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Measuring in-use fuel economy in Europe and the US: Summary of pilot studies

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Vehicle fuel economy (FE) is determined via a type-approval or certification process, which involves testing vehicles under laboratory conditions. For fuel economy labeling and standards compliance testing, it is important that test procedures be consistent, so that different vehicles can be fairly and accurately compared. One factor in achieving consistency is the use of a prescribed driving cycle, which the vehicle follows while mounted on a chassis dynamometer (hence this type of test is also known as a chassis test). The driving cycle is intended to represent real-life driving conditions, mixing stop-and-go driving patterns from urban transit and medium- and high-speed driving patterns from rural roads and highway transit.

However, the fuel economy information obtained via chassis testing under laboratory conditions cannot fully reflect the wide range of real-world driving conditions that vehicles and drivers experience during a vehicle's lifetime. The driving cycles and test procedures specified several decades ago are unable to represent current driving conditions and new vehicle technologies. The consequent deviations of real fuel economy from laboratory test results can have a significant impact in estimating real-world fuel consumption and greenhouse gas (GHG) emissions.

A technically precise definition of real-world driving conditions is elusive because of extensive variations in vehicle design and in the ways that drivers operate those vehicles. But by aggregating large sets of on-road driving data, clear trends can be observed. A recent report by the ICCT analyzed the real-world fuel consumption of several large datasets, for both private and company cars, from various European countries. It reveals an overarching trend: while the average discrepancy between type-approval and on-road CO_2 emissions was below 10 percent in 2001, by 2011 it had increased to around 25 percent.[1]

Comprehensive real-world information is needed to assess fuel economy label adjustments, properly determine off-cycle credits for fuel economy standards, evaluate the actual effectiveness of different technologies, and estimate real total fuel consumption. And that need has increased over the last decade, which has seen significant developments in power train technologies (e.g. gasoline direct injection, hybrids, plug-in hybrids) and changing fuel quality to accommodate renewable fuel sources (primarily ethanol, in E10 and E15 blends).

Gathering in-use (or off-cycle) fuel economy data on a large set of vehicles in actual operation over a significant period of time requires a method for capturing that information. The cost is considerable. Chassis testing is designed to yield accurate, reproducible and fair comparisons on a driving cycle. It provides an accurate benchmark for evaluating the accuracy of in-use fuel economy measurement, but its ability to represent in-use driving operation and a wide range of environmental conditions is limited.

1 Mock, P., et al., "From Laboratory to Road: A Comparison of Official and 'Real-World' Fuel Consumption and CO_2 Values for Cars in Europe and the United States" (Washington DC.: ICCT 2013), www.theicct.org/laboratory-road.

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Portable emissions measurement systems (PEMS) provide second-by-second fuel rates and have been used to gather data on in-use vehicles. However, PEMS data is expensive, even for a single vehicle over a short time. What is needed to ascertain real-world fuel economy is to obtain data on many vehicles over an extended period, so that an extensive dataset representing varied operating conditions and trip behavior in all seasons can be created. A more cost effective alternative to PEMS, for that purpose, is to use the OBD data stream to gather information either directly reporting fuel consumption rate or from which fuel rate can be calculated or estimated.

ICCT recognized that before a major OBD-based study of fuel economy characteristics could be undertaken, a pilot study addressing logistical and technical issues was required. ICCT therefore contracted with Eastern Research Group (ERG) in the US and TÜV NORD Mobilität (TNM) in Germany to conduct two such pilot studies, identifying areas of concern and potential solutions in four areas: vehicle sample structure and size, vehicle recruitment methodology, data logger evaluations, and estimated project cost. This report summarizes the results of those pilot studies.[2]

Vehicle Recruitment

The recruitment methodology for the full-scale study needs to result in a representative sample of vehicles and drivers that covers a range of technologies, operating environments, and driving conditions. Both the US and EU pilot studies explored methodologies for finding and recruiting drivers and vehicles, as well as mechanisms to maintain communication from beginning to end of the data collection process, motivate participation, and keep drivers actively engaged.

In the US, ERG concluded that coordinating with an on-going household travel survey is the most effective way to recruit drivers and vehicles. In Europe, TNM concluded that vehicle clubs, and specifically some club members of the Fédération Internationale de l'Automobile (FIA), are

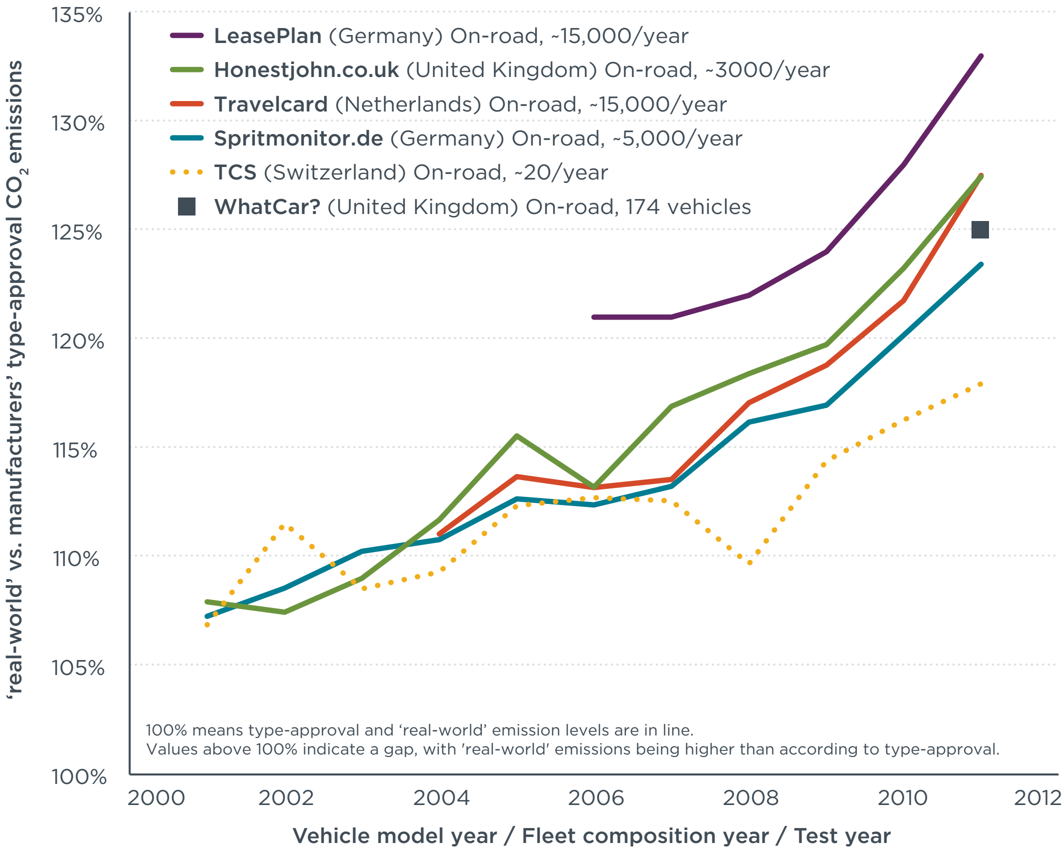

Figure 1. Real-world vs. manufacturers' type-approval CO_2 emissions for various on-road data sources. (Source: Peter Mock et al., "From Laboratory to Road.")

2 TÜV NORD Mobilität, "Project Report: ICCT Fuel Economy Data Collection Pilot Study," October 24, 2013; Eastern Research Group, "Light-Duty Vehicle In-Use Fuel Economy Data Collection: Pilot Study," November 8, 2013.

interested in the project. Another way to reach vehicles and drivers in both regions is through close collaboration with motor vehicle registration offices in specific regions, which increases the pool of potential participants but reduces the geographic coverage of the study.

In addition to identifying vehicle recruitment sources, the pilot studies provided an idea of the size of the vehicle pool needed to produce the desired sample. A survey conducted by TNM at five service centers across Germany showed that around 50 percent of those interviewed were aware of deviations between laboratory and real-world numbers with respect to the CO_2 label. About 25 percent of those surveyed were interested in participating in the OBD field investigation.

The pilots also found that monetary incentives increase drivers' willingness to participate and accomplish specific tasks. The incentive needed would be on the order of US$100 to US$500, and would be linked to task completion. Offering incentives would reduce the cost associated with recruiting participants, reduce the number of participants who drop out during the one-year survey period, and help ensure that the data is collected properly and drivers are performing some small tasks as required.

Sample Size

The pilot studies identified the sampling approach and demonstrated that the sample size required would strongly depend on the field-study main objectives and the level of OBD data available on each vehicle.

Both pilots concluded that a stratified sample is preferable to a simple proportional sample. Because of the makeup of the fleet, a proportional sample would include only a small number of relatively new technologies, such as GDI and hybrids, and would be dominated by common technologies, like gasoline port-fuel injection. The stratified sample, in contrast, allows for larger numbers of those technologies with smaller fleet shares, while keeping a significant yet small sample of widely available technologies. The stratification is based on known characteristics of vehicles, such as powertrain technology and FE/GHG label values. Gathering a national sampling of participants would be difficult and expensive, thus stratification would also reduce cost by allowing the study to be conducted in regions representative of the nation as a whole. The primary concern with sample stratification is additional uncertainty in whether or not the regions selected do properly represent the nation as a whole.

The sample size can vary significantly, depending on the main goals of the investigation:

- A smaller sample size, in the range of 200 vehicles, allows for a good representation of average real-world fuel consumption and average impacts of driver behavior and driving conditions.
- A size in the range of 500 vehicles allows a more detailed analysis of the deviation of real-world fuel consumption from official certification values. For example, it can verify the model-year curve from the Spritmonitor.de analysis performed by the ICCT.
- A large sample size, in the range of 800 vehicles or more, allows a detailed investigation into the impacts of real-world driver behavior and driving conditions on different vehicle models (e.g., car versus SUV) and different technologies (e.g., hybrids and downsized, boosted engines).

The analysis concluded that a sample no smaller than 200 vehicles should be used for a nationwide study.

Data logger Technology

Both pilot studies aimed to identify instruments and methods to capture fuel economy and factors that affect it. This included identifying data loggers capable of interacting with the vehicle engine control unit (ECU), capturing GPS data, and storing and/or sending the data to a server.

Both pilot studies presented a detailed review of data logger technology, how the vehicle OBD would provide the data, and what data would be available for estimating fuel economy and its influencing factors. The TNM report did a particularly good job of defining OBD system operation, codes, and limitations. The ERG report did a particularly good job of investigating the capabilities of existing data loggers.

The OBD standards specify a large set of sensor parameters that can be requested from the vehicle ECU connected to the diagnostics system. The investigation showed that most vehicles support only a small set of these paramaters as standard parameter ID (PID) signals. There are other non-standard signals that can be accessed, but these require support for proper signal interpretation from manufacturers; these are called enhanced PID signals. While standard PIDs are free, manufacturers charge a fee to give access to and translate enhanced PID signals.

While the objective of the main study is to investigate vehicle fuel economy, from a technical perspective this means measuring or calculating the fuel consumption rate (e.g., milliliters per second) from OBD signals on a second-by-second basis, from which fuel economy (e.g., miles per gallon) can then be calculated. Tests conducted on several vehicles show that the ability to read fuel consumption data accurately depends on combustion type (compression ignition vs. spark ignition), vehicle air-fuel management technology, and OBD protocol characteristics. TNM equipped three Otto engine vehicles and three Diesel vehicles with data loggers and tested them on a chassis dynamometer in Europe. ERG tested three US gasoline vehicles equipped with data loggers on the road using PEMS to gather real-time emissions; one of these vehicles was also tested on a chassis dynamometer. The tests suggest these conclusions concerning the accuracy of fuel economy estimates based on OBD data.

1. **Spark-ignition (petrol) vehicles**. Commercial data loggers commonly infer fuel consumption using standard OBD signals for air-flow rate and assuming stoichiometric combustion. However, the assumption of stoichiometric combustion does not accurately reflect fuel consumption during engine cold starts and during aggressive accelerations, when the engine does not operate at stoichiometry. This is especially important at cold ambient temperatures, where a vehicle may be driven a considerable distance before the engine warms up. Data output on the commanded air/fuel ratio can be used to accurately calculate fuel consumption under all conditions, but this data is usually available only on more recent model year vehicles.

   In addition, both teams carefully examined and experimentally tested ways to calculate fuel consumption rates based on air-flow measured OBD data. The two OBD techniques for gasoline vehicles are manifold air flow (MAF) measurement and manifold air pressure (MAP) measurement. The accuracy and ease of deriving fuel consumption rates from these OBD signals differ significantly.

   a. **Vehicles equipped with MAF sensors**. These are the best candidates for estimating fuel consumption from OBD data. They provided relatively accurate OBD-calculated fuel consumption during stoichiometric, closed-loop operation when compared with chassis tests measuring fuel consumption. Measurement accuracy during non-stoichiometric operation is dependent on the availability of OBD data on commanded air/fuel ratio.

   b. **Vehicles equipped with MAP sensors**. These vehicles require volumetric efficiency maps for fuel consumption calculations, which are not publicly available. In the US the share of petrol MAP vehicles is roughly 30 percent to 50 percent, according to preliminary estimates. (This information was not available for the EU.) A field study would most likely need to avoid gasoline MAP vehicles, unless enhanced PIDs could be purchased that directly output manufacturer-calculated fuel consumption.

2. **Compression-ignition (diesel) vehicles**. The experience in Europe and in the US shows that fuel consumption can only be estimated through the fueling rate PID, which is part of the enhanced PID signals. Access to US-diesel vehicle enhanced PIDs was possible, but enhanced PIDs for EU diesels were unavailable during the pilot.

Additional enhanced PIDs, such as hybrid battery state of charge and air-conditioning compressor status, may be necessary to achieve the objectives of a full-scale study. Recent tests performed by the US Environmental Protection Agency (EPA) indicate that these two signals are available as enhanced PIDs. Enhanced PIDs directly reporting fuel rate would also be necessary in order to include gasoline vehicles without mass air-flow or air/fuel ratio outputs, and for all diesel vehicles. It was understood during conversations with data logger producers in Europe that access to enhanced PIDs for diesel vehicles would require active interaction with vehicle manufacturers. In the US, access to enhanced PIDs is possible through the Equipment and Tool Institute for a wide range of manufacturers, although at substantial cost.[3]

Both pilot studies evaluated several commercial data loggers and concluded that storing and/or sending one year's worth of data was not a challenge. One year of 20 different signals including OBD, GPS, and additional data can be stored on a 2-gigabyte Secure Digital (SD) card. Data could also be transmitted over a cellular network in real time, or during the night to reduce transmission charges. Capture of GPS data was also available in most of the commercial data loggers evaluated by both teams.

How precise are the OBD fuel economy estimated values?

The accuracy of fuel economy measured through the OBD data stream was studied via two different methods: a comparison of fuel rate estimates derived from standard PIDs and enhanced PIDs, and a comparison of fuel rate estimates derived from air-flow OBD data and fuel rates derived from carbon-balance measurements under dynamometer chassis testing.

3 According to ERG's report, vehicle manufacturers can and do provide additional operational and diagnostic information data that is specific to each manufacturer. The information needed for a scan tool or data logger to request, decode, and translate these "enhanced parameter IDs, " or "enhanced PIDs, " is manufacturer-specific and is not provided in SAE specifications. It must be obtained from vehicle manufacturers, although in the US most manufacturers provide information through a central source such as the Equipment and Tool Institute. The enhanced PIDs available by manufacturer vary. Some enhanced PIDs of interest in this study include hybrid vehicle battery state of charge, air conditioning compressor status, and some indicator of fuel rate (e.g., fuel injection timing / duration, fuel injected mass / volume per cylinder rotation, or perhaps some form of calculated fuel rate).

Comparison of standard versus enhanced PID fuel rate estimates

ERG in the US ran in-use comparative tests on two different vehicles. Second-by-second fuel rate estimates calculated from standard PIDs were compared with fuel rate estimates calculated using an enhanced PID (OEM fuel-injector fuel rate) data from the same test. The vehicles tested were a Toyota Camry and a Toyota Prius. For the Toyota Camry the cumulative fuel derived from MAF-based (standard PID) fuel rate was approximately 13 percent lower than the injector-based (enhanced PID) value, while the Prius' MAF-based cumulative fuel was approximately 3 percent lower than the injector-based value. The accuracy of the enhanced PID fuel rates against a laboratory grade instrument (i.e., chassis test) was not verified and requires further investigation before launching the main study.

Comparison using dynamometer

Data was collected in the US and Europe to compare fuel rate based on OBD-generated information with fuel rate calculated from carbon-balance measurements under dynamometer chassis testing.

Fuel rates calculated from air-flow OBD data assuming stoichiometric conditions were very close to the carbon-balance measurement, except during periods identified as non-stoichiometric operation conditions (cold starts, fuel cutoff, and high load). Identifying those events and correcting the OBD MAF fuel rates reduced the overall deviation. An artificial neural network (ANN) model was used to confirm that the OBD MAF PID and the OBD commanded equivalence ratio PID contained sufficient information to predict the dynamometer-measured fuel rate during stoichiometric operation and during non-stoichiometric operation, including fuel cutoff events and cold start. The model predicted the dynamometer-measured fuel rate with an r^2 of 0.993 and a standard deviation of 0.12 mL/s, which is 2 percent of the maximum observed fuel rate for the vehicle and 25 percent of the observed fuel rate at idle. This suggests that additional analysis to correct MAF-based fuel rates using additional PID signals on a wide range on models would be required before commencing a full study.

Tests carried out in Europe also found an approximately 2 percent deviation for MAF-equipped gasoline vehicles. The results on diesel vehicles indicate that standard OBD data is not enough for adequate fuel rate determination.

Data logger costs

Current data logger costs vary between US$200 and US$1000. While further investigation would be needed into the technical capabilities of the best candidates identified in the pilots, it is reasonable to estimate that instruments for a full study could be purchased for no more than US$500 each. Current commercially inexpensive data loggers can transmit the data via cellular networks and/or store the data acquired for a full year.

How much is a full-scale study going to cost?

Cost of a full-scale study will depend primarily on sample size, defined by project objective, and data logger technology. The results of the pilot studies indicate that a full-blown effort to acquire accurate fuel economy data on any 1996 and newer vehicle of any technology would be an expensive undertaking. The estimated cost to acquire one year of second-by-second data ranges from $3,700 to $7,200 per vehicle for a 200-vehicle sample, and from $2,600 to $5,000 per vehicle for an 800-vehicle sample, assume that data loggers cost $875 for the 200-vehicle study and $568 for the 800-vehicle study. Additional pre- and post-processing costs are estimated at approximately $1,300 per vehicle for a 200-vehicle sample and $400 per vehicle for an 800-vehicle sample.