The In-Plume Emission Test Stand: An Instrument Platform for the Real-Time Characterization of Fuel-Based Combustion Emissions

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ABSTRACT
The In-Plume Emission Test Stand (IPETS) characterizes gaseous and particulate matter (PM) emissions from combustion sources in real time. Carbon dioxide (CO₂), carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO₂), and other gases are quantified with a closed-path Fourier transform infrared spectrometer (FTIR). Particle concentrations, chemical composition, and other particle properties are characterized with an electrical low-pressure impactor (ELPI), a light-scattering particle detector, an optical particle counter, and filter samples amenable to different laboratory analysis. IPETS measurements of fuel-based emission factors for a diesel generator are compared with those from a Mobile Emissions Laboratory (MEL). IPETS emission factors ranged from 0.3 to 11.8, 0.2 to 3.7, and 22.2 to 32.8 g/kg fuel for CO, NO₂, and NO, respectively. IPETS PM emission factors ranged from 0.4 to 1.4, 0.3 to 1.8, 0.3 to 2.2, and 1 to 3.4 g/kg fuel for filter, photoacoustic, nephelometer, and impactor measurements, respectively. Observed linear regression statistics for IPETS versus MEL concentrations were as follows: CO slope = 1.1, r² = 0.99; NO slope = 1.1, r² = 0.92; and NO₂ slope = 0.8, r² = 0.96. IPETS versus MEL PM regression statistics were: filter slope = 1.3, r² = 0.80; ELPI slope = 1.7, r² = 0.87; light-scattering slope = 2.7, r² = 0.92; and photoacoustic slope = 2.1, r² = 0.91. Lower temperatures in the dilution air (~25 °C for IPETS vs. ~50 °C for MEL) may result in greater condensation of semi-volatile compounds on existing particles, thereby explaining the 30% difference for filters. The other PM measurement devices are highly correlated with the filter, but their factory-default PM calibration factors do not represent the size and optical properties of diesel exhaust. They must be normalized to a simultaneous filter measurement.

INTRODUCTION
Gas and particle emissions from power generators, gasoline engines, and diesel engines affect attainment of air quality standards, human health, visibility, and climate. Real-world emission estimates from these sources are needed to improve air quality management strategies.

Engine certification emission factors (EFs) are determined from chassis or engine dynamometer tests following test protocols that vary vehicle operating conditions over time. Only a few vehicles or engines can be tested on dynamometers because of the time and effort required. Other methods can determine EFs for large vehicle fleets. Tunnel studies yield fleet EFs averaged over many vehicles, but these tests are unable to determine individual vehicle EFs and their distribution across vehicle type and age. Vehicle emission remote sensing systems (VERSS) and in-plume systems can measure fuel-based EFs for many individual vehicles over a wide range of real-world operating conditions. Fuel-based EFs are calculated as:

\[ EF_P = \frac{CMF_{\text{fuel}} \cdot \frac{C_P}{M_C} + C_{\text{CO}} \cdot \frac{M_C}{M_{\text{CO}}}}{C_{\text{CO}_2} \cdot \frac{M_C}{M_{\text{CO}_2}}} \] (1)

where \( EF_P \) is the EF of pollutant P in g pollutant/g fuel. \( CMF_{\text{fuel}} \) is the carbon mass fraction of the fuel, typically 85–88% for gasoline and diesel fuels, and 45–50% for wood fuels. \( C_P \) is the mass concentration of pollutant P in g/m³. \( C_{\text{CO}_2} \) and \( C_{\text{CO}} \) are the mass concentrations (g/m³) of species carbon dioxide (CO₂) and carbon monoxide (CO), and \( M_{\text{CO}_2} \) and \( M_{\text{CO}} \) are the molecular weights of CO₂ and CO in g/mol.

VERSS measure instantaneous fuel-based gas and particulate matter (PM) EFs by passing a light beam (ultraviolet [UV], visible, and/or infrared [IR]) through an exhaust plume and measuring its scattering and/or extinction.

In-plume techniques draw a diluted portion of exhaust through a broad array of instrumentation, including the carbon content as expressed in eq 1. In-plume systems have been mounted in aircraft to monitor emissions from power plants and industrial point sources.
biomass burning,\textsuperscript{13,14} and other aircraft.\textsuperscript{15,16} Measurements over the ocean have been used to distinguish emissions from ships from the ambient background.\textsuperscript{17} Each of these applications focused on identifying emissions of a large source above a well-dispersed and homogeneous background.

Several mobile emission laboratories (MELs) have been assembled and applied to in-plume measurements.\textsuperscript{18–21} The Aerodyne MEL combines a tunable IR laser differential absorption spectrometers (TILDAS), a proton transfer reaction mass spectrometer (PTR-MS), and an aerosol mass spectrometer (AMS) to sample gas and PM emissions from on-road vehicles.\textsuperscript{8,22,23} This unit was deployed in Mexico City and New York City in stationary and/or chasing modes.\textsuperscript{24–28} In a stationary mode, the MEL characterizes emissions from several vehicles driving by and calculates fuel-based EFs representative of the on-road fleet. It can also be applied in a chase mode, in which the plume from a single vehicle is followed through a typical roadway driving cycle that includes acceleration, cruising, and coasting. Pirjola et al.\textsuperscript{29} assembled a similar MEL with an electrical low-pressure impactor (ELPI); a scanning mobility particle sizer (SMPS), an ultrafine condensation particle counter (CPC); and CO, CO\textsubscript{2}, and NO\textsubscript{x} analyzers to obtain real-world in-plume EFs along Finland’s highways.

Hansen and Rosen\textsuperscript{30} used a simpler roadside in-plume approach for black carbon (BC) emissions, collocating IR absorption CO\textsubscript{2} aethalometer BC monitors downwind of a steeply graded road. The ratio of aerosol BC to CO\textsubscript{2} was calculated for the plume from each vehicle passing sampling inlets. Real-world BC EFs ranged over a factor of 100, from 0.004 to 1 g BC/kg carbon in the fuel. Such large variations in EFs, often accompanied by non-normal distributions, make it necessary to measure EFs of many units for each source type to accurately characterize fleet emission distributions.

The In-Plume Emissions Test Stand (IPETS) described here builds on the roadside approach of Hansen and Rosen by adding a larger array of observables, but at a fraction of the cost of assembling and supporting a full-fledged MEL. A comparison of measurements with one of the MELs is also reported.

**MEASUREMENTS METHODS AND CALIBRATION**

The IPETS configuration is illustrated in Figure 1 with instrument descriptions summarized in Table 1. The base components are an FTIR spectrometer (Illuminator series, Midac) and two LI-840 CO\textsubscript{2}/H\textsubscript{2}O gas analyzers (LI-COR Biosciences) for gas analysis. An ELPI (Dekati), two DustTraks (model 8520, TSI) and a photoacoustic spectrometer designed by Arnott et al.\textsuperscript{31} were used for the real-time measurement of PM size distribution and mass concentrations. Integrated filter samples are used for mass and source profile analysis and to determine sample-specific calibration factors for the continuous PM instruments.

Sample air is drawn into the IPETS manifold through 2-cm inner diameter, electrically conductive silicone tubing (TSI) at approximately 220 L/min. Mass flow is measured via factory-calibrated digital mass flowmeters (TSI 4000 series) with an accuracy of \(\pm 2\%\). The tubing length ranges from 2 to 4.7 m, depending on the source type and field access. Residence time in the tube is less than 2 sec. Although the large diameter conducting sample line and short residence times minimize PM loss due to electrostatic attraction and deposition, a portion of reactive species such as ammonia (NH\textsubscript{3}) might experience attenuation before reaching the measurement instruments. The inlet can be positioned to reach elevated plumes such as those from vertical exhaust pipes of heavy-duty diesel vehicles. The inlet can be placed on the road surface, protected by rubberized cable protectors, for sampling from low-level passenger vehicle exhausts.

Components are mounted on three handcarts and can be operated from within a cargo van or positioned near the exhaust duct. Measurements are made at near-ambient temperatures to represent real-world PM concentrations soon after ambient air dilution when nucleation
and condensation are expected. Temperatures are monitored by thermocouples exposed to ambient air and to the diluted plume at the FTIR inlet.

**FTIR Spectrometer**

FTIR spectroscopy has been used previously to characterize several gas concentrations in combustion emissions.\textsuperscript{32,33} The IPETS FTIR spectrometer draws 60 L/min to detect CO\textsubscript{2}, CO, NH\textsubscript{3}, nitric oxide (NO), water vapor (H\textsubscript{2}O), butane (C\textsubscript{4}H\textsubscript{10}), hexane (C\textsubscript{6}H\textsubscript{14}), ethylene (C\textsubscript{2}H\textsubscript{4}), nitrogen dioxide (NO\textsubscript{2}), and sulfur dioxide (SO\textsubscript{2}) concentrations. It scans through wave numbers of 1100–6500 cm\textsuperscript{-1} every 1.5 sec with a spectral resolution of 0.5 cm\textsuperscript{-1} over a 10-m optical path folded within a 2-L analytical chamber to limit the size of measured aerosol emissions.\textsuperscript{1} Spectral regions used for the measurement of individual gas concentrations, detection limits, and calibration concentration ranges are reported in Table \ref{tab:1}. Internally mounted pressure and temperature sensors account for changes in air density. Calibration spectra were prepared using U.S. Environmental Protection Agency (EPA)-certified gases diluted with ultrapure nitrogen by an Environics 2020 computerized gas dilution system. Species concentrations are determined using a classical least-squares (CLS) fitting technique as implemented in Autoquant Pro software (MidAC Corporation). Before measurements, the cell is purged with ultrapure nitrogen to reduce measurement interference from background air. A Teflon filter is inserted in-line to prevent contamination of the sampling cell by particles.

NO and NO\textsubscript{2} have many IR absorption regions coincident with those of H\textsubscript{2}O, but de Castro et al.\textsuperscript{34} have developed methods that minimize this interference by limiting spectral regions to those with minimal overlap.

![FTIR Spectrometer](image)

**Nondispersive IR (NDIR) CO\textsubscript{2}/H\textsubscript{2}O Analyzer**

The CO\textsubscript{2} concentration is crucial for fuel-based EFs, so a redundant Licor LI-840 CO\textsubscript{2}/H\textsubscript{2}O NDIR gas analyzer\textsuperscript{34} complements the FTIR CO\textsubscript{2} measurement, drawing a parallel airstream at 1 L/min with 1-sec sample durations. CO\textsubscript{2} is quantified by the 2347-cm\textsuperscript{-1} absorption line and H\textsubscript{2}O is quantified by the 3853-cm\textsuperscript{-1} absorption line. An in-line Teflon filter in the sample line reduces contamination of the cell by particles.

**ELPI**

The ELPI draws 10 L/min through a unipolar corona charger, which imparts a positive charge to the incoming aerosol. The charged particles are separated by impaction into 12 size fractions. Impaction surfaces are isolated with Teflon supports and the accumulating charge on each of the substrates is measured by an array of electrometers. The measured current on each of the stages is proportional to the number of particles deposited on the stage.\textsuperscript{35,36} The sintered impaction plates are oiled\textsuperscript{37} to minimize particle re-entrainment and have 50% cut points at 0.024, 0.03, 0.056, 0.10, 0.22, 0.32, 0.59, 0.91, 1.5, 2.5, 3.8, and 6.4 μm. The final stage does not efficiently capture particles less than 7 nm in diameter. The final six stages are used for analysis, corresponding to particles below 0.32 μm, because most engine exhaust PM emissions are in this size range.

**DustTrak Aerosol Monitor**

The Model 8520 DustTrak\textsuperscript{38} measures near-perpendicular particle scattering of a 780-nm laser diode beam. A coarse (PM\textsubscript{10}) or fine (PM\textsubscript{2.5}) PM inlet is installed upstream of its analytical chamber to limit the size of measured aerosol particles. There is little difference between the PM\textsubscript{10} and PM\textsubscript{2.5} DustTrak readings for engine exhaust PM, consistent with its small particle sizes. The DustTrak has a flow rate of 1.7 L/min and is factory-calibrated to the respirable fraction of standard ISO 12103-1 A1 test dust (previously

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Manufacturer</th>
<th>Measurement</th>
<th>Method</th>
<th>Response Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIDAC I-Series FTIR</td>
<td>MIDAC, Costa Mesa, CA</td>
<td>Molecular gas species concentration</td>
<td>Dispersive IR with a mercury-cadmium-tellurium (MCT) liquid nitrogen-cooled detector.</td>
<td>1.5</td>
</tr>
<tr>
<td>Dekati ELPI (10 L/min)</td>
<td>Dekati, Finland</td>
<td>Aerodynamic number size distribution of particles</td>
<td>Current dissipation arising from deposition of charged particles to impactor substrates</td>
<td>5</td>
</tr>
<tr>
<td>Model 8520 DustTrak</td>
<td>TSI, Shoreline, MN</td>
<td>Particle mass</td>
<td>780-nm laser light scattering of particle stream at 90°</td>
<td>1</td>
</tr>
<tr>
<td>Nucleopore filter sampler</td>
<td>TSI, Shoreline, MN</td>
<td>Mass and chemical composition of particles and gases</td>
<td>Collection and analysis of exposed filters</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Model 4043 mass flow meters</td>
<td>Desert Research Institute, Reno, NV</td>
<td>Mass flow through filter</td>
<td>Hot wire anemometer</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Photoacoustic spectrometer</td>
<td></td>
<td>EC concentration</td>
<td>Acoustic pressure wave generated through absorption induced gas expansion</td>
<td>1</td>
</tr>
<tr>
<td>Li-Cor 840 CO\textsubscript{2}/H\textsubscript{2}O gas spectrometer</td>
<td>Li-COR Biosciences, Lincoln, NE</td>
<td>CO\textsubscript{2} (ppm) and H\textsubscript{2}O (parts per thousand)</td>
<td>NDIR</td>
<td>1</td>
</tr>
</tbody>
</table>
called “Arizona road dust”). The DustTrak reading is usually calibrated for a specific application through linear regression with collocated filter measurements.\textsuperscript{39}

**Photoacoustic Spectrometer**

The photoacoustic spectrometer\textsuperscript{40} measures aerosol light absorption at 532 nm by illuminating particles with a modulated laser beam. This heats the particles and creates an acoustic pressure wave at the modulation frequency. A sensitive microphone monitors the acoustic signal and its energy is proportional to the absorbed light. Light absorption is related to elemental carbon (EC) by mass extinction coefficients derived from collocated EC measurements.\textsuperscript{31}

### Table 2. FTIR spectrometer spectral analysis regions, calibration ranges, and detection limits.

<table>
<thead>
<tr>
<th>Species</th>
<th>Reference Region $\nu_1$ (cm$^{-1}$)</th>
<th>Reference Region $\nu_2$ (cm$^{-1}$)</th>
<th>Detection Limit$^a$ (ppm)</th>
<th>Calibration Range (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>723.0</td>
<td>750.0</td>
<td>12</td>
<td>100 - 4730</td>
</tr>
<tr>
<td>CO</td>
<td>2133.5</td>
<td>2142.0</td>
<td>0.2</td>
<td>1.0 - 1005</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>955.5</td>
<td>976.0</td>
<td>0.06</td>
<td>1.0 - 110</td>
</tr>
<tr>
<td>NO</td>
<td>1873.0</td>
<td>1878.5</td>
<td>1</td>
<td>0.2 - 200</td>
</tr>
<tr>
<td></td>
<td>1880.5</td>
<td>1884.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1898.5</td>
<td>1901.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1926.0</td>
<td>1932.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1934.5</td>
<td>1940.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$O</td>
<td>1200.0</td>
<td>1300.0</td>
<td>60</td>
<td>5.0 - 5294</td>
</tr>
<tr>
<td>C$<em>8$H$</em>{16}$</td>
<td>3041.5</td>
<td>2825.5</td>
<td>0.05</td>
<td>1.0 - 100</td>
</tr>
<tr>
<td>C$<em>4$H$</em>{10}$</td>
<td>3030.0</td>
<td>2818.0</td>
<td>0.2</td>
<td>0.2 - 200</td>
</tr>
<tr>
<td>C$_2$H$_4$</td>
<td>958.0</td>
<td>936.5</td>
<td>0.12</td>
<td>0.5 - 20</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>1584.0</td>
<td>1588.5</td>
<td>0.4</td>
<td>0.2 - 20</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>1112.5</td>
<td>1120.5</td>
<td>0.54</td>
<td>1.0 - 100</td>
</tr>
<tr>
<td></td>
<td>1123.5</td>
<td>1134.0</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>1138.5</td>
<td>1148.0</td>
<td></td>
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<tr>
<td></td>
<td>1153.5</td>
<td>1164.0</td>
<td></td>
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<tr>
<td></td>
<td>1166.5</td>
<td>1172.5</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>1176.5</td>
<td>1185.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1188.0</td>
<td>1197.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1200.0</td>
<td>1209.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1227.0</td>
<td>1236.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: $^a$Detection limits were calculated as twice the standard deviation of the instrument response during a zero measurement (i.e., nitrogen-purged cell) over a period of 30 min.

**Figure 2.** Region of IR absorbance spectra for NO analysis.

**Figure 3.** Region of IR absorbance spectra for NO$_2$ analysis.
PM Filter System

Particles are sampled through Bendix 240 cyclones operating at 113 L/min (PM_{2.5}) onto filters for laboratory chemical analysis, which produces source profiles for receptor modeling. A typical filter pack consists of (1) a Teflon filter for mass by gravimetry and elements by X-ray fluorescence, followed by a quartz fiber backup filter, which allows for the evaluation of potential organic carbon (OC) sampling artifacts. (2) a quartz fiber filter for water-soluble ions by ion chromatography and OC and EC by thermal/optical reflectance, followed by a citric-acid-impregnated cellulose fiber filter that captures gaseous NH_{3}, (3) a quartz fiber filter for organic source markers by thermal desorption gas chromatography (GC) mass spectroscopy (MS), followed by a potassium-carbonate-coated cellulose fiber filter that captures SO_{2}, and (4) a Nuclepore etched polycarbonate membrane filter for particle morphology by scanning electron microscopy. Filter pack configurations can be changed depending on the application, and the cyclone can also be operated at a lower flow rate to obtain a PM_{10} cut point. Flow through each filter is accurately monitored with a digital mass flow meter. When the filter sampler is not needed, a bypass flow with the same flow rate as the filter sampling system is used to maintain a constant total flow rate through the system.

Data Acquisition

Data are logged in real time through a serial port to a laptop Ethernet server mounted on one of the handcars. The FTIR spectrometer communicates with the laptop through its A/D PCMCIA card. The ELPI and CO\textsubscript{2}/H\textsubscript{2}O detectors use data acquisition software provided by the manufacturers. Flowmeters and the DustTrak use Labview software (National Instruments, Inc.). The FTIR spectrometer uses Autoquant Pro version 1.0.104 to log IR spectra and quantify gas concentrations. The data acquisition system assigns a common time stamp to all measurements to ensure that data are synchronized at a frequency of 1 Hz. The use of real-time displays increases data recovery in the field because the operator can monitor the status of each instrument from a single location.

Instrument Calibration

CO\textsubscript{2} gas calibration standards ranging from 100 to 3000 ppm in air are generated by an Environics 2020 gas mixer. Samples were taken approximately 1.5 m downwind of a passenger car exhaust pipe with a revved engine to provide transient verified response times less than 1.5 sec. CO\textsubscript{2} concentrations agreed for the simultaneous FTIR and NDIR measurements over a range of 350–4730 ppm for the FTIR and 350–3000 ppm for the NDIR (regression slope = 0.98).

The ELPI particle charging efficiency depends on particle mobility diameter \(d_m\), but the size classification is based on aerodynamic diameter \(d_a\). The effective particle density \(\rho_e\) establishes the relationship between \(d_m\) and \(d_a\):

\[
\rho_e C_c d_m^2 = \rho_0 C_c (d_a)^2
\]

where \(C_c\) is the Cunningham correction coefficient and \(\rho_0\) the primary particle density, 2 g/m\textsuperscript{3}. Approximately 80–90\% of diesel particulate matter (DPM) mass is found in the 30- to 500-nm range. ELPI software converts the current measured on each stage to PM mass assuming that particles are spherical with unit density and that \(d_m = d_a\). DPM particles are fractal-like agglomerates of approximately spherical 10- to 30-nm diameter primary particles with an effective mass density decreasing with decreasing particle size.

Pagels et al. demonstrated that charge-bearing nanoparticles deposit on the upper ELPI stages, thereby creating biases in these results. Zhu et al. implemented an ELPI fitting procedure that accounts for these artifacts by iteratively adjusting the particle size and number concentrations for a bimodal distribution to match the current deposited on each impactor stage. This fitting algorithm is also used for IPETS ELPI measurements. Maricq et al. and Zhu et al. found fitted ELPI PM mass concentrations within ±20% of corresponding filter measurements.

IPETS/MEL COMPARISON

The IPETS sampled emissions simultaneously with the University of California–Riverside (UCR) MEL from a stationary diesel engine in 2004 to evaluate instrument comparability. The UCR MEL measures regulated gaseous emissions following engine certification procedures. Its function differs from the IPETS, which is intended to quantify real-world emissions at ambient temperatures and dilution ratios. For the MEL, the entire diesel exhaust stream enters a primary constant volume sampling (CVS) dilution tunnel (Model ESU 7000, Horiba) at 142,000 L/min (4000 std ft\textsuperscript{3}/min). A small fraction of the diluted exhaust is extracted from the primary dilution tunnel for continuous CO, CO\textsubscript{2}, methane (CH\textsubscript{4}), NO\textsubscript{x}, and total hydrocarbon (THC) measurements. A secondary dilution tunnel further dilutes the exhaust stream on a Teflon membrane filter for PM collection for mass emissions. The remainder of the diluted exhaust in the primary tunnel is vented through a bypass fan and exhaust pipe into ambient air on the MEL roof; IPETS sampled from this exhaust plume. A year-2000 Kamatsu Sa6D125E-2 engine (Japan) with 316 service hours, power output rated at 303 kW, and 11-L displacement was operated in a 250-kW (actual electrical output) DEWYO model no. DF-3300K power generator. The test protocol followed the nonroad compression ignition (CI) engine certification protocol consisting of time-weighted sampling for 5 min each at 100, 75, 50, 25, and 10% of maximum power. Test fuels consisted of military JP-8 and ultralow sulfur diesel (ULSD) fuels with average sulfur concentration of 476 and 2 parts per million by weight (ppmw), respectively. Each test fuel was directly fed to the engine from the fuel drum. After fuel switches, the engine was operated with the new test fuel for 30–60 min at 100% load to ensure complete removal of the previous test fuel from the engine and fuel line.

Filter pack sample durations ranged from 5 to 15 min, depending on PM concentrations estimated from the real-time DustTrak readings. Filter field blanks were collected at the end of each test day and were analyzed to subtract...
blank concentrations. These were low for all except OC because of adsorption of some organic vapors by the quartz fiber.46

Parallel DustTrak with PM10 and PM2.5 inlets showed little difference (slope = 0.99, r² = 0.99) in these tests, consistent with other size-related diesel exhaust studies. With TSI's Arizona road dust calibrations, the DustTrak PM2.5 mass EFs exceeded photoacoustic spectrometer and ELPI PM2.5 mass EFs by 30 and 40%, respectively (slope = 1.3, r² = 0.98 and slope = 1.4, r² = 0.85) (Figure 4). Photoacoustic spectrometer PM exceeded ELPI PM2.5 EFs by 10% (slope = 1.1, r² = 0.89), indicating that the default conversion coefficient may not apply in this case. The simultaneous filter packs with their PM2.5 mass and EC measurements allow a relationship to be derived for each IPETS test PM2.5.59 Comparison of real-time instrumentation with IPETS filters resulted in 80% overestimation of filter mass EF by DustTrak (slope = 1.8, r² = 0.83) and 40% overestimation by the photoacoustic spectrometer (slope = 1.4, r² = 0.82).

**Figure 4.** IPETS PM instrument intercomparison for (a) DustTrak PM2.5 vs. photoacoustic, (b) photoacoustic spectrometer vs. ELPI, (c) DustTrak PM2.5 vs. DustTrak PM10, and (d) DustTrak PM2.5 vs. ELPI. All values are reported as g/kg fuel.

**Figure 5.** IPETS vs. MEL gas measurement comparison for (a) DustTrak PM2.5 vs. MEL, (b) photoacoustic vs. MEL, (c) ELPI vs. MEL, and (d) IPETS filters vs. MEL. All values are reported as g/kg fuel.

PM2.5 mass EFs exceeded photoacoustic spectrometer and ELPI PM2.5 mass EFs by 30 and 40%, respectively (slope = 1.3, r² = 0.98 and slope = 1.4, r² = 0.85) (Figure 4). Photoacoustic spectrometer PM exceeded ELPI PM2.5 EFs by 10% (slope = 1.1, r² = 0.89), indicating that the default conversion coefficient may not apply in this case. The simultaneous filter packs with their PM2.5 mass and EC measurements allow a relationship to be derived for each IPETS test PM2.5.59 Comparison of real-time instrumentation with IPETS filters resulted in 80% overestimation of filter mass EF by DustTrak (slope = 1.8, r² = 0.83) and 40% overestimation by the photoacoustic spectrometer (slope = 1.4, r² = 0.82).

**Figure 6.** IPETS vs. MEL PM measurement comparison for (a) CO, (b) NO, and (c) NO₂. All values are reported as g/kg fuel.

PM2.5 mass EFs exceeded photoacoustic spectrometer and ELPI PM2.5 mass EFs by 30 and 40%, respectively (slope = 1.3, r² = 0.98 and slope = 1.4, r² = 0.85) (Figure 4). Photoacoustic spectrometer PM exceeded ELPI PM2.5 EFs by 10% (slope = 1.1, r² = 0.89), indicating that the default conversion coefficient may not apply in this case. The simultaneous filter packs with their PM2.5 mass and EC measurements allow a relationship to be derived for each IPETS test PM2.5.59 Comparison of real-time instrumentation with IPETS filters resulted in 80% overestimation of filter mass EF by DustTrak (slope = 1.8, r² = 0.83) and 40% overestimation by the photoacoustic spectrometer (slope = 1.4, r² = 0.82).

**Figure 7.** OC/EC from IPETS filters. Carbon evolved is categorized as either OC1, in which the semi-volatile organic fraction is evolved as the filter is heated to 120 °C; or OC2, OC3, or OC4, in which the nonvolatile organic fraction is evolved as the filter is heated to 250, 450, or 550 °C, respectively. EC is categorized into EC1, EC2, or EC3, in which carbon is evolved as the filter is heated with oxygen to 550, 700, and 800 °C, respectively.
The IPETS and MEL EFs are similar for the gaseous pollutants. CO EFs were highly correlated with a near-unity regression slope (slope = 1.1, \(r^2 = 0.99\)) as were NO and \(NO_2\) EFs (slope = 1.1, \(r^2 = 0.92\) for NO; slope = 0.8, \(r^2 = 0.96\) for \(NO_2\)), as shown in Figure 5. The lower IPETS \(NO_2\) EFs might be caused by many \(NO_2\) concentrations in the diluted plume that were below the FTIR detection limit.

IPETS PM\(_{2.5}\) EFs derived from the Teflon filter mass are 1.3 times those of the MEL. DustTrak PM\(_{2.5}\) EFs are highly correlated with those of the MEL, but they are 2.7 times higher (slope = 2.7, \(r^2 = 0.92\)) (Figure 6). PM EFs from the photoacoustic spectrometer and PM\(_{2.5}\) EFs from the ELPI are also highly correlated with the MEL EFs, but they are 2.1 and 1.7 higher, respectively (slope = 2.1, \(r^2 = 0.91\) and slope = 1.7, \(r^2 = 0.87\), respectively). These differences indicate that the default calibration factors are not appropriate for diesel exhaust and that they should be normalized to the Teflon filter mass measurement. Intercepts for the regressions in Figure 6 are all within 3 standard errors of zero.

IPETS filters present the most direct comparison of PM EFs with MEL. The observed difference is reasonable, given that the MEL dilutes the exhaust to approximately 47 °C, whereas the IPETS samples at ambient temperatures that ranged from 22 to 27 °C. Lower ambient temperatures favor the formation of nucleation mode particles that ranged from 22 to 27 °C. Lower ambient temperatures favor the formation of nucleation mode particles, primarily composed of water/sulfuric acid with peroxynitrous acid.

Table 3. IPETS replicate measurements.

<table>
<thead>
<tr>
<th></th>
<th>CO EF (g/kg)</th>
<th>NO EF (g/kg)</th>
<th>(NO_2) EF (g/kg)</th>
<th>DustTrak EF (g/kg)</th>
<th>Photoacoustic EF (g/kg)</th>
<th>ELPI EF (g/kg)</th>
<th>Filter EF (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replicate 1</td>
<td>2.60</td>
<td>18.6</td>
<td>0.94</td>
<td>0.53</td>
<td>0.49</td>
<td>0.93</td>
<td>0.39</td>
</tr>
<tr>
<td>Replicate 2</td>
<td>2.62</td>
<td>18.2</td>
<td>0.71</td>
<td>0.55</td>
<td>0.50</td>
<td>0.82</td>
<td>0.40</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.02</td>
<td>0.3</td>
<td>0.17</td>
<td>0.01</td>
<td>0.01</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>Average</td>
<td>2.6</td>
<td>18.4</td>
<td>0.83</td>
<td>0.54</td>
<td>0.50</td>
<td>0.88</td>
<td>0.40</td>
</tr>
<tr>
<td>Coefficient of variance</td>
<td>0.60%</td>
<td>1.4%</td>
<td>20%</td>
<td>2.3%</td>
<td>1.7%</td>
<td>8.7%</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

**SUMMARY**

An IPETS was developed and calibrated to quantify combustion emissions under real-world operating conditions. Fuel-based EF rates for criteria pollutants and source profiles for receptor modeling can be obtained. IPETS is more portable than MELs, which are housed in large trucks or buses. IPETS tubing, pumps, and data collection systems are mounted on three hand carts and can be moved close to various combustion source exhaust ducts.

Comparisons with a MEL used for diesel engine certification tests demonstrated comparable measurements for CO, NO, and \(NO_2\). IPETS PM\(_{2.5}\) EFs were approximately 30% higher than those from the MEL using filter measurements, about one-third of which could be attributed to condensable OC at the lower IPETS plume temperatures. PM\(_{2.5}\) EFs derived from a DustTrak nephelometer and ELPI impactor measured 2.7 and 1.7 those of the MEL, respectively, indicating that factory calibrations for these instruments are not appropriate for diesel exhaust and that their signals should be normalized to the colloccated filter mass.

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**REFERENCES**


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