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Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 1. Regulated Gaseous Emissions

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Information about in-use emissions from diesel engines remains a critical issue for inventory development and policy design. Toward that end, we have developed and verified the first mobile laboratory that measures on-road or real-world emissions from engines at the quality level specified in the U.S. Congress Code of Federal Regulations. This unique mobile laboratory provides information on integrated and modal regulated gaseous emission rates and integrated emission rates for speciated volatile and semivolatile organic compounds and particulate matter during real-world operation. Total emissions are captured and collected from the HDD vehicle that is pulling the mobile laboratory. While primarily intended to accumulate data from HDD vehicles, it may also be used to measure emission rates from stationary diesel sources such as back-up generators. This paper describes the development of the mobile laboratory, its measurement capabilities, and the verification process and provides the first data on total capture gaseous on-road emission measurements following the California Air Resources Board (ARB) 4-mode driving cycle, the hot urban dynamometer driving schedule (UDDS), the modified 5-mode cycle, and a 53.2-mi highway chase experiment. NO_x mass emission rates (g mi^{-1}) for the ARB 4-mode driving cycle, the hot UDDS driving cycle, and the chase experiment were found to exceed current emission factor estimates for the engine type tested by ∼50%. It was determined that congested traffic flow as well as "off-Federal Test Procedure cycle" emissions can lead to significant increases in per mile NO_x emission rates for HDD vehicles.

Introduction

Efforts over the past 25 years to reduce emissions from gasoline-fueled vehicles have resulted in new fuel, engine, and control technologies that have reduced per mile tailpipe hydrocarbon emissions by over 99% (*1*). This reduction came as a result of a determined effort by regulators and vehicle and fuel manufacturers. Regulators were guided by a substantial amount of research and development, including the extensive Auto/Oil study (*2*). Lloyd and Cackette (*3*) reported that regulators relied on data from thousands of gasoline-fueled vehicles but only 23 heavy heavy-duty diesel engines to make regulatory decisions. More emissions data are needed, considering that diesel engines may account for over 50% of the NO_x and particulate matter (PM) contributions to the mobile source inventory (*4*) and will continue to command a significant market share based on their durability, reliability, and fuel efficiency.

Regulations that aimed to significantly reduce diesel emissions started in the 1980s when regulatory controls were implemented for engines used in on-road diesel buses and vehicles (*5*). Later in 1996, non-road engines were regulated (*6*). Perhaps, the most significant step occurred after the Consent Decree of 1998 (3,5) when the EPA promulgated regulations for diesel fuel and heavy-duty diesel (HDD) on-road engines. These regulations require a 95% reduction in NO_x emissions and a 90% reduction in PM emissions by 2007 (*7*). Most of these regulatory decisions have been made without data from on-road operation.

With emphasis directed toward reducing emissions from diesel-fueled engines, more efforts are being undertaken to measure on-road emissions. Furthermore, it is recognized that data generated for engine certification are from a laboratory test stand and may not represent the emissions when the engine is part of a vehicle or another application. A number of investigators have developed tools to measure emissions from engine/vehicle combinations driven over standard cycles on stationary or portable chassis dynamometers. The number of these facilities is quite limited due to their expense, and using them still does not provide information on vehicles driven in the real world (*8*, *9*). Accordingly, some investigators are developing methods based on a mini-dilution tunnel with on-board instruments (*10*−*13*). Other systems sample the test vehicle's plume by either using a chase vehicle (*14*) or attaching their laboratory to the test vehicle (*15*).

The addition of the electronic control module (ECM) to modern HDD vehicles increased the difficulty in measuring emission rates due to the potential for multiple operating modes. During highway cruise conditions, the ECM advances fuel injection timing leading to better fuel economy at the expense of higher NO_x emissions (*16*). Further complicating emission measurements is the fact that the fuel-saving mode does not turn on during Federal Test Procedure (FTP) testing for engine certification standards. The EPA refers to such emissions as "off-FTP cycle" emissions where software or a vehicle component allows emissions in excess of the FTP certification standards to be produced during operating modes not explicitly covered by a certification test while still controlling emissions during the certification test (*16*). Such off-cycle emissions can significantly affect emission inventory estimates that are based on engine certification values and must be explored.

In this paper, we describe a unique mobile facility that allows for the direct measurement of on-road emissions using a full-flow dilution tunnel while meeting the guidelines specified in the Code of Federal Regulations (CFR) Parts 86 and 89 (*17*). Both gaseous and PM emissions are measured with the same levels of accuracy as measurements made in a stationary facility. A technical description of the mobile emissions laboratory (MEL), comparison with other laboratories, and data from field examples are discussed in the following sections. This paper is intended to provide a

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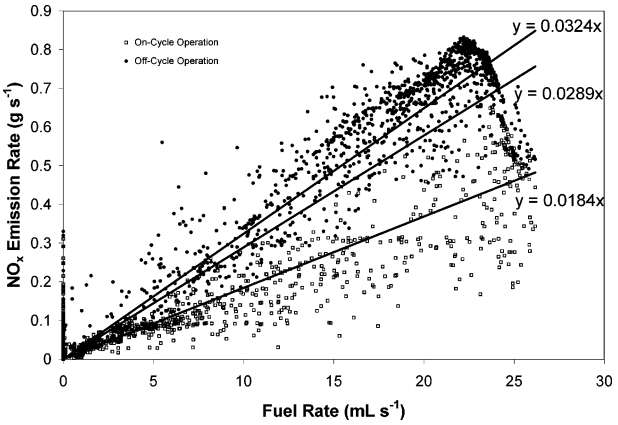


FIGURE 1. NO_x emission rate vs fuel consumption for a trip from Victorville to Riverside. Three NO_x vs fuel trendlines are shown. The upper trendline represents the off-cycle engine operation; the middle trendline is the average for the trip; the lower trendline represents on-cycle operation.

technical background for future studies performed using the MEL.

Motivation for Mobile Emissions Laboratory

The concept of a mobile laboratory evolved during discussions of off-FTP cycle (off-cycle) emissions and recognition of the need to measure real-world emission factors from HDD vehicles during on-road operation. The switching of the engine operating mode enabled by the engine control software leads to potentially nonlinear emissions when compared with other engine parameters (*18*). Figure 1 presents NO_x emission rate versus fuel consumption rate for a model year 2000 Freightliner tractor with a Caterpillar C-15 diesel engine when driven on the highway for 53.2 mi chasing another HDD vehicle (see Tests of Real-World Driving section for more route details). Two engine operating modes are clearly seen as two distinct trendlines present in Figure 1. The upper trendline represents off-cycle emissions during operation in the fuel-economy mode. The lower trendline represents on-cycle operation similar to what would be observed during FTP engine certification testing. Such off-cycle emissions can significantly impact the total emissions inventory for the HDD vehicles, the extent of which is dictated by the amount of time spent in each mode. For this engine, the slope of the trendline for off-cycle emissions is 1.8 times that of on-cycle emissions. A future publication will address such impacts and the role of the engine control software on total NO_x emissions. The time spent in each mode of engine operation is a complex nonlinear function of on-road engine operating conditions (*18*, *19*).

The MEL can measure these multiple operating modes. The current laboratory design includes a number of subsystems including the MEL structure, utilities, analytical sampling system, instrumentation, and data acquisition/control systems. Details of each subsystem are provided within the following sections. Figure 2 is a schematic of the MEL and its subsystems. This laboratory provides a platform to investigate effects of engine type, fuel composition, and driving cycles on mass emission rates under a variety of operating conditions. Parameters such as traffic, altitude, road grade, torque, load, wind, and many other factors can be measured to provide data for emission models. Measurements from these tests will allow for a more comprehensive understanding of the factors associated with emissions from HDD engines.

Laboratory Structure. A 53-ft refrigerated trailer was selected as the basic laboratory structure due to its low thermal and acoustic transmission properties. An additional enlarged door was added to the trailer side for installation of and access to analytical equipment. Structural bracing was added to the front of the trailer to support the sampling port linking the dilution tunnel to the diesel source. The trailer is equipped with a fully pneumatic bag system to dampen on-road vibrational noise and an integrated 4-channel anti-lock braking system.

Electrical/Climate Control. A Caterpillar SR4B (225 kW) diesel generator provides the electrical power for the laboratory. The generator is mounted in the rear of the trailer and is fueled by an auxiliary fuel tank located beneath the trailer. During on-road operation, this generator provides power for the analyzers, computer systems, compressors, pumps, dilution tunnel turbine, and air conditioning system.

A 5-ton heating ventilation and air conditioning (HVAC) system provides climate control inside the laboratory. The unit is capable of maintaining an interior temperature of 20 °C. Supply ducting and delivery registers are evenly distributed throughout the laboratory on the wall opposite to the dilution tunnel. An air purification system installed on the inlet of the HVAC unit reduces airborne dust within the laboratory.

Exhaust Dilution System. Engine exhaust is transferred through a double-wall insulated, gastight, flexible, 316-L stainless steel tube into a 15.2-cm stainless steel elbow located at the front end of the trailer. Dilution of the exhaust then occurs immediately upstream of a 27.4 cm i.d. orifice plate. Ambient air is conditioned and purified to provide the dilution air for the system. The dilution air is treated with a coarse filter to remove large particles, an activated charcoal filter to remove hydrocarbons, and a HEPA filter to remove fine particulate. Significant mixing occurs as the dilution air and diesel exhaust pass through the orifice plate.

The primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) venturi and dynamic flow controller. The SAO venturi has the advantage of no moving parts and repeatable accuracy at high throughput with low pressure drop. As opposed to traditional dilution tunnels with a positive displacement pump or a critical flow orifice, the SAO system with dynamic flow control eliminates the need for a heat exchanger. Tunnel flow rate is adjustable from 1000 to 4000 cfm with an accuracy of 0.5% of full scale. It is capable of total exhaust capture for engines up to 550 kW. Colorado Engineering Experiment Station Inc. initially calibrated the flow rate through both SAOs for the primary tunnel.

Analytical Sampling System. Heated probes, heated filters, and sample conditioning are used to prevent condensation and remove moisture in the system. Sample probes can be attached to any of 10 access ports to the primary tunnel ranging from 2.5 to 10 cm in diameter. The ports are located 10 tunnel diameters from the mixing orifice.

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical devices measure NO_x, methane (CH_4), total hydrocarbons (THC), CO, and CO_2 at a frequency of 10 Hz and were selected based on optimum response time and on-road stability. The 200-L Tedlar bags are used to collect tunnel and dilution air samples over a complete test cycle. A total of eight bags are suspended in the MEL allowing four test cycles to be performed between analyses. Filling of the bags is automated with LabView 7.0 software (National Instruments, Austin, TX). A summary of the analytical instrumentation used, their ranges, and principles of operation is provided in Table 1. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time. A flow schematic for gas-phase sampling within the MEL is provided as Supporting Information (Figure S1).

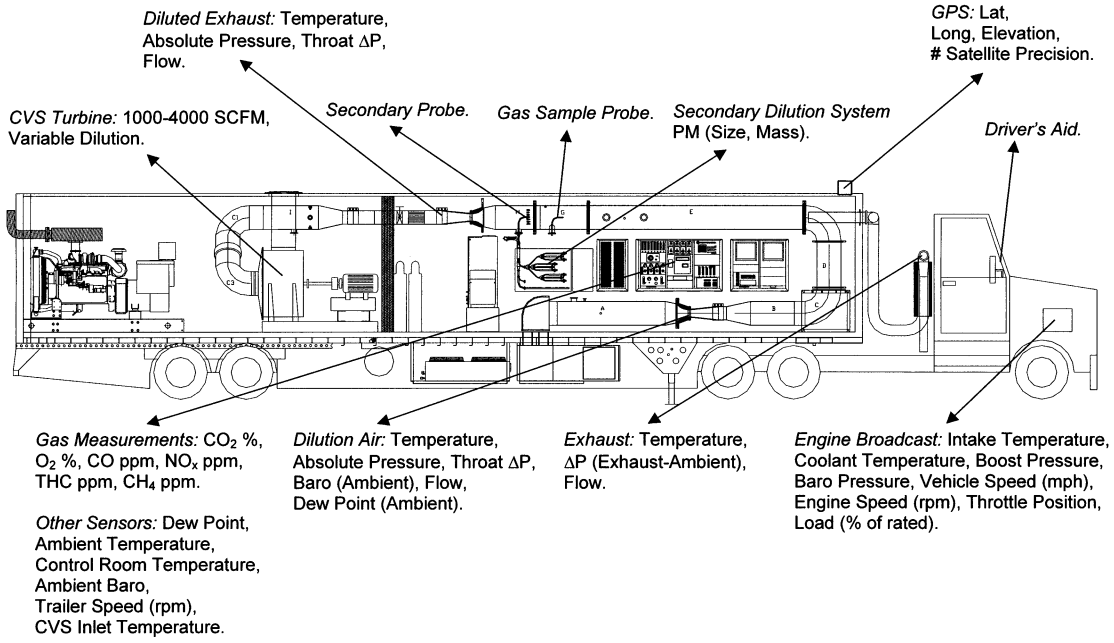


FIGURE 2. Schematic of MEL.

TABLE 1. Summary of Gas-Phase Instrumentation Present in the MEL

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]
CH_4	30/100/300/1000 (ppmC)	FID

[a] Multiple values of range indicate upper range of each instrument mode. [b] Nondispersive infrared detector. [c] Flame ionization detector.

Ambient dewpoint is measured with a 1211hx General Eastern Optical dewpoint sensor (Plainville, CT). Resistive thermal devices record temperature along the primary and secondary dilution tunnels, at the dilution air inlets, and at the exhaust outlet. Barometric pressure measured within the tunnel is used to adjust the dynamic flow controller to account for deviations from standard pressure conditions. Daily verification of the barometric reading is performed through comparison of the pressure readings to altitude-compensated ATIS (Automated Terminal Information Services) measurements from nearby airports.

PM and Non-Regulated Emissions. While particulate samples can be withdrawn from the primary tunnel, most are collected in a uniquely designed secondary tunnel (*20*). The secondary dilution system incorporates many of the requirements specified in the 2007 CFR, including the control of filter face temperature to 47 ± 5 °C at a fixed mass flow ratio (*17*). A multiple jet particle trap impactor based on the initial design of Biswas and Flagan (*21*) with a 50% cutoff particle diameter of 2.5 μm removes coarse particles. The secondary tunnel has several attached ports to allow simultaneous collection of $PM_{2.5}$ onto three separate filter media and up to four different phases before reloading sample media. Flow rates through the secondary ports are controlled with Unit 5300 and 7300 (Yorba Linda, CA) series mass flow controllers (MFCs). LabView-based software controls the duration of and sample timing for each of the sampling legs. The system is designed to monitor size and mass distribution while collecting sample substrates for detailed semivolatile and particulate chemical analyses.

Multiple ports on the primary and secondary tunnels allow a number of samples to be extracted simultaneously to obtain a complete chemical source profile of the exhaust stream being tested. For example, the laboratory allows for simultaneous sampling with XAD-4-coated annular denuders for semivolatile organic compounds; PUF/XAD cartridges for evaporative filter losses and the semivolatile organic components; 47-mm quartz filters for elemental carbon/organic carbon, polynuclear aromatic hydrocarbon (PAH) analysis, and detailed hydrocarbon (HC) analysis; 47-mm Teflon filters for elemental analysis and PM mass; 2,4-dinitrophenylhydrazine (DNPH) cartridges for carbonyls; gas impingers for alcohol and sulfate analysis; and 8-L Tedlar bags for speciated C_1−C_{12} volatile organic hydrocarbons. Thus, the design of the mobile laboratory provides considerable flexibility for measuring non-regulated emissions. The full description of the techniques and capabilities for PM and non-regulated emissions is reported in ref *20*.

Operating Systems and Data Acquisition (DAQ). DAQ cards and serial data streams are used to monitor, record, and control the entire MEL including sample timing and duration, analyzers, sample conditioning system, constant volume sampler (CVS), and broadcast ECM data. The systems' program software can correct for changes in flow across the fixed venturi during transient driving cycles, record analog data from the analyzers and other instruments, time-align the data with the driving trace, communicate to a driver's aid for trace following, interface with the diagnostic information from the OEM engine controller, and report the final data in a summary format. Additional monitored parameters include engine speed, percent engine load, trailer speed, fuel rate, intake manifold pressure, engine coolant temperature, and boost pressure. The entire measurement platform for the MEL is highly automated and can communicate through an Ethernet-based local area network.

A driver's aide is necessary to ensure repeatable testing over predetermined driving cycles. The driver's aide system consists of a video display in the test vehicle coupled to the DAQ computer systems in the MEL. Test cycles are presented to the driver as velocity versus time traces. As a test begins, the video displays required speed and current deviation from the requirement, aiding the driver in replicating a desired velocity trace while traveling on-road.

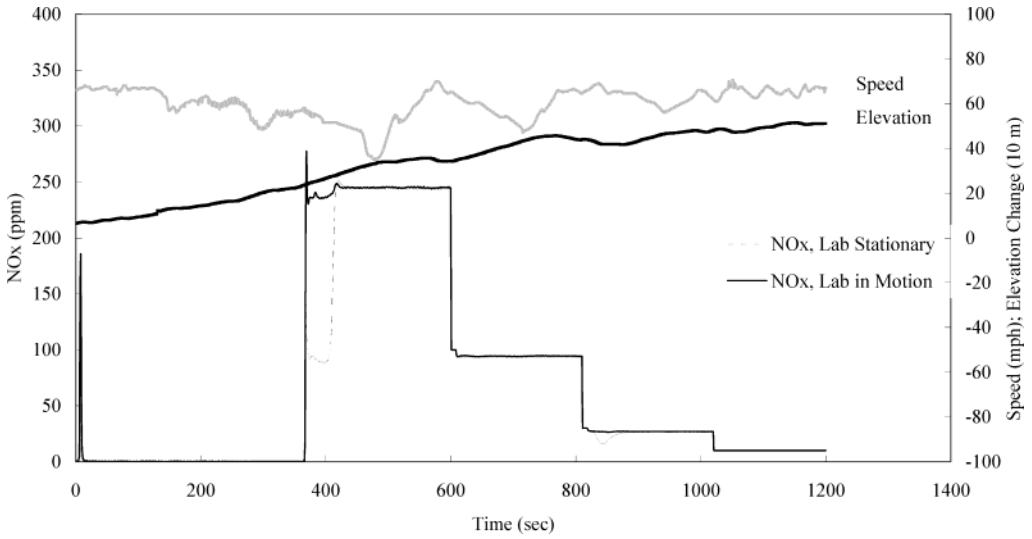


FIGURE 3. Comparison of NO_x measurements during on-road and stationary calibration.

System Calibration/Verification

Internal Checks. Internal calibration and verification procedures are performed regularly in accordance with the CFR (*17*). A partial summary of routine calibrations performed by the MEL as part of the data quality assurance/quality control program is provided in Supporting Information Table S1. The MEL uses precision gas blending to obtain the required calibration gas concentrations. The 1% certified calibration gas cylinders are obtained from Scott-Marrin Inc. (Riverside, CA). The gas blender contains a series of MFCs that are calibrated regularly with a Bios Flow Calibrator (Butler, NJ). The precision gas blending system was initially verified against standard CFR methods (*17*). Additionally, it has been found that analyzer calibrations can be performed on-road while the laboratory is in motion. Figure 3 shows the calibration for the NO_x analyzer at three different concentrations when the vehicle is on-road and when it is stationary. The CO, CO_2, and THC analyzers showed similar on-road stability during calibration.

In addition to weekly propane recovery checks, which yield 98−100% recovery, CO_2 recovery checks are also performed. A calibrated mass of CO_2 is injected into the primary dilution tunnel and is measured downstream by the CO_2 analyzer. These tests also yield 98−100% recovery. The results of each recovery check are all stored in an internal QA/QC graph that allows for the immediate identification of problems and/or sampling biases.

The CVS dilute exhaust temperatures reach up to 270 °C while sampling a 550-kW generator at full load. An experiment was conducted to determine the accuracy of the SAO measurements and flow control capabilities over a wide temperature range. Exhaust temperature was varied from 23 to 270 °C by sampling a diesel generator at various loads and dilution ratios. A MFC was used to inject propane into the exhaust after the muffler. Propane injections were cycled on and off every 2 min to allow for measurements of THC attributable to the engine and those attributable to the injections. The procedure was repeated four times at seven different CVS temperatures. Results of these tests are summarized in Supporting Information Table S2. The overall THC recovery was 99−100.1% for all temperatures.

The CVS should be capable of maintaining a constant total volume flow during hard accelerations and steady-state operation. The CVS is equipped with a computer-controlled valve that responds to changes in exhaust flow within a fraction of a second. Typical CVS flow deviations during hard accelerations are less than 10 and 20 scfm for steady-state and dynamic operation, respectively. Figure 4 illustrates the CVS control during steady-state and dynamic operation.

During the developmental stages of the laboratory, comparative tests of the measured/reported fuel consumption were performed on a chassis dynamometer and subsequently on the road. On the chassis dynamometer, fuel consumption was determined gravimetrically and electronically by the engine broadcast. These values showed an excellent correlation ($R^2 \sim 0.99$). Following this, the electronically broadcast fuel consumption was compared to that determined by the measured CO_2 concentration. Figure S2 in the Supporting Information shows the results of this test.

Cross-Lab Verification. A cross-lab correlation check was performed with a Freightliner tractor equipped with a 475 hp, model year 2000 Caterpillar C-15 diesel engine at the California ARB heavy-duty chassis dynamometer facility located at the Metropolitan Transit Authority (MTA) facilities in Los Angeles, CA. The vehicle was tested on the chassis dynamometer while emissions measurements were made using either the ARB laboratory or the MEL. The truck was tested on the hot UDDS and two steady-speed tests. Following the tests, the MEL emissions data were submitted blind to ARB, who provided the percent differences between the labs as shown in Table 2. These differences are the percent variation of the average integrated emissions for triplicate tests. A cross-laboratory check performed by other HDD laboratories reported similar deviations as those found in Table 2 (*22*).

Initial On-Road Testing

The selection of a road for on-road testing was based on several criteria: ability to safely perform multiple driving cycles without interfering with existing traffic; minimum road-grade or undulations; and proximity to UC Riverside. No test track with zero grade was available for testing such large vehicles. Therefore, the initial testing for the MEL was conducted in the Cabazon area of Riverside County on a lightly traveled 8-mi frontage road with a ~1.6% grade. The elevation at the Cabazon test site ranges from 442 to 558 m above sea level. The aim of the initial testing was to establish that driving cycles developed for chassis dynamometers could be performed on the road and to establish the repeatability (test-to-test and day-to-day) of on-road emission measurements.

The initial trials used an abridged version of the 5-mode driving cycle (*23*) since the test road was not long enough to complete the entire cycle. The nonaggressive, 5-mode

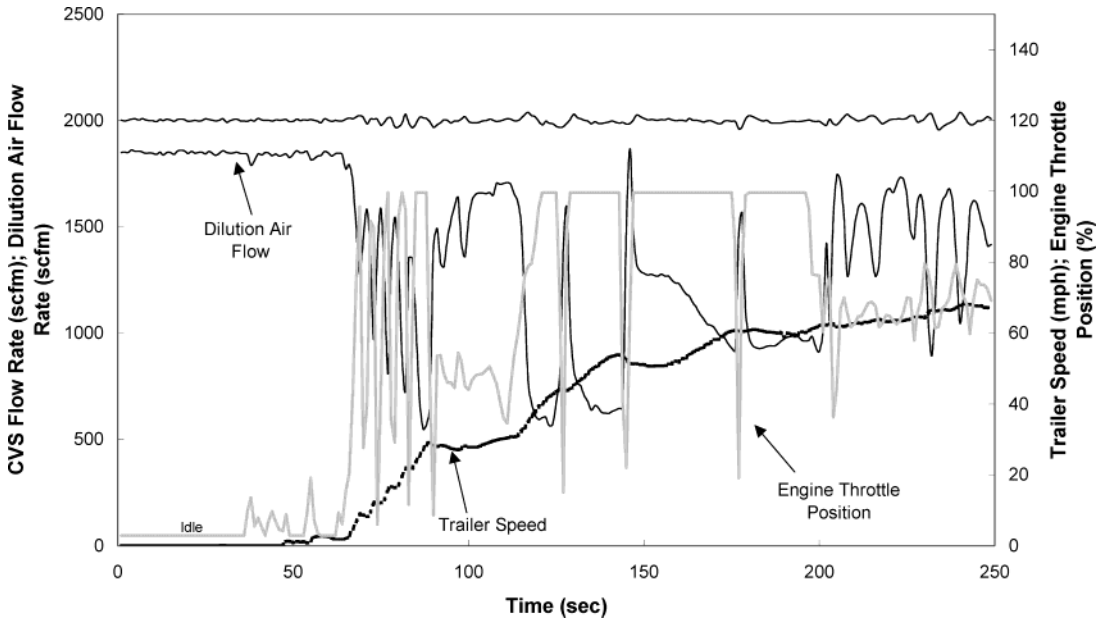


FIGURE 4. Typical CVS flow dynamics for hard acceleration onto the freeway.

TABLE 2. Percent Difference between ARB and MEL

test cycle	THC (%)	CO (%)	NO_x (%)	CO_2 (%)
hot UDDS	10.1	13.0%	8.9	5.2
SS[a] at 40 mph	7.4	12.3%	4.0	4.9
SS at 55 mph	16.4	3.7	4.0	5.5

[a] SS, steady state.

driving cycle was selected for initial proof-of-concept of on-road emission testing. The driving cycle involves acceleration to a fixed cruise speed, sustaining that speed for 100 s, and then deceleration to idle. The cycle is repeated at five different cruise speeds. Half of the 5-mode cycle is driven before the truck must be turned around to complete the second half of the cycle. Results showed that the driver could reproduce the cycle on-road with repeatability similar to a fixed laboratory. Table S3 in the Supporting Information is a summary of engine operating parameters and driver deviation for eight consecutive on-road tests. It should be noted that the MEL's inertial weight or the aerodynamic resistance during on-road operation cannot be adjusted. Chassis systems have this ability due to the load encountered at the wheels being controlled by the operators. The minimum weight of the MEL is 45 000 lbs, which puts a lower limit on the inertial weight of the vehicle. The addition of ballast material can increase the inertial weight of the lab. During testing, the MEL will follow a specified velocity profile as indicated by the selected cycle.

Emission Tests following Standard Cycles. A new test site was selected near Palm Springs, CA, that allows for lengthier driving cycles to be performed. The road chosen is at sea level, fairly flat, and has little traffic. On this road, we are able to replicate the velocity trace of most chassis dynamometer test cycles. One exception is the multi-mode Australian Combined Urban Engine Driving Cycle (CUEDC) (*24*) that has accelerations/decelerations too extreme to be driven on-road.

Figure 5 is a plot of measured NO_x, THC, and CO concentrations inside the dilution tunnel versus time for the ARB (*25*) 4-mode cycle for a vehicle equipped with a Caterpillar C-15 diesel engine operated on-road. This driving cycle was chosen to investigate the effect of different modes of driving on emission rates from HDD vehicles. The four modes of this cycle represent idle, congested traffic (creep), arterial flow (transient), and freeway driving (cruise). Table 3 summarizes emission factors for NO_x, CO, CO_2, and THC during each mode of this cycle for several repeat tests performed on several nonconsecutive days.

The NO_x emission factors were 47.7, 20.9, and 21.2 g mi^{-1} for the creep, transient, and cruise modes, respectively. The large difference seen in the creep mode NO_x emission rate compared with the transient and cruise mode is an indication of the significant impact congested conditions can have on inventory estimates of NO_x emissions. The lack of a significant drop in NO_x emission rates between the transient and the cruise mode results from the relatively high off-cycle engine operation encountered during portions of the ARB cruise mode. This will be discussed further in the On-Road versus EMFAC Emission Rates section.

Tests of Real-World Driving. In addition to measuring on-road emissions from standard driving cycles, the utility of the laboratory is evident when it is used to measure real-world emissions for trucks following a typical truck route. For example, the MEL measured emissions while traveling through a major transportation corridor between Riverside, CA, and Victorville, CA. This particular corridor also presented the opportunity to assess the impact of road grade on HDD vehicle emissions. The total distance of the route is 53.2 mi with an altitude change of over 3000 ft. Two round trips were made to gauge the repeatability of emission factors measured. A sample chart of gas-phase emissions, road elevation, trailer speed, and engine load for the trip is shown in Figure 6. Table 4 provides a summary of total mass emissions for NO_x, CO, CO_2, and THC following this route.

The total NO_x mass emissions, corrected for altitude, are extremely close for both trips leaving Riverside. The total NO_x mass emissions of the return trips are within 10% as measured but agree within 1% when referenced to CO_2 or fuel consumed. Note that the NO_x emission factors were approximately 24.4 and 18.4 g mi^{-1} for the uphill and downhill trips, respectively.

The demonstrated repeatability of integrated mass emissions for the truck route clearly demonstrates the ability of the MEL to monitor on-road, real-world emissions. Similar trips under different periods of congestion will allow for evaluation of the effect of operating mode on total emission rate.

On-Road versus EMFAC Emission Rates. The same test vehicle used for the ARB 4-mode tests (Emission Tests

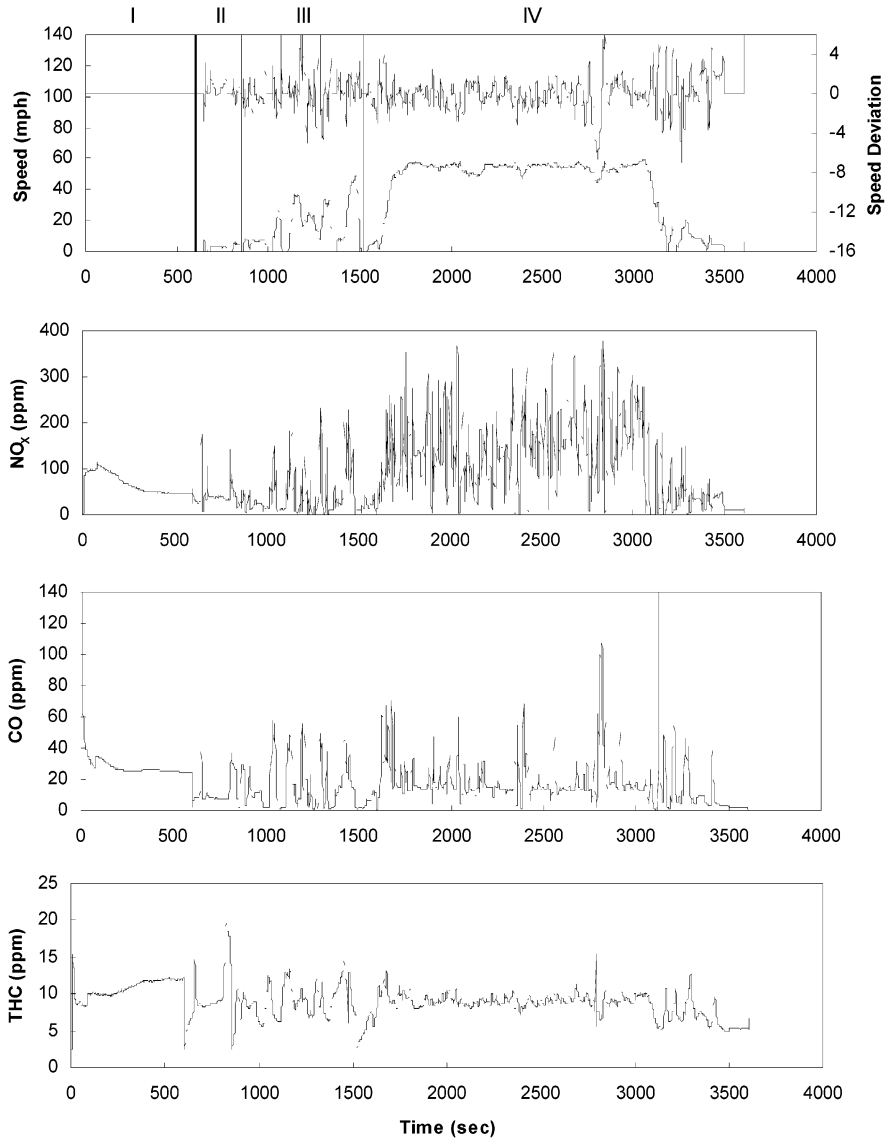


FIGURE 5. Gas-phase emissions measured on-road following the ARB 4-mode driving cycle. ARB diesel. CVS flow for idle (I), creep (II), transient (III), and cruise (IV).

TABLE 3. Emissions Measured during the 4-Mode ARB Cycle for a CAT-C15 Engine (60 000 lb GVW)

	n[a]	distance (mi)	time (s)	NO_x	CO_2	CO	THC
cold start/idle (g min^{-1})	5	na[b]	600	2.73 ± 0.25	172.8 ± 10.6	0.67 ± 0.10	0.089 ± 0.016
creep (g mi^{-1})	5	0.131 ± 0.0020	253	47.74 ± 2.47	5314 ± 207	14.6 ± 1.3	3.87 ± 0.33
transient (g mi^{-1})	8	2.82 ± 0.017	668	20.93 ± 0.98	3227 ± 173	5.40 ± 0.39	0.50 ± 0.27
cruise (g mi^{-1})	5	23.53 ± 0.125	2083	21.25 ± 0.53	1960 ± 105	1.95 ± 0.10	0.313 ± 0.042

[a] *n*, number of tests. [b] na, not applicable.

following Standard Cycles section) and the 53.2-mi on-road transit (Tests of Real-World Driving section) was tested on the ARB HDD chassis dynamometer following the hot UDDS. Emissions were again measured using the MEL. The average NO_x emission factor determined was 18.9 g mi^{-1}, similar to the transient and cruise modes of the ARB cycle. Therefore, the average NO_x emission rates measured for the ARB transient and cruise modes, hot UDDS, and uphill and downhill chase experiments were similar at 20.7, 21.4, 18.9, 24.4, and 18.4 g mi^{-1}, respectively. Regardless of driving cycle, these emission factors are well in excess of the 13.4 g mi^{-1} average NO_x emission factor found in EMFAC (*26*) for this particular vehicle class.

Simple comparisons of measured NO_x emission rates show good agreement between the different driving cycles. However, it is important to note that the values reported here represent the averages for each driving cycle. Figure 1 displays three trendlines for NO_x emission rate versus fuel consumption. The middle trendline represents a hypothetical mode of operation that yields the measured average NO_x emission rate during the downhill transit section. However, the middle trendline does not represent an actual operating mode of the engine but rather a weighted average of the two trendlines based on the relative time spent off-cycle. An accurate, weighted average emissions value is needed for emission inventories such as EMFAC. From this it is apparent that the

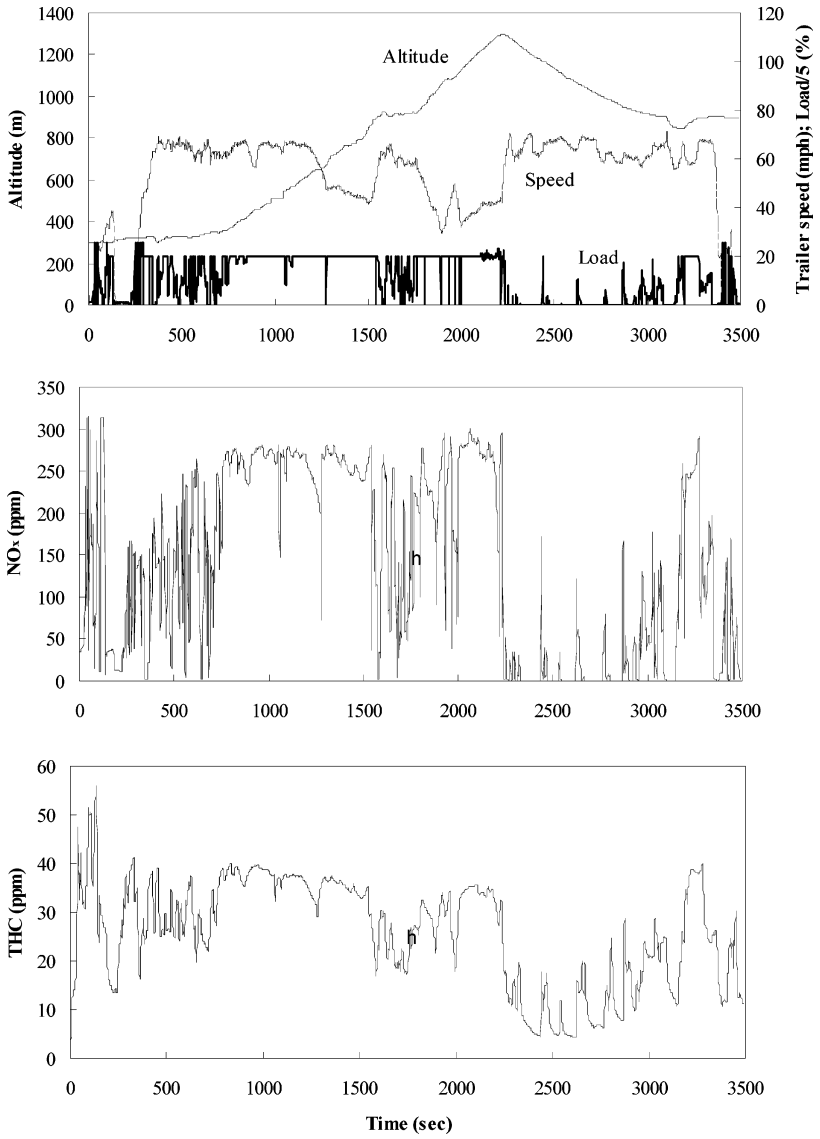


FIGURE 6. Gas-phase emissions measured on-road from Riverside to Victorville, CA. Charts from top to bottom show: altitude, speed, and load; NO_x (ppm) and THC (ppm) readings from primary dilution tunnel. ARB diesel, CVS total flow 2500 CFM.

TABLE 4. Total Mass Emissions for Travel between Riverside and Victorville with C15 Engine[a]

		NO_x (g)	CO_2 (kg)	CO (g)	THC (g)	fuel (mL/s)
Riverside to Victorville	trial 1	1223	119.3	111	17.6	12.3
	trial 2	1208	123.2	101	21.4	12.4
Victorville to Riverside	trial 1	865.8	81.9	96	12.9	8.4
	trial 2	969.7	95.2	93	14.6	9.4

[a] GVW = 60 000 lb. Trip distance = 53.2 mi.

most accurate average value is dependent on the relative time the engine spends in the off-cycle mode. The off-cycle mode is often triggered during steady-state cruise operation where the off-cycle emissions can be up to three times higher than on-cycle emissions.

We identified off-cycle operation based on plots similar to Figure 1. Using this information, we were able to estimate the time spent off-cycle. The hot UDDS time spent off-cycle was only 10.0%; the ARB creep, transient, and cruise phases were 0%, 32.7%, and 63.8%, respectively. Off-cycle time for on-road transit from Riverside to Victorville (uphill) was 85.5%, and for the return trip (downhill) was 53.3%. All of the testing performed with non-certification cycles showed significantly higher occurrences of off-cycle operation than the hot UDDS cycle. This further solidifies the importance of measuring emissions during real-world vehicle operation such as that seen through the transportation corridor.

On the basis of this information, the apparent similarities in the measured emission rates for different cycles must be reassessed. The occurrence of an increased amount of off-cycle operation would lead us to expect higher NO_x emission rates during transit through the transportation corridor and the cruise phase. This NO_x increase is offset by the relatively aggressive hot UDDS and transient cycles when compared with cruise operation or travel through the transportation corridor. Differences seen in the uphill versus downhill transit through the corridor are explained by the relative power requirement for each direction. The creep cycle (very low load) has elevated emissions relative to the other cycles as the engine is operating far from optimum conditions.

The results for off-cycle operations presented here apply only to the ECM for this test vehicle. Engines will have different off-cycle engine control strategies depending on manufacturer and model year. Finally, it should be noted that for all cases discussed, the on-road measurements of NO_x emission rate are significantly higher than predicted by EMFAC.

Comparison with Engine Certification Values. It is often of interest to measure the emission rates on a similar basis as engine certification data. Engine certification data are derived from the U.S. EPA's heavy-duty engine transient cycle and are reported in g bhp^{-1} h^{-1}. Data broadcast by the ECM can be used to calculate on-road derived emission rates on the same basis as engine certification data. By combining the data downloaded from the ECM and the engine map for the engine family used and adjusting for transmission and other losses, it is possible to estimate the power output of the engine. We estimate that the power during the ARB cruise cycle for our truck for the trip reported above was 175 hp. This translates to a cruise mode emission factor of ~7 g bhp^{-1} h^{-1}, exceeding the engine certification standard of 4 g bhp^{-1} h^{-1} set for engines manufactured post-1998 (*6*). Thus the emission factor for NO_x measured on the road is much higher than both the certification value and EMFAC estimates. A consequence of such underreporting is that inventory and air quality models will not adequately represent environmentally sensitive areas.

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Supporting Information Available

A laboratory flow diagram and a plot of measured fuel vs CO_2; additional tables for calibration routines, propane recovery at different tunnel temperatures, and repeatability of engine operating parameters during on-road testing. This material is available free of charge via the Internet at http://pubs.acs.org.

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