20IND13 Safest

D1: Report on the use of a new infrastructure for assessing the measurement performance of the flow meters and other systems, which are used in fuel consumption measurements of passenger cars, trucks and ships under dynamic flow changes

Lead partner: PTB

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1. Introduction

At operating conditions flow meters rarely experience constant flow rates as during laboratory calibrations but are typically exposed to variable and often irregular flow changes. The question is, what about the measurement accuracy of the devices under these conditions and how to prove it. Simpler tests include periodic or cyclic flow changes with varying repetition times. Information about the response behaviour is obtained by observing steps, i.e. abrupt flow changes such as an ideally instantaneous change from constant flow rate to zero flow or vice versa. Another option is to expose the flow meter to flows similar to those it will later experience in the field. This requires one or more application-specific test profiles. Characterization of flow meters based on test profiles is the subject of this guide.

The development of a metrological infrastructure to investigate the measurement performance of flow meters for dynamic flow changes consists of two key components:

- one or more test profiles that reflect flow variations occurring in the respective application, and
- a test bench capable to realize these profiles and to capture the measurement performance in a traceable manner.

This must be complemented by an appropriate validation strategy.

Test benches dedicated to evaluating the response of flow meters to dynamic flow changes need to meet additional requirements compared to test benches used for conventional flow meter characterizations including the need to ensure verification than an appropriate implementation of a test profile is realized. Likewise, the performance of a meter under test needs to be assessed in sufficient detail. This means that flow, reference, temperature, pressure data as well as data related to the ambient conditions need to be available at sampling intervals of typically a few 100 ms or less. What is exactly required depends on the flow rate changes being addressed.

It is important to note that there is no single technology for realizing dynamic flow changes, but suitable technologies depend on the actual flow rate changes to be realized. The quality with which dynamic flow profiles can be realized therefore vary and thus the measurement uncertainty. The assessment of the test bench performance should be carried out in a similar way to the characterization of the flow meter performance under dynamic flow changes described in deliverable D8 “Technical guide for the assessment of flow meter performance under dynamic load changes”.

2. Technologies

It is important to note that there is no single technology for realizing dynamic flow changes, but the suitable technologies depend on the actual flow rate changes to be realized. The quality with which dynamic flow profiles can be realized is therefore different and so is the measurement uncertainty. In the scope of the EMPIR projects Metrowamet (17IND13) and Safest (20IND13) different technologies to generate flow rate changes were investigated. In the first project the flow rate changes of interest were related to domestic water consumption. In the second project, flow profiles associated with fuel consumption of a passenger car (97 kW engine) related to the Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP), a truck (263 kW) and a ferry navigating in a harbour were considered. In the case of fuel consumption the demand of the engine control unit (ECU) is always taken into account. Figure 2.1 shows examples of different test profiles and their amplitude spectra. The profiles differ significantly in their dynamics and amplitude range. The fuel consumption profiles can be scaled according to engine size. The fuel consumption profiles are available for downloading at https://www.ptb.de/empir2021/safest/information-communication/downloads/.

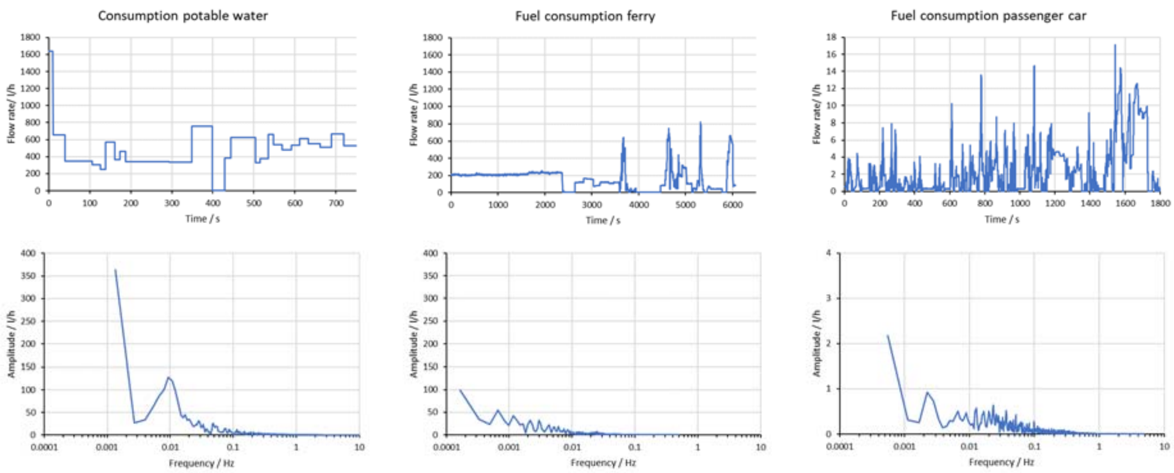

Fig. 2.1: Examples of test profiles for different applications; top: time series, bottom: amplitude spectrum. The profiles are linked to the consumption of potable water in households in Central Europe, to fuel consumption of a ferry navigating in a harbour and the fuel demand of the engine control unit of a passenger car on the basis of the Worldwide Harmonized Light-Duty Vehicles Test Procedure (partially different scaling of y-axes).

Investigations were carried out using water, white spirit, calibration oil and cold cleaner as fluids. A major difference between water and hydrocarbon liquids is the fact that water can be considered incompressible in a very good approximation, whereas hydrocarbons are compressible which can have consequences on the characteristics of the profiles realized.

Metrowamet

The following technologies were found to be particularly suitable [1]: fast closing electronic valves plus orifices, Herschel-Venturi cavitation nozzles. Pressure peaks could be reduced by using an expansion vessel.

Safest

For the realization of the ferry profile the generation of a needle valve controlled by a Coriolis flow meter worked well.

For the realization of the test profiles of the passenger cars and the trucks Herschel-Venturis and injectors in combination with valves were used.

The technical realizations developed in the Safest project for the car, truck and ferry profiles are explained in detail below.

2.1 Infrastructure to generate flow profiles associated with fuel consumption of passenger cars and trucks

The following explanations refer to the car profile shown in Fig. 2.1 on the right or sections from it resp. the truck profile available in the project's download area.

2.1.1 Realizations based on injectors

2.1.1.1 Realization at INRIM

The bench at INRIM was developed for the calibration of flow meters at static and dynamic operating conditions with liquids other than water. At present the liquid in use is the oil FUCHS VISCOR1487 AW-2, which complies with the ISO standard 4113 for calibration liquids.

The bench is based on the gravimetric method and the layout of the bench is schematically illustrated in Fig. 2.2.

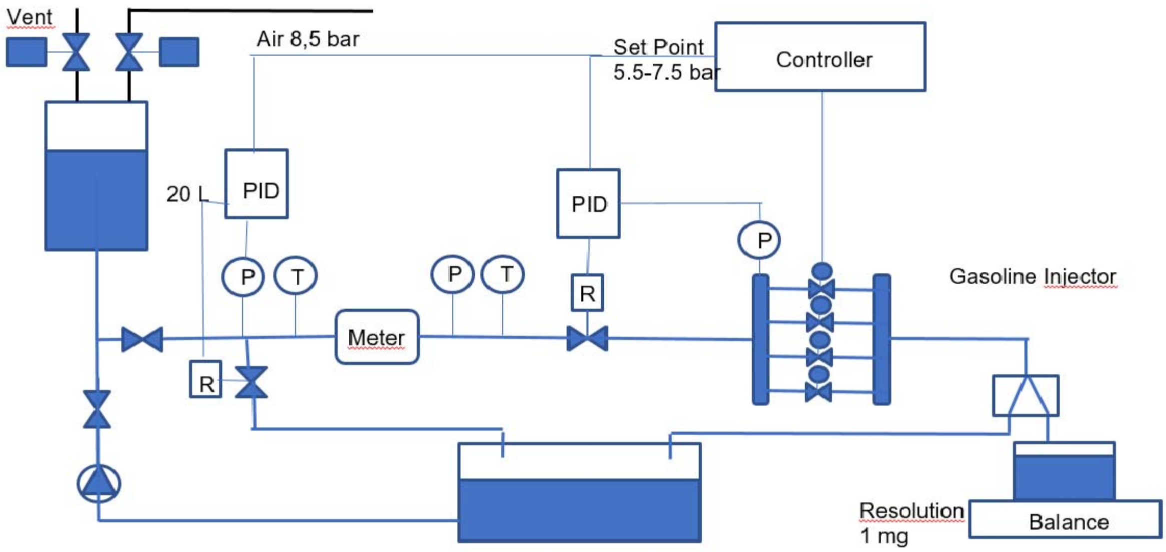

Fig. 2.2: The INRIM test bench for flow meter calibrations

Pressure is generated using a pressure vessel of 20 L, the pressure of which is kept constant. Additional control valves located upstream and downstream of the flow meter can be used to keep the oil pressure constant.

Downstream of the flow meter to be calibrated there are four gasoline injectors whose function is to generate the dynamic flow rate profiles. The bench can be operated in two different modes, "standing start and stop" and "flying start and stop". The method is defined by the use of the diverter. The balance has a capacity of 10 kg with a resolution of 1 mg. The bench is equipped with various thermometers and pressure transducers. Their position can be seen in Fig. 2.2. The bench is controlled by a National Instrument system and the control software was developed in a LabVIEW environment.

The injectors are controlled by an NI module 9401, which allows the frequency and duty cycle of the four injectors to be adjusted. With this configuration the flow rate can be adjusted as a function of the drop pressure and the opening time of the injectors. The injector opening time is not exactly the same as the supply time. Factors that influence the opening and closing time of the injector include the mechanical design of the injector (stem, spring, etc.), the electrical delay and the hydraulic delay. The latter depends on the injection process conditions such as injection pressure and back pressure.

The calibration of the injectors can be performed by the balance for different operating frequencies and duty cycle. An example of calibration is given in Fig. 2.3.

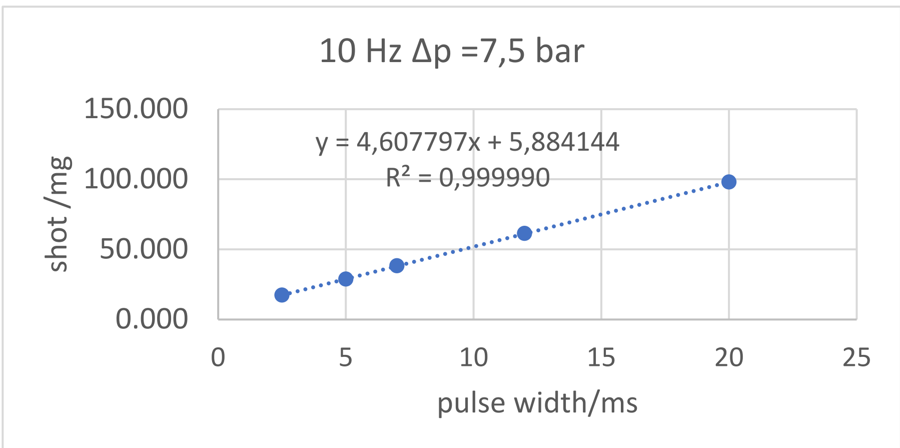

Figure 2.3. Calibration example.

With regard to the realisation of fuel consumption profiles e.g. for passenger cars, the approach is to control the injectors with a constant frequency of 20 Hz. Only for small flow rates below 0,4 kg/h the control frequency is 15 Hz. For the injectors used, the maximum flow rate for each injector is about 8 kg/h at an inlet pressure of about 4.5 bar. Depending on the section of the profile in Fig. 2.1 right, the generation can be performed using a single injector (e.g. test profile 1 for passenger cars, A.2) or two injectors are required. For test profile 2 (A.2) for passenger cars, only one injector is used up to 7 kg/h, and two for higher flow rates. The calibration of the two injectors used for flow rates above 7 kg/h is carried out by controlling both injectors simultaneously.

After determining the calibration curves for the single injector and the pair of injectors, it is possible to calculate the duty cycle of each injector for each flow rate to generate the profile, provided that the operating conditions of pressure and temperature are the same as the calibration conditions. The software based on the data of the profile flow rate and the calibration curves generates two tables with the values of the frequencies and duty cycles for each injector. These data have a timing of 100 ms, the same as the profile. If the initial flow rate is not zero, the injectors are controlled to generate the initial flow rate. At the start of the test the diverter is switched to the balance, then the required frequency and duty cycle values are sent to the injector control system with a timing of 100 ms. At the end of the test, the injectors are switched off and the diverter is switched to the storage tank.

2.1.1.2 Realization at UNIPG

At the SprayLAB of the University of Perugia a Dynamic Hydraulic Test Bench (DHTB) has been developed to test and calibrate both, injection systems and instrumentation such as sensors and flow meters. Both, static and dynamic flow operating conditions can be implemented. The main features of the bench are:

- Complete injection systems can be installed, consisting of low- and high-pressure pump, rail, connecting pipes and injectors;
- Diesel, GDI and PFI injection systems can be analysed (max. pump power 10 kW);
- The installed injection system can be operated in steady-state conditions or following a prescribed time-dependent profile for speed/pressure/injection strategy;
- In Diesel configuration, both injected fuel flow rate and the back leak flow rate can be measured by 2 Coriolis mass flow meters (Siemens MASS2100 DI1.5);
- Other quantities can also be acquired, e.g. pump torque, rail/pipe pressure, injector current. As a special measurement add-on, the injection rate produced by one of the injectors in the system can be analysed using a proprietary injection analyzer based on the Zeuch Method;
- The test bench control software has been developed in LabVIEW at UniPG and can be customized to specific requirements.

Bench description

The DHTB was used as a dynamic flow generator to calibrate a Coriolis mass flow meter, analysing the actual capability of the meter to dynamically and accurately follow the time-varying flow rate. The flow profile generated by the bench was one of the profiles shown in A.2. A standard test fluid (FUCHS VISCOR1487 AW-2) compliant with the widely adopted ISO-4113 rule was used in the tests.

In Fig. 2.4 a schematic of the bench arrangement used for the testing is shown. The hydraulic circuit is fed by an electric low-pressure pump (nominal features: 300 l/h at 6 bar). The fluid pressure in the circuit is regulated by a precision mechanical regulator, which returns part of the pressurized flow to the tank. The pressurized test fluid is fed to a common rail where both fluid temperature and pressure are monitored (by a K-type thermocouple and a Honeywell PX3 10bar, 1% f.s. accuracy, respectively). The common rail feeds up to four PFI injectors (Continental Type72351 in this application). Depending on the required flow rate a different number of the installed injectors can be activated.

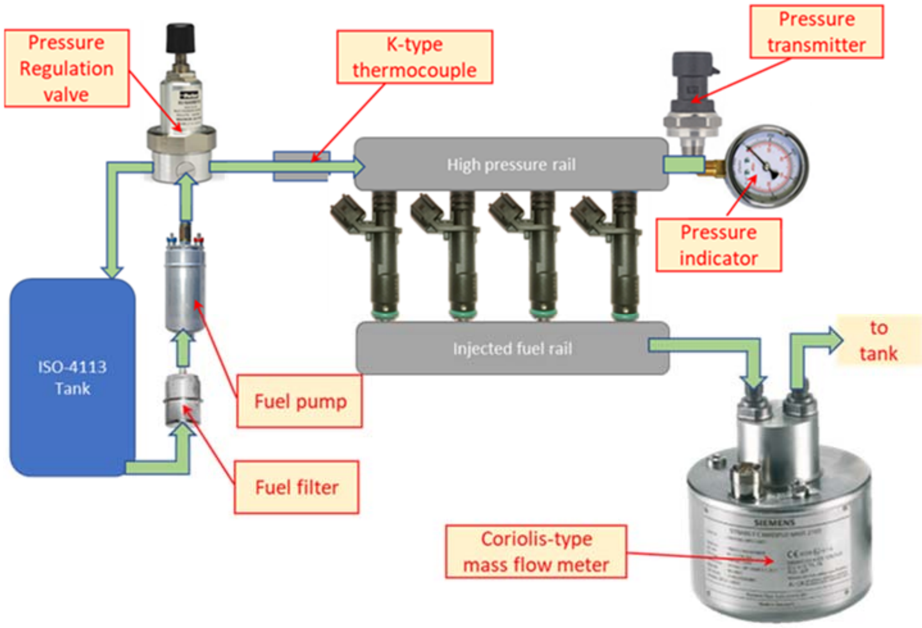

Fig. 2.4: Schematic of the Dynamic Hydraulic Test Bench used.

The injected fluid is collected by a second common rail from which the fluid is collected to the mass flow meter under test/calibration, currently a Siemens MassFlow2100 DI 1.5. In Fig. 2.5, a photo of the implemented system can be seen.

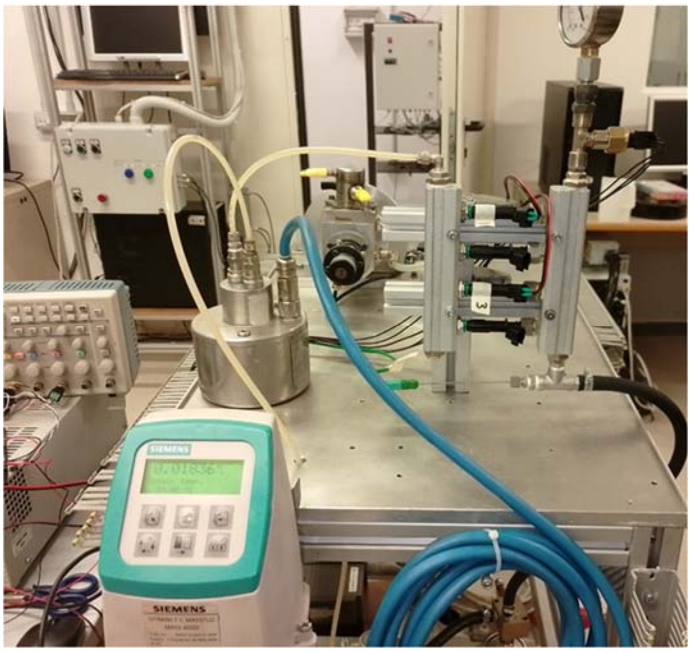

Fig. 2.5: The Dynamic Hydraulic Test Bench.

Two particular features of the bench are worth mentioning:

– A vertical arrangement of the downstream common rail has been chosen, by this to facilitate the evacuation of any eventual air or vapor bubbles that may form in the circuit, thus improving the stability of the Coriolis mass flow meter signal.

– In order to limit the delay in the flow meter signal with respect to any change of the injection strategy (frequency and/or activation time), a relatively small volume of the circuit has been implemented downstream of the injectors. To this end, the internal volume of the downstream rail was reduced to about 7 cm^3 and to connect it with the flow meter inlet a 250 mm long, 4 mm internal diameter pipe was used (about 3.14 cm^3).

The bench control system is based on proprietary software developed in a LabVIEW environment and National instrument multi-function boards. The control system consists of:

– a PCI-6602, 8-counter board used to generate TTL logic commands for driving up to 4 injectors, freely controlling frequency, duration and relative phase of the pulses. In order to produce a relatively smooth flow rate through the flow meter, the injector pulses are spaced evenly in time. The injection pulses are used to control the injector power drivers, which are based on TIP121 Darlington.

- a PCI-6221 multi-function acquires analog and digital signals from the field (flow rate, density, rail pressure, fuel temperature). In particular, the mass flow rate analog signal is acquired during the test (0-20 mA) with the cut-off set to zero. By default, the zeroing procedure was actuated just prior to each test start, with an instrument warm-up of 1 hour.

The system is operated with 1 or 2 injectors in the present project depending on the target maximum flow rate in the test; the target rail pressure level is set to 4 barg.

Bench Control Strategy

Different control strategies can be implemented to produce a prescribed flow time-profile:

a) Injection frequency is constant; Energizing Time (ET) is varied to produce the requested flow;

b) Energizing Time (ET) is constant; the injection frequency is varied to produce the requested flow;

c) Both, energizing Time (ET) and actuation frequency are varied to produce the requested flow time-history.

Strategy c) can be conveniently implemented when data is available from an real engine, in terms of rpm (actuation frequency), injector current time (ET) and injection pressure (Pinj). Normally, this approach leads to good results in terms of flow rate control capability as in the engine management system follows the most appropriate operating condition in terms of ET and Pinj to keep the injectors in their linear operating range.

When a complete engine dataset is not available, eighter strategy a) or b) must be implemented. In the following, the a) strategy is assumed. The following steps are therefore taken to define the bench control procedure:

1. The injectors are individually characterized so to determine the mean injected quantity per actuation as a function of the actuation signal duration (ET). Typically, two operation zones can be identified in the resulting EMI curve. For very short ET durations, the ballistic mode is obtained, where a non-linear correlation between the duration of actuation command duration and the mean injected quantity is obtained due to a partial rise of the injector needle. For longer command durations, the needle reaches its fully open position and a linear function of the mean injected quantity is obtained from the ET duration.
2. From the target flow rate curve, the number of injectors to be used and the injection frequency are set, thus calculating the mass to be injected per operating cycle and per injector.
3. By interpolating the EMI curve, the sequence of ET values is determined.
4. The injectors characterization – step 1 - is crucial. Significant differences are usually obtained by changing the actuation frequency. As an example, in Fig. 2.6 (left) the results obtained for a single injector operated at 10 Hz and 50 Hz are shown. As can be seen, the different thermal loads applied to the injector solenoid when actuated at different frequencies change the coil resistance, resulting in a significantly lower mean mass flow rate at higher actuation frequency.

Fig. 2.6 (right) shows the characterization of two injectors, demonstrating the importance of performing the hydraulic analysis for each single injector in order to account for the individual dispersion. Consequently, tests have been carried out with a minimum number of injectors, operated with a relatively long actuation ET to minimize the effects of ballistic operation. Where appropriate, a constant frequency strategy should be used to actuate the injector to control the bench flow rate. The reference EMI curve should be acquired at the same frequency.

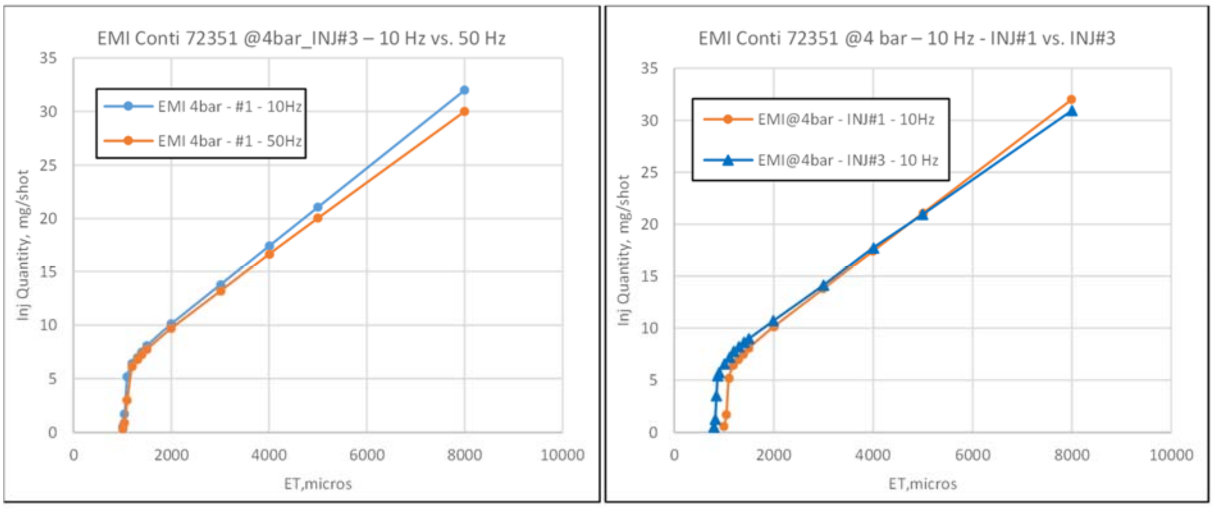

Fig. 2.6: Injector characterization - EMI curves

Results and comments

In Fig. 2.7 some obtained results relevant to a complete WLTP test cycle are summarized. In this specific case, the availability of both the injection frequency and the ET schedule allows a significant agreement with the target flow rate history (measured at the engine). In total, a delay of about 1.2 s was observed for the bench flow time history with respect to the trend measured on the engine. As can be seen from the zoom of Fig. 2.7 shown in Fig. 2.8, there is considerable room for improvement:

1) inaccuracy in idle conditions;
2) delay in replicating zero-flow conditions;
3) inability to follow peak flow rate values.

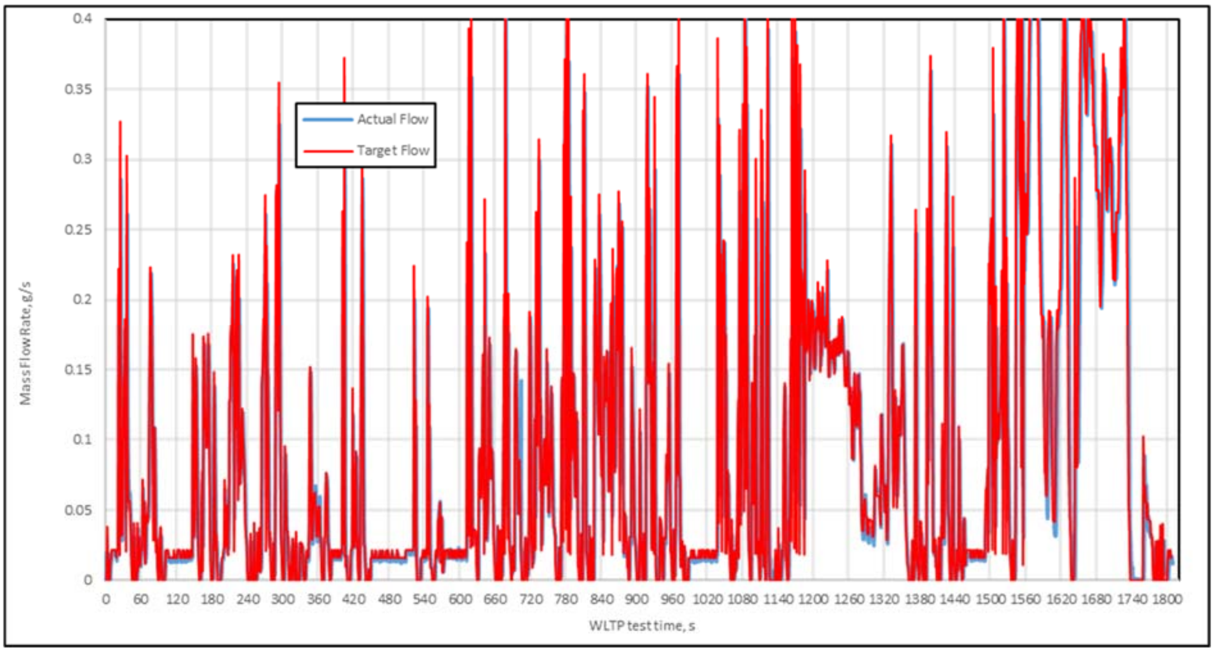

Fig.2.7: Actual vs. target flow time profiles, obtained with c) strategy.

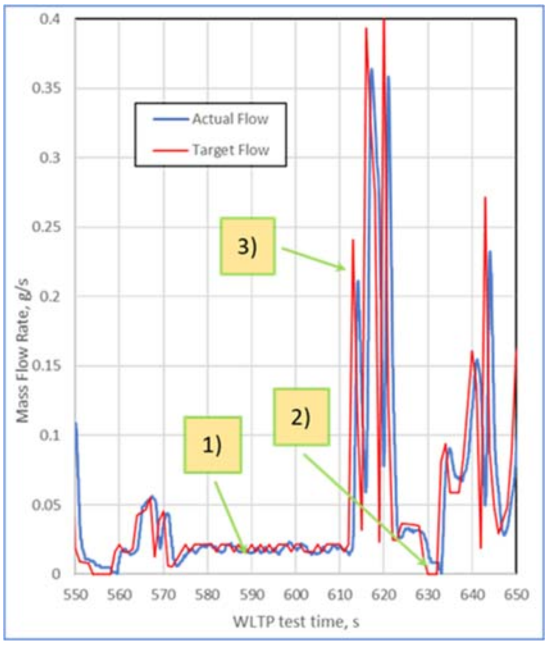

Fig. 2.8: Actual vs. target flow profile obtained with a) strategy; Zoom of Fig. 2.7

2) and 3) issues can probably be attenuated further reducing the downstream rail volume, i.e. reducing the hydraulic inertia of the system.

Fig. 2.9 illustrates the capability of the UniPG DHTB to reproduce the passenger car profile 1 (A2). In this case, the strategy a) was used with an injection frequency of 25 Hz. Despite the overall appreciable capability to reproduce the target profile, some inaccuracies were observed:

1) at low flow conditions;

2) difficulty in obtaining the peak flow rate values.

In this case, as in the previous one, a reduction in the mass and inertia of the fluid system between the injector and the Coriolis flow meter should be beneficial to improve the accuracy in reproducing the target flow rate history.

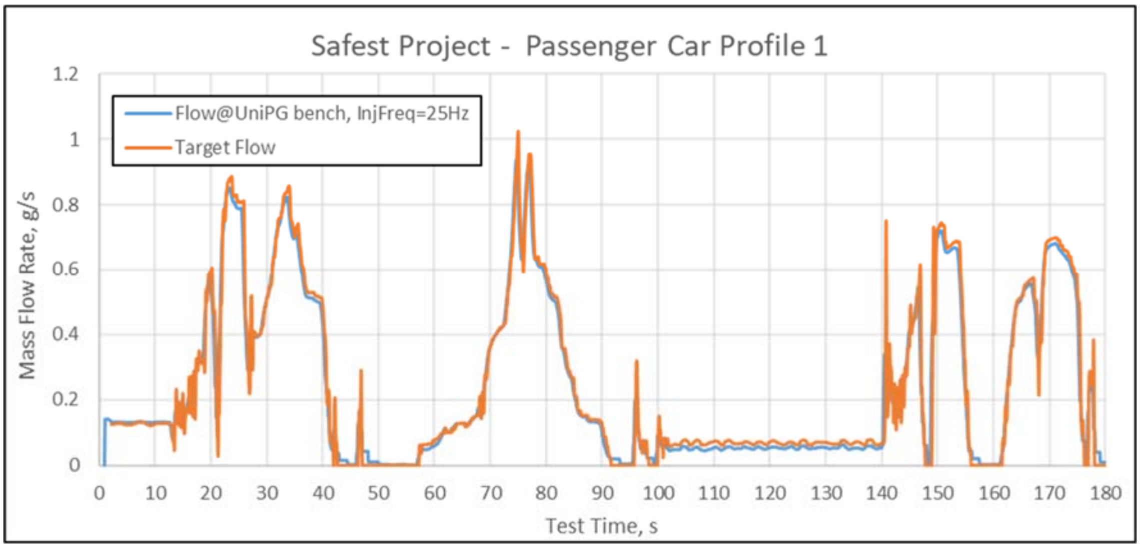

Fig. 2.9: Realization of the Passenger Car Profile 1 with the UniPG test bench

Further Steps

The following actions will be implemented to improve the dynamic hydraulic test bench capability to reproduce a prescribed flow rate time profile, thus consolidating its use as a calibration tool for mass flow meters under dynamic conditions:

- Improvements in the injector calibration at low to moderate flow rates;
- Implementation of a new control strategy, based on constant injection frequency for high to intermediate flow rates. Below a given flow rate, a reduction of the actuation frequency will then be applied to limit of the injectors in ballistic conditions operation;
- Reduction of the liquid volume downstream the injectors to the Coriolis meter inlet;
- Implementation of a gravimetric reference downstream of the Coriolis flow meter for the dynamic tests, in order to control the overall mass flowing in the measuring system.

2.1.2. Realization based on Herschel-Venturi cavitation nozzles and valves

At PTB a nozzle apparatus was developed (Fig. 2.10) into which up to 12 Herschel-Venturi cavitation nozzles can be installed. The apparatus can be integrated into a conventional test bench using hoses (in this instance DN25) for connections. The nozzles are opened and closed by valves. Different types of valves such as ball valve, flap armature valve and slide valve were tested. However, no significant advantage was found when a certain valve type was used. A study of the effect of the distance between valve and the nozzle on the quality of the flow change realization showed that the closer the valve and the nozzle are together, the better the desired flow rate is generated.

Depending on the pressure and internal diameter of the Herschel-Venturi nozzles, different flows can be generated. By combining nozzles, additional flow rates are possible. Since the pressure changes slightly in this case, the sum of the individual flow rates is not completely identical to the actual flow generated. Therefore, the nozzles should be individually characterized for different upstream pressures and to some extent as combinations. Calibrations can differ significantly for different liquids, so it may be necessary to repeat the characterization.

The more nozzles are used, the more flow rates can be generated. However, there is always a finite number of flow rates that can be generated. It is therefore important to select nozzles with internal diameters that are as close as possible to the flow rates specified in a test profile. It has proved advantageous to find a compromise between the number of switching operations and the actual flow realizations of the given profile as the opening and closing of nozzles can induce pressure peaks. For the realization of the passenger car profile six nozzles were used and seven nozzles for the realization of the truck profile. A list of the nozzle sizes used are given in Annex A.3

Fig. 2.10: Cavitation nozzle apparatus integrated in a conventional test bench with weighing system as reference.

In general, Cavitation nozzles offer the possibility of generating flow changes and stable flows quickly and with a high degree of reproducibility. Cavitation nozzles utilise the fact that cavitation is generated in a pipe flow by reducing the pressure by reducing the cross-section, so that the state of the fluid in this area changes from liquid to gaseous. The result is a very stable focussed liquid flow surrounded by a layer of gas. Cavitation based flows have been successfully used when realizing profiles related to the consumption of drinking water. However, when attempting to realize the fuel consumption profiles related to passenger cars and trucks, it became apparent that the flow rate changes happened too quickly for cavitation to form. A mixture of cavitation-based flows, non-cavitation related flows and flows with delayed onsetting cavitation occurred irrespective of the upstream pressure level (up to 5 bar). As a result, all nozzles are operated at fluid pressure levels where cavitation does not occur.

For quality assessment and troubleshooting, the pressure and temperature upstream and downstream of the meter under test and the device for flow change generation should be monitored in a high temporal resolution. The temperature sensors are Pt100 sensors of accuracy class 1/10 B and the pressure sensors have a measuring range of 0 bar to 10 bar and an expanded measurement uncertainty of 0.5 %. The sampling rate depends on the actual flow rate changes to be generated. A sampling rate of at least 20 Hz was found beneficial. As the generated flow rate is pressure-dependent, liquid pressure is kept stable to ± 0.01 bar. Depending on the load either a weighing system with 100 kg max. load and a resolution of 1 g or a weighing system with 30 kg max. load and a resolution of 0.01 g is used.

It is essential that the test bench, including the nozzle apparatus, is sufficiently vented before measurements are taken. This may take several hours. The nozzle apparatus needs to be set up in such a way that an appropriate venting is possible. Even if a filter is installed in the pipework to remove particles, it can happen that nozzles with small diameters become clogged. Flushing before measurements is helpful. Furthermore, it is helpful to install the nozzles in such a way that they can be easily removed and cleaned. An easy way for a quick check if a profile was realized appropriately is to compare the nominal total mass/volume with the amount measured by the reference. Larger deviations indicate trouble.

2.2 Infrastructure to generate flow profiles associated with fuel consumption of ships

To realise the fuel consumption profile of a ferry (Fig. 2.1 middle), a combination of needle valve DN04 and Coriolis flow meter DN08 as a control element is used [2]. Both are integrated into a conventional test bench in a DN25 pipe section (Fig. 2.11) with a weighing system as reference. The needle valve is operated by a stepper motor. The weighing signal is recorded with a sampling interval of up to 0.2 s. The valve performance and control as well as the performance of the Coriolis flow meter (max. mass flow of 2 t/h) and the weighing system were evaluated by step responses. The pulse output of the Coriolis flow meter is used in all cases. Any cut-off or data filtering is switched off and auto-zero is set.

Coriolis flow meters are not well suited to measuring flow rates in their lower measuring range. Typically, they measure too much mass or volume flow in this range compared to the actual flow. This problem has been addressed in the profile realization by implementing a software solution. If the flow rates of the given profile are below 15 l/h, the valve is completely closed, regardless of the Coriolis flow meter reading.

Tests have shown that it is extremely important to match the size of the control element and needle valve to the main flow range of the profile. Devices of size DN25 gave significantly inferior results. The distance between the unit generating the flow changes and the reference has no detectable impact in terms of changes in delay times (see section 3) in case of a fully filled pipe. Changes in ambient temperature and fluid temperature gave comparable results.

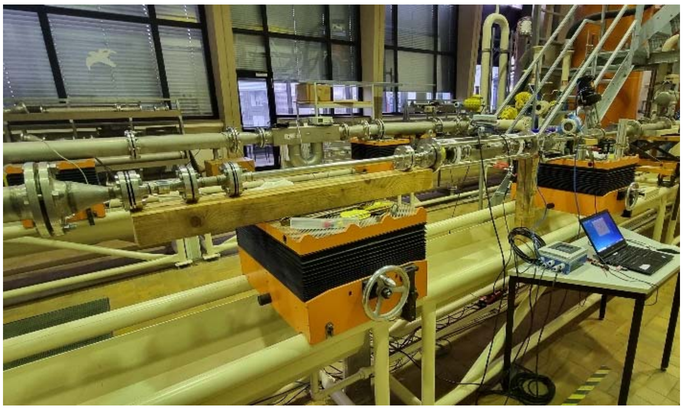

Fig. 2.11: Installation of Coriolis flow meter and needle valve in measuring section.

3. General things to be aware of

There are a few general things that should be considered. For an evaluation of the performance either of test bench or meter under test several data sets should be acquired: the time series of the model, measured by the reference and the meter under test[1], and the total mass or volume measured by the reference or the flow meter. It is not unusual for temporal offsets to occur here despite all efforts. Depending on the implementation and the integration of the system into the conventional infrastructure, a subsequent synchronization might be necessary. Synchronization of the data sets is possible on the basis of a marked change in flow rate or based on a cross-correlation between the data sets.

It must be distinguished between two main types of delay times. One type is when a device responds to a change at all, i.e. the individual instrumental response. Delay times of the control are also included here. The second is related to delay times associated with the actual implementation of the signal.

Each measuring device has its individual instrumental transfer function, which is why the response to different types of flow changes differs. A reference, such as a weighing system, will always have a general delay time because the flow change must first arrive at the location of the weighing vessel. Since this is a systematic effect, it can be estimated either by a synchronization or by a simple step response experiment.

[1] There might be limitations due the types of available outputs.

Even if the data sets are synchronized, delays due to the different instrumental responses will remain. The response times are typically different for decreasing flow rate changes and increasing flow rate changes as shown in the example in Fig. 3.1. Larger deviations between the measurement series (residuals) and the test profile or data from the weighing system usually occur with fast large flow changes.

It often makes a difference whether the meter under test is installed upstream of the control element or between control element and reference. The second solution is preferable.

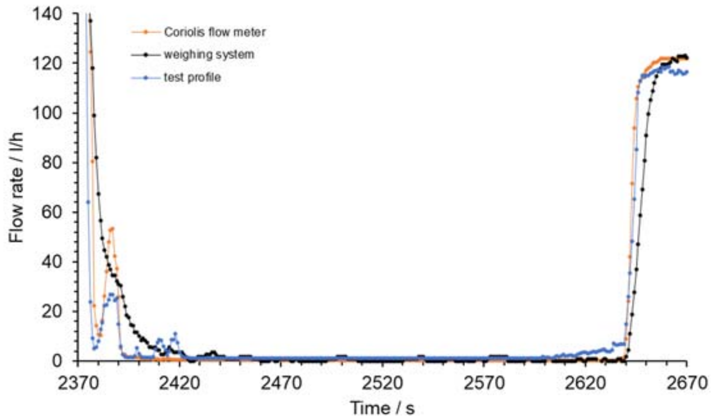

Fig. 3.1: Example of delayed responses of Coriolis flow meter and weighing system with respect to a given decreasing and increasing flow rate change.The data sets were synchronized beforehand.

Consideration of the response to a change from constant flow to zero flow is also relevant in determining how much additional time should be provided to ensure that the weighing system captures the complete mass flow that has passed through the meter under test. From step response experiments it can also be determined how well a reference or flow meter will detect low flows or zero flows.

At higher flow rates (with respect to the measuring range of the flow meter) it can happen that the number of pulses becomes rather large which can cause problems with the data acquisition system, which may not be fast enough. The result can be peaks and data with a frayed appearance. Either the pulse rate of the flow meter needs to be adjusted or the artificial signals need to be removed in the data processing.

The noise in the time-resolved data from the weighing system can be reduced if the weighing vessel is already partially filled with liquid. The actual benefit of this depends on the mass flows involved and the size of the weighing vessel.

When the consumption of liquid is of interest, the total volume or volume flow is the relevant measurand. This means that information on the density of the medium, and thus the fluid temperature, is needed to be able to convert between volume and mass. Attention must be paid if a given test profile is realized as mass flow or volume flow and which of the two is the control variable.

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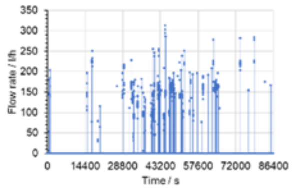
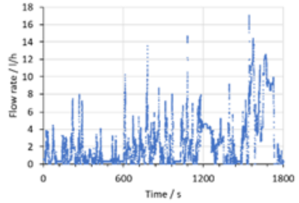
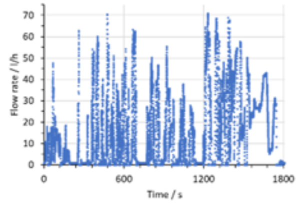
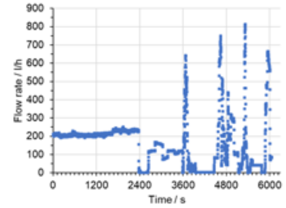
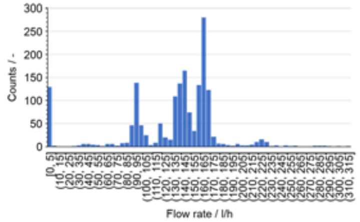
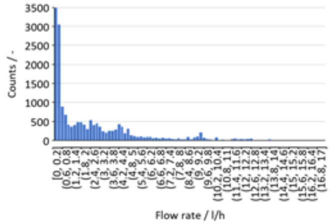
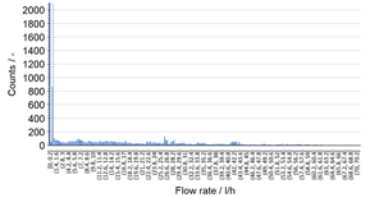
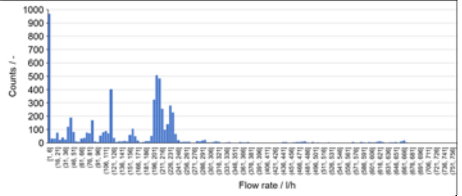
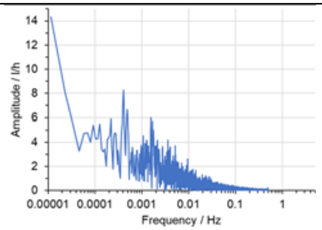
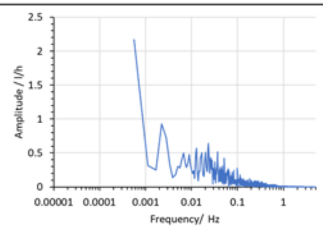
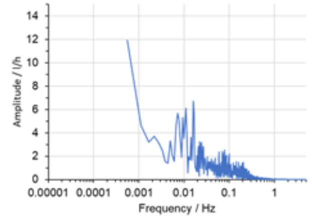
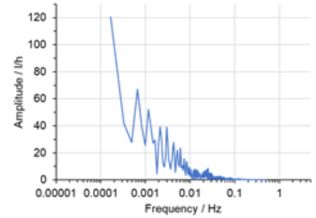
Annex

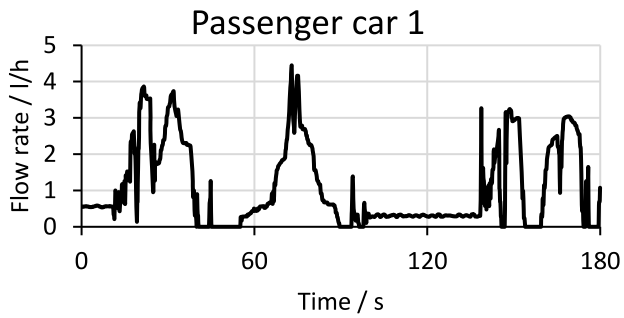
A.1 Characteristics of consumption profiles

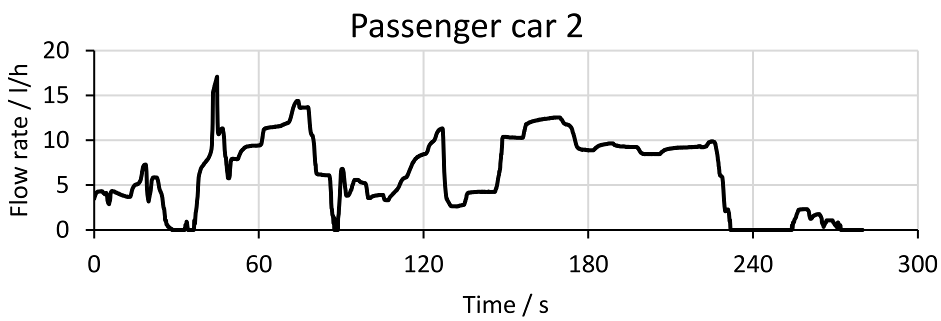
	Consumption of potable water in households	Fuel consumption passenger car	Fuel consumption truck	Fuel consumption ferry
Description	Example of potable water consumption during a day in a Central European household[2]	Example of the fuel demand of the ECU for a 97 kW engine	Example of the fuel demand of the ECU for a 263 kW engine	Example for fuel consumption of a ferry navigating in a harbour
Profile				
Histogram of flow rates				
Amplitude spectrum of flow rates				
Minimum flows[3]	7.7 % < 10 l/h	47.6 % < 1 l/h	39.8 % < 1 l/h	16.6 % < 10 l/h
Zero flows[3]	122 sections with lengths between 3 s and ~ 4 h	73 sections with lengths between 0.4 s and 10 s	63 sections with lengths between 2.4 s and 13.7 s	none
Maximum flow rate[3]	313.5 l/h	16.8 l/h	70.3 l/h	802.2 l/h
Maximum increasing flow rate changes[3]	170 l/h in 3 s 282 l/h in 1 s	14.5 l/h in 17.7 s 17 l/h in 10.3 s	66.3 l/h in 3.4 s 62.4 l/h in 4 s	659.6 l/h in 93 s 739.7 l/h in 31 s
Minimum decreasing flow rate changes[3]	222 l/h in 5 s	13.7 l/h in 7.9 s	70.3 l/h in 1.1 s	800.7 l/h in 100 s
Dominating flow rate range	80 l/h – 180 l/h in the example on a more general basis: 400 l/h – 800 l/h 0.00004 Hz ≤ frequencies ≤ 0.01 Hz	< 5 l/h 0.002 Hz ≤ frequencies ≤ 0.1 Hz	< 1.5 l/h, larger flow rates similarly often 0.004 Hz ≤ frequencies ≤ 0.4 Hz	clusters of flow rate ranges below 250 l/h 0.0005 Hz ≤ frequencies ≤ 0.03 Hz

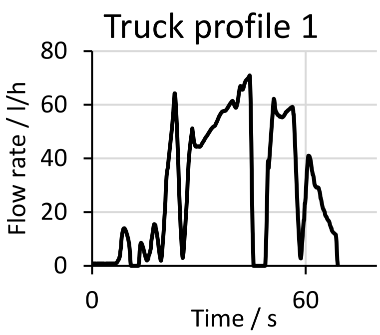
[2] The profile in Fig. 2.1 is a generalization of water consumption in households.

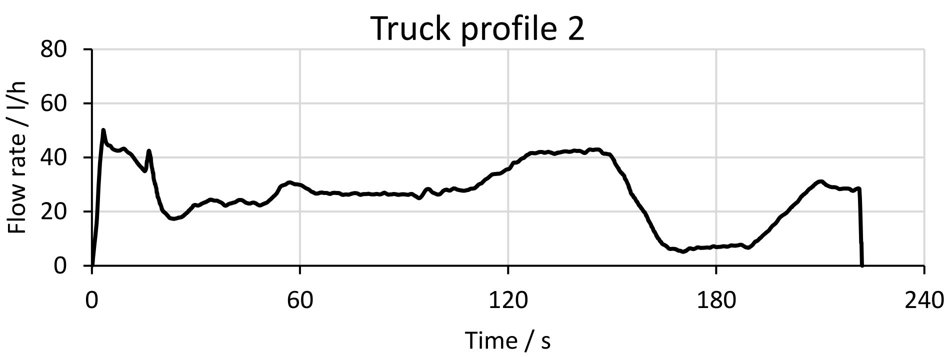
[3] Order of magnitude

A.2 Fuel consumption test profiles









Profile data available for downloading at: https://www.ptb.de/empir2021/safest/information-communication/downloads/

A.3 List of Herschel-Venturi nozzle sizes used for the generation of the test profiles

Passenger car profiles

No.	Nozzle throat diameter / mm
1	0.08
2	0.1411
3	0.2165
4	0.2691
5	0.3382
6	0.4179

Truck profiles

No.	Nozzle throat diameter / mm
1	0.08
2	0.1411
3	0.2153
4	0.2691
5	0.3404
6	0.5382
7	0.6913