AERIS: Assessment and Fusion of Commercial Vehicle Electronic Control Unit (ECU) Data for Real-Time Emission Modeling

FINAL REPORT

FHWA-JPO-12-051

June 2012

U.S. Department of Transportation
Research and Innovative Technology Administration

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-JPO-12-051	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle AERIS: AERIS: Assessment and Fusion of Commercial Vehicle Electronic Control Unit (ECU) Data for Real-Time Emission Modeling		5. Report Date June 2012 6. Performing Organization Code:
7. Author(s): Kanok Boriboonsomsin, Ross Sheckler and Matthew Barth		8. Performing Organization Report No.
9. Performing Organization Name and Address University of California, Riverside Center for Environmental Research & Technology 1084 Columbia Avenue Riverside, CA 92507 and Calmar Telematics, LLC 620 Old Liverpool Road Liverpool, NY 13088		10. Work Unit No. 11. Contract or Grant No. DTFH61-10-P-00174
12. Sponsoring Agency Name and Address United States Department of Transportation, Research and Innovative Technology Administration 1200 New Jersey Ave, S.E. Washington, DC 20590		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

16. Abstract

Heavy-duty trucks (HDTs) play a significant role in the freight transportation sector in the U.S. However, they consume a vast amount of fuel and are a significant source of both greenhouse gas and criteria pollutant emissions. In order to properly design strategies to reduce energy and environmental impacts of HDTs, accurate data of their fuel consumption and emissions are required, preferably in real-time. One of the important sources of these data is the on-board electronic control units (ECUs) that can provide hundreds of vehicle and engine operating parameters. This report investigates how data items from ECUs, such as engine speed, engine load, and fuel flow rate, might be collected and what value these data items might have in studying the environmental issues associated with highway transportation and in the development of advanced applications, such as real-time emission modeling and reporting system, to manage these issues.

17. Key Words AERIS, Vehicle emissions reduction strategies, heavy-duty vehicles, electronic control unit (ECU), telematics		18. Distribution Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class if. (of this report) Unclassified	20. Security Class if. (of this page) Unclassified	21. No. of Pages 51	22. Price Free

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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BACKGROUND

Over the last several years, transportation professionals have looked at the records of the on-board recorders of private vehicles as a potential source of data to support transportation research efforts. There are certainly millions of vehicles on the roads today that record every bit of their activity. Many of these vehicles are equipped with GPS tracking devices so that the vehicle data can be correlated with their location on the highway.

A number of technical groups have begun to gather basic location and speed data to support traveler information and mobility applications and studies. To date, efforts to use vehicle generated data to support applications and studies in the transportation field have largely been limited to location and speed data harvested mostly from the records of the suppliers of telematics services for commercial vehicles.

Heavy-duty trucks (HDTs) consume a vast amount of fuel and are a significant source of both greenhouse gas and criteria pollutant emissions, primarily due to their low fuel economy and high annual mileage. In order to properly design strategies to reduce energy and environmental impacts of HDTs, accurate data of their fuel consumption and emissions are required, preferably in real-time. One of the important sources of these data is the on-board electronic control units (ECU) that can provide hundreds of vehicle and engine operating parameters.

The ECU data of HDTs can be accessed through the industry-standard SAE J1939 data bus. Many fleet owners have equipped their truck fleets with on-board devices that couple ECU with telematics capabilities where vehicle and engine operating parameters as well as positioning information (i.e. via GPS) are wirelessly transmitted to a computer server on a periodic basis. Through partnership with these fleet owners, the research team has created a master database that gathers and aggregates these ECU data that can be used in real-time applications to evaluate and improve the performance of transportation systems, especially those related to freight movement.

This project has been chartered to investigate how broader data types from a vehicle's data bus, such as engine speed, engine load, and fuel flow rate, might be collected and what value these data types might have in studies of the environmental issues associated with highway transportation and in the development of advanced applications to manage these issues.

TASK 1

1 Electronic Control Unit (ECU) Data

A modern automobile is operated with electronic control of fuel delivery, ignition, and active cylinders. The air flow through the radiators is managed with clutched or electric fans and louvers to maintain the temperature of the drivetrain at an optimum level regardless of the weather. The list of items digitally managed through a vehicle's network of sensors and controls runs into the thousands. In order to do all of this, modern vehicles have one or more communication networks (data buses) running between the individual components.

Exactly what data are carried on these data buses varies from vehicle to vehicle and from manufacturer to manufacturer. The exact sensors used to manage a vehicle and the fast and efficient transmission of the data from the sensors to the devices which need them have become key intellectual property of the individual manufacturers. Because of the strategic advantage that the companies find in data management systems, the passenger car manufacturers have been resistant to requests for access to their vehicle data bus, throwing a roadblock in front of this line of exploration.

While intellectual property concerns may inhibit the use of vehicle data, there is an exception that provides immediate promise. The data protocols used in the commercial vehicle industry have been standardized. The heavy-duty truck industry is structured very differently than the passenger vehicle industry. The production of heavy-duty trucks is an assembly of drivetrain and suspension components that are specified by the buyer. For example, a truck produced by Kenworth may be specified by the buyer to have a specific Cummins or Detroit Diesel engine, an Allison or Eaton transmission, and TRW drive axles. Because the components of a heavy truck may be mixed and matched to meet the needs of each fleet, it has been necessary to establish a standardized data bus which has an open architecture that can be read by a variety of third-party devices.

The SAE J1939 and J1703 standards define the data protocols used by heavy-duty trucks. The most modern J1939 standard, which is replacing the older J1703, includes fields for thousands of variables. While the various manufactures of trucks and engines choose whether or not to actually place data on a particular field in the data bus, the bus protocol itself is standard and the primary fields such as vehicle speed, engine speed, fuel consumption, and coolant temperature are generally populated on all vehicles.

1.1 Access to Data

The data that is generated and stored in the operation of a vehicle are either those items necessary to efficiently run the mechanics of the vehicle or the data that the operator needs to operate the vehicle safely and conveniently. While the Connected Vehicle concepts will make the sharing of this data a routine exercise, in the case of most passenger vehicles this data resides on the vehicle itself and currently is only ever extracted when the vehicle is brought to a professional shop for maintenance. Access to archives of this data may become available through maintenance facilities if the consent of the private vehicle owners can be acquired.

In the commercial vehicle sector, much of the data associated with the operation of the vehicle is transmitted to fleet servers through telematics systems that are used to track the vehicles. As a result, basic data such as vehicle location and speed can be made available in five- or ten-minute intervals for hundreds of thousands of vehicles. Some of this data can be acquired through the telematics service providers, but a number of serious questions have been raised about the rights of the vehicle owners in this data transfer. A few firms, including Calmar, have entered into direct agreements with commercial fleets to make this data available at a cost of one to two hundred dollars per vehicle per year.

It is not uncommon for several other data fields to be available through the existing vehicle tracking platforms that are in place in the commercial vehicle industry. These include items such as odometer reading, parking brake application, hard brake application, trip fuel economy, trip speed bins, and trip engine speed bins. In order to get access to these data items in a resolution below the trip aggregation level or to get more exotic data items such as manifold temperatures or gear ratios, it will be necessary to work with the companies which manufacture the telematics devices to modify the data extraction and transmission software. It will also be necessary to work with a variety of fleets to encourage them to adopt the specialized telematics hardware as their vehicle tracking and management solution.

1.2 The Mechanics of Gathering Data

In order to approach the problem of extracting data from an operating vehicle, it is important to first understand the structure of the data bus. The modern commercial vehicle data bus, the SAE J1939 standard, is specified to contain more than two thousand data fields ranging from the vehicle identification number (VIN) to individual wheel speeds and brake settings.

Whether or not the particular field on the J1939 bus is populated with actual data is a decision made by the manufacturer of the vehicle or the engine. So, while each truck has a data position for ‘Engine Fuel Temperature 1,’ only some trucks will have actual data in that position. This reality of data population may dictate that an effort to gather very specific and somewhat unusual vehicle data will require the consideration of which fleets and which vehicles will be used to gather the data. While the research team has been successful in engaging specific fleets with specific vehicles, this situation may inhibit efforts to get data from a representative sample of the trucking industry as a whole.

Furthermore, for the hundreds of data fields that are populated on the J1939 bus, there is a need to consider the frequency at which the data is updated as well as the practicality of transmitting the large amount of data that might be generated every time a sensor updates a data field. The J1939 bus has two types of data—data that is broadcast across the bus automatically and data that must be requested.

Many of the fields that are defined on the J1939 bus are automatically filled and transmitted, or broadcast, for all commercial vehicles. Data fields that are broadcast are generally transmitted on a 10-50 millisecond cycle. The particular sensor that is generating the data may update its particular data capture on a different cycle but generally this cycle is no faster than the bus broadcast cycle.

The fields on the data bus that are populated but not broadcast must be queried directly by the telematics device. That is to say, if a variable such as ‘Diesel Particulate Filter Active Regeneration Status’ is not broadcast by the bus, the telematics device must place a query and wait for a response. Through discussions with multiple companies that specialize in telematics equipment and commercial vehicle interfaces Calmar has learned that the process of querying the bus without interfering with the successful operation of the vehicle is said to be more than a bit tricky. In general, the bus can be queried successfully no more than three times each second and this must be taken into consideration in a data strategy.

The telematics hardware that has been installed to monitor the vehicle and transmit its status to the owner can be configured to read the bus on any cycle desired. The telematics devices that are generally available on the market today tend to extract data from the bus on a cycle similar to the bus broadcast cycle storing the data for several seconds at a time. If an exception event (such as a hard brake) happens, all of the data for the preceding seconds are permanently recorded and possibly transmitted to the home server. If no exception happens, most of the data is discarded and only the data of interest is transmitted on the recording cycle which may be a five- or ten-minute interval.

As researchers, we need to decide what data recording cycle is appropriate and how does that cycle fit with the ability to query the bus and the practicality of data transmission. It is the opinion of the research team that some further effort will be required to devise data query strategies that fit with the technical realities of the J1939 data bus as well as the financial realities of transmitting data over a system that has been primarily installed on the vehicle for fleet operational reasons.

2 Comprehensive Modal Emissions Model (CMEM)

Over the years, the University of California at Riverside (UCR)’s College of Engineering – Center for Environmental Research and Technology (CE-CERT) has developed numerous models and tools to evaluate transportation environmental impacts. One of the major contributions was the development of the Comprehensive Modal Emissions Model (CMEM), which is a microscopic emissions model that was developed with the support from the National Cooperative Highway Research Program and the U.S. Environmental Protection Agency. It is capable of predicting second-by-second fuel consumption and tailpipe emissions of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) based on different modal operations from an in-use vehicle fleet.

In the modeling approach of CMEM, the entire fuel consumption and emissions process is broken down into components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component of CMEM is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to vehicle type, engine, emission control technology, and level of deterioration. The level of deterioration of the engine and emission control system is difficult to characterize beyond the as-built specifications, and vehicle mileage is typically used as a surrogate.

The initial versions of CMEM contain a model database for 23 light-duty vehicle categories. With the constant addition of new vehicle categories into the model database, the current version of CMEM includes 28 light-duty vehicle categories and three heavy-duty truck categories.

For the heavy-duty truck categories in CMEM, second-by-second tailpipe emissions are modeled as [Barth et al., 2004]:

$$\text{tailpipe emissions} = FR \cdot \left(\frac{g_{emissions}}{g_{fuel}} \right) \cdot \text{aftertreatment pass fraction} \qquad (1)$$

Here, FR is fuel use rate in grams per second; ($g_{emissions}/g_{fuel}$) is grams of engine-out emissions per gram of fuel consumed; and the after-treatment pass fraction is defined as the ratio of tailpipe to engine-out emissions. A variety of after-treatment devices can be modeled separately and integrated into this model structure without extensive retesting. For HDTs with no after-treatment devices, the after-treatment pass fraction is 100%. The ($g_{emissions}/g_{fuel}$) and the after-treatment pass fraction are different for each type of emissions, and the majority of the CMEM deal with modeling the fuel use rate.

The complete model is composed of six modules, as indicated by the six square boxes in Figure 1: (a) engine power demand, (b) engine speed, (c) fuel rate, (d) engine control unit, (e) engine-out emissions, and (f) after-treatment pass fraction. The model as a whole requires two groups of input (rounded boxes in Figure 1): (g) input operating variables such as second-by-second vehicle speed and (h) model parameters such as engine displacement and maximum horsepower. The output of the model is tailpipe emissions and fuel consumption. The vehicle power demand (a) is determined based on operating variables and specific vehicle parameters. All other modules require the input of additional vehicle parameters determined on the basis of on-road measurements, as well as the engine power demand calculated by the model. The core of the model is the fuel rate calculation. It is a function of power demand and engine speed. Engine speed is determined on the basis of vehicle velocity, gear shift schedule, and power demand.

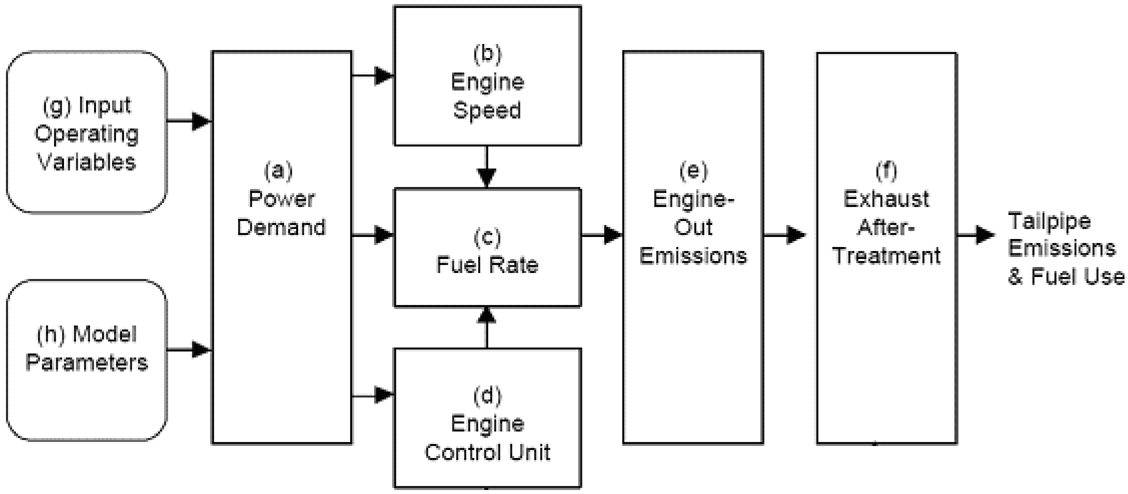

Figure 1. Structure of CMEM for heavy-duty-trucks

CMEM has been developed primarily for vehicle energy/emissions calculation where second-by-second vehicle trajectories (location, velocity, acceleration), and optionally road grade and accessory load, are measurable (e.g. through GPS technology). These vehicle trajectories can be applied directly to CMEM (as box (g) in Figure 1), resulting in both individual and aggregate vehicle energy/emissions estimates for existing HDT categories in CMEM. If vehicle and engine parameters are available from ECU, then they can be used to calibrate CMEM to produce energy/emission estimates for specific HDTs. These parameters include:

- Engine displacement
- Engine idle RPM
- Maximum engine power
- Maximum engine torque
- Engine speed at maximum engine power
- Engine speed at maximum engine torque
- Fuel rate at idle
- Engine running load
- Engine friction factor
- Accessory load

Alternatively, the measured fuel rate from ECU, if available on a second-by-second basis, can also be used directly to estimate engine-out emissions and tailpipe emissions.

3 Evaluation of ECU Data for Environmental Performance Modeling

In this task, the research team initially obtained an extensive list of available ECU data items on the data bus. This list includes the name, description, unit, and type of more than 500 ECU data items. We reviewed the list in detail and selected a subset of 17 data items that are potentially useful for environmental performance modeling based on our current understanding of the emission production processes. For instance, exhaust gas temperature is known to affect how diesel particles are formed. The selected data items are given in Table 1. The data items coded in green are of high interest, yellow moderate interest, and orange low interest.

Note that the selection is exploratory in nature, so these data items constitute a "wish list" rather than a mandatory list. Some of the data items are not currently used by CMEM in its calculation of emissions. As an example, engine fuel rate data from ECU will allow us to bypass the power demand and engine fuel rate estimation in CMEM.

In addition to data from ECU, there are data that can be available from other devices (e.g., GPS receiver, accelerometer, etc.) in the telematics devices. They are listed in Table 2. In this table, the data items coded in green are readily available on common telematics devices. They are being collected by Calmar. The data items coded in gray can be collected or derived with some effort. Calmar is pursuing them outside the scope of this project.

The research team has been working with telematics equipment providers to acquire sample data of the selected ECU data items. One of the sample data files acquired is for a truck being stationary for approximately three hours. The files contain 24 data items as shown in Table 3.

It should be pointed out that ECU data transmitted from the data bus are in SI units. They are converted into U.S. units in the telematics equipment before being reported. In the sample file, there are instantaneous readings of the data items every 30 seconds (see Figure 2). The data items coded in blue contain all zero values, of which some of them are legitimate but some of them are not. For instance, it is reasonable for Accelerator1Posiiton and VehicleSpeed to be zero during this stationary test. On the other hand, it is not expected that Aftertreatment1ExhaustGasTemp1 will always be zero.

Table 1. ECU data items potentially useful for environmental performance modeling

No.	Name	Unit	Description
1	Engine Fuel Rate	Liter Per Hour	Amount of fuel consumed by engine per unit of time.
2	Diesel Part. Filter Active Regen Status		Indicates the state of diesel particulate filter active regeneration.

3	Particulate Trap 1 Soot Load Percent	Percent [0-100]	Indicates the soot load percent of particulate trap 1. 100% is the level at which active particulate trap regeneration should be triggered.
4	Aftertreatment 1 Dsl Part. Filt. Outlet Gas Temp	Celsius	Temperature of engine combustion byproducts leaving the diesel particulate filter exhaust in exhaust bank 1.
5	Aftertreatment 1 Exhaust Gas Temperature 1	Celsius	The reading from the exhaust gas temperature sensor located farthest upstream in the aftertreatment system in exhaust bank 1.
6	Aftertreatment 1 Exhaust Gas Temperature 3	Celsius	The reading from the exhaust gas temperature sensor located farthest downstream in the aftertreatment system in exhaust bank 1.
7	Exhaust Gas Temperature	Celsius	Temperature of combustion byproducts leaving the engine.
8	Engine Speed	Revolution Per Minute	Actual engine speed which is calculated over a minimum crankshaft angle of 720 degrees divided by the number of cylinders.
9	Engine Percent Load At Current Speed	Percent [0-100]	The ratio of actual engine percent torque (indicated) to maximum indicated torque available at the current engine speed, clipped to zero torque during engine braking.
10	Engine Intake Manifold 1 Pressure	Kilopascal	The gauge pressure measurement of the air intake manifold. If there are multiple air pressure sensors in the intake stream, this is the last one in flow direction before entering the combustion chamber.
11	Engine Intake Manifold 1 Temperature	Celsius	Temperature of pre-combustion air found in intake manifold of engine air supply system.
12	Engine Fuel Temperature 1	Celsius	Temperature of fuel (or gas) passing through the first fuel control system. See SPN 3468 for the second control system
13	Actual Engine - Percent Torque	Percent [0-100]	The calculated output torque of the engine. The data is transmitted in indicated torque as a percent of reference engine torque (see the engine configuration message, PGN 65251). The engine percent torque value will not be less than zero
14	Transmission Actual Gear Ratio	Real Number	Actual ratio of input shaft speed to output shaft speed.
15	% Exhaust Gas Recirculation Valve #1 Position	Percent [0-100]	Ratio of current exhaust gas recirculation (EGR) valve position to the maximum EGR valve position. A value of 0% means no EGR.
16	Ambient Air Temperature	Celsius	Temperature of air surrounding vehicle.
17	Engine Coolant Temperature	Celsius	Temperature of liquid found in engine cooling system.

Table 2. Data items readily available and potentially derived from telematics equipment

No.	Readily Available Data Items on Common Equipment	Potentially Derived Data Items
1	Location	Grade
2	Speed	Elevation
3	Odometer	Acceleration (3-axis)
4	Heading	On-road/Off-road
5	Trip Fuel Economy	Vehicle Class
6	Trip Speed Bins	Vehicle Age (Model Year)
7	Trip RPM Bins	Body Type
8	Trip Hard Brake Count	Primary Commodity Code
9	Parking Brake Application	Engine Model Year
10	Fault Codes	Engine Model
11		Vehicle Model
12		Hard Brake Event Location
13		Trailer Attached/Detached
14		Axle Gear Ratio
15		Road Meta-Data

Table 3. Data items in the sample data file

No.	Name	Unit
1	Accelerator1Position	%
2	Aftertreatment1DieselParticulateFilterOutletGasTemp	Fahrenheit
3	Aftertreatment1ExhaustGasTemp1	Fahrenheit
4	Aftertreatment1ExhaustGasTemp3	Fahrenheit
5	AmbientAirTemp	Fahrenheit
6	BarometricPressure	PSI
7	CoolantTemp	Fahrenheit
8	DieselParticulateFilterPassiveRegenerationStatus	4 States
9	EngineExhaustGasTemperature	Fahrenheit
10	EngineFuelRate	gallons/hour
11	EngineFuelTemperature	Fahrenheit
12	EngineLoadPercent	%
13	EnginePercentTorque	%
14	EngineSpeed	rpm
15	ExhaustGasRecirculation1ValvePos	%
16	FuelLevel	%
17	FuelPressure	PSI
18	IntakeManifoldPressure	PSI
19	IntakeManifoldTemp	Fahrenheit
20	Odometer	mile
21	ParticulateTrap1SootLoadPercentage	%
22	TotalFuel	gallons
23	TransmissionActualGearRatio	Double (0 to 64.255)
24	VehicleSpeed	mph

Based on the available data items in this sample data file, we determine that the most valuable data item is EngineFuelRate. After being converted from gallons/hour to grams/second and aggregated from the existing data rate of the bus to second-by-second, it can be used to estimate engine-out emissions and tailpipe emissions in CMEM, as shown in Figure 1.

It should be noted that in the current version of CMEM, tailpipe emissions are modeled as a function of fuel rate, the ratio of engine-out emissions per gram of fuel consumed, and the ratio of tailpipe to engine-out emissions (see Equation (1)). There has been research suggesting that the effectiveness of emissions control technology (e.g., diesel particulate filter) could vary by filter temperature [Parks et al., 2007]. Thus, CMEM could be extended to capture this effect. After that, some of the ECU data items would allow CMEM to estimate emissions more accurately.

UnitID	Timestamp	EngineFuelRate	EngineFuelTemperature	EngineLoadPercent	EnginePercentTorque	EngineSpeed
30667	1/1/2006 0:02:28	0.673638733	1	21	15	699
30667	1/1/2006 0:02:57	0.673638733	1	21	15	700
30667	1/1/2006 0:03:27	0.66043013	2	21	15	700
30667	1/1/2006 0:03:57	0.739681746	2	21	15	698
30667	1/1/2006 0:04:27	0.686847335	2	21	15	699
30667	1/1/2006 0:04:57	0.726473143	3	21	15	701
30667	1/1/2006 0:05:27	0.673638733	3	22	15	698
30667	1/1/2006 0:05:57	0.752890348	4	21	15	700
30667	1/1/2006 0:06:26	0	4	100	65	0
30667	1/1/2006 0:06:56	0	4	100	65	0
30667	1/1/2006 0:07:26	0.686847335	5	22	16	698
30667	1/1/2006 0:07:56	0.673638733	5	23	15	698
30667	1/1/2006 0:08:26	0.673638733	5	21	15	699
30667	1/1/2006 0:08:56	0.686847335	5	21	15	700
30667	1/1/2006 0:09:26	0.66043013	6	22	15	698
30667	1/1/2006 0:09:55	0.726473143	6	21	15	699
30667	1/1/2006 0:10:25	0.647221527	6	22	15	698
30667	1/1/2006 0:10:55	0.673638733	6	21	15	699
30667	1/1/2006 0:11:25	0.71326454	6	21	15	700
30667	1/1/2006 0:11:55	0.647221527	7	21	14	700

Figure 2. Sample ECU data

4 Potential Applications of Real-Time Environmental Performance Information

Many fleet owners have equipped their truck fleets with on-board devices that couple ECU with telematics capabilities where vehicle and engine operating parameters as well as positioning information (i.e. via GPS) are wirelessly transmitted to a computer server on a periodic basis. Through partnership with these fleet owners, Calmar Telematics has created a master database that gathers and aggregates these ECU data that can be used in real-time applications to evaluate and improve the environmental performance of vehicle and transportation systems, especially those related to freight movement.

One of the applications that can take advantage of these telemetry-based ECU and GPS data is dynamically controlled energy/emissions management systems. In spark ignition engines, lowest overall tailpipe emissions (i.e. CO, HC, and NO_x) occur at the stoichiometric air/fuel ratio when equipped with a catalytic converter. [Note: Stoichiometric air/fuel ratio is the mass ratio of air to fuel present during combustion that allows all of the fuel to completely burn.] In contrast, it is possible to get better fuel economy (and thus, lower CO_2 emissions) with a leaner mixture while maintaining sufficient power. However, NO_x emissions are greater when running at this leaner mixture [Bosch et al., 2003].

For diesel engines commonly used in HDTs, the air/fuel ratio is not closely controlled for emissions or fuel economy, but it is possible to advance the injection timing to get better fuel economy. Again, this better fuel economy is at the expense of higher NO_x emissions. In the U.S., for years the heavy-duty diesel engine manufacturers have designed engine control strategies to pass a standard emissions certification test using procedures set up by the government.

Most heavy-duty diesel engines are found in large class-8 trucks, which are most often operated at freeway speeds (relatively high engine speed) for long durations. Since this type of operation was not really captured in the certification testing, the manufacturers have designed a “fuel economy mode” that is accomplished by advancing the injection timing during high-speed operation over long periods of time. In this mode, a fuel savings of approximately 5% is achieved. In this mode, however, higher than normal NO_x emissions result, violating the government-set emission standards. The government has since detected this operation, which has resulted in tighter emission standards across many operating modes for future-year vehicles.

The primary air pollution health hazard in many cities is ozone, which is a secondary pollutant formed by HC and NO_x interacting in sunlight. Ozone is particularly bad in cities that are located in “basins” where the pollutants are trapped by surrounding mountains. In these areas, it makes sense to control the NO_x emissions very closely; however, in other areas that are HC limited, there is a lesser need to control NO_x. Therefore, location information (i.e. via GPS) can be used by an advanced emission control system to better handle the tradeoff between fuel economy and NO_x emissions.

Given that the ECU data along with GPS information from fleets of HDTs can be available in real-time at a centralized management center (e.g. traffic management center), an active monitoring and management of their energy/emissions is possible. For example, it may be reasonable to allow long-haul HDTs to run in the fuel economy mode while traversing non-populous areas and switch to the emissions control mode when entering populous areas. The same logic can be employed when the air quality monitoring and forecasting system of an area alerts of a possible high ozone concentration (also known as "high ozone days").

TASK 2

1 Assessment of Data Fusion Requirements

Task 2 of this project is focused upon the practical issue of fusing data from these new sources (e.g., truck ECU) into the draft format developed by the industry over several years and tested at the Michigan test bed. Issues such as data restructuring are considered. Specifically, we ask the question: "Is the current framework sufficient or sufficiently flexible for environmental reporting purposes?" We feel that answering this question is critically important to permit the AERIS program to advance beyond the objectives within this BAA.

1.1 Connected Vehicle Data Structure

The Connected Vehicle model features multiple entities in the highway community as intelligent devices operating as independent nodes in the structure. The vehicles operating on the highway have one or more computing components that can communicate with peers through dedicated short range communications (DSRC) protocols. Likewise devices on the roadside such as traffic lights and tolling stations can act as a DSRC peer and communicate information to the vehicles. The equipment within a vehicle in the system is referred to as On-Board Equipment (OBE) and the equipment on the road-side is referred to as Road-Side Equipment (RSE). As we move toward a Connected Vehicle future, engineers are working to establish the structure for messages that will be sent and received by both the OBE and the RSE.

In the case of the OBE the current concept has three basic message sets that may be generated by the device. These include an Events file, a Trajectory file, and a Snapshot file. The efforts to define the data in the Trajectory and Snapshot files are described below.

1.2 Michigan Testbed Data Structure

The messaging standards for Connected Vehicle, currently under revision, incorporate a variety of message sets that incorporate data related to a number of subjects including data related to mobility, safety, routing, vehicle performance, and environmental factors.

As standards for operating in the Connected Vehicle continue to be developed, a number of efforts that test the various concepts have been established. Arguably the biggest effort in Connected Vehicle is the Michigan Testbed where vehicle (On-Board Equipment, OBE) to roadside (Road-Side Equipment, RSE) messages have been executed and are being offered to the greater transportation community for development purposes. For this extended field test the message sets and associated supplemental data files are defined in the *Documentation on Onboard Equipment Files from the Connected Vehicle Michigan Testbed.* (Attachment A)

The Connected Vehicle community has proposed RSE message sets which include local mapping data and GPS corrections to increase the vehicle's location accuracy to allow for lane-specific operation. At this point the project team is assuming that the OBE trajectory data will have correction data downloaded from near-by RSE adding precision above that which may be attained through independent means. This data set will provide analytical systems enough information to roughly determine the road that the vehicle is on, and presumably both the grade and elevation of the road.

It should be noted that this file does not provide for the transmission of data on the vehicle's elevation above sea-level, the grade of the road, or the acceleration along its path. These variables can be hard to determine with either standard GPS tracking or through cross-referencing with existing topological base-map data. As stated in the Task 1 report data on the elevation or the grade of the road could prove to be valuable in future efforts to establish the environmental performance of the vehicle. The project team should consider encouraging the Connected Vehicle community to enhance the trajectory data to include at least elevation and grade.

Table 1. Fields in the on-board equipment trajectory file

Number	Variable name	Description	Format	Units or other comments
1	Veh	Vehicle ID	4 characters	From the directory in which the file
2	Logfile	Suffix for the OBE logfile	Integer or '--'	--' appears if there is no suffix in the log file name
3	Line	Line number of the snapshot in the logfile	Integer	
4	date	Datestamp	MM/DD/YYYY	Combined from header or snapshot
5	time	Timestamp	HH:MM:DD	Combined from header or snapshot hour, minute, and second fields
6	secs	Number of seconds since the beginning of travel	Integer	
7	speed	Speed	Real 1 dec. place	Miles per hour
8	lat	Degrees latitude	Real 6 dec. places	Converted from integer in the log file by dividing by 8000000
9	long	Degrees longitude	Real 6 dec. places	Converted from integer in the log file by dividing by 8000000
10	x-ft	Location x value	Integer	Conversion from long to feet, adjusting for latitude
11	y-ft	Location y value	Integer	Conversion from lat to feet

The OBE Snapshot file gives the state of the vehicle at a moment in time. A total of 35 variables are transmitted in this message. The time, location, and heading are given to establish the snapshot in the vehicle's trajectory and in this file a geographic elevation is given in decimeters. The basic operational status of lights, wipers, brakes and tire pressures are also included.

What is notably lacking from the OBE Snapshot file is any significant data on the operating conditions of the vehicle's drive-train. There is no data for fuel flow rate, coolant temperatures, exhaust temperatures, exhaust treatment activity or several of the other variables which were mentioned in this project's Task 1 report.

Table 2. Fields in the on-board equipment snapshot file

Number	Variable name	Description	Format	Units or other comments
1	OBE_ID	OBE ID	4 characters	The OBE ID is found in the file name
2	Veh_id	Vehicle ID	4 characters	The Vehicle ID is found in the directory
3	Logfile	Suffix for the OBE logfile	Integer or '--'	--' appears if there is no suffix in the log file name
4	Line	Line number in the logfile	Integer	
5	date	Snapshot datestamp	MM/DD/YYYY	Combined from header or snapshot year, month, and date fields
6	time	Snapshot timestamp	HH:MM:DD	Combined from header or snapshot hour, minute, and second fields
7	lat	Degrees latitude	Integer	1/8000000 degrees
8	long	Degrees longitude	Integer	1/8000000 degrees
9	elevation	Decimeters, with 1 km offset	Integer	Decimeters, with 1 km offset
10	heading	Vehicle heading	Integer	0.005493247 degrees (360/65535)
11	speed	Vehicle speed	Integer	0.01 meters per second
12	cntVSDTs	Vehicle status device type count	Integer	Number of data fields that follow
13	psn	Probe segment number	Integer	Changing randomly generated number for anonymity
14	lights	On/off status of lights	Bitstring	Bits 0-7 indicate which lights are on (see documentation)
15	brake_status	On/off status of brakes	Bitstring	Bits 0-3 indicate which brakes are one (see documentation)
16	brake_boost	Brake boost	char	On, off, or notEquipped
17	abs	Anti-lock brake system	Char	On, off, engaged, or notEquipped
18	stability	Vehicle stability control	Char	On, off, or notEquipped
19	traction	Vehicle traction control	Char	On, off, engaged, or notEquipped
20	yaw	Vehicle yaw rate	Integer	0.01 degrees per second
21	steering_angle	Angle of steering wheel	Integer	0.2 degrees
22	steering_rate	Steering wheel rate of turn	Integer	Degrees per second
23	wheels	Angle of front wheels	Integer	0.3333 degrees
24	hozAccelLat	Lateral acceleration	Integer	0.01 meters per second squared
25	hozAccelLong	Longitudinal acceleration	Integer	0.01 meters per second squared
26	tirePress_lf	Left front tire pressure	Integer	pounds per square inch
27	tirePress_rf	Right front tire pressure	Integer	pounds per square inch
28	tirePress_lr	Left rear tire pressure	Integer	pounds per square inch
29	tirePress_rr	Right rear tire pressure	Integer	pounds per square inch
30	tirePress-spr	Spare tire pressure	Integer	pounds per square inch (not implemented)
31	front_ww	Front windshield wipers	char	off, intermittent, low, high, notEquipped, or automaticPresent
32	rear_ww	Rear windshield wipers	char	off, intermittent, low, high, notEquipped, or automaticPresent
33	ww_rate	Windshield wiper rate	integer	sweeps per minute
34	airTemp	Air Temperature	Integer	Centrigrade degrees, offset +40
35	barPress	Barometric Pressure	Integer	hectopascals (millibars), offset +580

1.3 SAE J2735 Standard

The current revision of SAE J2735 (2nd edition) is dated October 28, 2009. The standard specifies the definitive message structure and provides sufficient background information to allow readers to properly interpret the message definitions from the point of view of an application developer implementing the messages according to the DSRC Standards.

The DSRC data concepts in SAE J2735 are divided into messages, data frames, and data elements. A message is a well structured set of data elements and data frames that can be sent as a unit between devices to convey some semantic meaning in the context of the applications. A data frame (formerly called data structure) is a logical grouping of other data frames and of data elements to describe structures or parts of messages. A data element is a syntactically formal representation of some single unit of information of interest (such as a fact, proposition, observation, etc.) with a singular instance value at any point in time, about some entity of interest. It is considered indivisible. In the current revision of the Standard, there are 15 messages, 73 data frames, and 149 data elements, of which 17 are reused from SAE J1939.

Table 3. List of messages defined in SAE J2735 2nd Edition

No.	Message
1	Message: MSG_A_la_Carte (ACM)
2	Message: MSG_BasicSafetyMessage (BSM)
3	Message: MSG_CommonSafetyRequest (CSR)
4	Message: MSG_EmergencyVehicleAlert (EVA)
5	Message: MSG_IntersectionCollisionAvoidance (ICA)
6	Message: MSG_MapData (MAP)
7	Message: MSG_NMEA_Corrections (NMEA)
8	Message: MSG_ProbeDataManagement (PDM)
9	Message: MSG_ProbeVehicleData (PVD)
10	Message: MSG_RoadSideAlert (RSA)
11	Message: MSG_RTCM_Corrections (RTCM)
12	Message: MSG_SignalPhaseAndTiming Message (SPAT)
13	Message: MSG_SignalRequestMessage (SRM)
14	Message: MSG_SignalStatusMessage (SSM)
15	Message: MSG_TravelerInformationMessage (TIM)

We have reviewed all the data elements in SAE J2735, and found that none of them is geared directly towards environmental performance applications such as emissions monitoring and reporting. This is not unexpected as SAE J2735 has so far been focused on safety and mobility applications. Nevertheless, some of the data elements are needed or can be useful for environmental performance applications. They are listed below:

- Data Element: DE_Acceleration
- Data Element: DE_AccelerationConfidence
- Data Element: DE_AmbientAirPressure (Barometric Pressure)
- Data Element: DE_AmbientAirTemperature
- Data Element: DE_CoefficientOfFriction
- Data Element: DE_Elevation
- Data Element: DE_ElevationConfidence
- Data Element: DE_ExteriorLights
- Data Element: DE_J1939-71-Cargo Weight
- Data Element: DE_J1939-71-Trailer Weight
- Data Element: DE_J1939-71-Tire Pressure
- Data Element: DE_LightbarInUse
- Data Element: DE_Speed
- Data Element: DE_SpeedConfidence
- Data Element: DE_ThrottlePosition
- Data Element: DE_ThrottleConfidence
- Data Element: DE_TransmissionState

- Data Element: DE_VehicleHeight
- Data Element: DE_VehicleMass
- Data Element: DE_VehicleType
- Data Element: DE_VehicleWidth
- Data Element: DE_WiperRate
- Data Element: DE_WiperStatusFront
- Data Element: DE_WiperStatusRear

Although the current revision of SAE J2735 does not include any specifics that will sufficiently support environmental performance applications, it has been designed to support deployment in such a way as to remain compatible with additional further planned message content, still in development. Therefore, it should be possible to develop new messages, data frames, and data elements within the concept of SAE J2735 to support other emerging applications such emissions monitoring and reporting.

Some of the new developments can possibly "piggyback" on existing applications. Specifically, the real-time emissions monitoring and reporting application that is being investigated in this project has many characteristics that are similar to traffic probe application. Annex E of the SAE J2735 presents traffic probe message use and operation, where a probe message is transmitted from a vehicle to a roadside unit. The message contains several snapshots as well as the message common header, as shown in Figure 1. According to the figure, a snapshot consists of snapshot header and vehicle data elements. It is possible to expand or redefine the vehicle data elements to support the emissions monitoring and reporting application.

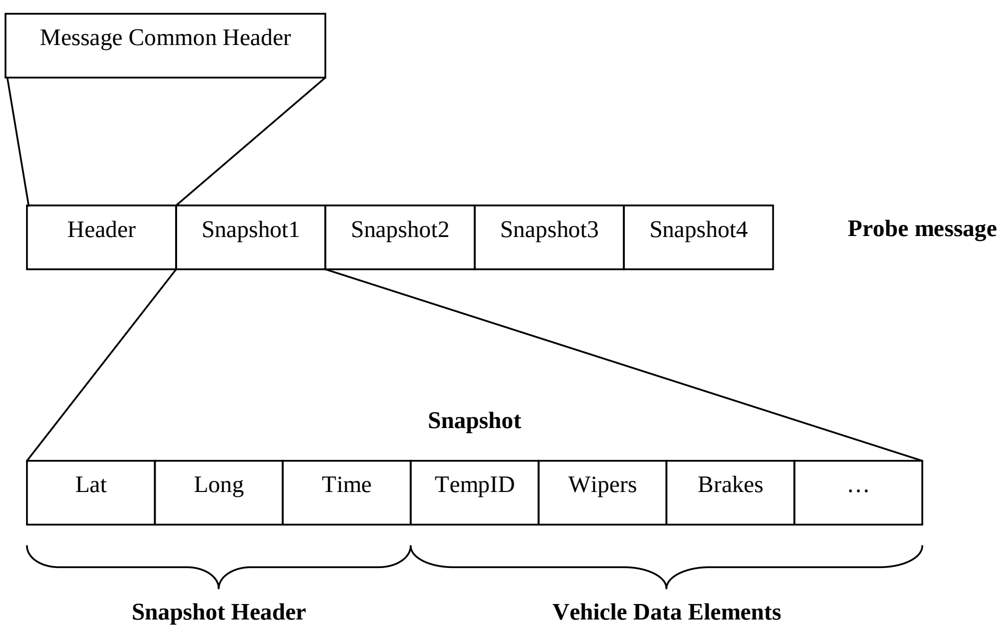

Figure 1. Probe message structure

TASK 3

1 Heavy-Duty Truck Emission Model in CMEM

Over the years, the UCR's College of Engineering – Center for Environmental Research and Technology (CE-CERT) has developed numerous models and tools to evaluate transportation environmental impacts. One of the major contributions was the development of the CMEM, which is a microscopic emissions model that was developed with the support from the National Cooperative Highway Research Program and the U.S. Environmental Protection Agency. CMEM is capable of predicting second-by-second fuel consumption and tailpipe emissions of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) based on different modal operations of an in-use vehicle fleet.

In the modeling approach of CMEM, the entire fuel consumption and emissions process is broken down into components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component of CMEM is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to vehicle type, engine, emission control technology, and level of deterioration. Note that the level of deterioration of the engine and emission control system is difficult to characterize beyond the as-built specifications, and vehicle mileage is typically used as a surrogate.

The initial versions of CMEM contain a model database for 23 light-duty vehicle categories. With the constant addition of new vehicle categories into the model database, the current version of CMEM includes 28 light-duty vehicle categories and three HDT categories [Barth et al., 2004]. This section discusses only the HDT model of CMEM.

1.1 Model Structure

The general structure of the HDT model of CMEM is presented Figure 1 [Scora, 2007]. It is composed of six basic modules as indicated by the boxes in the figure: engine power demand, engine speed, fuel-rate, engine control, engine-out emissions, and exhaust after-treatment. The model as a whole requires two groups of inputs: operating variables and vehicle parameters. The basic output of the model is tailpipe emissions and fuel consumption.

The vehicle power demand, engine speed, and fuel rate are determined based on operating variables and basic vehicle parameters. The remaining modules require the input of additional vehicle parameters determined from on-road or dynamometer measurements, as well as the engine power and fuel rate calculated by the model. The core of the model is the fuel rate calculation. It is a function of power demand and engine speed. Engine speed is determined based on vehicle velocity, gear shift module and power demand.

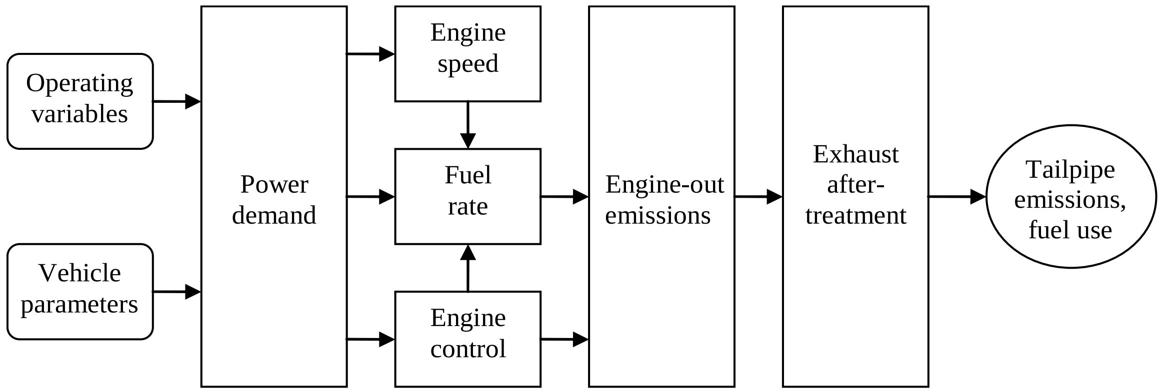

Figure 1. Heavy-duty truck emission model in CMEM

1.2 Model Inputs

CMEM requires two groups of data inputs: operating variables and vehicle parameters. "Operating variables" are variables that describe the vehicle operating conditions, on a second-by-second basis. Currently, there are three operating variables in the model including vehicle speed, road grade, and accessory load (such as air conditioning, wipers, infotainment system, and even refrigerator, microwave, and other electronics in some HDTs, especially those that do long haul.) Vehicle speed is used to derive acceleration. Optionally, acceleration can be input directly as a separate input variable. If road grade and accessory load inputs are not given, they are assumed to be zero.

In addition to the current three operating variables, environment variables such as wind speed and direction, ambient air pressure, ambient air temperature, and relative humidity can be obtained from direct measurements on the vehicle or from local weather stations (given the knowledge of the vehicle's position), and then incorporated into the model in the future to better characterize the actual conditions the vehicle is operated under. These environmental variables will constitute a new group of data input on the left of the model structure in Figure 1.

"Vehicle parameters" define vehicle and engine characteristics and can be grouped into two categories: readily available and calibrated. Readily available parameters are those parameters that define a vehicle's general characteristics, usually relating to physical properties, and can be readily obtained from external sources such as automotive statistics and vehicle or engine specification sheets. Examples include vehicle mass or weight, engine displacement, maximum torque, number of gears, etc.

A list of vehicle parameters is given in Table 1. Readily available parameters also include general values which are constant across all HDTs such as indicated engine efficiency or the lower heating value of diesel fuel. In contrast, calibrated parameters require fuel use and emission measurements in order to calibrate these parameters for a specific vehicle or engine. These parameters are also listed in Table 1.

Table 1. HDT model vehicle parameters

Readily Available	Calibrated
Vehicle Specific	***Fuel Related***
M = vehicle mass	k_0 = engine friction factor
V = engine displacement	k_1 = engine speed dependent engine friction factor
N_{idle} = idle speed	F_{idle} = fuel at idle
S = engine speed/vehicle speed	f_A = fuel strategy parameter
Q_m = maximum torque	f_B = fuel strategy parameter
N_{Qm} = engine speed at QM	***Engine-out Emission Parameters***
P_m = maximum engine power	aco = CO emission-index coefficient
N_{Pm} = engine speed at P_m	rco = CO emission-index coefficient
N_g = number of gears	aHC = HC emission-index coefficient
G_f = final drive ratio	rHC = HC emission-index coefficient
A_f = frontal area of vehicle	aNOx = NOx emission-index coefficient
C_d = drag coefficient	rNOx = NOx emission-index coefficient
	aNOxh = NOx off cycle emission-index coefficient
General	rNOxh = NOx off cycle emission-index coefficient
η = indicated efficiency	minCO = minimum CO value
Hg = heavy diesel lower heating value	minHC = minimum HC value
	minNOx = minimum NOx value

1.3 Fuel Rate Module

The backbone of the HDT model which ties engine load to exhaust emissions is the fuel rate module. The equation for modeling fuel rate in any driving cycle for any vehicle is [An and Ross, 1993]:

$$FR = (k \cdot N \cdot D + P_e/\eta)/LHV$$

where:

- k = engine friction term
- N = engine speed
- D = engine displacement
- P_e = engine power
- η = engine indicated efficiency
- LHV = the lower heating value of fuel

For a diesel engine, the value of indicated efficiency (η) is roughly 0.45 and the lower heating value for a typical diesel fuel is 43.2 kJ/g. The engine friction term can be approximated as a function of engine speed.

It has been observed that certain HDTs utilize alternative fuel injection strategies to improve fuel economy at the expense of NO_x emissions. For modeling purposes, a fuel use reduction factor to account for alternative fuel injection timing strategies is introduced according to the equation below.

$$FR_{off} = FR \cdot (1 - \mathrm{f}_{\mathrm{Red}})$$

where:

FR_{off} = off-cycle fuel rate

f_{Red} = fuel use reduction factor

1.4 Engine-Out CO Emission Module

The basis for engine-out emission estimates in the HDT model is the relationship between fuel rate and emissions. This relationship has been observed to be primarily linear with certain excursions. For some emissions, namely CO and particulate matter (PM), non-linear relationships have also been observed [Clark et al., 2002].

CO emissions are a product of incomplete combustion and are controlled primarily by the air-fuel ratios occurring during combustion [Heywood, 1988]. The formation of CO is typical for a rich air-fuel ratio where excess fuel is present and there is insufficient amount of air to combust it. Diesel engines typically run under lean air-fuel conditions which means they have an excess amount of air for the quantity of fuel they are burning.

Under these conditions, incomplete combustion is less common. Therefore, diesel CO emissions are extremely low unlike gasoline engines which usually run close to stoichiometry and run rich at full load. It has been shown that for diesel engines, CO does not vary significantly with the air-fuel ratio [Heywood, 1988]. Due to its low levels, diesel CO emission is not considered to be of great concern.

For modeling purposes, analysis of the test data has shown that there is a correlation between fuel use and engine-out CO emission. This is consistent with what others have found [Ramamurthy et al., 1998]. This correlation, however, is not particularly strong. For generalization, the equation below is used to model CO emission.

$$ECO = a_{CO} \cdot FR + r_{CO}$$

where:

ECO = engine-out CO emission

FR = fuel rate

a_{co}, r_{co} = CO emission index coefficients

1.5 Engine-Out HC Emission Module

Engine-out HC emissions are primarily a result of unburned hydrocarbons due to combustion inefficiencies which can arise in several ways. For instance, during the compression stroke, unburned fuel can be forced into crevices between the piston rings and cylinder walls where the combustion flame is too large to enter. Unburned fuel in crevices can escape later during the exhaust stroke. Another source of unburned hydrocarbons is a fuel “quench layer” left on the cylinder walls which remains unburned (not being reached by the combustion flame before it extinguishes). Yet another source of unburned hydrocarbons is the adsorption and desorption of fuel by any lubricating oil left on any of the cylinder surfaces [Heywood, 1988].

For diesel engines, fuel is injected toward the end of the compression stroke, shortly prior to combustion. For this reason, fuel has a limited time to distribute and fuel distribution becomes critical for the combustion process. This results in unburned hydrocarbons in areas of the combustion flame where air-fuel mixtures either prevent combustion from starting or the fuel spray is quenched on the cylinder walls [Heywood, 1988].

Much like CO emission, analysis shows that there is a correlation between fuel use and engine-out HC emission although it is not a very strong one. Similar to CO emission, the linear equation below is used to model HC emission.

$$EHC = a_{HC} \cdot FR + r_{HC}$$

where:

EHC= engine-out HC emission
FR = fuel rate
a_{HC}, r_{HC} = HC emission index coefficients

1.6 Engine-Out NO_x Emission Module

For diesel engines, the emissions of primary concern are NO_x and PM. The formation of NO_x emissions in diesel engines is well understood and is dependent mainly on the presence of sufficient oxygen and high temperatures. NO_x emissions exhibit a strong linear relationship with fuel use, which can be written as:

$$ENO_x = a_{NOx} \cdot FR + r_{NOx}$$

where:

$ENOx$= engine-out NOx emission
FR = fuel rate
aNO_x, rNO_x = NO_x emission index coefficients

NO_x emissions may be reduced by decreasing in-cylinder temperatures. This can be accomplished by retarding fuel injection timing. Fuel injection timing refers to the point during the combustion process in which fuel is injected into the combustion chamber. Retarding this timing lowers NO_x emission but promotes incomplete combustion, which leads to increased PM emission and lower fuel economy. On the other hand, advancing fuel injection creates higher in-cylinder pressures resulting higher fuel efficiency, but it increases combustion temperatures and as a result increases NO_x emissions. This relationship between NO_x, PM, and fuel economy is commonly referred to as the NO_x, PM, fuel "trade-off". For this reason, fuel injection timing strategies have a great impact on the formation of NO_x emissions.

It has been observed that the fuel injection timing strategies of many HDTs do not always remain consistent with those used during engine certification testing. It has been determined that under certain modes of operation, mainly highway driving, many of the HDTs found in today's fleet utilize off-cycle fuel injection timing strategies which result in higher NO_x emissions in favor of increased fuel economy. This resulted in the signing of a 1988 Consent Decree by the U.S. Environmental Protection Agency (EPA), the Department of Justice (DOJ), and diesel engine manufacturers that stated that the non-compliant diesel engines would not be recalled but new diesel engines would have to meet stricter emission standards sooner in order to compensate [U.S. EPA, 2003].

Figure 2 illustrates dual NO_x/fuel relationships as a result of off-cycle fuel injection timing strategies. The top plot in Figure 2 shows the velocity profile for a portion of test data. In the bottom plot, NO_x versus fuel data are plotted with colors corresponding to the data points in the top plot. From Figure 2, it can be seen that during the high-speed cruise section, off-cycle activity (shown in blue) has a higher NO_x to fuel ratio than the certified activity (shown in red). Also, both off-cycle and certified NO_x emissions have strong linear relationships with fuel, which can be modeled with Equations (5) and (6).

$$ENO_x = a_{NOh} \cdot FR + r_{NOh}$$

where:

ENO_x= engine-out NO_x emission
FR = fuel rate
a_{NOxh}, r_{NOxh} = off-cycle NO_x emission index coefficients

Off-cycle strategies employed by the various diesel engine manufacturers are not publicly documented. Also, they seem to differ by engine manufacturer, by engine model year, and sometimes even by drive cycle. This makes it very difficult to determine the conditions under which off-cycle strategies are activated during a given drive cycle. It has been observed that these strategies appear to be time-dependent and in some cases show a somewhat predictable pattern across similar cycles. For modeling purposes, off-cycle fuel injection timing strategies are characterized as a function of time and velocity in which these strategies occur after a given amount of time (e.g., 80 seconds) above a certain vehicle speed (e.g., 30 mph), and then, normal operation resumes once the vehicle speed drops below a certain point (e.g., 30 mph).

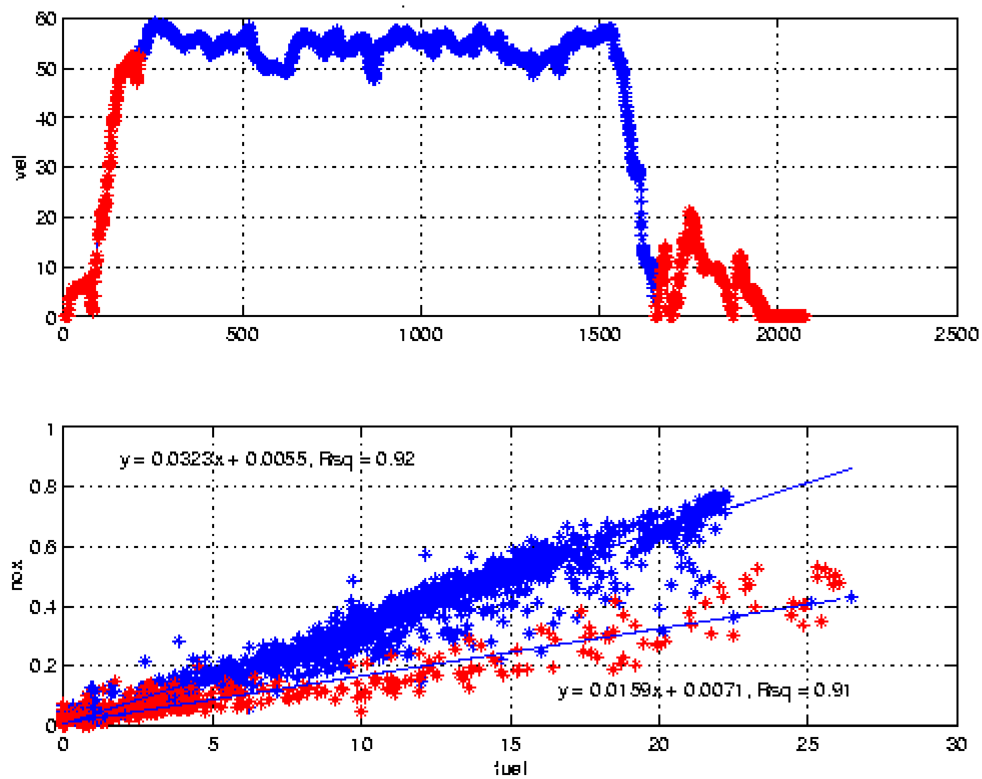

Figure 2. Two modes of NO_x versus fuel relationship for 2000 CAT C-15 engine

1.7 Exhaust After-treatment Modeling

Exhaust after-treatment technologies for HDTs have recently emerged to help newer model year HDTs meet more stringent emission standards. Examples are Lean NO_x Trap (LNT), Lean NO_x Catalyst (LNC), Selective Catalytic Reduction (SCR), Diesel Oxidation Catalyst (DOC), and Diesel Particulate Filter (DPF). Modeling emissions from HDTs that have these exhaust after-treatment technologies will require a model architecture that incorporates the effects of these technologies on emissions. This will require emission measurements from HDTs pre and post after-treatment devices in order to determine after-treatment pass fraction. In the current version of CMEM, the after-treatment pass fraction for all three HDT categories (model year ranging from 1994 to 2003) is modeled as 100%. This is because the use of after-treatment devices and systems was not prevalent when the HDT model of CMEM was developed in early 2000s. These devices and systems have become necessary to help HDTs meet the more stringent 2004 and subsequent emission standards. For future versions, new HDT categories representing newer model years should be added that account for the after-treatment effects.

2 Real-Time Emission Modeling with CMEM

As described in the previous section, CMEM requires detailed vehicle operating variables on a second-by-second basis. At a minimum, the operating variables must include vehicle speed. This requirement makes CMEM well suited for use with microscopic traffic simulation models, which can simulate vehicle speed and acceleration at high frequency (e.g., 1 Hertz or higher). In the real-world, this type of detailed vehicle trajectory (i.e., vehicle speed profile) data has traditionally been collected through the use of instrumented vehicles or GPS data loggers. Recently, emerging sensors (e.g., smart phones) and data collection techniques (e.g., computer vision) has also been used to collect vehicle trajectory data in a large scale.

CMEM has primarily been used to evaluate energy and emission impacts of traffic flow improvement projects such as those with intelligent transportation system (ITS) implementations. This use of CMEM often does not require real-time execution of the model. However, with the advancement in wireless communication in the last several years, it is now possible to perform real-time calculation of vehicle emissions with CMEM. This will allow for transportation systems to be actively managed so that their energy and environmental impacts are minimized. Examples of applications that can be enabled by this real-time capability are discussed in the next section.

The generic framework for using CMEM in real-time HDT emission modeling is illustrated in Figure 3. Under this framework, vehicle operating variables collected on-board the truck (e.g., via GPS data logger) are sent wirelessly to a backend server, which houses the HDT model in CMEM that has been calibrated for that specific truck or for a HDT category that the truck falls under. The primary vehicle operating variable to be sent is the second-by-second truck speed. Taking the truck speed data input along with the calibrated vehicle parameters, fuel consumption and tailpipe emissions of the truck can be calculated in real-time, following the existing model structure as shown in Figure 3.

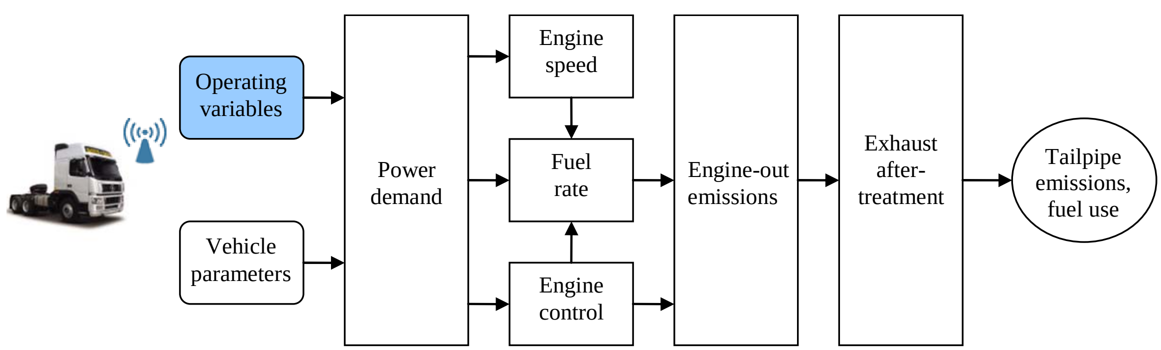

Figure 3. Real-time HDT emission modeling based on GPS data alone

Alternatively, if the truck's ECU is accessible, then the reported fuel rate data from the ECU can be sent wirelessly in lieu of or in addition to truck speed to the backend server. This is illustrated in Figure 4. In this case, the reported fuel rate data from the ECU can be used directly to calculate engine-out emissions, and subsequently, tailpipe emission, bypassing several of the preceding modules in the model structure of CMEM.

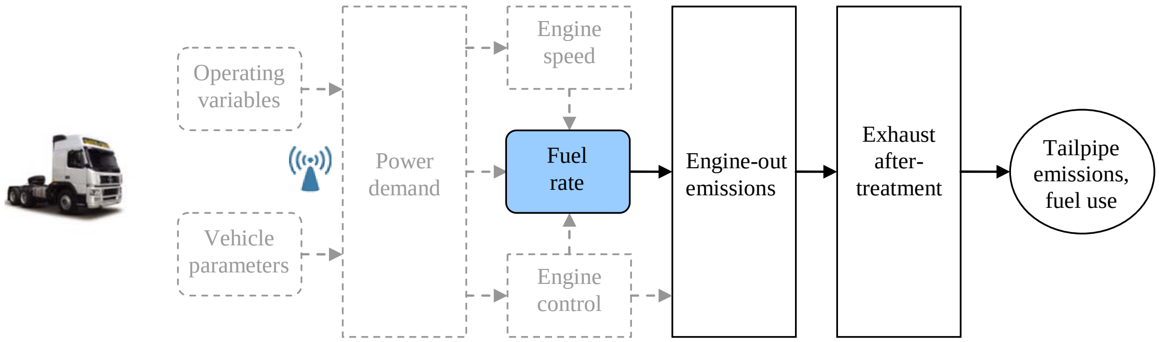

Figure 4. Real-time HDT emission modeling based on GPS and ECU data

The availability of measured fuel rate will help eliminate the error in the modeled fuel rate of CMEM, which can propagate to result in larger errors in emission estimates. An example is shown in Figure 5, where the modeled and measured fuel rates are compared for a transient drive cycle. In this example, the measured total fuel use is 1,002.2 g. The modeled value is 950.1 g, under predicting by approximately 5.2%. Based on our experience, the modeled total fuel use by CMEM could differ from those measured on-road by 0-10%, depending on the influence of operating variables that were not captured during the on-road testing (e.g., air temperature, wind speed, and road grade).

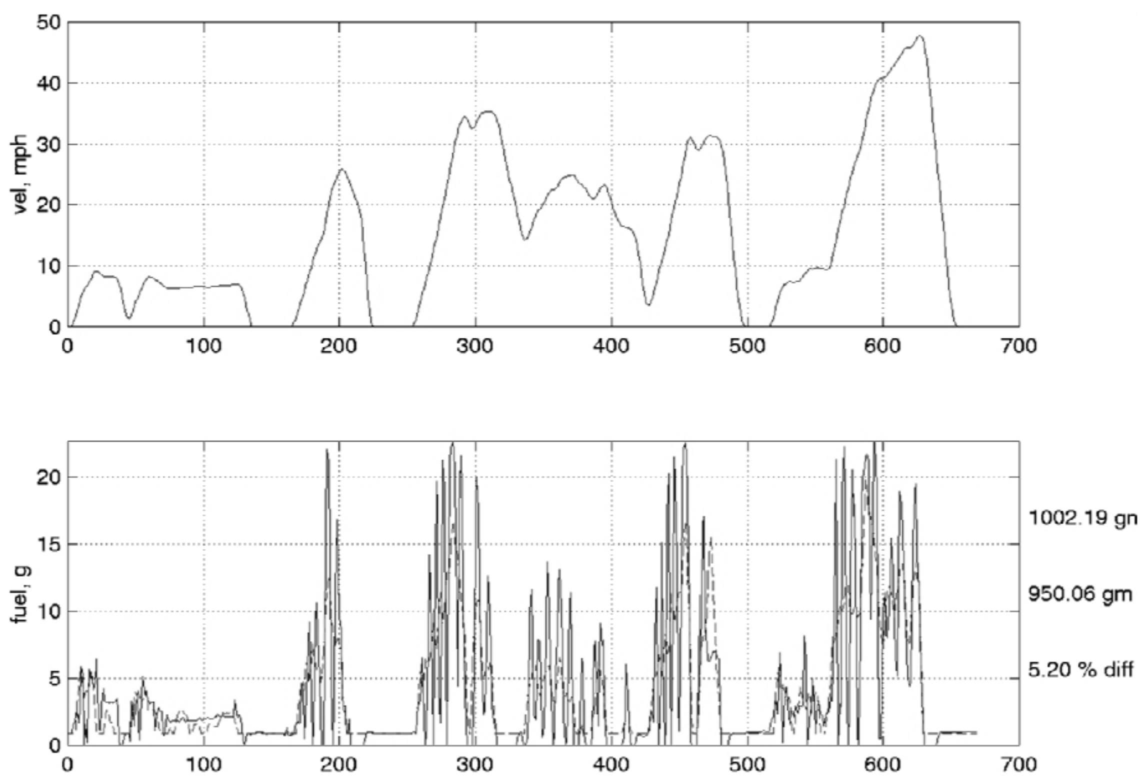

Figure 5. Modeled (dashed) and ECU (solid) fuel rate.

2.1 Architectures of Real-Time Emission Modeling

There are two general architectures for using ECU data to estimate emissions from HDTs:

1. Centralized: In this architecture, necessary ECU data items are compiled on-board the truck before being sent to a central server where the emission calculation is performed. The data compilation could be in the form of accumulation or concatenation. For example, the engine fuel rate that is read off the data bus can be accumulated over a pre-set interval (e.g., 30 seconds) before being sent periodically to the server. Alternatively, the data can be processed into a string of second-by-second values for the entire pre-set interval before being sent to the server. In this case, the concatenated data can be sent periodically or based on trigger events (e.g., data sent at the end of each roadway link), depending on the application needs.

   It should be noted that CMEM was developed based on second-by-second emission measurements, and thus, it works with second-by-second input data. The data accumulation approach discussed above will require that CMEM be modified to work with a coarser time-resolution data. Although the data concatenation approach will work well with the current version of CMEM, the size of the data to be sent wirelessly in real-time could be excessive. This issue and possible workarounds are discussed in more detail in a later subsection.

2. Decentralized: In this architecture, the emission calculation by CMEM occurs on-board the trucks, and only the emission results are sent to the central server, as illustrated in Figure 6. This architecture will require that CMEM is implemented in the on-board telematics equipment, preferably with direct connection to the truck ECU. In which case, the reported fuel rate from ECU along with a set of previously calibrated vehicle parameters that are stored on-board can be used to calculate engine-out emissions, and subsequently, tailpipe emissions. These emissions can be accumulated over time (e.g., every 5 minutes) and/or space (e.g., every roadway link) before being sent to the server. In addition, the accumulated emissions can be sent directly to roadside infrastructures or to other vehicles in the proximity, under the framework of Connected Vehicles, which enables applications to work in an ad-hoc network fashion.

   Although this decentralized architecture does not have the drawbacks of the centralized one, it requires model calibration and telematics software programming that are customized to individual trucks beforehand. Thus, the implementation cost up front will be higher, but the operation cost (mainly for data transmission) may be lower. Compared to the accumulation approach of the centralized architecture, the decentralized architecture will have a higher cost for data transmission as it will have to transmit multiple emission values in addition to the fuel use. However, it will have a much lower cost for data transmission compared to the concatenation approach of the centralized architecture. Also, the cost for updating the model software may be higher as the trucks will have to be called in for reprogramming of the telematics software. However, this model update can be included as part of the standard telematics software maintenance process so that there will be only a small cost associated with it.

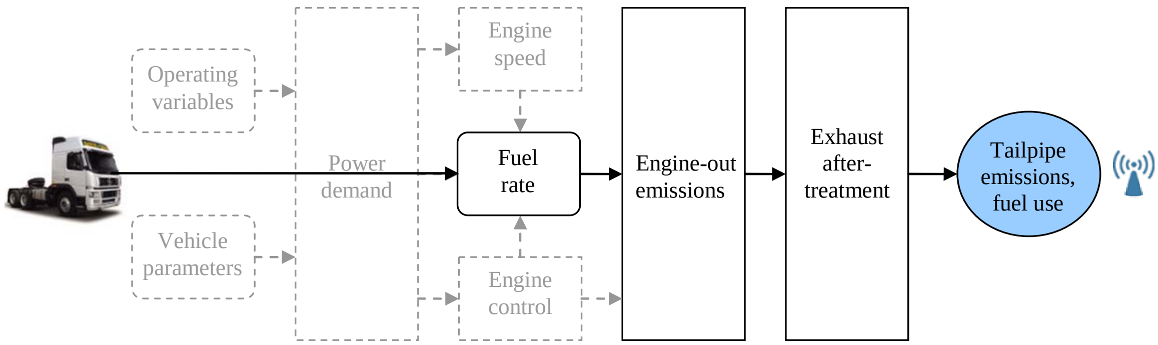

Figure 6. Decentralized real-time HDT emission modeling based on GPS and ECU data

2.2 Data Frequency

In terms of data frequency, CMEM has been developed based on second-by-second emission measurements, and been used primarily with vehicle operating inputs at the second-by-second level. However, if fuel rate data is directly available from trucks' ECU, the calculation of HDT emissions in the centralized architecture may be performed at other time scales without sacrificing much of the model accuracy, especially for CO_2 and NO_x (if the off-cycle strategies for NO_x are well understood). This is because the relationships between fuel rate and engine-out CO_2, CO, HC, and NO_x emissions (and subsequently, tailpipe emissions of these pollutants) are currently modeled as a linear function, which has additive property.

In the case of modeling HDT emissions at other time scales rather than second-by-second, a fuel use value while the truck is in off-cycle mode needs to be tracked and reported separately for proper NO_x emission calculation. This is because, as shown in Figure 2, the NO_x to fuel ratio during the off-cycle mode is higher than that during a normal operation. It is important to note that the modeling of HDT emissions with CMEM at other time scales rather than second-by-second is only appropriate as long as the relationships between fuel rate and engine-out emissions are modeled as a linear function. At present, we are working on the module for PM emission in the HDT emission model. It has been preliminarily observed that its relationship with fuel rate is not linear where the PM-to-fuel rate ratio is very high under certain operating conditions.

In the case that second-by-second fuel rate data is really needed in order to maintain the accuracy of the emission estimates (as for PM emission), there are some techniques that can be used to reduce the amount of data to be transmitted wirelessly to the server while preserving the fidelity of the data.

1. Aperiodic messaging: In this technique, data points (rather than data stream) are sent only when there are significant changes in the data pattern. For example, when the truck is idling and the fuel rate remains the same, there is no need to send that same fuel rate value to the server every second. Instead, the data is not sent until the fuel rate changes (after the truck starts moving, the air-conditioning is turn on, etc.). Then, the data gap can be filled by interpolating between the data points at both ends of the gap. This technique can save a lot of bandwidth from sending unnecessary data.
2. Data compression: The idea is simply to take the time-series data (i.e., fuel rate in our case) and compress it before sending it. Once the compressed data is received at the server, it is uncompressed back to the full level of detail. This is similar to MP3 data compression for music, which can get at least a 10:1 reduction ratio.

2.3 Geographical Scale

In terms of the geographical scale of data reporting, either in centralized or decentralized architecture, it is desirable to report data at the finest scale (i.e., second-by-second), which allows for the flexibility in aggregating the data to other coarser scales. However, that may not be practical and cost prohibitive. Therefore, it is most likely that the data will have to be aggregated in one way or another before being transmitted.

The choice of data aggregation depends largely on the application needs and the cost consideration. For example, for traffic management applications such as changing speed limits on roadways in order to reduce emissions, the data should be aggregated at the roadway link level. On the other hand, for air quality management applications such as ozone monitoring and mitigation, the data may be aggregated at a city or county boundary level.

2.4 Data Protocol

As discussed in the Task 2 report, we have reviewed all the data elements in the SAE J2735 standard, and found that none of them is geared directly towards environmental applications such as emissions monitoring and reporting. This is not unexpected as SAE J2735 has so far been focused on safety and mobility applications. Nevertheless, some of the data elements can also be used in environmental applications. For example, in the case of real-time emission modeling with CMEM, the following data elements can be useful although some are not directly used in the current version of the model:

Operating Variables Related

- Data Element: DE_Acceleration
- Data Element: DE_AccelerationConfidence
- Data Element: DE_AmbientAirPressure (Barometric Pressure)
- Data Element: DE_AmbientAirTemperature

- Data Element: DE_Elevation
- Data Element: DE_ElevationConfidence
- Data Element: DE_ExteriorLights
- Data Element: DE_LightbarInUse
- Data Element: DE_Speed
- Data Element: DE_SpeedConfidence
- Data Element: DE_ThrottlePosition
- Data Element: DE_ThrottleConfidence
- Data Element: DE_WiperRate
- Data Element: DE_WiperStatusFront
- Data Element: DE_WiperStatusRear

<u>Vehicle Parameters Related</u>

- Data Element: DE_CoefficientOfFriction
- Data Element: DE_J1939-71-Cargo Weight
- Data Element: DE_J1939-71-Trailer Weight
- Data Element: DE_J1939-71-Tire Pressure
- Data Element: DE_VehicleHeight
- Data Element: DE_VehicleMass
- Data Element: DE_VehicleType
- Data Element: DE_VehicleWidth
- Data Element: DE_TransmissionState

Although the current revision of SAE J2735 does not include any specifics that will sufficiently support environmental applications, it has been designed to support deployment in such a way as to remain compatible with additional further planned message content, still in development. Therefore, it should be possible to develop new messages, data frames, and data elements within the framework of SAE J2735 to support other emerging applications.

For instance, SAE J2735 can be used as a foundation for developing new data elements, or even new data frames and messages, based on ECU of HDTs to support various environmental applications such as real-time emissions monitoring and reporting. There are a number of vehicle and engine operating variables whose data are available on the ECU. However, the specific list of variables that should be reported and how they should be reported under the AERIS Program will largely depend on several factors, including the system architecture (whether centralized or decentralized) and the type of applications (e.g., monitoring versus management). These will require a more in-depth analysis of the ECU data and more elaborate system engineering beyond the scope of the current study.

For instance, in the centralized architecture, one of the most important variables to be reported is engine fuel rate, as shown in Figure 4. This variable will allow the tailpipe emissions to be calculated and reported in the current version of CMEM, therefore, meeting the objectives of the real-time emission monitoring and reporting application. However, if there are needs for developing countermeasures to mitigate high levels of emissions on the transportation system, then other fundamental variables (e.g., vehicle speed, road grade, accessory load) are also needed to be reported along with the engine fuel rate so that the causes of the high levels of emissions can be understood and properly addressed. For example, if the high emission levels are caused by excessive vehicle speeds on a particular section of highway, then speed management strategies can be implemented on that section of highway.

On the other hand, in the decentralized architecture the calculated tailpipe emissions are directly reported instead of the engine fuel rate. Still, as in the centralized architecture, other fundamental variables may also need to be reported along with the emissions in order for engineers/planners to understand the problems and develop appropriate countermeasures. In any case, the variables to be reported can be structured in a similar way to vehicle speed as currently defined in SAE J2735 (see Figure 7). An example of a possible format of engine fuel rate variable is shown in Figure 8.

Data Element: DE_Speed

ASN.1 Representation:

```
Speed ::=INTEGER  (0..8191) –- Units of 0.02 m/s
            -- The value 8191 indicates that
```

Figure 7. Vehicle speed as defined in SAE J2735 standard

Data Element: DE_EngineFuelRate

ASN.1 Representation:

```
EngineFuelRate ::=  INTEGER  (0..8191) –- Units of 0.1 g/s
            -- The value 8191 indicates that
```

Figure 8. Example of possible engine fuel rate variable in SAE J2735 format

CONCLUSIONS AND RECOMMENDATIONS

It has been shown that the truck ECU is an important data source for real-time emission modeling and reporting within the framework of CMEM. The ECU data has potential to even improve the accuracy of emissions estimated by CMEM. In the Connected Vehicle World, this real-time emission modeling capability can enable a variety of applications that improve the environmental performance of the transportation system.

To this point in time, the data necessary to direct the operation or planning of the transportation system based on environmental concerns has been very difficult to obtain. As a result, little work has been done on establishing the uses of fuel consumption and emissions data to better manage the transportation system. Therefore, the project team recommends the establishment of research programs under the AERIS umbrella to advance the science of vehicle emissions modeling based on the ECU data availability, and to explore innovative applications that can take advantage of this new emission modeling capability to benefit the environment. These research programs are discussed below.

Enhanced Emissions Modeling

The development of CMEM was started 15 years ago when even the collection of detailed vehicle speed profiles was difficult and expensive. Therefore, the model was designed in such as a way that emissions can be estimated given the basic vehicle operating variables. However, as we now realize, the model can be significantly improved with the use of direct engine fuel rate values from trucks' ECU. In addition, there are other variables in the ECU that have not been previously explored that may be able to improve the accuracy of emission estimates by CMEM. These variables are listed in Table 1 of the Task 1 report.

Therefore, it is recommended that a research program be established to advance the science of vehicle emissions modeling. There are several improvements that can be made to emission models like CMEM with the availability of ECU data, for example:

- How the environmental conditions (e.g., ambient air temperature, wind speed and direction) affect truck fuel economy and emissions on-road?

- How the aged engine or degraded components affect truck fuel economy and emissions?

- How the exhaust conditions (e.g., exhaust gas temperature) and after-treatment technologies affect truck fuel economy and emissions?

- How to adjust or improve the model (e.g., better account for accessory load) to accommodate new data items from the ECU (e.g., air-conditioning and wiper status)?

To answer these questions will require a series of truck emission testing that also captures ECU variables simultaneously so that the emission testing database can be used to develop the enhanced emission model.

Innovative Environmental Applications

With the availability of fine grain data related to fuel consumption and pollutant production from the vehicles that are operating in the transportation system we can now re-consider strategies for the development, maintenance, and operation of the transportation system. Examples of innovative applications that can be environmentally beneficial are briefly discussed below.

- Truck platooning: It has been shown that truck platooning can reduce aerodynamic drag, resulting in fuel and emission savings. In the Connected Vehicle World, a truck may communicate with other trucks to form a platoon when traveling through a windy area.

- Truck eco-routing: Traveling on different routes can result in significant differences in fuel consumption and emissions. This is especially true for trucks whose fuel consumption and emissions are very sensitive to vehicle speed, driving pattern, and road grade. Real-time energy and emissions data can help identify hot spots or highway sections that demand a lot of energy/emissions so that truck navigation systems can recommend routes that avoid those highway sections and areas.

- Active truck engine control: An example of dynamically controlling the NO_x to fuel ratio based on geographic locations is discussed in Task 1 report, where it may be reasonable to allow long-haul trucks to run in the fuel economy mode (high NO_x emissions) while traversing non-populous areas and switch to the emissions control mode (low NO_x emissions) when entering populous areas.

- Truck tolling: Real-time truck energy and emissions data can enable dynamic pricing/tolling schemes that are based not only on travel time, but also on energy and emissions.

The integration of real-time efficiency and emissions data into a connected vehicle system will likely take time to mature. While the industry is working to achieve this goal, it may be prudent to consider non-real-time applications of the information for planning activities. One such application may be using the fuel consumption and emissions data as a measure that helps prioritize the planning of reconstruction or capacity improvements in the system. For instance, it is altogether possible that we will be able to identify sections of the highway system such as on-ramp/acceleration lane that forces the drivers to push the limits of their vehicles causing an inordinate consumption of fuel and production of emissions. A carbon-trading approach to reconstruction efforts may very well move the reconstruction of such an on-ramp forward on the DOT’s calendar.

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ATTACHMENT A

Documentation of Onboard Equipment Files from the Connected Vehicle Michigan Testbed

1 Background

The Connected Vehicle Michigan Testbed (IMT) Data Environment makes available to the public data collected at the IMT as well as metadata and supplemental data. This document describes the background, organization, and content of raw data files collected by the Onboard Equipment (OBE) at the IMT, and of files derived from those raw data files. As of May 2010, data from two sets of driving trials have been included in the Data Environment:

- Proof-of-Concept (POC) trials, August 2008
- National Center for Atmospheric Research (NCAR) trials, April 2009

In the future, data from additional IMT trials, including those performed by NCAR in March 2010 may be added to the data environment.

1.1 Document Organization

The first section of this document provides an overview of the data collection process including the creation and transmission of the files by the OSEs. The second section documents the contents of the raw OBE log files. The third section documents the format and contents of the raw comma-separated value (CSV) files created from the log files. Finally, Appendix A presents a partial sample OBE log file.

1.2 OBE File Background

The OBE log files are data collected near the beginning of a data collection process that begins on the instrumented vehicles. The basic steps in the sequence are:

1. Vehicle and environmental data are collected by the vehicle's Onboard Diagnostic Unit (OBD2) and by sensors mounted on the vehicle.
2. The vehicle's OBE collects and records the information in log files.
3. At certain times defined by Annex B of the J2735 standard, the OBE "takes a snapshot". A snapshot is a record of the values of certain variables at the instant the snapshot was taken. According to Annex B of the J2735 standard, snapshots are taken:
    a. When the vehicle comes to a stop (stop snapshot)

    b. When the vehicle resumes moving after a stop (start snapshot)
    c. Periodically every 5 to 20 seconds, depending on vehicle speed (periodic snapshot)
4. If a snapshot is taken, but the vehicle's snapshot buffer is full, a snapshot is deleted according to a priority scheme described in Annex B of the J2735 standard, and the new snapshot is stored in the buffer.
5. When the vehicle comes within transmission range of an RSE (nominally 1 km), the OBE generates and transmits one or more messages. The format of the messages is specified by the J2735 standard. Each message contains:
    a. A serial number header with the OBE ID number and time
    b. A message header containing the time the message was sent and the vehicle's location when the message was sent
    c. One to four snapshots, each containing the time and location the snapshot was taken, vehicle information, and environmental data

   If more than four snapshots are in the buffer, the OBE composes and transmits multiple messages, each containing up to four snapshots, until either all snapshots have been sent or the vehicle has passed out of transmission range.
6. Snapshots that have been successfully transmitted to an RSE are deleted from the buffer. Snapshots that have not been successfully transmitted are retained, in hopes of a successful transmission later.
7. OBE log files are downloaded from each vehicle at the end of each day and are stored.

The collects a great deal more data than what is contained in the snapshots, and it produces a log file documenting all this information. These log files were retrieved from the vehicles at the end of each day. This document describes the format and contents of the OBE log files, and of three types of files created by Noblis as subsets of the OBE data.

1.3 OBE Log Files Included in the IMT Data Environment

The public applications testing phase of the POC trials lasted ten days. Noblis selected the six days for which the most RSE data files were available, and for which there were the fewest number of duplications and questionable data values. Similarly, Noblis selected the six days from the NCAR April 2009 trials with the most data and the best data. The IMT data environment proves one complete set of OBE log files for one day from each set of trials, and the three types of extracts described in Section 3 for all selected days. However, OBE log files are not available for 8/22/08 and 8/27/08. Table 1 presents the complete list of days for each set of trials, and the days for which OBE data is available in the IMT Data Environment.

Table 1. Days Included in the IMT Data Environment

POC Trial Day	Included in Data Environment	NCAR 2009 Trial Day	Included in Data Environment
8/20/2008	No	4/03/2009	No
8/21/2008	Extracts + Full day	4/05/2009	No
8/22/2008	Not available	4/06/2009	Extracts
8/25/2008	Extracts	4/13/2009	Extracts + Full day
8/26/2008	Extracts	4/14/2009	Extracts
8/27/2008	Not available	4/15/2009	No
8/28/2008	Extracts	4/20/2009	Extracts
8/29/2008	No	4/21/2009	Extracts
9/11/2008	No	4/22/2009	Extracts
9/12/2008	No	4/27/2009	No

The following table lists the ID numbers of the vehicles that were used for each test, the corresponding OBE IDs, and the type of vehicle. Note that although vehicle C141 participated in the POC trials, it did not successfully transmit any messages to any RSE, so no messages from vehicle C141 appear in the RSE files.

Table 2. Vehicle and OBE IDs used for POC and NCAR Trials

OBE ID	Vehicle ID	Vehicle type	POC	NCAR
C594	A2	Nissan Altima	Y	
C779	A6	Nissan Altima	Y	Y
C985	A8	Nissan Altima	Y	
C141	A9	Nissan Altima		Y
CC94	A11	Nissan Altima	Y	
C453	C1	Jeep Cherokee	Y	
B856	C2	Jeep Cherokee	Y	Y
B422	C3	Jeep Cherokee	Y	
B420	C4	Jeep Cherokee	Y	
B450	E1	Ford Edge	Y	
B042	E2	Ford Edge	Y	Y
B193	E3	Ford Edge	Y	Y
B325	E4	Ford Edge	Y	Y
C482	P1	Jeep Cherokee		Y
C862	P2	Jeep Cherokee	Y	
C694	P3	Jeep Cherokee	Y	Y
C256	P4	Jeep Cherokee	Y	
C832	P5	Jeep Cherokee	Y	Y
C194	P6	Jeep Cherokee	Y	Y
C992	P7	Jeep Cherokee	Y	
C548	P8	Jeep Cherokee	Y	Y
C082	P9	Jeep Cherokee	Y	
C590	P10	Jeep Cherokee	Y	Y
C545	P11	Jeep Cherokee	Y	
C366	P12	Jeep Cherokee	Y	

The following tables show the number of messages received by RSEs from each OBE ID number for each day of the two sets of trials. Each message received by an RSE is saved as a separate file. Each message file contains one to four snapshots.

Table 3. Number of Messages per Vehicle per Day (POC Trial)

	Number of Messages in POC Trial						
Vehicle ID	**8/21/08**	**8/22/08**	**8/25/08**	**8/26/08**	**8/27/08**	**8/28/08**	**Total**
B042	78	587	204	782		117	1768
B193	457	112	432	880	279	526	2686
B325	334	517	141	471	620	671	2754
B420	149	150	2	126	53	1	481
B422	194	138	108	317	257		1014
B450	485	329	817	716	264	509	3120
B856	89	268	6	129	12	18	522
C082	34	74	33	112	6	10	269
C194	64	88	274	166	4	131	727
C250	172				68	33	273
C256	139	148	96	106		1	490
C366	145	298	689	182	76	12	1402
C453	161	66		22	7	59	315
C545	5	55	161	10	32	5	268
C548	77	187	237	205	116	27	849
C590	45	131	228	77	18		499
C594	186	542	709	733	199	52	2421
C694	119	260	94	189	136	107	905
C779	133	161	585	502	212	513	2106
C832	16	78		91			185
C862	61	91	151	195		30	528
C985	146	357	455	388	176	277	1799
C992	68	60	14	52	112	150	456
CC94	234	600	90	1035	92	608	2659
F526	122	212	47	56	34		471
FFFF	74	44	185	249	2	29	583
Total	**3787**	**5553**	**5758**	**7791**	**2775**	**3886**	**29550**

There are log files for OBE C453 on 8/25/08 and OBE C832 on 8/28/08, but those OBEs did not successfully transmit any messages to RSEs on those days. There are no OBE log files at all for three OBE IDs on the list: C250, F526, and FFFF. Although the locations in snapshots from these OBEs are distributed as if on a vehicle, there is no mention of these OBEs in documentation from the POC operators.

Table 4. Number of Messages per Vehicle per Day (NCAR Trial)

	Number of Messages in NCAR Trial						
Vehicle ID	4/6/09	4/13/09	4/14/09	4/20/09	4/21/09	4/22/09	Total
B042	1042	1050	772	761	450	884	4959
B193	777	713				781	2271
B325	949	840	1021	436	1316	688	5250
B856	548	833	812	1131	768	697	4789
C141	55	103			12		170
C194	316	607	1476	503	844	674	4420
C482	1098	392	1195	1173	868	706	5432
C548	535	915	663	927	1123	1209	5372
C590	438	700	1554	1458	877	653	5680
C694	916	1003	959	682	1031	867	5458
C779	83	22	8	65	85	20	283
C832	523	755	581	487	902	807	4055
Total	7280	7933	9041	7623	8276	7986	48139

2 OBE Log File Documentation

2.1 Log File Organization

The dataset for each day contains a directory for each vehicle. The directory names match the vehicle IDs. Within each directory is a sequence of log files, each beginning with the OBE ID. A vehicle's OBE log file for a day of trials starts out being labeled "OBE_ID_OSGi_Log.txt", where "OBE_ID" is the 4-character identifier for an OBE, e.g., B420 or C694. When that file reaches a certain size (around 10 Mb), it is closed and renamed "VehID_OSGi_Log_00.txt" and a new "Veh_ID_OSGi_Log.txt" file is started. When that file is filled, "VehID_OSGi_Log00.txt" is renamed "Veh_ID_OSGi_Log_01.txt", "VehID_OSGi_Log.txt" is renamed "VehID_OSGi_Log_00.txt", and a new "VehID_OSGi_Log.txt" file is started. Thus for each vehicle, "VehID_OSGi_Log.txt" contains the most recent data, "VehID_OSGi_Log00.txt" contains the next most recent, and so on. The highest number of log files observed for a single vehicle is eight ("VehID_OSGi_Log_00.txt" through "VehID_OSGi_Log_06.txt" plus "VehID_OSGi_Log.txt".

Table 2 lists the vehicle IDs and OBE IDs used for each day of the POC and NCAR 2009 trials.

2.2 Contents of the OBE Log Files

The OBE log files contain detailed information recorded by the data logger on each vehicle for an entire day's worth of driving. Appendix A shows a sample of what the log file looks like, including a portion of an included snapshot.
The IMT Data Environment provides a complete set of OBE log files for one day from the POC trials and one day from the NCAR 2009 trials.

Generally, a line in the log file contains the following information:

- Time in milliseconds since 1/1/1970 ("the epoch")
- Date and time in standard DD MMM YYYY HH:MM:SS format (times are reported in Greenwich Mean Time (GMT))
- Vehicle identifier (matches the identifier found in the header for the RSE data)
- CommManager identification (e.g. OBE#1.14.2#4). Documentation for this field has not been provided.
- (usually) DEBUG or INFO or ERROR or WARNING identifying the type of message
- (sometimes) a key code identifying the type of message and (sometimes) a text string naming the message type.
- Data fields specific to the message type

The message types whose contents are clearly understood are:

DEBUG MESSAGES

- 031 – PSN EXPIRED – DISTANCE
- 032 – PSN EXPIRED – TIME
- 050 – PERIODIC SNAPSHOT GENERATED
- 051 – START SNAPSHOT GENERATED
- 052 – STOP SNAPSHOT GENERATED
- 057 – TIME FOR NEXT PERIODIC

INFO MESSAGES

- 058 – ATTEMPTING TO SEND A SECURE MESSAGE
- 059 – SENT A SECURE MESSAGE
- 061 – ATTEMPTING TO CONNECT TO VDTLS SERVER
- 062 – CONNECTED TO VDTLS SERVER
- 068 – DISCONNECTING

ERROR MESSAGES

- 060 – VDTLS SEND MESSAGE FAILED

Of particular interest is the INFO 028 message, which is always followed by the body of a snapshot. This record indicates the attempted transmission of the snapshot. Snapshots appear in the log file in groups of one to four. Section 3.2 provides more information about these INFO 028 records.

Other messages are followed by unlabeled data fields, for which documentation has not been provided. Documentation received to date does not say anything about what types of messages are defined and what the data fields are.

3 OBE Data File Subsets

Noblis has created three extracts from the OBE files:

- Events file
- Snapshot file
- Trajectory file

The remainder of this section documents those three files.

3.1 Events file

The OBE log file contains records with the message "PERIODIC SNAPSHOT GENERATED," "START SNAPSHOT GENERATED" and "STOP SNAPSHOT GENERATED." Although the contents of the snapshot do not appear in the log file at that point, these records document when each snapshot was generated, and what type. The body of a snapshot appears following an INFO 028 record, indicating when the OBE attempts to transmit the snapshot to an RSE. If the transmission was not successful, the same snapshot may appear later in the log file when the OBE attempts to resend the snapshot. Occasionally (less than 5% of the time) a snapshot appears in the log file in an INFO 028 record, but its time does not match the time of a snapshot generation record.

The OBE log file also contains records that document the interaction of the OBE and a Vehicular Datagram Transport Layer Security (VDTLS) server (another name for an RSE). Records indicate when the OBE attempted to establish a connection with an RSE, when the connection was successful, when the OBE attempted to send a messages, when the message transmission succeeded or failed, and when the OBE terminated the connection to the RSE.

Noblis extracted each of these types of records, and created a text file called the action log file for each day. Each record in the action log file contains the following fields:

- OBE Id
- Log file Id
- Date
- Line number from the original log file
- Key phrase, from the following list:

- PERIODIC SNAPSHOT GENERATED
- START SNAPSHOT GENERATED
- STOP SNAPSHOT GENERATED
- ATTEMPTING TO CONNECT TO VDTLS SERVER
- CONNECTED TO VDTLS SERVER
- ATTEMPTING TO SEND A SECURE MESSAGE
- SENT A SECURE MESSAGE
- VDTLS SEND MESSAGE FAILED
- DISCONNECTING FROM VDTLS SERVER
- (either Start/Stop or Periodic) snapshot with time (HH:MM:SS) in OBE file

The following table provides the data types and descriptions for these fields. The same file can be found as a standalone spreadsheet in the Documentation section of the IMT Data Environment.

Table 5. Fields in OBE Events File

Number	Name	Description	Format
1	Veh_ID	Vehicle ID	2-4 char
2	Log_suffix	Suffix for the OBE log file ('--') if no suffix	2 char
3	Line_num	Line number from the log file from which the event was extracted	Integer
4	Date	Date of OBE log file	MM/DD/YYYY
5	Time	Time of entry in the OBE log file	HH:MM:SS
6	Event	One of the following:	Char
		PERIODIC generated	
		STOP generated	
		START generated	
		ATTEMPTING TO CONNECT TO VDTLS SERVER	
		CONNECTED TO VDTLS SERVER	
		ATTEMPTING TO SEND A SECURE MESSAGE	
		SENT A SECURE MESSAGE	
		DISCONNECTING FROM VDTLS SERVER	
		VDTLS SENT MESSAGE FAILED	
		(snapshot type) snapshot with time HH:MM:SS in OBE file	

3.2 Snapshot File

The INFO 028 message in the OBE log file is always followed by a snapshot. The record indicates whether the snapshot is “start/stop” or “periodic”. The record does not indicate the time of snapshot generation, since record types 050, 051, and 052 document snapshot generation. Snapshots appear in the log file in groups of one to four.

It is evident that often these snapshot groups appear in the log at the time the OBE attempts to send them in a message to an RSE, because approximately half the time that snapshots appear in the log, they are followed by the message “ATTEMPTING TO

SEND A SECURE MESSAGE" (message type INFO 058). When this is the case, the type INFO 058 message is followed within a few seconds in the log by either the message "SENT A SECURE MESSAGE" (message type INFO 059) records or the message "VDTLS SEND MESSAGE FAILED" (message type ERROR 060) records. Clearly this sequence documents the attempt of the OBE to send a message consisting of one to four snapshots, and the indication of whether that attempt was successful.

Often when a snapshot appears in a message that is followed by the message "VDTLS SEND MESSAGE FAILED", it appears again later in the log file, indicating another attempt by the OBE to send the snapshot in another message. However, this is not always the case.

However, roughly half the time snapshots appear in the OBE log file not followed by "ATTEMPTING TO SEND A SECURE MESSAGE" and not followed by either "SENT A SECURE MESSAGE" or "VDTLS SEND MESSAGE FAILED". That is, although the snapshots appear in the log file, there is no record of an attempt by the OBE to transmit a message containing the snapshots. Noblis has not yet determined the significance of these snapshot appearances.

Table 6. Fields in OBE Snapshot File

Number	Variable name	Description	Format	Units or other comments
1	OBE_ID	OBE ID	4 characters	The OBE ID is found in the file name
2	Veh_id	Vehicle ID	4 characters	The Vehicle ID is found in the directory
3	Logfile	Suffix for the OBE logfile	Integer or '--'	--' appears if there is no suffix in the log file name
4	Line	Line number in the logfile	Integer	
5	date	Snapshot datestamp	MM/DD/YYYY	Combined from header or snapshot year, month, and date fields
6	time	Snapshot timestamp	HH:MM:DD	Combined from header or snapshot hour, minute, and second fields
7	lat	Degrees latitude	Integer	1/8000000 degrees
8	long	Degrees longitude	Integer	1/8000000 degrees
9	elevation	Decimeters, with 1 km offset	Integer	Decimeters, with 1 km offset
10	heading	Vehicle heading	Integer	0.005493247 degrees (360/65535)
11	speed	Vehicle speed	Integer	0.01 meters per second
12	cntVSDTs	Vehicle status device type count	Integer	Number of data fields that follow
13	psn	Probe segment number	Integer	Changing randomly generated number for anonymity
14	lights	On/off status of lights	Bitstring	Bits 0-7 indicate which lights are on (see documentation)
15	brake_status	On/off status of brakes	Bitstring	Bits 0-3 indicate which brakes are one (see documentation)
16	brake_boost	Brake boost	char	On, off, or notEquipped
17	abs	Anti-lock brake system	Char	On, off, engaged, or notEquipped
18	stability	Vehicle stability control	Char	On, off, or notEquipped
19	traction	Vehicle traction control	Char	On, off, engaged, or notEquipped
20	yaw	Vehicle yaw rate	Integer	0.01 degrees per second
21	steering_angle	Angle of steering wheel	Integer	0.2 degrees
22	steering_rate	Steering wheel rate of turn	Integer	Degrees per second
23	wheels	Angle of front wheels	Integer	0.3333 degrees
24	hozAccelLat	Lateral acceleration	Integer	0.01 meters per second squared
25	hozAccelLong	Longitudinal acceleration	Integer	0.01 meters per second squared
26	tirePress_lf	Left front tire pressure	Integer	pounds per square inch
27	tirePress_rf	Right front tire pressure	Integer	pounds per square inch
28	tirePress_lr	Left rear tire pressure	Integer	pounds per square inch
29	tirePress_rr	Right rear tire pressure	Integer	pounds per square inch
30	tirePress-spr	Spare tire pressure	Integer	pounds per square inch (not implemented)
31	front_ww	Front windshield wipers	char	off, intermittent, low, high, notEquipped, or automaticPresent
32	rear_ww	Rear windshield wipers	char	off, intermittent, low, high, notEquipped, or automaticPresent
33	ww_rate	Windshield wiper rate	integer	sweeps per minute
34	airTemp	Air Temperature	Integer	Centrigrade degrees, offset +40
35	barPress	Barometric Pressure	Integer	hectopascals (millibars), offset +580

Noblis has created a snapshot file that contains the contents of each snapshot appearing in the OBE log files. The first four fields in each record identify the OBE log file and the line number in the file at which the snapshot occurred. The remaining fields contain all the data from the snapshot. The following table provides the data types and descriptions for these fields. The same file can be found as a standalone spreadsheet in the Documentation section of the IMT Data Environment.

3.3 Trajectory File

The OBE log files contain records of type "INFO" (but no 3-digit message type) that contain values of latitude and longitude, as well as the vehicle speed in meters per second and a timestamp. Generally these records occur every second in the log files. Noblis has extracted these latitudes, longitudes, and speeds every second to create a trajectory file. The extraction program also computed X and Y positions corresponding to the latitude and longitude, correcting for the different number of feet in a degree of longitude at each latitude. The fields of the trajectory file are as follows. The same file can be found as a standalone spreadsheet in the Documentation section of the IMT Data Environment.

Table 7. Fields in the OBE Trajectory File

Number	Variable name	Description	Format	Units or other comments
1	Veh	Vehicle ID	4 characters	From the directory in which the file
2	Logfile	Suffix for the OBE logfile	Integer or '--'	--' appears if there is no suffix in the log file name
3	Line	Line number of the snapshot in the logfile	Integer	
4	date	Datestamp	MM/DD/YYYY	Combined from header or snapshot
5	time	Timestamp	HH:MM:DD	Combined from header or snapshot hour, minute, and second fields
6	secs	Number of seconds since the beginning of travel	Integer	
7	speed	Speed	Real 1 dec. place	Miles per hour
8	lat	Degrees latitude	Real 6 dec. places	Converted from integer in the log file by dividing by 8000000
9	long	Degrees longitude	Real 6 dec. places	Converted from integer in the log file by dividing by 8000000
10	x-ft	Location x value	Integer	Conversion from long to feet, adjusting for latitude
11	y-ft	Location y value	Integer	Conversion from lat to feet

Appendix – Sample Extract from an OBE Log File

```
1219244661697   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          DEBUG   023,1,30,0,0,1,0,0,
1219244661698   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          DEBUG   022,"SingleBuffer",
1219244661701   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          INFO    068,"DISCONNECTING
1219244661702   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          INFO    068,"DISCONNECTING
1219244661704   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          DEBUG   Received  event AVA
1219244661706   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          DEBUG   The type is 5
1219244661706   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          DEBUG   Setting wsmp addres
1219244661706   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          INFO    Setting address 00:
1219244661706   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          INFO    Received event noti
1219244661707   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          DEBUG   Availability is fal
1219244661707   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          INFO    Creating info event
1219244661710   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45    [Event Admin Dispatcher][MAIN][DW:
1219244661714   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          INFO    029,1219244661713,4
1219244661787   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45    [Event Admin Dispatcher][MAIN][DW:
1219244661791   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          INFO    029,1219244661789,4
1219244661801   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45    [Event Admin Dispatcher][MAIN][DW:
1219244661804   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          INFO    029,1219244661803,4
1219244661807   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          DEBUG   Socket announced ir
1219244661807   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          DEBUG   Starting EventMessa
1219244661820   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          DEBUG   Received info event
1219244661820   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          INFO    Continuing event th
1219244661826   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          INFO    043,1219244661826,4
1219244661827   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          DEBUG   The number of liste
1219244661835   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          INFO    061,"ATTEMPTING TO
1219244661842   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          INFO    062,"CONNECTED TO W
1219244661898   Wed, 20 Aug 2008 15:04:21 GMT   B420   CommManagerOBE#1.14.2#34        34          DEBUG   Listening for data.
1219244661944   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          DEBUG   031,"PSN EXPIRED BY
1219244661965   Wed, 20 Aug 2008 15:04:21 GMT   B420   com.vii.delphi.probedata#4.6.2  45          INFO    028,value OCTET STR
,27,"Periodic",1219244648265,1219244661697,0,1219244661847,"2001:1890:110e:ba27:0000:0000:0000:0001,00:06:80:13:da:b9",value Snapsh
  thePosition {
    utcTime {
      year 2008,
      month 8,
      day 20,
      hour 15,
      minute 4,
      second 8
    },
    longitude -667487552,
    lat 339555236,
    elevation 3605,
    heading 55897,
    speed 1800,
    timeConfidence notEquipped,
    posConfidence {
      pos notEquipped,
      elevation notEquipped
    }
```

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