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ABSTRACT

Speed-time and video data were logged for tractor-trailers performing local deliveries in Akron, OH. and Richmond, VA. in order to develop an emissions test schedule that represented real truck use. The data bank developed using these logging techniques was used to create a Yard cycle, a Freeway cycle and a City-Suburban cycle by the concatenation of microtrips. The City-Suburban driving cycle was converted to a driving route, in which the truck under test would perform at maximum acceleration during certain portions of the test schedule. This new route was used to characterize the emissions of a 1982 Ford tractor with a Cummins 14 liter, 350 hp engine and a 1998 International tractor with a Cummins 14 liter, 435 hp engine. Emissions levels were found to be repeatable with one driver and the driver-to-driver variation of NO_x was under 4%, although the driver-to-driver variations of CO and PM were higher. Emissions levels of NO_x for the Ford tractor at a test weight of 46,400 lb. using the CSHVR were comparable with values obtained using the WVU 5 mile route and the EPA Urban Dynamometer Driving Schedule for Heavy Duty Vehicles ("Test D"). The PM emissions were slightly higher for the CSHVR than the 5 mile route and Test D. The effect of test weight on emissions, in units of mass/distance, was assessed using the International tractor with the CSHVR at 26,000, 36,000 and 46,400 lb. test weights. Variation of all regulated exhaust emissions was small between test weights, although the CO_2 level reflected the additional energy used at higher weights. The small variation in regulated emissions may be attributed to the fact that in all three cases, the route called for full power operation of the vehicle, and that PM puff associated with gear shifting would be similar. It is concluded that the CSHVR represents a useful and realistic test schedule for truck emissions characterization.

INTRODUCTION

Alternative fuels have been promoted as a national approach to the reduction of harmful atmospheric emissions, but in the heavy duty vehicle arena, testing methods for emissions comparison have not been well established. Although there are claims that certain species in the tailpipe are reduced, relative to diesel, when employing biodiesel (1,2), Fischer-Tropsch fuels (3), alcohols (4, 5) and natural gas (6), it is difficult to quantify the actual in-use benefits unambiguously because the test schedule used can influence the conclusions reached. For example, chassis dynamometer tests with high idle time were found to favor the engine of one manufacturer over another, relative to tests with less idle time (7). There is a need to develop a standardized test protocol for heavy duty chassis dynamometer based emissions characterization that reasonably represents vehicle behavior in actual use. Since one substantial contributor to the urban mobile source emissions inventory is the Class 7 or 8 delivery truck, these were selected as the subjects for cycle development. This paper presents some of the first emissions data using test schedules arising from the cycle development study, while the creation of these schedules has been discussed in more detail elsewhere (8,9).

Reasonably representative test protocols for the comparison of the emissions performance between diesel and alternative fuel vehicles do not exist and present testing procedures use outmoded or *ad hoc* cycles for this purpose. For buses the Central Business District Cycle (SAE Recommended Practice J1376) has become the norm, but for truck testing there is no nationally recognized test schedule. Previously the West Virginia University (WVU) researchers have employed the 5 peak cycle (10) and the 5 mile route (11) while researchers in Colorado have employed the 5 peak cycle and the EPA Urban Dynamometer Driving

Schedule for Heavy Duty Vehicles (12). It is widely acknowledged that the emissions, reported in units of mass/distance, are influenced by the driving cycle used (6, 12) and that the cycle variation will cause different engine technologies to alter the emissions in different ways. In other words, one may reach different conclusions on the benefits of a technology based upon the cycle chosen (7).

With funding from the National Renewable Energy Laboratory, the present researchers have logged data from trucks in service to create both traditional speed vs. time cycles and routes, in which some acceleration at maximum power is required from the vehicle under test. (9, 8, 13). This paper reports the emissions data gathered from two trucks using these new cycles.

VEHICLES TESTED

Two Class 8 heavy duty road tractors were used to evaluate the CSHVR developed previously (8,9) using the Transportable Heavy Duty Vehicle Emissions Testing Laboratory (THDVETL) at WVU. A 1982 Ford L9000 road tractor, powered by an older technology 14 liter Cummins 350 horsepower engine with a PT injection system using #2 diesel fuel, was used to verify the cycles initially on a heavy duty chassis dynamometer. Shifting the Ford L9000 tractor was accomplished through a 15 speed unsynchronized transmission (this transmission has one set of deep reduction gears and is typically used as a 10 speed). A 1998 International Eagle road tractor, powered by a Cummins 435 horsepower engine with electronic injection and using #2 diesel fuel, was used to show repeatability of test-to-test emissions results, to show driver-to-driver variability in emission results due to differing driver behavior patterns, and to determine the effect of changing the simulated test weight. Shifting the International Eagle tractor was accomplished through a 10 speed unsynchronized transmission.

WVU CHASSIS DYNAMOMETER

All cycle and route emissions tests were completed on the WVU THDVETL. Testing was completed while the transportable laboratory was located at its home base in Morgantown, West Virginia. This transportable laboratory was designed to evaluate the emissions from heavy duty trucks and buses, and has been used widely in the evaluation of alternative fuel technologies (6, 7, 14). The chassis dynamometer test bed is constructed from a flat bed trailer. Setting up the chassis dynamometer is accomplished by first separating the tractor from the test bed. Next, four hydraulic lifts are used to raise the test bed so that the rear axles can be removed. Once the tractor and rear axles are removed the test bed can be lowered to the ground for chassis dynamometer use. After placing the test bed on the ground a vehicle can be driven onto the test bed for testing. The vehicle's drive wheels are placed on two sets of 12.6 inch diameter rollers. Axle power is distributed from the vehicle to the test bed by use of two hub adapters. The hub adapters are connected directly to the drive axle of the vehicle to eliminate frictional losses on the rollers. Two Lebow torque transducers are linked to the hub adapters by driveshafts so that instantaneous axle torque measurements can be made with minimal chassis dynamometer drive train loss. Weight simulation for each heavy duty vehicle is accomplished through two sets of inertia flywheels. Wind drag and tire loss simulation is accomplished through the use of two eddy current dynamometers. The second part of the transportable laboratory is dedicated solely to emissions measurement. The vehicle's exhaust is connected to a full scale ambient air dilution tunnel. Air flow through the dilution tunnel is controlled by critical flow venturis. Exhaust samples of Hydrocarbons (HC), Carbon Dioxide (CO_2), Carbon Monoxide (CO) and Oxides of Nitrogen (NO_X) are collected using heated probes and lines after mixing has occurred in the dilution tunnel. Particulate Matter (PM) is collected by filters located below a secondary dilution tunnel, that withdraws a slipstream from the main tunnel. A vehicle is exercised through a test schedule by a commercial driver prompted by a screen trace, or driver,s aid.

CYCLE AND ROUTE DEVELOPMENT

This section describes briefly the origin of the new cycles employed in the present research. A full account of the development of cycles used in this program has been given in references (8,9).

Two heavy duty tractors were selected by the American Trucking Association (ATA) for data acquisition by West Virginia University. The on-road tractors selected were fueled by liquid natural gas (LNG) and stationed at Roadway Express, Inc. in Akron, Ohio and Overnite Inc. in Richmond, Virginia. These tractors had daily operating routes, which included 4-lane freeway travel, inner city pickups and deliveries, 2-lane suburban road driving, and industrial park pickups and deliveries. A 5.9 liter Cummins engine operating on liquid natural gas (LNG) powered the single drive axle Roadway Express, Inc. tractor and shifting was accomplished through an unsynchronized 6-speed manual transmission. An 8.3 liter Cummins engine operating on LNG powered the single drive axle Overnite Transportation tractor and shifting was accomplished through a 5-speed automatic transmission.

Speed and distance data were collected on these two vehicles for a total of 49 hours. A videotape record of these tractors was also collected so that the speed and distance database could be separated into microtrips. A microtrip is defined as a burst of driving activity typically due to driving from one delivery site to another (9). The database consisted of 130 microtrips, with 77 microtrips from Roadway Express, Inc. and 53 microtrips from Overnite Transportation Co. Each microtrip was classified into one of four following driving modes: Freeway, Suburban, City and Yard. Freeway microtrips included four-lane highways with entrance and

exit ramps. City microtrips encountered denser traffic and multiple stop lights. Suburban microtrips were delivery routes on the outskirts of the city, which included industrial parks and some rural areas as well. Yard microtrips were considered any microtrips that involved changing trailers, changing tires or driving to fueling sites.

Three criterion were calculated for each of the four driving modes in the database, namely average vehicle speed, standard deviation of vehicle speed, and average cruise time. Each criterion was calculated with the idle time of the vehicle removed so that each microtrip could be characterized by the vehicle's motion and not the time spent at a standstill. After all criteria for each microtrip were calculated, idle times were once again added back into the microtrip.

A Basic program was written to concatenate microtrips randomly within each driving mode. The program added together microtrips until the total time of the concatenated microtrips was between 1000 and 1600 seconds in length, to form a cycle. Then comparing statistics between the entire driving mode database and the cycle, a Root Mean Square (RMS) error value was calculated for the cycle. The three criteria were weighted evenly in calculating the RMS error Value. Then the cycle with the lowest RMS error value was selected to be the representative cycle for that particular driving mode.

Three cycles developed using this reduction procedure, namely the Yard, City-Suburban and Freeway cycles, are discussed in this paper. Properties for each of these cycles are shown in Table 2, and speed vs. time graphs for the cycles are shown in Figures 1, 2 and 3. The City-Suburban cycle was converted to the City-Suburban Heavy Vehicle Route (CSHVR) using the videotape information. If the videotape did not show that the truck was inhibited by ulterior conditions when accelerating, the acceleration was said to be "free" and should be interpreted as acceleration at the maximum rate. When the tape showed that the progress of the original vehicle was inhibited, then that acceleration ramp portion was left exactly as recorded. Free accelerations were exhibited in the test schedule and on the driver's aid by converting an acceleration ramp into an instantaneous speed jump to the desired speed (9). Since the accelerations are free, the scheduled route speed is now a function of distance traveled and not a function of time. Properties for the CSHVR are shown in Table 3 and a speed vs. distance trace is shown in Figure 4.

Table 1. Specifications on the two vehicles used for testing at WVU.

Make and Model	Ford L9000	International Eagle
Year	1982	1998
Displacement	14 liters	14 liters
Rated Horsepower	350	435
Manual Transmission	15-speed	10-speed

Table 2. Properties for Yard, City-Suburban and Freeway cycles.

Driving cycle	Distance (miles)	RMS error Value	Average Velocity (mph)	Stdev. of Velocity (mph)
Yard	1.08	42.77	3.33	4.64
City-Suburban	6.68	14.20	14.15	13.06
Freeway	15.51	16.09	34.05	21.85
Driving cycle	**Idle Time**	**Deceleration Time**	**Average Deceleration (mph/s)**	**Stdev. of Deceleration (mph/s)**
Yard	38.83%	11.60%	-0.989	0.650
City-Suburban	19.82%	23.94%	-1.183	0.651
Freeway	7.87%	24.02%	-0.642	0.541
Driving cycle	**Cruise Time**	**Acceleration Time**	**Average Acceleration (mph/s)**	**Stdev. of Acceleration (mph/s)**
Yard	31.70%	17.87%	0.6828	0.3544
City-Suburban	22.06%	34.18%	0.8510	0.4984
Freeway	36.04%	32.07%	0.5071	0.3117

Figure 1. Scheduled speed vs. time trace for the Yard cycle. This cycle covers a distance of 1.08 miles in 1164 seconds, with a maximum speed of 16.8 mph.

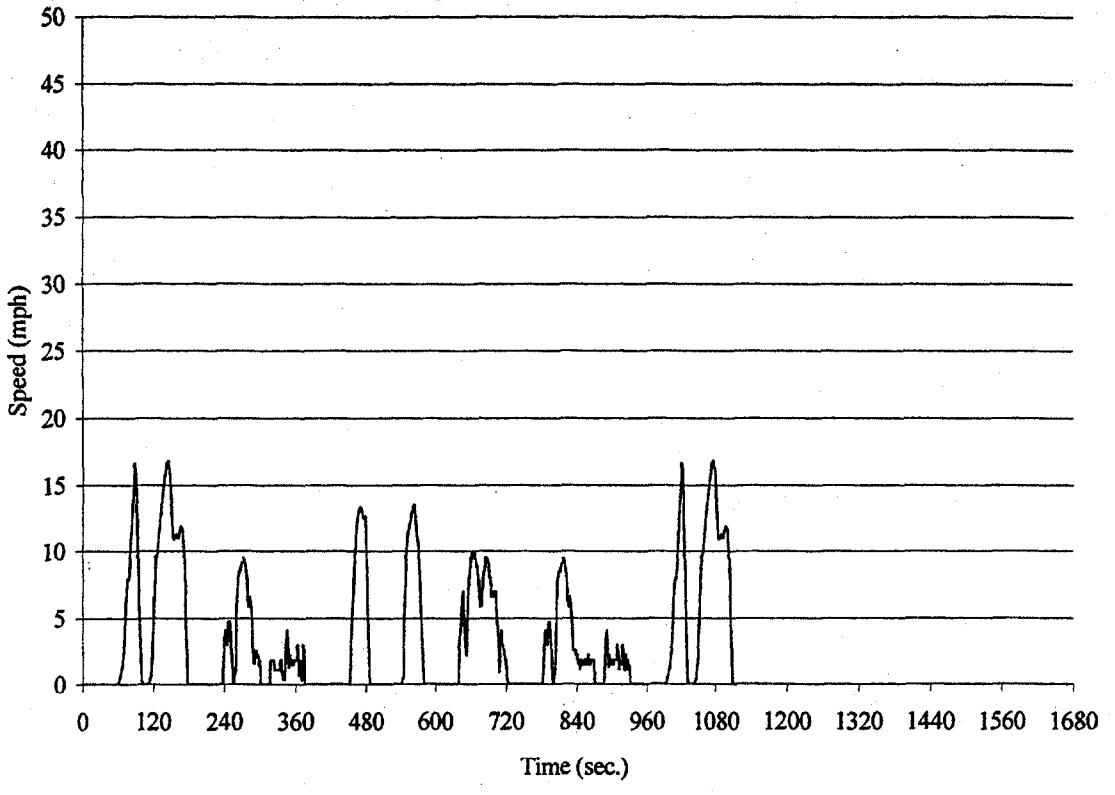


Figure 2. Scheduled speed vs. time trace for City-Suburban cycle. This cycle covers a distance of 6.68 miles in 1700 seconds, with a maximum speed of 43.8 mph.

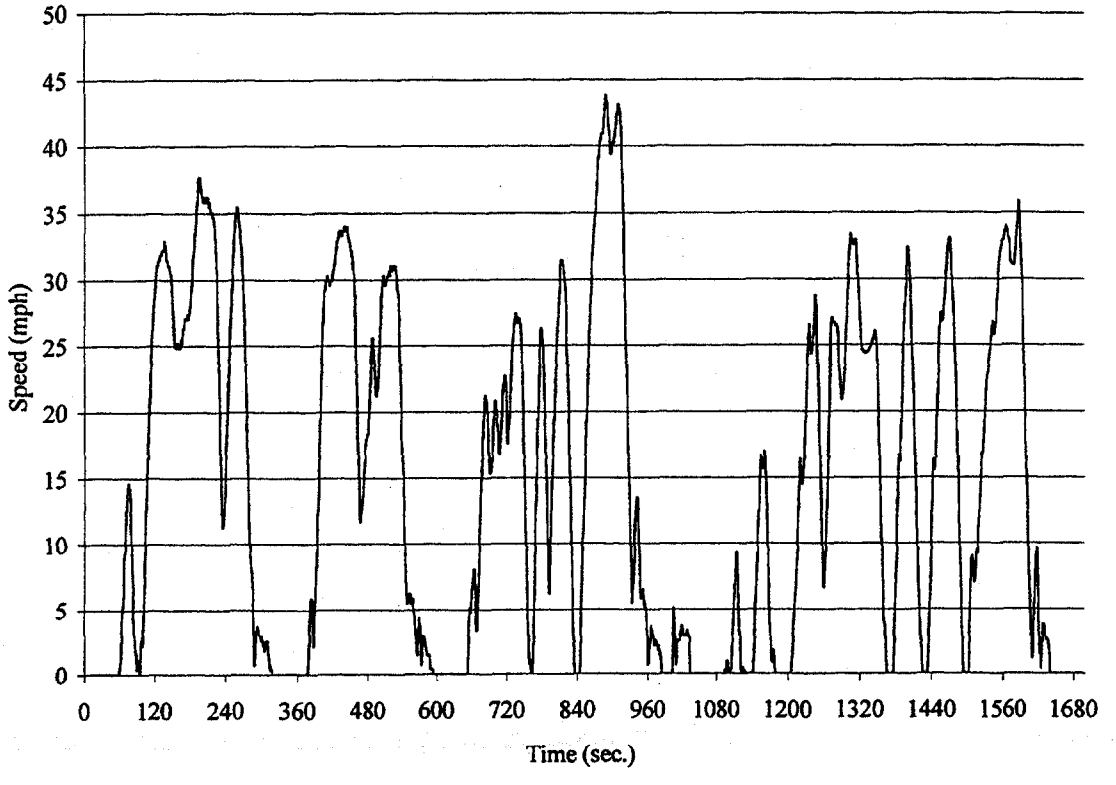


Figure 3. Scheduled speed vs. time trace for Freeway cycle. This cycle covers a distance of 15.51 miles in 1640 seconds, with a maximum speed of 60.7 mph.

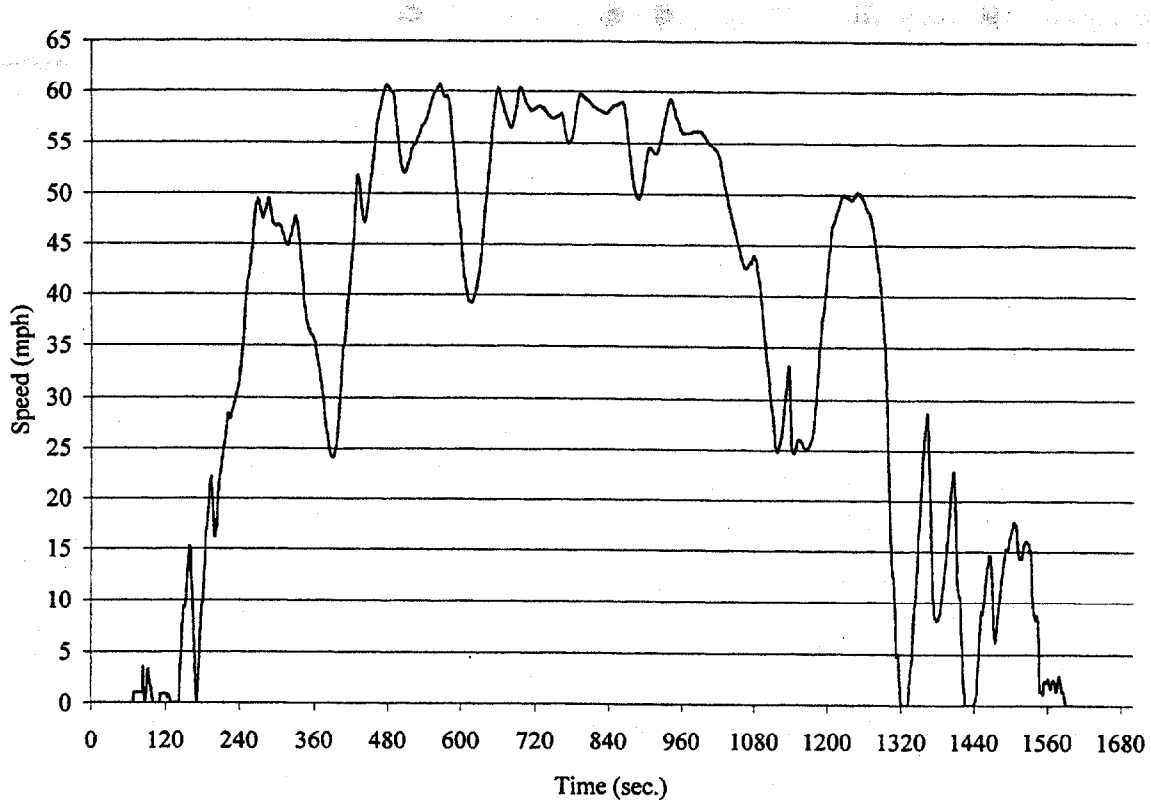


Table 3. Properties for run number 1126 of the CSHVR by the International tractor at a 46,400 lb. test weight.

Route	Distance (miles)	RMS error Value	Average Velocity (mph)	Stdev. of Velocity (mph)
City-Suburban	6.69	14.20	14.60	12.92
Route	**Idle Time**	**Deceleration Time**	**Average Deceleration (mph/s)**	**Stdev. of Deceleration (mph/s)**
City-Suburban	18.24%	26.00%	-1.06	0.55
Route	**Cruise Time**	**Acceleration Time**	**Average Acceleration (mph/s)**	**Stdev. of Acceleration (mph/s)**
City-Suburban	22.18%	33.58%	0.83	0.46

Figure 4. Scheduled speed vs. distance trace for CSHVR. This route covers a distance of 6.68 miles with a maximum speed of 43.8 mph. Idle times for the CSHVR are identical to the idle times in the City-Suburban cycle. However, they cannot be depicted on a speed vs. distance trace.

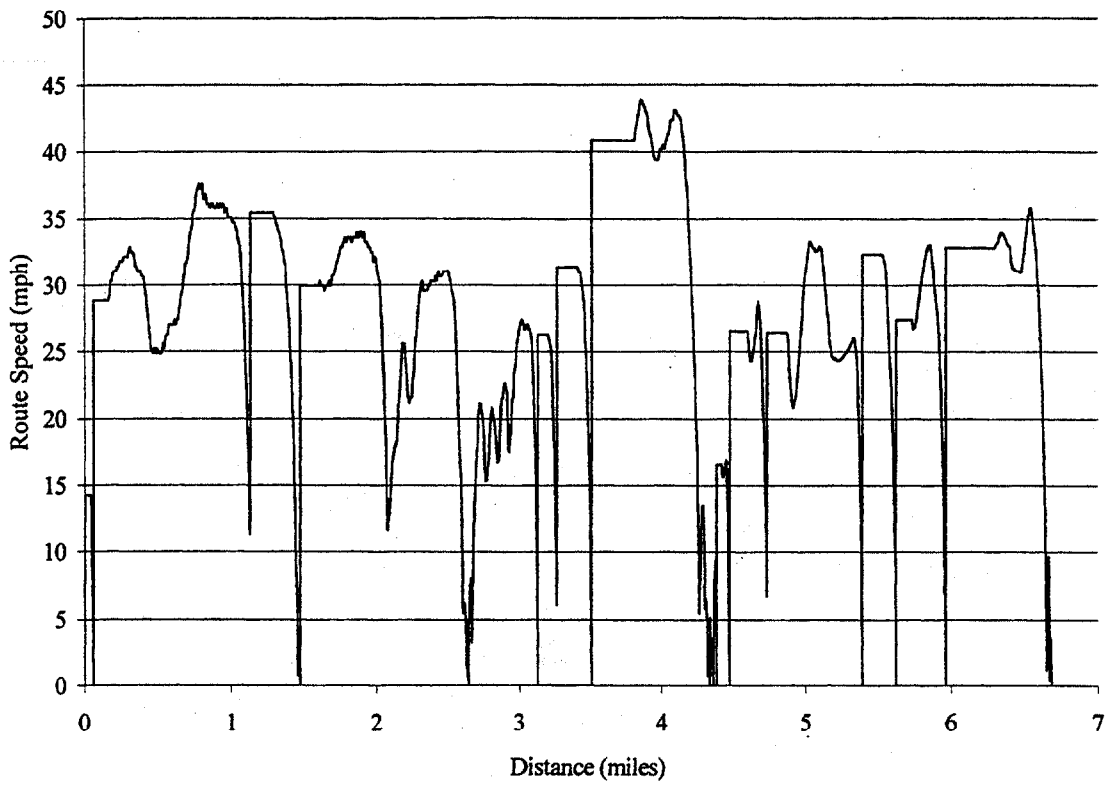


Table 4. Values for coefficients used in road load equation.

Coefficient	Ford L9000	International Eagle
C_d	0.79	0.79
A (ft^2)	64	81
μ	0.00938	0.00938
ρ ($lb./ft^3$)	73.5×10^{-3}	73.5×10^{-3}
M (lbs)	46000	46000

APPLICATION OF CYCLES AND ROUTE

In practice, the vehicle is driven through a transient test by a human driver who is prompted by a driver's aid, or screen, which presents the driver with a target speed vs. time trace. In the case of a route, which is speed vs. distance based, the time axis on the driver's aid is expanded or contracted to account for faster or slower accelerations of the vehicle in practice. In other words, there is feedback from the dynamometer control system to alter the screen according to the cumulative distance traveled. The vehicle is assumed to be driven through the cycle using a mimicry of flat ground, so that the road load, excluding transient inertial effects, is given by equation (1):

$$\text{Power} = 0.5(C_d\, \rho\, A v^3) + Mg\mu v \qquad (1)$$

The values used for drag coefficient (C_d), frontal area (A), tire rolling loss coefficient (μ), the air density (ρ), the vehicle velocity (v), and the vehicle mass (M) in the present testing are shown in Table 4.

DATA AND DISCUSSION

FORD TRACTOR

The Ford tractor was driven through 4 repetitions of the CSHVR, 3 repetitions of the 5 peak cycle, 3 repetitions of the 5 mile route and 2 repetitions of the Heavy Duty Urban Dynamometer Driving Schedule. Tables 5 through 8 present the emissions data for the four cycles in units of g/mile. In Table 8 the difference as a percentage was calculated using the difference divided by the average. In the other tables, the coefficient of

variance between runs is presented. In all cases the CO_2 repeatability was outstanding, and the NO_X repeatability was always below 5%. Provided that injection timing does not change, the ratio of NO_X to CO_2 is known to be well defined for diesel engines (15). Hydrocarbon emissions for this older truck were far higher than is generally encountered with advanced, electronically managed engines with high pressure injection, but repeatability for the HC was at worst 7.9% Higher test to test variations were encountered for CO. CO is known to be highly sensitive to small changes in driving style, and responds in a non-linear fashion to power demand when near full load. This issue of CO sensitivity is the topic of another paper at this conference (16). PM varied in sympathy with the CO, and the explanation is similar to that for CO presented above. Table 5, for the CSHVR runs, shows a steadily declining trends in both the CO and PM emissions over the first three runs, that were conducted in sequence, and this trend continued with the fourth run, which was conducted four days later. All four runs had the same driver. This could be ascribed to the driver becoming used to the CSHVR, which was in its infancy at time of testing. As the driver learns the cycle, and becomes more relaxed, the rapidity and extent of pedal movement is expected to decrease, and this would result in a reduction in CO and PM emissions.

The differences in emissions between cycles merit discussion. The 5 mile route and 5 peak cycle yielded similar gaseous and PM emissions. This is because the Ford tractor was powered such that its full performance potential did not significantly outstrip the accelerations on the 5 peak cycle, so that the behaviors on the 5 mile route and 5 peak cycle were similar. The fifth peak of the 5 mile route ended (i.e. the truck returned to idle) at 790 seconds from the start of the test, while the equivalent time for the 5 peak cycle was 817 seconds. Graboski et al. (12) have commented previously that the 5 peak cycle yielded lower emissions than the Urban Dynamometer Driving Schedule and this was borne out by the present data. The NO_X for Urban Dynamometer Driving Schedule was 46% higher than for the 5 peak cycle, while CO was almost twice as high. Curiously, the PM was not raised much, and this may be attributed to the style of fuel injection, which could encourage high soluble organic content of PM at low loadings. The new CSHVR yielded the highest emissions of all four test schedules. The NO_X emissions were 63% higher than for the 5 mile route and 13% higher than for EPA Urban Dynamometer Driving Schedule for Heavy Duty Vehicles. The PM emissions for the CSHVR were about 40% higher than for the other three test schedules. Since the CSHVR was derived from actual, recent urban and suburban truck behavior, this implies that present day emissions inventories may be higher than would be estimated from previous chassis test schedules.

Table 5. Emissions results from 4 repetitions of the CSHVR driven by the Ford tractor at a simulated test weight of 46,400 lbs.

	1091-1	1091-2	1091-3	1094-1	Average	Stdev.	COV
CO (g/mile)	34.76	29.55	30.76	27.02	30.52	3.23	10.6%
NO_X (g/mile)	32.16	34.13	32.12	30.80	32.30	1.38	4.3%
HC (g/mile)	4.43	3.91	4.01	3.67	4.01	0.32	7.9%
PM (g/mile)	7.69	6.02	6.34	5.38	6.35	0.97	15.3%
CO_2 (g/mile)	2987	2843	2925	2936	2923	59.79	2.0%

Table 6. Emissions results from 3 repetitions of the 5 peak cycle driven by the Ford tractor at a simulated test weight of 46,400 lbs.

	1089-1	1089-2	1089-3	1089-4	Average	Stdev.	COV
CO (g/mile)	11.78	11.13	12.82	12.75	12.12	0.95	7.9%
NO_X (g/mile)	20.24	19.32	19.86	19.97	19.85	0.34	1.7%
HC (g/mile)	2.12	2.02	2.23	2.04	2.10	0.11	5.5%
PM (g/mile)	5.48	3.91	4.67	4.46	4.63	0.39	8.5%
CO_2 (g/mile)	2237	2130	2212	2117	2174	51.94	2.4%

proportional

Table 7. Emissions results from 3 repetitions of the 5 mile route driven by the Ford tractor at a simulated test weight of 46,400 lbs.

	1092-1	1092-2	1092-3	Average	Stdev.	COV
CO (g/mile)	11.91	12.86	13.47	12.75	0.78	6.2%
NO_X (g/mile)	22.66	21.56	21.68	21.96	0.60	2.8%
HC (g/mile)	2.12	2.14	2.22	2.16	0.05	2.4%
PM (g/mile)	4.84	4.47	4.69	4.67	0.19	4.1%
CO_2 (g/mile)	2293	2316	2356	2322	32.24	1.4%

Table 8. Emissions results from 2 repetitions of the Urban Dynamometer Driving Schedule driven by the Ford tractor at a simulated test weight of 46,400 lbs.

	1093-1	1093-2	Average	Difference
CO (g/mile)	20.33	23.04	21.69	-12.5%
NO_X (g/mile)	29.41	28.72	29.07	2.4%
HC (g/mile)	3.09	3.00	3.04	3.0%
PM (g/mile)	4.67	4.58	4.62	2.0%
CO_2 (g/mile)	2608	2543	2576	2.5%

INTERNATIONAL TRACTOR

The International tractor was exercised through the CSHVR, the new City-Suburban cycle, the WVU 5-Mile Route, the new Yard cycle and the new Freeway cycle. The Freeway cycle was driven by a different driver than the driver for the other cycles and the CSHVR was driven by several drivers, as shown in Figure 10. Time constraints forbade repetitions of the last three schedules, but the test to test repeatability found using the Ford tractor gave confidence that the test data would be representative. Figure 5 and Figure 6 present the actual speed versus time trace and the instantaneous measured NO_X versus time trace for the International tractor performing the CSHVR. Figure 7 shows engine speed for the same run, while Figures 8 and 9 show the axle torque and the ratio of vehicle speed to engine speed respectively. Figure 9 reflects the instantaneous choice of gear. This newer tractor yielded NO_X emissions that were similar to those of the Ford tractor on the 5 mile route, and PM was cut by an order of magnitude, as shown in Table 9. For the 5 mile route, CO_2 and NO_X were again highly repeatable, but variation between the two tests was evident for CO and PM. Once again, CO and PM varied in sympathy.

Tables 10, 12 and 11 present the remaining data for the International tractor on the Yard, Freeway and City-Suburban cycles. The NO_X level for the City-Suburban cycle was 19% higher than for the 5 mile route and PM was about 50% higher. The yard cycle yielded high PM and NO_X emissions, partly because little distance is traveled for the power expended. The Freeway cycle yielded low PM emissions but high NO_X emissions, which might be attributed to an off-cycle injection timing strategy (15).

The CSHVR, averaged for all drivers, as shown in Figure 10, yielded NO_X emissions that were similar to the cycle from which it was derived. Although PM emissions were slightly higher, it is not fitting to reach a conclusion on PM since only one cycle was performed and since the coefficient of variance was 12.5% for the route. CO emissions were also slightly higher but the HC difference was small.

Table 9. Emissions results from 2 runs of the WVU 5-Mile Route driving, by the International tractor at a simulated test weight of 46,400 lbs.

	1121	1123	Average	Difference
CO (g/mile)	3.75	2.75	3.25	30.8%
NO_X (g/mile)	20.1	19.8	19.95	1.5%
HC (g/mile)	1.7	1.73	1.715	-1.7%
PM (g/mile)	0.51	0.33	0.42	42.9%
CO_2 (g/mile)	1880	1892	1886	-0.6%

Table 10. Emissions results from one Yard Cycle driving by the International tractor at a simulated test weight of 46,400 lbs.

	1147
CO (g/mile)	15
NO_X (g/mile)	52.9
HC (g/mile)	6.57
PM (g/mile)	1.00
CO_2 (g/mile)	4051

Table 11. Emissions results from one City-Suburban Cycle driving, by the International tractor at a simulated test weight of 46,400 lbs.

	1148
CO (g/mile)	4.93
NO_X (g/mile)	23.7
HC (g/mile)	1.79
PM (g/mile)	0.64
CO_2 (g/mile)	2444

Table 12. Emissions results from one Freeway Cycle driving, by the International tractor at a simulated test weight of 46,400 lbs.

	1157
CO (g/mile)	2.33
NO_X (g/mile)	30.2
HC (g/mile)	0.91
PM (g/mile)	0.35
CO_2 (g/mile)	1485

Table 13. Emissions results from 5 repetitions of the CSHVR driving by the International tractor at a simulated test weight of 46,400 lbs.

	1122-1	1122-2	1122-3	1126	1131	Average	Stdev.	COV
CO (g/mile)	6.48	5.93	5.67	5.52	5.20	5.76	0.48	8.4%
NO_X (g/mile)	23.60	23.20	23.00	24.40	22.50	23.34	0.71	3.1%
HC (g/mile)	1.95	2.01	1.98	1.89	1.82	1.93	0.08	3.9%
PM (g/mile)	0.80	0.77	0.76	0.60	0.63	0.71	0.09	12.5%
CO_2 (g/mile)	2565	2572	2553	2511	2412	2523	66.20	2.6%

Repeatability of the emissions generated from cycles and route was demonstrated by monitoring the coefficient of variance for a set of repeat runs: Table 13 shows the data from repeat runs, all executed by the same driver, for the International truck on the CSHVR.

Figure 5. Continuous speed vs. time trace of run 1126 of the CSHVR driving by the International tractor at a simulated test weight of 46,400 lbs.

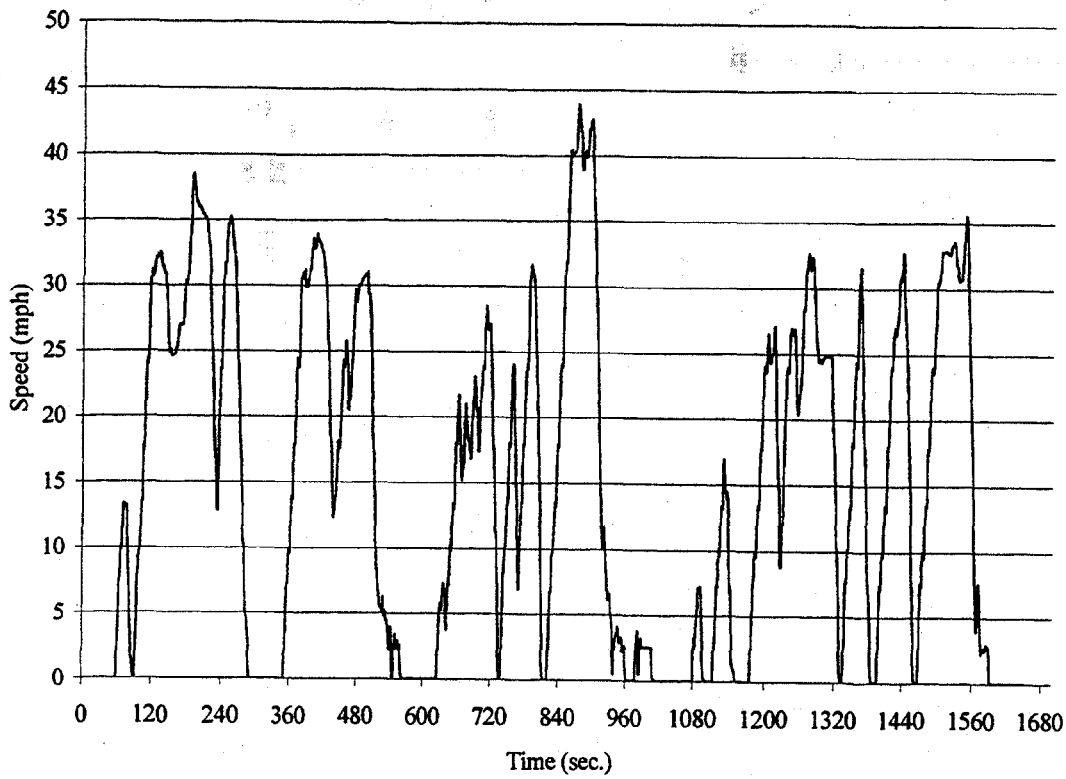


Figure 6. Continuous NO_X trace of run 1126 of the CSHVR driving by the International tractor at a simulated test weight of 46,400 lbs.

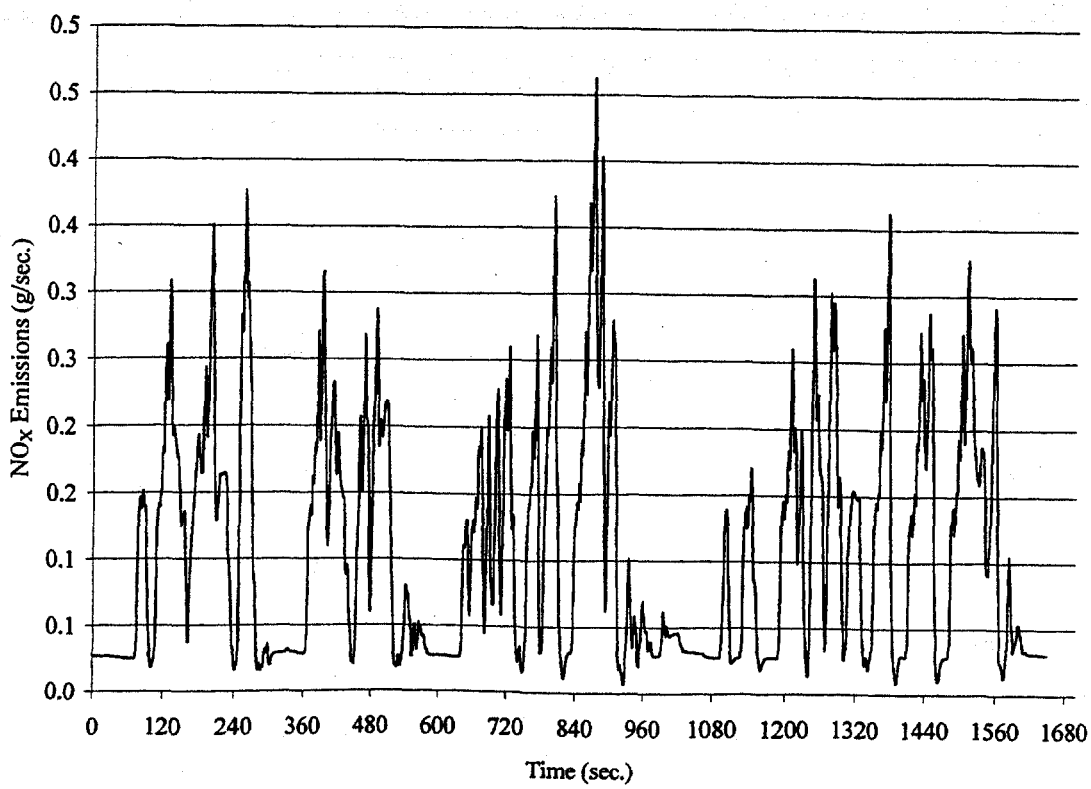


Figure 7. Continuous engine speed trace of run 1126 of the CSHVR driving by the International tractor at a simulated test weight of 46,400 lbs.

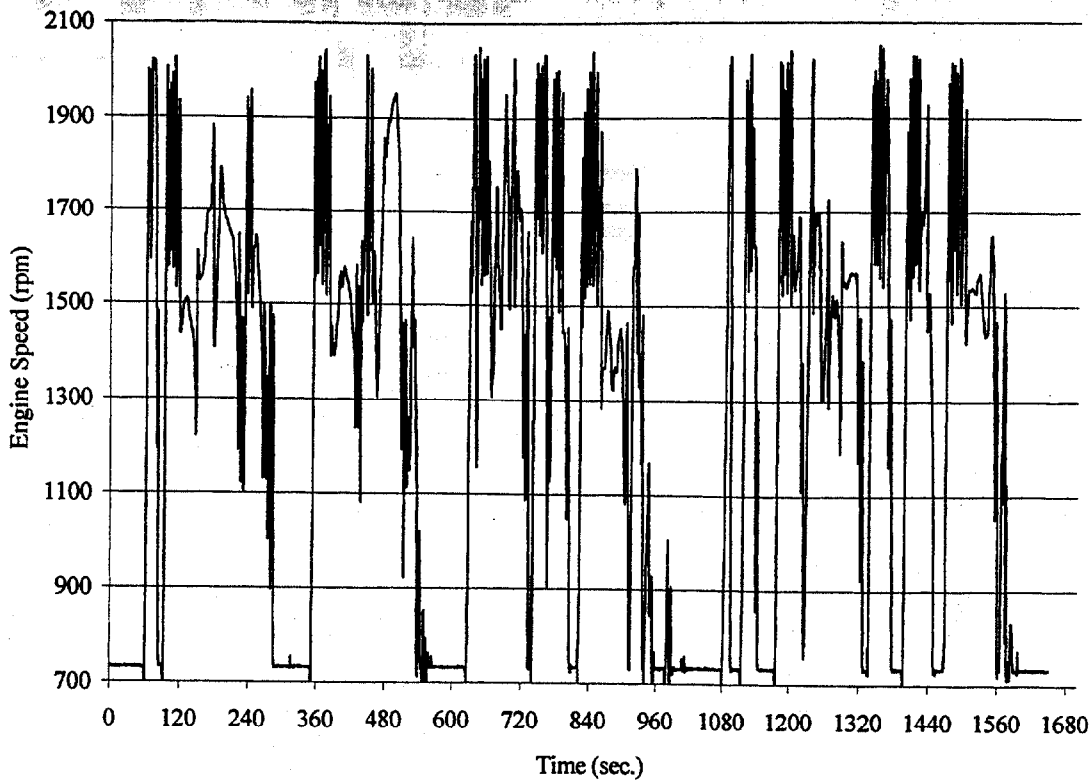


Figure 8. Continuous axle torque trace of run 1126 of the CSHVR driving by the International tractor at a simulated test weight of 46,400 lbs.

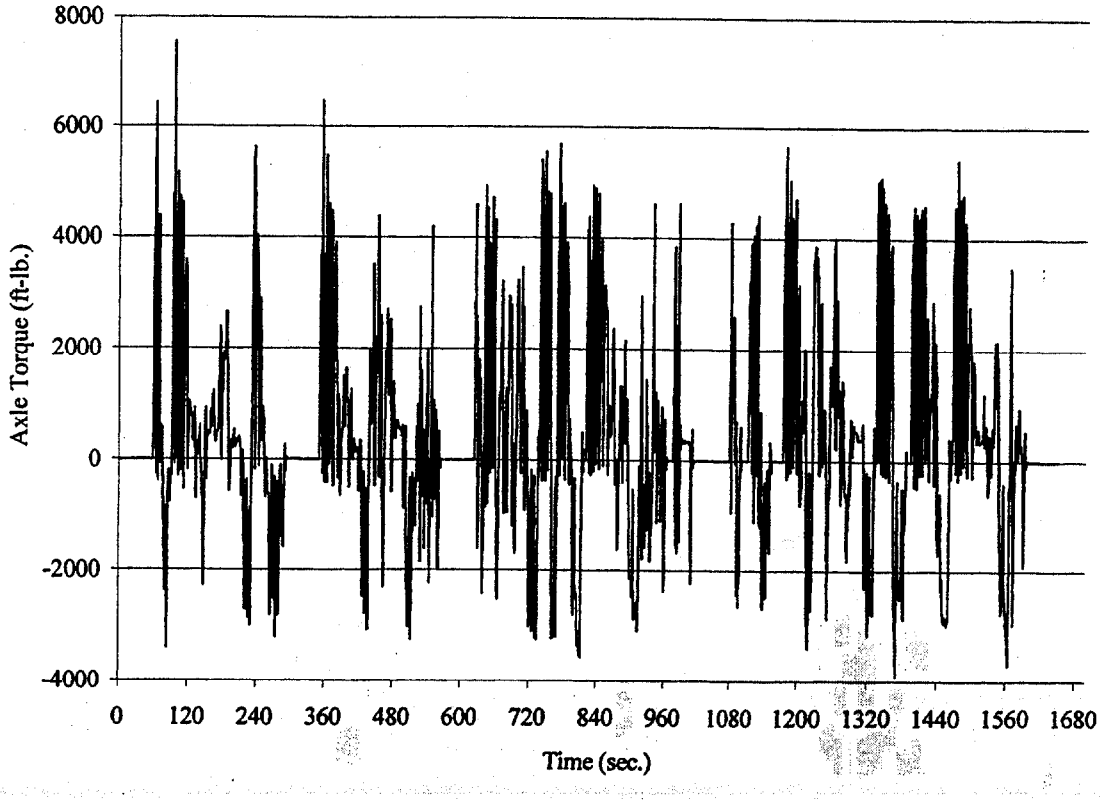


Figure 9. Continuous ratio of vehicle speed to rotational engine speed trace of run 1126 of the CSHVR driving by the International tractor at a simulated test weight of 46,400 lbs.

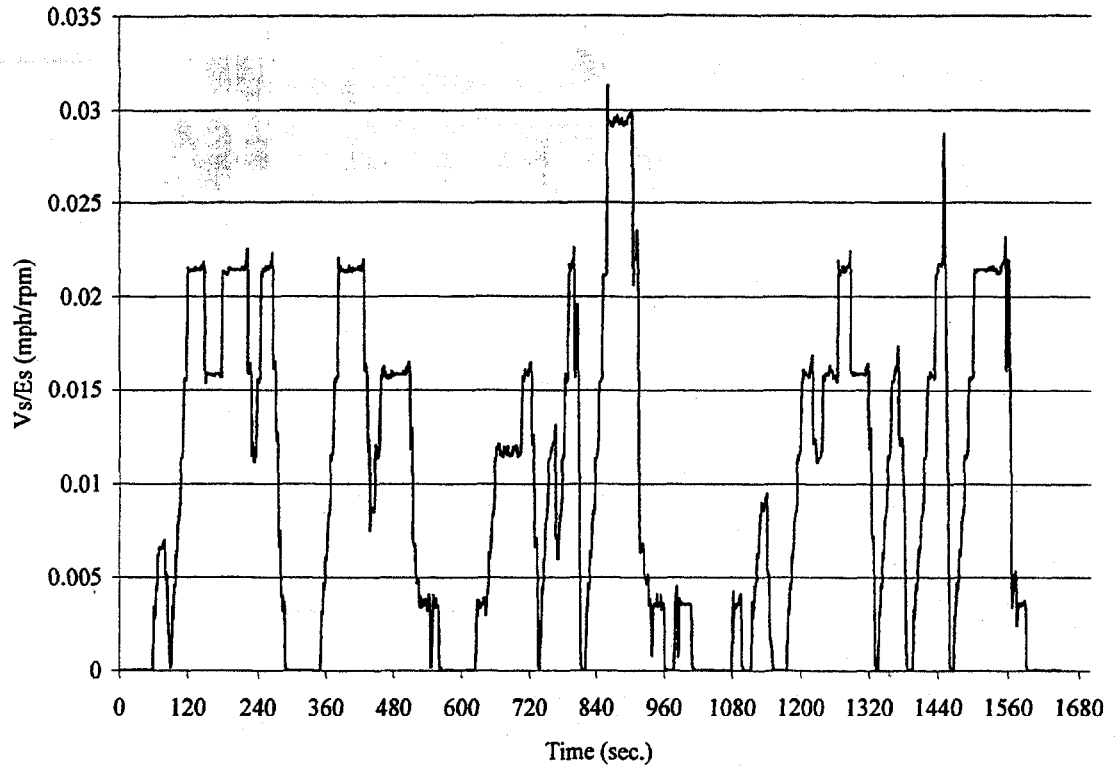
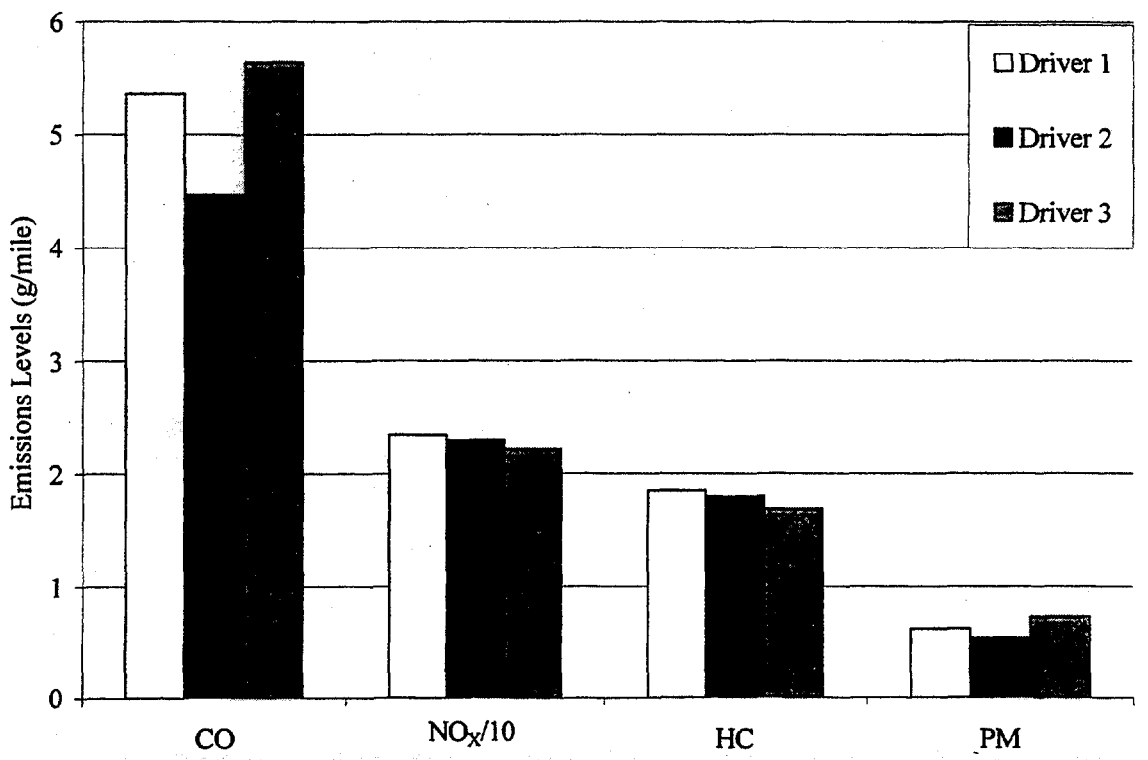


Figure 10. Comparisons between three drivers, driving the CSHVR using an International road tractor at a 46,400 lb. test weight.



Driver-to-driver variations were evaluated using three drivers. Each driver held a commercial driver's license (CDL). All driver-to-driver variation tests were completed during one day of testing in order to eliminate variations from day-to-day. The drivers' driving order was selected randomly so that influence of other variables could be reduced. Driver-to-driver variation tests were completed using the International tractor at a 46,400 lb. test weight. Figure 10 shows the average emissions results of each driver running the CSHVR. The NO_X emissions varied little between drivers, but the driving styles influenced CO and PM, which varied in sympathy with one another. Nevertheless, the coefficient of variance (as a percentage) for CO between drivers was 11.1% and for PM was 14.8%, which the authors believe to be an acceptable variation for diesel fueled vehicles.The main difference in the driver-to-driver emissions results is due to the aggressiveness of each driving style on the chassis dynamometer. Vehicle shifting patterns are also different when the vehicle is operated by different drivers. This is shown by plotting a vehicle speed engine speed (Vs/Es) ratio as displayed in Figure 10. The Vs/Es ratio is constant when a driver is locked into a certain gear. During shifting the ratio is not constant and is shown as an instantaneous change in the Vs/Es ratio. This ratio can be used when comparing a single driver for repeatable driving behavior or when comparing the driving patterns of two different drivers operating vehicles with unsynchronized transmissions. This ratio will show clear differences when drivers follow the same section of the CSHVR in a different gear. In the future it may become possible to reduce variation by prescribing gear selection, but such a prescription remains more difficult with heavy duty than light duty vehicles.

Figure 11. Vehicle speed/ Engine speed ratio used to show differences in vehicle shifting patterns between different drivers.

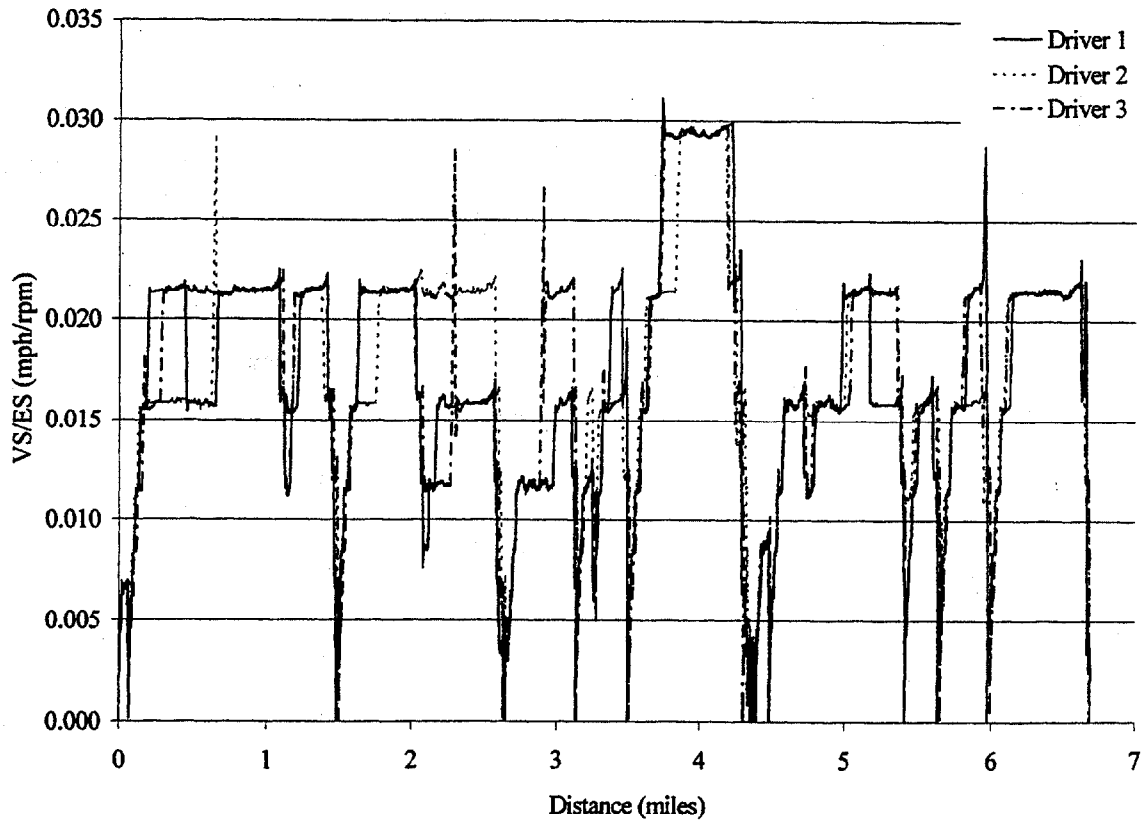
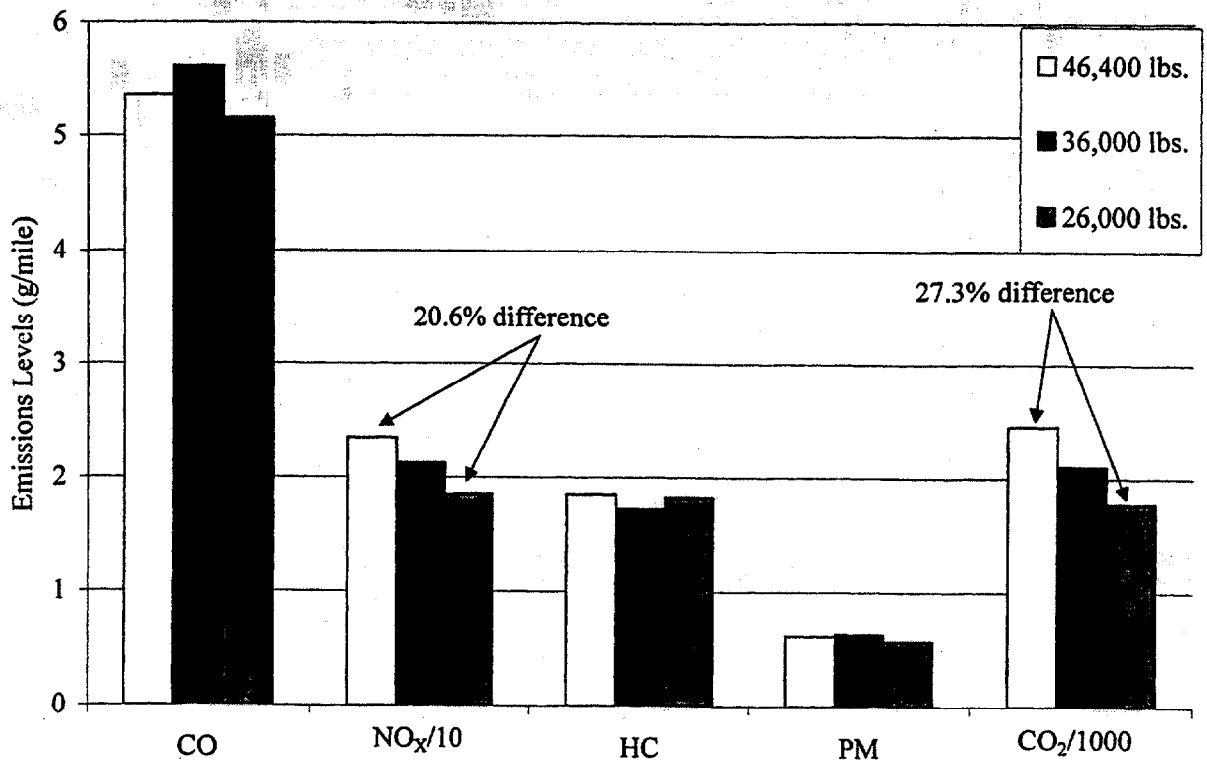


Figure 12. Average emissions results using three different simulated test weights. Tests were performed using the International tractor at a simulated weight of 46,400 lbs., 36,000 lbs. and 26,000 lbs.



The effect of test weight on emissions, in units of mass/distance, was assessed using the International tractor with the CSHVR at 26,000, 36,000 and 46,400 lb. test weights as shown in Figure 12. Variation of all regulated exhaust emissions was modest between test weights, although the CO_2 level reflected the additional energy used at higher weights. The small variation in CO and PM emissions may be attributed to the fact that in all three cases, the route called for full power operation of the vehicle and demanded a similar number of shifts with associated transient CO and PM emissions. Also, the wind resistance component remained the same regardless of test weight. Emissions of NO_X were reduced by 20.6% as the test weight was reduced by 44%, from 46,400 to 26,000 lb. The NO_X/CO_2 ratio varied little, from 0.0095 at 46,400 lb. to 0.0104 at 26,000 lb.

CONCLUSIONS

Over the road tractors have been exercised through a new Yard cycle, a new Freeway cycle, a new City-Suburban cycle and a new City-Suburban Heavy Vehicle Route (CSHVR), as well as cycles already in use for heavy truck emissions characterization. In the case of the tractor with an electronically managed engine, the Yard cycle returned the highest NO_X and PM emissions in units of g/mile, because little distance is traveled. The Freeway cycle yielded high NO_X but low PM relative to both the City-Suburban cycle and CSHVR. Repeatability of the CSHVR was excellent for CO_2 and NO_X, and coefficients of variation among five runs were 8.4% for CO and 12.5% for PM which is considered acceptable for diesel engines, which have high CO and PM sensitivity. Driver-to-driver variations were also higher for PM than for NO_X. The CSHVR proved relatively insensitive, in the emissions that it yielded, to the test weight, with NO_X showing the greatest variation and CO_2 levels reflecting the energy consumed. Following this preliminary testing effort, the CSHVR has now been applied in field emissions characterization. It is concluded that the CSHVR represents a useful and realistic test schedule for truck emissions characterization.

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