996 Ford F250 pickup truck with a direct-injection, turbocharged Navistar 7.3 liter engine. The Navistar engine has hydraulic electronic unit injectors (HEUI), with true "drive-by-wire" engine control. The accelerator pedal sensor (APS) is electronically sensed by the engine computer. This engine is emissions certified as a heavy-duty engine, and as such, is only available in vehicles over 8500 pound Gross Vehicle Weight Rating (GVWR), also known as heavy light-duty trucks.

ON-ROAD - Test vehicles are instrumented, tapping into as many on-board sensors as possible to minimize setup time. A Davit Lightspeed optical fifth wheel is used to sense vehicle speed, and all data are collected using an Advance Electronic Diagnostics Rough Ryder PC and VMS 1220 datalogger. After installation of the datalogger and optical fifth wheel, vehicles are road tested at steady speeds from 32 to 105 km/h (20 to 65 mph), in nominal 4 km/h (2.5 mph) increments on public roads with minimal grade. Since the East Tennessee area is somewhat hilly, all data are gathered in opposite directions on the same road to reduce grade (and wind) effects. Cruise control is used whenever possible during steady speed data collection.

Following steady speed road testing, vehicles are exercised on a 1.5 km (5000 ft) airport runway. The airport runway is used for very low and very high speed runs, and acceleration and deceleration runs which cannot be safely conducted on public roads. Acceleration runs are typically performed at 10 different throttle or rack settings ranging from 10% to 100%. All data on the runway are also gathered in both directions to reduce wind and grade effects, and typically two full sets of data are gathered. The runway has a maximum grade of 1%. Parameters typically collected on-road include vehicle speed, ambient, coolant and exhaust temperatures, manifold pressure, engine speed, throttle or accelerator pedal position, and fuel injection parameters.

DYNAMOMETER - Following on-road data collection, the vehicles are brought to the chassis dynamometer for emissions and fuel consumption measurements. The chassis dynamometer used is a twin-roll, eddy-current Sun Roadamatic. For transient testing, the dynamometer's discrete mass and drag coefficient times frontal area (C_dA) settings were adjusted to match on-road data. The C_dA was adjusted at high speed cruise until the engine condition matched that measured on-road at the same speed. Full power (100% APS) rolling acceleration runs were then used to set the inertia weight that matched the on-road time required to accelerate from 32 to 97 km/h (20 to 60 mph). This process ensured that transients on the dynamometer most closely matched similar on-road conditions. During steady-state testing on the dynamometer, the load was manually adjusted to obtain the desired engine conditions.

Modal Testing - On the dynamometer, the same datalogger is used for collecting data similar to that collected on-road. In addition, fuel consumption and engine-out and tailpipe emissions constituents are measured and logged (HC, CO, NO_x, CO_2, O_2). The two parallel raw exhaust streams are pumped and cooled by a two-head ADI teflon/stainless steel diaphragm pump and a Baldwin Environmental thermoelectric chiller, respectively. Two identical emissions benches measure the exhaust species using Rosemount NGA 2000 gas analyzers. The analyzers include flame ionization detectors for hydrocarbons, non-dispersive infrared detectors for CO and CO_2, chemiluminescence detectors for NO_x, and paramagnetic detectors for oxygen. Heated FIDs are used for measuring diesel HC emissions.

The fuel consumption is measured using a Max Machinery 710 Fuel Flow Measurement System. The Max system contains a positive-displacement fuel flowmeter, heat exchanger, pumps, level controller, pressure regulators, and vapor eliminators to facilitate measuring the net fuel consumed by engines with high return flow. The fuel flow measurement system is accurate to ±0.5% with a turndown ratio of 200:1, however, it can take several seconds for it to respond to a transient event. As such, the flowmeter was used to measure flow under steady conditions on the dynamometer while recording other engine parameters. For spark ignition engines, the injector pulse width and frequency are measured. For the Navistar diesel reported on here, the fuel consumption is based on the accelerator pedal sensor position (APS) and the engine speed.

The on-road APS and RPM data were plotted to provide a guide or "roadmap" for dynamometer measurements, so that on-road engine conditions could be duplicated on the dynamometer. On-road APS vs RPM for the diesel pickup truck is shown in Figure 1. On the dynamometer, engine conditions were held steady for about 10 seconds while emissions data were recorded. Transient data were recorded between the steady set points. Data were gathered until the on-road APS vs RPM plot was adequately covered with steady-state dynamometer data. Transients were also recorded from idle to 120 km/h at various throttle settings, to ensure full coverage of the engine map, and to provide the resulting models with a composite of transient and steady-state data. Figure 2 shows the dynamometer APS vs RPM.

Driving Cycle Testing and Dilute Exhaust Sampling - The ORNL dilution tunnel consists of a positive-displacement pump (PDP) operating at 620 cfm with an eight inch stainless steel tunnel. A laminar flow element on the intake side as well as a rotation counter provide redundant measures of total volume. A 40 liter per minute

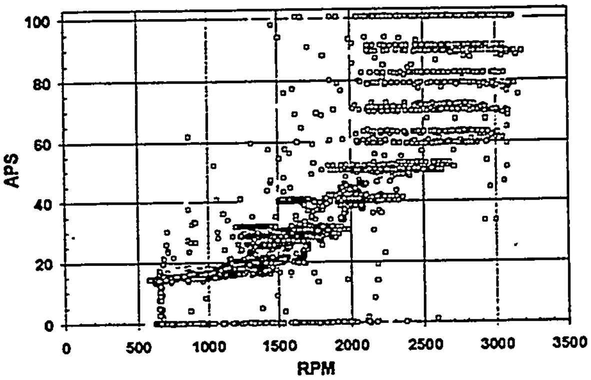

Figure 1. On-Road accelerator pedal sensor (APS) vs engine speed for diesel truck

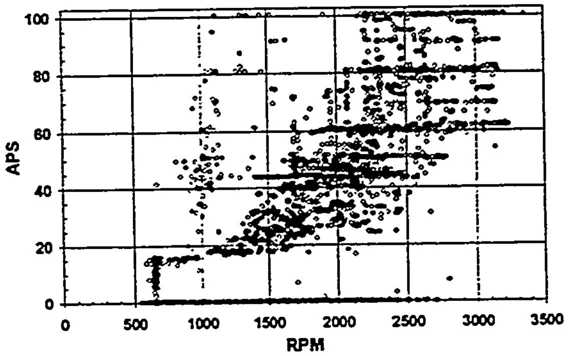

Figure 2. Dynamometer APS vs engine speed for diesel truck

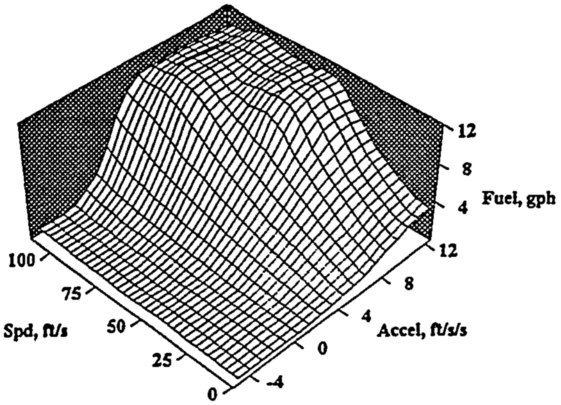

Figure 3. Gasoline composite vehicle fuel consumption

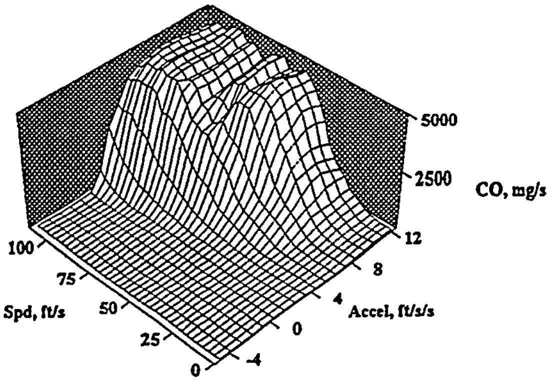

Figure 4. Gasoline composite vehicle CO emissions

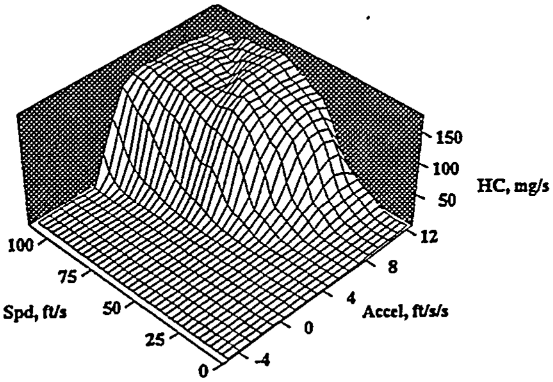

Figure 5. Gasoline composite vehicle HC emissions

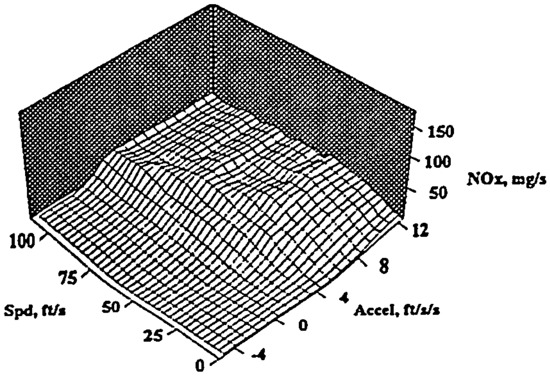

Figure 6. Gasoline composite vehicle NOx emissions

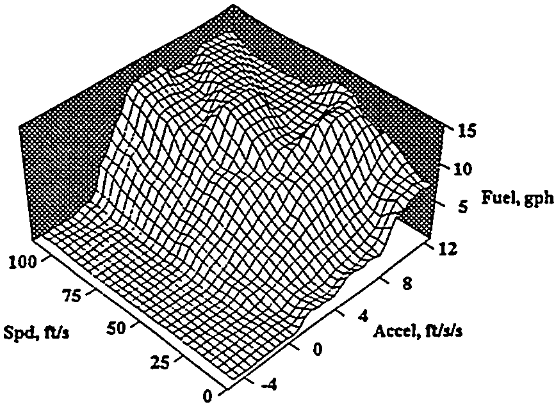

Figure 7. Diesel truck fuel consumption

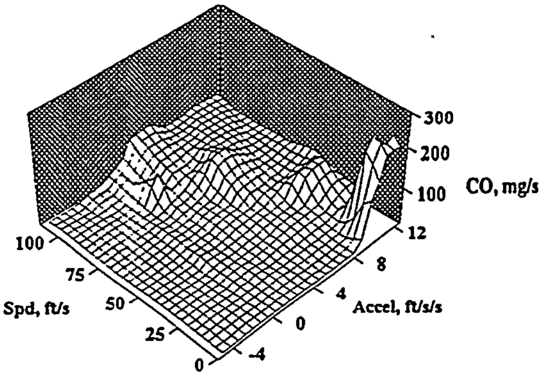

Figure 8. Diesel truck CO emissions

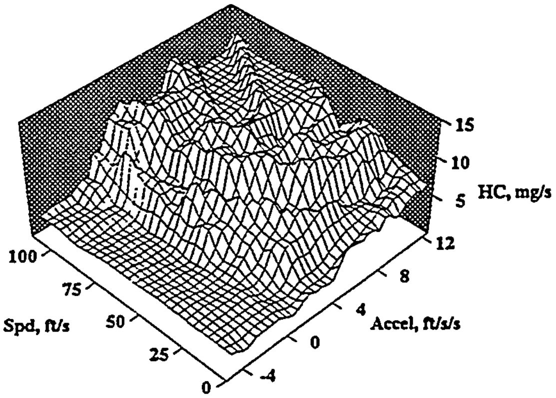

Figure 9. Diesel Truck HC emissions

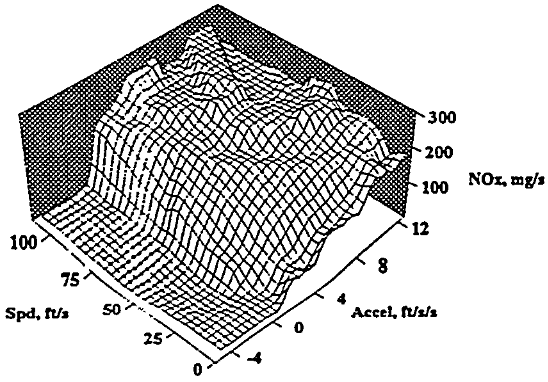

Figure 10. Diesel truck NOx emissions

(LPM) pump collects particulate samples through a 0.5 inch I.D. probe and dual 47 mm filter holders. Another smaller pump is used to fill the tedlar bags and provide samples for aldehyde and ketone analysis. The bag samples were analyzed for C_3-C_{12} hydrocarbons using a Hewlett Packard 5890/5970B GC/MS. Single point calibration with a standard mixture of exhaust HCs at ~ 1 ppm was performed. The aldehydes and ketones were collected on di-nitro phenyl hydrazine cartridges (Waters DNPH Sep-Paks), and analyzed with HPLC according to established methods [3]. Multipoint calibration using commercially-prepared DNPH standards was used for quantification.

The light-duty Federal Test Procedure (FTP) was modified to elevate the mass of particulate collected during testing. The FTP consists of a 505 second phase (Bag 1), an 867 second phase immediately following Bag 1 (Bag 2), a ten-minute soak, and finally a repeat of the first 505 seconds (Bag 3). Composite emissions are calculated with the assumption that the fourth phase (a repeat of the 2nd 867 second phase) results are identical to the Bag 2 results, so this phase is not normally repeated. To obtain a larger particulate sample, a modified FTP was used in which one filter and one bag were collected for the first two phases, and another filter and bag collected 10 minutes later, comprising a full repeat of the 1372 second cycle. Bag emissions were analyzed for CO, NO_x, and CO_2, as well as carbonyls and HC species.

A new "high-load" cycle will be added to the FTP for light-duty vehicles in the near future. This new cycle (called US06) demands much higher speeds and accelerations than the current FTP. The intent of the new cycle is to reduce emissions from enrichment events in spark ignition engines, although the higher engine loads could affect diesel emissions as well. It is not clear whether this cycle will apply to light-duty diesels, but with the possibility that it *will* apply, US06 driving cycle tests were also conducted on the diesel truck. For a thorough discussion of the development of the US06 cycle and its intent, the reader should consult the literature [4-7].

On-line particulate measurement - For a very short time, two on-line particulate instruments from *Rupprecht and Patashnick Company were* installed on the tunnel. The Tapered Element Oscillating Micro-balance (TEOM, model 1100) instrument provides near-real time information on PM emission rate. A sample is drawn at 2 LPM through a small filter which oscillates on the tip of a tapered element. The oscillation frequency is proportional to mass on the filter so a total mass as well as a rate-change of mass is recorded. The Diesel Particulate Measurement System (model 5100) measures volatile, semi-volatile, and elemental carbon fractions of PM based on thermal gravimetric analysis. A sample is drawn through a quartz filter held at constant temperature and then analyzed off-line by thermal oxidation followed by CO_2 analysis. The temperature ramp defines the volatile, semivolatile and elemental fractions. These instruments are particularly suited to rapidly comparing fuel effects under identical vehicle condi-tions, and although only a few tests were performed, some interesting comparisons between B100 and diesel fuel can be made.

RESULTS

MODAL TESTING - The on-road and dynamometer data were processed using desktop personal computers, and commercially available software. Custom FORTRAN programs were used to smooth the on-road data and put it into a more manageable size using a moving window average technique [8]. On-road data were collected at 10 Hz (10 samples per second), so it was not unusual for the aggregate on-road data file to contain over 30,000 lines of data. The smoothing routine reduced the file size to one fourth its original size.

The dynamometer data were collected at 2 Hz because the response of the gas analyzers and fuel flowmeter were on the order of seconds. Output from each gas analyzer was offset by a measured amount from realtime measurements of engine parameters to allow for transport of the gas and analyzer response time. Following computation of emissions rates (g/s), surface maps of emissions were generated as functions of RPM and APS.

On-road data were used to generate surface maps of RPM and APS as functions of vehicle *speed and acceleration.* Using the RPM and APS surface maps, for any given speed and acceleration one can compute the engine condition. Given RPM and APS, one can then go to the dynamometer maps and compute the emissions. The resulting maps, or lookup tables, provide emissions and fuel consumption as functions of vehicle speed and acceleration. Graphical representations of the lookup tables for the light duty gasoline vehicles are shown in surface plots of the modal fuel consumption, CO, HC and NO_x emissions in Figures 3, 4, 5, and 6, respectively. These plots are for the average of the eight vehicles, or for a composite vehicle. The onset of enrichment is very clearly seen in the CO and HC plots, when the emissions increase drastically. The NO_x emissions are shown on the same scale as the HC emissions.

Graphical representations of the diesel truck's fuel consumption and emissions lookup tables are shown in figures 7, 8, 9, and 10. Note the differences in the general shape of the surfaces and the overall magnitudes as compared to the light duty composite maps. The CO and HC emissions are much lower, while the NO_x is much higher. Modal surface maps for the biodiesel fuel and blends have not yet been completed, but will be reported in a future publication.

It is important to point out that most vehicles cannot operate in every mode represented here. For almost any vehicle the maximum obtainable acceleration rate decreases at higher speeds. Since the lookup tables are provided on a rectangular matrix, the unobtainable cells are filled with their nearest neighbor. That is, the emissions or fuel consumption for that same speed.

DRIVE CYCLE TESTING - Results of FTP tests with Number 2 diesel fuel and B100 are shown in Figure 11. The use of B100 lowers CO, HC, NO_x, and PM at the expense of fuel economy. Similar results are seen in Figure 12 for the US06 cycle, except for an increase in NO_x emissions.

HC speciation - The amount of hydrocarbon in the bags was very low - most compounds were on the order of 100 ppb by mass, so accurate quantitation will require the use of a flame

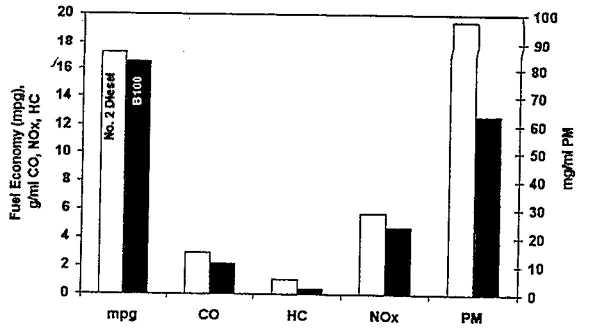

Figure 11. Diesel and Biodiesel results for light-duty FTP cycle

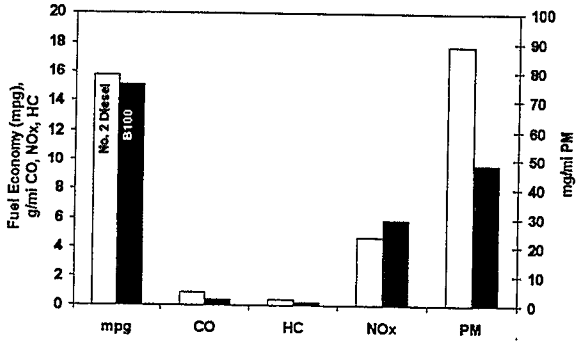

Figure 12. Diesel and Biodiesel results for light-duty US06 cycle

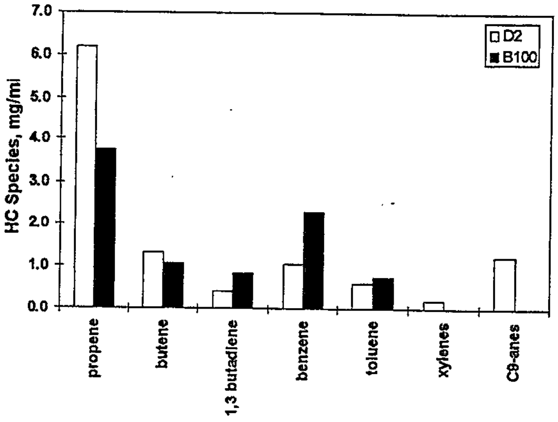

Figure 13. Select HC species for diesel and B100 on light-duty FTP cycle

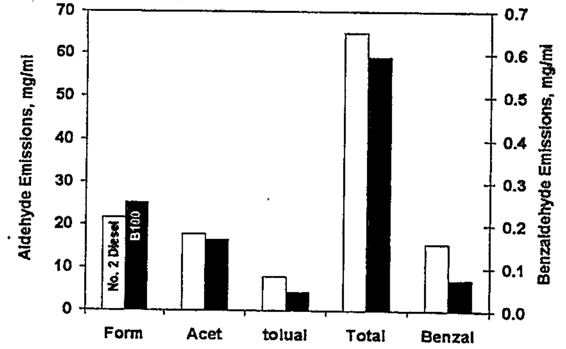

Figure 14. Select carbonyls for diesel and B100 on light-duty FTP cycle

ionization detector. Our interests included identifying what species were present; therefore, the mass spectrometer was used in this initial work. The preliminary results of the bag speciation for the FTP are shown in Figure 13. B100 reduced the overall HC emissions rate but some compounds, including the air toxics benzene and 1,3 butadiene were enhanced over that of diesel. The quantities are still very low, on the order of milligrams per mile. As expected, the heavier aromatic and aliphatic compounds were not present with the B100.

The carbonyls (aldehyde and ketones) analysis saw the majority of emissions from both fuels to be three compounds, formaldehyde, acetaldehyde, and tolu-aldehyde. Figure 14 shows that total aldehydes were reduced with the use of B100, although not significantly. Notably, benzaldehyde emissions from B100 were one half the level of the emissions from diesel. This is in contrast to the result for benzene which saw a twofold increase in concentration.

Real-time PM measurement - These results should be considered quite preliminary, as the instruments were only available for a few days. Nonetheless, some interesting observations and comparisons can be made between the two fuels. The TEOM data shown in Figure 15 follows the accumulation of particulate mass over the FTP cycle for B100 fuel. Note that the filter loses mass under some conditions; typically, load points followed by idle. This occurs on the regular 47 mm filters as well, when water and volatiles blow off the filter, but the integrated sample only measures net weight gain. The modal data in Figure 16 show the instrument response for a series of steady state conditions during the mapping activities with B100. For a given load and speed, the PM emission rate can be determined. Hopefully, this will allow mapping of PM for diesel vehicles in the same manner that the HC, NOx, CO and fuel consumption are mapped.

The data from the Diesel Particulate Measurement System show large differences in the fuel's effect on PM. For the FTP data, Figure 17 shows that the biodiesel lowers the semivolatile fraction (350°C - 650°C) by a factor of two and the elemental carbon (650°C-750°C) by a factor of 5 or more. Results from a heavier load steady-state test are shown in Figure 18, where all three fractions are greatly reduced with B100 fuel. The lower semivolatile and elemental fractions can be attributed to the lack of aromatics in B100. As catalyst temperatures were higher under the steady load condition, the "wetter" B100 particulate was probably more readily oxidized under these conditions. The average catalyst temperatures over the FTP rang-ed from 300-320°F with peaks less than 450°F, while the averages over the chosen steady-state condition (40% APS at 2000 RPM) were on the order of 700°F with peaks above 800°F.

SUMMARY AND FUTURE WORK

Data-based modal models provide a simple means to predict cycle emissions or make vehicle-to-vehicle, or fuel-to-fuel comparisons. Driving cycle tests of a heavy light-duty diesel truck have shown that neat biodiesel fuel can reduce cycle particulates, semi-volatile PM fraction, aldehydes, and some HC species. Future testing will include diesel and biodiesel blends, Fischer-Tropsch (FT) diesel, and F-T blends.

ACKNOWLEDGEMENTS

This work was conducted by Lockheed Martin Energy Research Corporation for the U.S. Department of Energy under contract number DE-AC05-96OR22464. The authors wish to thank the U. S. Department of Energy for funding this work, particularly Mr. Steve Goguen.

REFERENCES

1. West, Brian H., Ralph N. McGill, Jeffrey W. Hodgson, C. Scott Sluder, and David E. Smith, "Development of Data-Based, Light-Duty Modal Emissions and Fuel Consumption Models," Society of Engineers Paper No. 972910, October 1997.

2. McGill, Ralph N., John. N. Hooker, and Jeffrey W. Hodgson, "Fuel Consumption and Emissions Values for Traffic Models," U. S. Department of Transportation, Federal Highway Administration, Report No. FHWA/RD-85/053, May 1985.

3. Swarin, S. J., J. F. Loo, E. Chladek, M. S. Drouillard, and S. B. Tejada, "Advanced Emission Speciation Methodologies for the Auto/Oil Air Quality Improvement Research Program - II. Aldehydes, Ketones, and Alcohols," SAE Paper number 920321.

4. Haskew, Harold M., Kevin Cullen, Thomas F. Liberty, and William K. Langhorst, "The Execution of a Cooperative Industry/-Government Exhaust Emission Test Pro-gram," SAE Technical Paper 94C016, 1994.

5. Kishan, S., T. H. DeFries, and C. G. Weyn, "A Study of Light-Duty Vehicle Driving Behavior: Application to Real-World Emission Inventories," SAE Paper No. 932659, October 1993.

6. Environmental Protection Agency, "Federal Test Procedure Review Project: Preliminary Technical Report," May 1993.

7. Environmental Protection Agency, "Final Technical Report on Aggressive Driving Behavior for the Revised Federal Test Procedure Notice of Proposed Rulemaking," Office of Mobile Sources, January 1995.

8. Annino, Raymond, and Richard D. Driver, *Scientific and Engineering Applications with Personal Computers*, John Wiley and Sons, 1986.

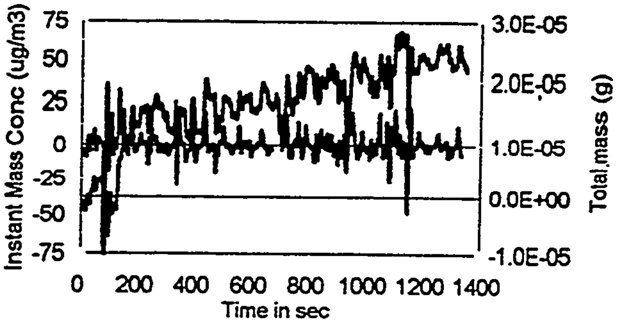

Figure 15. TEOM data for diesel truck on light-duty FTP, B100 fuel

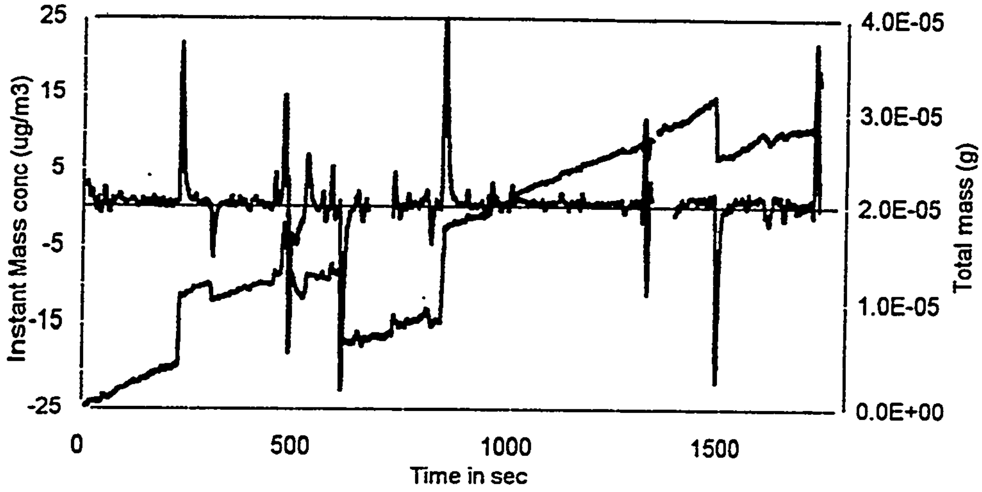

Figure 16. TEOM data for diesel truck during modal testing, B100 fuel

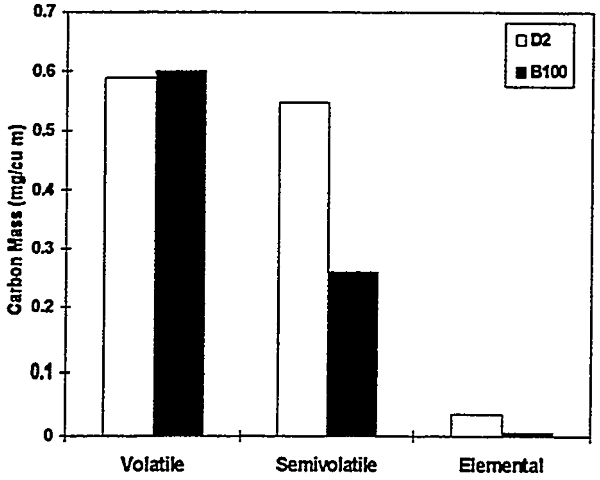

Figure 17. Particulate fractions for diesel truck on light-duty FTP for diesel and B100 fuels

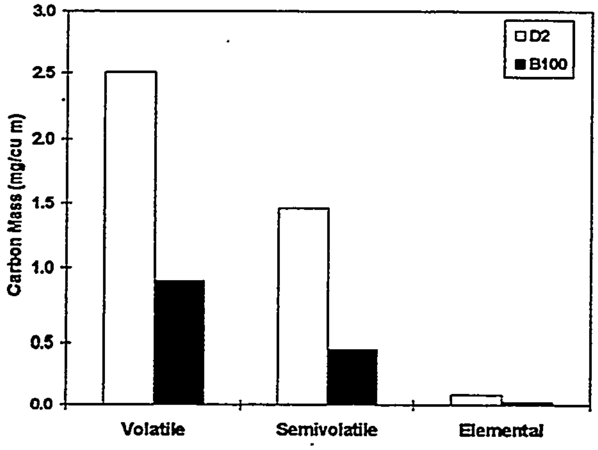

Figure 18. Particulate fractions for diesel truck under steady load for diesel and B100 fuels