WORKING PAPER 2021-01

JANUARY 2021

Avoiding a gap between certified and real-world CO_2 emissions: Technical considerations for on-board fuel consumption measurements in trucks

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Keywords: CO_2 emissions, fuel consumption, on-board fuel consumption metering

Introduction

The European Commission recently adopted CO_2 standards to reduce the CO_2 emissions from trucks in the European Union by mandating reduction targets for 2025 and 2030.[1] Compliance with these targets is determined by the reporting and monitoring of the CO_2 emissions from all newly registered trucks with emissions certified via the simulation tool VECTO. It is necessary to ensure that no gap arises between the certified and real-world CO_2 emissions from trucks—as has already happened for light-duty vehicles—as it would threaten the climate benefits of the CO_2 standards.[2]

To preemptively address this situation, the regulatory framework introduces two elements that correlate the fuel and energy consumption reported in VECTO with real-world performance:

1. The CO_2 certification methodology, Regulation (EU) 2017/2400 and its amendments, introduces an on-road verification testing procedure. The objective of the test is to evaluate the conformity of the operation of the simulation tool and of the certified CO_2 performance of the components used as input to VECTO.[3] Notably, the use of a fuel flow meter is mandated to verify the engine fuel consumption data. On-road verification testing is currently only required

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1 European Commission, "Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 Setting CO2 Emission Performance Standards for New Heavy-Duty Vehicles and Amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC," *Official Journal of the European Union* L 198 (July 25, 2019), https://eur-lex.europa.eu/eli/reg/2019/1242/oj#d1e1921-202-1.

2 Uwe Tietge et al., "From Laboratory to Road: A 2018 Update of Official and 'Real-World' Fuel Consumption and CO2 Values for Passenger Cars in Europe" (ICCT, 2019), https://www.theicct.org/publications/laboratory-road-2018-update.

3 Further information on VECTO and the certification procedure can be found in this ICCT policy update: Felipe Rodriguez, "Certification of CO2 Emissions and Fuel Consumption of On-Road Heavy-Duty Vehicles in the European Union" (The International Council on Clean Transportation, August 1, 2017), http://theicct.org/hdv-co2-certification-eu-policy-update-20170731.

as part of the type-approval process. The extension of the test for in-service verification is being developed.

2. The truck CO_2 standards, Regulation (EU) 2019/1242, amend the type-approval requirements to mandate the introduction of on-board devices for the monitoring and recording of fuel and energy consumption, payload, and mileage. These on-board fuel consumption meters (OBFCM) are already required for light-duty vehicles.[4]

The latter is the focus of this paper. The technical and legal framework for the fitting of OBFCM devices to heavy-duty vehicles (HDVs) is yet to be determined. By the end of 2021, the European Commission must develop the technical requirements for the monitoring of OBFCM data. To ensure the real-world representativeness of the certified CO_2 emissions and help achieve the climate benefits of the CO_2 standards, the European Commission must ensure that a certain level of accuracy is mandated in the measurement of OBFCM data. The accuracy of the OBFCM data must be verifiable under restricted testing procedures, which usually encompass short driving distances.

To inform this process, several methods to measure fuel consumption were tested on a series of trucks during two test campaigns commissioned by ICCT. This paper assesses the viability of these methods for measuring real-world fuel consumption of trucks based on the available data. First, the viability of several candidates to serve as the reference method, against which the accuracy of the OBFCM devices is determined, is assessed. Next, two methods for OBFCM data collection are assessed:

1. The fuel consumption estimation from the engine control unit (ECU), which can be read from the standardized on-board diagnostics (OBD) interface.
2. The direct measurement of fuel consumption by an external system. In this case, an on-board fuel level sensor was used.

Closing the paper, qualitative and quantitative recommendations are made for establishing the technical framework of OBFCM for trucks.

Methodology

The Forschungsgesellschaft für Verbrennungskraftmaschinen und Thermodynamik at Graz University of Technology was commissioned to test the fuel consumption of four trucks from different manufacturers. The technical specifications of the trucks tested are summarized in Table 1.

4 European Commission, "Comission Regulation (EU) 2018/1832 of 5 November 2018 Amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) 2017/1151 for the Purpose of Improving the Emission Type Approval Tests and Procedures for Light Passenger and Commercial Vehicles, Including Those for in-Service Conformity and Real-Driving Emissions and Introducing Devices for Monitoring the Consumption of Fuel and Electric Energy" (European Commission, November 5, 2018), https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R1832&from=EN.

Table 1. Specifications for the trucks used to test the OBFCM methods.

	HDV 1	HDV 2	HDV 3	HDV 4
Vehicle first registration	2019	2015	2016	2014
Vehicle manufacturer	Mercedes Benz	Mercedes Benz	DAF	MAN
Vehicle model	Atego 1524	Actros 1845 LS	LF 250 FA 18T	TGX 18.440
Vehicle category	N3	N3	N3	N3
Chassis type	Rigid truck	Tractor-trailer	Rigid truck	Tractor-trailer
Body / Trailer type	Curtain side	Curtain side	Box body	Curtain side
Cabin type	Day cab	Sleeper cab	Extended day cab	Sleeper cab
Engine displacement (L)	7.7	12.8	6.7	12.4
Engine power (kW)	175	330	184	324
Axle configuration	4x2	4x2	4x2	4x2
Max. weight (tonnes)	15	40	18	40

Fuel consumption measurement methods

Five different fuel consumption measurement methods were investigated in this analysis. The methods include both laboratory, portable, and on-board instruments with different working principles for the determination of the fuel consumption. Table 2 provides an overview of the measurement methods. Further details are included below.

Table 2. Overview of the fuel consumption methods investigated in this analysis.

Method	Type	Manufacturer	Working principle
Constant volume sampling (CVS)	Laboratory equipment	AVL	The exhaust gases are diluted with air, sampled in a collection bag, and analyzed in terms of composition. The carbon content of the bag is then traced back to fuel burn via a carbon balance analysis, which requires knowledge of the fuel properties.
Portable fuel flow meter	Portable	AVL	A positive displacement sensor, placed downstream of the fuel tank, continuously measures the instantaneous volumetric fuel flow. A density meter provides instantaneous density measurements to convert the volumetric flow into mass flow.
Portable emissions measurement systems (PEMS)	Portable	Sensors Inc.	The mass emissions of exhaust gases are determined by the combined measurements of exhaust mass flow and exhaust species composition. The carbon content of the exhaust gases is then traced back to fuel consumption via a carbon balance analysis, which requires knowledge of the fuel properties.
Engine control unit (ECU)	On-board	OEM	The ECU controls fuel injection in the engine to ensure an optimal air/fuel ratio over the entire range of operating conditions. The fuel injector actuation time is used by the ECU to compute fuel consumption and communicates it via the vehicle's controller area network (CAN) bus.
On-board fuel level sensor	On-board	Fuel level sensor manufacturer operating at the European level	A capacitive probe placed inside the fuel tank provides real-time fuel level measurements, which are converted into fuel volumes knowing the tank geometry. The difference in fuel volume before and after a trip gives the fuel consumption over the trip.

Constant volume sampling

Constant volume sampling (CVS) is currently the reference method used to test pollutant emissions in the type-approval of HDVs, for which measurements are obtained via an engine dynamometer test. In this analysis, CVS was also used to evaluate fuel consumption, although it was used on a chassis dynamometer test. Constant volume sampling is also currently set as the reference method against which the accuracy of the on-board fuel consumption data is evaluated for light-duty vehicles (LDVs). In this paper, CVS is considered as the most likely reference method option for HDVs, although the technical requirements for the latter have not yet been defined.

In the CVS method, the exhaust gases are diluted with air in a mixing tunnel to obtain a constant total flow—that is, the exhaust sample is combined with dilution air—under all operating conditions. Samples of the diluted exhaust are continuously captured in bags, and the resulting diluted exhaust is analyzed in terms of its chemical composition after the end of the test. Since the diluted exhaust gas is flowing at a known volumetric rate, the total volume of diluted exhaust over the test is also a known quantity. The mass emissions of the different species in the exhaust gas are then easily calculated by relating the concentration measured in the sample of the diluted bag—the so-called bag analysis—and the total volume of diluted exhaust gas. A representation of the CVS system is shown in Figure 1.

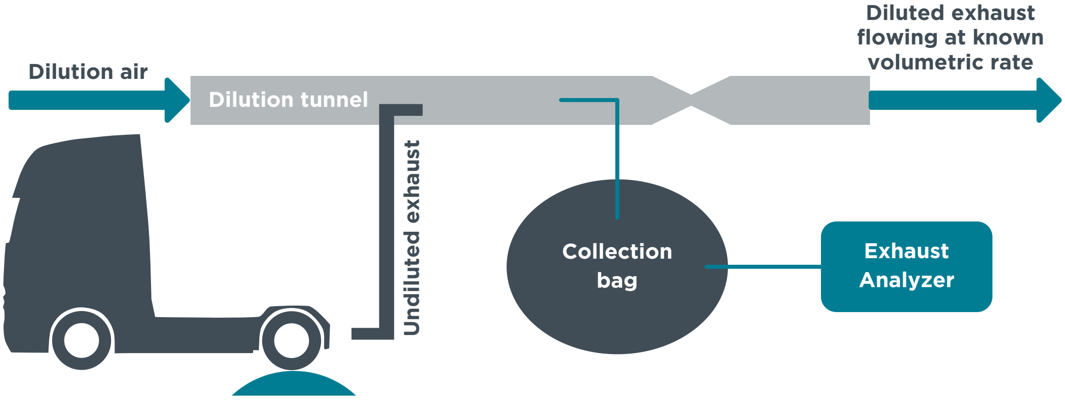

Figure 1. Schematic of the constant volume sampling system used in this analysis.

To determine the fuel consumption, a carbon balance analysis is performed. The carbon content in the sampling bags—that is all the carbon atoms in the CO_2, CO, and hydrocarbons—can be traced back to the burned fuel. However, the carbon balance analysis requires a detailed knowledge of the carbon content of the fuel and fuel density.

Compared to other carbon balance methods that measure exhaust flow and concentration separately, CVS has the advantage of directly accumulating all the carbon content from a constant volume sample, eliminating the need for the alignment of two independent signals and the associated uncertainties. Additionally, the CVS methodology also includes a step in which the carbon content of the ambient air used for dilution is determined by sampling and subtracted from the sample bag contents, further increasing the accuracy of the measurement.

Portable fuel flow meter

The fuel consumption was also measured using a portable device, which allows continuous measurements of the instantaneous fuel flow into the engine during on-road testing. The device used was the KMA Mobile, developed by the engineering company AVL. The instrument is equipped with a positive-displacement sensor which is inserted in the low-pressure fuel supply line and uses a servo-controlled gear meter to determine the fuel flow.[5] The high-resolution and data acquisition rate of this PLU[6] sensor claimed by the manufacturer allow accurate dynamic measurements, even under transient conditions and in low fuel consumption cases. Further, the device is equipped with a conditioning module, which cools the return fuel flow and feeds it back into the fuel supply line, only measuring the additional fuel supplied to this circuit.

5 AVL, "AVL KMA Mobile Fuel Measurement System," May 29, 2009, https://www.avl.com/documents/10138/885965/AVL_product_description_KMA+Mobile_+EN.pdf.

6 The PLU measurement principle was patented by the German company Pierburg Luftfahrtgeräte Union in 1972.

The device is also equipped with a density meter, which provides instantaneous fuel density measurements. The average density value recorded over each cycle was used to convert the fuel consumption measurements from grams of fuel per kilometer to liters of fuel per 100 kilometers, instead of using the standard Diesel B7 density value from the regulation. The density meter recorded values were also used to convert the measurements obtained with the engine control unit (ECU). For the CVS and Portable emissions measurement system (PEMS) methods, when a conversion was required, the standard Diesel B7 density was used.

The technical specifications of the device suggest a measurement uncertainty of ±0.1% for the fuel flow sensor and 1 kg/m^3 for the density meter.

Portable emissions measurement system (PEMS)

An estimation of the fuel consumption was also obtained using a portable emissions measurement system (PEMS) device. PEMS is the common method used for the type-approval and in-service conformity testing of pollutant emissions from HDVs. In this method, the mass emissions of the different exhaust gases are obtained by the careful alignment of two signals, recorded in parallel: an exhaust gas analyzer records the instantaneous concentrations of the different pollutant species, while an exhaust flow meter records the total tailpipe mass flow. The time alignment of these two signals is a significant challenge, which usually leads to a degree of uncertainty in the measurements obtained with PEMS devices, typically up to 3%.[7]

A carbon balance is performed to determine the truck's fuel consumption from the carbon content of the exhaust gases and fuel properties. For this step, the stated density of the reference fuel (835 g/L) is used. The carbon content is obtained from the measurement of CO_2 emissions only and not from total hydrocarbon contents. Because CO_2 emissions are several orders of magnitude higher than other hydrocarbon emissions, this adds more uncertainty to the process. For the reference fuel, the stated values for the ratios of hydrogen to carbon content and oxygen to carbon content (H/C = 1.86 and O/C = 0.007, respectively) were used. The CO_2 mass flow measurements obtained with this method were available for all trucks – that is, 38 data points were available.

Engine Control Unit (ECU) fuel consumption estimation

The fuel consumption estimation of the Engine Control Unit (ECU) is prevalent in HDVs to inform truck operators; it is therefore natural to consider its extension to meet OBFCM requirements. It is also likely to be the preferred method for OBFCM data monitoring in light-duty vehicles (LDVs). The purpose of the ECU is to accurately control the air and fuel intake to the engine to deliver the required torque with optimal performance, by processing the data from various sensors in the engine and in the intake and exhaust gases. This includes air mass intake, oxygen level in the exhaust, and engine operating speed, among others. Based on the required torque demand, fuel pressure, and other engine and fuel parameters, the ECU measures the required injector actuation time. A resulting fuel consumption estimate is therefore computed, the accuracy of which is limited by the rather low computing capabilities of the ECU. It is recorded as part of a broader On-Board Diagnostics (OBD) system and communicated via the Controlled Area Network (CAN) bus, which centralizes all control data from the vehicle. To convert the ECU fuel consumption measurements from g/km to L/100km, the average density value recorded by the portable fuel flow meter is used, as it is expected to yield better accuracy than using the reference fuel properties.

For LDVs, the accuracy of the OBFCM device is validated in WLTP during both type approval and conformity of production (CoP) testing. As part of these verifications,

7 Giechaskiel B. et al., "Real Driving Emissions: 2017 Assessment of Portable Emissions Measurement Systems (PEMS) Measurement Uncertainty" (Publications Office of the European Union, Luxembourg: Joint Research Centre (JRC), 2018), https://publications.jrc.ec.europa.eu/repository/bitstream/JRC109841/kjna29138enn.pdf.

the OBFCM must demonstrate no more than a 5% deviation in the measurement of volumetric fuel consumption, as compared to the reference measurement obtained with constant volume sampling on an engine chassis dynamometer test. However, there are currently no requirements for the accuracy of OBFCM data under real-world driving conditions, although this is part of ongoing policy developments. Further, as only OEMs have access to the signals processed in the ECU's software, there is currently no way to verify that the ECU accuracy implemented by OEMs is the highest possible and that the data transferred for monitoring purposes is exactly as measured by the ECU.[8] The HDV regulation should therefore address these caveats identified in the technical framework of OBFCM data monitoring for LDVs.

For this analysis, OBFCM data from the ECU are available for all trucks—that is, 38 data points are available.

On-board fuel level sensor

Finally, the viability of using an on-board fuel level sensor to determine fuel consumption was assessed. In this method, the main device is a connected probe placed inside the fuel tank, which measures the fuel level via a series of capacitive sensors across the length of the tank and converts it into an electric signal. The fuel signal is then processed by an external company. It is first converted into a fuel volume, knowing the tank geometry. The real-time data recorded by the probe is then transmitted over-the-air in 30 second intervals via an embedded data acquisition system to an in-house data-processing platform, and the processed output is made available for tracking by the end user on a web application. In this analysis, the fuel consumption is obtained by the difference in instantaneous fuel volumes recorded in the tank before and after each test.

The fuel level sensing system provider presents this technology as a more accurate method for fuel consumption estimation than the engine control unit. The company claims a 1/17,000th precision in the measurements of the capacitive probe.

Data collection

The fuel consumption measurements took part over two separate test campaigns in 2017 and 2020. Not all fuel consumption measurement methods were tested on all trucks. The CVS method was tested on HDVs 2, 3, and 4 only, while the on-board fuel level sensor was tested only on HDV 1. For each truck, between 7 and 11 fuel consumption measurements were taken with different methods and instruments. Each measurement corresponds to a different driving cycle combining urban, rural and motorway driving, with lengths ranging from 35km to 180km, to account for the range of conditions experienced by the vehicles during real-world operation. These cycles are expected to be representative of the testing procedure that will be implemented to demonstrate the accuracy of OBFCM data for trucks. A total of 38 fuel consumption measurements was therefore obtained. Figure 2 summarizes all the measurements available for comparison.

8 Jan Dornoff, "One Goal, Multiple Pathways: A Review of Approaches for Transferring on-Board Fuel Consumption Meter Data to the European Commission," White Paper, October 22, 2019, https://theicct.org/publications/transferring_obfcm_fuel_data_ec.

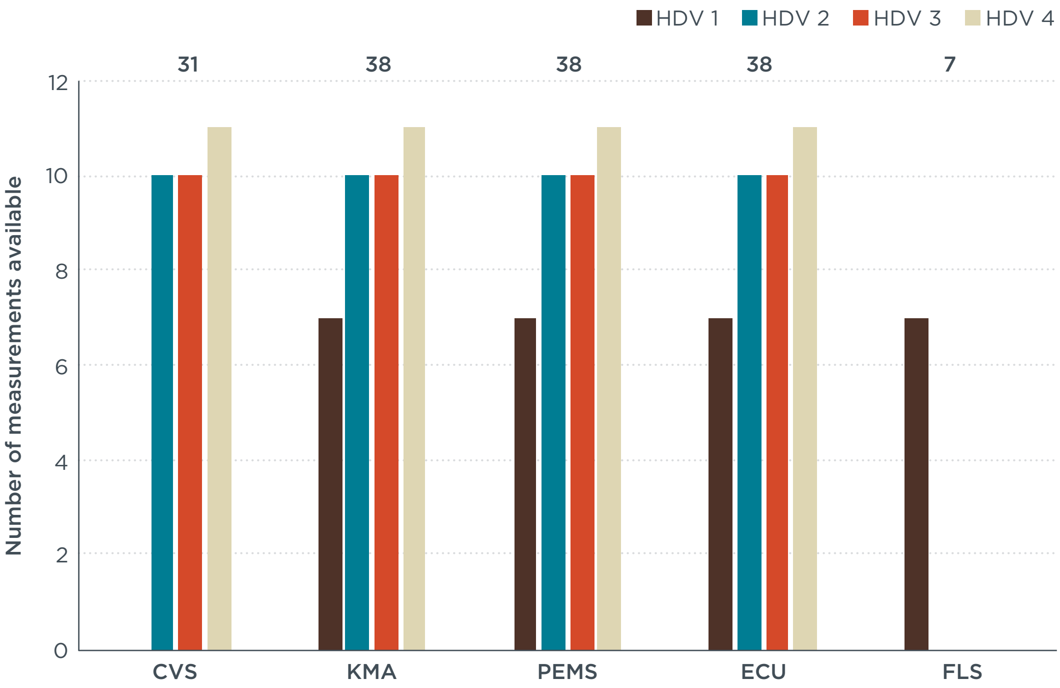

Figure 2. Number of fuel consumption measurements available for the different methods.

Results and discussion

Evaluation of reference methods for determining the accuracy of OBFCM devices

The CVS method is currently the regulatory reference method for verifying the accuracy of on-board fuel consumption meters in LDVs and is also the most likely option considered for trucks. Yet, as it is a laboratory method, usually performed for HDVs on an engine dynamometer, its representativeness of real-world conditions is limited. Furthermore, it incentivizes the optimization of the OBFCM's accuracy only on the regulatory test procedure rather than on all real-world driving conditions. The use of a portable measurement method as the reference could improve the representativeness of the procedures for type approval and in-service conformity tests by also accommodating for on-road testing of the OBFCM data accuracy. This section of the paper evaluates the viability of portable reference methods to assess the accuracy of the OBFCM measurements, based on the results of the tests described in the previous section of the paper.

Portable fuel flow meter

The fuel consumption measurements obtained with the portable fuel flow meter—KMA Mobile—were very close to those obtained with the CVS method, as shown in Figure 3. For HDVs 2, 3, and 4, 92% of the measurements obtained with these two methods lie within a ±1% accuracy envelope—that is, 35 of the 38 available data points. Additionally, the accuracy of the measurements did not seem to decrease at lower volumes of fuel consumed, which correspond to shorter driving cycles, showing the technology's viability over the entire range of test cycles considered in these campaigns. It can therefore be deduced that the fuel consumption measurements recorded with the portable fuel flow meter are a good representation of those obtained with the CVS method.

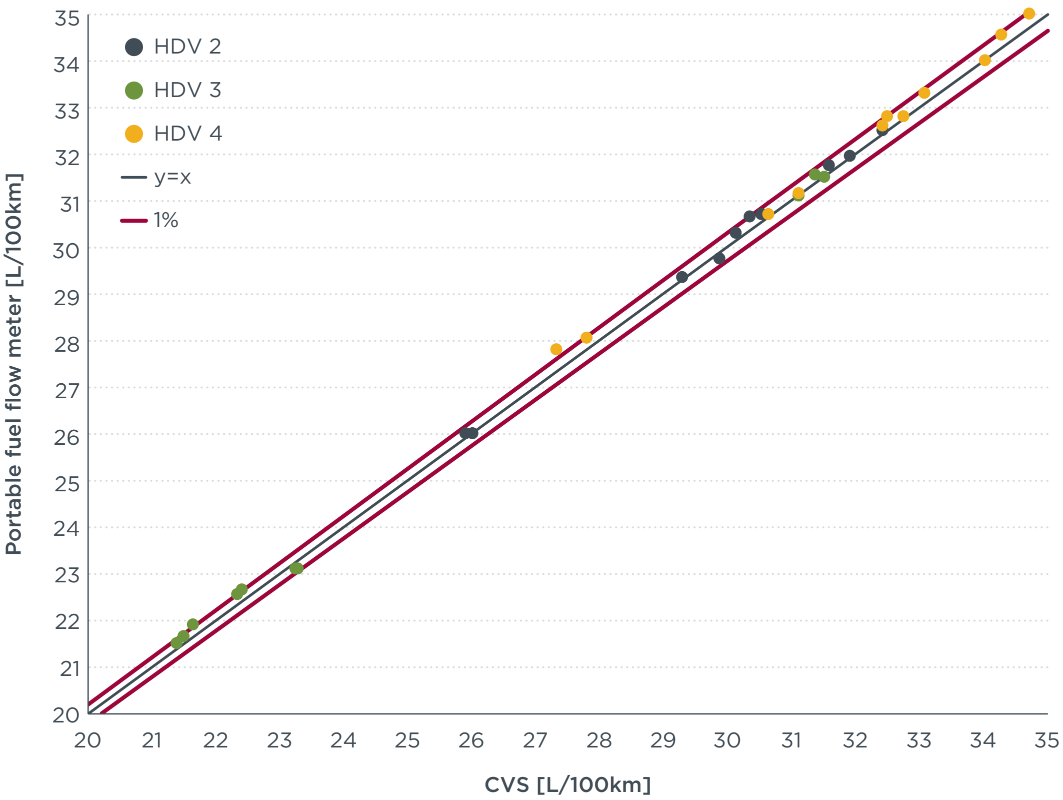

Figure 3. Accuracy of the portable fuel flow meter as compared to the constant volume sampling (CVS) method. A ±1% envelope contains 92%, or 35 of the 38 available data points.

This observation has two main implications. First, it shows the viability of using the portable fuel flow meter—already required for the on-road verification test presented in the introduction of this paper—for evaluating the accuracy of OBFCM devices, instead of the CVS method during engine dynamometer testing. This, in turn, would enable evaluating the OBFCM data accuracy during real-world operation.

Additionally, given the good agreement between the CVS and the portable fuel flow meter, and the fact that CVS measurements were not available for all trucks tested, the portable fuel flow meter will be used as the reference metric in the remainder of this paper.

Portable emissions measurement systems (PEMS)

PEMS is the current method used for type approval and in-service conformity testing of pollutant emissions. The possibility of using this method as the reference to validate the accuracy of the real-world data recorded by OBFCM devices was therefore explored, as procedures for PEMS testing are already well established. Our results show that the fuel consumption measurements obtained with the PEMS method lie within a ±10% uncertainty envelope with respect to the portable fuel flow meter measurements, as shown in Figure 4, raising questions regarding the viability of this method to provide the reference metric. The PEMS method is found to overestimate fuel consumption over the entire range of test cycles, with all data points on Figure 4 above the parity line (solid dark line in Figure 4). Yet, the PEMS device achieves reasonably good precision as shown by the strong correlation between PEMS and fuel flow meter measurements. From this regression analysis, the PEMS overestimation bias is assessed at 3.8%.

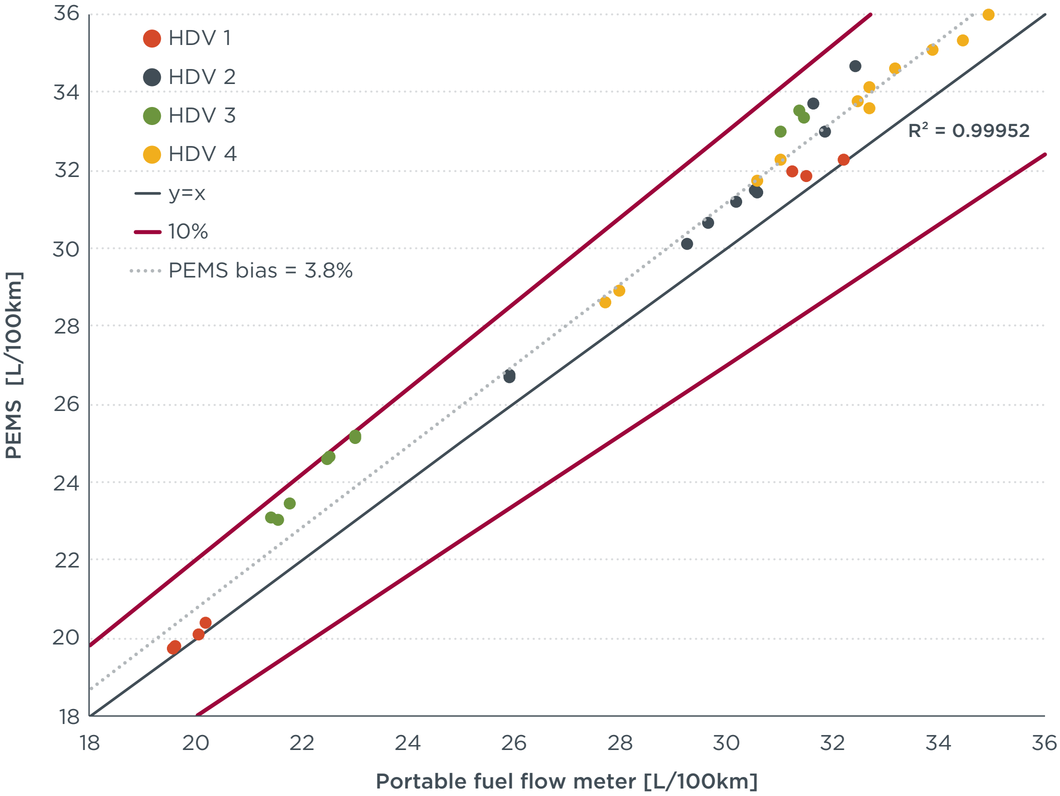

Figure 4. Accuracy of the PEMS method as compared to the portable fuel flow meter.

The inaccuracy of the results obtained with PEMS therefore comes from a bias introduced in the measurement. Known sources of uncertainty with this method are the measurement of the carbon content of the exhaust gas—alignment of mass flow and chemical composition signals, and interference with ambient carbon—and the knowledge of fuel properties. The latter has a considerable impact on the accuracy of the measurement. For this test campaign, standard Diesel B7 from the fuel station was used. The volumetric biodiesel content of market Diesel B7 fuels for trucks varies between 0% and 7%. While this variation has a minor impact on the carbon content of the fuel—impacting it by no more than 1%—it can have significant effects on the fuel density. Since standard density values are used to estimate the fuel consumption from PEMS measurements, any deviation in the density of the test fuel directly affects the estimation. The reference Diesel B7, as defined by the regulatory framework, can have a density in the range of 833 kg/m^3–837 kg/m^3, that is a 0.5% uncertainty range.[9] However, the market B7 fuels across the EU can have densities in the approximate range of 800 kg/m^3–845 kg/m^3, a significantly wider range. Due to the lack of information on the properties of the test fuel, the reference properties from the regulation were used, introducing some level of uncertainty.

While PEMS showed significantly worse performance than the portable fuel flow meter in this analysis, the latter comes at a high cost and additional calibration steps could make the PEMS method more viable for the considered purpose. By correcting for the identified bias, the data would fit within a ±5% accuracy envelope with respect to measurements obtained with the portable fuel flow meter, significantly improving its accuracy. This bias could be addressed during in-service conformity testing by introducing a fuel sample analysis procedure, removing some of the uncertainty introduced by the knowledge of fuel properties. The improved accuracy obtained

9 Commission Regulation (EU) No. 582/2011, "EC, Commission Regulation (EU) No. 582/2011 of 25 May 2011 Implementing and Amending Regulation (EC) No. 595/2009 of the European Parliament and of the Council with Respect to Emissions from Heavy Duty Vehicles (Euro VI) and Amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council," (2011).

would therefore increase the viability of the PEMS method, which is already used for other regulatory purposes, as the reference method to evaluate the accuracy of OBFCM devices.

Interim conclusion

Overall, the portable fuel flow meter is found to achieve the best representation of the fuel consumption measurements that are obtained with constant volume sampling. Although CVS is currently used as the reference, carbon balance methods present the major limitation of requiring knowledge of the fuel properties. While this is not an issue during type-approval where reference fuel is used, it is an issue for in-service conformity testing where it is desirable for manufacturers to use market fuel. On the contrary, direct fuel flow measurements, which eliminate the need for any conversion steps, could be a better representation of the reality. This also supports the use of devices equipped with fuel density meters, like is the case for the portable fuel flow meter tested in this analysis.

Alternatively, one could make the case that, since the aim of monitoring on-board fuel consumption is to assess and monitor the gap between certified and real-world CO_2 emissions, the regulation should mandate measurements of CO_2 emissions rather than fuel consumption. If the latter were used as the prevalent metric for OBFCM data monitoring, the relative performance of the different methods would be affected. Thus, methods like PEMS, which is already used for other regulatory purposes and is relatively cost-effective, could become a more viable reference method for the validation of OBFCM devices accuracy.

Accuracy of on-board fuel consumption monitoring devices

ECU fuel consumption estimation

The measurements recorded with the ECU were generally found to underestimate fuel consumption, lying within a ±14% accuracy envelope relative to the measurements obtained with the portable fuel flow meter, as shown in Figure 5. The ECU measurements recorded for HDV 1 (2020 campaign) were significantly less accurate than those from the other trucks (2017 campaign), which lie within ±5% of the portable fuel flow meter measurements. Ignoring data for HDV 1, which stand out as poorly accurate compared to the rest of the data, the measurements obtained with the ECU were found to yield good precision over the entire range of measurements, despite the identified bias. A regression analysis was performed to gain more insight into this phenomenon.

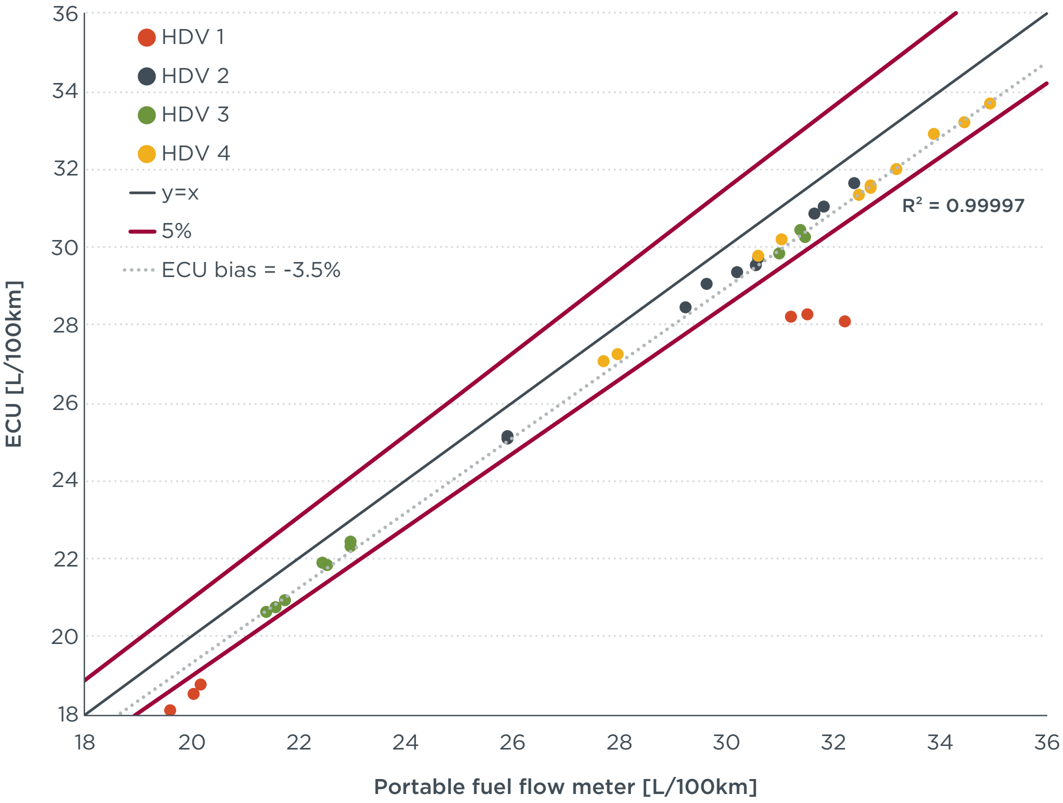

Figure 5. Accuracy of the ECU as compared to the portable fuel flow meter. The regression curve (ECU bias) and R^2 value were determined ignoring data points for HDV 1.

The measurements obtained with the ECU showed a strong correlation with those from the portable fuel flow meter. However, and despite the low spread in the data, the results show that the ECU underestimates fuel consumption by 3.5%. This is shown in Figure 5, where the data for HDVs 2 to 4 show little spread around the linear regression curve. Additional calibration effort, avoiding the identified bias, would improve the accuracy of the ECU measurements. We estimate that an accuracy of 1.5% would be possible using current methods, which is what would be obtained by aligning the data regression line to the parity line (dark solid line in Figure 5).[10]

The results show that the ECU fuel consumption estimates can achieve good precision (i.e., limited data spread) and that the accuracy (i.e., deviation compared to the reference method) can be improved by addressing the underreporting bias apparent in the on-board fuel consumption data recorded as part of this study.

On-board fuel level sensor

This section assesses the viability of an on-board, high resolution fuel level sensor as a possible technology to meet future OBFCM requirements. The fuel level sensor was only assessed on HDV 1, for which the data obtained with the ECU was found to yield significantly higher deviation in the fuel consumption measurements than with the other trucks. However, there is good confidence in the viability of the tests carried with this truck as the two assessed reference methods, the portable fuel flow meter—used as the reference metric—and the PEMS, were found to yield very similar results, as depicted in Figure 4. The fuel level sensor is therefore evaluated on this limited dataset.

Over the range of test cycles available, the on-board fuel level sensor measurements are found to yield both poor accuracy and precision, as shown in Figure 6. Out of the seven fuel consumption measurements available, three were outside the ±5% accuracy envelope achieved by the ECU for HDVs 2, 3, and 4. Removing the worse data point, for

10 Estimates disregarded data from HDV 1, which are considered outliers.

which refueling of the truck seems to have introduced some perturbations in the probe measurements, results in the data lay within ±10% of the fuel flow meter measurements. While this constitutes a significant improvement, the device remains poorly accurate compared to the best performing methods.

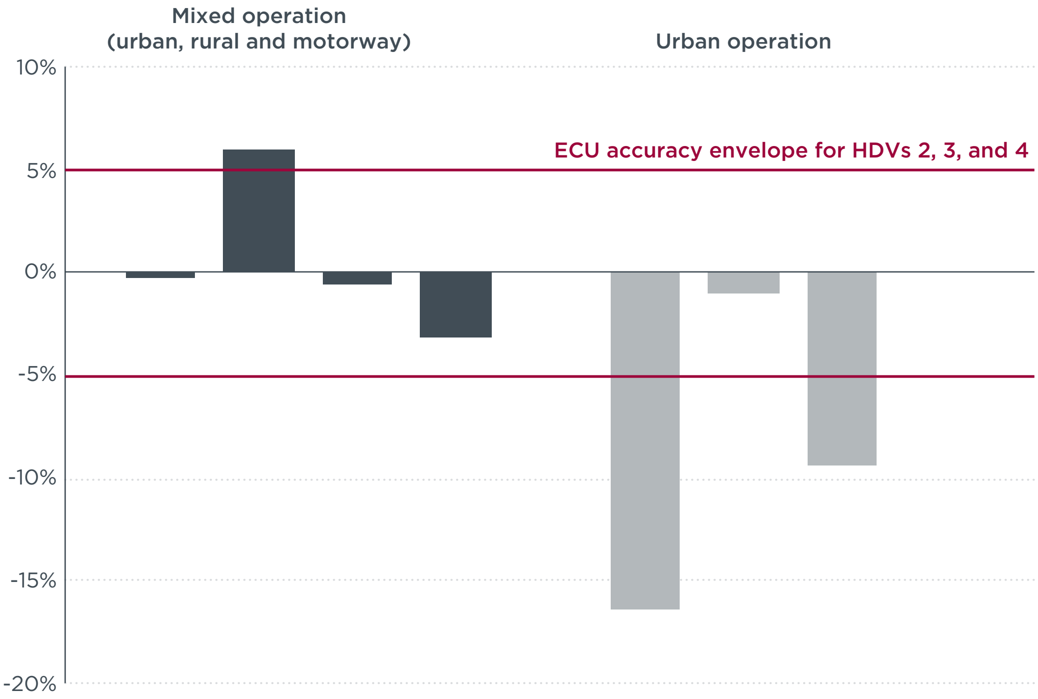

Figure 6. Accuracy of the on-board fuel level sensor technology as compared to the portable fuel flow meter.

Looking at individual trips, the cycles corresponding to urban delivery yield a much lower accuracy for most methods, as expected from the small fuel consumption volumes. Yet this is particularly the case with the on-board fuel level sensor measurements, as highlighted in Figure 6. These are cases of low cumulative fuel consumption, due to the short distances travelled in these cycles, but high distance-specific fuel consumption as the driving is usually inefficient in these conditions. By removing the two urban cycles from the on-board fuel level sensor data (i.e., the two worst data points), the accuracy of the method improves to 7%, although the small number of remaining data points makes it difficult to draw conclusions.

Additional analysis was performed to explain the poor accuracy of the trip-by-trip fuel consumption measurements obtained with the on-board fuel level sensor. First, although changes in temperature are expected to impact the fuel volume, the fuel level sensor used for this testing campaign was equipped with a temperature sensor with automatic data correction. Additionally, the temperature is only expected to influence diesel's volumetric mass by about 1% every 10ºC.[11]

Further, to fit the frame of the 2020 testing campaign, the usual calibration process performed when installing the technology on a new truck had to be shortened, skipping one step referred to as the "control of calibration," as explained by the data processing providing company. Discussions with the developers of the technology also made clear that it was not designed to measure the fuel consumption of short, isolated trips, but for large volumes of fuel consumed over the life cycle of a truck. We therefore looked at the measured values for the total fuel consumption of HDV 1 over the entire testing campaign. The total fuel volume recorded with the on-board fuel level sensor was within

11 Internal communication with the fuel level sensing system provider.

1.6% of that obtained with the portable fuel flow meter, 171.4 L and 168.8 L, respectively. This result tends to confirm that the device becomes highly accurate as larger volumes of fuel consumption are considered. However, as the accuracy of the OBFCM data must be verifiable over short trips, it seems unlikely the fuel level sensor method will be a suitable alternative to the ECU.

Interim conclusion

The fuel consumption measurement obtained with the engine's control unit were found to introduce a bias, underestimating fuel consumption by about 3.5%. Yet, the data obtained with the ECU yields a high precision and some additional calibration effort could yield an estimated 1.5% accuracy in ECU measurements. This makes the ECU the most viable option for OBFCM to date, and we consider that with reasonable additional calibration effort, current ECU algorithms can improve the accuracy of the fuel consumption estimators to meet future tight accuracy requirements. The on-board fuel level sensor, which was assessed as a potential alternative, showed poor accuracy for HDV 1 with 3 of the 7 data points outside of the ±5% accuracy envelope achieved by the ECU for the other trucks. From the available data, the fuel level sensor therefore does not appear to be a viable OBFCM option as it shows low accuracy over short trips, like those expected to be used for accuracy verification. However, a more comprehensive analysis, including a larger number of vehicles and tests, could show otherwise.

Conclusions & policy recommendation

The monitoring of OBFCM data is aimed at preventing a growing gap between the certified and real-world CO_2 emissions from trucks. Although the direct monitoring of tailpipe CO_2 emissions would eliminate the need for knowledge of the fuel properties, the current regulatory framework requires the monitoring of fuel consumption data. Data monitoring via OBFCM enables the identification of calibration strategies that artificially improve the vehicle's performance during certification. This can only be achieved, however, if the regulation mandates a certain accuracy for the OBFCM methods in real-world operation. The first step in achieving this is to determine a reference method against which the on-road accuracy of the OBFCM methods will be validated.

The PEMS method is commonly used for the determination of pollutant emissions but is not necessarily the most viable option to evaluate fuel consumption, as it requires the careful alignment of two signals as well as knowledge of the fuel properties. While this is not problematic for test procedures where reference fuel is used, the aim of OBFCM data monitoring is to assess the performance of vehicles in use, for which the exact composition of the market fuel used is unknown. An additional analysis of the test fuel during in-service conformity testing would be required to make PEMS a viable reference to evaluate the on-road accuracy of OBFCM data. Additionally, the viability of the PEMS method would increase if the monitoring of OBFCM data focused on CO_2 rather than fuel consumption. Alternatively, direct fuel flow measurements, such as those obtained with a portable fuel flow meter, might be more appropriate as the reference method. Under laboratory conditions, the measurements obtained with the portable fuel flow meter were found to match those obtained with the reference CVS method within a ±1% accuracy envelope and were therefore used as the reference metric in this paper. Consequently, we believe that fuel flow meters, which are already required as part of the on-road verification testing procedure for CO_2 emissions, should also be used to verify the accuracy of OBFCM data.

The most likely option for OBFCM to date is to monitor the estimates from the ECU using the vehicle's on-board diagnostics system (OBD). The engine control unit was found to yield good precision in the measurement of on-board fuel consumption. Yet, for all tested trucks, it presented an estimated 3.5% bias towards underestimating the fuel consumption compared to the measurements obtained with the fuel flow meter.

As only the OEMs have access to the data processed by the ECU, there is currently no way to verify whether the ECU accuracy being implemented is the highest possible. Therefore, high OBFCM accuracy requirements of around 1.5% seem to be already achievable with some additional calibration effort by manufacturers. Overall, this would require more transparency from OEMs as to how the ECU signals are being processed. The assessment of an alternative method for OBFCM based on a fuel level sensor found the measurement accuracy relatively poor for short, isolated trips over limited data. Under such conditions, the ECU estimates therefore remain the most accurate option for OBFCM to date and do not justify introducing another sensor.