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Characterisation of a Coriolis flow meter for fuel consumption measurements in realistic drive cycle tests

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ABSTRACT

When testing light-duty and heavy-duty vehicles on chassis dynamometers, as in the WLTP, or engines on engine test benches, as in the WHDC, it is required to measure the fuel consumption. In the preferable case, the measurement of the fuel consumption is carried out with suitable flow meters. These require high measurement accuracy in a wide flow range, independent of the fuel type, as the flow rate range is often very large and depends on the power range of the vehicle engines. Moreover, the fuel flow rate in the test cycles is very dynamically related to the loads. In the scope of the ongoing EMPIR Joint Research Project 20IND13 SAFEST the dynamic flow behaviour as well as the measurement accuracy of flow meters for different types of fuels are investigated. This paper presents first results from the realisation of dynamic flow profiles, and flow measurements with a Coriolis Flow Meter with different representative fuels in a wide density and viscosity range and a wide flow rate range at different fuel temperatures.

1. Introduction

The sector that contributes most to air pollutant emissions in Europe is transport. Transport is divided into road transport and non-road transport (air, rail, sea and inland water transport). The road transport sector was not only the largest contributor to total nitrogen oxide (NOx) emissions in the EU-28 in 2018 [1], accounting for 47% (39% road transport and 8% non-road transport) but was also responsible for 27% of CO_2 emissions in 2019 [2]. This is not the only reason why more and more stringent limits are being applied to NOx and CO_2 but also to CO (carbon monoxide), HC (hydrocarbons) and PM (particulate matter) emissions as well as particle number (PN) from light-duty and heavy-duty vehicles.

For more than 60 years, vehicles have been tested for compliance with emission standards with cycle tests during type approval. These test cycles serve as standardised measurement procedures for pollutant emissions and fuel consumption in the certification process in many regions of the world. The representativeness of the test cycles is important for the accurate emission assessment and for the subsequent certification process. The European emission standards (Euro) are vehicle emission standards for light-duty and heavy-duty vehicles sold in the European Economic Area (EEA) and the United Kingdom. The standards are defined in a series of EU directives that provide for the gradual introduction of increasingly stringent standards and thus emission limits. The stages are usually referred to as Euro 1, Euro 2, Euro 3, Euro 4, Euro 5 and Euro 6 for light-duty vehicles and Euro I, Euro II, Euro III, Euro IV, Euro V and Euro VI for heavy-duty vehicles. Euro 1 and Euro I were both introduced in 1992. A few years ago, the United Nations Economic Commission for Europe (UNECE) World Forum for Harmonisation of Vehicle Regulations (WP.29) set up an informal group under its Working Party on Pollution and Energy (GRPE) [3] to establish a roadmap for the development of Worldwide harmonized Light Vehicles Test Procedure (WLTP) and Worldwide harmonized Heavy Duty Certification (WHDC). The work of the GRPE contributed to the development of global technical regulations (GTR) [4] for light-duty vehicles (GTR no. 15) [5] and heavy-duty vehicles (GTR no. 4) [6]. It should be mentioned that only emission limit values are specified in the EU regulations, but not the test procedure and test cycles. These are only included in the corresponding GTRs.

The necessary comparability favours a laboratory measurement. Only on chassis dynamometers under a dynamic driving profile with

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defined conditions can fuel consumption and emissions be reliably and representatively determined. However, vehicle testing on chassis dynamometers is much more difficult for heavy-duty vehicles due to the size and weight of the vehicles. For this reason, the tests are carried out on an engine test bench and not on a chassis dynamometer. The results of engine test benches regarding fuel consumption and CO_2 emissions are rather inaccurate because, for example, the vehicle weight is not included in the measurements. In fact, volumetric fuel consumption is not directly measured over a test cycle. During the test cycle, the quantity of pollutants emitted by the vehicle is collected and analysed to calculate emission levels and fuel consumption. From the measured emissions of the carbonaceous components such as HC, CO and CO_2 (track-specific $\mathrm{g/km}$ or performance-specific $\mathrm{g/(kWh)}$) and the standardised fuel type and density, the corresponding mean fuel consumption (L/100 km) can be indirectly calculated through the distance covered during the test cycle. The fuel consumption measurements are therefore not time resolved, which would be desirable for dynamic test cycles. Real-time fuel consumption measurement on chassis dynamometers and engine test benches would be a great improvement and would also allow redundant respectively targeted measurements. That is why especially engine developers and test bench operators demand precise fuel consumption flow meters that provide highly accurate measurement results with different fuels in a wide flow rate range, even during cycle tests.

2. Background

2.1. Realistic drive cycle tests

With the introduction of the Euro 6c standard, a new mandatory measurement procedure called Worldwide harmonized Light vehicle Test Procedure (WLTP) and a new driving test cycle, Worldwide harmonized Light vehicles Test Cycle (WLTC) were introduced. The WLTP and WLTC are based on real-driving data gathered from 14 countries (some EU countries plus Switzerland, USA, India, South Korea and Japan). This has resulted in average driving profiles. Since 1 September 2018, the WLTP is obligatory for the initial registration of every new car. This means that this procedure is used during type-approval of all new passenger car models in the EU. This covers testing of fuel consumption and emissions for Internal Combustion Engine vehicles and electric power consumption and driving range for Hybrid-Electric Vehicles and Battery-Electric Vehicles. The WLTP includes three different driving cycles (WLTC) based on the power-to-mass ratio (PMR) of the vehicle. By far the majority of cars in Europe fall into the third cycle class (Class 3) with a PMR > $34\,\mathrm{W/kg}$ ($46\,\mathrm{hp/t}$) and a maximum speed $v_{\max} \geq 120\,\mathrm{km/h}$ (Class 3b or Class 3-2). The WLTC developed for Class 3b vehicles comprises four phases with different speed distributions, during which fuel consumption is measured and exhaust emissions are sampled, Fig. 1. The duration of the entire WLTC is $1800\,\mathrm{s}$ and is composed of the low speed (urban traffic, $589\,\mathrm{s}$), medium speed (country road, $433\,\mathrm{s}$), high speed (expressway, $455\,\mathrm{s}$) and extra high speed (highway, $323\,\mathrm{s}$) phases. Usually, a trained driver is employed to ensure that the cycle driven is as close as possible to the defined cycle.

The results of a chassis dynamometer test may differ from actual on-road pollutant emissions because several factors affecting on-road emissions are not taken into account, such as road gradient, road surface, use of (electrical) consumers and different traffic or weather conditions [7]. For this reason, in addition to the laboratory tests, the vehicles are tested under real environmental conditions during additional road drives, so-called Real Drive Emissions (RDE) tests. A Portable Emission Measuring System (PEMS) measures the pollutant emissions, but also simultaneously acquires the related parameters of the vehicle and the ambient conditions.

For heavy-duty vehicles, the fuel consumption and emissions are determined in a similar procedure. With the introduction of the Euro VI standard in 2013, the Worldwide harmonised Heavy-Duty Certification (WHDC) procedure developed by the GRPE [8] was launched at the same time, establishing a worldwide harmonised engine test cycle for the emission certification of heavy-duty vehicles. The WHDC procedure consists of two representative test cycles, the World Harmonized Transient Cycle (WHTC) and the World Harmonized Stationary Cycle (WHSC) which are specified in GTR no. 4. The WHSC test is a steady-state engine test bench (engine dynamometer) test and the WHTC test is a transient engine dynamometer test with a duration of $1800\,\mathrm{s}$ which consists of the three segments: urban, rural and highway. To be able to perform the drive cycle tests on an engine dynamometer a denormalization procedure must be carried out to obtain the actual engine speeds and torques at each operating point, Figs. 2 and 3. The torque and the specific fuel consumption can be used to determine the fuel consumption during the test cycles.

Table 1
Fuel consumption at idle for different vehicles [10].

Vehicle type	Fuel type	Engine size	Idling fuel use ($\mathrm{L\,h^{-1}}$) No load	With load
Passenger car Ford Focus	G	2.0	0.60	1.10
Passenger car VW Jetta	D	2.0	0.65	1.50
Passenger car Ford Crown Vic	G	4.6	1.50	2.10
Medium heavy Truck	G	5–7	3.20	–
Medium heavy Truck	D	6–10	1.70	–

In addition to the transient WHTC, the GPRE has also developed a stationary cycle, the WHSC. The WHSC is a ramped steady-state test cycle with a sequence of steady-state engine test modes with defined speed and torque criteria for each mode and defined ramps between these modes.

2.2. Real fuel consumption

The brake-specific fuel consumption (BSFC) given in $\mathrm{g/(kWh)}$ can be estimated beforehand by the fuel consumption map of the respective vehicle depending on the gear stage according to the required tractive force and the required engine speed as well as the driving resistance and driving speed. The specific consumption in a test cycle is generally between $200\,\mathrm{g/(kWh)}$ and $350\,\mathrm{g/(kWh)}$ for diesel engines and $220\,\mathrm{g/(kWh)}$ to $450\,\mathrm{g/(kWh)}$ for petrol/gasoline engines, Fig. 4.

With these values, extreme values for instantaneous fuel consumption under full-load of up to and more than $300\,\mathrm{L\,h^{-1}}$ can result. In contrast, the instantaneous fuel consumption at idle can be less than $1\,\mathrm{L\,h^{-1}}$, or even lower if a start-stop system is installed, Table 1.

In the WLTC and WHTC tests, light-duty and heavy-duty vehicles are rarely operated at full-load and the accelerations in these tests are also moderate. In the part-load range, where the full engine power of the vehicle is not used, consumption is therefore also significantly lower. The fuel consumption for compact and mid-size cars equipped with start-stop systems can here be estimated at between about $0.2\,\mathrm{L\,h^{-1}}$ to $25\,\mathrm{L\,h^{-1}}$. In contrast, the fuel consumption of sports cars, supercars, large Sport Utility Vehicles and pickup trucks can range from significantly more than $1\,\mathrm{L\,h^{-1}}$ to significantly higher values, depending on the engine power. Without reference to Table 1, it can be stated as a guide [11] that heavy-duty vehicles have a fuel consumption at idling of about $3\,\mathrm{L/h}$ ($0.8\,\mathrm{gallons/h}$). These vehicles (especially long-haul trucks) are also usually not equipped with a start-stop system. However, higher fuel consumption is to be expected in engine development. Here, the vehicles are also measured under full-load on the chassis dynamometers and engine test benches. Depending on the vehicle, this can lead to fuel consumption of several hundred litres per hour.

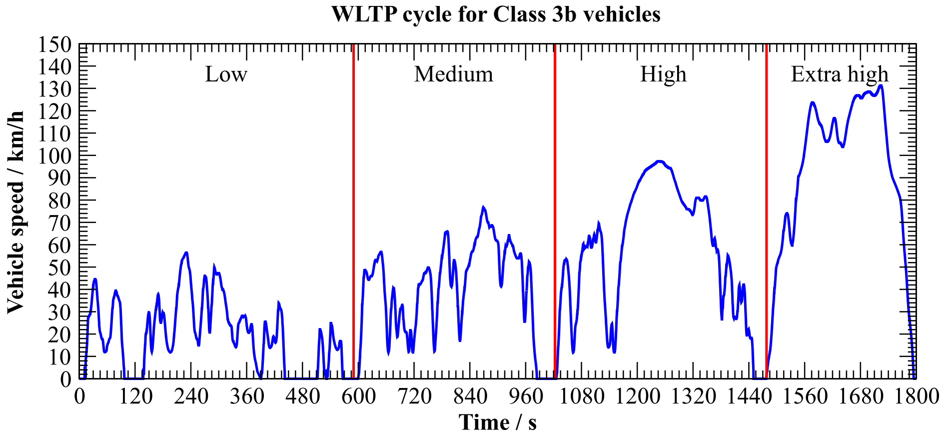

Fig. 1. WLTP cycle test for class 3b vehicles. Class 3 (highest power-to-mass ratio) is representative of vehicles driven in Europe.

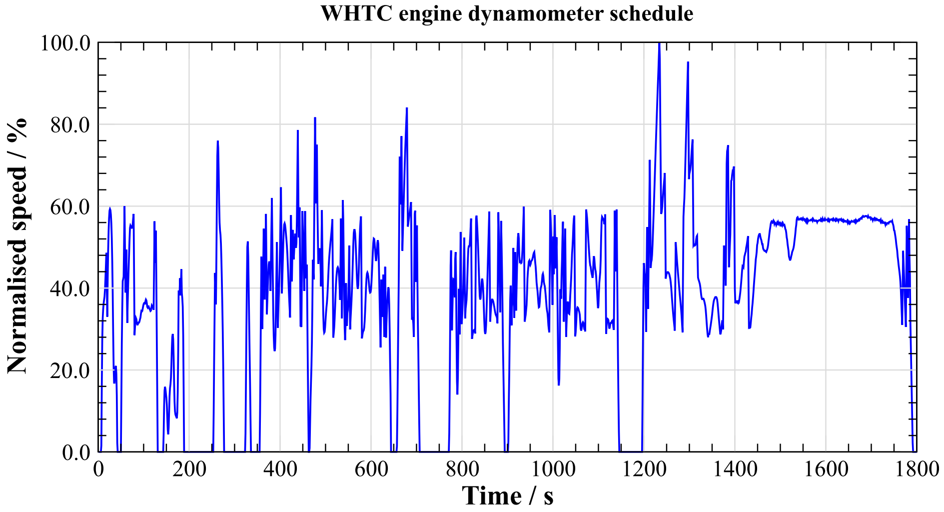

Fig. 2. WHTC engine dynamometer schedule, normalised engine speed over time.

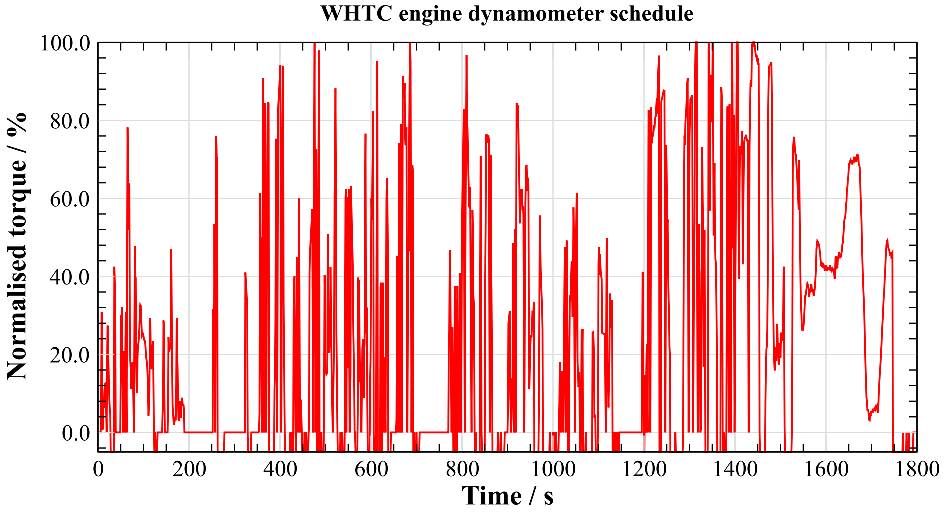

Fig. 3. WHTC engine dynamometer schedule, normalised torque values over time.

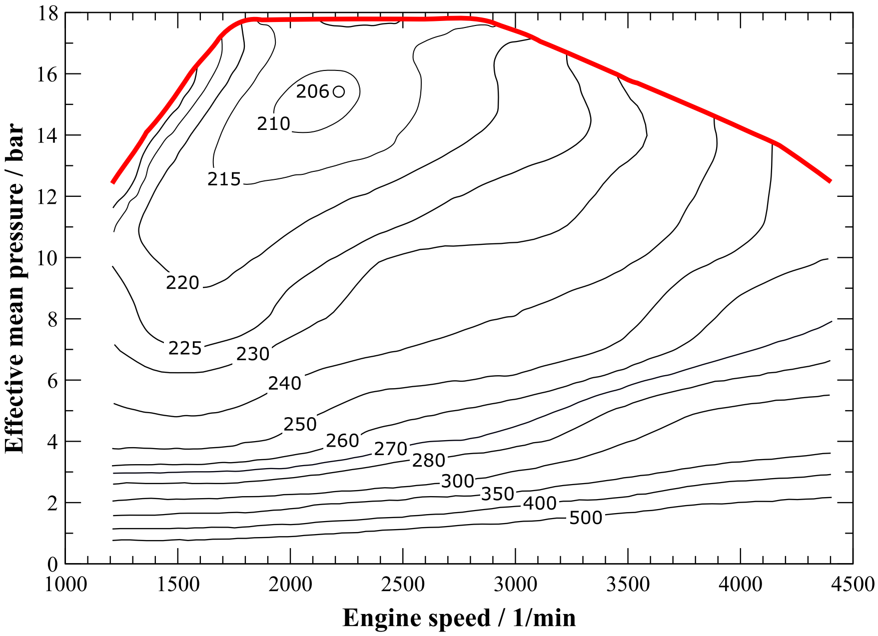

Fig. 4. Brake-specific fuel consumption (BSFC) of a small 1.5 L 3-cylinder diesel engine [9].

The consumption of heavy-duty vehicles is generally also significantly higher than that of light-duty vehicles, and in the order of magnitude of high-performance cars. One difference between high-performance cars and trucks, however, is that cars usually run on different fuels.

3. Material and methods

Within the European Metrology Programme for Innovation and Research (EMPIR) Joint Research Project (JRP) 20IND13 SAFEST [12], a wide range of issues related to fuel consumption flow meter performance is addressed. Currently, the flow meters are calibrated statically, that means at fixed flow rates, but are subject to very dynamic load changes. The project aims to create the first metrological infrastructure for the dynamic calibration of such flow meters. As part of the work, simple and scalable test profiles are to be derived for various engine sizes that reflect the flow variations occurring during fuel consumption. Using the new measurement infrastructure, it should then be possible to calibrate fuel consumption flow meters with these profiles. In this context, particular attention is paid to the performance of flow meters at zero flow or very low flow rates of a few hundred millilitres per hour. Finally, the effects of operating conditions such as fluid density, viscosity and temperature on the performance of the flow meters are investigated.

3.1. Dynamic load changes

Physikalisch-Technische Bundesanstalt (PTB) is addressing the dynamic fuel consumption measurement of small to medium-sized passenger cars ($\leq 25\,\mathrm{L\,h^{-1}}$) and smaller trucks ($\leq 100\,\mathrm{L\,h^{-1}}$). This is achieved with help of input and real consumption data collected at chassis dynamometer and engine test benches of the project partners Engineering office Hagemann (IB-HAWE) and University of Perugia (UniPG) with support from the collaborator Polytechnic University of Turin (PoliTO). A special focus here is on idling consumption.

The development of the metrological infrastructure consists of several parts: Firstly, the provision of test profiles that reflect the flow variations which occur during fuel consumption, and secondly the development of an infrastructure that is capable of realising these profiles. Furthermore, a suitable evaluation of the measurement data must be established.

3.1.1. Adaptation of dynamic flow profiles

The original profiles were obtained based on WLTC and WHTC test cycles. With the amendment of WLTP in 2018 and WHDC in 2019, On-Board Fuel and energy Consumption Monitoring (OBFCM) requirements were introduced in the EU for all newly type-approved vehicles and one year later for all vehicles in the respective class. OBFCM means that the amount of fuel and/or electrical energy consumed is determined and stored using equipment already available in the vehicle, such as the Engine Control Unit (ECU). Real-time fuel consumption is usually determined with the help of the Mass Air Flow sensor and the Vehicle Speed Sensor. More modern vehicles also use the lambda value (oxygen sensor), which provides information on combustion and controls the air-to-fuel ratio. The lambda sensor requires a working temperature of several hundred degrees Celsius. For this reason, the procedure does not work well in the cold-running phase. Then the engine runs in open loop with default parameters, i.e. the exhaust values are not of interest. When the engine has reached operating temperature, the ECU switches to closed loop and the air-to-fuel ratio is adjusted to the exhaust gas values. Experience has shown that the real-time fuel data generated in this way are very close to reality and also provide a dynamic pattern, e.g. over an entire driving test cycle. Based on these real test runs, the fuel requirements of the ECUs were determined and correlated with the dynamic behaviour of the test equipment used. Two test cycle profiles were derived from this, one for a passenger car and one for a truck, Figs. 5 and 6.

From the two profiles, two test profiles each for passenger cars and trucks were derived, which take up characteristic sequences of the harmonised test cycles, Figs. 7 and 8 and Figs. 9 and 10. A broad applicability is made possible by the fact that the test profiles can be simply scaled to reflect different engine sizes. In addition to closeness to reality attention was paid in the profile development to suitability for practical implementation. For this reason, individual sections of the original cycles were selected.

The test profiles serve as basis for the development of test rigs.

3.1.2. Measurement setup for dynamic measurements

The profiles are realised on test rigs with gravimetric reference. The measurement setup consists of a tank, a pump, the measuring section with a Device Under Test (DUT), a cavitation nozzle apparatus for profile generation (Fig. 11) and a balance.

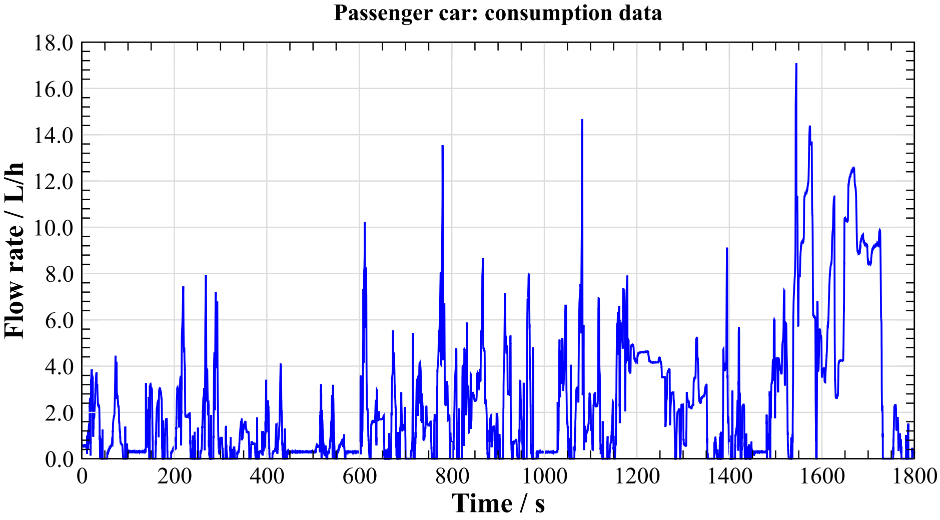

Fig. 5. Test cycle profile (according WLTC) derived for a petrol passenger car with a 97 kW engine.

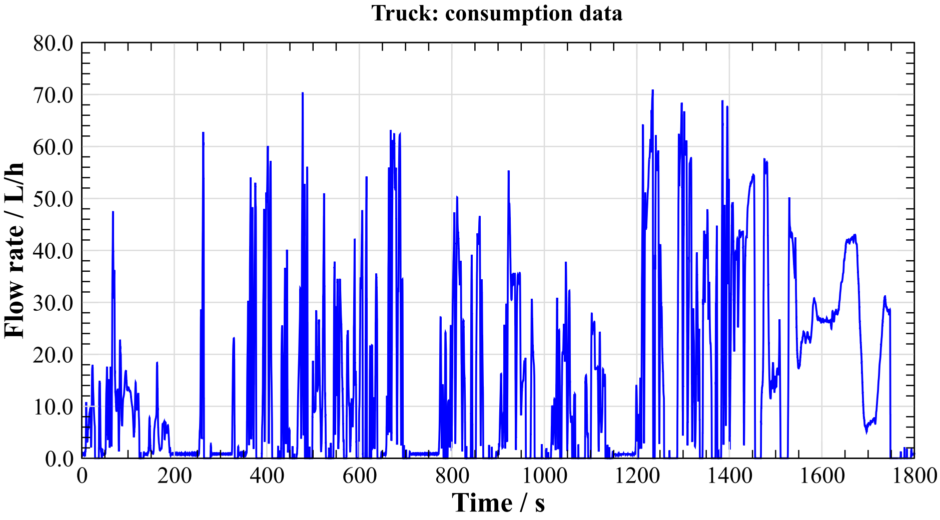

Fig. 6. Test cycle profile (according WHTC) derived for a diesel truck with a 263 kW engine.

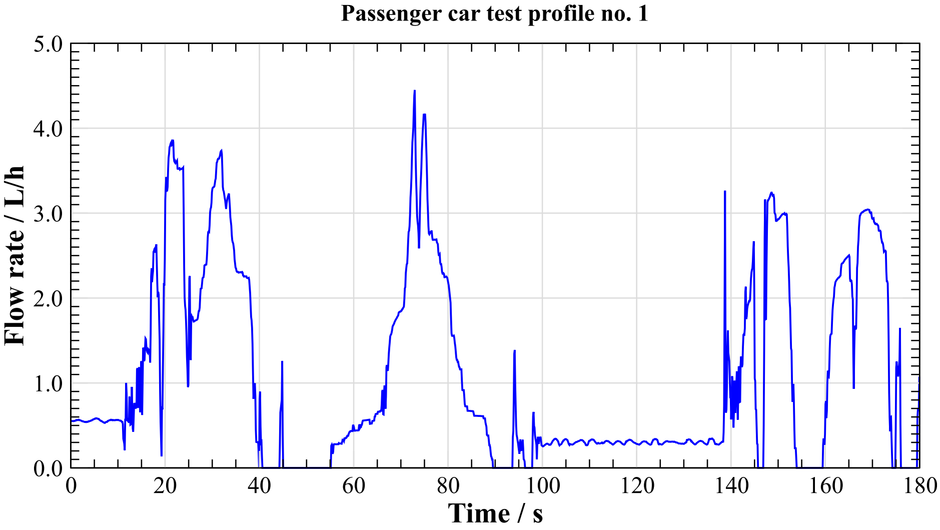

Fig. 7. Passenger car test profile no. 1, derived from the passenger car test cycle profile (Fig. 5, interval 0.14 s to 179.14 s). The test profile represents the low (urban) phase.

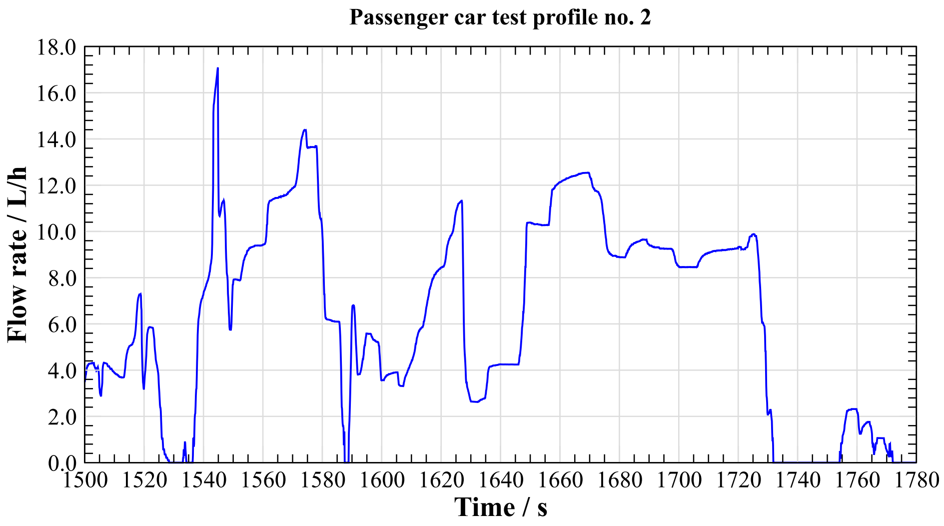

Fig. 8. Passenger car test profile no. 2, derived from the passenger car test cycle profile (Fig. 5, interval 1500.04 s to 1779.94 s). The test profile represents the extra high (motorway) phase.

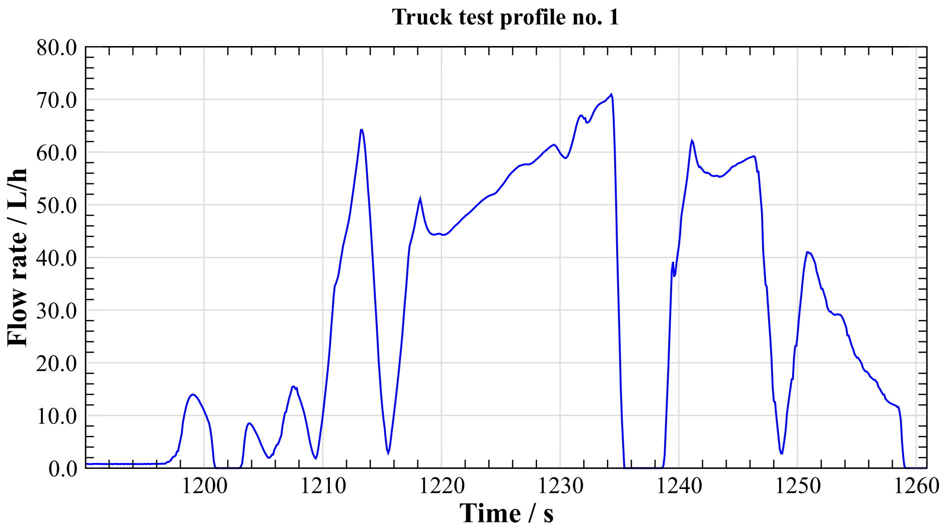

Fig. 9. Truck test profile no. 1, derived from the truck test cycle profile (Fig. 6, interval 1190.01 s to 1259.01 s). The test profile represents the rural phase.

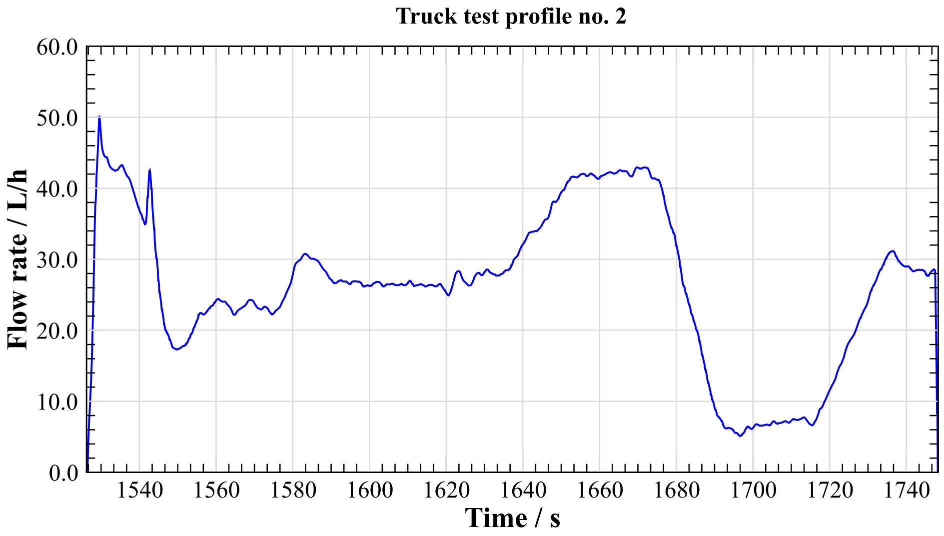

Fig. 10. Truck test profile no. 2, derived from the truck test cycle profile (Fig. 6, interval 1526.21 s to 1748.31 s). The test profile represents the motorway phase.

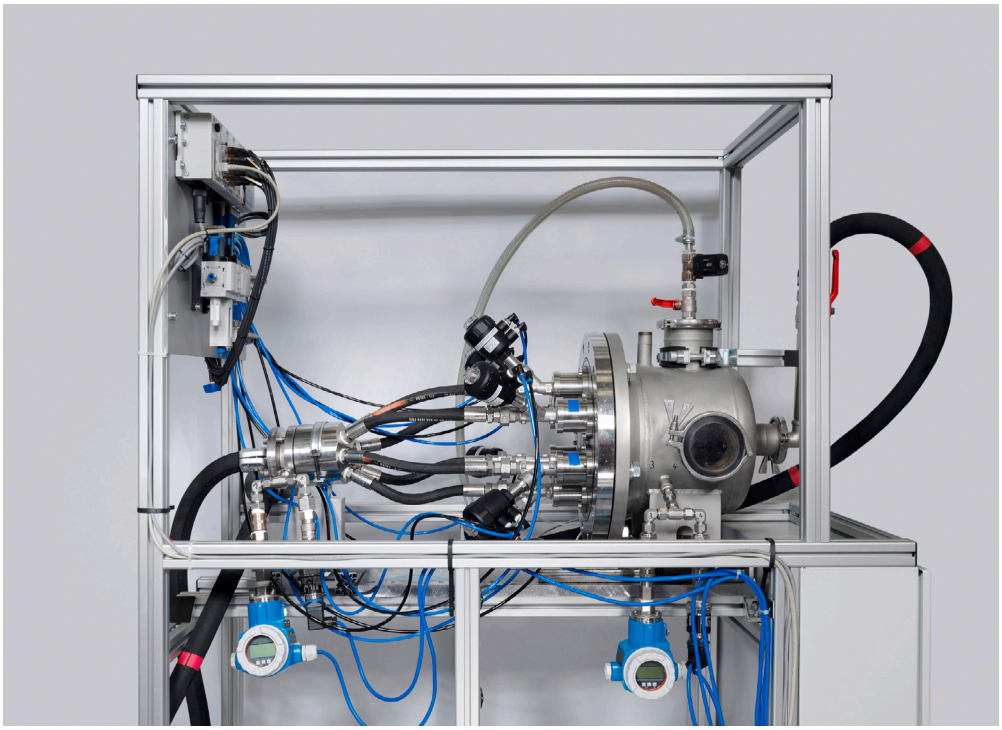

Fig. 11. Cavitation nozzle apparatus for vehicle profile realisation at PTB.

In order to record the dynamics of the profile generation, all test rig data are read out and recorded at a 20 Hz frequency. Due to the spatial separation between the scale and the DUT by pipes, the time delay of the flow rate change must be taken into account in subsequent comparative measurements. The realisation and measurement are carried out via a flying start-stop operation and a diverter to the balance. The data is then averaged over 6 s, as the jet impinging on the balance causes fluctuations in the balance readings.

3.2. *Operation conditions and fluid temperature*

Fuel consumption can be measured directly in several ways. On the one hand, the amount consumed can be determined by weighing the tank (gravimetric) or by level measurement in the tank (volumetric) before and after the test (statically) or during the test (dynamically). Another possibility is to determine the fuel consumption by measuring the flow during testing with a traceable, calibrated flow meter. There are currently mainly two flow measurement principles used for this purpose. One is the Positive Displacement (PD) flow meter, as a volume flow meter, with or without auxiliary drive, i.e. with or without pressure loss and thus possible pressure loss and leakage flow, and the other one the Coriolis Flow Meter (CFM), as a mass flow meter. Both flow meter types have been proven to have a high measurement accuracy (typically better than 0.1%) and an excellent response time (typically better than 100 ms) to accurately measure even fast flow changes. The PD meter has a larger dynamic range (typically 1:1000) compared to the CFM (typically 1:100), but experience shows that the PD meter is more commonly used for smaller flow facilities. One disadvantage of the PD meter is an additional density measurement that is required to provide the mass flow rate, whereas the CFM can in most cases provide both the mass flow rate and the volumetric flow rate, as in most cases the density is measured directly by the instrument. Recent research has also shown that CFMs are suitable for use in dynamic flow measurements [13,14]. Within the SAFEST project, different flow meters are investigated for their suitability as fuel consumption flow meters from these points of view. At RISE a CFM was investigated in a flow range from $3\,\mathrm{L\,h^{-1}}$ to $400\,\mathrm{L\,h^{-1}}$ in a temperature range between 15 °C to 30 °C using four different fuel types to cover different densities and viscosities. The lowest temperature value was chosen to closely match the WLTP test carried out in Europe at 14 °C, and the lowest flow rate value was chosen to correspond to the idling fuel consumption of heavy-duty vehicles. In contrast to PTB, RISE examined the CFM at higher but steady flow rates.

3.2.1. *Device Under Test (DUT)*

Due to its measuring principle, a CFM is a promising candidate for the use as a fuel consumption meter [15]. For this reason, a DN 4 (1/8-in.) Endress+Hauser (E+H) Proline Promass A 500 CFM was chosen for the investigations. The compact single-tube Promass A 500 is suitable for continuous process control in very demanding applications. It could be expected that the high dynamic range (1:400) may pose a challenge. The investigated Promass A 500 is known to have only a very small zero point error and an outstanding repeatability, even at small flow rates. In addition to the compact design, this is mainly due to the innovative wave-shaped measuring tube. As direct mass flow meters, CFMs are known to be independent of the inlet velocity profile although there are studies that indicate that there is a slight dependence on the inlet velocity flow profile. However, this dependence is obviously greater for smaller tube aspect ratios α (α = Coriolis tube length/Coriolis tube radius) [16]. Generally, large flow meters show a greater dependence on the velocity flow profile. For example, while the Coriolis tube length of a large flow meter may double compared to a small one, the Coriolis tube radius easily changes by a factor of five or more, resulting in a smaller α value. It can be assumed that due to the wave-shaped measuring tube of the Promass A, the ratio of measuring tube length to measuring tube diameter reaches a maximum value, resulting in a very large aspect ratio ($\alpha > 300$) and thus a negligible velocity profile dependence based on the quadratic dependence of α. It can also be stated that in the measurements presented later, the influence of the velocity profile due to the installation situation is negligible, as a more than 50 D inlet section was provided.

In addition, CFMs are known to be almost insensitive to the physical properties such as the density and viscosity of the fluid. However, for highly viscous fluids, i.e. with very low Reynolds (Re) numbers,

Table 2
Specifications of the DN 4 (1/8-in.) E+H Proline Promass A 500.

Specification	Value
Measuring range	$0\ \mathrm{kg\,h^{-1}}$ to $450\ \mathrm{kg\,h^{-1}}$
Max. measurement error flow rate (liquid)	±0.10% mass flow ±0.10% volume flow
Max. measurement error density (liquid)	$\pm 0.0005\ \mathrm{g\,cm^{-3}}$
Dynamic range	1 : 1000
Zero point stability (DN 4 device)	$0.0100\ \mathrm{kg\,h^{-1}}$
Pressure range	Up to 430 bar
Medium temperature range	−50 °C to 205 °C
Signal outputs (configuration during the measurements)	Mass flow: pulse/frequency, 10 kHz Volume flow: pulse/frequency, 10 kHz Density: analog, 4 mA to 20 mA Temperature: analog, 4 mA to 20 mA

some manufacturers have implemented a pseudo Re number correction, usually for larger CFMs to meet the highest accuracy requirements. At low Re numbers, there are secondary flow effects associated with the measurement principle of the CFM itself [17], leading to underreading. However, these secondary effects disappear above a sufficiently high Re number and a correction (compensation) is no longer necessary. For this reason, we refer to this as a pseudo Re number correction, because unlike turbine meters, for example, there is no real Re number dependence. As mentioned, such a Re number correction is usually only applied to larger CFMs. For the correction, an on-line (real-time) determination of the Re number is required in the best case. For the determination of the Re number, the measurement of the volume flow or the mass flow and the density and the kinematic viscosity or the dynamic viscosity and the density is required. In most cases, a CFM measures mass flow and density by default. A determination of the viscosity required for the Re number calculation is possible and has been implemented by E+H [18]. The direct dynamic viscosity determination of Newtonian fluids is optional for the larger devices from E+H (Promass I from DN 8 and larger), this option is not available for the smaller devices (Promass A). What we have found in customer measurements with highly viscous fluids is that problems can also occur at high flow rates, i.e. where there is a very high pressure drop across the flow meter. This phenomenon can probably be explained by the fact that due to the low pressure on the outlet side compared to the inlet side, the density on the outlet side is also lower and thus underreading occurs. For the sake of completeness, it should be mentioned that smaller CFMs are also not as dependent on the line pressure as large CFMs [19], although this can be neglected in our case anyway, as the maximum inlet pressure was 6 bar for all measurements. All these effects and problems mentioned apply rather to larger CFM and, for example, if one looks at the linearity of the measurement results ('flat spec') in Section 4, could not be found for the smaller CFM we investigated. The manufacturer of the CFM, with whom we were in contact during the measurement campaign, also had no negative experience in this regard.

As can be seen in Table 2, the mass flow rate and volume flow rate were measured using the pulse/frequency outputs and density and temperature were logged via analog signals.

3.2.2. Test fluids

The Promass A 500 was measured with water (baseline measurement), Exxsol D40, Exxsol D120, HVO100 and RME100 in a flow rate range from $3\ \mathrm{L\,h^{-1}}$ to $400\ \mathrm{L\,h^{-1}}$ each in a temperature range from 15 °C to 30 °C (15 °C, 20 °C, 25 °C and 30 °C). Exxsol D40 is a substitute for petrol/gasoline and Exxsol D120 represents a slightly heavier diesel. In general, Exxsol D80 is considered as a substitute for diesel. Due to the higher viscosity, Exxsol D120 has been used for several years at the RISE National Laboratory for Volume and Flow to provide a wider viscosity range. RME100 (Rapeseed Methyl Ester) is a first-generation biodiesel. First-generation biofuels are produced from crops grown directly in the fields, such as cereals, maize, sugar beet, sugar cane and rapeseed. In Europe, rapeseed oil is mainly used for biodiesel. HVO100 (Hydrogenated Vegetable Oil) is a second-generation biodiesel, also called advanced biofuel. Second-generation biofuels are produced from residual and waste products from, for example, industry and households. Large quantities of used cooking oil and offal (slaughterhouse waste) are also used. The use of biodiesel has several advantages and can also help reduce CO_2 emissions. For example, RME100 minimises CO_2 emissions by up to 70% [20] and HVO100 by up to 90% [21] compared to conventional diesel. Another advantage of the renewable diesel HVO100 is that animal fats can be used that would otherwise end up unused. In addition, biodiesel is biodegradable, non-toxic and, in the case of HVO100, produces fewer PM emissions than conventional diesel. Finally, in contrast to the first generation, second-generation biodiesel does not require any modifications to the engine, as it is compatible with almost all diesel engines. Petrol/gasoline is regulated in the European standard EN 228 [22] and diesel in the European standard EN 590 [23]. For FAME (Fatty Acid Ethyl Ester), as the generic chemical term for biodiesel, and thus for RME100, the own European standard EN 14214 [24] applies. Since the paraffinic diesel HVO100 has a too low density to comply with EN 590, the European standard EN 15940 [25] was introduced in 2016. The density and viscosity values of the four test fuels were determined in a temperature range between 10 °C to 30 °C and entered into the database of the hydrocarbon calibration facility (OM2). The density [26,27] and viscosity [27,28] values determined at RISE Chemistry department can be found in Table 3.

Table 3
Density $U(k = 2) \leq 0.02\%$ and viscosity $U(k = 2) \leq 0.50\%$ values of the test fuels at different temperatures determined by RISE Chemistry (and Applied Mechanics) department.

Test liquid	Temp. °C	Viscosity cSt	Density $\mathrm{g\,mL^{-1}}$
Exxsol D40	10	1.79	0.7785
	20	1.54	0.7711
	30	1.29	0.7636
Exxsol D120	10	7.20	0.8300
	20	5.35	0.8231
	30	4.16	0.8161
RME100	10	9.15	0.8844
	20	6.90	0.8770
	30	5.39	0.8696
HVO100	10	7.05	0.7938
	20	5.31	0.7868
	30	4.15	0.7799

3.2.3. Water calibration facility – VM7

For the baseline measurements with water, one of the primary standard water flow calibration facilities (VM7) at RISE [13] was used (see Fig. 12).

VM7 consists of a high and a low pressure tank. The pressure is kept constant in both tanks. Flow is the generated by means of a pressure difference between both tanks. The desired flow rate is set using digital valves with different opening scenarios depending on the flow rate. All measurements were carried out in flying start-and-stop using a piston prover with two calibrated test volumes of 1.0 L and 5.0 L as reference. The expanded measurement uncertainty of the calibration facility is $U(k = 2) \leq 0.1\%$. A periodic internal calibration ensures the accuracy of the flow rates and volume. The uncertainty of the test facility is also regularly confirmed by comparison measurements with other National Metrology Institutes (NMI), i.e. bilateral and intercomparison measurements.

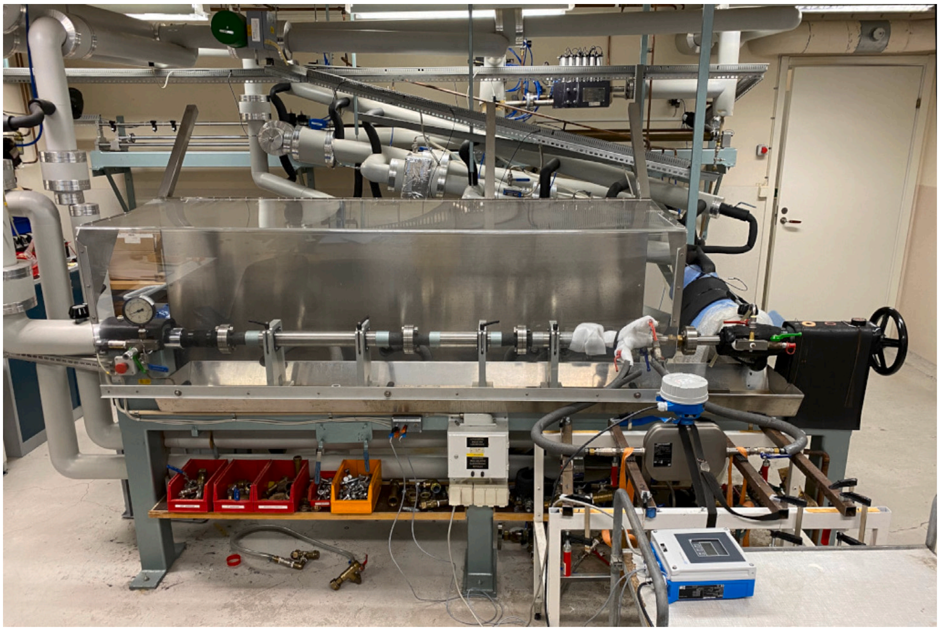

Fig. 12. Water calibration facility VM7 used for the measurements with water and temperatures between 15 °C and 30 °C. The photo also shows the E+H Proline Promass A 500 CFM as DUT.

Fig. 13. Overview of the TriFlow Low Flow Liquid Calibrator System TF030 (OM2).

3.2.4. Hydrocarbon calibration facility – OM2

The measurements with the different fuel types were carried out using a commercially available calibration facility (OM2), Fig. 13.

The TriFlow TF series primary liquid flow meter calibration system is a compact, hydraulically operated system, closed-loop system, based on the PD principle. The flow rate is generated by using a precisely honed, chrome-plated stainless steel cylinder, which is inserted into a liquid container and displaces a precisely known volume, which then serves as a reference for calibration. By means of a linear encoder, the movement of the displacement cylinder generates a continuous sequence of electrical pulses. It can be used to calibrate virtually any type of flow meter quickly and accurately. Double-time chronometry and quadrature-time methods according to ISO 7278-3 [29] are used to eliminate timing errors and improve overall accuracy. The displacement calibrator is practically insensitive to viscosity, density, and compressibility effects of the test liquid. The specifications of the calibration facility can be found in Table 4.

For stable temperature measurements with OM2, the system was equipped with an additional heat exchanger in the return line and a construction that can keep the area around the piston temperature stable. Furthermore, the measuring section was equipped with an additional temperature conditioning and enclosure.

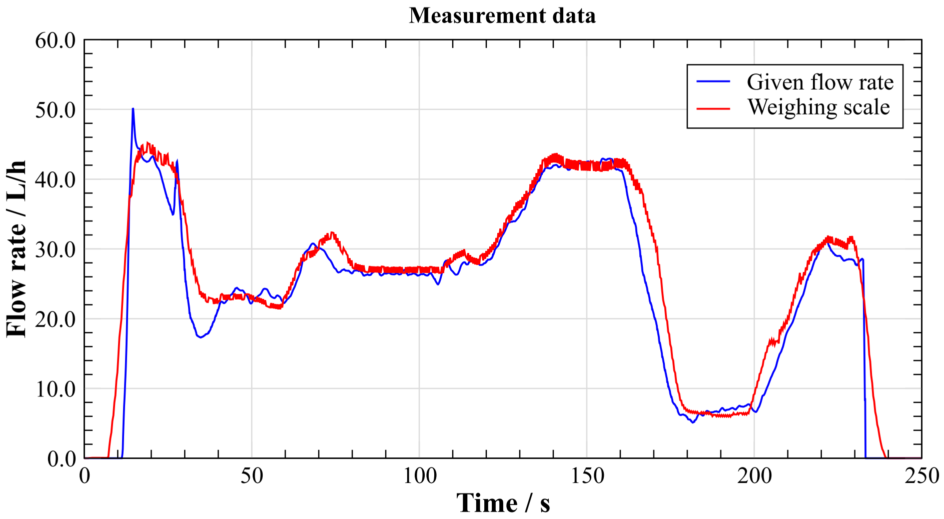

Fig. 14. Cavitation nozzle apparatus for vehicle profile realisation at PTB.

Table 4
Specifications of the TriFlow Low Flow Liquid Calibrator System TF030 (OM2).

Specification	Value
Standard flow rate ranges	$0.015\,\mathrm{L\,min^{-1}}$ to $30\,\mathrm{L\,min^{-1}}$ ($0.900\,\mathrm{L\,h^{-1}}$ to $1800\,\mathrm{L\,h^{-1}}$)
Minimum achievable flow rate	$0.0005\,\mathrm{L\,min^{-1}}$ $0.030\,\mathrm{L\,h^{-1}}$
Accuracy	±0.03% of reading
Repeatability	±0.02% of reading
Pressure range	Up to 12 bar
Temperature range	10 °C to 50 °C
Viscosity range	Up to 10 000 cSt
Signal inputs	Frequency: 10 kHz Analogue: 0(4) mA to 20 mA Analogue: 0 VDC to 5(10) VDC Visual

4. Results and discussion

4.1. Dynamic load changes

Initial results of the realisation of the Truck test profile no. 2 (Fig. 10) on the PTB test rig with water as test fluid are shown in Fig. 14. As can be seen, the results of the scale agree very well in terms of quality with the given flow rate.

Due to the damping in the current setup, the first and last slopes of the profile in the realisation are lower than in the specification. This can be improved in future implementations by changing the configuration in the cavitation nozzle apparatus. It should also be noted that the balance readings are averaged in the current evaluation method. This results in systematic changes to the profile realisation in the measurement section, which are worth noting. With this result it could be shown for the first time that ramps of different flow rate changes can be realised with cavitation nozzles. These are adapted to the given profile via second-by-second changes so that the realisation corresponds to the specification. For the future, parameters influencing the damping are to be varied and the effects on the profile generation are to be investigated. Furthermore, the profiles are to be assessed quantitatively with regard to newly developed evaluation criteria. This concerns i.e. the residuals and the standard deviation of repeated profile realisations.

4.2. Operation conditions and temperature

4.2.1. Measurement results with water

Before using the test fluids, measurements were carried out with water at eight flow rates, each with five repetitions. A suitable heating jacket for the CFM was available for the temperature measurements. In order to investigate the influence of the heating jacket, a measurement was also carried out at the beginning (at 20 °C) without heating jacket, which was compared with the measurement at 20 °C with heating jacket at the end of the measurement campaign. All other measurements were carried out with heating jacket. A zero point adjustment was carried out at 20 °C and not changed for the other temperatures.

As can be seen in Fig. 15, the CFM repeats and reproduces very good in the measurements with water. The maximum scatter within a flow rate value is 0.14% and the standard deviation is better than 0.05% for all flow rates. As can also be seen, the DUT shows the same measurement deviation at the higher flow rates regardless of the temperature. At the lower flow rates the influence of the zero point is noticeable. Here, the meter tends to go into the minus range for temperatures below 20 °C and into the plus range for temperatures above 20 °C. However, an influence of the heating jacket on the calibration curve of 20 °C could not be determined.

4.2.2. Measurement results with test fuels

The constructional changes to OM2 have ensured that the temperature can be kept stable over the entire temperature range. The temperature stability is ≤ ±0.3 °C for the five repeated measurements at one flow point and ≤ ±0.6 °C for all flow points at one temperature. As for the water measurements, the results obtained from the volume flow signal of the CFM are shown in the following.

Test fuel: Exxsol D40 (petrol/gasoline)

The measurements with Exxsol D40 show a similar characteristic as the measurements with water, Fig. 16. The performance of the CFM is also excellent. The maximum scatter at the two lowest flow rates is ≤0.34% and the standard deviation is ≤0.14%. At the higher flows the maximum scatter is ≤0.14% and the standard deviation is ≤0.06%.

Test fuel: Exxsol D120 (diesel)

As can be seen in Fig. 17, the CFM repeats and reproduces very good for the measurements with Exxsol D120. The maximum scatter at the two lowest flow rates is ≤0.31% and the standard deviation is ≤0.12%. At the higher flows the maximum scatter is ≤0.16% and the standard deviation is ≤0.07%. The temperature effect is exactly the other way round compared to the measurements with water.

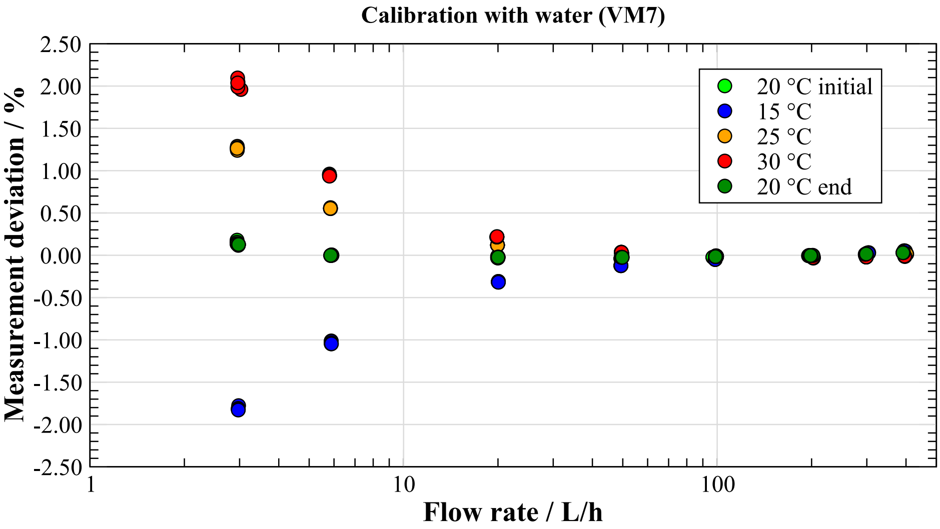

Fig. 15. Calibration measurements with water in a temperature range from 15 °C to 30 °C. (The *x*-axis is represented logarithmically.)

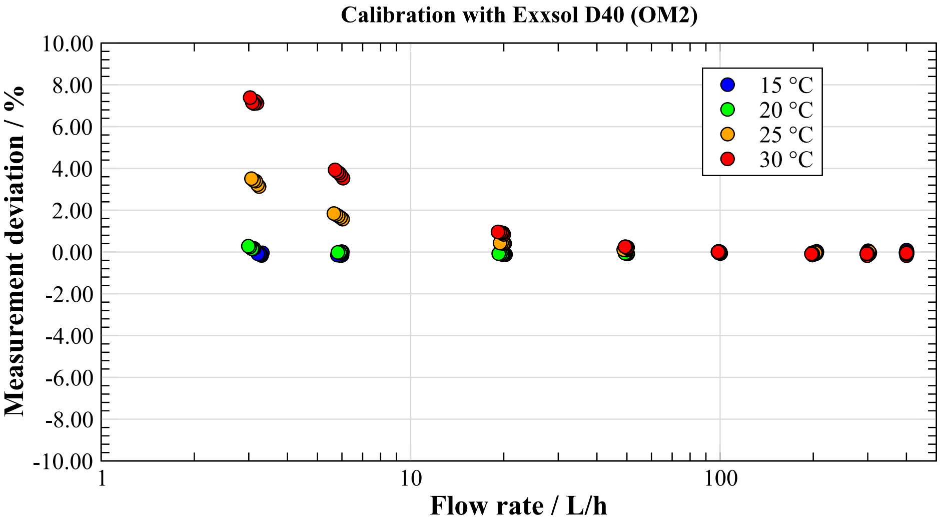

Fig. 16. Calibration measurements with Exxsol D40 in a temperature range from 15 °C to 30 °C. (The *x*-axis is represented logarithmically.)

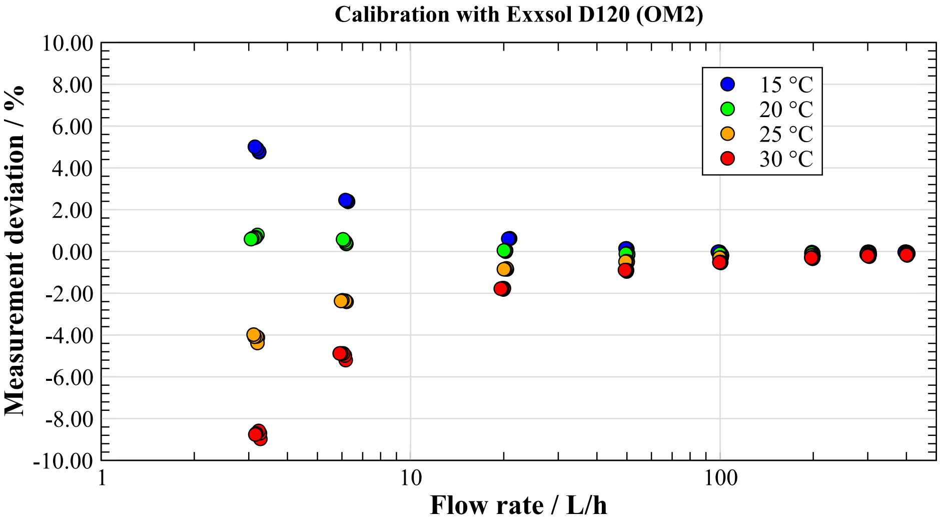

Fig. 17. Calibration measurements with Exxsol D120 in a temperature range from 15 °C to 30 °C. (The *x*-axis is represented logarithmically.)

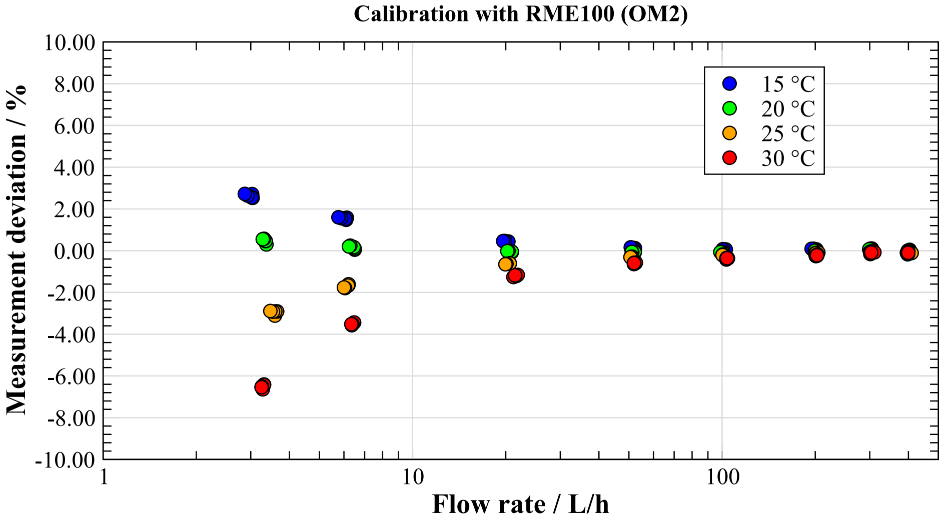

Fig. 18. Calibration measurements with RME100 in a temperature range from 15 °C to 30 °C. (The *x*-axis is represented logarithmically.)

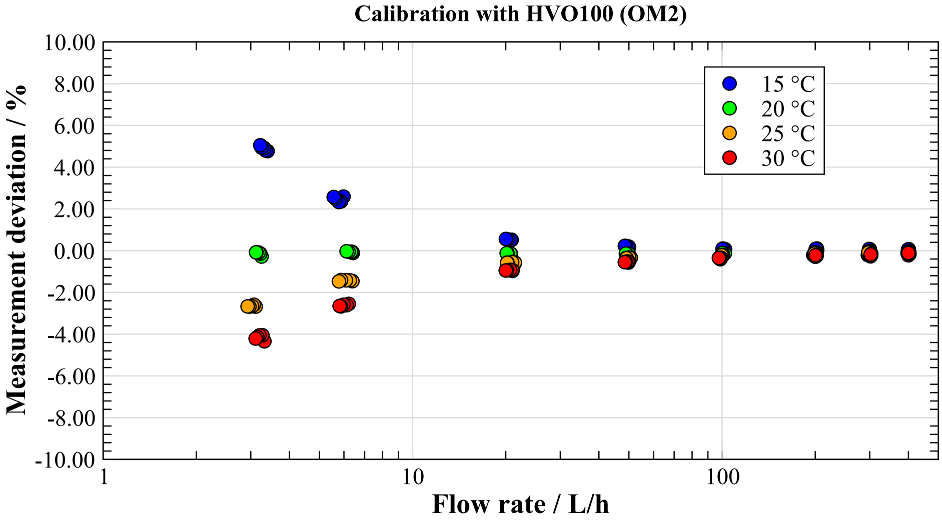

Fig. 19. Calibration measurements with HVO100 in a temperature range from 15 °C to 30 °C. (The *x*-axis is represented logarithmically.)

Test fuel: RME100 (first-generation biodiesel)

RME100 measurement results are similar to the measurements with Exxsol D120, Fig. 18. The maximum scatter at the two lowest flow rates is ≤0.24% and the standard deviation is ≤0.10%. At the higher flows the maximum scatter is ≤0.13% and the standard deviation is ≤0.05%.

Test fuel: HVO100 (second-generation biodiesel, synthetic fuel)

The measurements with HVO100 are similar to the measurements with RME100, Fig. 19. The maximum scatter at the two lowest flow rates is ≤0.27% and the standard deviation is ≤0.12%. At the higher flows the maximum scatter is ≤0.13% and the standard deviation is ≤0.06%.

In summary, it can be stated that the CFM performs very well for all fuels investigated over the entire flow and temperature range, which includes Re numbers from 30 to 30000. At higher flow rates, the measurement deviation is close to zero. The lower flow rates are, as expected, dependent on the zero point. The most important result here is not the measurement deviation, but the repeatability. But even at the lowest flow rates the CFM has very good repeatability, especially since no zero point adjustment was carried out at temperatures other than 20 °C. What is noticeable is that for fluids with low viscosities (water, Exxsol D40) the calibration curves go into the minus range for temperatures below 20 °C and into the plus range for temperatures above 20 °C. For test fluids with higher viscosities, it is the other way round. Whether this is a coincidence or not, however, cannot be conclusively said and more investigation would be required to clarify these observations.

5. Conclusions

Engine developers and test bench operators are demanding precise fuel consumption flow meters that provide highly accurate measurement results even during dynamic test cycles on chassis dynamometers or engine test benches. Not only the wide dynamic range and the dynamic flow changes in these tests are a challenge for any flow meter. In addition, the wide range of fuels with their different physical (viscosity, density) and chemical properties (composition, proportion of biofuels) must not affect the accuracy of the fuel flow meter or must be able to be taken into account accordingly in the measurement uncertainty evaluation. Finally, the same applies to the fuel temperature. The flow meters should also provide reliable values within a certain fuel temperature range.

As part of the ongoing European Metrology Programme for Innovation and Research (EMPIR) Joint Research Project (JRP) 20IND13 SAFEST, investigations on the measuring accuracy of fuel consumption meters are carried out. The focus here is on the determination of fuel consumption in real time during test cycles. A particular success of this study is the realisation and measurement of low flow rates that occur in the range of a few hundred millilitres per hour. With the newly created infrastructure at Physikalisch-Technische Bundesanstalt (PTB), it is possible for the first time to generate traceable real-world consumption profiles as they occur in driving cycles. Two sets of consumption profiles, one for light-duty vehicle (passenger car) and one for a heavy-duty vehicle (truck), are derived from real consumption measurements. Both data sets provide the basis for dynamic flow measurements. This will allow to compared test facilities with each other in the future. Furthermore, it enables flow meters to be tested on a test facility according to the subsequent dynamic operating conditions.

At Research Institutes of Sweden (RISE) a Coriolis Flow Meter (CFM) was investigated for use as fuel consumption meter with flow rates up to $400\,\mathrm{L\,h^{-1}}$. At the same time, the influence of different types of fuels (conventional, alternative and synthetic fuels) on the measurement accuracy of the CFM has been investigated. Here, for the first time, the measurement results in a temperature range from $15\,°\mathrm{C}$ to $30\,°\mathrm{C}$ are presented, which were obtained with four different fuel types that have a wide density and viscosity range. Altogether the CFM performed very well with all fuel types in the flow rate range investigated. The investigations carried out have confirmed that the CFM is suitable for measuring different fluids accurately. The ability to accurately measure a wide range of fuels with different physical properties means that the flow meter can be used even as fuels in the transport sector change. The results presented regarding the dynamic behaviour of the CFM suggest that this meter is suitable for measuring dynamic fuel consumption as it occurs on chassis dynamometers and engine test benches.

Nomenclature

The following **abbreviations** are used in this manuscript:

ASTM	American Society for Testing and Materials
CFM	Coriolis Flow Meter
DUT	Device Under Test
E+H	Endress+Hauser
ECU	Engine Control Unit
EEA	European Economic Area
EMPIR	European Metrology Programme for Innovation and Research
EN	European Standard
EU	European Union
FAME	Fatty Acid Methyl Ester
HVO	Hydrogenated Vegetable Oil
IB-HAWE	Ingenieurbüro (Engineering office) Hagemann
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
JRP	Joint Research Project
NEDC	New European Driving Cycle
NMI	National Metrology Institute
OBFCM	On-Board Fuel and energy Consumption Monitoring
OM2	Oljemätbänk (Oil flow facility) no. 2
PD	Positive Displacement
PEMS	Portable Emission Measuring System
PoliTO	Polytechnic University of Turin
PTB	Physikalisch-Technische Bundesanstalt
RDE	Real Drive Emissions
RISE	Research Institutes of Sweden
RME	Rape(seed) Methyl Ester
UniPG	University of Perugia
VM7	Vattenmätbänk (Water flow facility) no. 7
WHSC	World Harmonized Stationary Cycle
WHTC	World Harmonized Transient Cycle
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicle Test Procedure

Declaration of competing interest

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Data availability

Data will be made available on request

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