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A test bench for the assessment of flow meters accuracy for fuel consumption measurement in highly dynamic drive cycle tests

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Abstract. The transport sector is one of the most significant contributors in terms of NO_x, particulate matter and net CO₂ emission. In order to mitigate this environmental impact, severe homologation limits have been introduced by the different regional Authorities. Both pollutant emissions and CO₂ production of vehicles are measured during standardized laboratory test cycles and road tests, both characterized by relatively abrupt powertrain load and fuel rate transients. This dynamic approach results in severe issues in terms of fuel flow measurement capabilities as flow meters are typically calibrated in steady fuel flow conditions. In the present activity, an experimental test bench was developed with the aim of offering a flexible and affordable test system to evaluate the performances of different flow meters in dynamic conditions. The test bench consists of a complete fuel injection system managed to reproduce an assigned cycle; by this approach the highly-dynamic engine-like fuel flow rate is replicated, offering the opportunity to compare the accuracy of the flow meter under test with both a master Coriolis-type flow meter and the nominal fuel flow time-profile. This bench allows the execution of flow meter accuracy tests in controlled operating conditions with reduced efforts with respect to conventional vehicle test benches and with a high reproducibility level.

1. Introduction

The environmental impact in terms of pollutants and CO₂ emission is the major concern of thermal powertrain-based vehicles used in the transport sector. As a matter of fact, with the current composition of the vehicles fleet in Europe, the on-road and off-road transport sector is the largest contributor to NO_x emissions (39% in 2018) and one of the most significant in terms of PM 2.5, CO and HC [1]. In parallel, significant efforts are being made to reduce the CO₂ impact of the transport sector, that can be evaluated to be around 14.5% of the total emission in Europe [2], with the final goal of zero-equivalent carbon emissions set by the European Commission by 2035 [3]. In this complex scenario, two different paths are being developed by the Legislator, acting on different time-scales.

In the short-medium term, the automotive industry is sustaining significant efforts to reduce its environmental impact in order to comply with the upcoming Euro 7 standard [4] by July 2025 in terms of pollutant emissions, implementing increasingly sophisticated after treatment systems (e.g. SCR-on-filter, gasoline particulate filter, burner and electric heaters to speed-up the aftertreatment system warm-up), on-board emission measurement capability and innovative engine management technologies. In the same time, the CO₂ emissions reduction request is supported by pushing the on-going implementation of the Corporate Average Fuel Economy limits in terms of CO₂/km [3] for vehicles adopting thermal or



hybrid powertrains (with the development of innovative technologies, *e.g.* ultra-lean combustion systems) and by spreading the electrification of the fleets. In parallel and on a longer time-scale, the adoption of the European Climate Law introducing the concept of overall climate neutrality by 2050, imposed the challenging target for the automotive industry of zero-equivalent carbon emissions by 2035 in Europe. This target is pushing the research on cheaper energy storage systems to enable an effective diffusion of pure electric vehicles and, in the same time, is forcing the development of carbon-neutral fuels like bio-fuels, e-fuels and the research to obtain economically competitive, green hydrogen.

In the above described frame, characterized by an unparalleled fast (and in some aspects tumultuous) adoption of emission targets, a more and more significant role is being played by the test cycle standards during which both pollutants and CO₂ emissions are measured. To control the vehicles emission, the Legislator has developed laboratory and road test cycles that need to be carried out during the vehicle homologation procedure. Up to 2017, in Europe, the final emissions have been measured through the NEDC (New European Driving Cycle), composed by a sequence of constant vehicle speed phases separated by slow transients, resulting in moderate powertrain load conditions with respect to on-road actual operation. The observed relevant gap between the type-approval and the real-world operation in terms of both emission and fuel consumption, has led to the introduction of the WLTP (Worldwide harmonized Light vehicles Test Procedure) and more recently of the RDE (Real Drive Emissions). Unlike the NEDC, these last tests are more representatives of the vehicle actual on-road operation, investigating a wider range of engine operation points.

The adoption of these new test procedures resulted in a significantly higher level of measured emissions during the vehicles homologation test cycles, that made more challenging the vehicles compliance to test limits and induced the development of advanced emission control technologies by the automotive industry. In the same time the new, highly dynamic test procedures requested an important upgrade of the measuring instruments (*e.g.* torque meters, air and fuel flow meters, gas analyzers) to be appropriate for the wider range of powertrain operating conditions and, mostly, to improve the measurement accuracy in the transients.

As a matter of facts, all the new standardized procedures are characterized by a relatively high dynamicity in terms of powertrain load, in order to reproduce the actual, real-world vehicle dynamic. This approach results in particular in severe issues in terms of fuel flow measurement capabilities, being marginal during the homologation tests the steady fuel flow conditions in which flow meters are normally calibrated. In the present activity, an experimental test bench was developed with the aim of offering a flexible and affordable test system to dynamically evaluate the performances of different flow meters in dynamic conditions. The developed test bench is based on a so-called “wet-system” in which a complete fuel injection system (composed of low- and high-pressure pumps, fuel pipes, fuel rail and injectors) is managed reproducing its actual operation during an assigned test cycle in terms of injection frequency, rail pressure and injected fuel quantity. The transient operation fuel flow rates are in this way accurately reproduced, offering the opportunity to compare the accuracy of the flow meter under test with both a master Coriolis-type flow meter and the nominal fuel flow time-profile. The flow meter accuracy tests can be carried out with time and cost efforts significantly lower than it would be required on the complete vehicle. Further, in the developed bench the reproducibility level of the calibration is inherently higher being the bench operation fully controllable in terms of operating conditions sequence and in terms of test fluid and injection hardware temperature.

2. Experimental Set-Up

The proposed test bench is intended for supporting the development of both hardware and actuation strategy of the main components of a fuel injection system feeding a thermal powertrain (*i.e.* high-pressure pump, injectors, rail, connecting pipes) and the appropriate calibration of sensors and instruments used for the injection system management (*e.g.* temperature and pressure transmitters, fuel flow meters). With these goals, the bench can mimic the actual operation of a complete injection system in static and dynamic operating conditions, reproducing with a high-fidelity level a prescribed sequence of operating conditions in terms of injection pressure, injection frequency and injection strategy (phase

and duration with respect to a virtual engine crankshaft). During the bench operation, different measurements can be carried out to completely characterize the actual injection system operation and/or the bench itself can be used as driving force to produce and un-steady, intermittent fuel flow to be used for sensors/instruments development and calibration. The control system of the proposed hydraulic dynamic bench has been developed at the University of Perugia [5], [6], [7], [8] and its flexible architecture allows the operation with gasoline port injection (PFI), gasoline direct injection (GDI) and Diesel injection systems.

2.1. Dynamic Hydraulic Bench Global Structure

In Figure 1 (a) the dynamic hydraulic bench is represented in a Diesel configuration, while in (b) the overall bench layout is sketched. As depicted in Figure 1 (b), the bench fuel circuit starts from a fuel tank, eventually featuring a fuel heating/cooling auxiliary circuit to control the fluid temperature. From the tank, a low-pressure DC pump supplies the fuel to the high-pressure pump (or directly the fuel rail in PFI systems), which is driven by an AC motor controlled by an inverter. A high resolution, wide frequency range torque meter (Kistler 4503) is used to measure the input torque to the pump. The rail pressure level is controlled by a metering valve at the high-pressure pump inlet (Pressure Control Valve, PCV) for GDI systems or by the combined action of a metering valve and a discharge valve installed on the rail for Diesel systems (typically named SCV and DRV respectively).

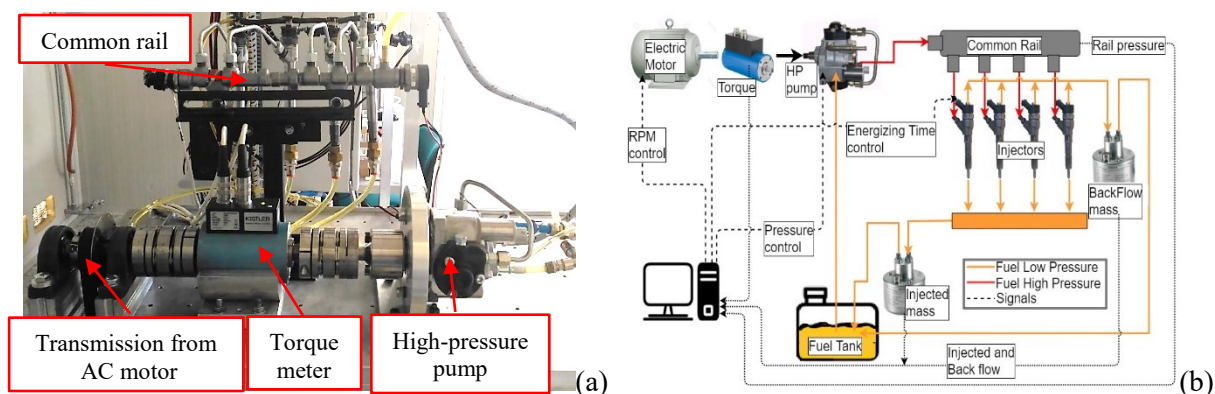


Figure 1. Dynamic hydraulic bench: Diesel arrangement (a); global layout (b).

The injected fuel is collected in a low-pressure rail and metered by a fast response, Coriolis-type mass flow meter used as reference or master flow rate instrument. An eventual flow meter under calibration is connected directly at the master flow meter exit, so to minimize any delay among the two instruments signals. Only for Diesel injection systems, a second mass flow meter is typically required to evaluate the so-called back-leak flow, a secondary flow produced by the injectors during their normal actuation cycle. The back-leak clearly represents a significant energetic loss as the corresponding fuel was compressed at the rail level by the high-pressure pump. Depending on the hardware under test, the back-flow rate can be comparable to the injection flow and should hence minimized. Both the injection flow and eventually the back-leak flow are returned to the tank completing the fuel circuit.

2.2. Dynamic Hydraulic Bench Control Functions and Software Structure

The main logic functions of the bench control system (mentioned in Figure 1 (b)) are:

- **RPM control:** the control system defines the command to the AC motor inverter to manage the high-pressure pump rotation speed so to define the injection frequency. An incremental encoder installed on the pump shaft is used to generate the general trigger of the system and to determine the actual pump shaft phase, so to actuate all the injectors and the metering valve commands.
- **Pressure Control:** for GDI and for second generation common rail Diesel systems, the pump shaft position is used to actuate the metering valve (PCV or SCV); all the control valve architectures can be managed by the bench rail pressure control system according a PID regulation strategy

operated in the Real Time layer of the control software (see below). Given the relevance of the back-leak pressure level for Diesel common rail injectors, a PID control strategy is also used to actively control this parameter in the eventual back-leak circuit, using an ancillary PFI injector as discharge valve.

- Energizing Time Control: this Real-Time software function uses the pump shaft position to determine the timing in which the pulse-train or sequence must be initiated for each injector following the proscribed engine sequence. Each injector injection sequence is composed on a number of injection events per each cycle (up to 8 events per cylinder are frequently used for automotive Diesel engines), separated by appropriate dwell times.
- Fast Signals Acquisition: a separate software module is used to operate at high sampling rate (typically 100 kHz) the acquisition of a number of wide frequency spectrum physical quantities, among which the instantaneous torque, the rail pressure in several positions along the circuit, the injectors current and voltage shape and eventually the injector needle lift. Signals provided by additional instruments (such as an injection analyzer measuring the shot-to-shot resolved, instantaneous flow rate produced by one or more injectors) can complete the analysis.

The control software was developed in LabVIEW environment, using a three-layer structure to implement the above-mentioned functions; each of the software layers runs on a different hardware depending on the required process and timing accuracy. In the following Figure 2 the three-layer structure of the control system is briefly described:

PC/Windows: the user interface is implemented in this top-level layer, so to allow the test plan definition, the on-line signals monitoring and data archive management. In this environment, the Fast Signal Acquisition task is also accomplished using a PCIe-6537 multifunction acquisition card.

Remote Controller/Real-Time LabView: all time critical functions, among which Pressure Control and ET Control, are implemented in this layer. The Real-Time controller allows to obtain the system robustness, reliability and timing accuracy required by critical tasks such as the PID regulation for rail pressure. The Real-Time controller typically receives macro inputs from the user interface and exchanges data with the low-level FPGA layer to generate hardware commands and to acquire data from the field.

FPGA: in this low-level layer, using specific input/output modules, basic tasks such as TTL pulse train generation to actuate injectors and valves, encoder position decoding and analog input are accomplished. All TTL pulse trains are supplied to external programmable drivers to generate the required current time profiles to actuate the injectors and the control valves.

2.3. Dynamic Hydraulic Bench Master Flow Meter: Calibration

The master flow meter adopted on the Dynamic Hydraulic Bench is a Coriolis-type mass flow meter by Siemens (MassFlow 2100 DI 1.5) operating in a range 0.1 to 30 kg/h with a 0.1% nominal measuring accuracy. The master flow meter was calibrated at INRIM laboratories by using a new test bench, recently developed in the framework of the EMPIR Project 20IND13 SAFEST [9]. Although it is currently in the testing phase and not yet running with fluids having similar characteristics to fuels, such as the calibration oil ISO 4113, it was possible to perform calibrations with water at ambient temperature of about 21 °C.

The calibration was performed at constant flow rate in the range from 1 kg/h to 30 kg/h by using the gravimetric method. Two calibration methods were used, the standing start and stop method, and the dynamic weighing method developed at INRIM [10]. The weighing system consists of a balance of 10 kg, with resolution of 1 mg, with a weigh-tank of 3 L which are enclosed inside an evaporation trap. The flow generation was performed by a pressure vessel maintained at constant pressure with an air pressure regulator, and a control valves located upstream and downstream of the meter under calibration.

The comparison between the static and dynamic weighing method was performed at the flow rates of 10 kg/h and 20 kg/h, the results have been consistent considering the uncertainties, but with a systematic difference of about 0.04 %. This difference is probably due to the difference in calibration methods, or the fact that the tests were not carried out with degassed water, further studies will be carried

out when it will be possible to use the oil as a calibration fluid. With the aim of reducing the uncertainty contribution due to the repeatability of the measurements the minimum amount of water for each run was at least of 1 kg with a duration of the run of at least 5 min. Each calibration point, at constant flow rate, q , was repeated five times, and the percentage error E and standard deviation $s(E)$ were calculated, the results are shown in table 1 and Figure 3.

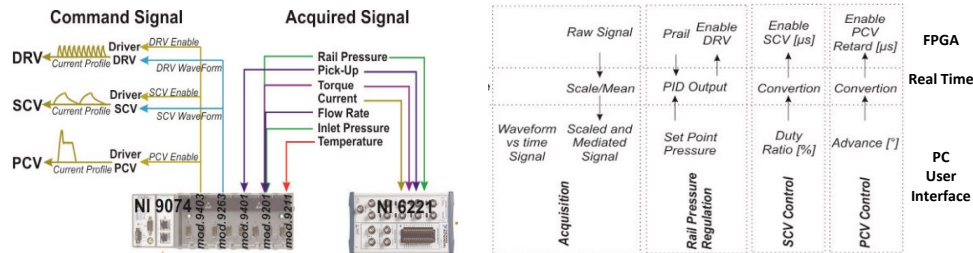


Figure 2. Dynamic hydraulic bench – control system structure.

A number of calibration repetitions were performed on different days, from which the contribution of uncertainty u_{inst} due to the stability was assessed. The uncertainties of the reference standard u_{ref} , shown in table 1, include the uncertainty contributions due to the weighing, the evaporation and the standing start and stop method, this later evaluated at 0.015%. For the evaluation of the standard uncertainty of the error $u(E)$, the uncertainty contribution due to the repeatability has been estimated as $s(E)/\sqrt{5}$, where 5 is the number of repetitions.

Table 1. Calibration results and associated uncertainties.

Water flow rate [$q / \text{kg h}^{-1}$]	E [%]	$s(E)$ [%]	u_{inst} [%]	u_{ref} [%]	$u(E)$ [%]	$U(E)$ [%]
0.97	0.057	0.010	0.015	0.023	0.028	0.06
2.07	-0.080	0.010	0.015	0.017	0.023	0.05
4.90	-0.007	0.010	0.015	0.016	0.022	0.05
9.50	0.061	0.010	0.010	0.015	0.019	0.04
14.90	-0.039	0.010	0.010	0.015	0.019	0.04
19.93	-0.165	0.010	0.010	0.015	0.019	0.04
25.05	-0.196	0.010	0.010	0.015	0.019	0.04
29.36	-0.186	0.010	0.010	0.015	0.019	0.04

The results have shown good behaviour of the meter, even at low flow rates. The errors are always between 0.2 %, with a very good repeatability, which are more than adequate for the requirements of the hydraulic dynamic bench at the University of Perugia. It is planned to repeat the calibration of the flow meter as soon as possible using as fluid a calibration oil and in addition evaluate the measurement performance of the flow meter under dynamic loads

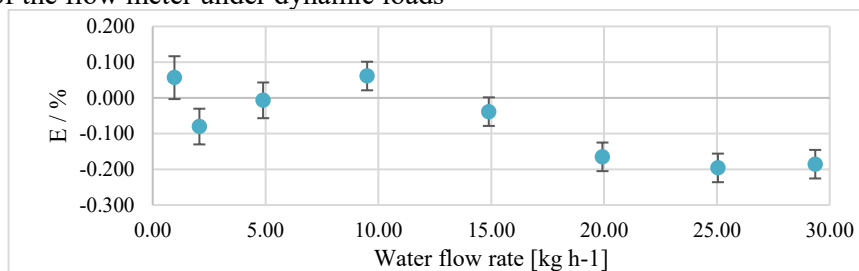


Figure 3. Relative errors with expanded uncertainty bars, as a function of the water flow rate.

3. Results and Comments

As an example of the Dynamic Hydraulic Bench capabilities, in the following some acquisitions are reported relevant to the simulation of an WLTP homologation test carried out for a 1.3 liters displacement, 4-cylinder passenger car in the power range 55 - 65 kW/l. In all the following plots, the following nomenclature is adopted:

- **Nominal quantities:** data recorded during the WLTP test executed in the homologation cell with the complete vehicle are named as “nominal” (injection pump speed, injection pressure level, injection pulse train as produced by the engine ECU) and are used as target quantities to be replicated on the Dynamic Hydraulic Bench.
- **Experimental quantities:** data recorded during the WLTP test on the Dynamic Hydraulic Bench with the injection system alone are named as experimental.

The injection system installed on the Dynamic Hydraulic Bench replicates the components installed on the tested vehicles, namely: Injection Pump: Denso HP3 (2 pistons); Rail: Bosch 0445214224; Injectors: Bosch CRI 2.20

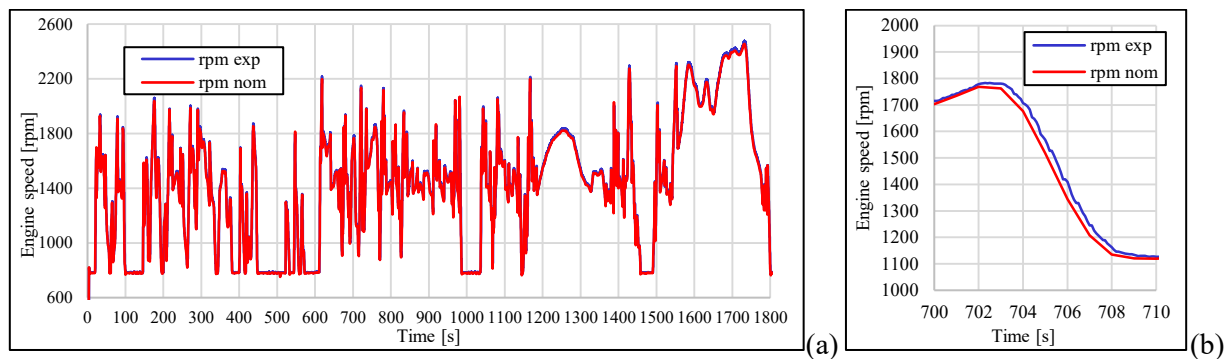


Figure 4. WLTP test, Nominal vs Experimental engine speed (a); zoom on (b)

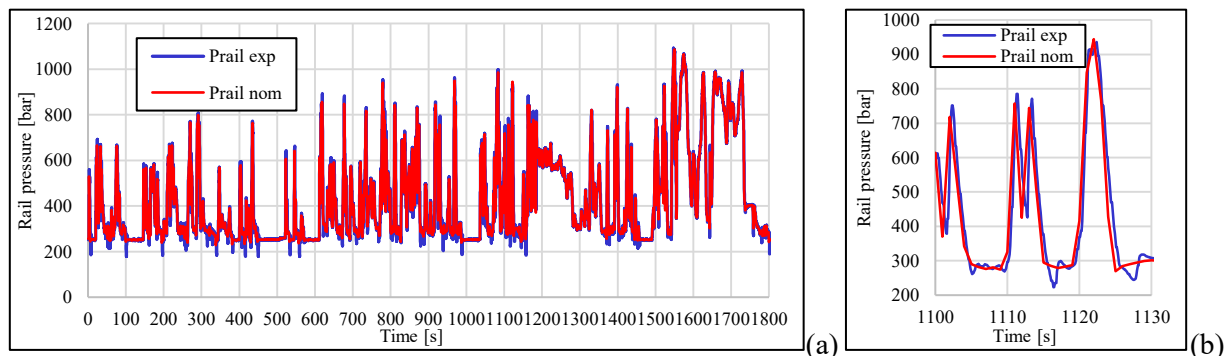


Figure 5. WLTP test, Nominal vs Experimental common rail pressure (a); zoom on (b).

In Figure 4 the comparison among the equivalent engine speed (doubled pump speed) obtained during the entire WLTP test for the vehicle and on the dynamic hydraulic bench is reported. As can be seen, the hydraulic bench has the capability of reproducing the engine behavior with an appropriate accuracy. In detail (see Figure 4 (b) for a typical speed transient), the experimental line (blue) seems to be in delay (about 0.35 s) with respect to the nominal signal (red). This delay corresponds to the RPM control system reaction and actuation times, as the red line is used directly as target for PID control system. Conversely, the same quantity is a logic output for the complete vehicle system.

In Figure 5 the comparison among the rail pressure time history measured on the vehicle by the engine ECU during the WLTP test and the corresponding injection pressure obtained on the dynamic hydraulic bench is reported. As for the pump speed control system, the comparison between the target (red) and the obtained (blue) P_{rail} time-profiles evidences globally a good efficacy of the pressure regulation system,

based in this test only on the SCV actuation (DRV closed during the WLTP test). As for the pump speed, the rail pressure control system seems to follow the nominal trace with an acceptable delay of about 0.3 s. At the same time, some undershooting can be appreciated during the fast pressure decrease transients, possibly to be ascribed to the decision of excluding the DRV from the regulation strategy.

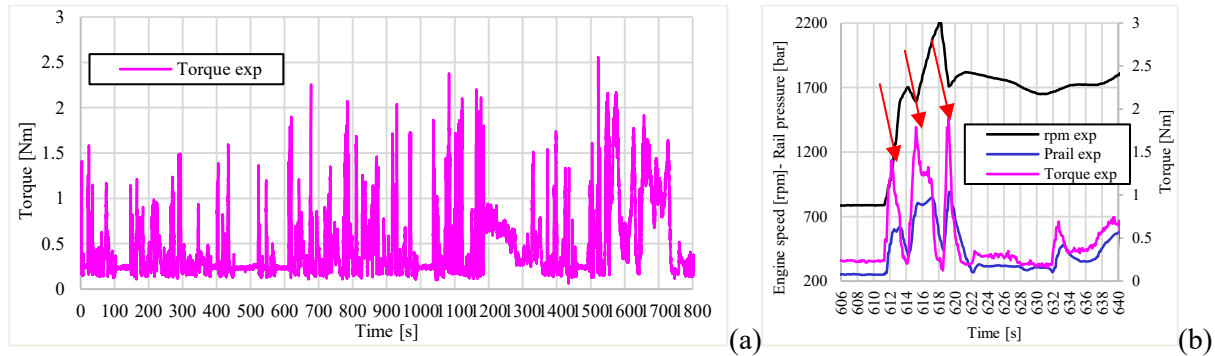


Figure 6. WLTP test, input torque to the high-pressure pump (a) torque, RPM and rail pressure (b).

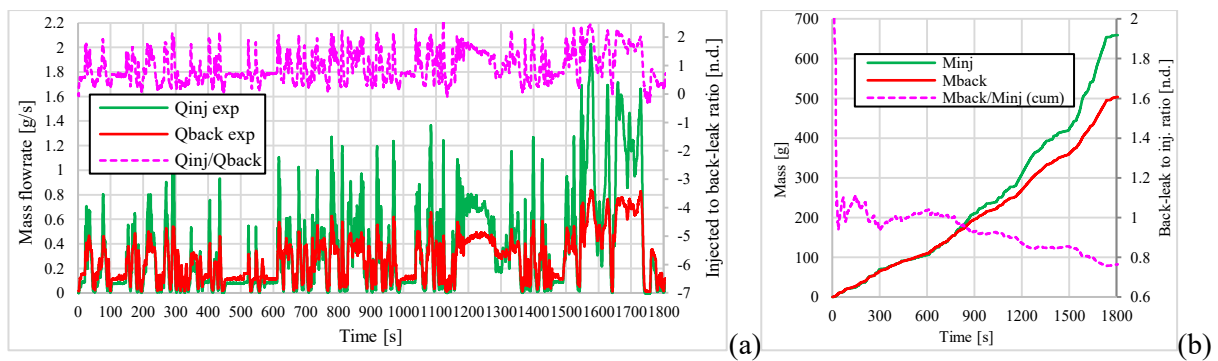


Figure 7. WLTP test, dynamic (a) and cumulated (b) injected and back-leak mass flow rate.

The instantaneous torque input to the pump (Figure 6) measured on the Dynamic Hydraulic Bench during the WLTP test was acquired by a Kistler 4503 meter, set to its wider operating range (0-50 Nm). The corresponding measurement on the complete vehicle is clearly not feasible. As can be observed in Figure 6, only for short periods during the test the actual torque request was higher than 2 Nm, with a peak of 2.56 Nm and a cycle average value of 0.47 Nm. The peculiar analysis of torque, pressure and rpm time history plot can reveal interesting details about the analyzed system dynamics, well-captured by the present experimental setup. As an example, in the plot in Figure 6 (b) the correct timing agreement among the acquired quantities is reported: the 3-step rail pressure increase at 611, 613 and 617 s (about 350 bar globally) is well captured in terms of pump torque. It is interesting to note that while for the first of these three steps also the pump shaft speed is being increased, during the last 2 pressure steps the pump speed is decreasing. Notwithstanding, the torque signal reaches the highest peaks in the test, suggesting the rail pressure to be the primary mechanical load in the considered system while the pump inertia plays a secondary role. As above mentioned, the simultaneous measurement of both the injected and the back-leak flows from the four injectors was carried out. As reported in Figure 7 (a), with the analyzed injection system and actuation strategy, the maximum instantaneous back leak flow rate was 0.82 g/s while the maximum injected flow rate was 2.01 g/s. Both the flow traces evidenced an appreciable capability of the used Coriolis-type flow meters and circuit configuration to follow the cycle dynamics. The instantaneous injected to back-leak ratio ranges from 0 up to 2.2 for the maximum load conditions

The cumulative flow injected and backflow mass measurement (Figure 7 (b)) evidenced how the two flows are distributed over the WLTC cycle. During the first 600 s the back-leak mass is slightly bigger than the injected one due to the low load and the long idle periods. The globally injected mass was 659 g, the global back-leak mass was 504 g i.e. 76% of the injected mass, confirming the relevance of the energetic loss associated with the back-leak flow required to operate common rail injectors.

4. Conclusions

In the global trend of adopting more and more severe legislations to limit both pollutant emissions and CO₂ production in the transport sector, the introduction in recent years of highly dynamic homologation test cycles for the automotive sector arose significant technical issues for the fuel flow measurement. While commercial fuel flow meters are normally calibrated in steady flow conditions, current test procedures include significant powertrain load dynamics, resulting in considerable fuel flow transients that could cause significant measurement errors. Consequently, meters accuracy should be verified in operating conditions similar to those faced in the vehicle operation. In the present paper, the capability of a dynamic hydraulic bench of replicating the operation of a complete injection system in realistic operating conditions is discussed. The bench, composed of low- and high-pressure pumps, rail and injectors, can be managed replicating a highly dynamic test cycle by imposing the high-pressure pump speed, rail pressure time-history and injection sequence. The reported results relevant to the WLTP homologation cycle of a B-segment vehicle equipped with a 4-cylinder Diesel engine evidence the bench capability of reproducing the injection system dynamic behavior, enabling the comparison of different type of fuel flow meters with both a master Coriolis-type flow meter and with the nominal fuel flow time-profile.

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