United States
Environmental Protection
Agency

Air and Radiation

EPA420-R-02-030
October 2002

On-Road Emissions Testing of 18 Tier 1 Passenger Cars and 17 Diesel-Powered Public Transport Busses

Printed on Recycled Paper

EPA420-R-02-030
October 2002

On-Road Emissions Testing of 18 Tier 1 Passenger Cars and 17 Diesel-Powered Public Transport Busses

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Prepared for EPA by
Carl Ensfield Sensors, Inc.
EPA Contract No. QT-MI-01-000659

NOTICE

This technical report does not necessarily represent final EPA decisions or positions.
It is intended to present technical analysis of issues using data that are currently available.
The purpose in the release of such reports is to facilitate the exchange of
technical information and to inform the public of technical developments which
may form the basis for a final EPA decision, position, or regulatory action.

USEPA STATEMENT OF WORK
Reference# QT-MI-01-000659

ON-ROAD EMISSIONS TESTING OF 18 TIER 1 PASSENGER CARS AND 17 DIESEL POWERED PUBLIC TRANSPORT BUSSES

Final Report
V 1.4

Carl Ensfield
Sensors, Inc.
October 22, 2002

1 Introduction

Sensors, Inc. has supplied gas analyzers and portable emissions testing systems worldwide for over three decades. They currently supply over 75% of the worldwide market for OEM gas analyzers for the Inspection & Maintenance (I/M) industry. In the past four years, Sensors, Inc. has devoted considerable effort in the development of gasoline and diesel emissions testing systems for in-use (on-road) applications. This new direction was greatly accelerated when Ford Motor Company selected Sensors, Inc. as their development partner for PREVIEW, an on-vehicle emissions tester for gasoline vehicles. This development spawned three generations of equipment for Ford alone. Subsequently, Sensors, Inc. built on this experience and its expertise to develop variants to the Ford gasoline system. Current products are named SEMTECH-G for gasoline powered vehicles, and SEMTECH-D for diesel powered vehicles, and are commercially available.

In XXX, 2001, Sensors, Inc. was awarded a contract by the USEPA to conduct real-world, on-road emissions measurements of 15 gasoline powered passenger cars and 15 heavy-duty diesel vehicles. The purpose of the contract was to generate on-road gaseous emissions data to facilitate the development and evaluation of EPA's mobile emissions models. The passenger cars used in the study were primarily recruited from EPA personnel, although some rentals were also used. The cars were subject to Tier 1 emissions standards. The Ann Arbor Transit Authority generously provided city transit busses for the heavy-duty diesel on-road data collection.

This report describes the test vehicles, test equipment, validation testing, on-road test procedures, and data reduction procedures. Analysis of the on-road data itself was not performed by Sensors, Inc., and is not covered in this document.

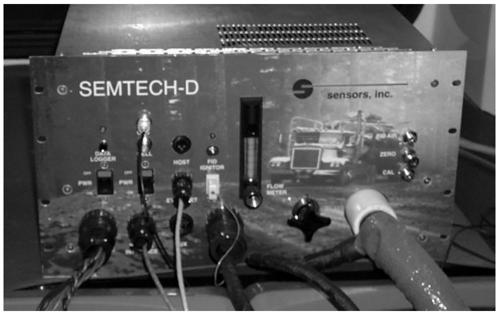
The SEMTECH systems used in this study rely on certain ECM data to compute mass emissions results. Some of the exact equations and methodologies used to compute mass emissions are considered proprietary to Sensors, Inc., and are not disclosed in this document. However, adequate data is provided to validate the calculated results. Future models of SEMTECH will include a direct exhaust measurement device as a redundant or primary method of mass emissions determination.

2 Test Equipment

To support this study, two SEMTECH-G systems and one SEMTECH-D system were produced. These were the first of the current generation of SEMTECH analyzers, which later served as prototypes for commercial production systems. These systems are described in detail below.

2.1 SEMTECH-D

The SEMTECH-D prototype analyzer used in the study measures raw vehicle exhaust, collects vehicle ECM data, and stores the data on an internal data logger. A post processing utility computes real-time fuel-specific, distance specific, and brake-specific mass emissions.



Dimensions:	10”H x 19”W x 18”D
Weight	80 lb
Power:	12 VDC
Power Consumption:	400W steady state

Figure 2.1 SEMTECH-D Analyzer used in Study

The SEMTECH-D prototype analyzer consists of the following components:

- Heated FID Total HC analyzer
- 195 C Heated Sample line, filter, and sample pump
- NDIR CO2 analyzer
- NDIR CO analyzer
- NDUV NO and NO2 analyzers
- Thermo-electric chiller and coalescing filters for sample conditioning
- Sample pressure control via proportional feedback control valve
- Vehicle Interface with J1587 (HD engine protocol) data acquisition.
- Garman GPS
- PC104 Data logger with VenturCom ETS 10.0 RTOS
- Compact flash removable data storage

2.1.1 Heated Flame Ionization Detector and Sample System

The first consideration for proper sampling of any type of hydrocarbon is to minimize the loss of hydrocarbons from the exhaust sample before they enter the cell or chamber where analysis is performed. Some species of hydrocarbons characteristic to diesel exhaust have very high condensation temperatures and will collect on the various surfaces of the sample system and never make it to the analyzer. Some species of hydrocarbons found in diesel exhaust are also soluble in water, so any condensation of water in the sample system will further remove HC before it enters the analyzer. For these reasons, the standard practice for sampling of diesel HC is to operate the entire system, including the analyzer, at 195 C.

Through affiliations with several manufacturers of portable FIDs, Sensors has incorporated a compact heated FID and sample system operating at 195 C in SEMTECH-D. This heated FID has been used in commercially available portable FIDs designed for raw diesel exhaust measurements for several years. This same FID chamber is also used in laboratory equipment. Once the sample is extracted from the exhaust stack, SEMTECH-D maintains the diesel exhaust sample at elevated temperatures throughout the entire sample system and analyzer with the use of special heated lines, pumps, and filters.

- Filtered probe: A stainless steel sample probe integrated with a 2 micron stainless-steel mesh filter is inserted into the exhaust stack of the vehicle. The filter removes the bulk of the particulates.
- Heated sample line: A 10 ft heated, insulated sample line operating at 195 C delivers the exhaust to the analyzer. The wetted surface of the line is teflon because of its high heat resistance and low absorbing properties. The teflon line is wrapped with a heater and molded inside a larger insulated flexible tube with a durable outer skin.
- Heated filter and pump: The heated sample line connects directly to a heated filter and pump operating at 191 C. The heated filter is constructed of boro-silica glass and removes particulates as low as 0.1 micron, and is accessible to the user for easy replacement. The pump is specially designed with a 191 C heated head.
- Fittings and tubing: All fittings and tubing leading to the HC analyzer are maintained at 195 C and constructed of stainless steel. Stainless steel has very low absorbing properties, so HC loss will be minimized.

2.1.2 CO and CO2 Analyzers

Like typical certification grade systems, CO and CO2 are measured on a dry basis with non-dispersive infra-red (NDIR) technology. SEMTECH utilizes Sensors' second generation Automotive Microbench (AMB-II) module for CO and CO2, which has been extremely successful in the inspection and maintenance industry, with over 60,000 sold worldwide. For SEMTECH products, the AMB-II NDIR analyzer was further enhanced in efforts to achieve laboratory quality data in a portable application. After expanding the memory capacity and processor speed, more sophisticated algorithms were developed that accounted for second order effects from cross interference of other gases and water vapor that were previously ignored due to lack of processing power in earlier models.

The primary sample system concerns with NDIR are liquid water contamination or interference from water vapor, and effects of operating temperature and pressure. To eliminate the interference of water vapor, the sample is conditioned with a thermo-electric chiller and two coalescing filters after first passing through the heated filter to remove particulates. To eliminate pressure effects, a feedback control to a proportional valve maintains a constant backpressure to the analyzers. Pressure fluctuations in the exhaust stack or plugged filters will not alter the operating sample pressure. Finally, precise temperature control is maintained for the NDIR detectors to eliminate ambient temperature effects.

One area of improvement needed for the CO analyzer in diesel applications is the calibration range. The CO analyzer in the SEMTECH-D prototype unit for this study was designed for gasoline exhaust, and is not yet optimized for low concentrations that are often found in diesel exhaust. The analyzer is calibrated between 0.5%, or 5000 ppm and 8%. However, the levels measured on the Ann Arbor busses rarely approached the lower portion of this range.

Correlation testing of the SEMTECH-D prototype demonstrates a detection limit and measurement uncertainty of 50 ppm (see Correlation Testing results).

2.1.3 NO and NO2 Analyzers

Chemiluminescence (CLD) is the most established technique for measurement of NO in vehicle exhaust in stationary certification systems. It offers wide measuring ranges down to 1 ppm with a fast response time. However, there are several drawbacks for this technology that makes it impractical for portable applications. The analyzer requires an ozone generator (operating at high voltage), a vacuum pump, and a de-ozonizer to scrub out toxic ozone from the analyzer vent gases. Because of these requirements, the analyzer is quite bulky and not suitable for integration into a portable system. It is also likely that vibrations in a vehicle may adversely affect performance of its photomultiplier tube. Since the CLD measures only NO (and not NO_2), it requires the use of a high-temperature catalytic converter to convert NO_2 to NO prior to measurement. The CLD cannot measure NO and NO_2 simultaneously.

Aqueous electro-chemical cells are one alternative commonly used for in-use testing, since they are compact and very simple to operate. However, they suffer from high response times (5-10 secs) and even higher recovery time. They also provide relatively poor accuracy (± 25 ppm) especially in the low measurement range, and are known for poor reliability. Like chemiluminescence analyzers, electrochemical sensors measure NO and hence a catalytic converter is necessary to monitor $NO_{x.}$

In order to provide laboratory grade performance of NO and NO_2 detection for in-use testing, Sensors, Inc. developed a proprietary, non-dispersive ultra-violet (NDUV) analyzer. Both NO and NO_2 have unique adsorption bands in the UV range, with little interference from other gasses, and can be measured independently with this technology. Any interference (typically from HC) is compensated with reference detectors. UV analyzers have not commonly been used for NOx measurements, primarily because the UV lamps typically have limited life of less than 1000 hours. However, Sensors has developed a partnership with a company that has developed an electrode-less UV lamp with a life of at least 20,000 hours, which makes it practical for emissions analyzers.

Sensors, Inc.'s NDUV NO and NO_2 gas analyzer is unique because it offer simultaneous monitoring of NO and NO_2 in the exhaust gas. For SEMTECH-D, this analyzer has an operating range of 0 to 3000 ppm for NO, and 0 – 500 ppm for NO_2 with better than +/-10 ppm accuracy through these ranges. The amplified signal from the NDUV optical bench is in the range of 1 mvolt/ ppm of NO with less than 1 ppm noise. This patent pending analyzer is compact and easy to integrated into on-vehicle emission analyzers. Active temperature control stabilizes the instrument at 60 C and provides immunity to changing ambient conditions. Its steady state power consumption is less than 7 watt. As discussed in later sections, correlation testing of the NO and NO2 analyzers in the SEMTECH-D prototype analyzer shows outstanding correlation to laboratory systems for both accuracy and response time.

2.1.4 Vehicle Interface (VI) Modules

SEMTECH-D utilizes a Nexiq Technologies (formerly MPSI) Serial Data Module (SDM) vehicle interface to retrieve real-time engine operating conditions during in-use testing. The

SDM module complies with SAE J1587 communications and hardware protocols for heavy-duty diesel engines. The data transfer rate is variable up to 10 Hz. The SDM module is integrated into the SEMTECH system. One end of a serial data cable connects through a serial port on the SEMTECH, and the other end connects to the vehicle data port with standard SAE J1587 connectors.

The SAE J1587 communications protocol defines the parameters that are available from the ECM data link. Unlike OBDII, the J1587 hardware continuously broadcasts all of the available data. There is also much better consistency as to how the parameters are defined than with OBDII. To retrieve the desired data, the SEMTECH PC104 data logger/controller communicates to the SDM module to tell it which parameters to retrieve. The SDM module then intercepts the broadcast data, decodes it, and sends it back to the SEMTECH data logger. A complete list of parameters obtained from the diesel busses is provided in section 3.2.1.

2.1.5 GPS

SEMTECH uses Garmin's Global Positioning System (GPS 25LP) to keep track of the route taken by the vehicle under scrutiny. Garmin International is the industry leader in Global Positioning System technology. This GPS module is suited for broad spectrum of OEM system applications. Its compact design is ideal for applications with minimal space. It does not require any user initialization. This module can simultaneously track up to twelve satellites providing fast time-to-first-fix, one-second navigation updates and low power consumption. It is also designed to withstand rugged operating conditions. SEMTECH communicates with this module via RS-232 compatible bi-directional communication channel.

The Garmin GPS has a resolution of one meter and an absolute accuracy of 15 meters for latitude, longitude and altitude. However, the repeatability has been shown to be significantly better at approximately 1 – 2 meters. Because grade is computed with the GPS data, instantaneous results can have significant uncertainty, especially at low speeds. The grade calculations are described further in section 5.2.

2.1.6 Weather Probe

A combination probe provides ambient pressure, temperature, and humidity to the data logger each second. This information is used to compute the NOx humidity correction factor, Kh. It also provides useful information about the test conditions. The probe can be placed remotely from the SEMTECH analyzer. However, the systems used in this study had the probes mounted internally within the SEMTECH. For the bus data, windows were kept open in order to provide ambient conditions to the analyzer. The gasoline vehicles were tested with the analyzers enclosed in the trunk, so the temperatures may differ from ambient.

2.1.7 Data Logger

The electronics and software for data logging and control provides the ability to acquire, store and transmit data, and also controls the operation of sample system and other modules. The core component is a CPU card with two asynchronous serial ports, parallel interface and integrated RAM. Individual support cards include a power supply, flash memory, digital I/O, A/D, eight port asynchronous serial expansion, signal conditioning driver, and an Ethernet controller card. PC-104 was the standardized format selected for SEMTECH, which was designed for industrial applications and it lends itself for ease of packaging.

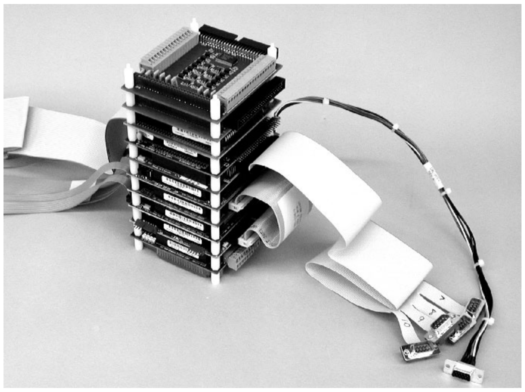


Figure 2.2 Semtech Data Logger

The following briefly describes performance capability and/or capacity of each of the modules selected for the current SEMTECH prototypes.

CPU Card: Industrial grade AMD-586 running at 133 megahertz. The processor card also includes support for the parallel port and two EIA-232 serial ports. These can also supports RS485 communications. PC-AT system architecture leverages x86 platform's popularity and widespread compatibility.

Power Supply: Rugged industrial grade supply. Input power can change from 8 to 30 volts while maintaining +5, -5, +12, and -12 volt output.

Flash Memory: Support for both Compact Flash and disk-on-chip technologies. IDE interface ensures future compatibility as memory densities increase. Type I Compact Flash cards with capacities up to 192 MB are readily available.

Digital I/O: Provides simple logic output for heater and pump controls. Unused channels can be used for application specific purposes. This card supports up to 48 digital channels.

Analog to Digital Converter: Sixteen channels with 12-bit resolution. Used to measure analog signals from thermocouples, pressure transducers, humidity sensors or other auxiliary modules.

Eight Port Serial: Expansion board adds an additional eight EIA-232 communication ports to the system. This board incorporates eight individual UARTS each with a 32 byte FIFO. The deep FIFO memory helps eliminate bottlenecks often associated with serial communication. Also, this card includes EIA-485 and EIA-422 communication support.

Ethernet Controller: Network card provides a standard 10Base-T connection conforming to IEEE 802.3 standard. This provides high-speed link to control analyzer and access files stored on the system. This card can easily be changed to support the faster 100Mbps speed networks or to a 10Base-2 connection.

<u>Signal Conditioning/Driver</u>: Provides the amplification and thermocouple junction compensation that precedes the analog to digital conversion. The driver circuitry buffers the digital I/O from the pumps and heaters.

The software for the data logging and control function runs on the hardware platform described above. The design of the software architecture accommodates easy addition and removal of hardware. A VenturCom ETS 10.0 real-time operating system (RTOS) provides the foundation for the software system. It provides superior reliability and reduces the overhead. The operating system implements a subset of the Win32 API providing the programmer with a well documented and extensively used tool set.

The SEMTECH control software itself was developed using the standard Microsoft Visual C++ 6.0 compiler. The C++ compiler supports object oriented design methodologies, which facilitate extensible design and long term maintenance. The software has been designed to allow for maximum flexibility. Each device that connects to PC104 stack has a corresponding object in the software. As devices are added and removed from the system, the software dynamically configures itself to add or remove them. Another feature of the software design is the wide set of communication options it supports to send the logged data to a host computer. Since the ETS operating system incorporates a TCP/IP stack, data can be sent seamlessly over numerous physical links. The TCP/IP stack also provides the mechanism needed to send information across the Internet.

2.2 SEMTECH-G

The two SEMTECH-G prototype analyzers used in the study measure raw vehicle exhaust, collect vehicle ECM data, and store the data on an internal data logger that is automated by key-on / key-off events. A post-processing utility computes real-time fuel-specific and distance specific mass emissions based on engine airflow computed from the ECM data.

Figure 2.3 SEMTECH-G System used in Study

Dimensions:	10"H x 19"W x 18"D
Weight	45 lb
Power:	12 VDC
Power Consumption:	100W steady state

The two SEMTECH-G prototypes systems used in the study consist of the following components:

- NDIR CO2 analyzer
- NDIR CO analyzer
- NDIR HC analyzer

- Thermo-electric chiller and coalescing filters for sample conditioning
- Sample pressure control via proportional feedback control valve
- NDUV NO analyzer
- J1850 (OBDII) ECM data acquisition.
- Garman GPS
- PC104 Data logger with VenturCom ETS 10.0 RTOS and compact flash removable data storage

2.2.1 HC Measurement

The primary difference between the SEMTECH-G and the SEMTECH-D analyzers used in this study is in the measurement of HC. Since gasoline engines emit hydrocarbons primarily in the form of hexane, which has strong infra-red absorbing properties, SEMTECH-G can measure HC with NDIR technology instead of a FID. While the NDIR technology cannot measure total HC like the FID, there is a reasonable correlation between NDIR and FID measurements as described below.

In addition, NO_2 from gasoline engines is generally considered negligible, and was not measured. This results in significant differences in the sampling system for SEMTECH-G vs SEMTECH-D. Since hexane hydrocarbons do not condense at ambient temperatures, SEMTECH-G does not require a heated sample system like SEMTECH-D. SEMTECH-G pulls the sample through an unheated teflon sample line, then conditions the sample through a thermo-electric chiller prior to analysis. Without the heated sample system, SEMTECH-G consumes less than 100 Watts, which is significantly less than SEMTECH-D. This allows continuous operation of the instrument for over 8 hours on a deep cycle 12V battery.

There is still a considerable difference in performance between NDIR hexane measurements compared to a total HC measurement with a FID, as the correlation data shows. That is because the hexane HC species only accounts for approximately 60% of the total HC during an FTP test. That percentage is not exact for every vehicle or all driving conditions, but provides a reasonable estimate of total HC over the test cycle.

Current versions of SEMTECH-G are available with a heated FID, if desired.

2.2.2 Vehicle Interface

SEMTECH-G utilizes a Vetronix Enhanced OBDII Interface Module, with custom software to allow proprietary parameter (PID) collection. It supports SAE J1850 variable pulse width protocol (VPW) for GM and Chrysler vehicles, and pulse width modulation (PWM) for Ford vehicles. It also supports ISO 9141 protocol that is commonly found on foreign-made engines. With this combination, all OBDII equipped vehicles are supported.

The Vetronix Enhanced OBDII Interface Module is integrated into the SEMTECH system. One end of a serial data cable connects through a serial port on the SEMTECH, and the other end connects to the vehicle data port with standard OBDII connectors. To retrieve the desired data, the SEMTECH PC104 data logger/controller communicates to the VI module to tell it which parameters to retrieve. Using the appropriate protocol, the VI module then sends a request to the vehicle electronic control module (ECM) requesting the specific data. The VI module intercepts the responding data, decodes it, and sends it back to the SEMTECH data logger. Each parameter is requested individually, one at a time.

The scope of the Statement of Work required a large number of PIDs that are proprietary to the vehicle manufacturers. Sensors, Inc. contracted Vetronix to develop custom interfaces in order to access large numbers of proprietary PIDs at 1 Hz sample rates. However, not all of the requested PIDs were available on GM and Ford vehicles, and Chrysler does not publish information on their proprietary PIDs. A summary of the PIDs accessed by each vehicle is provided in Table 4.2.

2.2.3 Other components

Aside from the HC measurement and vehicle interface, all other analytical equipment is identical between SEMTECH-G and SEMTECH-D, including the data logger/controller, GPS, NDIR CO and CO2, NDUV NO, and the weather probe. The only remaining differences are in the data processing and computation of mass emissions, which are described below.

3 Diesel Bus Testing

3.1 Busses and Routes

EPA approached the Ann Arbor Transit Authority (AATA) as a possible source for test vehicles in the study, and were greeted with enthusiasm and complete cooperation. Not only did AATA allow us to test the busses on an aggressive schedule, they provided technicians as needed and dedicated drivers who performed whatever routes we requested. In addition, AATA provided busses for on-road emissions testing demonstrations at EPA in Ann Arbor and the SAE World Congress in Detroit.

The busses that were tested include 15 New Flyer models with Detroit Diesel Series 50 engines. All of these busses were of model year 1995 or newer. In addition, a model year 2000 Gillig bus was tested with a Detroit Diesel Series 40 engine. Also, a model year 1992 New Flyer was tested with a 6V92 two-stroke engine that had recently been overhauled and upgraded to a DDEC4 engine control and a new emissions system including a reduction catalyst. AATA was interested to know how the upgraded two-stroke engine compared to the newer engines. A summary of the busses tested is shown below, and a more detailed table is provided in the appendix.

Bus #	Bus ID	Model yr	Odometer	Engine series	Displ. liter	Peak torque	Test date
1	BUS380	1996	223471	SERIES 50 8047 GK28	8.5	890	10/23/01
2	BUS381	1996	200459	SERIES 50 8047 GK28	8.5	890	10/22/01
3	BUS382	1996	216502	SERIES 50 8047 GK28	8.5	890	10/17/01
4	BUS383	1996	199188	SERIES 50 8047 GK28	8.5	890	10/19/01
5	BUS384	1996	222245	SERIES 50 8047 GK28	8.5	890	10/17/01
6	BUS385	1996	209470	SERIES 50 8047 GK28	8.5	890	10/18/01
7	BUS386	1996	228770	SERIES 50 8047 GK28	8.5	890	10/19/01
8	BUS379	1996	260594	SERIES 50 8047 GK28	8.5	890	10/23/01
9	BUS377	1996	252253	SERIES 50 8047 GK28	8.5	890	10/24/01
10	BUS363	1995	283708	SERIES 50 8047 GK28	8.5	890	10/24/01
11	BUS361	1995	280484	SERIES 50 8047 GK28	8.5	890	10/25/01
12	BUS375	1996	211438	SERIES 50 8047 GK28	8.5	890	10/25/01
13	BUS360	1995	270476	SERIES 50 8047 GK28	8.5	890	10/25/01
14	BUS372	1995	216278	SERIES 50 8047 GK28	8.5	890	10/26/01
15	BUS364	1995	247379	SERIES 50 8047 GK28	8.5	890	10/24/01
16	BUS404	2000	60000	S40E8.7LTA	8.7	900	11/1/01
17	BUS352	1992	206443	6V92TAC/JWAC	9.1	766	11/1/01

Table 3.1 Buses used in Study

Sensor's employees preformed the instrument setup and data collection for all the tests. All of the bus tests consisted of approximately 2 hours of data collection during standard Ann Arbor bus routes. The drivers displayed an "out of service" message on the busses, but stopped at all regular stops as if they were performing real routes. The routes were mostly different for each test, and were selected for a wide variety of driving conditions.

3.2 Analyzer Setup and Operation

The physical setup for the bus testing was relatively simple, and took approximately 30 minutes for all of the busses. The instrument warmup time was an additional 30 minutes minimum (60 minutes for a cold start). The following steps were involved in setting up an operating the equipment:

- Place SEMTECH-D analyzer in rear of bus with 12V deep cycle battery.
- Attach power cables from the SEMTECH battery to the bus 12V equalizer. The bus power was used to keep the SEMTECH battery charged during the test.
- Turn on power to the SEMTECH to begin warmup.
- Run heated sample line out rear window to stack. Install exhaust probe in stack and secure line with a rail clamp.
- Attach J1587 vehicle ECM interface to the connector in the rear engine compartment. Verify communication by turning the bus engine control to "on" (without starting). Secure wires to bus chassis with tape. ECM PIDs are all consistent for J1587 protocols, so no PID setup was required after the first test.
- Mount GPS antenna on roof of bus.
- Insure that adequate FID fuel pressure is available in the portable bottle.
- Ignite FID when testing is ready to begin.
- Attach laptop computer, and zero the instruments.
- Perform single point gas audit with portable gas bottle.
- Manually start and stop data collections at approximately 30 minute intervals. This is to keep file sizes manageable, since VI data was collected at up to 10 Hz.
- Check zero between data collections.

Unlike the passenger vehicles, the heated components of the SEMTECH-D draw too much power to operate for more than two hours on a battery. Fortunately, the power output on the diesel busses is sufficient so that the SEMTECH did not place any noticeable load on the engine. The steady-state power consumption of the SEMTECH-D prototype system was approximately 400 watts.

The following photographs illustrate the SEMTECH-D setup on the busses.

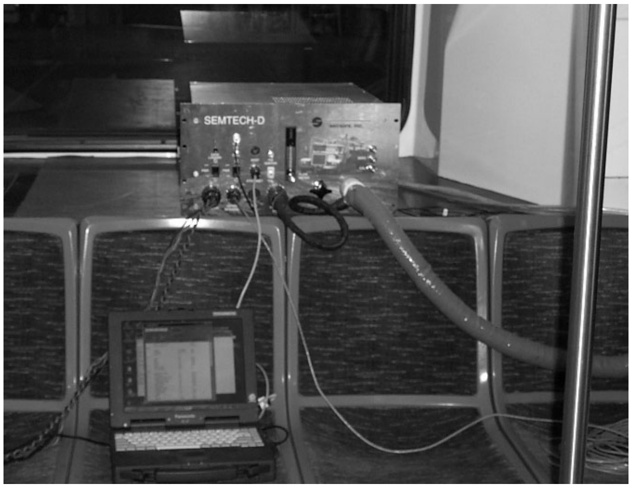


Figure 3.1 SEMTECH-D in back of Bus

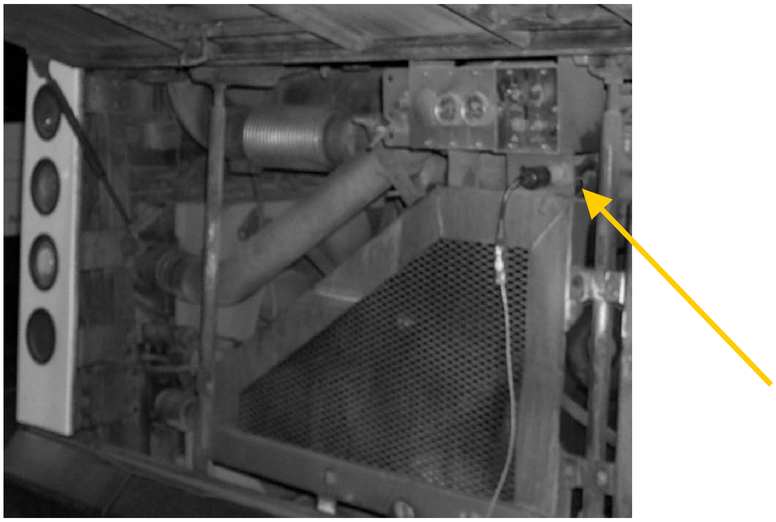


Figure 3.2 Vehicle Interface Connection in Rear Engine Compartment

Figure 3.3 Heated Sample Line

3.2.1 SEMTECH-D Vehicle Interface Setup

The vehicle interface setup for the heavy-duty diesel engines is very simple, because the SAE J1587 communications specification provides broadcast data instead of two-way communications as required for OBDII communications. Also, the parameter availability and definitions are more universally applied for heavy-duty engines, and it is unnecessary to experiment with the PIDs to see what is available or what definitions are used. One set of PIDs seems to apply universally for ECM equipped heavy-duty diesel engines sold in the U.S. The following is the list of parameters that were collected during the Ann Arbor bus testing through the vehicle interface:

Parameter	**Units**
Engine speed	RPM
Vehicle Speed	MPH
Throttle position	%
Engine Load	%
Fuel flowrate	gal/sec
Fuel economy	MPG
Oil temperature	Deg F
Oil pressure	KPa
Coolant temperature	Deg F
Warning lamp	binary

Table 3.2 Heavy-Duty Vehicle Diesel Interface Parameters

One issue that arose during the testing was the large amount of data that was collected from the ECM. Because the J1587 data is broadcast continuously at rates as high as 10 Hz, the test files became large rather quickly. Because of this, new data files were started every 30 minutes during the 2 hour test, so a total of four files was generated per bus. The four files for each bus were later combined into one file after post-processing. The post-processing procedure eliminates the extra data by interpolating and synchronizing all the data to 1 Hz as described in section 5.1. Current SEMTECH-D analyzers store the ECM data into a buffer and computes a moving average at user-defined intervals, so the user can specify the data collection rate.

Another issue that arose was a significant amount of data errors from the ECM, including random, non-physical data spikes. The source for the errors is unknown; they could have been generated from external sources or from the ECM itself. This erroneous data was filtered using techniques described in section 5.4.

For HD diesel engines, the Load Factor is defined as the fraction of maximum engine torque for the current RPM. When combined with the engine lug curve (maximum torque curve), real-time engine torque can be computed as described in section 5.2. Also, NTE zone operation can be determined with this information, as well as brake-specific emission. These calculations are described in section 5 in more detail. The fact that fuel volumetric flowrate is provided directly from the ECM is very convenient for emissions calculations. However, an accurate specific gravity measurement of the fuel is required.

3.3 Fuel Analysis

In order to compute mass emissions accurately using the reported fuel flow, the specific gravity of the fuel was required. Other fuel analysis data was required by EPA in addition. A single sampling of the fuel from the AATA depot was provided at the beginning of the study, and was analyzed at the EPA laboratories. AATA personnel believed that the fuel properties would not change significantly during the course of the two-week study. The results of the fuel analysis are summarized below:

AATA Fuel Sample Analysis Parameter	**Result**
Specific Gravity	0.8814
API Gravity	42.7
Density	7.355
Sulfer content, ppm	150
Cetane index	44.7
ibp	348
t10	391
t50	432
t90	482
ep	504

4 Gasoline Passenger Vehicle Testing

4.1 Vehicles and Operators

Each passenger car was recruited and selected by EPA for the study. Some of the vehicles were owned by Sensors employees, some by EPA employees, and some were rented. All of the vehicles were of model year 1996 or newer, and certified to Tier 1 emissions standards with the exception of one vehicle which was certified to California LEV standards. A complete table of the test vehicles is listed below. More detailed specifications for each test vehicle is found in the appendix.

Vehicle #	model_yr	make	model_name	disp_liter	test_date
1	1998	CHEVROLET	LUMINA LS	3.1	8/15/01
2	1997	FORD	TAURUS GL	3	8/17/01
3	1996	MERCURY	SABLE LS	3	8/21/01
4	1997	CHRYSLER	CIRRUS LXI	2.5	8/24/01
5	1998	SATURN	SATURN	1.9	8/24/01
6	1999	CHEVROLET	MALIBU LS	3.1	8/28/01
7	1999	SATURN	SATURN	1.9	8/28/01
8	1999	FORD	ESCORT	2	8/31/01
9	2000	FORD	ESCORT	2	8/30/01
10	1999	GEO	PRIZM	1.8	9/5/01
11	1998	FORD	TAURUS SE	3	9/5/01
12	1997	FORD	ESCORT	2	9/7/01
13	1998	MERCURY	SABLE GS	3	9/7/01
14	1998	FORD	TAURUS SE	3	9/12/01
15	1996	CHEVROLET	CAVLIER	2.2	9/12/01
16	1998	CHEVROLET	CAVLIER	2.2	9/14/01
17	1998	MERCURY	MYSTIQUE SPORT	2	9/14/01
18	1996	FORD	TAURUS GL	3	9/19/01

Table 4.1 Gasoline Passenger Vehicles used in Study

During the study, the vehicles were all operated by their owners or renters with a SEMTECH-G analyzer installed in their trunks. They were encouraged to operate their vehicles in a normal fashion and on normal routes, in order to provide real-world emissions. The only requirement was that they operate the vehicle for at least one hour with the SEMTECH-G analyzer collecting data. The operators were given a log sheet to record the time and distance traveled for each trip. A trip was defined by an engine start and stop cycle.

The operators were given brief instructions and a test protocol handout, which is included in the appendix. They were not required to perform any other duties, except to plug in the automatic charger for the SEMTECH-G battery at night to keep it charged. The analyzer was set up to operate continuously and automatically with no user intervention, as described below.

4.2 Analyzer Setup and Operation

SEMTECH-G analyzers were installed in the vehicles by Sensors' employees. This installation procedure took approximately 15 minutes, followed by a one hour warm up period. There were two SEMTECH-G analyzers used in the study, so that two vehicles could complete on-road testing simultaneously. The physical setup included:

- Place SEMTECH-G analyzer in trunk of vehicle with battery and automatic charger
- Attach exhaust probe and sample hose
- Attach OBDII interface to vehicle connector
- Verify OBDII communication
- Set-up desired PIDs (paramenter IDs) specific to the vehicle.
- Allow one hour of warmup before data collection.

While the physical setup was very easy, setting up the desired PIDs proved to be difficult in some cases because the definitions were not always available from the vehicle manufacturer. This is discussed in detail in section 4.3.

Because this study was conducted with the purpose of obtaining real-world emissions data, the equipment was set up to operate automatically, without any user intervention. This required the following:

- Continuous power and operation
- Automated zero calibrations with LED indicator
- Automated data collections with LED indicator

Power for the SEMTECH-G analyzers could have been supplied by the vehicle's generator without adding significant load to the engine, but then the analyzer would have to be shut down if the vehicle was off for long. For this study, the SEMTECH-G analyzers were powered from external batteries with an automatic charger attached. This way, the operator could plug the charger in and keep the battery charged when the vehicle was not in use. Typically, the operators would drive their vehicle home, plug in the charger, and let the analyzer operate overnight. The next day, they can simply unplug the charger, turn the key on to initiate data collection, and then start the vehicle and drive away without having to warm-up the instrument.

Like most instruments, the analytical instruments in the SEMTECH-G analyzers will drift from their zero setting over time. This is corrected with a zero calibration, which was initiated automatically by the SEMTECH data logger/controller every 30 minutes when the instrument is not in a data collection mode. Ambient air is pulled through a sample port on the instrument for the zero calibration. It first passes through a charcoal filter to remove trace organic contamination before reaching the analyzers. However, this may not be sufficient if there is significant ambient hydrocarbon contamination. A green LED on the instrument and also on a remote cable placed near the driver would illuminate steadily if a zero is in progress. The process takes approximately one minute. If the instrument happened to be in a zero calibration mode when the operator was ready to use the vehicle, they were instructed to wait for the zero process to complete before starting the engine.

Data logging was also automated through a key-on signal from the vehicle interface. When the SEMTECH-G data logger/controller receives the key-on signal, it engages a solenoid that switches the analyzer from the Ambient port to the Sample port, where the vehicle exhaust sample hose is attached. At the same time, it initiates a new data file on the data logger which will capture all data from the analytical instruments, GPS, and vehicle interface. To insure the data collection was initiated properly, the LED indicators would flash at 1 Hz. The operators were instructed to turn the key to the "on" position, wait for the LED indicator to flash, then start the engine. When the key is turned to the "off" position, the data collection would cease after an additional 15 seconds. This additional time allows for the transport and analysis of the exhaust sample at the time the key-off signal is given. It also allows for brief interruptions in the ECM data, which can occur on some vehicles.

4.3 Vehicle Interface Setup

A significant amount of vehicle interface data was requested by EPA for the study, but not everything was available. Many of the desired PIDs were proprietary to the vehicle manufacturer, which caused additional difficulties because only GM and Ford provide the required information to access these parameters. A list of parameters that was obtained for each vehicle is shown below.

Parameter ID	’98 Lumina	’97 Taurus	’96 Salbe	’97 Cirrus	’98 Saturn	’99 Malibu	’98 Saturn	’99 Escort	’00 Escort	’99 Prizm	’98 Taurus	’97 Escort	’98 Sable	’98 Taurus	’96 Cavalier	’98 Cavalier	’98 Mystique	’96 Taurus
Vehicle #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Used in Study		x			x	x	x				x	x	x	x	x	x	x	x
RPM	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Vehicle Speed	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Load Factor type 1					x		x			x					x	x		
Load Factor type 2	x			x		x												
Load Factor type 3		x	x					x	x		x	x	x	x			x	x
MAF	x	x	x			x		x	x		x	x	x	x			x	x
Coolant Temp.	x	x	x		x	x	x	x	x		x	x	x	x	x	x	x	x
AC clutch on/off		x	x		x		x	x	x		x	x	x	x			x	x
AC high pressure	x														x	x		
Inlet Air Temp.		x	x	x	x	x	x			x	x		x	x			x	x
Inlet Manifold Press.	x			x	x		x			x					x	x		
Fuel Trim	x			x	x	x	x			x					x	x		
Lambda		x	x					x	x		x	x	x	x			x	x
Spark Advance	x	x	x		x	x	x	x	x		x	x	x	x	x	x	x	x
Throttle position	x			x	x	x	x								x	x		
All/Part throttle		x	x					x	x		x	x	x	x			x	x
MIL on/off	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Table 4.2 Vehicle Interface Parameters Collected on Passenger Vehicles

Not all parameters (PIDs) were available for each model. As part of the setup procedure, each vehicle ECM was scanned to verify which PIDs are available. Any parameters that were not available on the screening test were omitted from the data list, so that the data logger did not ask for data that did not exist (that would have needlessly delayed all the VI time responses). For example, all engines have either MAF or inlet manifold pressure, but usually not both (except for the Lumina). Most vehicles had either AC clutch on/off or AC high Pressure, except for the Malibu and Prizm.

The following paragraphs provide a brief description of the parameters that are not self-explanatory.

4.3.1 Load Factor

Engine Load Factor is critical to the computation of mass emissions, since it is used to compute engine airflow. This method was first developed for specific Ford Motor Company vehicles with the assistance of Ford personnel who provided information for their proprietary engine load factor (referred to as type 3).

For other vehicles where proprietary ECM PID definitions were not identified, engine airflow was computed using SAE J1850 Load Factor. The general SAE J1850 definition of Load Factor is

$$Load\ Factor = \frac{Current\ Engine\ Airflow}{Reference\ Airflow} x100$$

The reference airflow is loosely defined in SAE specifications as the "maximum engine airflow". This appears to have been interpreted by vehicle manufacturers in two different ways depending on vehicle Make and Model. Once the reference airflow is identified, the current engine airflow can be computed by multiplying the reference airflow by the Load Factor.

The variations of Load Factor are described below. Sensors, Inc. has arbitrarily chosen to refer to the various Load Factors as Type 1, Type 2, and Type 3.

Type 1 Load Factor

With a Type 1 Load Factor, the reference airflow is defined based on:

- Current RPM
- Reference inlet temperature
- Wide-open throttle
- Engine displacement
- Current volumetric efficiency

This definition appears to be the most common, and is used on Ford (J1850) and some GM vehicles. However, Ford also uses a proprietary Type 3 Load Factor as described below. There were five non-Ford vehicles in the study that used the Type 1 Load Factor. All were GM vehicles. You can identify type 1 load factor by its range under idle conditions, which is around 15 – 25% for the vehicles tested. The vehicles had to be tested first in order to make this determination.

The only uncertainty with this Load Factor definition is the unknown volumetric efficiency. Volumetric efficiency can typically vary between 0.80 and 0.95 depending on the engine speed and other variables. Because this information was not available, a fixed "average" volumetric efficiency had to be assumed. The value selected was 0.85 based on limited information. The simultaneous FTP correlation tests confirmed that this value was appropriate.

Type 2 Load Factor

With Type 2 Load Factors, the reference airflow is defined based on:

- Reference RPM (fixed)
- Reference inlet temperature
- Wide-open throttle

- Engine displacement
- Volumetric efficiency at the reference RPM

This definition seems less common, but was found on the single Chrysler vehicle and two of the GM vehicles. Type 2 Load Factor typically have a range of 3 – 8% under idle conditions, which is significantly lower than type 1 and easy to identify (after a test is performed). Unfortunately, there were now two unknown parameters with these vehicles: the reference RPM and the volumetric efficiency at the reference RPM. Since specific manufacturer definitions were available, these parameters had to be determined empirically based on the FTP correlation data.

First, it was decided to again use an average volumetric efficiency of 0.85. The reference RPM was then determined empirically for each of the three vehicles from the FTP correlation testing. From these experiments, the reference RPM appears to be the "rated" RPM that provides the maximum engine power.

Type 3 Load Factor (Ford Proprietary)

In addition to the standard J1850 Type 1 Load Factor, Ford provides this third (proprietary) variation of engine load factor. It is similar to type 1 load factor, except that no assumption of volumetric efficiency is required. This means that there are no assumptions or "calibrations' that need to be performed before collecting data and computing results. There are probably similar parameters that exist for the other engine manufacturers, but they are unknown at this time. For all the Ford vehicles, the Type 3 proprietary load factor was used for engine airflow computations.

As noted above, the Load Factor type had to be determined "after the fact" for GM and Chrysler vehicles. Furthermore, for the three vehicles with Type 2 load factors, the reference engine speed had to be determined empirically based on the FTP correlation data. Since some of the SEMTECH-G calculations were first "calibrated" using the FTP data in this manner, it may not be appropriate to consider the final comparison to FTP true correlation data, which is typically collected and analyzed "blind". However, the purpose of this FTP testing was to provide validation that the SEMTECH-G on-road data is accurate, especially since GM and Chrysler vehicles had never before been tested by Sensors, Inc.

Until all the engine manufacturers provide a definition of Load Factor type by make and model, any vehicles that have not previously undergone correlation testing against a laboratory reference should be validated in this manner. Because the Load Factor is a standard OBDII parameter required by EPA for engine diagnostics, it seems very plausible that the vehicle manufacturers could provide information as to which definition applies to each make and model. If type 2 is used, then they should provide the reference RPM. With this information, the VI method of computing engine airflow and mass emissions could be applied without having to perform verification testing.

4.3.2 MAF

Mass airflow sensors are used for fuel engine control strategies on many vehicles, along with the lambda sensors. Those that do not have MAF sensors rely on intake manifold pressure. The MAF data was not used for the mass calculations in this study, but can be used as redundant engine airflow information for comparison. It should further be noted that units for

MAF may not be reported as specified in SAE J1850. It has been reported that some manufacturers report voltage, rather than mass flowrate units.

4.3.3 AC on/off Indicators

All the Ford vehicles and the two Saturns have an “AC clutch on/off” parameter, that indicates when the AC compressor is actually engaged. It does not simply indicate that the AC dashboard switch is on or off. The Lumina and Cavaliers have an “AC High Side Pressure” parameter that also indicates when the AC compressor is engaged.

4.3.4 Fuel Trim

The short-term fuel trim parameter is a J1850 parameter that gives an indication of stoichiometry. The engine control always attempts to maintain a lambda of 1, so that there is exactly the correct amount of fuel for complete combustion without any excess air. When the short-term fuel trim is positive (say - .15), it indicates that the ECM is calling for 15% less fuel in order to achieve a lambda of 1. From this, you can infer that the current lamda is 0.85. This PID is not required if lambda is available directly from another parameter.

4.3.5 Lambda

Ford provides direct, real-time lambda readings from the on-board sensors, so the fuel-trim parameter is not required.

4.3.6 APT (All/Part Throttle)

When Ford parameters are retrieved using proprietary protocols, the J1850 “% throttle position” PID is not available. Instead, the APT (all/part throttle) PID is available, which has three states: Fully closed, partly open, and fully open.

4.4 FTP Correlation Testing Protocol

In order to validate the test data, each vehicle underwent FTP correlation testing at the EPA facility in Ann Arbor. Full FTP tests were conducted with SEMTECH-G collecting data simultaneously.

Each vehicle was prepared for full FTP testing at EPA’s facility in Ann Arbor. The vehicles were cold soaked overnight in a temperature controlled environment, and the fuel was exchanged with certification grade fuel.

SEMTECH-G data collections during FTP testing were conducted in the same manner as the on-road data collection. The analyzer was allowed to warmup and stabilize before the test. A zero calibration and gas audit were also performed prior to FTP testing for each vehicle.

For FTP correlation testing, additional HC data was collected with a portable FID from Sensors, Inc. This is the same FID model that is integrated into the SEMTECH-D system, and is available for SEMTECH-G as well. It was desirable to see how much improvement is possible with a FID versus the NDIR measurements.

Complete correlation test results are provided in section 8.

5 Data Processing

5.1 Data Synchronization

The first step in post processing is to precisely synchronize the raw data. Each of the analytical instruments, vehicle interface, and GPS equipment report data to the SEMTECH data logger asynchronously and at differing rates, but with a timestamp at millisecond precision. The data is first interpolated to a common 1 Hz time interval. The first data point reported by any of the instruments defines the first interval.

With all the raw data synchronized to the same data rate, it is then time aligned so that engine data corresponds to emissions data in real time. Data from each of the analytical instruments is time shifted according to its delay in the system relative to the engine data from the ECM. The delay for NDIR CO2 and CO is typically 6 seconds, accounting for transport time of the gasses and response time of the analyzer. The delay for total HC from the FID and NDUV NO and NO_2 is typically 5 seconds.

For the diesel bus tests, time alignment between engine data and emissions data were verified on most tests by plotting CO2 and fuel flow rate in real-time. A typical time-aligned data set is shown below for one of the busses.

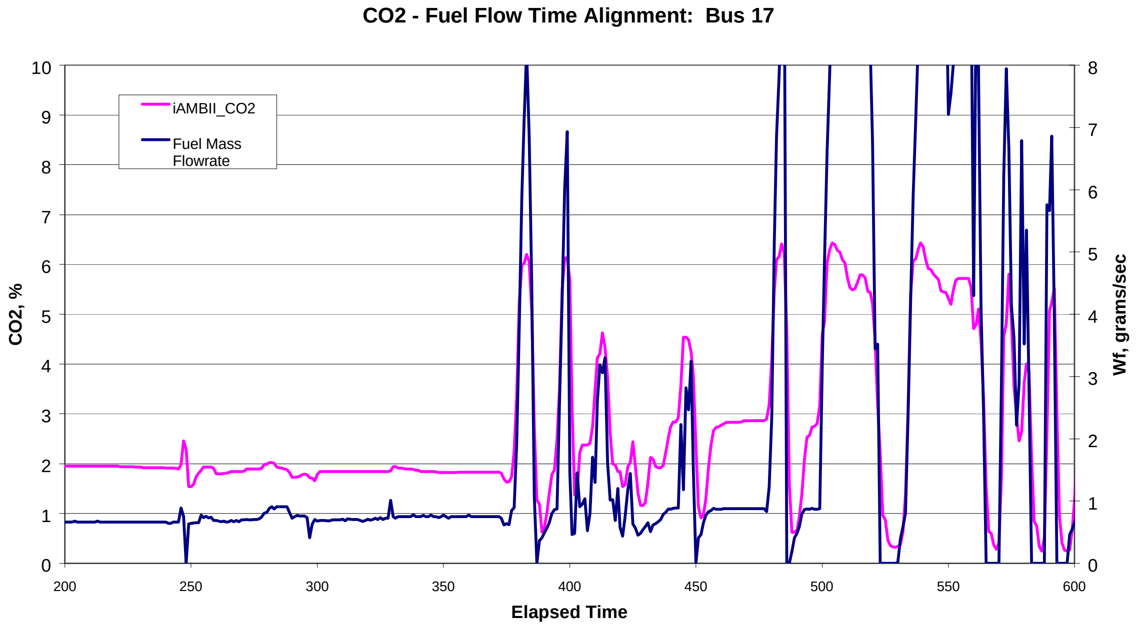


Figure 5.1 Time Alignment of VI and Emissions Data

For the gasoline vehicle tests, this method of time alignment is only possible during the engine start transients, since CO2 is relatively constant thereafter. However, NOx typically correlates well to engine load and fuel flow rate, which provided additional evidence of proper time alignment. This method of time alignment is somewhat subjective and time consuming, and not appropriate for large-scale data collections. More sophisticated techniques should be developed as part of the development of in-use testing equipment where proper time alignment is essential.

For diesel engine testing, the fuel-flow vs CO2 alignment strategy would be plausible through software that can identify the best correlation between the two parameters over a short test cycle by iteratively shifting the data until the best fit regression is found. For gasoline vehicles, it may be plausible to inject a fixed amount of propane into the air inlet of the engine while performing several snap accelerations. The propane would be diluted by the engine airflow during the snap accelerations, so the computed engine airflow could be correlated to the diluted propane measured from the exhaust. In order for this to work, the propane levels would have to be significantly higher than the exhaust HC, and high enough so that catalyst break-through would occur. The data could then be aligned with software through a best-fit regression analysis described above.

5.2 Diesel Engine Emissions Calculations

The next step in the data processing is the computation of emissions results. The following sections describe the various calculations performed for diesel emissions.

5.2.1 Fuel-specific emissions

Fuel specific emissions are the mass fractions of each pollutant to the fuel in the combusted air/fuel mixture. This fraction is easily computed directly from concentrations of the measured exhaust constituents. No additional measurements are required.

For example, to express NO fuel specific emissions, you start by computing the mole fraction of NO to fuel burned. This is simply the ratio of the measured concentration of NO to the sum of the CO, HC, and CO_2 concentrations in the exhaust, which reflect the number of moles of fuel that is consumed per mole of exhaust. The ambient CO_2 concentration must be zeroed on the instrument or subtracted from the exhaust measurement. Ambient CO and HC are not subtracted from raw exhaust concentrations because it is assumed these are destroyed in the combustion process.

For example, the mass fraction of NO to fuel burned is then computed by multiplying the mole fraction by the ratio of the molecular weights of NO to the molecular weight of the fuel. This mass fraction is expressed as an equation below. Fuel specific emissions for all other species are computed in a similar manner.

$$NO_{fs}\left(\frac{g\_NO}{g\_fuel}\right)=\left(\frac{[NO]}{[CO]+[HC_1]+[CO_2]-[CO_2]_{ambient}}\right)\times\left(\frac{MW_{NO}}{MW_{fuel}}\right)$$

There are several advantages of computing fuel specific emissions, particularly with diesel engines. First, you do not need any additional measurements such as torque, speed, exhaust flowrate, or fuel flowrate. You can completely characterize a vehicle operating under various driving and loading conditions, and later compute mass emissions for a drive cycle by applying an estimated or measured specific fuel consumption along with the fuel specific emissions for various segments of the cycle.

5.2.2 Mass Emissions (grams/second) by Fuel Flow Method

Because today's diesel engines that are equipped with an ECU generally provide real-time fuel flow information, the fuel flow method for mass emissions calculations is preferred. This was the case with all of the Detroit Diesel engines on the Ann Arbor busses.

With access to real-time, second-by-second fuel flowrate, transient mass emissions is computed by multiplying these by the real-time fuel-specific emissions. This method has been commonly used for steady-state emissions testing, when exhaust flow measurements are not available. CFR40 Part 86.345-79 describes the fuel flow method as an alternative for mass emissions computations for diesel engine dynamometer testing. Using NO for example,

$$NO(g / sec) = NO_{fs}\left(\frac{g\_NO}{g\_fuel}\right) \times Fuelflow(g / sec)$$

Real-time mass emissions were computed for other species in a similar manner.

As discussed in section 5.4, the fuel flowrate was found to be unreliable at engine speeds under 1000 RPM. Under these conditions, two other methods were explored to compute mass emissions.

1. Compute engine airflow using speed-displacement method. This seems reasonable at lower RPMs when there is no turbo boost or sharp transients. Compute fuel flowrate using air/fuel ratio and engine airflow.
2. Estimate engine fuel flowrate using computed engine torque (see below), engine speed, and BSFC curve provided by the manufacturer.

These methods were compared, and found to yield reasonable similar results. Method 2 was selected for mass computations below 1100 RPM. This is further explained in section 5.4.

5.2.3 Fuel Mass Flow Rate and Fuel Economy

The mass flow rate of the fuel is critical to the calculation of mass emissions, as described above. For HD diesel engines, the SAE J1587 protocol provides volumetric fuel rate data (gallons/second) directly based on the fuel injector pulse width. To convert to a mass flow rate, the fuel specific gravity is required. Any error in the fuel specific gravity (SG) will have a matching impact on the mass emissions results. The fuel SG was measured at EPA laboratories for the bus testing.

Fuel economy is easily computed for a test period by summing the fuel consumed and dividing by the distance traveled. These results are provided as a 30 second moving average, and for the entire test duration.

5.2.4 Exhaust Flow Computation

Exhaust flowrate was not used to compute mass emissions in this study, but is still computed for both diesel and gasoline engines. For diesel engines, exhaust flowrate was back-computed from the mass emissions generated with the fuel flow method. This is because engine airflow cannot be computed from the diesel engine ECM data provided. Unlike gasoline engines, there is no parameter that leads to engine airflow.

This back-calculation also served as a useful tool for checking the time alignment of the data. If the time alignment is off by any significant amount (2 seconds or more), then back-calculated exhaust flowrates can be larger than possible during transients. Maximum engine airflow for a given RPM is easily computed assuming maximum boost pressure for the engine.

5.2.5 Engine Torque

Engine torque is computed on diesel engines by applying the Percent Load parameter with an engine lug curve (maximum torque curve). It is required for the computation of brake-specific emissions as described below. The Percent Load parameter is defined as

$$\%Load = \frac{Current\_Engine\_torque}{Max\_Engine\_torque}$$

where the maximum engine torque is defined at the current engine RPM. The engine lug curve, supplied by the engine manufacturer, defines the maximum engine torque for all engine speeds. The following chart and data table shows the lug curves used in the study for the Detroit Diesel Series 50, 6V92, and Series 40 engines. Data at highest and lowest engines speeds were not available, and had to be extrapolated. These data points were necessary to compute the NTE zone boundaries as described below. The original data sheets supplied from the engine manufacturer is included in the appendix.

The accuracy of the torque computed from Percent Load and the engine lug curve is not well established. Engine manufacturers cannot provide precise accuracy specifications for this measurement, but generally agree it is within 10 percent of actual values. Limited correlation testing performed by Sensors supports this claim for torque levels above 30% of maximum (NTE zone operation), but significant errors were observed at lower torque levels near idle conditions. There was no opportunity to perform correlation testing on the Detroit Diesel Series 50 engines tested in this study. However, the small variance of the brake-specific CO_2 emissions indicates good consistency of the computed torque for all of the 15 buses.

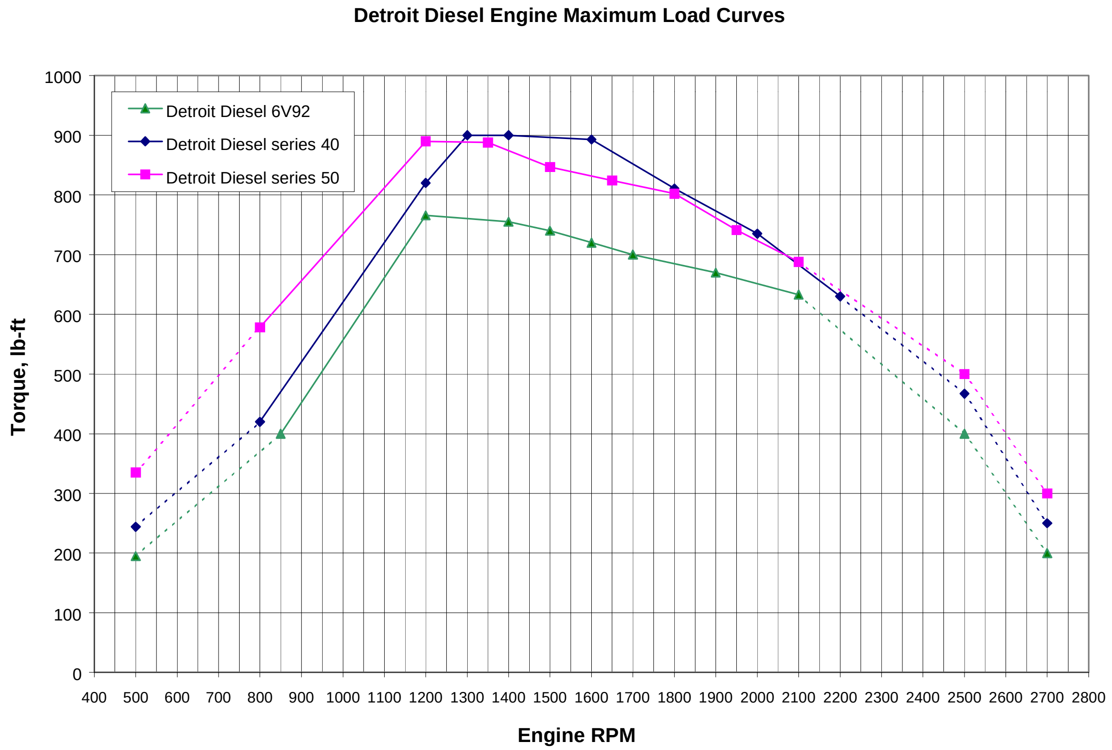


Figure 5.2 Engine Lug Curves used in Study

Detroit Deisel Series 50			**Detroit Deisel Series 40**			**Detroit Deisel Series 6V92**		
RPM	Torque	Power	RPM	Torque	Power	RPM	Torque	Power
500	335*	31.9	500	244*	23.2	500	195*	18.6
800	578	88.1	800	420	64.0	850	400	64.8
1200	890	203	1200	820	187	1200	766	175
1350	888	228	1300	900	223	1400	755	201
1500	847	242	1400	900	240	1500	740	211
1650	824	259	1600	893	272	1600	720	219
1800	802	275	1800	811	278	1700	700	227
1950	741	275	2000	735	280	1900	670	242
2100	688	275	2200	630	264	2100	633	253
2500	500*	238	2500	467*	222	2500	400*	190
2700	300*	154	2700	250*	129	2700	200*	103

Table 5.1 Engine Lug Curve Data

* Extrapolated data

5.2.6 Brake Specific Emissions (grams/BHP-hr)

To compute brake specific emissions, engine torque is first computed from ECM data and the engine lug curve (maximum torque curve). Engine torque is then converted to engine horsepower using RPM from the ECM. Work (BHP-hr) is computed for each second of the test, and then summed over the desired interval. Brake specific emissions are reported as the sum of the grams of pollutant emitted over the interval divided by the total work.

5.2.7 Not to Exceed Zone

To determine emissions compliance of heavy-duty diesel vehicles, the “Not to Exceed Zone” was established for each engine model tested. The Not to Exceed Zone is a subset of the engine lug curve (maximum torque curve), bounded by minimum and maximum RPM levels and minimum torque levels at each RPM. When operating in this zone for a minimum of 30 consecutive seconds, the average emissions are not to exceed 1.5 times the certification standard according to the Consent Decree. The NTE zone is illustrated in the figure below.

The upper RPM limit (UL) is defined as N_{high}, the point at which only 70% of the maximum rated power is generated. The lower RPM limit is called the 15% ESC speed, which is a function of N_{low}, the point at which 50% of the maximum power is generated, and the ESC speed, which is the difference between N_{hi} and N_{low}.

$$15\%\ \text{ESC Speed} = N_{low} + .15(N_{hi} - N_{low}),$$

Finally, the minimum torque is defined by 30% of the maximum rated torque, or by 30% of the maximum power when the torque level at that condition is greater. A graphical depiction of the NTE zone is shown below.

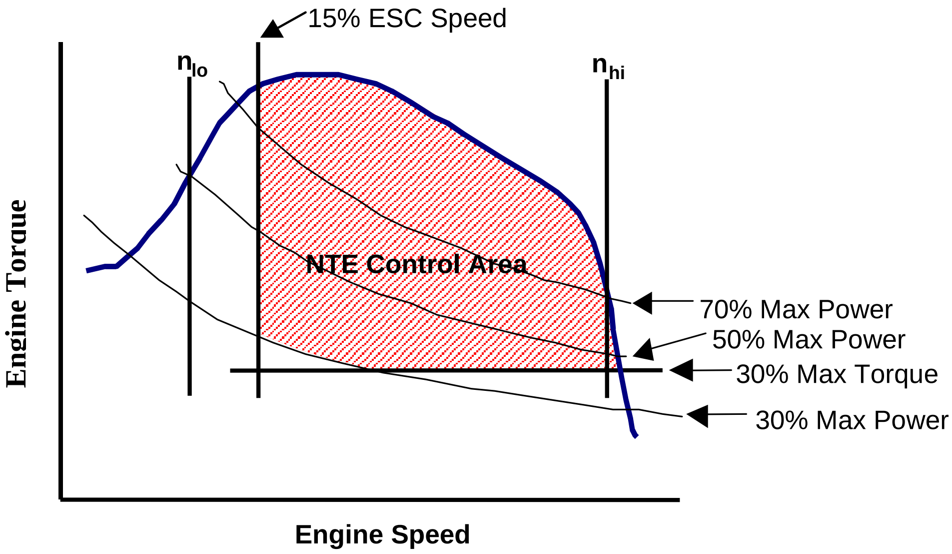


Figure 5.3 NTE Zone Boudaries

The following tables show the NTE zone boundaries for the engines tested in this study.

	Series 50	6V92
30% Max Torque =	267	267
30% Max Power =	82.6	82.6
50% Max Power =	138	138
70% Max Power =	193	193
Nhi RPM =	2607	2607
Nlo RPM =	973	973
15% ESC Speed	1218	1218

Table 5.2 NTE Boundaries

One important consideration is the curb-idle torque specification, which varies among manufacturers. Some report zero torque at the curb-idle condition, while other report actual (estimated) torque. It is obvious which is the case during a test, but it is still important to obtain the curb-idle torque specifications from manufacturers that omit it from the lug curve. Sensors, Inc has already developed the software platform to enter a lug curve for an engine and automatically indicate NTE zone operation during a test.

All of the Detroit Diesel engines report a Percent Load at curb idle, indicating that they account for all loads on the engine, including alternator, A/C , hydraulics etc. The torque computed using the above method is actually the torque at the crankshaft of the engine, rather than the flywheel.

5.2.8 Road Grade

Initially, the grade was to be measured with a liquid-level inclinometer. However, the vehicle acceleration introduced too much error for this method to be used for in-use testing, even when averaging over 10 seconds. Instead, the GPS data was used for grade calculation. Velocity is provided as one of the GPS data strings in addition to positional data. Combining the velocity at time t with the difference in altitude between time t and t-1 second, the instantaneous grade is computed as shown below. For this study, grade was computed on a 1 Hz basis without any time averaging or filtering.

$$Grade_t = \frac{velocity_t(\ ft / sec)}{altitude_t - altitude_{t-1}}$$

Obviously, there was significant instantaneous error in this calculation given the uncertainty in the GPS position. While the rated accuracy is 15 meters absolute, the repeatability in altitude was found to be much better at 1 – 2 meters based on limited testing. Still, this can generate significant errors, particularly at low speeds where there is less of a differential in distance traveled over the one-second interval.

It was left to the modelers to use this data in a manner that they deem appropriate. It was recommended that at least a 10 second moving average be applied to the raw data, after some basic filter function is applied to eliminate singularities. Future grade measurements can be enhanced by more accurate GPS devices. Sensors, Inc. has already incorporated alternate GPS products with significantly better accuracy in current production SEMTECH products.

5.3 Gasoline Engine Emissions Calculations

Gasoline emissions calculations are computed somewhat differently than with diesel engines, although many of the steps are similar. The following sections describe the various calculations performed for gasoline emissions.

5.3.1 Engine Airflow

Since fuel flowrate is not directly available from the OBDII vehicle interface on gasoline vehicles, it must be computed using engine airflow and air/fuel ratio. Section 4.3 describes the parameters obtained from the vehicle interface. The engine Load Factor (Type 1, 2 or 3) is used to compute real-time engine air flowrate in SCFM. The SAE J1850 general definition for Load Factor is

$$Load\ Factor = \frac{Current\ Engine\ Airflow}{Reference\ Airflow} x100$$

As discussed in section 4.3, the reference airflow is defined as the “maximum engine airflow”. This has been interpreted in a variety of ways, resulting in three types of load factor identified. See section 4.3 for further details. Complete equations for computing engine airflow are proprietary for Sensors, Inc. and are not provided in this report.

5.3.2 Exhaust Air/Fuel Ratio

Engine air/fuel ratio can be computed in a number of ways. The vehicle interface provides short-term Fuel Trim as a standard OBDII parameter, which can be used to compute lambda as described in section 4.3 above. Also, Lambda is directly provided from certain proprietary parameters based on the on-board sensors. However, there are limitations to this method. Fuel-rich, open-loop conditions resulting from aggressive accelerations or engine starting are often not reflected accurately with these parameters. Also, lambda from the vehicle interface does not account for mixing with the air volume in the tailpipe. Actual exhaust air/fuel ratios are much leaner at start conditions (due to mixing with the stagnant air) than indicated by the ECM. In fact, all transient exhaust air/fuel ratios are dampened by the mixing that takes place in the exhaust system.

For these reasons, the exhaust air/fuel ratio is computed using exhaust analysis techniques. It should be pointed out that the exhaust air/fuel ratio differs from the engine air/fuel ratio during such transients for the reasons described. However, the engines operate at stoichiometry for the vast majority of the time, when differences in lambda are negligible. The exact equations for exhaust air/fuel ratio computation are not provided in this document, but are widely available.

5.3.3 Fuel Flowrate and Fuel Economy

For gasoline engines, fuel flowrate is generally not provided directly. Some manufacturers provide pulse width of the fuel injectors, which could be use along with engine RPM to compute fuel rate. In this study, gasoline fuel rate was determined from the computed engine airflow and exhaust air/fuel ratio. Since the gasoline vehicles typically operated at stoichiometry, the variable most important in the calculation is the engine airflow.

5.3.4 Mass Emissions (grams/second)

Fuel-specific emissions and mass emissions are computed in the same manner as with diesel engines. The fuel flowrate is multiplied by the fuel-specific emissions.

5.3.5 Distance Specific Mass Emissions (grams/Mile)

Distance-specific emissions are computed for gasoline vehicles over a 30 second moving window and cumulative over the entire test. The mass emissions are summed over the test period and divided by the distance driven. The distance driven is computed from the vehicles speed data from the vehicle interface.

5.4 Quality Assurance

Because the SEMTECH products used in this study were prototypes, most of the data quality assurance was performed manually. There were cases of improper data, primarily from the ECM on some gasoline vehicles and many of the busses. There were also some cases where improper exhaust concentrations were recorded for reasons explained below. All of the anomalies were corrected if possible, or omitted from the data set.

5.4.1 Erroneous ECM data

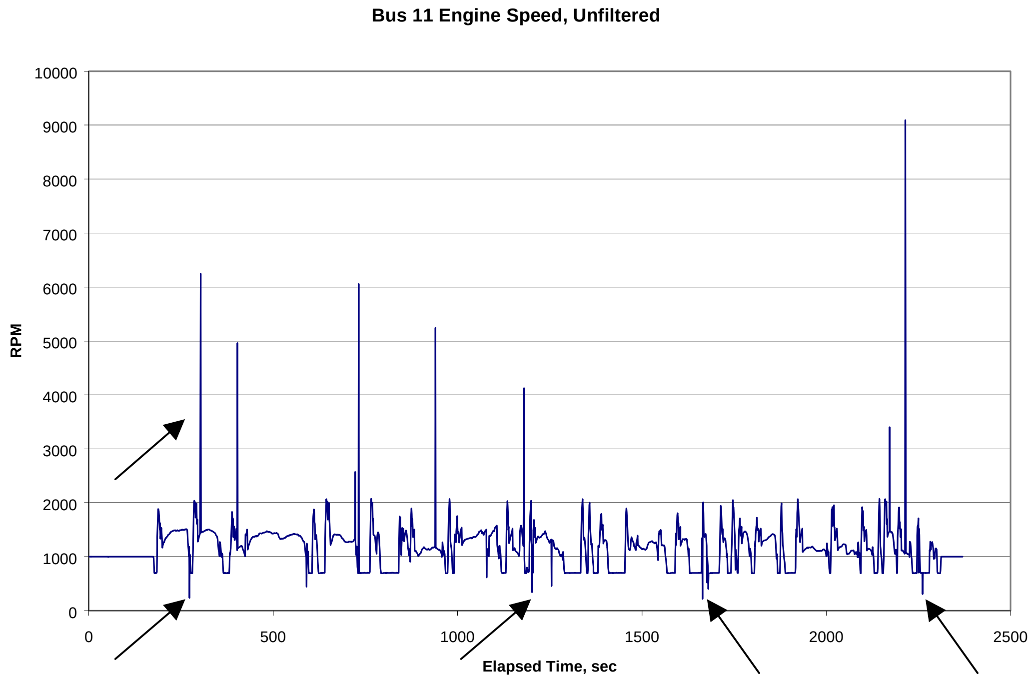
There were many cases where certain engine parameters were well outside of physical limits, particularly engine RPM and fuel flowrate on the busses. Because the errors were so great, they were easy to filter out with the post-processor. The following filter limits were imposed on the rate of change of RPM, fuel flow, and vehicle speed data:

- Rate of change limit for RPM = 10,000 (RPM)/sec (both gasoline and diesel)
- Rate of change limit for Fuel flow = .003 (gal/sec)/sec (diesel only)
- Rate of change limit for Vehicle speed = 21 (mph)/sec (both gasoline and diesel)

These filters will remove the data outside the defined limits. The SEMTECH post processor automatically interpolates between the remaining data, and produces results at 1 Hz as before. The reason the filters are applied to the rate of change of the parameters is because negative spikes can also occur. Data could be erroneous because of unreasonable engine acceleration or decelerations, and still be within reasonable absolute limits.

For example, Figure 5.4 shows erroneous engine speed data on bus 11, where positive spikes occur above 5000 and even 9000 RPM. Negative spikes also occur as pointed out with the arrows, and RPM data is below the curb idle levels. Figure 5.5 shows the same test with the RPM filters applied. Both the positive and negative spikes are removed by the filters, and RPM data is consistent and within physical limits.

Similar results are achieved by applying the filters to the vehicle speed and fuel flow data. Most of the data was screened by manually plotting the ECM parameters and computed mass results. However, there was no means to verify that all erroneous data was eliminated by these filter settings for all the busses. If any remaining data spikes exist in the data, then Sensors can modify further optimize the post processing software and re-process the data.



Erroneous positive
and negative spikes

Figure 5.4 Unfiltered Engine RPM

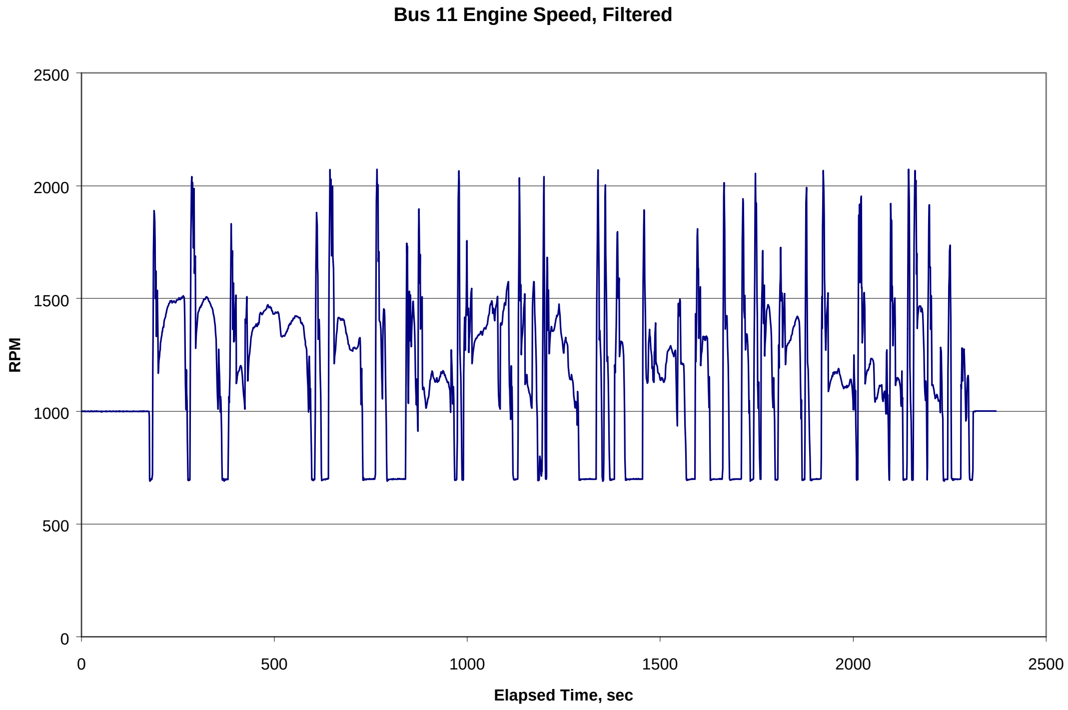


Figure 5.5 Filtered Engine RPM

5.4.2 Vehicle Speed Validation

Vehicle speed is a critical parameter from the vehicle interface that is easy to validate with the GPS. In general, there was good agreement with the GPS on the passenger cars. The following charts show this comparison for car 2. The slope of the regression line shows that the speeds agree within 2.5% for this vehicle, although there is some scatter in the instantaneous data at lower speeds. In addition, the GPS speed was validated manually using highway mile markers for 10 miles, and found to be within 1% accuracy based on this limited data.

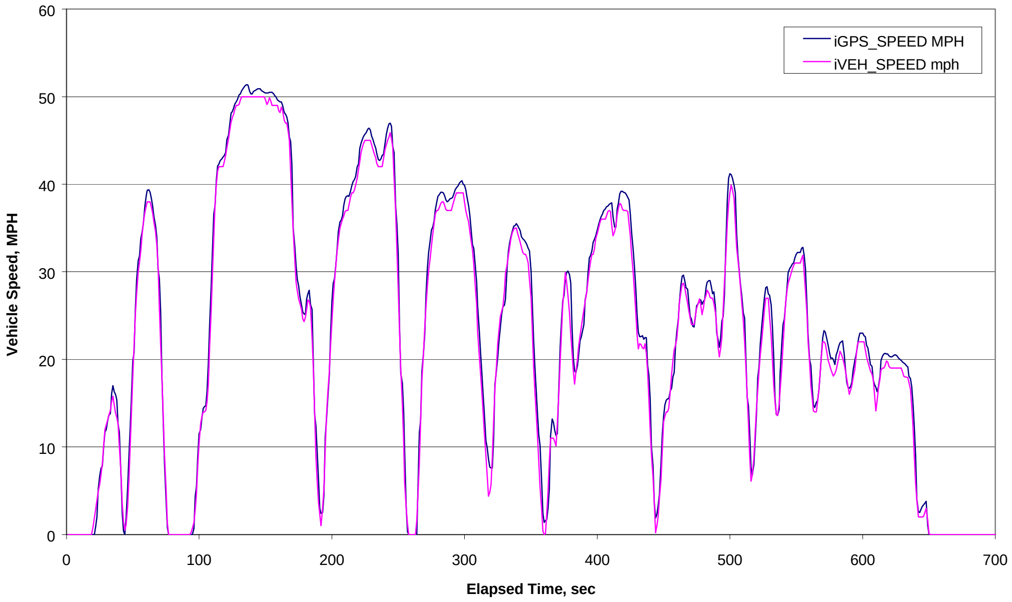


Figure 5.6 GPS vs ECM Vehicle Speed for Car 2

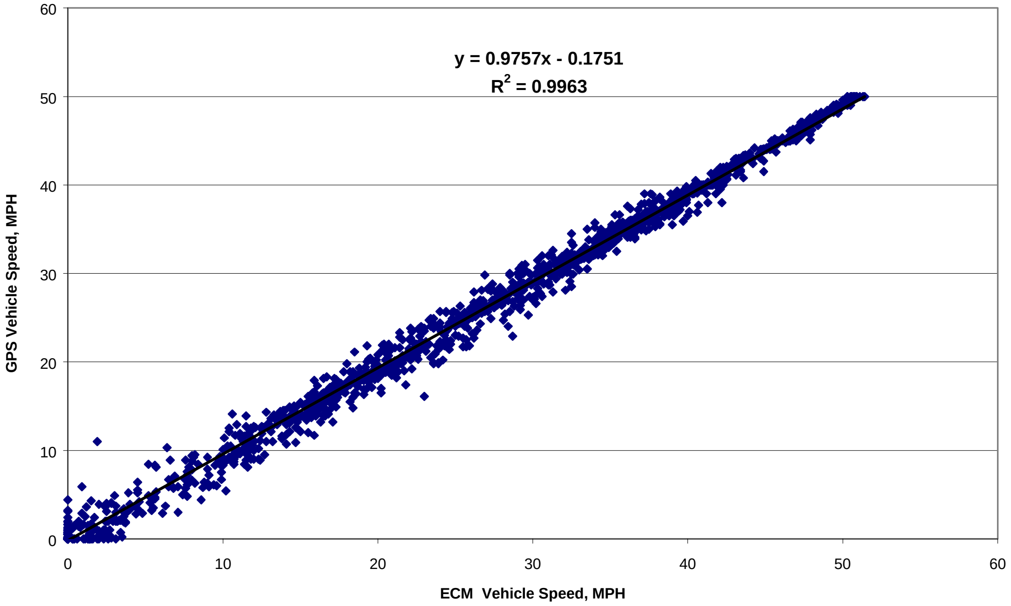


Table 5.3 GPS vs ECM Vehicle Speed Correlation for Car 2

For the busses, the ECM vehicle speed was not always as accurate or reliable. Figure 5.7 shows the GPS vs ECM comparison for Bus 1. The regression analysis shows that the ECM data is 10% high compared to the GPS. This comparison was not performed for all the buses, but suggests that GPS data may be more reliable for on-road testing. This may not be significant for diesel-powered vehicles since the vehicle speed is not used in the mass emissions calculations.

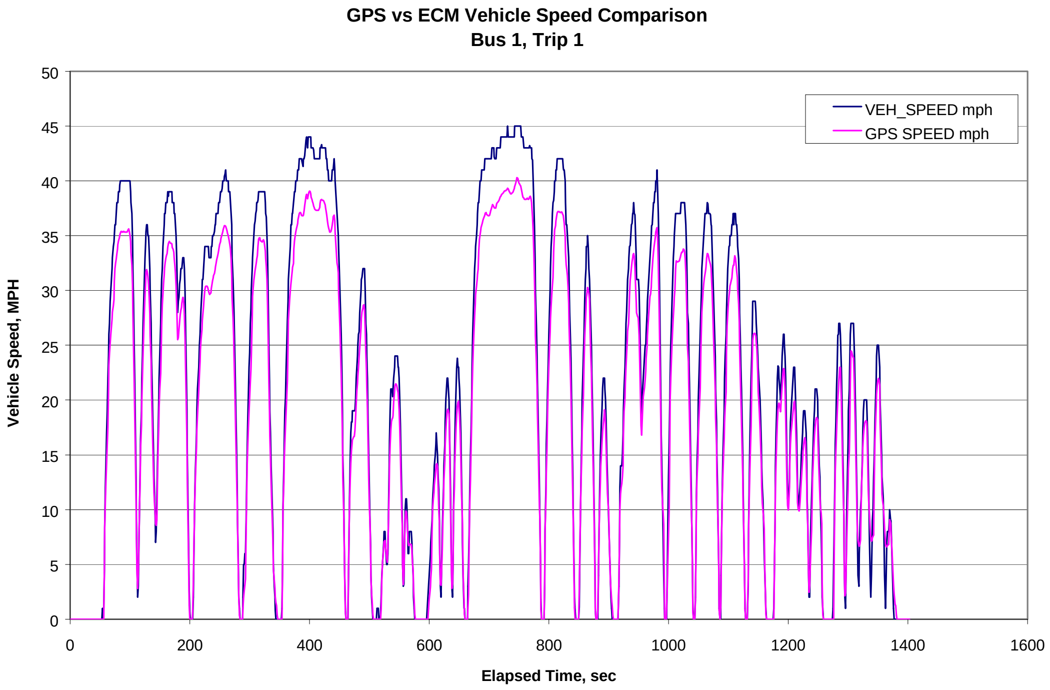


Figure 5.7 Bus 1 GPS vs ECM Vehicle Speed

Older (model year 1995) buses were equipped with an earlier version ECM that did not provide vehicle speed. This was also the case with the 1992 bus with the upgraded 6V92 engine. In these cases, the GPS velocity data was used in place of the ECM data. This affected buses 9,12,13, and 11. This was a relatively easy correction to make, since the GPS provides velocity data. The post processor was modified to report the GPS velocity instead of the ECM vehicle speed for these busses.

There were some erroneous vehicle speed data points (drop-outs) on several of the buses and two suspect data points for car 9. To catch bad data and correct it, an algorithm was implemented that searches for unreasonable accelerations and deletes the suspect velocity data points. The post-processor then interpolates a new velocity based on the surrounding good points.

5.4.3 GPS Dropouts

There were a few instances when the GPS lost communication with the satellite for unknown reasons. When this occurs, the GPS signal is not necessarily reported as zero, but some fixed, default position. It is usually obvious in the data when this occurs. This type of error was not prevalent, except for bus 11. The erroneous GPS data for this bus was discovered by the modelers, who had to remove it manually.

5.4.4 Fuel flow QA

As discussed in section 5.2.4, the reported fuel flow on the diesel buses proved to be unreliable at low levels, (below 1000 RPM). Fuel flows were checked at low power conditions by comparing CO_2 mass emissions using the fuel-flow method with results based on calculated engine airflow. Engine airflow can be computed with reasonable accuracy at low RPM conditions (when the turbo is not engaged) using a simple displacement method with an assumed volumetric efficiency of 0.85.

Figure 5.8 illustrates this point for bus 10. At curb idle (600 RPM), we see that the mass values based on the reported fuel flow method differ significantly from the mass values using the exhaust flow method. That is because the fuel flow readings become erratic and often approach zero below 1000 RPM at steady-state, and 1400 RPM on decels. When the bus was set to “high” idle (1000 RPM), the two methods match very closely, providing validation of the fuel flow accuracy. At higher power conditions, the turbo-charger is engaged, and engine airflow cannot be computed with the displacement method.

.

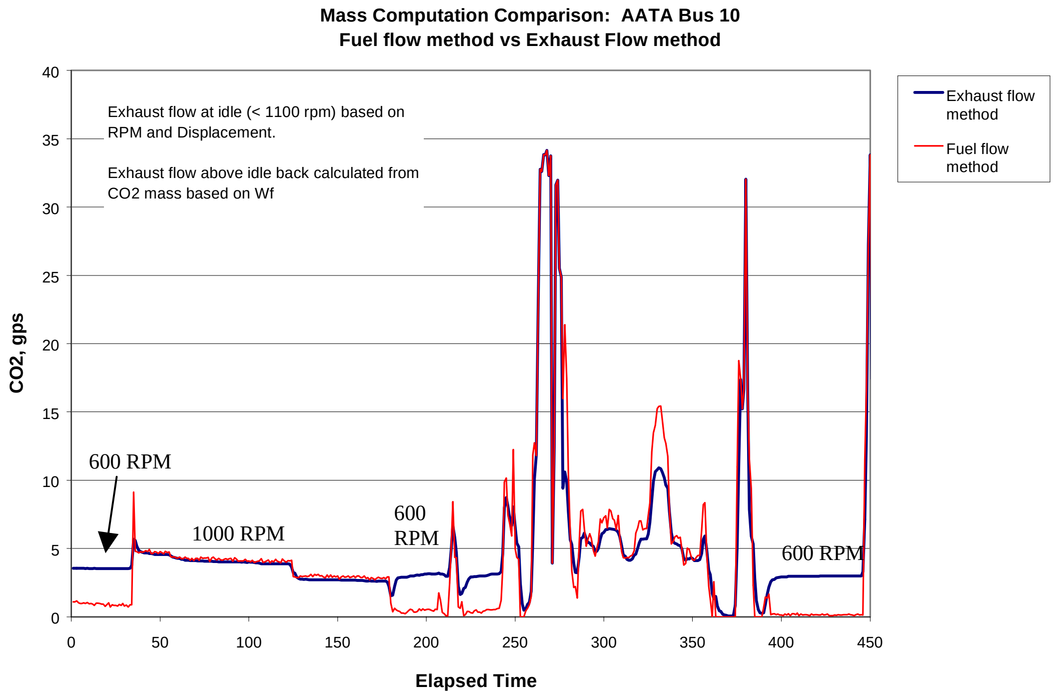


Figure 5.8 Fuel Flow Errors at Low RPM

To correct the inaccurate fuel flows at idle, there were two plausible choices. First, the engine airflow method could have been used to compute mass emissions below 1400 RPM. We would still have incorrect fuel flow readings however. The second possible solution was to use an alternate fuel flow that is computed based on the brake-specific fuel consumption (BSFC) curve supplied by the engine manufacturer. This also proved to be a reliable approach, and mass results matched well with the exhaust flow method at low RPMs.

Figure 5.9 shows the BSFC data from the engine manufacturer over the range of engine speeds. In order to compute fuel flow from this data, the engine torque data is applied. At each second during the test, engine power is computed based on the real-time torque, and fuel flow is computed using the BSFC value:

Wf_BSFC (g/sec) = Engine Power (BHp)/3600 x BSFC (gram fuel/BHp-hr)

where the BSFC value is a function of the current RPM. A polynomial curve fit shown on the chart was used to compute the BSFC values.

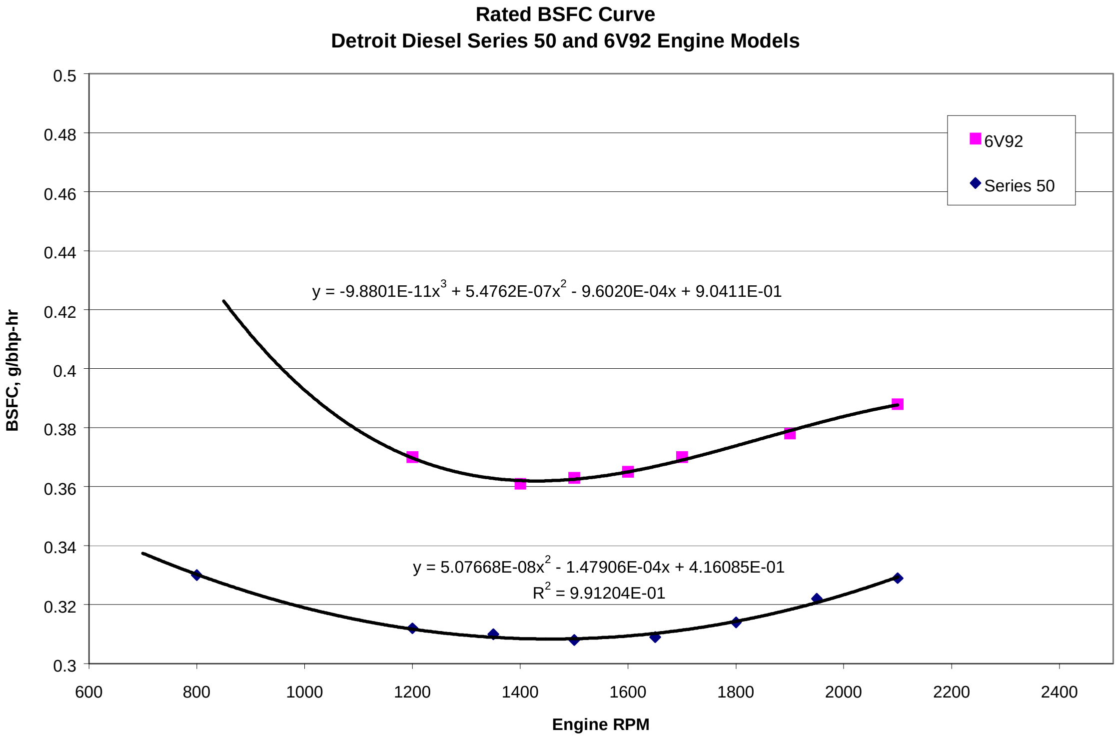


Figure 5.9 BSFC Curves for Detroit Diesel Engines

Figure 5.10 again shows the ECM fuel flow data for bus 10 compared to fuel flow derived from the BSFC curve. There is good agreement in the two methods at 1000 RPM, but the BSFC-based flowrate generates mass results that match much better with the exhaust flow method. Note the good agreement at higher flowrates as well.

The BSFC fuel flow also provides a good cross-check against the ECM reported fuel flowrate. As you can see, there is good agreement at all conditions above idle. This comparison was performed on several other bus tests and was found to be favorable as well.

The solution that was selected to correct the ECM fuel flow was to use the BSFC-based fuel flow anytime the RPM dropped below 1400. This provided more accurate mass emissions at these conditions, and also provided more accurate fuel flow results.

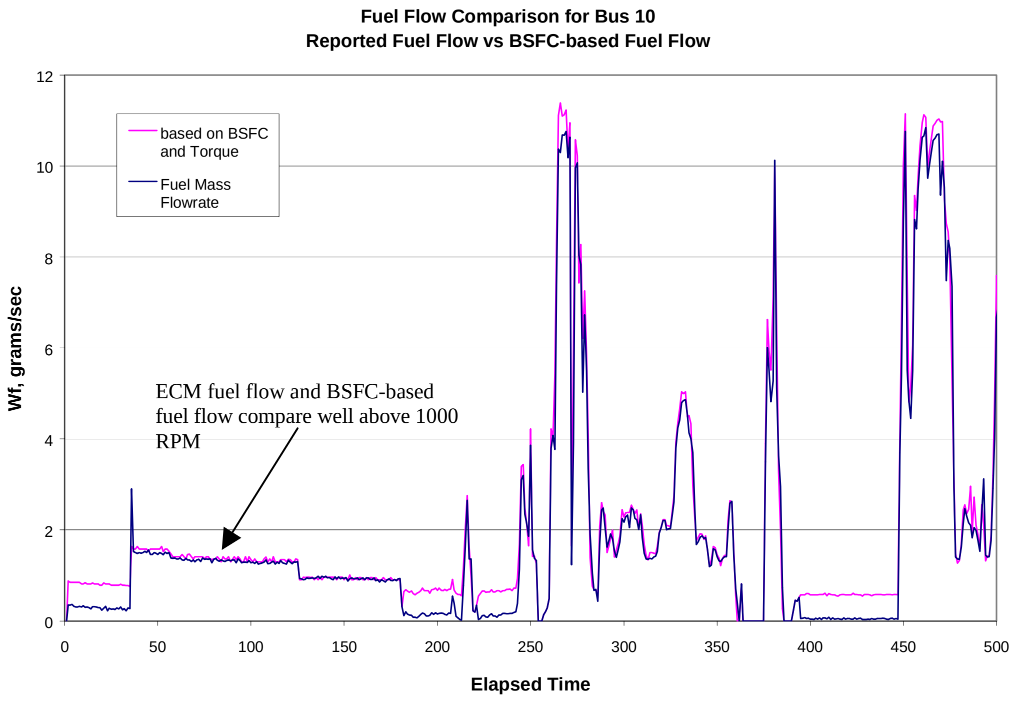


Figure 5.10 Corrected Fuel Flows at Low RPM

5.4.5 Erroneous zero Calibration

Car 12, trip 1 showed an improper zero calibration for HC. The readings were significantly negative (-48 ppm) for nearly the entire first test, and then were OK on the subsequent test. The other emissions were normal. This indicates that the analyzer was zero calibrated in the presence of a significant HC source. A gasoline container in the garage could cause this problem. The mass emissions are reported as zero for these negative readings, and users should ignore this data.

5.4.6 Erroneous NO results

One of the SEMTECH-G systems had an intermittent electronics failure on the NDUV NO analyzer, causing it to occasionally lock up during a test for significant periods. Data was manually removed in these cases. This only affected cars 12, 15, and 16.

The NDUV NO analyzer was not communicating for Car 13, so NO data was not available for this vehicle. The communications were re-established after cycling power to the analyzer. It is unknown what caused the malfunction.

5.4.7 FID flame outs

The FID flamed out several times during the bus testing either due to user error or because the fuel ran out. The data was manually removed in these cases:

Bus 1: FID was off for first 6 minutes of trip 1.
Bus 2: FID was off for entire 1st trip; FID was out during small portion of 2nd trip.
Bus 4: FID was off for first 7 minutes.
Bus 9: FID was off for small portion of trip 4 to change fuel bottle.

5.4.8 Erroneous Throttle Position Data

For the HD diesel bus data, the throttle position values from the ECM were converted incorrectly. Reported values need to be multiplied by 10. This problem has been fixed in current SEMTECH-D software.

6 Bus Emissions Summary

Because most of the buses were of the same model with the same engine, the road test data itself was valuable for comparison. Some statistics were computed that show good consistency in results among the buses.

The results of the emissions testing for the 15 series 50 engines is shown in the tables below. Table 6.1 is a summary of driving conditions, including elapsed test time, average bus speed, total fuel consumed, total distance traveled, overall fuel economy, and frequency of NTE zone operation. The frequency of NTE zone operation gives an indication of how the bus was operated.

Bus #	DATE	Elapsed Time	Average speed	Total fuel used	Total Distance Traveled	NTE_ZONE occurrences
		seconds	mph	gal	miles	% of total
1	10/17/01	3140	19.93	3.46	17.4	34.0%
2	10/17/01	8461	18.24	6.99	42.9	30.6%
3	10/18/01	8431	16.54	6.85	38.7	25.4%
4	10/19/01	10347	17.31	8.46	49.7	26.4%
5	10/19/01	7951	18.24	6.88	40.3	27.0%
6	10/22/01	7295	16.32	6.63	33.1	25.2%
7	10/23/01	8023	13.03	7.80	29.0	17.0%
8	10/23/01	7888	15.10	8.24	33.1	26.4%
9	10/24/01	8091	12.10	7.85	27.2	20.9%
10	10/24/01	8069	13.82	6.48	31.0	26.7%
11	10/25/01	5644	23.65	5.81	37.1	50.8%
12	10/25/01	7858	15.69	8.31	34.2	25.2%
13	10/25/01	8061	10.50	6.99	23.5	19.3%
14	10/26/01	5283	21.43	5.12	31.4	32.3%
15	10/26/01	5688	17.71	5.30	28.0	29.7%

Table 6.1 Overall Trip Summary for each Bus

Table 6.2 shows the average emissions over the entire test in grams/bhp, as well as fuel economy. It also shows statistics for the 15 bus sample, including average, standard deviation, and upper an lower control limits based on two standard deviations. The control limits give an indication as to whether there were any significant outliers in the bus data.

The CO2 results are important to consider when evaluating the data quality. Typically, the brake-specific CO2 emissions are consistent for a given engine family, regardless of the operating conditions. For the 15 Series 50 engines, the CO2 results were very consistent, with a standard deviation of only 20.2 g/bhp-hr, or 4.4% of the average. This indicates that both the bus test population is consistent, and the mass emissions results from SEMTECH are consistent among the population. Fuel economy varied between 3.37 mpg and 6.39 mpg. This is not expected to be as consistent as brake-specific CO2, since the route and driving conditions can greatly affect the result.

Corrected NOx emissions varied from 3.45 to 6.36 g/bhp -hr for the population, with and average of 5.25 compared to a certification standard of 5.0 g/bhp -hr. The standard deviation was 0.89 g/BHp-hr, or 17%. While these results fall within 1.5 x the certification standard, the NTE zone emissions must be evaluated to determine if the busses were in violation. Average CO and THC emissions were well below the standards at 1.56 and 0.073 g/bhp-hr respectively.

Bus #	Fuel economy	CO2	CO	NOx	KNOx	THC
	mpg	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
1	5.03	461.3	2.23	7.39	5.95	0.056
2	6.13	460.3	2.03	7.27	5.86	0.077
3	5.66	460.0	1.35	6.81	5.53	0.098
4	5.88	459.8	2.69	7.13	6.08	0.084
5	5.85	460.8	1.40	7.23	6.36	0.097
6	4.99	499.1	1.88	5.64	4.94	0.033
7	3.72	485.1	2.59	5.32	5.13	0.053
8	4.02	447.1	1.30	4.61	4.52	0.077
9	3.46	452.0	1.32	3.58	3.45	0.026
10	4.78	447.3	1.22	3.52	3.69	0.015
11	6.39	415.6	0.78	7.35	6.13	0.057
12	4.12	462.2	1.34	7.02	5.74	0.059
13	3.37	441.7	1.49	6.84	5.48	0.093
14	6.15	472.9	0.83	5.27	4.36	0.118
15	5.28	431.0	0.96	6.59	5.51	0.157
average	4.99	457.1	1.56	6.10	5.25	0.0733
Std dev	1.03	20.2	0.60	1.36	0.89	0.0369
2S UCL	7.06	497.6	2.75	8.82	7.03	0.1471
2S LCL	2.92	416.6	0.37	3.39	3.47	0.0000

Table 6.2 Average Trip Emissions for each Bus and Statistics

7 Heavy Duty Diesel Correlation Testing

A heavy-duty chasis dynamometer test cell was not available to perform correlation testing on any of the buses tested in the study. However, considerable correlation testing has been performed on SEMTECH-D in engine test cells at various locations. Extensive correlation testing of SEMTECH-D was performed at various engine manufacturers, including Caterpillar, and two other anonymous customers (hereafter referred to as Customer 2 and Customer 3). While this testing helped to fulfill requirements for the EPA Statement of Work, the engine manufacturers provided this cooperation mostly for their own evaluation of SEMTECH. The following is a summary of the correlation testing performed:

<u>February, 2002. Caterpillar</u>

- Six 13-mode steady-state tests on C-10 engine compared to Horiba Mexa 7100.
- 3 transient FTP tests compared to Horiba Mexa 7100.
- Correlation data is public.

<u>February, 2002. Customer 2</u>

- 34 steady-state points on undisclosed engine compared to Horiba Mexa 7100.
- FTP transient tests compared to Horiba Mexa 7100.
- Correlation data is public, but engine information is undisclosed.

<u>May, 2002. Customer 3</u>

- 75 steady-state test points compared to laboratory equipment.
- Same engine installed in HD truck, then tested on chassis dynamometer and on-road from Detroit to Portland, Oregon.

While much of the test data has been made public, a significant portion has not been released and is considered proprietary information. Further, none of the raw data from the test cells can be released to the public.

Most of the testing has been performed in engine dynamometer cells, and very limited ECM data was available. Therefore, most of the direct comparisons are for emissions concentrations only. Even if the ECM data was available, it was not on the same engine family as tested. Parameters that contribute to mass emissions (such as engine torque from the ECM) are unique to each engine family, and cannot be directly validated in a sample study.

Still, there is extensive data to demonstrate the performance of the various SEMTECH-D gas analyzers, and to quantify the mass emissions ucertainty due to concentration measurements. When the other measurement uncertainties are determined, the overall system accuracy can easily be determined through a root-mean-square (RMS) error analysis.

7.1 Steady-State Correlation Testing

There have been numerous steady-state tests performed on SEMTECH-D at Caterpillar, Customer 2, and Customer 3. In each case, raw exhaust emissions were compared against laboratory instruments during typical 13-mode testing as well as off-cycle points. Figure 7.1 through Figure 7.4 show regression charts for the steady-state correlation testing performed at Caterpillar. On each chart is 78 data points, representing six 13-mode steady-state tests performed over a two-day period on a C-10 production engine. These results show good agreement with the Horiba MEXA 7100, and are typical for direct concentration comparisons performed at other facilities. The repeatability of the SEMTECH data is also demonstrated on these charts.

Table 7.1 summarizes the majority of steady-state correlation testing performed at the various facilities. The regression slopes, intercepts, and correlation coefficients are very near perfect, and very consistent for the three data sets. All of this data has been independently verified by the manufacturers who hosted the studies. Customer 2 and Customer 3 elected to keep the engine family undisclosed, but are willing to release the regression statistics.

The standard error of each regression line was determined for each constituent in each study. Multiplying this value by 2 gives an approximation of the 95% CI measurement uncertainty for the full range of steady state concentrations. The standard errors were typically 17 ppm for CO, 7 ppm for NO_x, and 3 ppm for THC. The NO_x standard error was higher (12 ppm) for the Customer 2 study, but still well within acceptable limits.

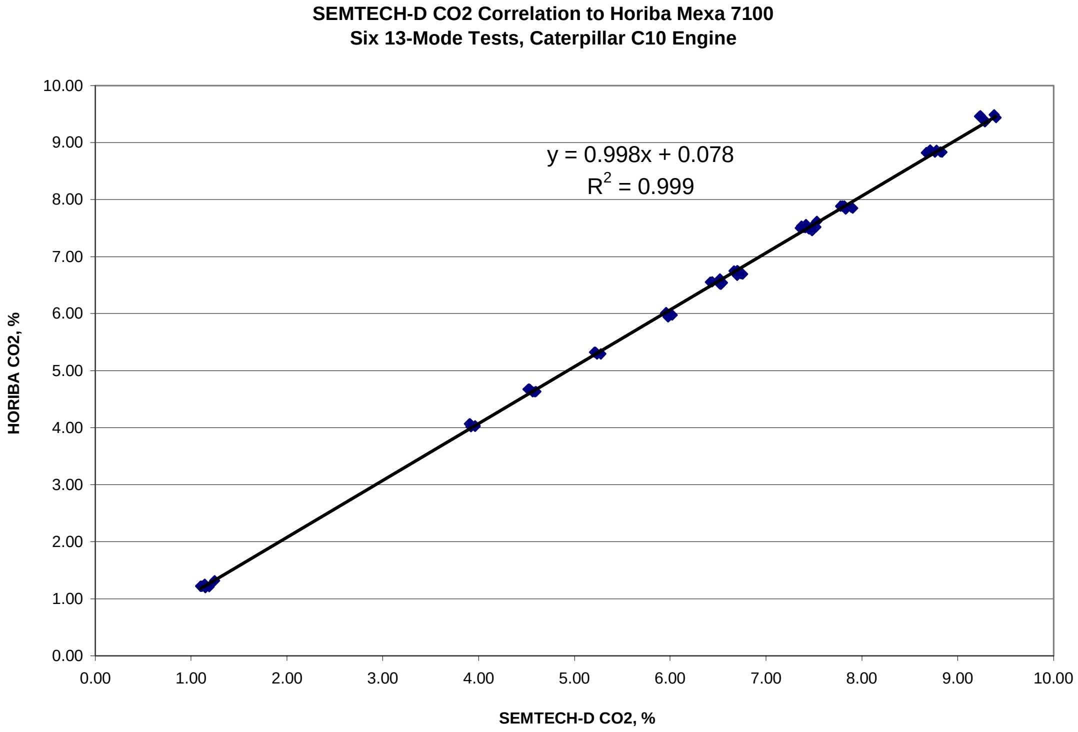


Figure 7.1 SEMTECH-D Steady-State CO_2 Correlation

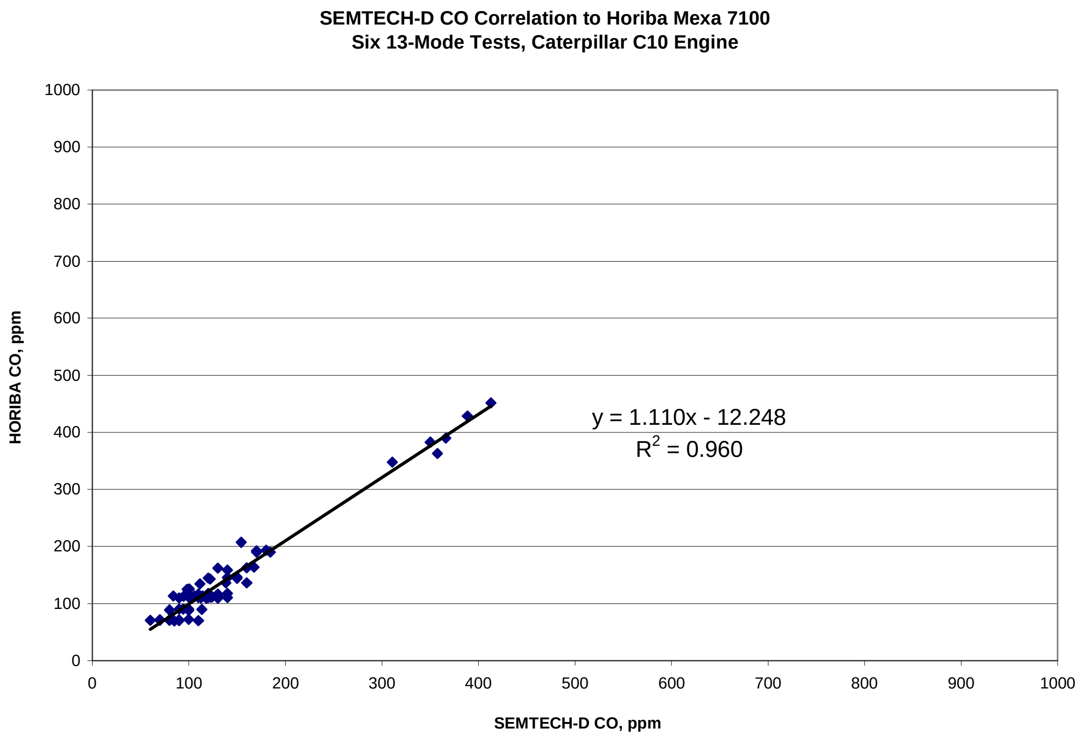


Figure 7.2 SEMTECH-D Steady-State CO Correlation

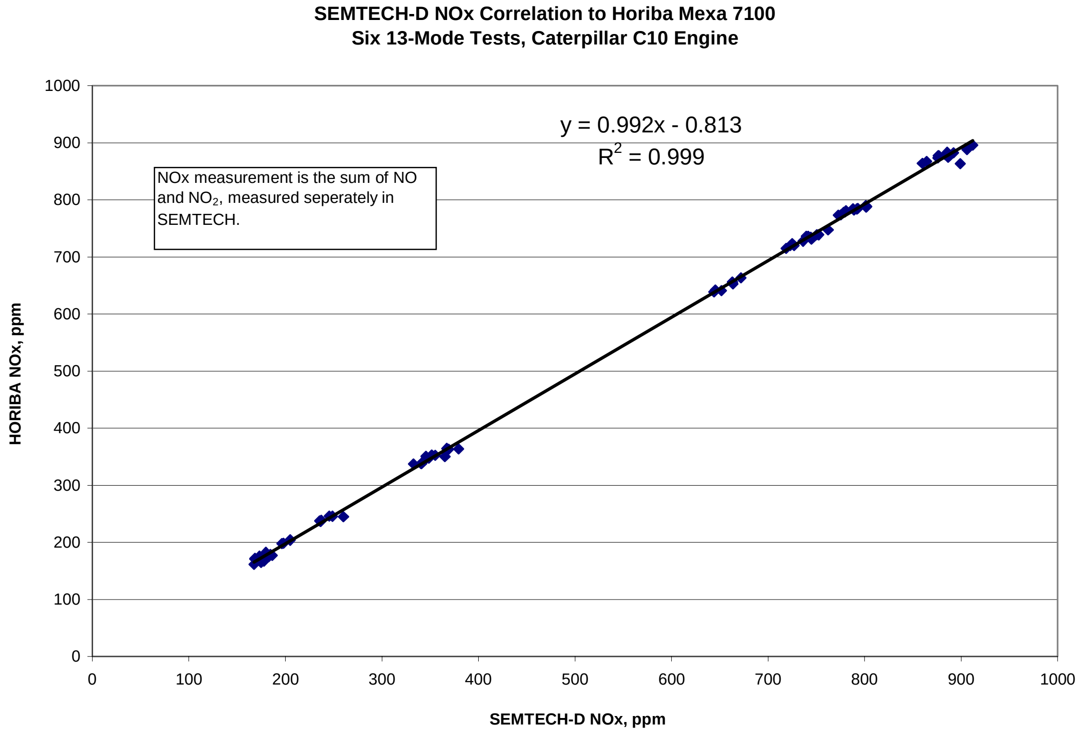


Figure 7.3 SEMTECH-D Steady-State NO$_x$ Correlation

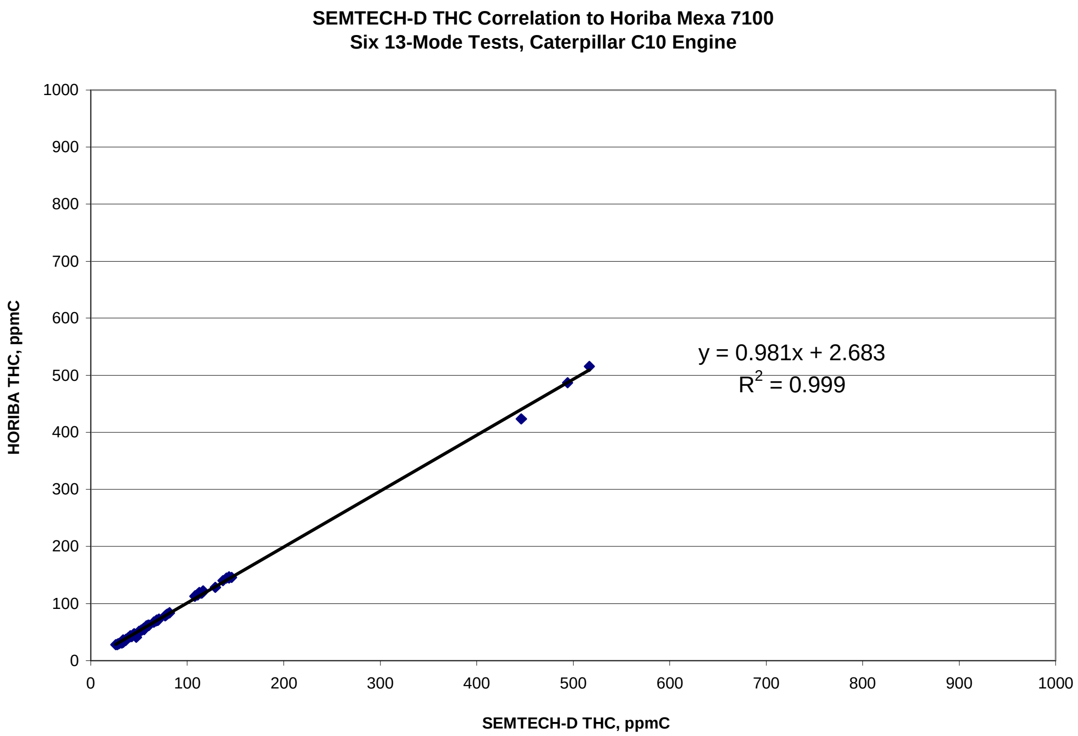


Figure 7.4 SEMTECH-D Steady-State THC Correlation

	n	Slope	Intercept	Data Range	Correlation Coefficient, r^2	Std Error
Caterpillar C-10 Engine						
CO_2	78	.998	.078%	1.1 – 9.4%	.999	.067%
CO	78	1.110	-12 ppm	70 – 451 ppm	.960	16.7 ppm
NO_x	78	.992	-.81 ppm	160 – 900 ppm	.999	6.6 ppm
FID THC	78	.981	2.68 ppm	26 – 515 ppm	.999	3.3 ppm
Customer 2 Engine						
CO_2	34	.982	-.076%	4.1 – 12.7%	.999	.083%
CO	34	1.00	-20.9 ppm	10 – 760 ppm	.980	16.7 ppm
NO_x	34	1.022	-10.2 ppm	175 –1470 ppm	.999	12.8 ppm
FID THC	34	1.055	-1.8 ppm	7 – 49 ppm	.943	2.8 ppm
Customer 3 Engine						
CO_2	74	.963	.074%	1.4 – 9%	.999	.054%
CO	74	1.02	-6.4 ppm	23 – 163 ppm	.934	8.4 ppm
NO_x	74	.999	-5.4 ppm	185 – 1175 ppm	.999	7.0 ppm
FID THC	74	.73	5.9 ppm	7 – 31 ppm	.934	1.4 ppm

Table 7.1 SEMTECH-D Steady-State Correlation Results Summary

7.2 Transient FTP Comparisons

In addition to the steady-state testing, eleven transient FTP cycles were also performed in order to assess SEMTECH-D accuracy and repeatability under these conditions. Figure 7.5 through Figure 7.8 show SEMTECH-D transient raw emissions compared to a Horiba MEXA 7100 during one of the FTP tests. These charts are typical of all of the transient tests performed. While the transient response time of SEMTECH meets the requirements of the RFP, it is evident that the Horiba achieves higher peaks in some cases. However, the error of the integrated mass due to response time differences is negligible, as demonstrated below.

In order to quantify the error associated with the SEMTECH-D transient concentrations, mass emissions results were calculated using engine airflow and engine torque as reported by the test cell instrumentation. Exhaust flow was computed by determining the chemical air/fuel ratio of the exhaust, and adding the fuel mass to the airflow. Also, dry concentrations were converted to wet using appropriate equations. The integrated brake-specific emissions results were then computed and compared to the Horiba MEXA 7100 results. Figure 7.9 through Figure 7.12 show the transient mass comparison for one of the FTP tests. Since the MEXA 7100 uses the same data compute mass emissions, the differences are due solely to the concentration measurements. Note that the overall integrated mass results were within 2.5% of the Horiba MEXA 7100 for all of the constituents. The NO_x mass result was an exact match, indicating that the response time differences average out over the cycle.

Note that in the case of CO and CO_2, the integrated mass values using the SEMTECH-D concentrations were within 1% and 2% of the Horiba system respectively. This was consistent with other tests as well, as discussed below. This data demonstrates that the .83 Hz data rate for these analyzers is sufficient.

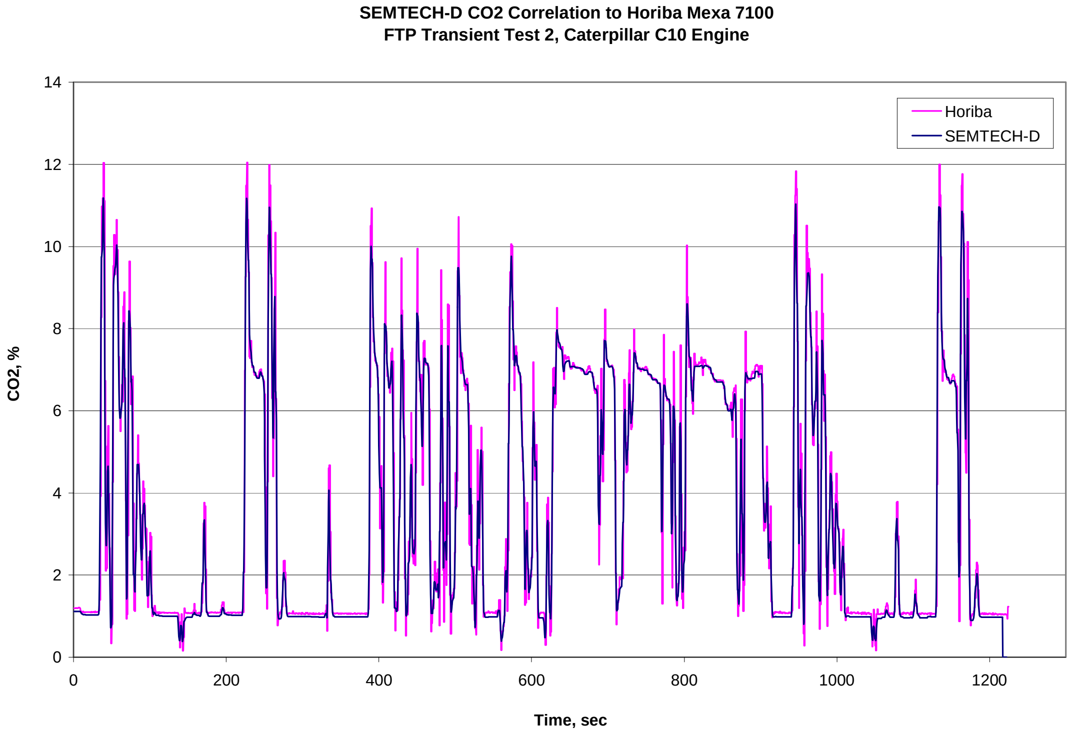


Figure 7.5 SEMTECH-D Transient CO_2 Comparison

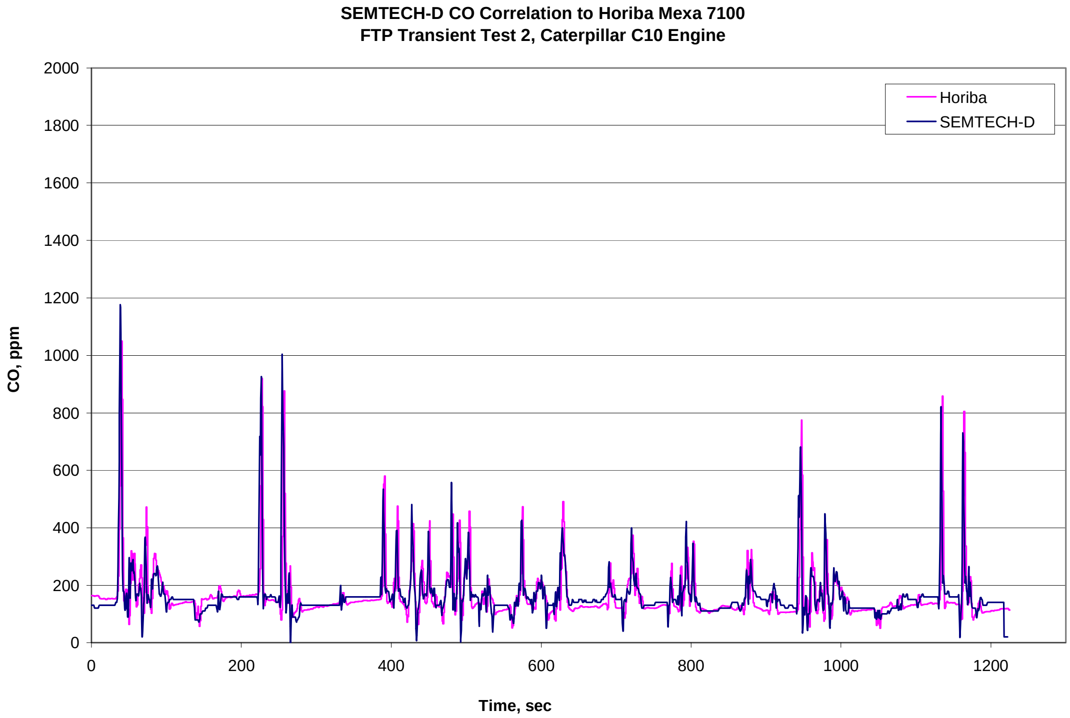


Figure 7.6 Transient CO Comparison

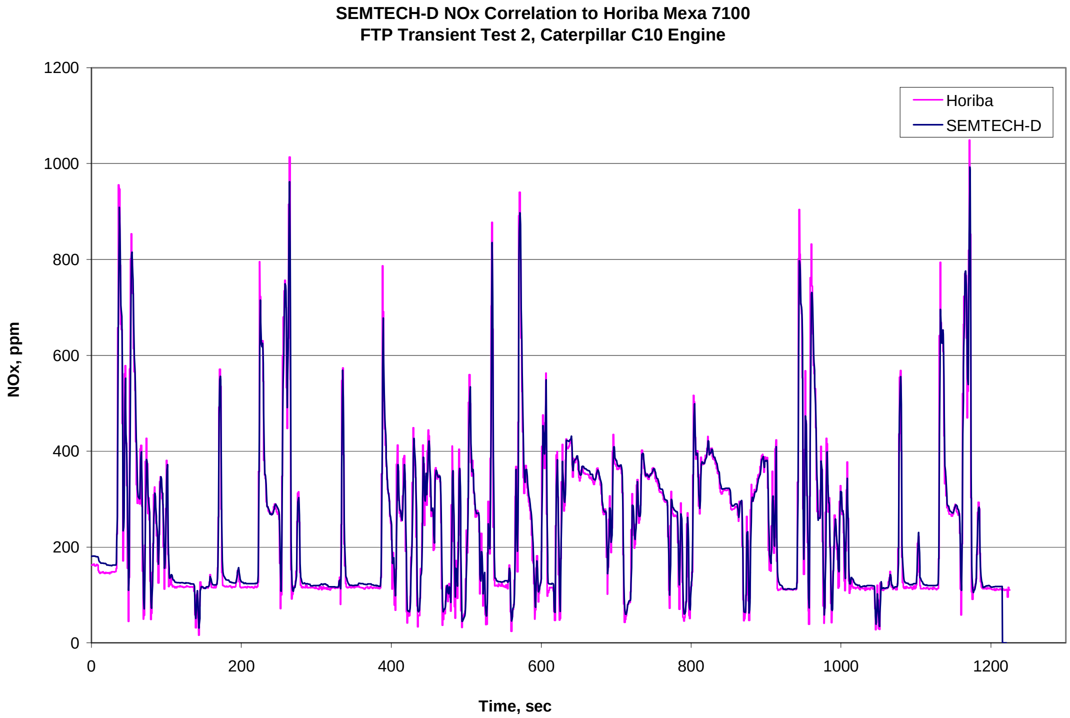


Figure 7.7 Transient NO_x Comparison

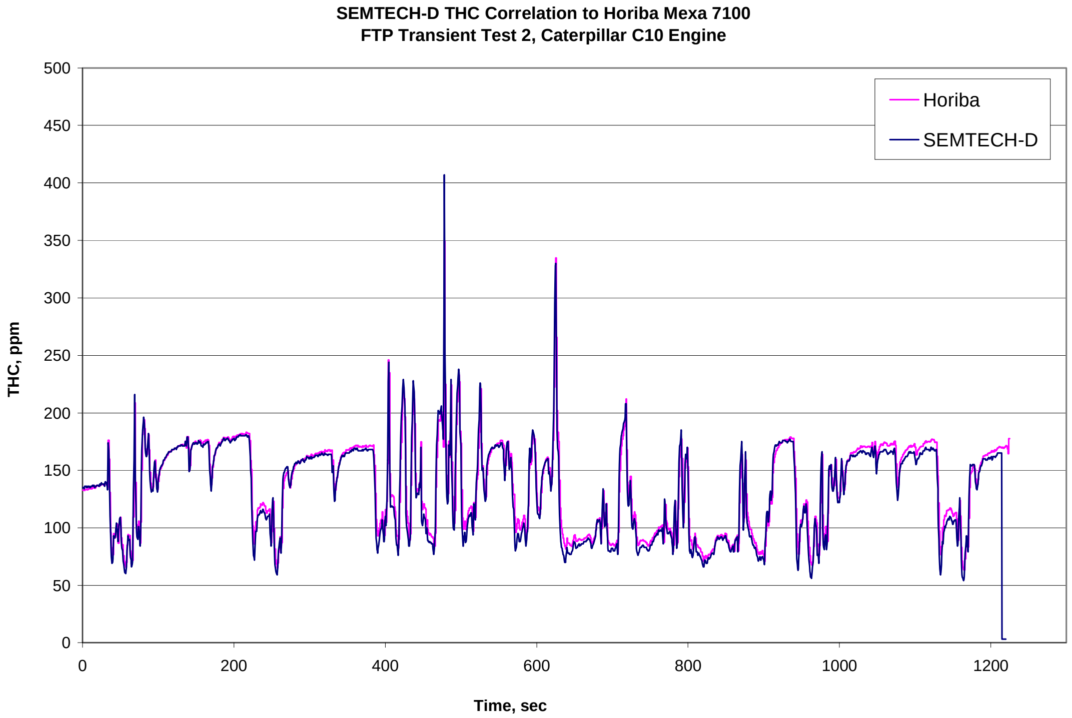


Figure 7.8 Transient THC Comparison

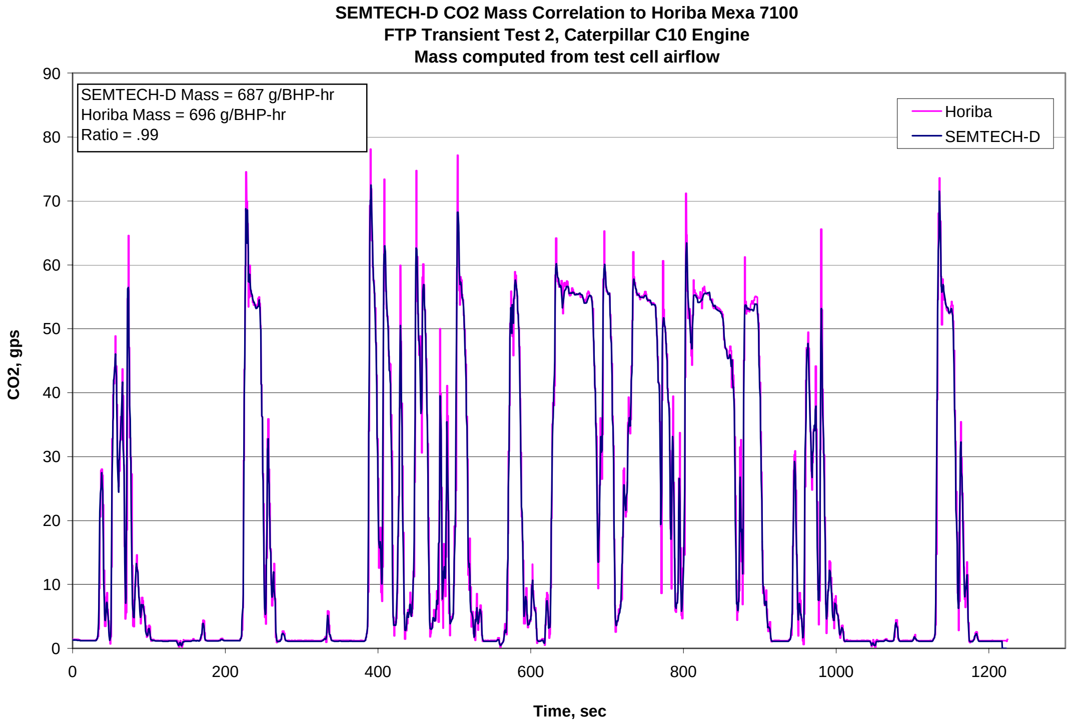


Figure 7.9 Transient CO_2 Mass Comparison

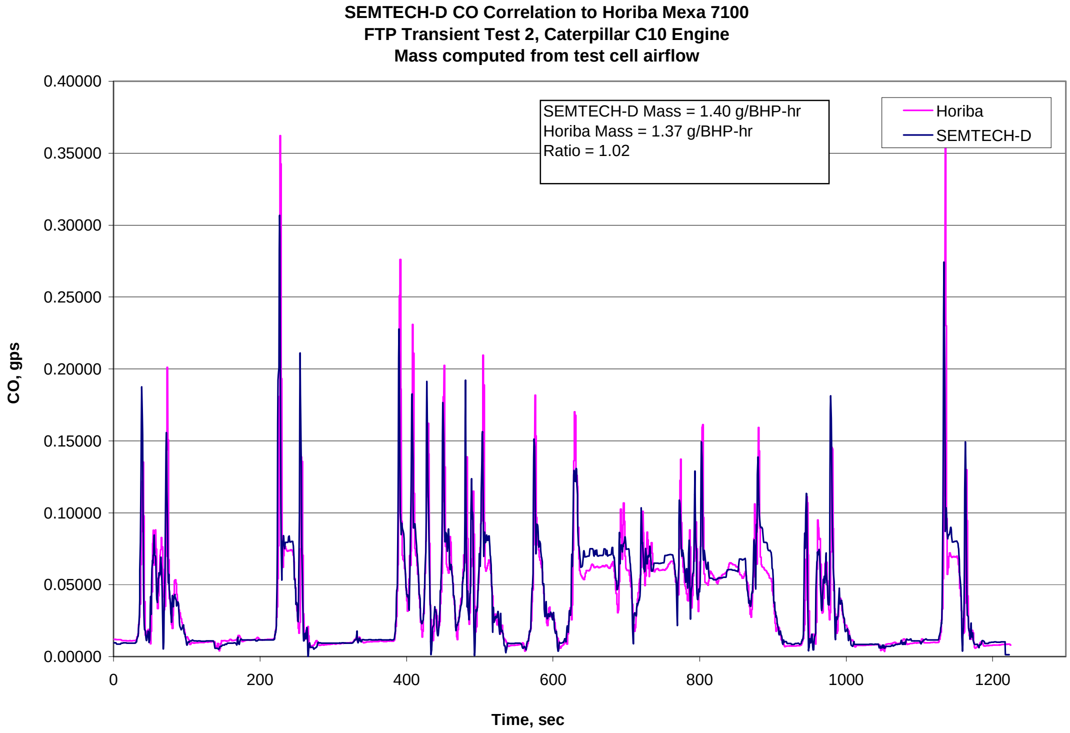


Figure 7.10 SEMTECH-D Transient CO Mass Comparison

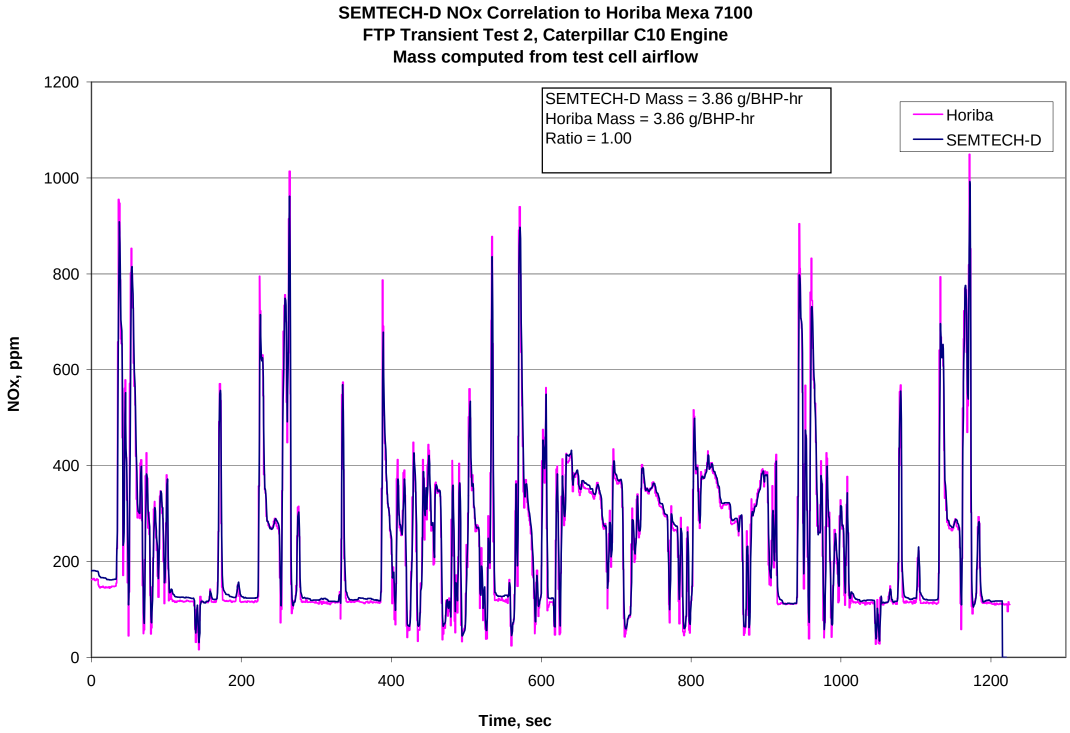


Figure 7.11 Transient NO_x Mass Comparison

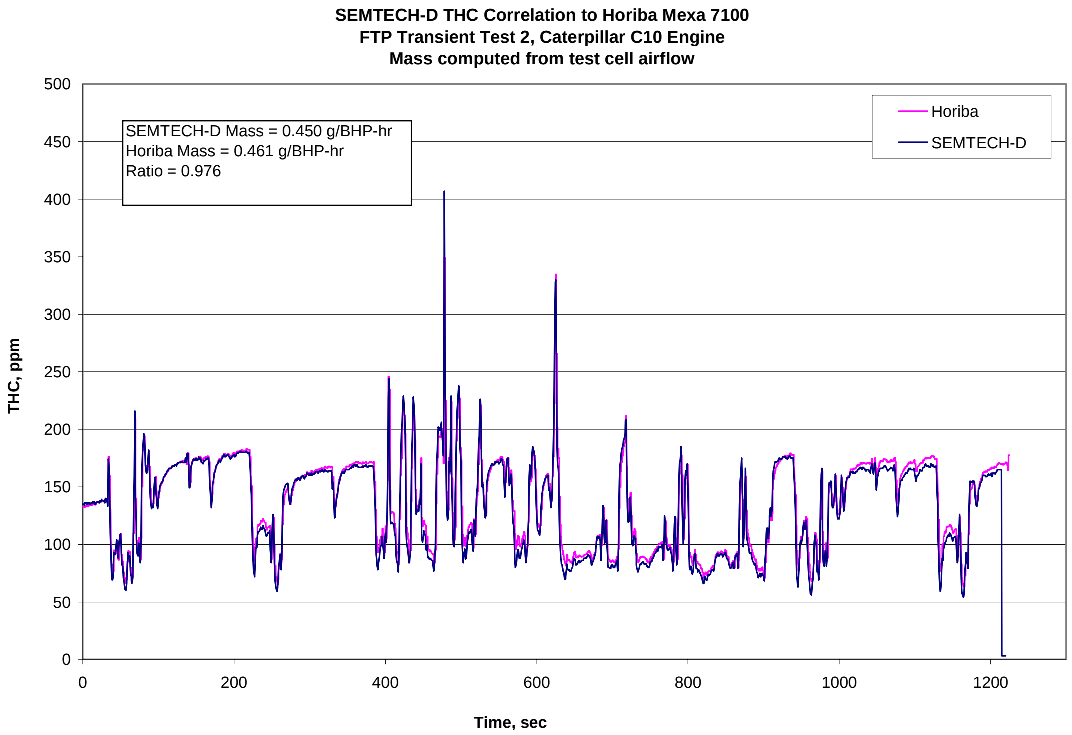


Figure 7.12 SEMTECH-D Transient THC Mass Comparison

The other FTP tests demonstrate similar results. Figure 7.13 shows a control chart of the percent mass emissions error for each of the constituents for each of the eleven FTP tests. Three of the tests were performed over a two-day period at Caterpillar on a C-10 engine. The other eight were all performed on a single Customer 2 engine over a 2-day period. All of the results are well within the required 10% error limit. Again, the errors shown are primarily attributed to the concentration measurement. These results demonstrate quantitatively the accuracy and repeatability of the concentration measurements over a transient cycle.

This data also substantiates over the entire set of transient tests, that the data rate for the CO and CO_2 measurements are sufficient at .83 Hz.

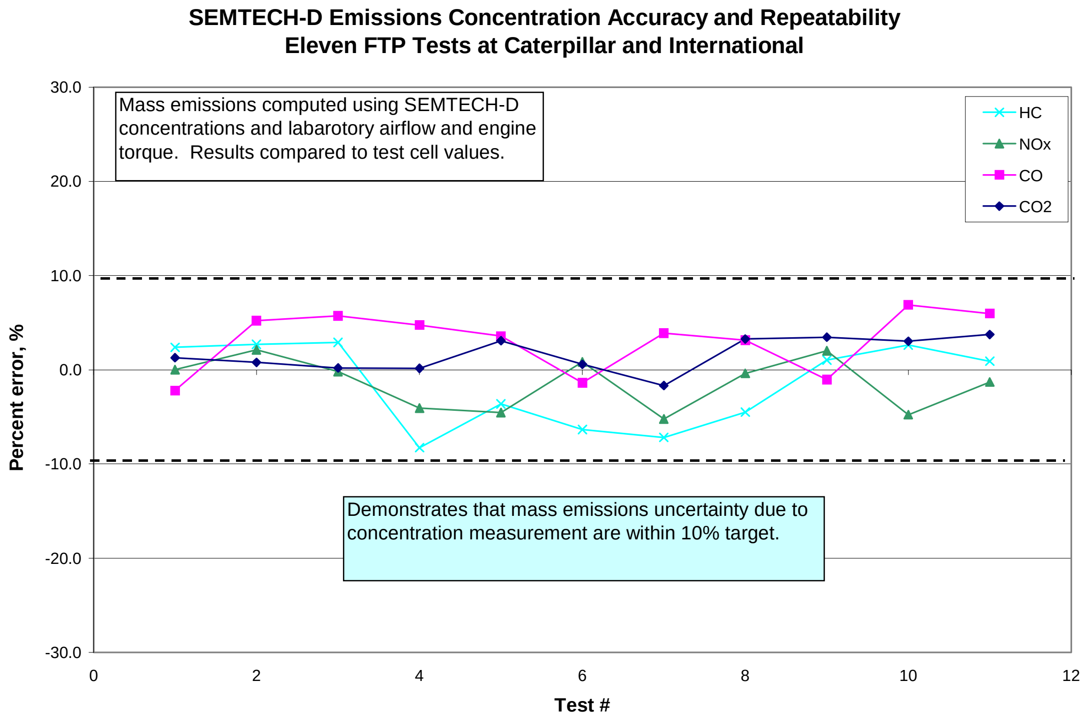


Figure 7.13 SEMTECH-D Transient Emissions Accuracy and Repeatability

Table 7.2 summarizes the mass emissions uncertainties due to the concentration measurements. The standard deviation of the mass error was computed for each constituent; the 95% CI uncertainty was determined by doubling the standard deviation. As the table shows, the 95% CI uncertainty is less than 10% of the average measured value for each constituent. However, the uncertainty was 8.9% for HC and 6.4% for CO, which does not leave much room for other uncertainties in the system. However, the uncertainties are quite small relative to the current emissions standards.

	CO_2	CO	NO_x	THC
Sample Size	11	11	11	11
Standard Deviation of Error, g/Bhp-hr	11.14	0.041	0.087	0.008
95% CI Uncertainty, g/Bhp-hr	22.28	0.0826	0.1743	0.0169
95% CI Uncertainty % of average measured values	3.55	6.42	5.54	8.86
95% CI Uncertainty % of Current Emissions Standards		0.5	4.4	1.3

Table 7.2 Transient Mass Uncertainty Due to Concentration Measurements

7.3 ECM Validation Data

It is not possible to validate all ECM data for all engine families with a small sample. However, we did collect some data during the correlation testing that is useful in both heavy-duty (SAE-J1708) ECM protocols and light-duty OBD II (SAE-J1850) protocols.

Figure 7.14 shows an example of the heavy-duty (SAE-J1708) ECM torque correlation to the engine dynamometer on the Caterpillar C-10 engine. The ECM torque was determined by applying the ECM Engine Load parameter, engine RPM, and the appropriate engine lug curve supplied by the manufacturer. At loads above idle, the ECM data appears reasonably accurate. However, the ECM torque is inaccurate at lower loads, and cannot be used under these conditions. That does not pose a problem for NTE zone testing. These results are typical of other correlation results on this engine, and consistent with on-road data observed in the bus study with Customer 3 engines.

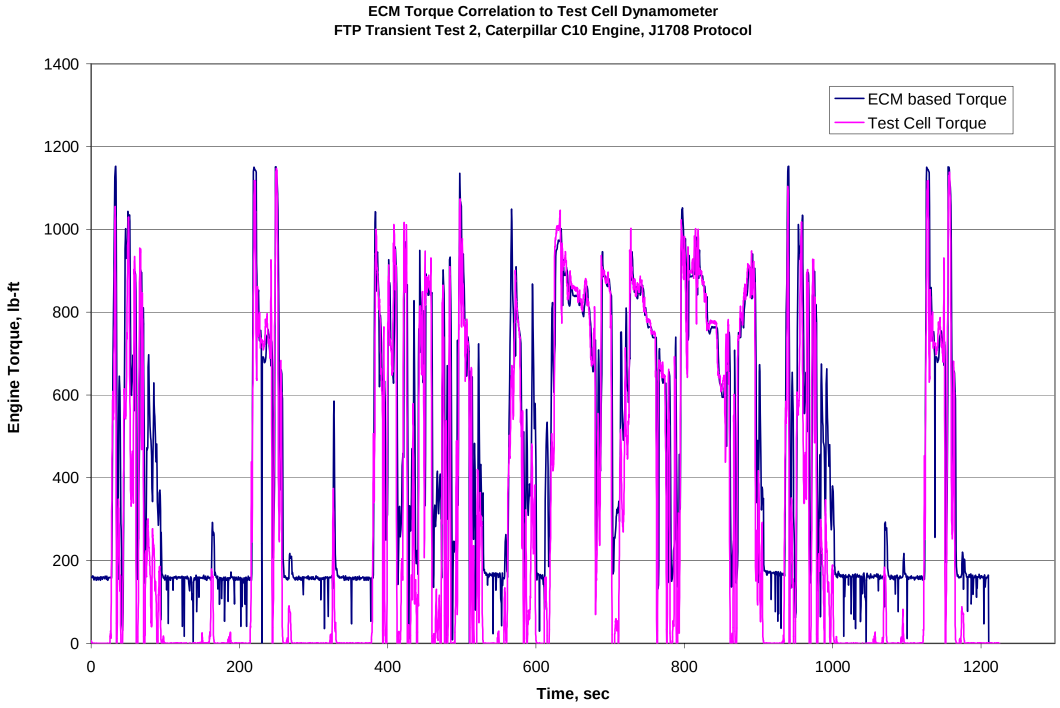


Figure 7.14 ECM Torque Correlation to Engine Dynamometer on Transient Test Cycle

7.4 Overall System Accuracy

The SEMTECH-D correlation results presented above quantify the emissions measurement uncertainty, with a 95% confidence interval, attributable to concentration measurements in both steady-state tests and transient emissions tests. The SEMTECH-D measurement uncertainty due to concentration is expressed in terms of concentration and brake-specific mass emissions as describe above. However, this does not create the complete picture for the overall system accuracy. To do this, we need to know the effect of the other primary measurements that contribute to mass emissions computations. These include:

- Either the fuel-flow data from the ECM, or a direct exhaust flow measurement
- ECM torque data.

The 95% CI uncertainty of these measurements over the FTP cycle must be quantified in order perform an error stack-up analysis. The error stack-up due to the three primary measurements is computed using the root-mean-square (RMS) technique, as shown below.

$$System\_error = \sqrt{(concentration\_error)^2 + (flow\_error)^2 + (ECMtorque\_error)^2}$$

For example, if the error in integrated mass over the FTP cycle attributable to concentration measurement uncertainty is 5%, and the error in integrated mass associated with flow measurement uncertainty is 5%, and the error in integrated mass associated with the ECM torque is 7%, then the overall system error would be 9.9%.

8 Gasoline Vehicle Correlation Testing

This section presents the result of the SEMTECH-G correlation testing compared to the FTP bag and modal data from EPA. The purpose of the correlation testing was to establish validity of the SEMTECH-G emissions measurements, as well as mass emissions computations using ECM data.

As discussed in section 4.3, GM and Chrysler vehicles had not previously been testing in this manner by either EPA or Sensors, Inc., so the precise definition of some of the vehicle interface parameters were unknown prior to the testing. Since the FTP correlation tests were the first test for these vehicles, this data was first used to validate the emissions computations using new ECM parameters. In this sense, the data was not collected and processed in a "blind" fashion as often prescribed for the most rigorous correlation analysis. In the three cases where Type 2 Load Factors were identified, the FTP data was required to actually "calibrate" the SEMTECH-G emissions calculation algorithms, by empirically determining the reference engine speed used for the reference airflow. It is up to the reader to determine the validity of the correlation under these circumstances. Nevertheless, we are confident that the mass emissions calculations for SEMTECH-G are correct based on the FTP data, and that the on-road data is valid.

8.1 FTP Composite Correlation Data

The composite FTP emissions results are shown in table Table 8.1. For the SEMECH-G data, two files had to be manually combined into one since the vehicle was shut off between bags 2 and 3. The SEMTECH automatically starts a new data file at key-on events.

Test #	**Vehicel Info**			**Semtech-G**					**FTP Bag results**				**FTP Modal Results**			
	Disp	Model	Year	CO2	CO	NO	HC	HC FID	CO2	CO	NO	HC	CO2	CO	NO	HC
1	3.1	Lumina Ls	1998	398	2.396	0.243	0.138		377	2.275	0.239	0.184	392	2.344	0.179	0.096
2	3.0	Taurus GL	1997	419	5.120	0.797	0.154		392	4.750	0.795	0.244	397	4.535	0.719	0.247
3	3.0	Sable LS	1996	412	2.889	0.434	0.179	0.355	381	2.882	0.444	0.362	384	2.813	0.486	0.335
6	3.1	Malibu LS	1999	386	2.432	0.369	0.152		381	2.270	0.362	0.190	392	2.250	0.379	0.183
7	1.9	Saturn	1999	299	1.283	0.736	0.074	0.136	298	1.283	0.701	0.137	289	1.219	0.733	0.148
8	2.0	Escort	1999	273	0.936	0.181	0.063		290	0.946	0.189	0.100	279	0.974	0.192	0.088
9	2.0	Escort	2000	292	0.680	0.061	0.057	0.060	280	0.699	0.066	0.061	276	0.635	0.067	0.064
11	3.0	Taurus SE	1998	401	2.35	0.260	0.121	0.202	386	2.224	0.289	0.209	389	2.224	0.297	0.222
12	2.0	Escort	1997	349	1.71	0.342	0.072	0.125	355	1.685	0.347	0.133	356	1.651	0.360	0.133
13	3.0	Sable	1998	408	1.562	0.107	0.086	0.137	392	1.460	0.107	0.163	404	1.428	0.112	0.175
14	3.0	Taurus Wagon	1998	457	0.91	0.20	0.15	0.28	460	0.955	0.207	0.260	494.6	0.993	0.216	0.297
16	2.2	Cavalier	1998	353	10.517	0.483	0.116	0.237	351	9.890	0.493	0.276	365	10.272	0.522	0.325
18	3.0	Tarurus	1996	387	3.651	0.626	0.172	0.220	384	3.434	0.606	0.231	405	3.542	0.614	0.261

Table 8.1 SEMTECH-G FTP Composite Correlation Results

More detailed results are provided in the appendix, including distance traveled, fuel consumption, and fuel economy comparisons.

As mentioned in section 4.4, additional HC measurements were made through the SEMTECH system by attaching an external heated FID through an analog data connection. The external FID is identical to the one integrated in the SEMTECH-D system used in this study. It is also available fully integrated into SEMTECH-G systems. It was desirable to evaluate the performance improvement from using a heated FID instead of the NDIR HC measurement.

8.2 Omissions

There were several tests omitted from the correlation results due to suspect data.

Vehicles 4 and 5 were omitted because the FTP modal CO_2 results were more than 10% greater than the bag data. EPA indicated that a 5% tolerance was commonly used, however even more tests would have to be omitted in that case. There was no apparent reason for these discrepancies, although EPA had noted that the particular test cell had not been used for several years.

One notable observation from the FTP modal data is that the exhaust flow, computed using the CO_2 tracer method, is unstable and often drops to zero at idle conditions. It is unknown if this indicates a potential problem with the bag data also. An example is shown in figure Figure 8.1. While this may have caused some of the bag vs modal disagreement on the tests in questions, it should be noted that this behavior was observed on nearly all of the tests.

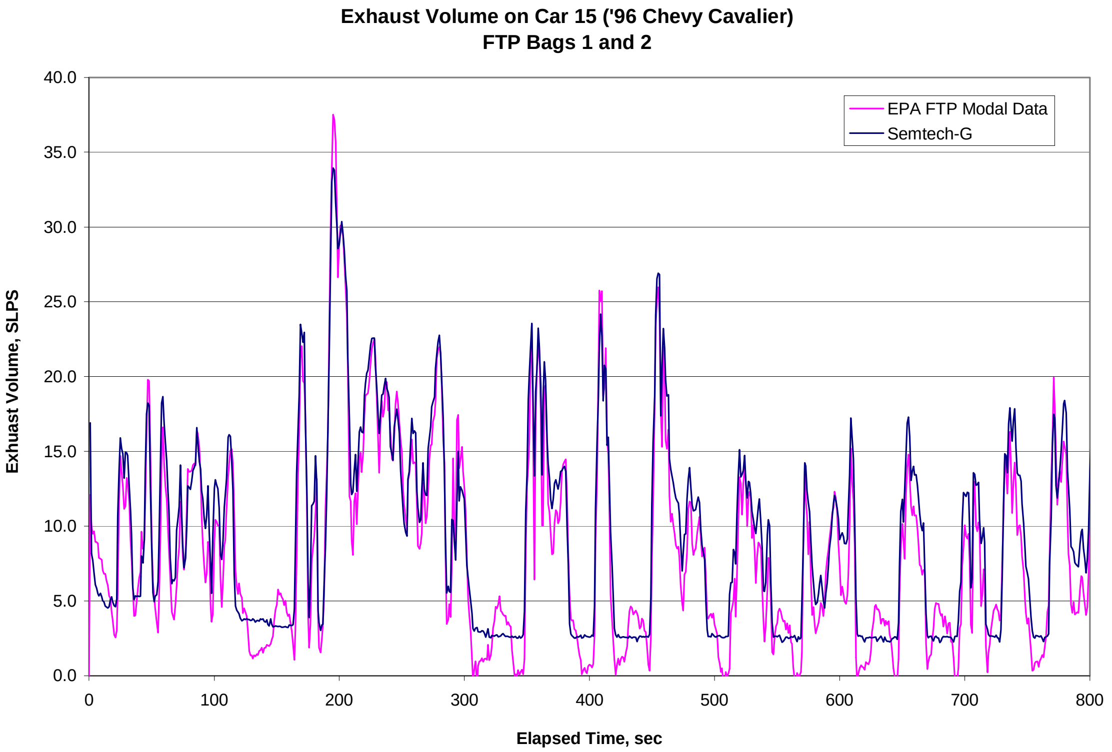


Figure 8.1 FTP Modal Exhaust Volume Instability at Idle

Vehicles 10 and 15 were omitted due to a very large number of data dropouts observed on the FTP modal data. There was no known reason for the data dropouts, but they were far worse on these tests than any other. There was no cause identified for these occurrences, and it was agreed that these tests should be treated as suspect. Figure 8.2 shows the FTP data dropouts for the CO_2 concentrations on car 10. Data for car 15 was similar.

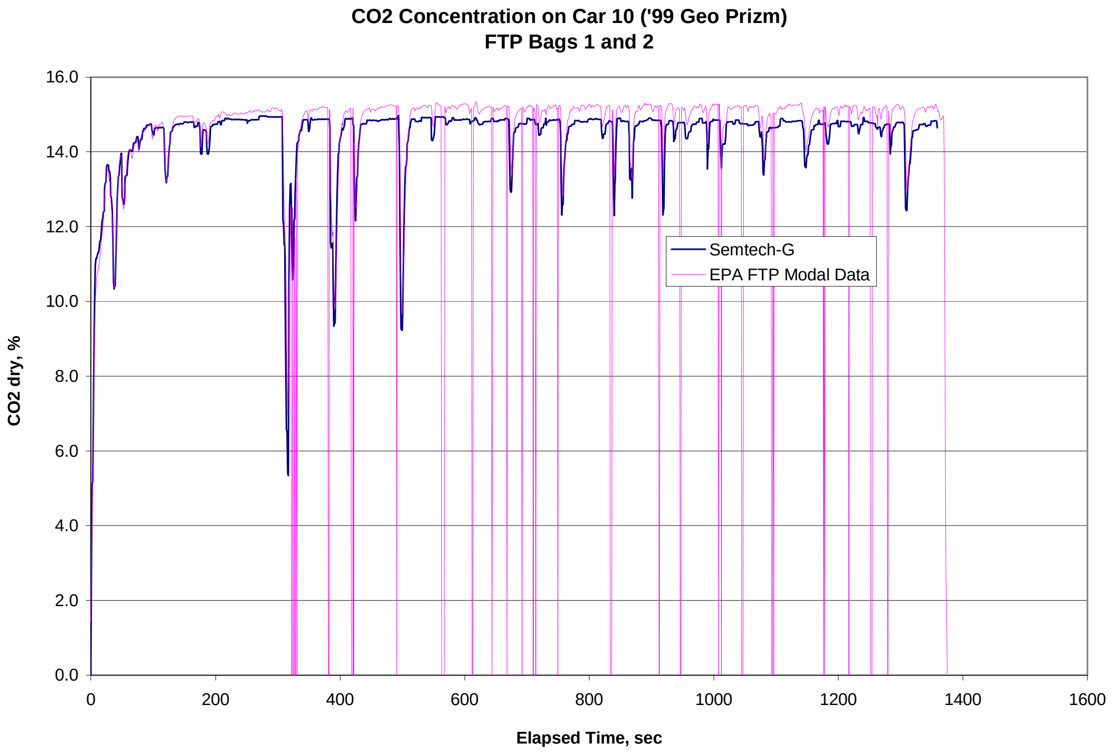


Figure 8.2 FTP Data Dropouts

There was one additional omission: Car 17 was omitted because it failed a SEMTECH-G post-test zero audit by a significant margin. It appears that the analyzer was accidentally zero calibrated while sampling span gas or exhaust prior to the test. This could have been user error, or a mechanical failure of a solenoid valve.

A post test zero check is standard procedure for on-road testing, and this would always indicate a failure.

8.3 US06 Correlation Data

The US06 emissions results were puzzling. Correlation to bag data deteriorated significantly for both the SEMTECH-G and FTP Modal data. While bag vs modal CO_2 was generally in agreement, other emissions showed significant discrepancies. For example, on all but one of the valid tests, CO emissions differed between 15% and 40% between bag and modal results. SEMTECH-G results were similar.

US06 test results are shown in table Table 8.2.

Test #	**Vehicel Info**			**Semtech-G**					**FTP Bag results**				**FTP Modal Results**			
	Disp	Model	Year	CO2	CO	NO	HC	HC FID	CO2	CO	NO	HC	CO2	CO	NO	HC
1	3.1	Lumina LS	1998	402	10.95	0.217	0.063		385	13.91	0.210	0.150	383	8.57	0.168	0.108
2	3.0	Taurus GL	1997	370	15.09	1.079	0.084		371	19.24	1.024	0.224	368	14.78	1.073	0.145
6	3.1	Malibu LS	1999	386	4.56	0.400	0.075		389	6.85	0.393	0.116	384	4.29	0.403	0.082
8	2.0	Escort	1999	279	4.38	0.715	0.032		299	6.33	0.769	0.045	293	4.73	0.933	0.037
9	2.0	Escort	2000	294	12.85	0.142	0.045	0.094	296	13.30	0.162	0.104	292	9.69	0.207	0.082
11	3.0	Taurus SE	1998	386	11.97	0.348	0.099	0.191	396	16.05	0.390	0.209	391	12.43	0.417	0.150
12	2.0	Escort	1997	317	32.38	0.966	0.082	0.225	340	34.78	0.894	0.268	338	31.33	0.993	0.296
13	3.0	Sable	1998	369	6.44	0.180	0.018	0.063	382	7.00	0.211	0.076	373	4.94	0.223	0.062
14	3.0	Taurus Wagon	1998	425	4.76	0.230	0.025	0.081	443	5.01	0.242	0.087	441.8	3.11	0.162	0.060
16	2.2	Cavalier	1998	347	17.62	0.880	0.134	0.197	371	21.26	0.974	0.206	367	18.68	1.024	0.225
18	3.0	Tarurus	1996	364	16.75	0.639	0.097	0.260	389	24.35	0.673	0.280	390	18.29	0.706	0.203

Table 8.2 US06 Correlation Data

Two additional tests were omitted from the US06 results. Car 7 was omitted simply because the US06 cycle was not performed on this vehicle due to time constraints. Car 3 was omitted because EPA results showed an unrealistic 27 mpg fuel economy for the 3.0 liter Ford Taurus. This was a 22% higher fuel economy than measured on the FTP. All other tests showed a noticeable decrease in fuel economy with the US06 cycle.

9 Appendix

- Statement of Work documentation
- Documentation for test procedures
- Test file database
- Correlation test charts-gasoline
- Correlation test charts – diesel
- Diesel engine spec sheets

The various gas analyzers have different types of calibrations and span adjustments. The following describes the general approach for each.

Heated FID: The FID is fully linear, so that all concentrations are interpolated from a single point calibration and zero offset. This it typical of most FIDs. We used a single range of 0 - 1000 ppmC during the bus study, but the analyzer has other ranges available. Each range has its own zero offset, but all ranges scale the concentration from a single point span on one of the ranges. There is an option to account for any non-linearity by manually adjusting the calibration at various concentrations, but we have never found enough error to bother with this.

NDIR CO2 and CO: These are both single range devices. The CO2 range is 0 - 16% and the CO is 0 - 8%. There is a "Factory" multi-point calibration curve that is hard-coded into each analyzer when it is first made. This factory calibration curve is typically never changed. This is a 4th order polynomial, I believe, but I will have to verify. To account for short term drift and linearity changes, the user performs periodic "span adjustments", or "user calibrations". A single point user-calibration will adjust the entire factory calibration curve to match the gas bottle at a particular concentration (typically near the maximum of the range) while holding the zero point fixed. A two-point user calibration uses a high concentration gas to adjust the high concentration range, and a lower concentration gas to adjust the mid-range if the linearity does not meet specification. This increases or decreases the midpoints of the calibration curve, while holding both the zero and upper span points fixed.

NDUV NO and NO2. These are also single range devices. The NO range is 0 - 3000 ppm, and the NO2 is 0 - 500 ppm. The calibration is exactly the same as for the NDIR analyzers. There is detailed, multi-point factory calibration hard-coded into the analyzer. Again, this is a 4th or maybe 5th order polynomial (higher orders are not significantly more accurate). Single or two-point user calibrations adjust the factory calibration curve as described above. The NDUV analyzers are typically much more linear than the NDIR analyzers, and almost never need more than a single point span adjustment.

O2: This is a galvanic cell that produces a voltage that is linearly proportional to the O2 concentration. No zero offset is typically required. A single-point calibration using ambient air or bottled air is sufficient.

Audit/Calibration procedures used during the bus study:

At a minimum, the SEMTECH-D was audited at the beginning of each day of testing during the bus study using a BAR-97 Low quad-blend carried in Scotty III portable bottles with the following concentrations:
CO2: 6%
CO: 0.5% (5000 ppm)
NO: 300 ppm
HC: 200 ppm propane

A data file was recorded during the audits. If an audit failed, then a single-point user calibration was performed on the analyzer that failed. A 3% audit limit is typically used for CO2 and CO, and 2% for NO and THC. These evaluations were performed visually during the study. NO2 required a full gas cylinder, and was therefore only audited on several occasions when the analyzer was briefly returned to Sensors.

We did not keep records on the frequency of calibrations that were required during the study, but I can say that the CO2, CO, and NO required single point adjustments on only a few occasions. The FID required a single point calibration more often, nearly every day. That is not unusual for FIDs, however, especially when routinely cycling power as we did.

When a single-point user calibration was required for CO2, CO, or NO, a BAR97 High quad blend was used (also carried in a Scotty III portable bottle) with the following concentrations:

CO2: 12%
CO: 8%
NO: 3000 ppm
HC: 3000 ppm propane

When a single-point calibration was required for the FID, the BAR97 Low bottle was used, since it better matched the operating range we were interested in.

For the gasoline car tests, the SEMTECH-G analyzers were audited in the same manner after they were installed in the vehicles and allowed to warm up for approximately 1 hour. The same portable bottles were used for the audits and calibrations.

Note: Since the bus study, we have switched to different audit and calibration blends that better match the range we observe in diesel exhaust. Our current bottles are:

SEMTECH-D Audit:
CO2: 6%
CO: 200 ppm
NO: 300 ppm
HC: 50 ppm propane

SEMTECH-D Calibration:
CO2: 12%
CO: 1000 ppm
NO: 1500 ppm
HC: 200 ppm propane