

In-Use Fuel Economy and CO₂ Emissions Measurement using OBD Data on US Light-Duty Vehicles

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ABSTRACT

Fuel economy (FE) and greenhouse gas (GHG) emissions measured via chassis testing under laboratory conditions were never intended to represent the wide range of real-world driving conditions that are experienced during a vehicle's lifetime. Comprehensive real-world information is needed to better assess US FE label adjustments, determine off-cycle credits for FE standards, and forecast real-world driving behavior, fuel consumption, and CO₂ emissions. This paper explores a cost effective method to collect in-use fuel consumption data using the on-board diagnostics (OBD) data stream in light-duty vehicles (LDVs). The accuracy of fuel consumption calculated from the OBD data was analyzed in two ways. First, fuel rates calculated from standard OBD Parameter IDs (PIDs) were compared with fuel rate estimates based on enhanced PID (OEM fuel injector fuel rate) data in two different vehicles. The cumulative fuel rate derived from standard PIDs was lower than the fuel rate values obtained from injector-based data (Enhanced PID) for the tested vehicles by approximately 3% and 13%. A second analysis compared fuel rates calculated from OBD inputs, including mass air flow (MAF) sensor and narrow-band O₂ sensors, against fuel rates determined through carbon balance measurements from dynamometer chassis testing. The OBD MAF data were sufficient to closely match the fuel consumption measured by chassis testing during stoichiometric operation. Vehicle-specific algorithms were developed for cold start and deceleration fuel cut-off events, identified from the narrowband O₂ sensor signal, resulting in cumulative fuel consumption within 3% of the dynamometer results.

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INTRODUCTION

Light-duty vehicles are responsible for a large share of fuel consumption and CO₂/GHG emissions in the US and around the globe. In the US light-duty vehicles consume about 45% of the total petroleum for the entire fleet [1]. In absolute terms, LDVs the US consume about 8.5 million barrels of petroleum per day [1].

As fossil fuel resources become scarcer and the demand for products derived from fossil fuels grows, pressure increases to develop new ways of improving vehicle fuel economy. Volatile fuel price signals have turned the interest of new vehicle customers towards more fuel-efficient vehicles [2, 3].

Regulators in the US and Europe have implemented more stringent FE and CO₂/GHG standards aiming to improve the performance of the entire fleet of LDVs [4, 5].

Responding to these two clear signals, vehicle and engine manufacturers are continuously searching for new technologies that would result in higher fuel economy. Recent developments of gasoline/electric hybrid propulsion systems, gasoline direct injection, turbocharging and downsizing, and automatic transmissions with more than five gears are results of those efforts [6, 7, 8].

Understanding the way these technologies respond to the wide variety of environmental and driving conditions would be useful for regulatory and technology development purposes. To identify those conditions and the impact on FE, measurements of second-by-second fuel economy in parallel with FE-influencing factors is needed.

The objective of this paper is to provide a detailed analysis on obtaining fuel economy data from the OBD data stream of a LDV. This involves calculating fuel rate (mL/s) on a second-by-second basis and using vehicle speed (mi/h) to obtain miles per gallon (MPG) on an instantaneous basis. The scope is,

restricted to gasoline port fuel injection (PFI) and direct-injection (GDI) vehicles; diesel vehicle fuel rate determination was not investigated.

The technical information presented here is part of a pilot study designed to explore the technical and logistical aspects of carrying out a nationwide study on fuel economy of LDVs. The goal of the nationwide study would be to create a database of second-by-second fuel economies versus operating conditions for a large sample of vehicles.

Before dealing with the intricacies of fuel economy determination, a brief description of OBD systems is presented here. All 1996 and newer light-duty gasoline-powered vehicles and 1998 and newer light-duty diesel-powered vehicles manufactured for sale in the U.S. are equipped with second-generation on-board diagnostic systems, generally referred to as OBDII [9]. These OBDII systems provide SAE-standardized information known as standard PIDs, which is an open data stream, as well as manufacturer-specific or enhanced PIDs, which is only accessible by using special request and decoding information available from the vehicle manufacturers.

FUEL CONSUMPTION DETERMINATION VIA OBD

The use of standardized PIDs or enhanced-PIDs depends on vehicle technology and driving mode. Our objective in this study was to obtain acceptably accurate instantaneous fuel economy estimates from a broad variety of vehicles under a diverse range of operating conditions using standardized SAE J1979 PIDs [10]. However, there are some scenarios in which the use of the SAE J1979 PIDs might not provide suitable results, since the availability of some standard PIDs varies among vehicle technology and vehicle operating conditions. This section presents a recommended approach for estimating fuel consumption for each of the scenarios

Vehicle OBD Technology

The vehicle OBD technology options for estimating fuel consumption covers gasoline vehicles that broadcast mass air flow (MAF), manifold absolute pressure (MAP), and fuel rates from OEM-specific queries (enhanced PIDs).

Gasoline Vehicles that Broadcast Mass Air Flow

Many gasoline-powered vehicles directly report an estimate of the mass of air entering the engine as measured by the engine's mass airflow (MAF) sensor. These can include port fuel injected vehicles, gasoline direct injection vehicles, and hybrids. For these vehicles, the gasoline combustion equation and the reported mass of air provided to the engine can be used to calculate the amount of fuel required **assuming stoichiometric** engine operation.

Fuel economy and fuel rates under non-stoichiometric operation conditions can be determined in vehicles with wide-band oxygen sensors (O2S). Deviations from stoichiometric operation can be calculated in these vehicles using the ratio of actual combustion to theoretical stoichiometric combustion, λ , which is reported as a standard PID. The following equation may therefore be used to calculate a vehicle's instantaneous fuel economy:

$$FE \left[\frac{\text{distance}}{\text{vol}_{fuel}} \right] = \frac{k_1 \text{ Speed} * \lambda * AF_{stoich}}{\dot{m}_{air}}$$

Equation 1

In the above equation, λ represents the adjustment for nonstoichiometric operation, and k_1 is a constant that accounts for various unit conversions and the estimated density of the fuel; speed is the engine rotational speed. The mass of air, $\dot{m}_{air}$, required for stoichiometric combustion will vary based on the ethanol content of the fuel, and thus, corrections have to account for that factor.

The following equation, with similar variable definitions, may be used to calculate fuel rates on a time-basis:

$$\text{Fuel rate} \left[\frac{\text{vol}_{fuel}}{\text{time}} \right] = \frac{k_2 * \dot{m}_{air}}{\lambda * AF_{stoich}}$$

Equation 2

For vehicles without wide-band O2S, λ is not available as a standard SAE J1979 PID. Instead, a voltage output from a narrow-band oxygen sensor is typically available. As opposed to the wide-band oxygen sensor, which provides a moderately linear output signal over a relatively wide operating range, the narrow-band oxygen sensor functions like a binary switch (rich or lean). Because small changes in the amount of exhaust gas oxygen content radically change the output voltage, voltage output from a narrow-band sensor cannot be used to accurately quantify deviation from stoichiometric, but instead only indicates whether a vehicle is operating at stoichiometric, rich, or lean conditions. Therefore, for these vehicles, overall average fuel economy estimates can be determined using standard SAE J1979 PIDs (since these vehicles generally target stoichiometric operation), but accurate instantaneous fuel economy estimates using narrow-band oxygen sensor data can be problematic.

For narrow-band O2S vehicles, it may be possible to use other available standard PIDs, like commanded equivalence ratio or commanded load, to calculate fuel rate during nonstoichiometric operation, as will be presented in the results and discussion sections.

Results from analysis of vehicles with both wide-band and narrow-band O2S are tested, and results discussed in detail.

Gasoline Vehicles that Do Not Broadcast Mass Air Flow

Some vehicles use the absolute pressure measured in the intake manifold by the manifold absolute pressure (MAP) sensor, to estimate the mass of air entering the engine. This method uses models involving the volumetric efficiency and displacement of the engine. This type of engine management is referred to as the Speed-Density method, and is based on the ideal gas law but with a volumetric efficiency factor to account for the volume variable in the ideal gas law:

$$\dot{m}_{air} = \frac{MAP * V_d * RPM * eff_{vol}}{k_3 * R * T}$$

Equation 3

In the above equation, MAP is the manifold absolute pressure, R is the ideal gas constant, T is the absolute temperature, eff_{vol} is the volumetric efficiency, and k_3 is a constant that accounts for unit conversions.

Volumetric efficiency is calculated using look-up tables stored in a vehicle's engine control unit (ECU). Using the appropriate value for volumetric efficiency (based on engine speed and load), the vehicle's ECU can then calculate an estimated mass of air entering the engine at that point in time, and determine the amount of fuel necessary for optimal combustion.

However, this presents a problem when trying to estimate fuel economy using standard SAE J1979 OBDII data. While it is possible to assume an average volumetric efficiency for an engine, this estimate will not accurately represent instantaneous volumetric efficiency, since values for volumetric efficiency vary significantly based on engine load and speed, and the volumetric efficiency maps vary among engine types. For individual vehicles, it may be possible to obtain the factory volumetric efficiency look-up tables in order to determine mass air flow, but it would be expensive and difficult for a broad vehicle study. Enhanced PIDs may be used for calculating fuel rates in these vehicles. MAP equipped vehicles are not studied in this paper.

Use of OBD Enhanced PIDs

Use of OEM-specific queries (enhanced PIDs) of fuel injector rate is another alternative for determining instantaneous fuel economy estimates. If fuel injector rate is not available as an enhanced PID, it may be possible to use fuel injector pulse width, also as an enhanced PID.

Testing experience shows that standard fuel rate (mL/s or similar) will not generally be directly broadcast as an enhanced PID, at least on older vehicles. In addition, as shown later in the Results and Discussion section (Standard SAE J1979 vs. OEM-enhanced Testing), some potential issues were identified with the accuracy of fuel economy estimates based on fuel injector rate (an enhanced PID).

Enhanced PIDs can also be used to track factors that affect fuel economy, such as air conditioning (AC) use [11] or the battery state of charge (SOC) for a hybrid. The strategy to determine the instantaneous fuel economy in these cases is the same as described above, and OEM-specific parameters are recommended for collection of AC and hybrid battery state of charge data. SOC data may be required in determining the overall energy (fuel and electrical) consumed during any particular trip.

Some late model vehicles may also directly report fuel economy as a standard PID, but the accuracy of this PID and prevalence in the on-road U.S. fleet is unknown.

Vehicle Operation Types

Stoichiometric Operation: Low- and Mid-Load Operation

Fuel economy under stoichiometric combustion conditions, typical of low- and mid-load operation in gasoline vehicles, can be estimated using standard PIDs mass airflow and lambda for vehicles that broadcast that information.

MAP-equipped vehicles require OEM-specific fuel injector rate information to obtain accurate instantaneous fuel economy estimates, even under stoichiometric conditions, as previously discussed.

Non-Stoichiometric Operation: Cold-Start (Open Loop)

A focus of this study was to determine methods for estimating accurate instantaneous fuel economy during cold-start operation. During this time the engine may operate in open-loop, which means feedback from the oxygen sensor is not available for tailoring the fuel to match the amount of air entering the engine. Also during this period of open-loop operation, the engine may be programmed to provide a fixed air/fuel ratio that is richer than stoichiometric to improve cold start emissions while the engine and aftertreatment warms up.

Since under this type of operation vehicles do not always target stoichiometric combustion and no real-time information is available regarding the actual air/fuel ratio being provided during this operation, again the use of OEM-specific queries of fuel injector rate may be a way to achieve instantaneous fuel economy estimates for cold-start operation. If fuel rate is not available as an OEM-specific query, it may be possible to use fuel injector pulse width (this would also be an OEM-specific query) to estimate instantaneous fuel consumption. As another alternative, target air fuel ratios, such as those given by the commanded equivalence ratio PID during cold-start operation, may also be used to estimate fuel rate during open-loop operation.

Non-Stoichiometric Operation: Wide-Open Throttle (Enrichment) and Deceleration (Fuel Cut-Off)

Strategies for estimating instantaneous fuel economy during enrichment mode and fuel cutoff mode (open-loop operation) may be similar to those for gasoline low- and mid-load operation. It may be possible to obtain acceptably accurate fuel economy estimates using SAE J1979 mass airflow and lambda if it is broadcasted during these non-stoichiometric operating modes).

For vehicles that do not broadcast MAF PIDs and lambda, or if lambda information is not broadcast during open-loop operation, this type of operation requires modeling with standard PIDs or OEM-specific fuel injector rate to obtain accurate instantaneous fuel economy estimates.

Summary of Measurement Strategies based on Vehicle and Fuel Types

Table 1 provides a summary of data collection strategies that could be used in a full-scale study. Rankings are provided for which strategy is believed to be the best approach for collecting data for each of the vehicle technology combinations. Best strategy rankings include consideration of cost and accuracy; rankings could vary depending on the suitability of the accuracy relative to the costs. A rank of "1" indicates that this is the best approach, a "2" indicates this is the second choice, and so on.

Table 1. Logging Strategies for Various Vehicle, Fuel, and Data Types

Vehicle / Fuel / Data Type	Standard PIDs				Enhanced PIDs		
	Fuel rate (Std PID 5E)	MAF	MAP	O2 Sensor and/or Calculated Load	Mfr-specific fuel rate (mass or volume)	Injector mass or flow rate per injection(s)	Mfr-specific injector time duration
Gasoline MAF with wide-band O2 sensor	1	2		2	-	-	-
Gasoline MAF with narrow-band O2 sensor	1	2, 4, 5		2	3	4	5
Gasoline MAP with wide-band O2 sensor	1		5	5	2	3	4
Gasoline MAP with narrow-band O2 sensor	1		5	5	2	3	4

METHODOLOGY

This paper explores two methods for determining fueling rates based on vehicle OBD data. The first method discussed is second by second fuel rate determination from standard SAE J1979 PID (i.e., MAF/O2S based PIDs) compared to OEM-enhanced (i.e., Fuel rate PIDs). The second method compares fueling rates from standard SAE J1979 PID (i.e., MAF/O2S based PIDs) against fueling rate calculated from carbon balance during laboratory chassis testing.

A description of the datalogger used for OBD data capture is presented first, followed by vehicles and testing conditions.

OBD Datalogger

The datalogger selected for capturing OBD data is the HEM Data DAWN OBD Mini Logger (Figure 1). The DAWN OBD Mini Logger is small and plugs directly onto the vehicle's OBDII port. A summary of the features and functionality of the HEM Data DAWN OBD Mini Logger is presented Table 2. This datalogger allows the user to fully configure which standard (SAE J1979) PIDs to acquire. Also the unit can be programmed for enhanced PID collection capability.



Figure 1. OBD HEM Data DAWN OBD Mini Logger

Table 2. Datalogger features

Feature	HEM Data DAWN OBD Mini Logger
Auto sleep / power-up	Yes
Adjustable data acquisition rate	Yes
Internal clock	Yes
Auto-establish connection	Yes
Size and ease of installation	Good
GPS	Yes
Accelerometer	Future
Internal thermocouple	Future
On-board data storage	Yes, up to 32 GB card
CAN protocols	Yes
Legacy protocols	Future
Standard PID selection configurable	Yes
Enhanced PIDs (powertrain / other)	May be added at additional cost
Cellular data transmission	May be added
Supplier accessibility	Good
FE calculations from standard PIDs	MAF vehicles only
FE estimates for all vehicle types	MAF gasoline only
Barometric altimeter	No

Testing Methodology: Vehicles and Conditions

Testing of FE calculation methods was performed in three different vehicles and under various conditions, including on-road and chassis testing. Along these tests, the vehicles were exposed to a wide variety of driving conditions including low and mid-throttle closed-loop (engine hot) operation, and cold-start vehicle operation (in which the vehicle operates in open-loop mode).

Standard SAE J1979 PID vs. OEM-Enhanced PID Testing

Second-by-second fuel economy estimates from standard SAE J1979 parameters (MAF/wide-band O₂S data) were compared with paired fuel economy estimates calculated using OEM-enhanced fuel injector fuel rate data from the same test. The tests were performed on two vehicles under on-road driving conditions:

1. Toyota Camry 2012: Port-fuel injected gasoline vehicles with wide-band oxygen sensors),
2. Toyota Prius 2011: Port-fuel injected gasoline hybrid vehicle, non-plug-in, with a wide-band oxygen sensor

For this validation analysis, standard SAE J1979 OBDII data was paired along with fuel injector volume (an enhanced PID). Specifically, this PID is reported as the volume (mL) of cylinder one's last 10 injections. Fuel injector volume data was converted to a second-by-second fuel rate by multiplying by the number of cylinders, multiplying by the RPM/(2*10) (2 since it's a 4-stroke and "10" because of the prior "10 injection" cumulative), and converting minutes to seconds. It should be noted that at engine speeds greater than 600 rpm, this calculation methodology assumes the total fuel consumed over the last second of operation is proportional to the last 10 injections, which may induce errors.

Approximately 53 minutes of on-road driving data was collected for a 2012 Toyota Camry, including cold-start. The coolant and ambient temperatures were 23 C and 25 C at startup and the engine transitioned to closed loop nearly immediately after the vehicle was turned on and before driving. Also, 14 minutes of similarly paired data from the 2011 Toyota Prius was collected.

For both vehicles, the fuel consumption calculated using each vehicle's MAF sensor and wide-band oxygen sensor with the fuel injector-based fuel consumption rate were compared.

Standard SAE J1979 PID vs. Dynamometer Carbon Balance Testing

Chassis dynamometer laboratory testing was performed on a 2009 Saturn Outlook using different test cycles. These tests were conducted in Aurora, Colorado. Fuel consumption and emissions were measured on a second-by-second basis during each test, and standard protocols were used to determine the

second-by-second fuel consumption and emissions over each drive cycle. Standard SAE J1979 OBDII data was also logged throughout the testing using the datalogger described before. The 2009 Saturn Outlook was equipped with a 3.6L V6 gasoline direct injection (GDI) engine. The vehicle was equipped with a mass airflow sensor (rather than using MAP / speed-density) and a narrow-band oxygen sensor. The fuel used was EPA Tier II certification fuel with no ethanol. The specific gravity was 0.7389, and the API Gravity was 60.0. The 2009 Saturn Outlook was tested on a chassis dynamometer over three cycles: the FTP75, HFET and US06 driving schedules. The FTP75 test was made up the traditional three bags: a cold start for Bag 1, which was immediately followed by Bag 2, then a 600-second soak, which was followed by Bag 3. Two HFETs and two US06s were run with the first of each pair being used to warm up the vehicle for the dynamometer data acquisition on the second of each pair.

The analysis, which is described below, compares fuel rate calculated from dynamometer data with fuel rate calculated from OBD MAF/Oxygen sensor data. It compares the fuel rates during normal operation (closed loop and non-enrichment) and also in heavy-throttle/load operation (with enrichment).

RESULTS

Results are presented for both methods of fuel economy determination testing conditions: Standard PIDs vs. Enhanced PIDs, and Standard PIDs vs. dynamometer carbon balance.

Results on Standard SAE J1979 PID vs. OEM-Enhanced PID Testing

Figure 2 a) and b) show time-series plot comparisons of fuel consumption (mL/s) calculated using Standard PIDs, MAF sensor and wide-band oxygen sensor, with the enhanced PID fuel-injector-based fuel consumption rate for both Camry and Prius vehicles. This plot presents only first 1000 and 800 seconds of test data, respectively for the Camry and the Prius. The fuel-injector fuel rate was calculated as previously described.

Figure 3 a) and b) show a parity plot which compares the fuel rate computed using MAF and wide-band oxygen sensor air/fuel ratio (x-axis) with the injector fuel rate (y-axis); the 1:1 line is shown in red. As can be seen in Figure 3, the correlation between the hybrid Prius injector vs. MAF fuel rates was much better than for the conventional (non-hybrid) Camry.

Table 3 summarizes results on trip fuel consumption from the MAF-based fuel rates (Standard PID) and the Enhanced injector-based fuel rates PID for both vehicles. These values correspond to data taken over the 53-minute drive for the Camry and 14 minutes drive for the Prius. Values are provided with wide-band oxygen sensor lambda corrections (with λ) and also without the lambda correction (no λ) to provide an estimate of results that would be obtained for a vehicle that were equipped with a narrow-band oxygen sensor.