Validation of fuel consumption calculated by a driving simulator

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***Abstract** – The driving simulator is one of the main tools for development and investigation of driving behaviour and new assistance systems. To investigate the impacts of the driver behaviour on fuel consumption in a driving simulator a validated fuel consumption calculation is needed. This work describes the validation of fuel consumption calculated by a driving simulator. Two approaches were done. One method is to compare the calculated fuel consumption with a real car. For this the New European Driving Cycle (NEDC) was rebuild in the simulator to assess the fuel consumption and to compare it with a real car. The big advantage of the NEDC is that the test is repeatable and is obligatory for every car in Europe, so comparable data is available. It can be shown that the driving simulator has a comparable fuel consumption in the NEDC to a real car. The other approach in this study was to compare the distribution of fuel consumption of real car drivers with the distribution from drivers in the simulator. The results of a study with 30 participants in the simulator showed that the resulting fuel consumption is good comparable to real car data.*

***Key words:** fuel consumption, validation of driving simulation*

Introduction

The evaluation and development of driver assistance systems to reduce fuel consumption is one of the main research topics at the Institute of Ergonomics at the Technische Universität München e.g. in the project eCoMove. The goal of many studies is to identify fuel savings potential for individual drivers as well as for different situations and to develop driver assistance systems for fuel saving. The main research tool for these topics is the driving simulator with its well-known advantages. Therefore it is required to have a driving simulator which measures not only individual differences for example in acceleration or speed but also in fuel consumption. Although many driving simulators calculate fuel consumption in many cases the data still has to be validated.

Two approaches to validate the fuel consumption were done. One is to compare the fuel consumption of the driving simulator with real cars. For this approach the New European Driving Cycle (NEDC), which every new vehicle model in the European Union has to pass [CEC1], was chosen. The other approach is to compare the distribution of fuel consumption data of different car drivers from real drives with a comparable drive in the simulator. The goal is to have a simulation with which it is possible to estimate differences in fuel consumption between different assistance system or different drivers. It is not goal to simulate the exact amount of fuel on a given route because that depends in reality of the type of car, weather conditions, traffic conditions etc.

Driving simulator

In the following the driving simulator and the simulation model of the fuel consumption is described.

Hardware and simulation software

The fixed base driving simulator which needed to be validated is located at the Institute of Ergonomics at the Technische Universität München, Germany. The simulator has three projection screens for the front view with a 180° field of view. For the rear-view mirrors projection three additional projection screens are implemented. The Mock-Up is a complete BMW 6 convertible (E64) with automatic gear shift. The CAN-Bus from the Mock-Up is connected to the simulation. The standard instrumental cluster of the car was replaced by a free-programmable TFT-Display.

Fig. 1. Panorama view from inside of the driving simulator of the Institute of Ergonomics

The simulation software used is SILAB from WIVW GmbH (www.wivw.de) which allows a precise and flexible creation of driving situations as well as full control over the simulated traffic. SILAB is connected to the software CarSim in the version 7.11 from Mechanical Simulation (www.carsim.com). CarSim is responsible for the vehicle dynamics simulation including the calculation of the fuel consumption. All data from the simulation is recorded at a frequency of 100 Hz.

Simulation of fuel consumption

The simulation of the fuel consumption is part of the vehicle dynamics simulation and done by the software CarSim. It was decided to model a compact class car because it is the most common vehicle class and therefore it is the most suitable to use for comparison. Therefore a model was created with the size, weight and other parameters so that it represents a typical compact class car. A 75 kW engine model was used for simulation. It was adapted from an 150 kW engine model which is included in CarSim. This again was derived from a real car. The simulation calculates a fuel flow rate through a fuel-consumption map. The fuel consumption in liter per 100 km is calculated through the fuel flow rate, time and distance.

Validation Methods

The following chapters describe the validation of fuel consumption by using driving cycles and a driving simulator study.

Validation with Driving Cycles

The standardized measurement of fuel consumption for new vehicle models is done normally through driving cycles. A driving cycle consists of a given sequence of different speeds for a given duration and defined accelerations and decelerations. It is performed on a roller bench. The measurement is done under predefined conditions like for example outside temperature and vehicle specific conditions like cold motor in the beginning and full battery. Vehicles in Europe for example have to pass the New European Driving Cycle (NEDC) [CEC1] whereas for USA and Japan other cycles exist. The big advantage for measuring fuel consumption through driving cycles is the repeatability of the test and defined conditions which leads to a good comparability between different cars.

The New European Driving Cycle (NEDC)

The NEDC is the cycle used in Europe. Therefore it was chosen to measure the fuel consumption of the simulation with it. It is specified in the directive 70/220/EC of the Council of the European Commission. For each new car model in Europe it is obligatory to pass the test to specify the fuel consumption. The NEDC includes an urban scenario and an extra-urban scenario which are combined to the full cycle [CEC1]. The figures published from the cycle are the urban, the extra-urban and the overall fuel economy. Figure 2 shows the speed profile of the full cycle.

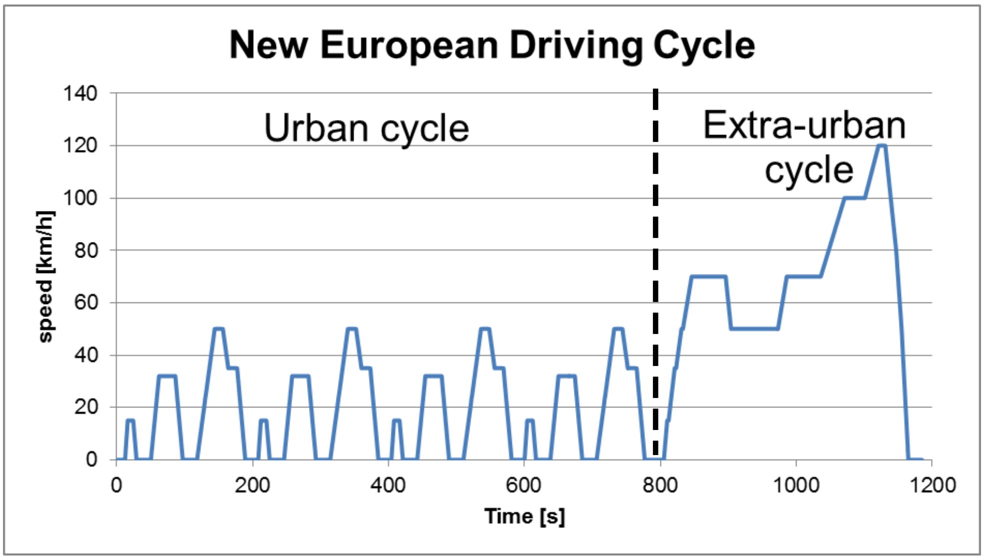

Fig. 2. Velocity profile of the full New European Driving Cycle

Newspapers and magazines (e.g. [FOC1]) often criticize the NEDC because the published fuel consumption is very often lower than the typical fuel consumption experienced during normal driving. Reasons for this are amongst others that the accelerations and the maximum speeds in the NEDC are lower than in reality and additional electrical consumers like air-conditioning or heating are switched off during the test [BAS1]. Although the NEDC does not represent the typical driving behaviour and therefore typical fuel consumption. But it is still due to the fact that the test is standardized and repeatable one of the best ways to compare different vehicles.

The NEDC in the driving simulator

The NEDC for real cars is normally performed on the roller bench. There a trained test driver gets the actually driven speed and the target speed displayed. The NEDC allows a tolerance of ±2 km/h of the defined speed [CEC1].

Fig. 3. The NEDC performed on a roller test bench with a monitor showing the target speed [FOC1]

In the driving simulator there is naturally no roller bench, so a long, straight and plain road was implemented for the test. Additionally a visualization of the NEDC was implemented in Adobe Flash and displayed in the instrument cluster. The visualization helps the test driver by showing actual speed, actual and upcoming target speed and tolerances (Fig. 4). With its support of it was possible for a test driver to perform the NEDC also correctly in the driving simulator.

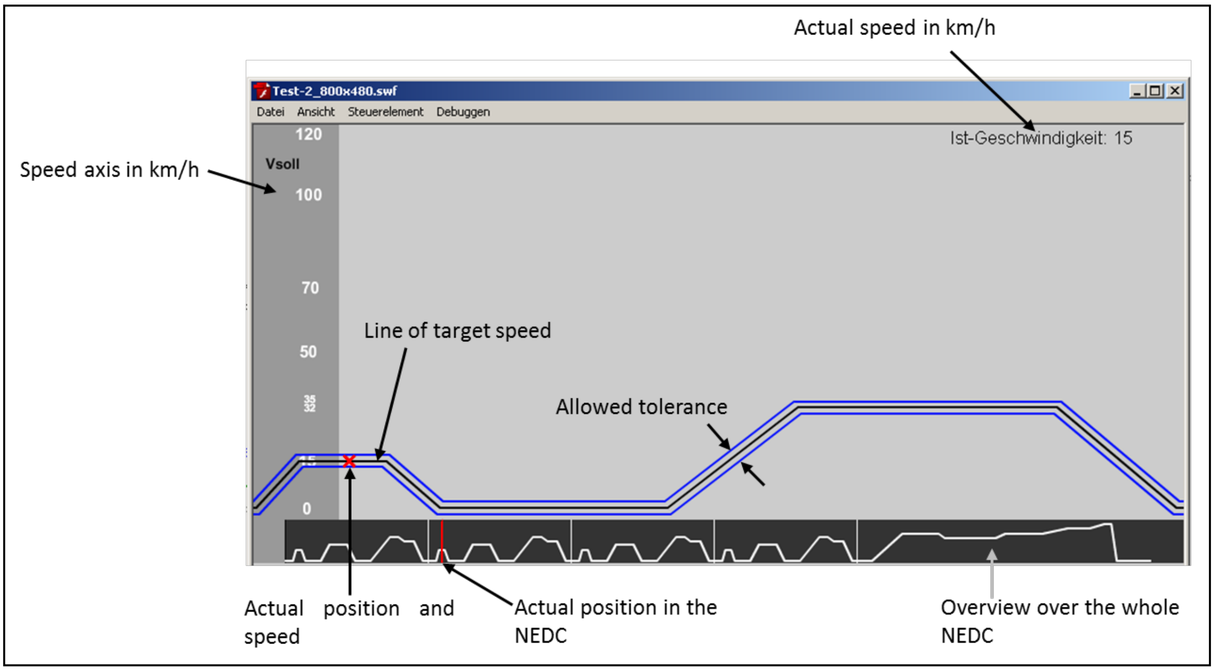

Fig. 4. Visualization displayed in the instrument cluster for performing the NEDC

Results of the NEDC

As it was described earlier a compact class car with 75 kW is modelled in the vehicle simulation. Therefore a Volkswagen Golf IV one of the best-selling cars in Europe with an 1.6 l engine and 75 kW was chosen for comparison. The data for the fuel consumption was extracted from the official brochures for this car [VW1]

The NEDC was carried out and checked multiple times in the simulator to guarantee that it was performed correctly. Figure 5 shows the results of the NEDC for the simulator compared to the Volkswagen. It can be shown that the fuel consumption of the simulation is although not identical to the Golf it is quite good comparable. This is a first indication that the fuel simulation is quite good.

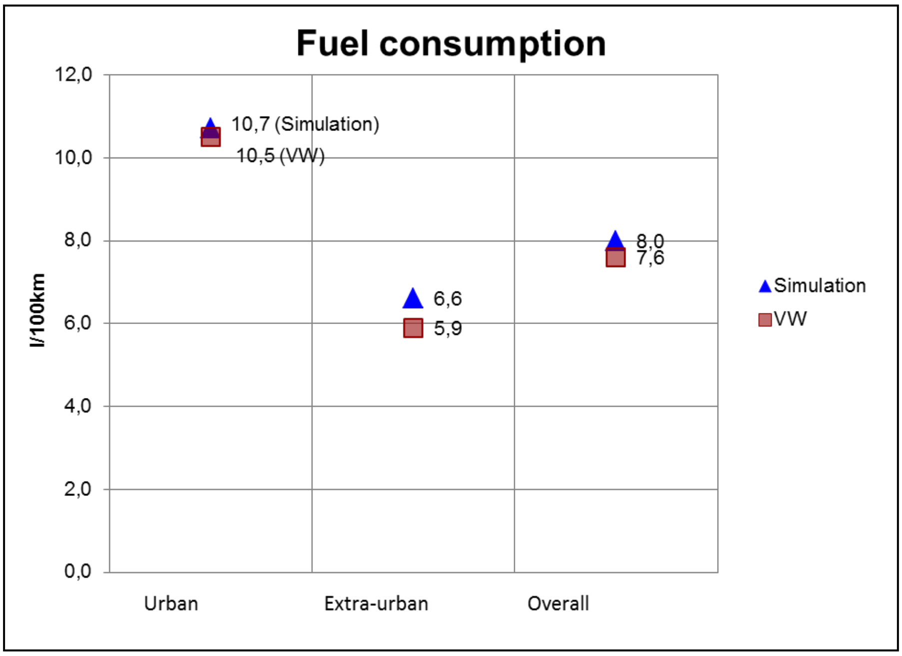

Fig. 5. NEDC fuel consumption of the simulation compared to the VW Golf IV

But the goal is not to get exactly the same fuel consumption as the VW. The target is to simulate a comparable characteristic of the fuel consumption during acceleration, deceleration and different speeds. Therefore a comparison of the fuel consumption trends of simulation and the Volkswagen Golf VI [VW2] during the NEDC was done (Fig. 6). Although the overall fuel consumption at the end of the NEDC is different, the graphs show that the behaviour of the simulation (black graph) and of the measured Golf (green and blue graph) is very good comparable. This proves that the results of the fuel simulation are very good in the case of using the NEDC.

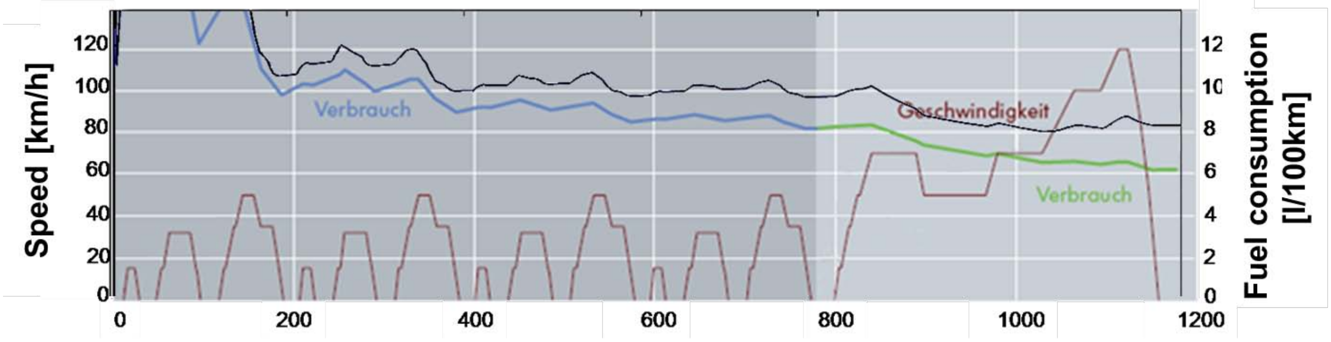

Fig. 6. Fuel consumption during the NEDC from simulation (black graph) and Volkswagen Golf (blue and green graph) [VW2]

Validation through driving tests in the simulator

In the previous chapters it could be shown that the results of the driving simulation are very good if the NEDC is used. But the problem of the NEDC is that it does not represent the typical driving behaviour. In the NEDC the accelerations are lower than under usual driving conditions and it has very long parts of constant speed which is not usual under normal driving conditions [GAS1]. Therefore a method was needed to validate the fuel consumption also for real driving conditions. A literature research for fuel consumption under real driving conditions was already done by Dorrer [DOR1]. The main results of his research were that the distribution of fuel consumption between different drivers lies between 25% and 62% of minimum fuel consumption. Also typical is that the distribution of the fuel consumption is asymmetric (Figure 7). On highways the fuel consumption depends mostly of the driven speed whereas in urban areas the fuel consumption is independent of the speed. There, in the city, differences of up to 50% can be observed. The idea for the following study was to look if the results Dorrer found for real driving scenarios can be repeated in the driving simulator.

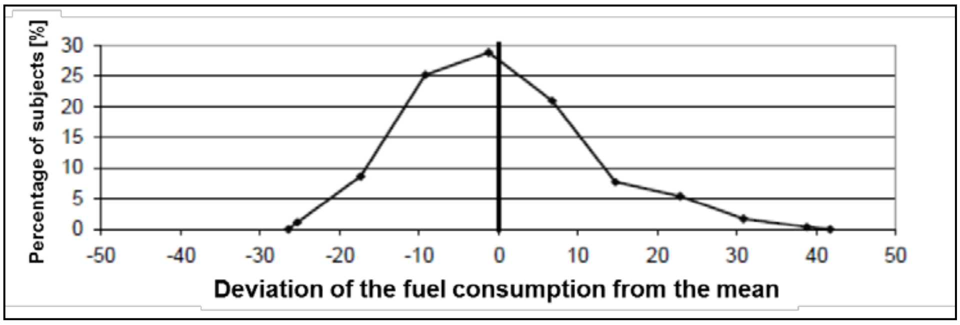

Fig. 7. Typical asymmetric distribution of fuel consumption for car drivers derived from a consumer questionnaire [DOR1]

Experimental design for the driving tests

The length of the test course is about 31 km. It includes 5 km of urban and 16 km of rural roads as well as 10 km of a highway. Different situations like traffic lights, different crossings, different speed limits and traffic conditions were implemented to have a typical driving scenario.

30 subjects aged between 19 and 57 (Mean: 24 years, SD: 7 years) took part in the experiment. The 17 male and 13 female drivers all held a valid driver's license. Five participants drove less than 5,000 km per year, four more than 20,000 km and the rest between 5,000 and 20,000 km per year. For most of the participants it was the first driving simulator study.

After an introduction and a practical drive in the simulator each subject had to do the test course. The participants got the advice to drive like they would do with their real car. They got no information or hint before they did the test drive about the goal of the study. After the test they were informed about the objective of the study they took part in.

Results of the driving tests

As not the absolute figures of the fuel consumption is of interest the mean fuel consumption of all participants is defined as 100%. The minimum fuel consumption reached by a participant for the whole drive is 74%, the maximum is 141%, the standard deviation 18.2%. Figure 8 compares the distribution of the fuel consumption for the simulation and for real world data. Although the data from the simulation was accessed through driving tests and the distribution for the real world is an outcome of consumer questionnaires no big differences between both distribution can be observed. Not only the minimum and maximum fuel consumption is the same, also between 25% and 30% of the participants of both studies have about the mean fuel consumption. The only conspicuous difference which cannot be explained is that at 30% over the mean fuel consumption in the simulation the percentage of subjects which have this fuel consumption is higher than expected.

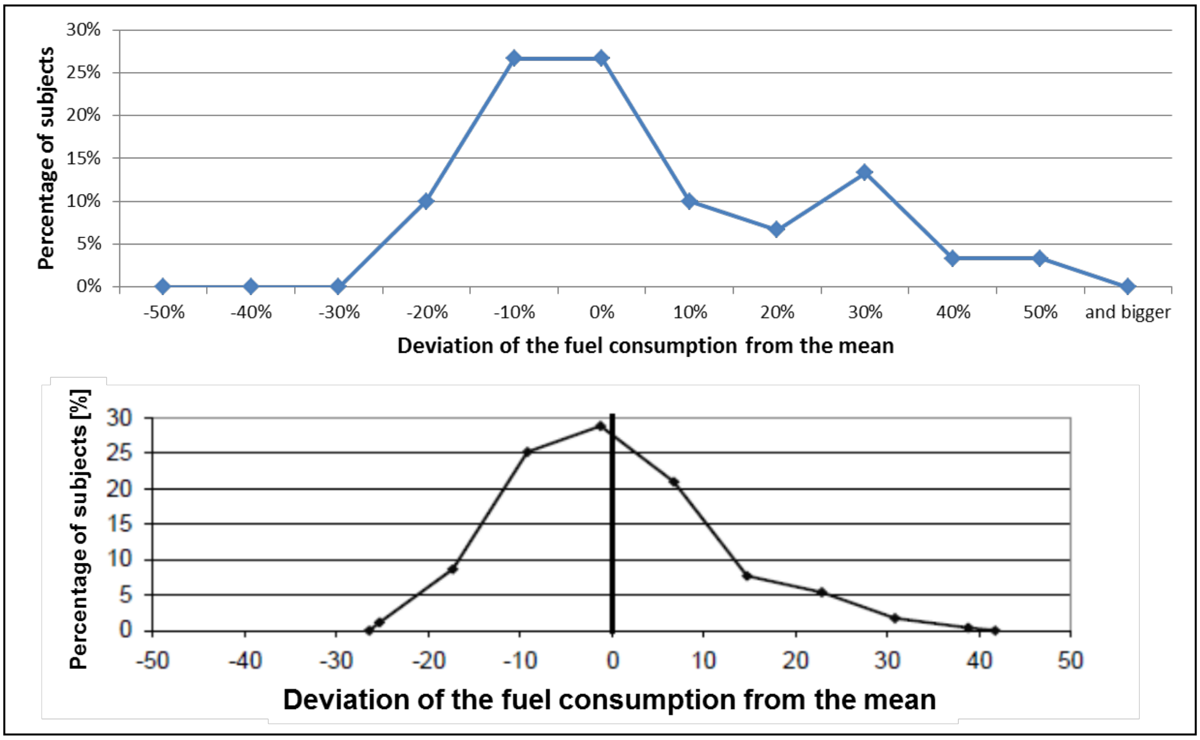

Fig. 8. Distribution of fuel consumption for simulation (top figure) and real world (bottom figure [DOR1])

According to Dorrer [DOR1] the fuel consumption on highways is mostly influenced by the speed. The regression analysis of the fuel consumption on 3 km free driving on a highway is highly significant. There a minimum fuel consumption of 43% and a maximum fuel consumption of 220% can be observed. Two urban scenarios where analysed as well. One was passing a roundabout in the city and one was passing a red traffic light. In both situations the regression analysis showed no significance between mean, maximum or minimum speed and fuel consumption. But the difference between maximum and minimum fuel consumption is over 42% (roundabout) and 28% (traffic light). This is consistent to the results of Dorrer [DOR1].

Fig. 9. Roundabout and traffic light scenario

Summary

The goal of the validation was to show that the driving simulator can estimate differences in fuel consumption for different driving behaviours. Two approaches were done to validate the simulation. The NEDC showed that the absolute fuel consumption of the simulation is not exactly identical to the for the comparison used VW Golf. But the comparison of the fuel consumption trend during the NEDC shows no big differences. Due to the fact, that the NEDC does not represent normal driving behaviour a second approach for validation was done. A study on a representative test route in the driving simulator with 30 subjects showed the distribution of the fuel consumption of the different drivers in the simulator is nearly identical to drives in the real world.

Overall it can be stated that for future studies differences in fuel consumption can be good measured. But it has still to be kept in mind that the fuel consumption depends not only on the individual driving behaviour, it also depends for example on the type of car, different environmental conditions etc.

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