Validation of a simulation model for the assessment of CO_2 emissions of passenger cars under real-world conditions

The gap between real-world fuel consumption and manufacturers' figures has been increasing since 2001. Could the use of generic simulation models making use of on-road test data provide a more accurate approach to measuring fuel consumption and CO_2 emissions?

Background

Currently, European CO_2 emission and fuel economy targets for the automotive sector are based on the New European Driving Cycle (NEDC), a driving cycle that was not originally designed for this purpose. This has led to an increasing gap between the real-world average fuel consumption experienced by drivers and the respective type approval values reported by manufacturers. The divergence between real-world and type approval fuel consumption from 2001 onwards is depicted in Figure 1.

This gap is expected to decrease after the introduction of the new World-wide harmonized Light vehicles Test Procedure (WLTP), however, it will not disappear completely. One of the reasons for this is that the WLTP still covers only a limited area of the engine operating range, albeit a wider range than that covered by the NEDC. Consequently, it will still be possible for manufacturers to develop fuel economy measures applicable only within this limited engine operating range, and to follow different strategies outside of this range. It is therefore particularly important to explore the possibilities of using on-road test data and following a simulation approach to assess real-world CO_2 emissions, i.e. to cover the widest possible (if not the whole) area of the engine operating range.

The engine range covered during NEDC, WLTP and RDE is illustrated in Figure 2. It can be seen that, during an RDE test, contrary to NEDC and WLTP, a wider engine operating range is used.

Objectives

European regulation has already established RDE measurements for the evaluation of NO_x emissions from vehicles, providing the opportunity to expand this methodology to fuel consumption and the evaluation of CO_2 emissions, since current regulation covers only pollutant emissions and not CO_2.

Hence, this study investigates the possibility of evaluating real-world CO_2 emissions with generic simulation models, developed on the basis of portable emissions measurements system (PEMS) data and RDE recordings. The aim is to provide accurate and reliable CO_2 emissions simulations for any modern vehicle model, combined with RDE measurements. Additionally, the target is to further enhance the development of a methodology for the measurement and evaluation of real-world fuel consumption and CO_2 emissions. The final outcome could provide direction for further research into the development of a procedure that may be able to use RDE testing of CO_2 emissions for regulatory purposes.

Figure 1 Divergence between real-world and manufacturers' type-approval CO_2 emissions for various real-world data sources, including average estimates for private cars, company cars and all data sources [1]

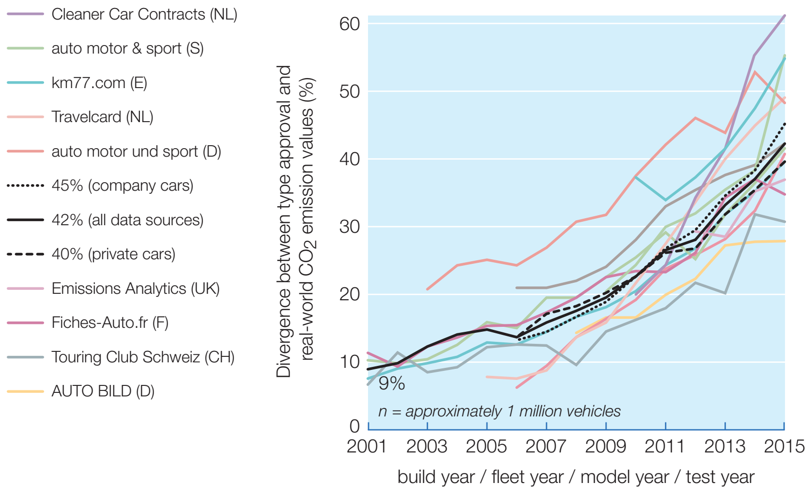
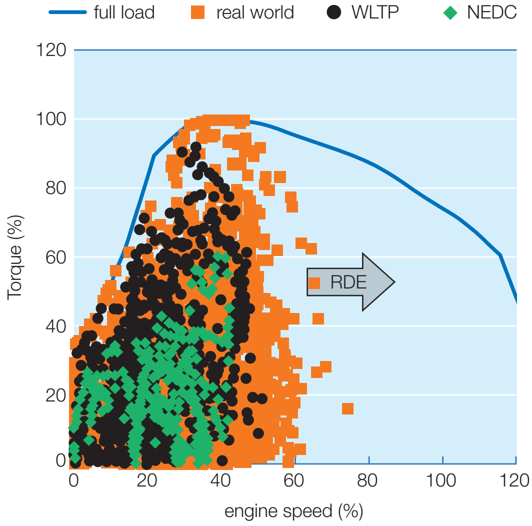


Figure 2 Engine operating range for NEDC, WLTP and RDE



Methodology

The procedure that was followed to develop a methodology for evaluating real-world CO$_2$ emissions using a simulation approach is summarised in the following steps and demonstrated in Figure 3.

As a first step, a validated vehicle model was used to specify and investigate the difficulties and limitations of such an approach. The real-world measurements are simulated with the existing model, which was built with input data derived by the respective OEM, and the results are compared against experimental data. These simulations provide some first indications of the difficulties and the limitations of the approach. At a second step, the same procedure is repeated for a new developed vehicle model with generic data, such as the engine map and the powertrain losses. In the third step, a comparison between the simulated CO$_2$ results for the two vehicle models is conducted, which highlights any differences among them, and indicates the parameters that need further calibration.

Simulation model

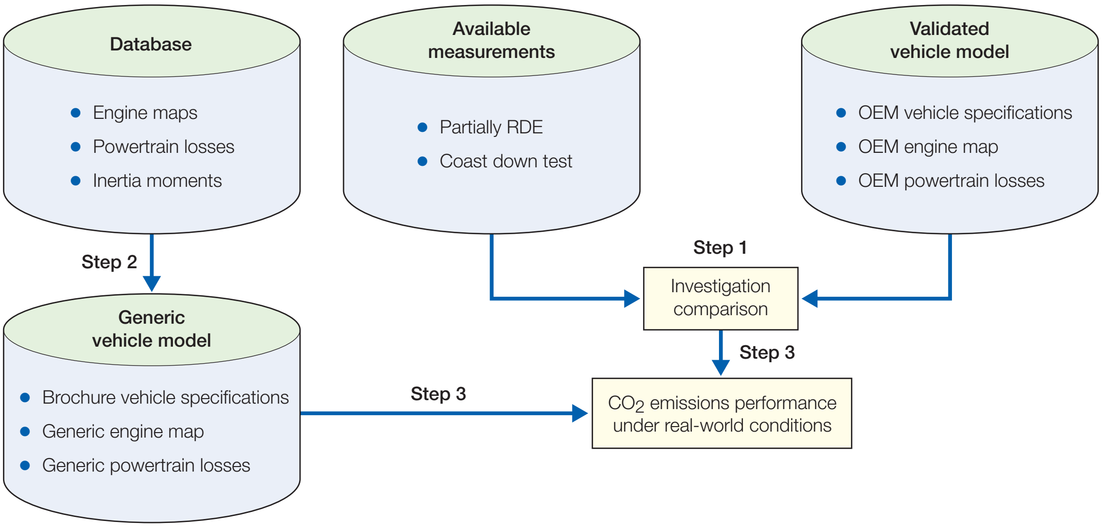
The aforementioned methodology was applied on a sport utility vehicle (SUV) equipped with a 2.0 litre diesel engine and 6-speed manual transmission. This vehicle is considered to be a mild hybridized Euro 5 passenger car, equipped with start-stop and brake energy recuperation features; its main specifications are summarised in Table 1.

Table 1 Vehicle specifications

Engine	diesel
Displacement (cc)	1995
Curb weight (kg)	1465
Maximum engine power (kW @ rpm)	120 @ 4000
Maximum engine torque (Nm @ rpm)	380 @ 1750
Gearbox	6-gear manual transmission
Tyres	225/50 R17
Emission standard	Euro 5
Type approval CO$_2$ emissions (g/km)	119

This vehicle was tested in facilities at the Laboratory of Applied Thermodynamics (LAT), Aristotle University of Thessaloniki, and a simulation model was developed and validated. All required data for the model was provided by the respective automotive OEM; hence it is considered as being an ‘original model’ of the vehicle. This model was calibrated and validated over cold and hot start NEDC and WLTP chassis dynamometer measurements; the

Figure 3 Schematic of the methodology

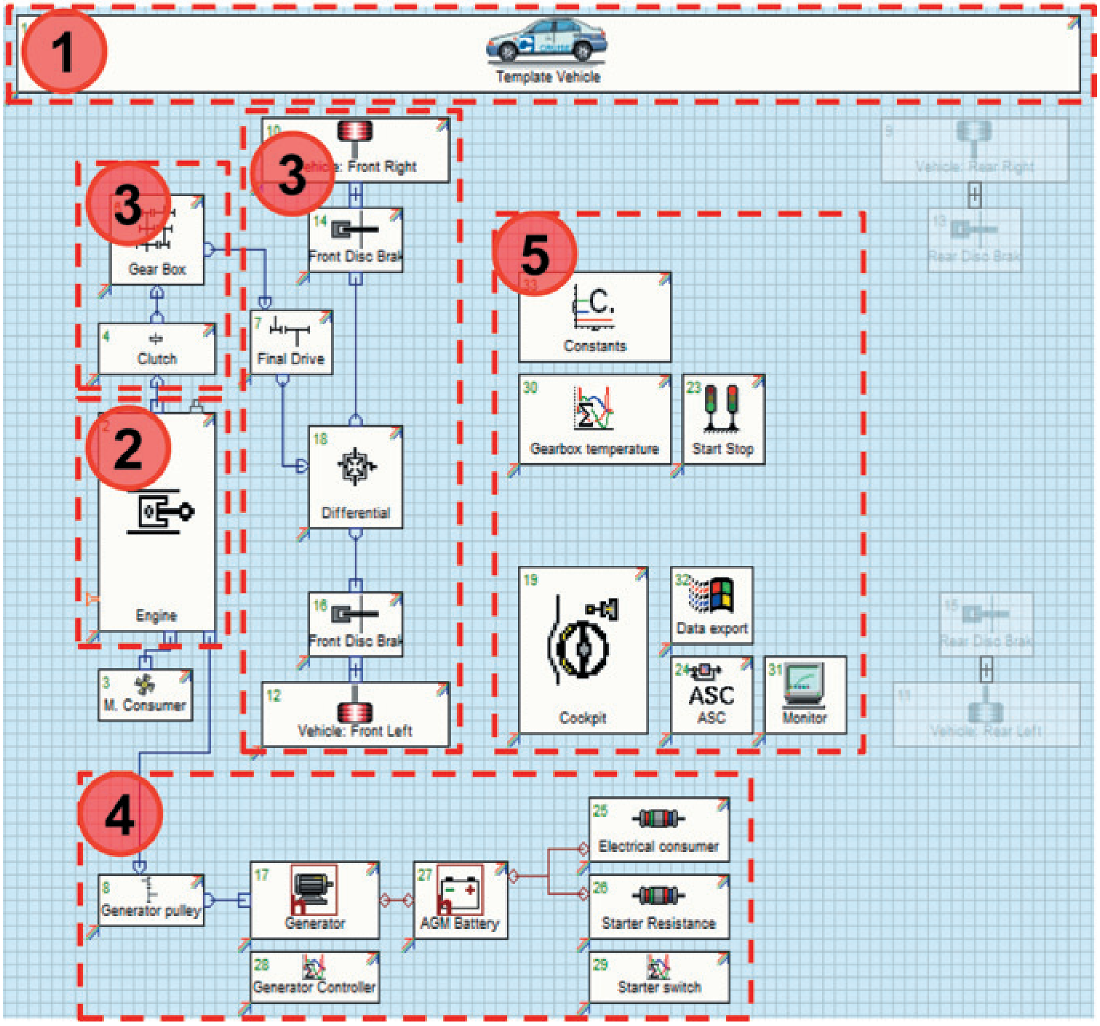


total error of the simulated fuel consumption for both cycles is below 1% compared to the measured value.

The commercial simulation platform, AVL Cruise™, was used to build the model and run the simulations. This is a micro-simulation tool used for emissions and powertrain analysis. It covers a wide range of vehicle types and is characterised by a fast calculation time with a multi-physics solver, as well as a modular and component-oriented modelling approach and onboard integration platform[2]. The graphical user interface of AVL Cruise™, together with the main vehicle components that were used for the simulations, is presented in Figure 4 and explained below:

- Component No. 1 describes the vehicle body, and is where information relevant to the test mass and the driving resistance coefficients are inserted as input.
- Component No. 2 describes the internal combustion engine, and is where the engine specifications (fuel, displacement, number of cylinders, etc.) for the simulated vehicle are inserted. Additionally this component also uses the fuel consumption (FC) map, the full load and the motoring curves.
- Component No. 3 (group of components) includes the drivetrain, and consists of the clutch, the gearbox, the final drive, the differential and the powered

Figure 4 AVL Cruise™ graphical user interface and topology for a conventional vehicle equipped with manual transmission and start-stop. The main vehicle components are highlighted.



wheels. The most important input parameters of this component are the gear and final drive ratios, the torque loss map of the drivetrain system and the dynamic radius of the tyres.

- Component No. 4, which consists of the generator and its pulley, the battery, the starter, and the electrical consumer unit along with their controllers, simulates the electrical system of the vehicle.
- Component No. 5 consists of the start-stop system together with other necessary modules essential for the simulation.

Measured data and model calibration

After the model had been completed, the next step was the validation of the model, which is based on data obtained with PEMS during real-world tests (including partial RDE measurements that were not fully compliant with the RDE regulation at that stage) held around the region of Thessaloniki, Greece.

The available instantaneous data from those tests include time, altitude and vehicle speed provided by the installed GPS, ambient temperature, engine load, battery voltage, engine coolant temperature, engine speed, intake air temperature, air flow rate, vehicle speed from the vehicle's on-board diagnostics (OBD) system and CO_2, CO, NO_2 and NO_x emissions from the PEMS instrument, while fuel consumption was calculated. The vehicle with the PEMS installation is shown in Figure 5.

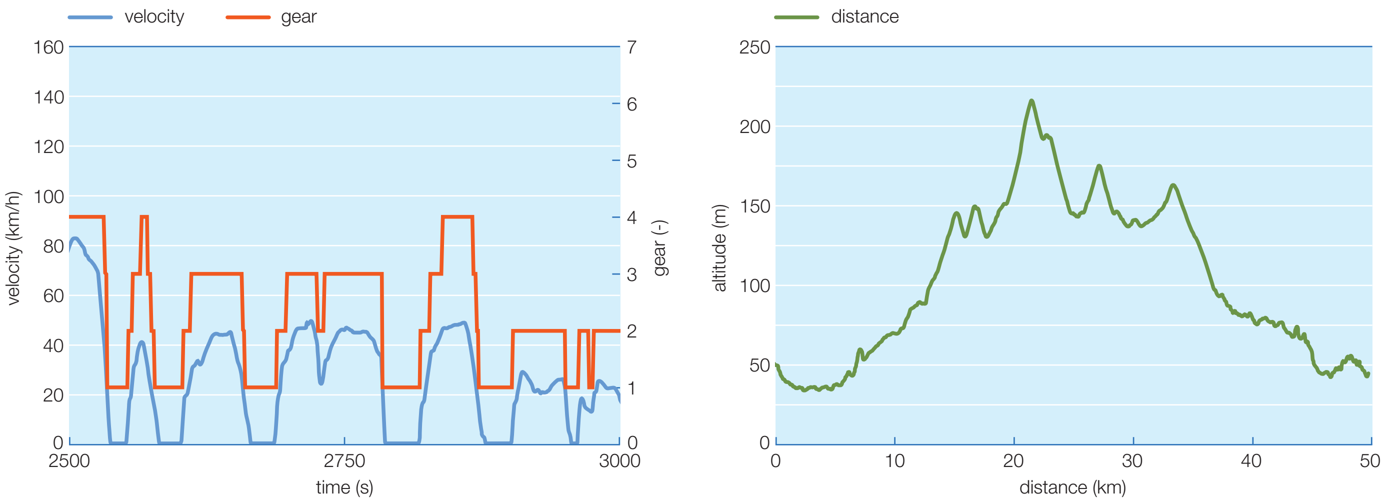
During the validation of the simulations, various parameters were used including time, altitude, vehicle speed from the GPS, engine speed from the OBD system and CO_2 emissions from the PEMS instrument, together with the calculated fuel consumption. For the determination of driving resistance, a coast-down test at a public site was performed. With regard to the alternator current, the measured signal from chassis dynamometer tests over WLTP was used (on-road measurements of alternator current were not included at that time). Alternator current during on-road testing can be also measured, thus the actual alternator's power consumption can be added to the simulation.

Figure 5 PEMS installation on the vehicle

The calibration of the model can be summarized in the following 5 steps:

- The first step involves the preparation of the gear shifting sequence as shown in Figure 6a on page 10. The selected gear versus time is calculated based on the total transmission ratio and engine/vehicle speed ratio.
- The second step is to use the altitude information from the trip, obtained using a GPS device (an example of altitude evolution as a function of distance can be seen in Figure 6b on page 10).
- The third step is to calculate the actual driving resistance of the simulated vehicle. This step is not required if a coast-down test is available. Otherwise approximations and assumptions based on the vehicle's geometry and specifications are conducted.
- The fourth step is to integrate the electrical model of the vehicle. At this point, the battery, alternator, starter motor and constant electrical consumption are added to the simulation.
- The fifth step involves evaluation of the simulation results. Simulated instantaneous engine speed, FC and CO_2 emissions are compared with the respective measurements.

Figure 6 Example of velocity, gear shifting and altitude


a) Velocity and gear shifting

b) Altitude

Internal database—generic model

The second step in this methodology is the development of a vehicle model with generic characteristics derived from LAT's internal database.

In the context of previous activities, LAT has developed a number of validated vehicle models using detailed necessary input data which were largely provided by the respective OEMs. This has led to the creation of an internal database, which consists of vehicle simulation models for 20 passenger cars and 3 light commercial vehicles (LCVs) equipped with manual or automatic transmissions. For the gasoline and diesel vehicles in the database, information related to fuel consumption engine maps, powertrain losses, inertia moments, gear shifting strategy and driving resistance coefficients are available from the respective OEMs. Figure 7 summarizes the contents of the database.

Using this database it was possible to derive generic engine maps, powertrain losses or powertrain efficiency maps, or to estimate the driving resistance coefficients. For example, diesel vehicles were divided into three clusters according to their displacement, as shown in Table 2 on page 11, and for each engine cluster one generic fuel consumption map was derived.

Figure 7 Contents of the LAT database

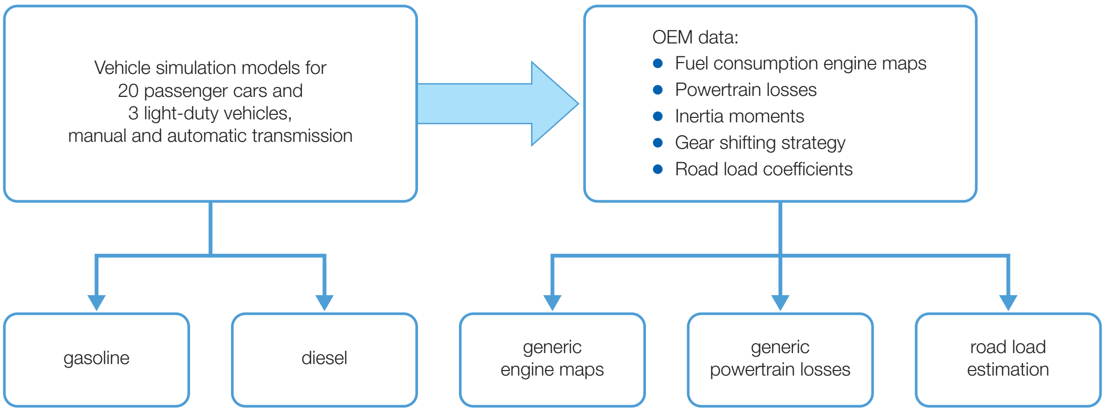


Table 2 Engine clusters

Engine cluster	Vehicle segment
1200–1400 cc	B, B, C
1500–1700 cc	C, MPV, SUV
1900–2200 cc	SUV, LCV, LCV

Simulation results

The outcome of the approach was the development of two simulation models, one with data provided from OEMs and one with generic data extracted from the internal database. The two models were used to calculate the CO_2 emissions performance for the same real-world driving velocity profile.

Figure 8 illustrates the measured (black line) and simulated (blue line) cumulative FC of the trip used in the simulation. The green line corresponds to the second-by-second difference between the measured and the simulated FC. The red dashed line is the 5% margin of the difference. Simulated FC does not include the altitude effect and, as a result, an underestimation is observed between 500 and 1500 seconds; this shows the importance of using accurate altitude recordings in simulation.

Looking into the instantaneous signals of the measured and simulated FC from 500 to 1000 seconds (see Figure 9) it can easily be seen that the measured signal is above the simulated signal for the given time period. However, areas where the measured signal is below the simulated one for the given time period are also present. This can be attributed to changes in the engine load caused by uphill and/or downhill driving.

After introducing the instantaneous altitude in the simulation, the calculated FC is seen to improve, and the underestimation between 500 and 1500 seconds is eliminated. The measured (black line) and simulated (with altitude effect) (blue line) cumulative FC data are presented in Figure 10. The slight constant overestimation in the simulated FC observed until 2500 seconds, may be attributed to driving resistance inaccuracies. Improvement of predicted FC is also observed in the instantaneous signals of the measured and simulated FC (Figure 11) where a good match between the two signals is indicated.

Figure 8 Measured and simulated cumulative fuel consumption, and the difference between measured and simulated fuel consumption
(altitude recordings are *not* included in the simulation)

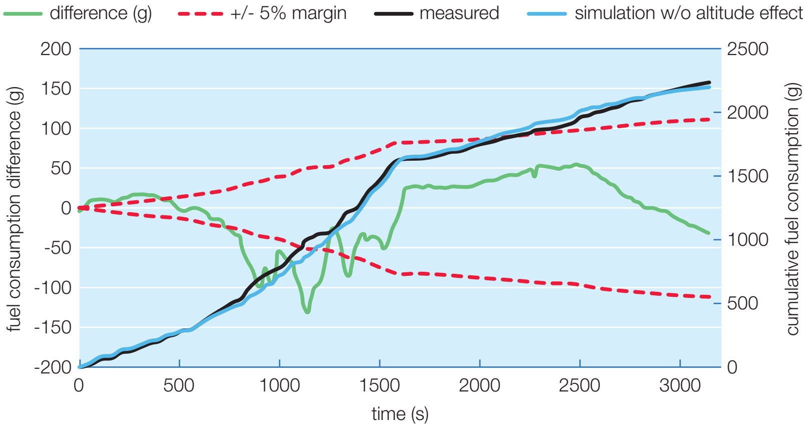


Figure 9 Measured and simulated instantaneous fuel consumption
(altitude recordings are *not* included in the simulation)

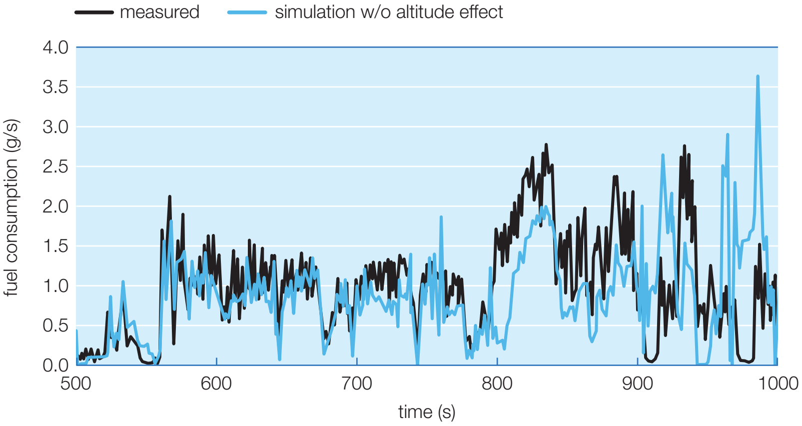


Figure 10 Measured and simulated cumulative fuel consumption, and the difference between measured and simulated fuel consumption
(altitude recordings *are* included in the simulation)

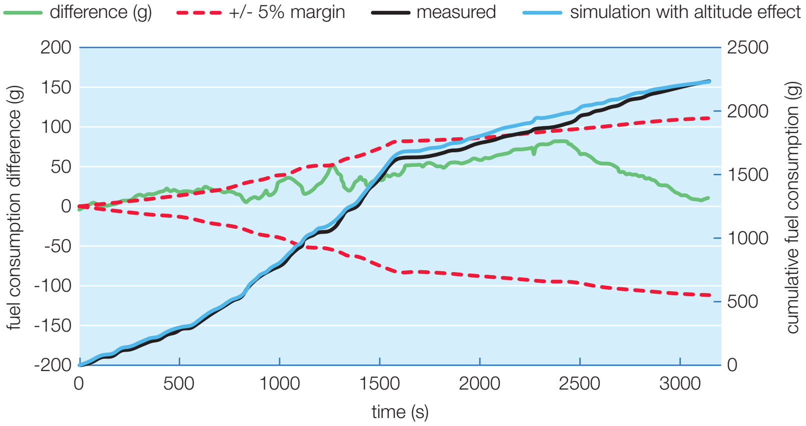
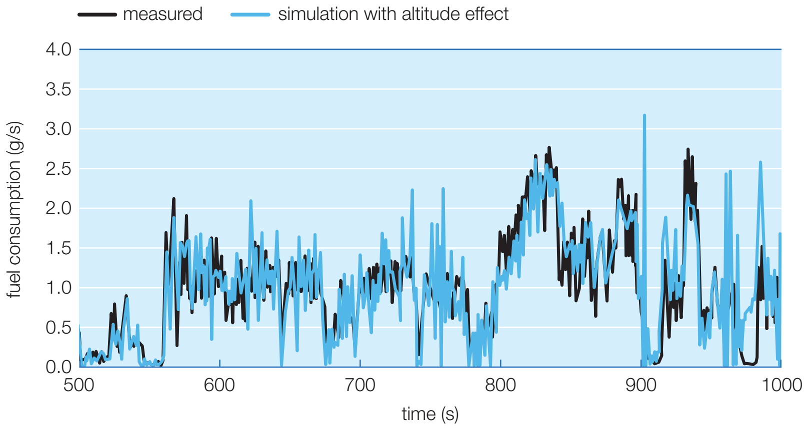


Figure 11 Measured and simulated instantaneous fuel consumption
(altitude recordings *are* included in the simulation)

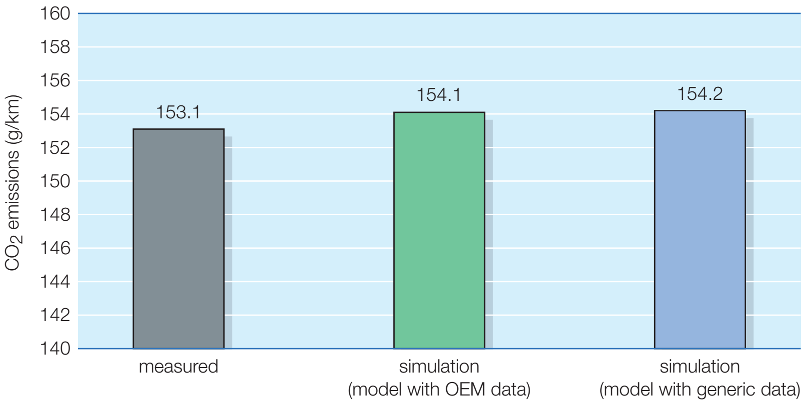


Finally, both models (i.e. the model with OEM data and the model with generic data) were used to predict FC and CO_2 emissions performance for the same measured trip. The total simulated CO_2 emissions results from the models are shown in Figure 12, compared with the measured value. From this comparison it can be seen that both models provide accurate results, only 1 g/km higher than measured.

The results of the simulation can be summarised as follows:

- The difference between measured and simulated FC remained within ±5% over the entire test.
- There was a slight overestimation of simulated FC for a small section of the test.
- The difference between measured and simulated total FC was less than 1%.

Figure 12 Simulated CO_2 emissions results compared with the measured value



Conclusions and future actions

The main objective of this study was to investigate the possibility of evaluating real-world CO_2 emissions with simulation models developed on the basis of portable emissions measurements system (PEMS) data and Real Driving Emissions (RDE) recordings.

During the analysis in this study, two simulation models were developed, one with data from the respective OEM and one with generic data extracted from LAT's database. For both models, CO_2 emissions and fuel consumption were simulated successfully and results from both models showed a good agreement with experimental data. The error in total simulated CO_2 emissions was lower than ±2.5%, and the cumulative fuel consumption calculated over the entire test remained within ±5%, compared to the measurements. The important outcome of the study is that a methodology to validate a simulation model for the assessment of CO_2 emissions under real-world driving conditions was drafted.

The results of the study provide a good basis for the rationale that could underpin a real-world based assessment of fuel consumption and CO_2 emissions and the development of a consistent methodology. However, an extensive investigation is required to cover all existing engine types (e.g. gasoline, both MPI and GDI, diesel, etc.), powertrains (e.g. manual and automatic transmissions, torque converter or double clutch systems) and vehicle segments (e.g. sizes, configurations and topologies, including hybrid systems, etc).

References

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