The University of Vermont TOTEMS Instrumentation Package for Real-World, On-Board Tailpipe Emissions Monitoring of Conventional and Hybrid Light-Duty Vehicles

Paper No. 10-3023

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November 15, 2009

Word Count: 5712
Number of Figures: 4
Number of Tables: 2
Total Word Count: 7212

Abstract

TOTEMS is a unique assembly of 20 instruments that have been chosen for their ability to quantify a suite of parameters associated with tailpipe emissions for improved real-world measurement and modal emissions modeling of light-duty vehicles. These parameters include tailpipe gas and particle concentrations, exhaust flow rates, exhaust temperatures, sampling temperatures, vehicle position, engine operating behavior, ambient conditions, and instrumentation condition. Descriptions of each of the instruments are the focus of this paper. Unlike previous studies, this *new instrumentation package* collects, while the vehicle is traveling on the real-world road network: (i) the full *number distributions* of particle emissions using a particle spectrometer instrument that was not available previously; and (ii) quantifies *mobile source air toxic* (MSAT) gaseous emissions in addition to criteria pollutant (CO, NOx, HC) and greenhouse gas (CO_2, N_2O) using a high-speed FTIR instrument specifically designed for on-board vehicle exhaust testing. Initial pilot study data sets have been collected for on-road driving in Chittenden County, Vermont, using a 1999 Toyota Sienna minivan. We will soon initiate year-long testing of two Toyota Camry study vehicles: one hybrid and one conventional. The sampling with these vehicles will include three-season, day-of-week, traffic peak and off-peak test periods. The Camry data will be used to build the first second-by-second, real-world gas and particle number emissions database for hybrid and conventional light-duty vehicles under cold climate and hilly terrain conditions experienced in Vermont. This data will be modeled and ultimately lead to improved estimates of mobile source emissions at multiple scales (from project level to regional emissions estimates). In this paper we also examine a new tri-axial accelerometer for synchronous measurement of road grade for possible future inclusion in TOTEMS.

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Introduction

The health hazards of transport-related air pollution have been clearly identified by the WHO as one of the principal risks to populations that rely on motorized transport [1]. Indeed, diseases related to air pollution affect at least tens of thousands of people each year, and may be responsible for a significant number of fatalities. Accumulated evidence indicates up to 100,000 deaths per year may be associated with ambient air pollution, and the life expectancy overall may be reduced by as much as one year for the average European population [2]. It is possible that the health impacts from air pollution are similar for inhabitants of North America. Thus it is important to gain a better understanding of the role of different pollutants on human health, as well as quantify the emissions of pollutants from vehicles. The concerns about pollution-induced health effects have motivated a number of studies in the United States to better quantify specific vehicle exhaust components that have been classified as pollutants ("regulated" emissions species). In addition, currently *unregulated* exhaust species exist in vehicle exhaust that may contribute to serious health risks. Developing robust emissions monitoring systems to quantify the concentrations of both currently regulated and unregulated exhaust species will provide the foundation to better protect both the public health and the environment. Of direct interest to the current study are unregulated greenhouse gases (GHGs), mobile source air toxics (MSATs) and ultrafine and nanoparticle emissions. Ultrafine (particle diameter, Dp<100nm) and nanoparticle (Dp< 50nm) emissions are quantified on the basis of particle *number* rather than the mass-based PM regulations due to the fact that these particles make insignificant contributions to total particle mass. Particle number and mass seem to have little correlation and adverse health effects have been more strongly tied to particle number than particle mass.

The University of Vermont Transportation Research Center is currently conducting a study on the tailpipe emissions of hybrid and conventional vehicles with a specific interest in the differences in the emissions due to the relatively cold climate and hilly terrain of Vermont. This research has three main objectives: (1) quantify second-by-second emissions of regulated and unregulated exhaust gases and particles; (2) understand the relationships between tailpipe emissions and major factors such as road grade, engine load, traffic/driving conditions and ambient environmental conditions (temperature and humidity); and (3) quantify the relationships between various exhaust emission species, especially between regulated and unregulated pollutants for mobile source emissions modeling purposes.

To achieve these objectives, a new instrumentation package was assembled and proof-of-concept runs were conducted using a conventional light-duty vehicle (a Toyota Sienna minivan). The instrument components of the UVM "Total On-Board Tailpipe Emissions Measurement System" (TOTEMS), operating protocols and preliminary emissions data for the Sienna vehicle are discussed in detail in this paper. A larger study that will quantify emissions and performance from two models of Toyota Camry-- hybrid and conventional – is also discussed. The testing will comprise both urban and rural driving routes during typical daytime driving hours throughout the year. The testing will account for season, day-of-week, and peak or off-peak traffic periods. The instrumentation is carried within the vehicle during all test runs, and the data that collected from each instrument is saved to an on-board computer in the vehicle. This data is processed after each test run to build a database containing all the information gathered from the experiment.

This paper first describes an overview of the instrumentation that is used for the on-board vehicle data collection. Second, a description of the importance of road grade is given with respect to the usefulness this information has in computing real-world Vehicle Specific Power (VSP). Third, the efficacy of a GP2x accelerometer is discussed for use as a tiltmeter to measure the instantaneous road grade of the testing routes. Last, a methodology is proposed for processing the accelerometer data to minimize the noise in the data due to driving conditions.

TOTEMS On-board Instrumentation

The Total On-Board Tailpipe Emissions Measurement System (TOTEMS)

Table 1 summarizes the TOTEMS sensors used to record vehicle, engine and emissions data during vehicle test runs and Figure 1 shows the setup for this study. “Total” refers to the complete suite of gas and particulate emissions species being quantified at 1 Hz resolution. Data from the accelerometer, differential and static pressure (via a pitot tube) sensors, thermocouples and MD19-2E monitoring pins are all obtained from Data Acquisition cards (DAQ) through a Labview interface. Data from all other instruments are collected through instrument-specific software via RS-232 serial cables. Two computers are run to collect all real-time data (1) the Dell OptiPlex GX620 desktop “Emissions PC” is outfitted with two data acquisition cards and 5 serial ports; and (2) for the high-speed FTIR instrument only, a special MKS Dell Latitude D630 laptop is equipped with direct Ethernet connection to the instrument.

Pitot Tube and Tailpipe Adapter

The tailpipe adapter (TPA, see Figure 1a) is a custom built fitting used to connect a collection of sampling and data lines to the vehicle’s exhaust pipe. Instruments that attach to the TPA include:

a. Pitot Tube and Differential Pressure Transducers, for exhaust flow rate
b. Thermocouple, for exhaust temperature
c. Heated Transfer Line, for gas and particle emissions

Because both the gas and particle instruments record their measurements as concentrations per unit volume, the exhaust flow rate (or volume/time) is needed to calculate second-by-second exhaust emission rates (mass or number/time). The pitot tube differential pressure reading is used to provide the needed measurements on the exhaust flow rate. LabView 7.0 captures the data from the Pitot tube’s four variable-range differential pressure transducers that are connected via manifold to the static and dynamic pressure ports of the pitot tube. Regular calibration of the pitot tube using a Sierra Instruments Model 620S Fast-Flo Insertion Mass Flow Meter determines the voltage-to-flow rate relationships and is an integrated part of the test procedures.

The TOTEMS emissions measurement setup pulls engine exhaust from the tailpipe adapter connected to the end of the vehicle’s exhaust pipe (Figure 1a,b) through the 191^{o}C heated line at an exhaust sample flowrate of 13 liters/min (Lpm). At the end of the heated line is a 4-way fitting that splits the flow of undiluted exhaust: 12 Lpm to the FTIR and 1.0 Lpm to the particle measurement dilution system followed by both the EEPS and CPC instruments (Figure 1b).

Instrument Power Supply

An on-board battery system powers all instruments without drawing electrical power from the test vehicle itself, which would add load to the engine and thereby affect exhaust emissions. Although the additional weight of the batteries also adds load to the vehicle's engine during acceleration and climbing, this added load is compensated for by expressing it as the difference in weight between a stock vehicle and our loaded test configuration.

A pair of AGM (Absorbent Glass Mat) sealed lead-acid batteries provides all instrument power. This variety of battery is more durable, has a longer life-span, and is safer than other heavy-duty rechargeable battery types. The batteries are charged from utility power inside the UVM Transportation Air Quality (TAQ) Lab. The automatic transfer switch allows the instruments to keep operating during grid-to-vehicle power crossover. Once the vehicle leaves the TAQ Lab, the batteries supply DC power to the inverter that provides power equivalent to the standard 120 Volt, 60 Hz utility power that the instruments are designed to use.

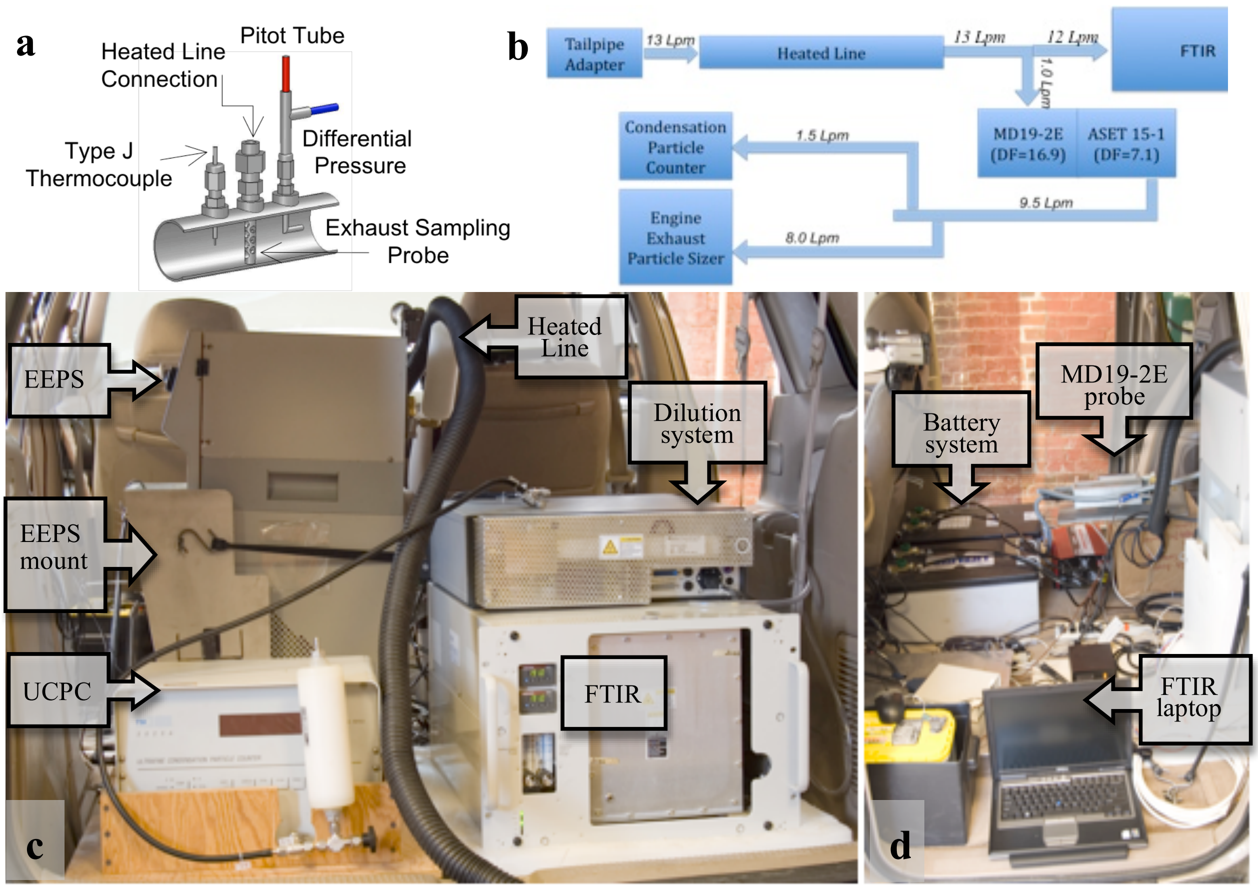

Figure 1. TOTEMS setup. (a) Schematic of the tailpipe adapter (TPA). (b) Flow schematic for raw and diluted exhaust showing dilution factors (DF). (c, d) photographs of TOTEMS instrument package inside the Sienna minivan as viewed from the rear hatch and side door. EEPS measures particle number distribution, UCPC counts total particle number and "FTIR" is the MKS MultiGas for gas-phase species.

Table 1. TOTEMS Instrument Descriptions

Instrument	Make/Model	Instrument Acronym	Measurement Rate	Purpose
Engine Exhaust Particle Sizer Spectrometer	TSI, Inc./3090	EEPS	10 Hz	Size (5.6 to 562.3 nm) and count the particles
Ultrafine Condensation Particle Counter	TSI, Inc./3025A	UCPC	1 Hz	Count particles from 3–3000 nm
MD19-2E Rotating Disk Diluter	Matter Engineering/379020	RDD	1 Hz	First stage of dilution (DF = 16.9)
Air Supply Evaporation Tube 15-1	TSI, Inc./379030	ASET	N/A	Second stage dilution (DF = 7.1)
Fourier Transform Infrared Spectrometer	MKS/MG2030HS	FTIR	1 Hz	Quantify gaseous species
Type T thermocouple	Omega/GTMQSS-125E-2	N/A	1 Hz	Monitor temperature of exhaust at end of heated line and FTIR inlet
Type J thermocouple	Omega/GJMQSS-125E-3	N/A	1 Hz	Monitor temperature of exhaust at end of tailpipe
Accelerometer	Crossbow/CXLO2LF3	N/A	10 Hz	Records acceleration in x, y, and z directions
Scan Tool	AutoEnginuity	SCN	1 Hz	Records engine operating parameters
Garmin GPS Reciever	Garmin/GPS16-HVS	GAR	1 Hz	Records vehicle location
Geologger	Geostats/DL-04, Ver. 2.4	GEO	1 Hz	Records vehicle location
Pressure Transducers 1 - 4	Omega/PX-277	N/A	10 Hz	Records exhaust flowrate
Tailpipe Adapter	Custom Built	N/A	N/A	Connects instruments to tailpipe for exhaust measurement
Video Camera	Canon/Optura 30	N/A	N/A	Record audio and video of run
Heated Line	Atmoseal/IGH-120-S-6/X-G13	N/A	N/A	Keep exhaust at temperature while transferring it from the tailpipe to the instruments
Automatic Transfer Switch	GoPower Electric/GP-ATS-30	ATS	N/A	Switch instruments from grid power to battery power without having to power down
Absorbent Glass Mat sealed lead-acid batteries	Lifeline 12 volt, 255 amp-hour	N/A	N/A	Supply power to instruments
DC to AC power inverter	Vector/VEC56D	N/A	N/A	Convert DC battery power to AC
Relative Humidity and Temperature Sensors	HOBOware/pro v2 U23-001	RHT	1 Hz	Collect in and out of vehicle relative humidity and temp
FTIR Laptop	Dell/Latitude D630	N/A	N/A	Records the data from the FTIR. Has an Intel Core 2 Duo CPU, T7700 at 2.40 GHz, 1.0 GB of RAM
On-Board Emissions PC	Dell/Optimplex GX620	N/A	N/A	Records all data except the FTIR output. Has an Intel Pentium D CPU, 3.60 GHz, 3.49 GB of RAM

Battery Life and Test Plan Constraints

Battery run time must be considered when determining both the run length and the number of runs that can be completed in one day. Through in-lab battery tests and from on-road data collection, the maximum time the complete TOTEMS system should be run before recharging the batteries is approximately 120 minutes, which corresponds to the batteries being drained to 60% of their maximum capacity. The AGM batteries should not drop below this threshold in order to maximize their useful lifespan. Because the test driving route – including warm-up – takes about 90 minutes to complete and recharging the batteries takes about 6 hours, to collect two runs in a day, including individual quality assurance/quality control (QA/QC) samples before and after each run, collecting the A.M. peak and P.M. off-peak in a single day is possible. This scheduling demands a considerable time investment on study team personnel for each run, but may be required to collect sufficient data at a given set of ambient environmental conditions for the conventional and hybrid vehicle comparison in future tests.

Accelerometer

The Crossbow 3-axis accelerometer unit measures real-time vehicle acceleration in the x, y, and z directions, where the x-axis is “forward” (in the vehicle’s body frame coordinate system), y is “lateral”, and z is “vertical”. This data is recorded by the LabView software that runs on the “Emissions PC”. The vehicle acceleration data provides a profile of the kinetic state of the vehicle over time with which to compare the data on tailpipe emissions.

Scan Tool

The AutoEnginuity ScanTool OBD-II connected to the On-Board Diagnostics (OBDII) communication system of the vehicle to record user-selected parameters directly to the on-board computer via AutoEnginuity ScanTool 4.1.0 software. Parameters recorded were: vehicle speed (miles/hr), engine RPM, throttle position (%), and Mass Air Flowrate (Lb/min) to the engine. Mass Air Flowrate (MAF) is used to compute air-to-fuel ratio for second-by-second fuel consumption rate.

Garmin GPS

The Garmin GPS16-HVS receiver provided real-time location information and was used to synchronize the two computer clocks. From the data available through this sensor, the vehicle velocity, direction, and acceleration could also potentially be determined, but with much less accuracy than is available from other instruments. Therefore, in this application the GPS sensor is only used for determining the vehicle's position (Latitude and Longitude). The position enables use of GIS data so that vehicle performance can be related to road characteristics.

The Garmin antenna is Wide Area Augmentation System (WAAS) enabled. WAAS is a type of GPS correction that uses precision base stations to measure GPS error and then broadcast corrections via satellite. According to the Vermont Center for Geographic Information (VCGI), WAAS has limited value in Vermont due to the large distance to the nearest base station. Therefore, post processing is used as the preferred method of correction. The software used to collect data from this sensor was Fugawi version 3.1.4.881.

Geostats Geologger

The Geologger is an automated GPS data-recording device. It is generally less precise in comparison to the Garmin GPS unit, but tends to have less missing data. It is therefore used as an ancillary (or backup) sensor to fill in gaps in the Garmin GPS data. The Geologger was a GeoStats GPS Data Logger, Model DL-04, Version 2.4, and the software used to acquire the data was Geologger Download Utility 4.0.9.

Thermocouples

Temperature sensors include both Type T and Type J exposed junction thermocouples (Omega Engineering) with a 2-inch long, 0.125 inch diameter probes. Type T thermocouples are used at (i) the 4-way fitting connected to the heated transfer line and (ii) at the inlet of the FTIR gas instrument. Type T thermocouples operate normally between -200 and 300°C with a 1°C limit of error. A Type J thermocouple is used on the tailpipe adapter because of its higher operating range (normally between 0 and 700˚C with a 2˚C limit of error). This variety of thermocouple is resistant to corrosion and electrical interference due to its non-magnetic Copper-Constantan alloy conductors and shielded thermocouple wiring. The sensitivity of this device's output is 43 microV/^{o}C. An exposed probe tip is used with the thermocouple to provide the fastest response, but this makes it somewhat more fragile in comparison to a sheathed-tip thermocouple.

Relative Humidity and Temperature Sensors

TOTEMS uses 2 identical Onset HOBO remote operation relative humidity and temperature sensors; one is located inside the vehicle and the other is attached outside the vehicle. The sensors monitor and record the air relative humidity and temperature at a time resolution of 1 second.

Traffic Conditions

Traffic conditions, driver behavior, and driving constraints were recorded with a video camera mounted to the passenger seat. The visual account of sampling verifies events noted by the passenger throughout the study. A wide-angle lens allows for the video to document road and traffic conditions.

Fourier Transform Infrared Spectrometer for Gas Emissions

An MKS, Inc. MultiGas 2030 High-Speed Analyzer model of Fourier Transform Infrared (FTIR) spectrometer quantified 27 gas-phase species (Table 2) based on the manufacturer's calibrations of a predetermined set of gasoline-exhaust compounds. The FTIR was set up to quantify these species (Table 2) at an operating temperature of 191°C. Therefore, prior to measurement, the exhaust sample passed through an Atmoseal Heated Line IGH-120-S6/X-G13 10-foot, 3/8 inch ID heated transfer line from the tailpipe adapter to the inlet of the FTIR instrument.

Table 2. Gas-phase species quantified by TOTEMS with corresponding lower and upper concentration limits and comparison to traditional 5-gas analyzer

	Compound	On-Board Detection Limit* (ppm or %)	Lowest Calibration Std (ppm or %)	Highest Calibration Std (ppm or %)	Range (ppm or %)	Autologic AutoGas Analyzer
"Criteria"	Carbon Monoxide	3.01	99.6	5000	4997	
	Carbon Monoxide (%)	0.02	3.19	7.99	8	0-15
	Nitric Oxide	1.47	279	2795	2794	0-5,000 (as NO_x)
	Nitrogen Dioxide	0.54	358	488	487	
	Ammonia	0.42	12.73	2995	2995	
	Sulfur Dioxide	1.00	19.6	964.5	963	
Hydrocarbons	Ethane	2.09	100.4	1004	1002	0-2,000 (as HC, propane surrogate)
	Octane	1.64	20	1000	998	
	IsoOctane	1.66	20	1000	998	
	1,2,4-Trimethylbenzene	3.49	20	1000	997	
	1,3,5-Trimethylbenzene	1.77	100	1000	998	
	Ethylene	1.51	9.74	3000	2998	
	Propylene	4.76	89.8	194	189	
	1,2-Propadiene	1.11	306	1020	1019	
	2-Methylpropene	1.82	150	500	498	
	2-Methyl-2-Butene	11.08	19.57	19.57	8	
	Ethanol	3.28	20	1000	997	
	Methanol	1.35	18.63	931.74	930	
	Acetylene	1.77	101.6	1016	1014	
	Propyne	4.43	50	500	496	
"MSAT"	Formaldehyde	1.16	4.2	69	68	
	1,3-Butadiene	3.18	8.3	83.4	80	
	Toluene	22.55	18.63	931.74	909	
	m-Xylene	5.56	93.17	931.74	926	
GHG	Carbon Dioxide (%)	0.15	4.6	23	23	0-20
	Methane	3.64	414	3143	3139	
	Nitrous Oxide	0.77	146.9	200.1	199	
	Water (%)	1.17	17.87	20.57	19	

* Detection Limit computed from on-board tunnel blank data as mean + 3(standard deviation)

Sample flow through the sample cell of the FTIR instrument at 12 LPM allows for one-second-sample turnover for second-by-second analysis. The 12 LPM flow is achieved by drawing exhaust through a series of filters and into the FTIR unit by a SKC Leland Legacy personal sampling pump. Filters are used at the inlet of the instrument to prevent particulate from entering the sample cell, which contains delicate gold-plated mirrors and potassium bromide windows. The filters include two inline filter housings containing diesel particulate filters rated at 2 micron and 0.01 micron.

The FTIR passes infrared light through the exhaust sample over a 5.11-meter path length. Each compound within the sample has a distinct light absorption fingerprint in the IR spectra and is quantified at a specified wavenumber by the MKS software. Detection limits vary between compounds, depending on the calibrations existing within the MG 2000 software package and the absorbance spectrum of each compound relative to other interfering species. The detection limits reported in Table 2 were calculated from pre-run tunnel blank data collected by drawing ambient air through the vehicle's exhaust system for 10 minutes. The detection limits are computed as the mean plus 3 times the standard deviation of the tunnel blank concentration and therefore represent the actual lower quantifiable concentrations that can be measured with the species list used in TOTEMS. The last column in Table 2 highlights the fact that a typical 5-gas analyzer used previously in our and other on-board studies does not have the ability to quantify individual gas species such as NO vs. NO_2 or MSAT gases and individual hydrocarbons. Thus, the TOTEMS gas-phase instrumentation provides more detailed speciation information and at higher temporal resolution than traditional gas analyzers. This level of detail can be used to better understand both regulated and unregulated emissions as a function of vehicle operation and performance.

Exhaust Dilution System: MD19-2E and ASET 15-1

The dilution system for particle measurement includes two separate components – the Matter Engineering, Inc. MD19-2E Rotating Disk Mini-diluter and the Air Supply Evaporation Tube (ASET 15-1) – designed to work together, to provide 2-stage dilution in one self-contained device. Where the MD19-2E's main purpose is to dilute the raw exhaust gas, the ASET 15-1 provides the flow rate required by the connected particle instruments. This second dilution stage is necessary due to the 5 Lpm flow rate limit of the MD19-2E.

The ASET 15-1 draws air from the MD19-2E at a constant flow of 1.5 Lpm (± 3%). This dilution stream is sent through a HEPA filter, ensuring no outside influence from ambient particulate matter. It is also heated to 120˚ Celsius to prevent water from condensing out of the gas when the dilution air mixes with the raw exhaust gas. Pockets of raw gas from the MD19-2E are mixed with the steady clean, ambient air dilution stream, creating the first stage of diluted gas with a dilution ratio of 1:17. The diluted gas then enters the evaporation tube (ET) which is also heated to 120˚ Celsius. At the outlet of the ET, the second stage of dilution takes place with a dilution ratio of 1:7.1, resulting in the total dilution ratio is 1:120 (one part raw exhaust to 120 parts particle-free ambient air). From the dilution system, particles are transported to the EEPS and UCPC particle instruments via 42 inches of 1/4 inch inner diameter conductive silicone tubing.

It should be noted that measurements of particle number are extremely sensitive to exhaust dilution conditions. The 120x dilution ratio employed in TOTEMS is set to optimize particle detection over the entire set of anticipated driving conditions and at the same time limit the creation of artifacts due to dilution. These artifacts have been examined in previous work [4].

Engine Exhaust Particle Sizer Spectrometer (EEPS)

The particles are counted (± 20% accuracy) and sized (± 10% accuracy) with the TSI, Inc. Engine Exhaust Particle Sizer Spectrometer (EEPS). The EEPS operates using the theory of electrical mobility.

As particles flow into the instrument, they pass through a positive charger which applies a positive charge to the particles, reducing the potential for overcharging by the negative charger. The particles then flow past the negative charger – which applies a predictable charge based on particle size – and then enter the electrometer column. In this column, there are 24 electrometer rings, 22 of which actively measure and the other two act as spacers at the top of the column. The 22 active rings record across 32 different particle diameter channels from 5.6 to 560 nanometers. The reported particle size (or aerodynamic diameter) is the midpoint of each channel. The EEPS can record particle number distribution data at a rate of 10 Hertz, but reported values for this project are at a 1 Hertz rate. The 1 Hertz measurements are discrete averages of all measurements within a given second and are recorded to the on-board emissions PC using TSI EEPS version 3.1.0 software.

Maximum total concentration (i. e., the sum over all particle channels) limits are not provided for the EEPS. This is because the maximum concentration for each individual channel is of greater importance, and the maximum is different for each channel. In general, the maximum concentration for channel 1 is 1 x 10^7 #/cm^3 and decreases linearly on a log -scale to 1 x 10^5 for channel 32. If the maximum concentration is exceeded during sampling, the concentration reported for that specific channel is clipped at the maximum value.

Ultrafine Condensation Particle Counter

A TSI Model 3025A Ultrafine Condensation Particle Counter (UCPC) was used in parallel with the EEPS to count the total particles in vehicle exhaust every second. This measurement was made partly due to accuracy limitations of the EEPS, but also to validate the EEPS concentration, to compare results to previous on-board studies and to validate EEPS response to sudden concentration changes. The UCPC counts the particles in the range of 3 to 3000 nanometers with a detection efficiency of 90% at and above 5 nanometers. The data is recorded to the computer at 1 Hertz using TSI AIM version 8.1.0 software.

The UCPC counts particles by first sending the aerosol through a saturator filled with butanol-laden air. The butanol subsequently condenses onto the particles, growing them to a light-scattering detectable size. After the aerosol passes through the condenser chamber, it passes through an laser optical detector that counts the particles. The total concentration limit on the UCPC is 9.99 x 10^4 #/cm^3.

Anti-vibration platforms were constructed for both the EEPS and UCPC to minimize inaccuracy and instrument error due to noise resulting from vibration while driving. The platform the instruments sit on are isolated from the floor of the vehicle using anti-vibration mounts. The UCPC is mounted upon 6 natural rubber mounts, and because the UCPC is influenced little by vibrations, these mounts serve to help minimize instrument malfunctions that could result from be jostled. The EEPS is mounted on 10 silicone gel type mounts, which reduced the noise caused by driving by 64%.

Methods: Data Collection

Individual emissions tests consist of a single driver operating the vehicle under real-world driving conditions over a specified driving route. Prior to beginning the route, a series of quality assurance/ quality control measurements and operations are performed in order to collect accurate instrument and vehicle baseline data for each run. This section briefly summarizes these data collection procedures.

Pre- and Post-Run Quality Assurance/ Quality Control Activities

A "full run" consists of 5 phases as follows.

Pre-run QA/QC: Instrument zeroing followed by collection of instrument blanks (10 min) and tunnel blanks (10 min). Vehicle engine is off.

Cold Start:	Instrumentation collects emissions during engine start. The duration of this phase depends on ambient temperature as discussed in two companion TRB papers [5,6].
Warm-Up Run:	A ~ 3 mile drive, including a steep upgrade is used to bring the vehicle's engine coolant to a specified temperature that indicates the engine is operating in hot-stabilized mode.
Run:	The real-world driving route is run, collecting data from all TOTEMS instruments. The route consists of three types of driving: urban stop-and-go, highway, and rural/suburban arterial.
Post-run QA/QC:	After vehicle engine is off, repeat collection of instrument and tunnel blanks.

Driving Route

A driving route incorporating a variety of road types and terrain was selected to incorporate different types of real-world driving conditions. The route, shown in Figure 2, consists of a 41-mile loop within Chittenden County, Vermont, is sectioned into different phases.

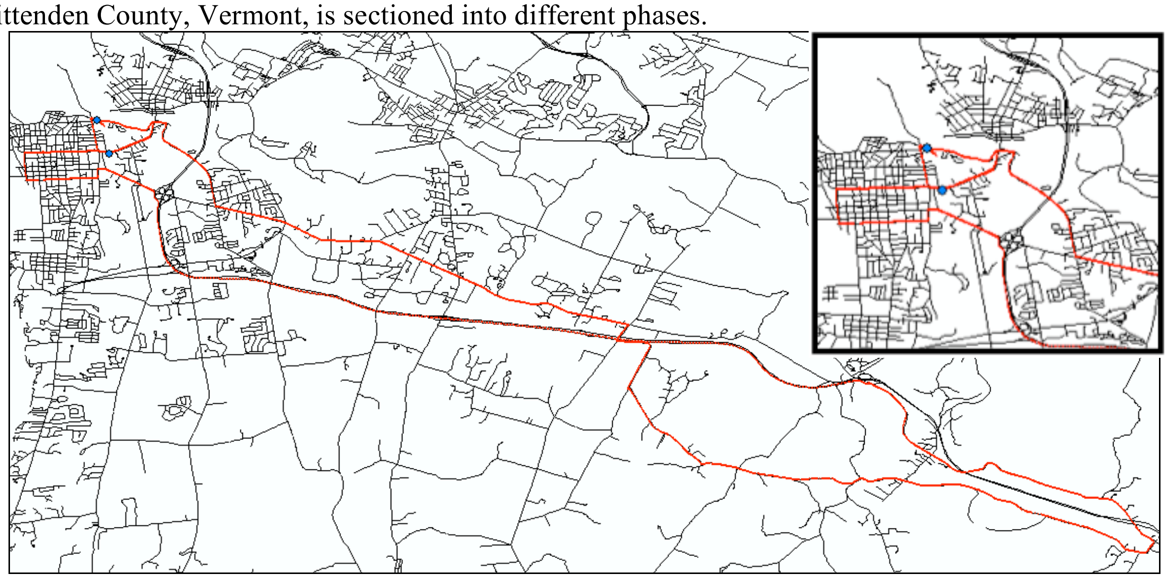

Figure 2. Real-world driving route beginning in Burlington, Vermont. Inset shows close-up of downtown Burlington section of route. Red lines indicate the full route and blue dots are the start point on Colchester Avenue and the gas station on Riverside Avenue.

The **Warm-Up** phase begins at the start of the engine after the Pre-Run QA/QC data collection is complete. The driver maneuvers the vehicle on urban streets from the TAQ Lab to a gas station located 0.8 miles from the starting point. The **Warm-Up** continues for a total of 2.5 miles after the vehicle is refueled.

The **Run** phase is divided into sections, including *urban*, *highway*, and *rural/surburban arterial* driving. The urban driving section in Burlington VT continues from 33 Colchester Avenue (sample run starting point), west down Pearl Street, south on Battery Street, and then heading east up Maple Street. Maple Street provides significant sections of elevation gain and provides stop-and-go driving with stop signs at each block. At the top of Maple Street, travel northbound on South Prospect Street to Main Street (westbound) until arrival at the Main Street/Route 2 junction with I-89 completes the *urban* driving phase.

The *highway* driving section begins with the Exit 14 on-ramp heading southbound on I-89. Driving continues on the highway for 10.4 miles to Exit 11 in Richmond. VT. A section of *rural arterial* roads takes the vehicle through Richmond and Jonesville on Route 2, crossing the Winooski River at Cochran Road. The route loops back towards Richmond on the southern side of the river and continues out on Huntington Road toward Hinesburg Road. Hinesburg Road to East Hill Road provides a section of steep, steady incline. The return trip to Burlington includes a short section of rural roads returning the vehicle to Route 2 in the town of Williston. From there, Route 2 brings the vehicle as far as South Burlington before turning westbound onto Patchen Road. The last significant feature of the route is the hill away from the Winooski River on Colchester Avenue. The **Run** phase ends at 33 Colchester Avenue, but the vehicle continues on past the 33 Colchester Avenue endpoint approximately 0.8 miles more to the gas station on Riverside Avenue. A fill-up at the gas station indicates the amount of fuel used during the run.

Data Management and Analysis

MATLAB Programming

MATLAB programs were developed to combine and process the data collected by the TOTEMS instruments. One program combines the data from TOTEMS instruments into a single output file with 1-second data synchronized according to time stamp. The sorting by time is accomplished by converting each of the original time stamps to integer values in units of *seconds of the year*. A second program uses the raw data to compute:

1. Exhaust Flow Rate based upon differential pressure sensor data
2. Temperature-compensated Exhaust Flow Rate
3. Fuel Efficiency, based on Carbon Mass Balance using the concentration of CO_2
4. Fuel Efficiency, based on two scantool parameters (MAF and vehicle speed)

The following sections summarize the calculations using general assumptions. For future work, specific instrument calibration parameters and detailed fuel composition will be used to tailor these calculations for the specific TOTEMS sampling conditions. It should be noted that one major objective of performing these calculations is to provide an automated methodology for checking the internal consistency of the TOTEMS database.

Raw Exhaust Flowrate

Exhaust flow rate at the tailpipe is calculated from the differential pressure transducer raw recorded voltages. Each of the four differential pressure transducers has a different sensing range. The program preferentially uses the data from the most sensitive pressure sensor (Sensor 4). If Sensor 4 is at its maximum voltage (10 V) value, then the program uses the data from Sensor 3. Similarly, if Sensor 3 is at its maximum, then Sensor 2 is used, and if Sensor 2 is at its maximum, then Sensor 1 is used to compute raw exhaust flow rate. In this way, the data used for flow rate calculations is always based upon the most accurate measurement that was available.

Calibration equations are derived in a laboratory test apparatus using a Sierra Instruments Series 620S Fast-Flo Insertion Mass Flow Meter to measure flow rate (Lpm) while recording voltage from the four pitot tube sensors. A variable high volume pump is used to set flow at a minimum of 5 settings during calibration. Assuming a linear relationship between the volumetric flowrate (LPM) and differential pressure sensor voltage, the calibration constants are determined for each sensor.

Temperature-compensated Exhaust Flowrate

The exhaust flowrate calculation is subject to differences in the assumed exhaust temperature and the actual temperature during calibration measurements. A simple calculation (derived from the ideal gas law) adjusts for the actual instantaneous temperature at the tailpipe during sampling:

$$TC\_flowrate = Calculated\_flowrate * (T_1 / 25)$$

The variable T_1 represents the instantaneous (1-sec resolution) measured temperature at the tailpipe in degrees Centigrade.

Real-Time Fuel Efficiency Estimates

Fuel Efficiency Derived From Carbon Mass Balance

The instantaneous fuel efficiency of the vehicle is computed from the stoichiometric relationship between carbon-bearing exhaust species (specifically CO_2, the carbon-bearing exhaust gas species of highest concentration) per unit quantity of fuel. The FTIR instrument provides accurate measurement of the concentration of CO_2 in the exhaust. By determining the proportional relationship between the CO_2 in the exhaust and the fuel consumed, the fuel efficiency is calculated on a second-by-second basis, using only the concentration of CO_2 and vehicle speed as the input parameters.

Several assumptions are applied for the derivation of the relationship between fuel consumption and CO_2 in the exhaust. For example, the fuel elemental composition and density must be known or measured. In the example calculation below, the fuel is assumed to be composed purely of C_8H_{18} (octane). Second, the density of gasoline is assumed to be 6.15 lb/gal. Third, CO_2 is considered to be the only product that contains carbon (in reality, there are small concentrations of CO and HC that are produced as well, but these are considered negligible for the purposes of this estimate). Fourth, it is assumed that there is neither a surplus nor deficit of oxygen available for the reaction. In other words, the combustion conditions are stoichiometric at all times (This of course can be adjusted if air-to-fuel ratio is measured second-by-second via scantool). A summary of the derivation follows below:

1 gallon of Octane = 6.15 [lb/gal] * 454 [g/lb] = 2792 [g/gal]
Molecular Weight of C_8H_{18} = 114 [g/mol]
2792 [g/gal] * (1 mol / 114 g) = 24.5 [mol/gal] of C_8H_{18}

Assuming that stoichiometric combustion of 1 molecule of C_8H_{18} yields 8 molecules CO_2 in the exhaust, then 24.5 mole of C_8H_{18} yields 196 mole of CO_2.

Molecular Weight of CO_2 = 44 [g/mol]
196 mol CO_2 * 44 [g/mol] = 8624 g CO_2

Therefore, stoichiometric combustion of 1 gallon of octane yields 8624 g CO_2. Therefore, the estimate of carbon-balance fuel efficiency is computed by the MATLAB program based on the measured CO_2 concentration, as follows:

$$\text{Fuel\_Consumption}|CO_2 \ \text{[gal/sec]} = \frac{[CO_2]_{meas}}{8624}\rho_{exh}Q_{exh}$$

Where $[CO_2]_{meas}$ is the percent mass CO_2 measured by the FTIR and the density of exhaust (ρ_{exh}, g/L) and temperature-compensated exhaust flowrate (Q_{exh}, L/sec) are determined based on exhaust temperature and pitot tube data.

As required by USEPA regulations, the fuel economy must be calculated to the nearest 0.1 mpg. As the data is accumulated during testing, the accuracy of the computations for fuel economy that were derived above will be verified against the procedures given in the national fuel economy determination regulations [7].

Fuel Efficiency Derived From Scantool Parameters

The Scantool provided information at approximately 1 Hz sample frequency on vehicle speed (in miles/hr) and mass air flowrate (MAF) to the engine. These two parameters give a second estimate of the vehicle's fuel efficiency (miles/gal):

$$\text{Fuel\_Efficiency [mi/gal]} = \frac{VehicleSpeed\left[mi/hr\right]*6.15\left[lb/gal\right]*14.7[lb_{air}/lb_{fuel}]}{MAF\left[lb_{air}/\min\right]*60\left[\min/hr\right]}$$

MAF represents the mass air flow rate. Because light-duty vehicle air-to-fuel (A/F) ratio is a major determinant of fuel consumption rate, this equation only approximates the fuel consumption unless A/F is measured simultaneously via scantool. For the Proof-of-Concept study, only 4 parameters could be logged at 1Hz from the 1999 Sienna vehicle, but this sampling frequency will be increased in future studies using newer vehicles (i.e., model year 2010 Camry) equipped with more advanced CAN data bus for on-board diagnostics.

Vehicle Specific Power

Vehicle Specific Power (VSP), a measure of engine power demand, is calculated from velocity, acceleration and road grade. The joining of second-by-second road grade to the dataset allows for a detailed calculation of VSP where previous efforts had to ignore or estimate grade for the calculation of VSP. Previous research on vehicle emissions suggests VSP is highly correlated to increased concentrations of gas-phase and particulate exhaust emissions [8-13]. VSP for each second of data was calculated (see Equation 1) using an expression derived from the United States Environmental Protection Agency's (EPA) Motor Vehicle Emission Simulator (MOVES) manual [12]. The general form of the equation for VSP (kW) shown below was taken from page 56 of [12].

$$\mathbf{VSP = (A/M)*v + (B/M)*v^2 + (C/M)*v^3 + (a + g*\sin\theta)*v}$$

a = vehicle acceleration (m/s^2)
θ = fractional road grade (as decimal fraction, *not* percent)
g = acceleration due to gravity, 9.81 m/s^2
v = vehicle velocity (m/s)
A, B, and C are the road load coefficients, which are defined on page 58 of [12] for a light-duty passenger car as having the following values:

A = 0.031292
B = 0.002002
C = 0.000483

RESULTS

Second-by-Second TOTEMS Data

Four proof-of-concept runs of the full driving route in Figure 2 were collected from the 1999 Sienna minivan. Figure 3 shows a temporal plot of data for gas and particle emissions as well as scantool and exhaust temperature for a stop-and-go driving on an uphill street portion of Run 4. This selection of data from TOTEMS instruments demonstrates the capability of obtaining high-resolution data for modal modeling purposes. The upper plot in Figure 3 shows engine speed (RPM, blue line), vehicle speed (mph, green line) and exhaust temperature (^{o}C/10, red line) and these data are aligned with the color 3-D color time-series plot of particle number distribution (color indicates particle number concentration, and y-axis is particle diameter, Dp [nm] from the EEPS instrument). These EEPS data show instances of high emissions (red/orange color) associated with vehicle acceleration events (jumps in vehicle speed, green line). Similarly, the bottom plot shows gas-phase concentrations of CO, CO2 and formaldehyde, an air toxic. The CO concentrations spike with the particle concentrations (see for example 40 sec, 60 sec), but formaldehyde tends to show a slightly different pattern that may be indicative of its formation as a secondary combustion product. More detailed analysis of the data will eludicate these relationships.

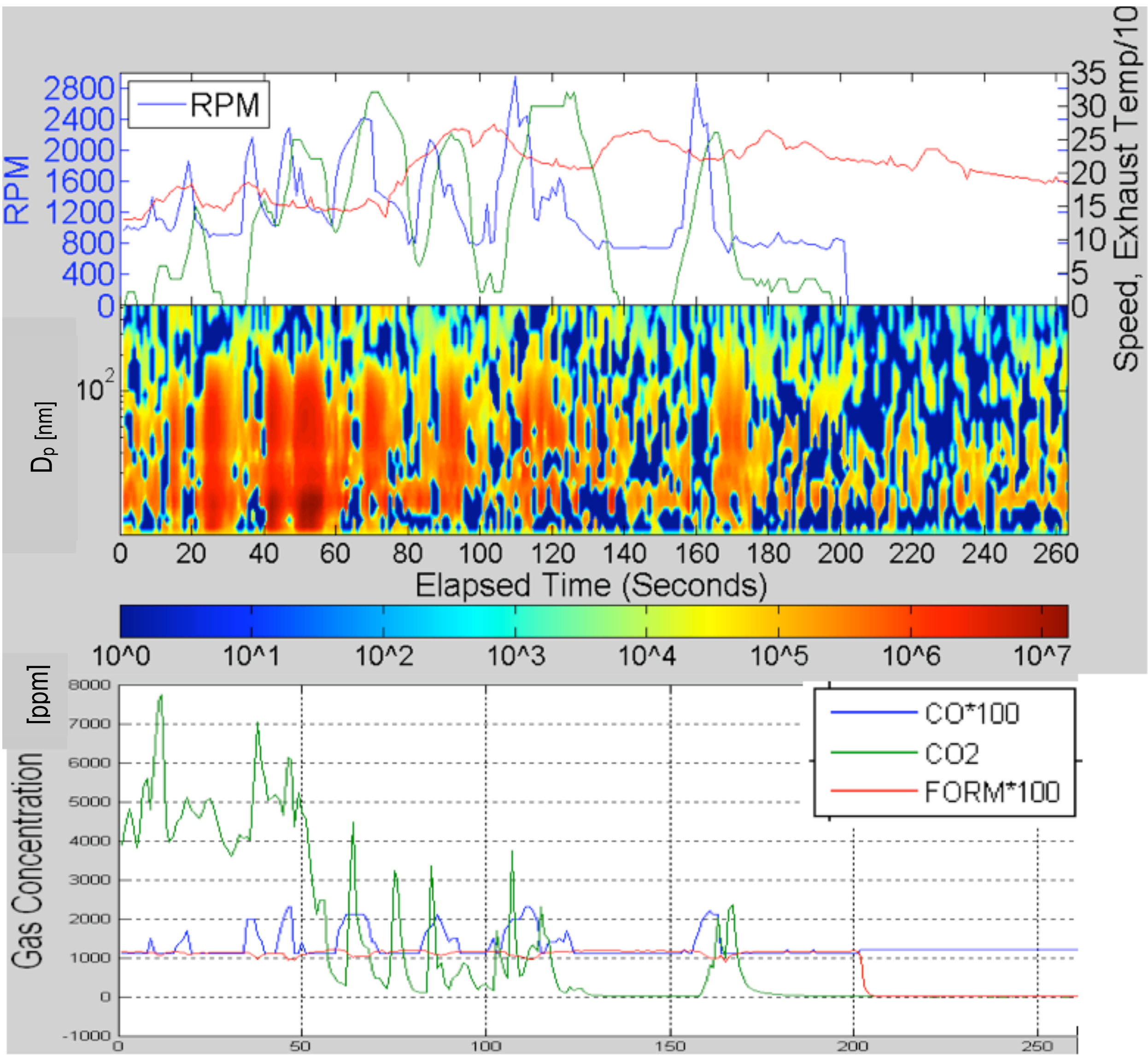

Figure 3. Example gas and particle number 1Hz data from TOTEMS. Bottom is FTIR gas emissions data for 3 of the 27 gases, color bar is particle number concentration (#/cc) for the EEPS color time-series plot shown in middle panel (Dp = particle diameter). Vehicle operating parameters (engine speed (RPM), vehicle speed (mph) and exhaust temperature (^{o}C/10)) are shown in top panel.

One of the unique aspects of TOTEMS is the ability to measure exhaust particle size distributions every second. It is anticipated that particle number distribution varies with vehicle operation due to the formation of nuclei-mode (Dp< 50 nm) particles during heavy load and enrichment operating events. The limit of detection of the EEPS particle distribution instrument was evaluated based on the instrument blanks collected pre- and post- Run 4. These data (not shown) indicate the inherent instrument bias in particle number due to the relative sensitivity of the EEPS electrometers in different particle size ranges. For the smallest particles, EEPS appears to be unable to accurately quantify concentrations less than ~ 100 #/cc and this minimum detectable concentration decreases with increasing particle size. It should be noted, however, that only during vehicle idle conditions are particle counts below the detection limit. For this reason, under low concentration conditions, the UCPC total particle number concentration is likely a more reliable indicator of particle number emissions. At the other extreme, the UCPC maximum concentration limit is 10^5 #/cc, making the EEPS instrument the more reliable measurement for emissions during cold start (see [5] for detailed analysis of cold start particle emissions).

Second-by-Second Road Grade Evaluation

In order to calculate "instantaneous" VSP, road grade measurements are needed for each second of the dataset. Grade data were collected along a preliminary test route by the Vermont Department of Transportation's Automatic Road Analyzer (ARAN) Photologging Van. The ARAN van provided road grade (in %, at survey level accuracy) every 10 meters along the route. Here, ARAN data is used to evaluate the ability of a SENSR GP2x tri-axial accelerometer to determine second-by-second road grade. The SENSR software package, Sensware version 2.2.06 reports tilt values (in degrees) based on the GP2x acceleration measurements. Sections of the original ARAN route were driven for data collection using the GP2x. The GP2x collects raw data at 400 Hz. A comparison of the smoothed (i.e. averaged over 400 data points per second) GP2x tilt data vs. ARAN grade data is shown in Figure 4.

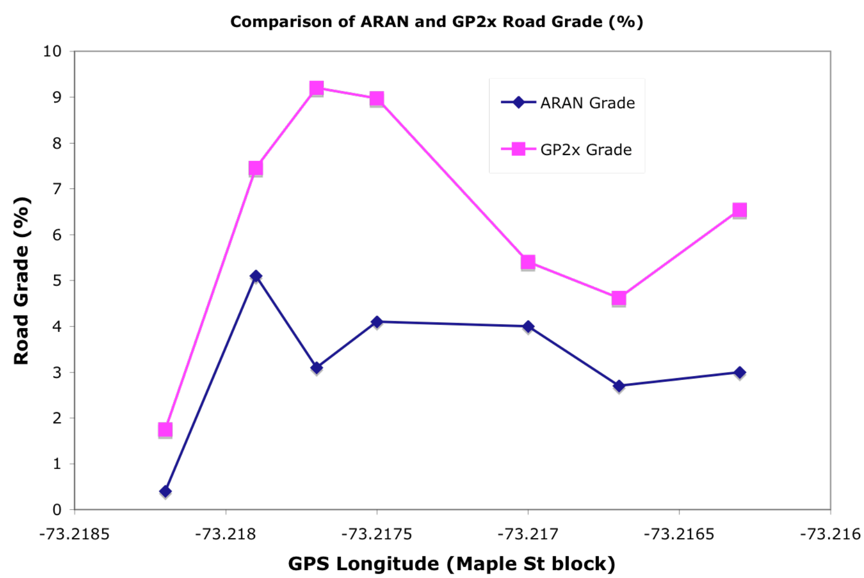

Figure 4. Comparison of ARAN and GP2x road grade (%) for a one block section of Maple Street in Burlington, VT.

Based on this initial comparison, the general trends in road grade over the very short section of data shown in Figure 4 are somewhat captured by the GP2x, however the magnitude was always greater than the ARAN grade, by 1.5 to 4.4 times. This is a significant discrepancy in road grade values! So, while the trend is encouraging, it is reasonable to conclude that significantly more work needs to be done in processing the GP2x sensor data to enable its use in place of the ARAN road grade data tables. This work will be extremely useful for tailpipe emissions testing, however, because road grade measurements would then be synchronized to the rest of the parameters collected by the TOTEMS instrument suite.

A number of issues that need to be considered before using the GP2x data as a reliable replacement for the ARAN road grade data. The major consideration is the level of vibrational noise that is present in the signal during driving due to fluctuations in acceleration caused by variables such as the roughness of the road, the speed of the vehicle, the rate of change of the overall grade of the road, acceleration spikes and dips from road anomalies like potholes and bumps, and changes in the acceleration readings due to weather-related road conditions or other sources. Any of this excess noise in the accelerometer's signal must be filtered and processed to provide accurate road grade results that can be used for computation of real-world VSP. This is achieved by converting the time-domain acceleration to Fourier Transformed waveform, and determine a suitable cutoff frequency for low-pass filtering of the data to truncate the high frequency noise. The high sampling rate (400 Hz) greatly reduces the error from noise, and allows for an accurate 1-second average to be derived, which is more reliable than a single 1-second value measured at 1 Hz. Once the data is collected and saved to a file, the corresponding FT waveform is computed. Most of the power in the signal occurs under 100 Hz (data not shown), so it is reasonable to assume that the frequencies above 100 Hz may be filtered out as noise. However, this cutoff frequency is an initial estimate and the ideal cutoff frequency for noise filtering will depend on further analysis. This analysis is anticipated to improve agreement in the two data sets in Figure 4.

Conclusions

The TOTEMS instrumentation for on-board collection of vehicle data is a uniquely comprehensive system which allows for the side-by-side comparison of many parameters pertaining to tailpipe emissions, environmental conditions, and the state of the vehicle itself. Novel features of the TOTEMS package are simultaneous collection of tailpipe emissions for greenhouse gases, particle number distributions and mobile source air toxics in addition to vehicle operating parameters and air temperature and humidity. Road grade has been identified as an important parameter that is not currently being measured by the TOTEMS system, but needs to be added so that real-world VSP may be calculated. To this end, preliminary tests of the tri-axial accelerometer and comparison to established ARAN road grade data suggest the possibility of developing a methodology to use a tri-axial accelerometer to obtain tilt data on a second-by-second basis. The methodology proposed here will involve oversampling (400Hz) of the vehicle x,y and z acceleration, signal filtering via Fourier Transform, and averaging to a 1-second smoothed signal that omits the erratic values that result from transient driving conditions. Future work in this area will enable better quantification of real-world road grade and second-by-second VSP for modal emissions modeling.

Acknowledgments

Funding for this research is from the United States Department of Transportation (USDOT) under Signature Project 2 at the University of Vermont Transportation Research Center. We also thank fellow researchers in the Holmén Group for their assistance with graphics preparation, especially Scott Quinn and Abby Franklin.

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