Emission Rates of Regulated Pollutants from On-Road Heavy-Duty Diesel Vehicles

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1.0 Abstract

Emissions from heavy-duty diesel (HDD) vehicles are affected by many factors. Changes in engine technology, operating mode, fuel properties, vehicle speed and ambient conditions can have significant effects on emission rates of regulated species. This paper presents the results of on-road emissions testing of eleven HDD vehicles (model years 1996 to 2000) over the ARB Four Phase driving schedule and the Urban Dynamometer Driving Schedule (UDDS). Emission rates were found to be highly dependent on vehicle operating mode. Per mile NO_x emission rates for vehicle operation at low speeds, in simulated congested traffic, were three times higher per mile emissions then while cruising on the freeway. Comparisons of NO_x emission factors to EMFAC baseline emission factors were within 5 to 40% for vehicles of various model years tested over the UDDS. A comparison of NO_x emission factors for a weighted average of the ARB Four Phase Driving Schedule yielded values within 17 to 57% of EMFAC values. Generally, particulate matter (PM) emission rates were lower than EMFAC values.

Keywords: Diesel emissions; NO_x; oxides of nitrogen, on-road emissions; regulated pollutants; heavy-duty diesel

2.0 Introduction

Heavy-duty diesel (HDD) vehicles account for 30 to 60% of the on-road NO_x emissions inventory (U. S. EPA, 1998; Kean et al., 2000). The variability in the estimated HDD contribution to inventories is due to the uncertainty the relationship between emission rates and factors such as test cycle, activity, engine programming and vehicle age (Clark et al., 2002; Dunlap, et al., 1993; Dietzmann and Warner-Selph, 1985). Until recently, most emissions data were based on results testing engines in a laboratory following certification cycles. Dietzman et al. (1985) have demonstrated that emissions measured over certification cycles do not compare well with chassis dynamometer testing of vehicles over comparable test cycles. Currently, emission factors used in inventory estimates are based on compilations of data found in sources such as the California Air Resources Board's (CARB) EMFAC model (CARB, 2002). These emission factors are primarily based on certification data developed from stationary dynamometer testing or limited testing of vehicles on chassis dynamometers over standard cycles (CARB, 2002).

Yanowitz et al. (1999) suggest that per mile NO_x emission rate variations due to differences in operating modes can be normalized on a fuel consumption basis. However, with the development of advanced engine controls, such as the Electronic Control Module (ECM), newer HDD vehicles tend to stray from this generalization (Clark et al., 2002; Federal Register, 1998). The ECM controls fuel injection timing in such a manner that during certain cruising conditions, fuel consumption is reduced while NO_x emissions are increased. This effectively varies the emission rate of NO_x on a basis of fuel consumption (Federal Register, 1998). In order to accurately model and predict emissions, there is a critical need to measure the in-use emission factors of these newer vehicles as they operate on-road.

The effects of driving cycle on PM emissions and composition were the subject of a previous publication (Shah et al., 2004). In this paper, we examine the effects of various driving cycles on regulated gaseous emissions from HDD vehicles operated on the road. For the first time, on-road emission factors of gaseous pollutants, measured using a laboratory designed to meet the Code of Federal Regulations requirements for determining emissions from HDD engines, are presented for a fleet of vehicles. Comparisons of measured values to published EMFAC values are made and differences in emissions due to increased vehicle cruise speed are presented.

3.0 Experimental Section

3.1 Mobile Emissions Laboratory

Emissions testing was performed using CE-CERT's Mobile Emissions Laboratory (MEL). The MEL is comprised of a 53-foot refrigeration trailer equipped with a full-scale dilution tunnel. The laboratory can be connected to test-vehicles and driven over the road with the total exhaust plumbed directly into the dilution tunnel via an insulated, gastight, flexible, 316-L stainless steel tube. The MEL is designed to measure emissions at the quality level specified in the U.S. Congress Code of Federal Regulations for Heavy Duty Diesel Engines (40 CFR 86). Details of the laboratory are provided elsewhere (Cocker et al., 2004).

3.2 Gaseous Analyzers

Analyzers for CO, CO_2, NO_x and THC extract samples from the dilution tunnel via heated filters and lines. The gaseous emissions analyzers utilized in the laboratory are listed in Table 1. Span and zero calibrations on each range of the analyzers are performed throughout the test day (a minimum of once every two hours). In addition, the laboratory undertakes weekly checks of the dilution tunnel and sampling systems via the injection of a known mass of propane and CO_2; audit bottle checks, NO_x converter checks, leak checks, and calibrations of all auxiliary measurement devices such as mass flow controllers, thermocouples, barometric pressure and dewpoint sensors are performed on a routine basis. For every test, ambient measurements are compared against local reported values (airports) or independent measurements. The full details of QA/QC program can be found elsewhere (Cocker, et al., 2004).

3.3 Test Fleet, Fuel and Cycle

Table 2 summarizes the eleven HDD vehicles tested. Vehicles were procured from a truck dealer and tested on-road without modifications or repairs. Vehicle 10 was unable to maintain the most severe speeds and accelerations of portions of the test cycles. This vehicle was tested as is except for a change to CARB ultra-low-sulfur-diesel fuel (<15ppm S); typical properties of the test fuel can be found in Table 3. Emissions testing were conducted following the ARB Four Phase Schedule and the Urban Dynamometer Driving Schedule (UDDS) (40 CFR 86; Gautam et al., 2002). The ARB Four Phase Driving Schedules were derived based on activity data collected for 84 HDD vehicles operating in California and it consists of four phases: Cold-Start/Idle, Creep, Transient and Cruise (Gautam et al., 2002). Cold-Start/Idle consists of a vehicle cold-start followed by ten minutes of idling; Creep simulates vehicle operation in heavily congested conditions; Transient simulates vehicle operation on arterial roads; Cruise simulates freeway driving. All on-road testing was conducted on local roads and Freeway 10 in Coachilla, CA. This area provided a test location near sea-level with minimal road grade (e.g., the cruise mode road had an uphill grade of 31.9 ft mi^{-1}). Figure 1 presents the vehicle speed versus time trace for the driving cycle. The UDDS consists of a single phase and is meant to simulate vehicles operating over a range of modes in an urban environment. The UDDS was developed thirty years ago for chassis dynamometer testing of HDD vehicles.

4.0 Results

4.1 Repeatability of On-Road Emissions Testing

A Freightliner truck equipped with a 2000 Caterpillar C-15 was tested on several non-consecutive days in order to determine the repeatability of on-road emissions testing. Table 4 presents the results of these tests. Results indicate that emissions during cold-start/idle were less repeatable than for the other phases of the ARB Four Phase Driving Schedule. This variation is believed to be due to the larger dependence of cold-start emissions on ambient conditions such as temperature and humidity (Gautam et al., 1992).

4.2 Fleet Averaged Emission Factors

Fleet averaged THC, CO, NO_x and CO_2 emission rates for the eleven vehicles tested on the ARB Four Phase Driving Schedule are presented in Table 5. Per mile Cruise emission rates were lowest for THC, CO, NO_x and CO_2 and PM. Per mile NO_x

emission rates were similar for Transient and Cruise and one-third the value for Creep. Per mile emission rates for PM, THC, CO, NO_x, and CO_2 for Creep were higher than Transient and Cruise for all the vehicles tested.

Previous papers have utilized CO_2 to normalize NO_x emissions to account for differences in test cycles (Clark et al., 2002; Yanowitz et al., 1999). This approach suggests that a fuel consumption based emissions inventory estimates will account for differences in engine activity. However, for our post 1996 test fleet, there is no significant correlation between NO_x and CO_2. Figure 2 presents NO_x/CO_2 ratios for the test fleet. Creep and Cruise NO_x/CO_2 ratios exceed Transient by a factor of two for most of the vehicles. The NO_x/CO_2 variations indicate that factors in addition to fuel consumed drive NO_x emissions. The elevated NO_x/CO_2 values (~ 0.02) seen in Figure 2 are evidence of off-cycle operation in these vehicles.

4.3 Gaseous Emission Rates for Individual Vehicles

Emission rates of THC, CO, NO_x and CO_2 for the ARB Four Phase Driving Schedule are presented in Figures 3 and 4. For all four gaseous emissions, each vehicle showed the highest per mile emission rate for creep. From 1996 to 2000, EPA and CARB's certification values for NO_x emissions have decreased from 5 to 4 g $(bhp\text{-}hr)^{-1}$. This required reduction is not seen in the emissions from our test fleet. NO_x emission rates have remained fairly constant for each operating mode for engines over the span of 1996 to 2000 (Figure 4). Yanowitz et al. (2000), reported similar findings for vehicles in model years 1974 to 1998.

4.4 Comparison to EMFAC Values

EMFAC is an emissions inventory model used to estimate emissions from on-road sources (CARB, 2002). This model utilizes baseline emission factors determined from chassis dynamometer testing of vehicles over the UDDS, for HDD vehicles. The model applies corrections to baseline emission factors to account for other variables such as fuel composition, tampering with emissions control systems, malmaintenance, and engine deterioration. Table 6 presents a summary of emission factors in EMFAC, those determined from on-road testing of the UDDS, and each phase of the ARB Four Phase Driving Schedule. PM values are also presented in Table 6. Details of the PM measurements can be found in Shah et al. (2004). EMFAC emission factors are based on 5 vehicles from model years 1994 to 1997 and 4 vehicles from model year 1998. The EMFAC emission factors for model years 1999 to 2002 are based on emissions reductions expected to be achieved through standards enacted during these years. As seen in Table 2, the emission factors shown in this paper are based on the same number of vehicles for the 1994 to 1997 and 1998 bins and 2 vehicles in the 1999 to 2002 bin.

Due to similarities in their speed traces, we previously compared the emissions of one vehicle during the Transient Phase of the ARB Four Phase Driving Schedule to EMFAC and UDDS values (Cocker et al., 2004). Table 6 presents data from our entire test fleet. NO_x emissions for Transient, Cruise and UDDS are comparable for the entire test fleet; however, there is a large difference with Creep phase emissions. The large difference between EMFAC and Creep phase emissions indicates that emissions modeling applied to small geographic regions that are subject to frequent heavily congested conditions will underpredict emissions inventories. 1994-1997 engines tend to have substantially higher NO_x emission rates during Cruise than EMFAC values. This may be due to off-cycle operation occurring during the Cruise phase. Generally speaking, compared to EMFAC values, the weighted average NO_x emission rates are higher while PM emission rates are lower. As stated previously, the ARB Four Phase Driving Schedule was developed based on the driving behavior of vehicles in California (Gautam, et al., 2002). The emission rates in Table 6, demonstrate the need to incorporate these values into the baseline emission rates data used in EMFAC.

5.0 Conclusions

The emission rates of regulated species from on-road HDD vehicles have been demonstrated to differ from those previously published. NO_x emissions in the Creep phase of the ARB Four Phase Driving Schedule were three times higher than the Transient and Cruise phases; however, NO_x emissions are comparable between the Transient, Cruise and the UDDS. The differences in emission rates during congested conditions (Creep) indicate that models that attempt to examine emissions inventories in small microscale environments should examine vehicle activity to determine the importance of emissions due to congestion. The weighted average of the ARB Four Phase Driving Schedule for the vehicles tested show on-road NO_x emission rates higher than EMFAC values, while PM emission rates were lower than the EMFAC tables. This difference may be due to the use of different cycles or fuels; however, when the UDDS was performed on a test vehicle the on-road emission rates for NO_x exceeded the EMFAC values.

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7.0 References

California Air Resources Board, 2002. EMFAC2001/EMFAC2002. Calculating emissions inventories for vehicles in California: User's Guide.

Clark, N.N, Kern, J.M., Atkinson, C.M., Nine, R.D., 2002. Factors Affecting Heavy-Duty Diesel Vehicle Emissions. Journal of the Air and Waste Management Association 52, 84-94.

Cocker, D.R., Johnson, K.J., Shah, S.D., Miller, J.W., Norbeck, J.M., 2004. Development and Application of a Mobile Laboratory for Measuring Emissions From Diesel Engines I. Regulated Gaseous Emissions. Environmental Science and Technology 38, 2182-2189.

Code of Federal Regulations: Protection of the Environment, 40 CFR 86

Dietzmann, H., Warner-Selph, M. A., 1985. Comparison of Emissions from Heavy Duty Engines and Vehicles During Transient Operation. ASME Technical Paper 85-DGP-10.

Dunlap, L. S., Pellegrin, V., Ikeda, R., Wilson, R., Stanley, S., Porter, H., 1993. Chassis Dynamometer Emissions Testing Results for Diesel and Alternative-Fueled Vehicles. SAE Technical Paper No. 931783.

Federal Register, 1998. 63, No. 212.

Gautam, M., Ferguson, D. H., Wang, W. G., Bata, R. M., Lyons, D. W. Clark, N. N., Palmer, G. M., 1992. In-Use Emissions and Performance Monitoring of Heavy Duty Diesel Vehicles Using a Transportable Chassis Test Facility. SAE Technical Paper No. 921751.

Gautam, M., Clark, N., Riddle, W., Nine, R., Wayne, W.S., Maldonado, H., Agrawal, A., Carlock, M., 2002. Development and Initial Use of a Heavy-Duty Diesel Truck Test Schedule for Emissions Characterization. SAE Technical Paper No. 2002-01-1753.

Kean, A.J., Sawyer, R.F., Harley, R.A., 2000. A Fuel-Based Assessment of Off-Road Diesel Engine Emissions. Journal of the Air and Waste Management Association 50, 1929-1939.

Shah, S. D., Cocker, D. R., Miller, J. W., Norbeck, J. M., 2004. Emission Rates of Particulate Matter and Elemental and Organic Carbon from In-Use Diesel Engines. Environmental Science & Technology 38, 2544-2550.

U.S. Environmental Protection Agency, 1998. National Air Pollutant Emission Trends Update, 1990-1997, EPA 454/E-98-007, U.S. Government Printing Office, Washington, D.C.

Yanowitz, J., Grabowski, M.S., Ryan, L.B.A., Alleman, T.L., McCormick, R.L., 1999. Chassis Dynomometer Study of Emissions from 21 In-Use Heavy-Duty Vehicles. Environmental Science and Technology 33, 209-216.

Yanowitz, J., McCormick, R. L., Graboski, M. S., 2000. In-Use Emissions from Heavy-Duty Diesel Vehicles. Environmental Science and Technology 34, 729-740.

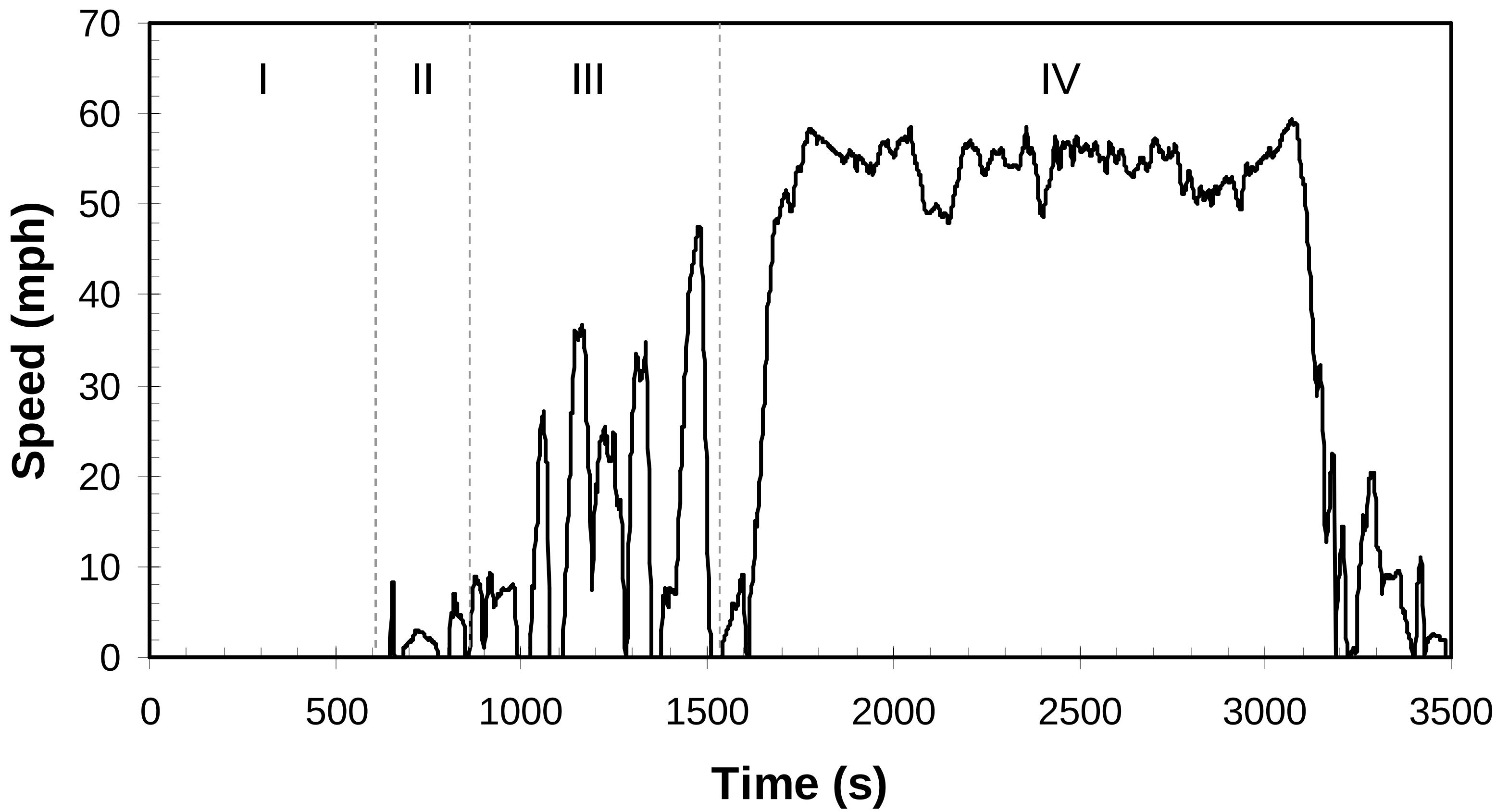

Figure 1: CARB Four Phase Driving Schedule consisting of Cold-Start/Idle (I), Creep (II), Transient (III) and Cruise (IV).

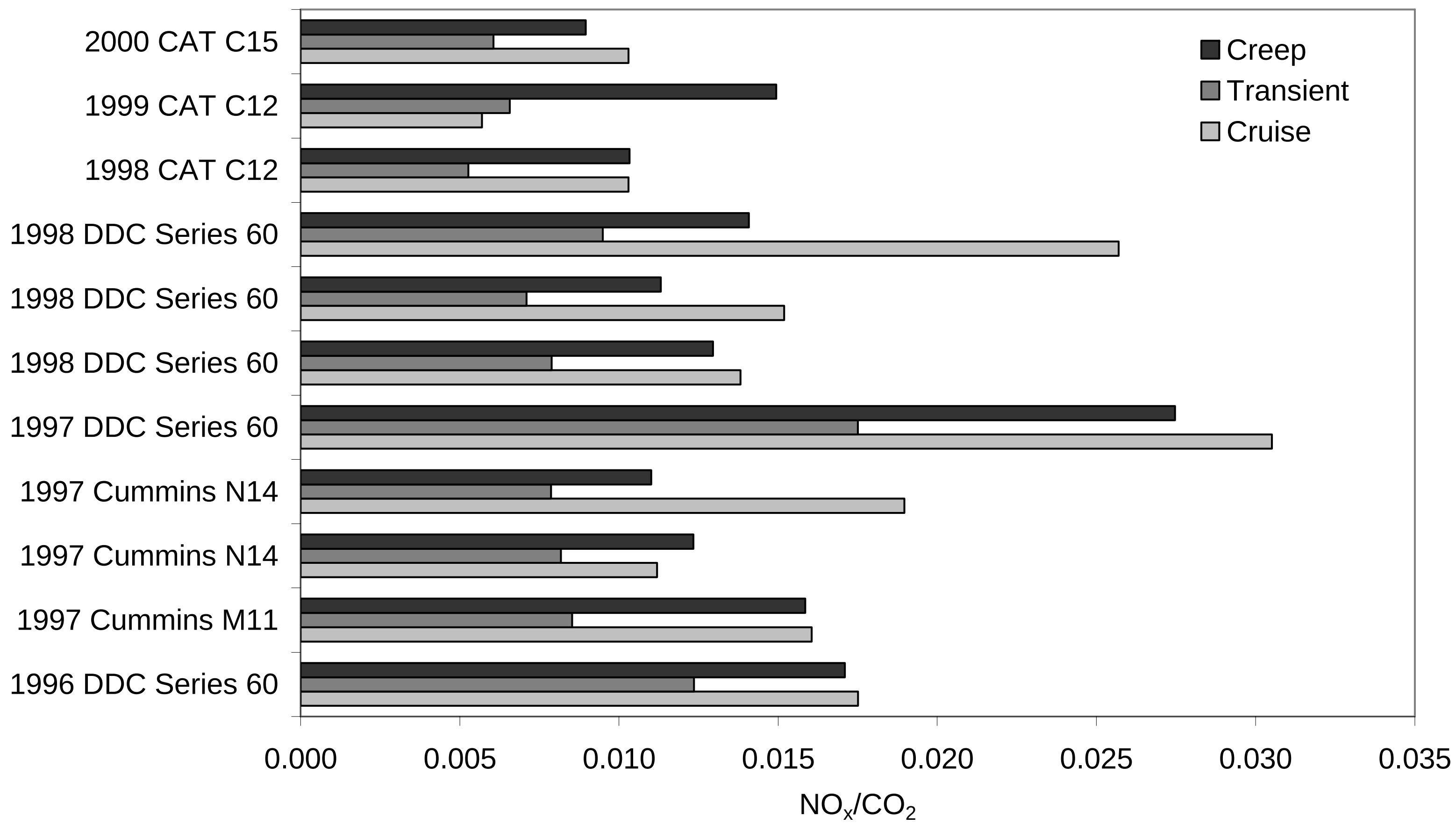

Figure 2: NO_x/CO_2 Ratios of Eleven HDD Vehicles Over the Three Mobile Phases of the ARB Four Phase Driving Schedule.

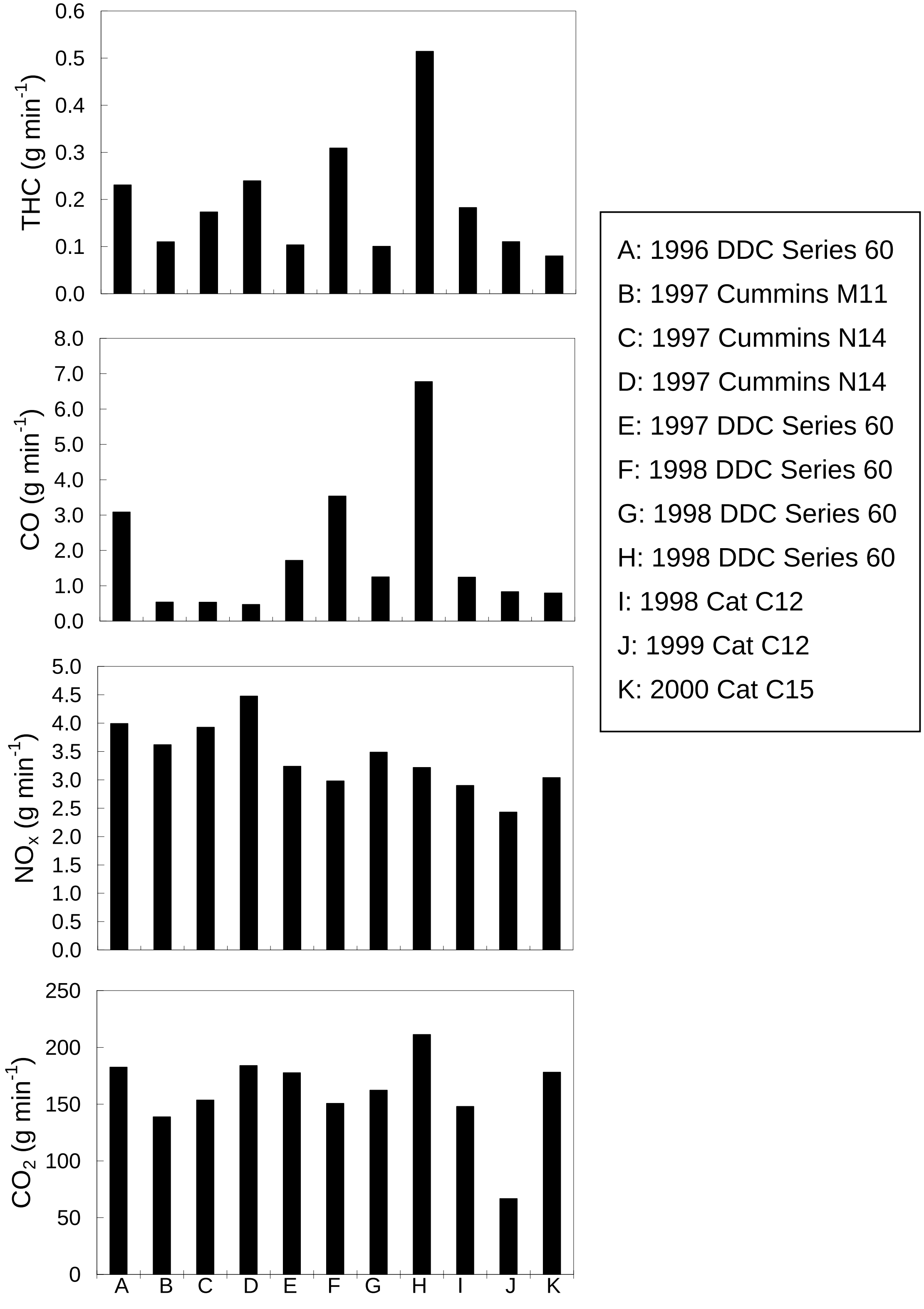

Figure 3: Emissions during Cold-Start/Idle.

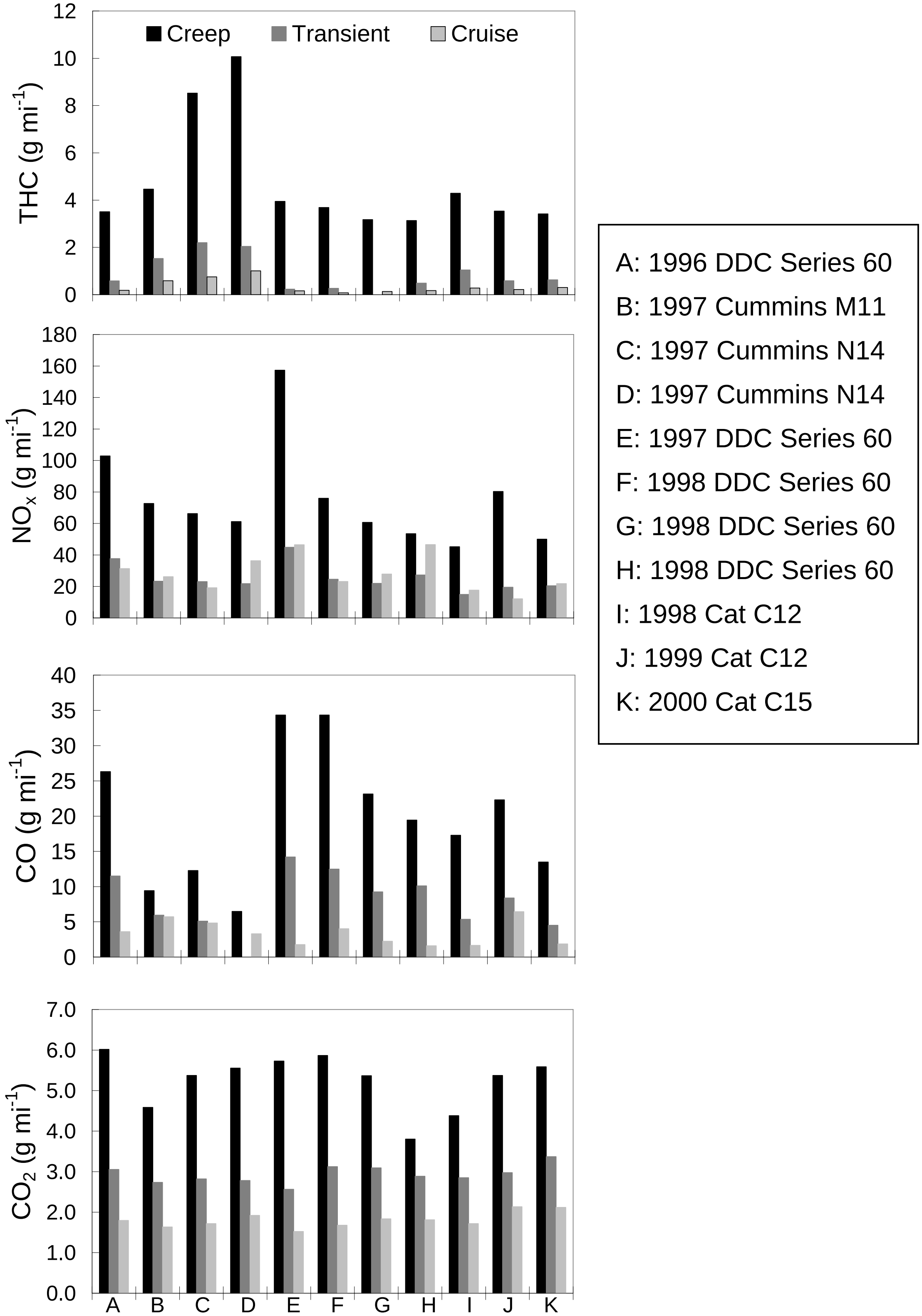

Figure 4: Emission rates of gaseous pollutants from eleven HDD vehicles tested on-road.

Table 1: Summary of Gas-phase Instrumentation in the MEL (11)

Gas Component	Range[a]	Monitoring Method
NO_x	10/30/100/300/1000 (ppm)	Chemiluminescence
CO	50/200/1000/3000 (ppm)	NDIR[b]
CO_2	0.5/2/8/16 (%)	NDIR
THC	10/30/100/300/1000 & 5000 (ppmC)	Heated FID[c]

a) Multiple values of range indicate upper range of each instrument mode
b) Non-dispersive Infrared Detector
c) Flame Ionization Detector

Table 2: Vehicle Test Fleet

Vehicle #	Test Date	Truck Model	Odometer (miles)	Engine Year	Engine Model	Rated Power (hp)	Speed (RPM)	GVW* (lb)
1	7/20	Freightliner D120	545,700	1996	Detroit Diesel Series 60	360/400	1800	17,240
2	7/18	International 9800 SBA	442,674	1997	Cummins M11	330	1800	15,960
3	7/24	Freightliner D120	512,786	1997	Cummins N14	370/435	1800	15,620
4	7/29	Freightliner C-120	353,953	1997	Cummins N14	370/435	1800	16,940
5	8/14	Freightliner C-120	449,404	1997	Detroit Diesel Series 60	370/430	1800	17,840
6	8/17	Freightliner C-120	489,310	1998	Detroit Diesel Series 60	470	2100	18,040
7	9/6	Freightliner C-120	469,801	1998	Detroit Diesel Series 60	360	1800	18,040
8	12/18	Freightliner C-120	163,349	1998	Detroit Diesel Series 60	370/430	1800	17,380
9	1/24	Freightliner C-120	521,048	1998	Caterpillar C-12	355/410	2100	16,500
10	1/10	Freightliner C-120	382,246	1999	Caterpillar C-12	355/410	1800	16,160
11	9/17	Freightliner C-120	9,000	2000	Caterpillar C-15	475	2100	15,760

*The MEL adds 45, 000 lbs to the total weight of the vehicle.

Table 3: Typical properties of ultra-low sulfur diesel fuel used in this work

Property	Test Method	Limit
Ash, wt. %, max	D-482	0.01
Carbon Residue, 10 % Btms, wt. %, max	D-524	0.35
Cetane Index, typical	D-4737	55
Cetane Number, typical	D-613	53.5
Cu Strip Corr., 3 hrs @ 122 F, max	D-130	3
Distillation	D-86	
T 90%, F		540-640
Final Boiling Pt., F, max		698
Flash Point, F, min	D-56	125
Gravity, API, typical	D-287	38
Lubricity, g, typical	D-6078	3100
Stability, mg/100mL, max	D-2274	1.0
Sulfur, ppm	D-5453	15
Viscosity, cSt @ 40 C	D-482	1.9-4.1

Table 4: Results of repeatability testing of a Freightliner truck equipped with a Caterpillar C15 engine.

	THC	CO	NO_x	CO_2
Cold-Start/Idle				
Average (g min^{-1})	0.08	0.79	3.04	178.
St. Dev.	0.02	0.24	0.56	12.6
n	7	7	7	7
Creep				
Average (g mi^{-1})	2.51	15.58	48.6	5337.
St. Dev.	1.35	2.85	4.13	506.
n	11	11	11	11
Transient				
Average (g mi^{-1})	0.49	5.33	20.8	3209.
St. Dev.	0.26	0.42	1.03	170.
n	9	9	9	9
Cruise				
Average (g mi^{-1})	0.29	1.93	21.6	1982.
St. Dev.	0.08	0.11	0.97	108.
n	6	6	6	6

n: Number of test

Table 5: Fleet average emission rates of THC, CO, NO_x and CO_2 for eleven on-road HDD vehicles.

	Avg. Speed (mph)	THC	CO	NO_x	CO_2	PM
Cold-Start/Idle (g min^{-1})	0	0.124±0.0527	0.956±0.250	2.79±0.319	130.±57.6	0.301±0.0210
Creep (g mi^{-1})	1.77	4.71±2.34	19.9±9.33	75.2±31.7	5024. ±682.	1.02±0.426
Transient (g mi^{-1})	15.4	0.962±0.720	7.90±4.16	25.5±8.59	2933.±221.	0.656±0.153
Cruise (g mi^{-1})	39.9	0.352±0.300	3.38±1.72	28.1±11.3	1808.±190.	0.215±0.201

Table 6: Comparison of on-road emission rates to values used in EMFAC.

	Model Year	Creep (g mi^{-1})	Transient (g mi^{-1})	Cruise (g mi^{-1})	Weighted Average (g mi^{-1})	UDDS (g mi^{-1})	EMFAC (g mi^{-1})
THC	1994-1997	6.10	1.32	0.539	0.651	1.01	0.710
	1998	3.57	0.601	0.166	0.229	0.363	0.650
	1999-2002	3.48	0.259	0.259	0.274	0.584	0.650
CO	1994-1997	17.8	7.35	3.85	4.30	4.07	3.07
	1998	23.6	9.31	2.40	3.26	5.21	2.24
	1999-2002	17.9	4.16	4.16	4.22	5.63	2.24
NO_x	1994-1997	92.1	30.2	32.0	32.1	29.3	20.4
	1998	58.9	22.3	28.8	28.3	25.0	24.2
	1999-2002	65.2	17.0	17.0	17.2	17.5	14.1
CO_2	1994-1997	5454	2792	1719	1854	2074	2179
	1998	4856	2989	1760	1909	2410	2179
	1999-2002	5483	2128	2128	2144	2729	2179
PM	1994-1997	1.29	0.700	0.223	0.280	NA	0.65
	1998	0.590	0.618	0.109	0.167	NA	0.48
	1999-2002	1.18	0.407	0.407	0.411	NA	0.39

NA: not available