Extended Flexible Environment and Vehicle Simulation for an Automated Validation

Albert Albers, Rolf Hettel, Matthias Behrendt, Tobias Düser and Alexander Schwarz

Abstract In FISITA 2010 IPEK (Institute of Product Engineering) introduced the vehicle-in-the-loop platform based on its X-in-the-loop approach (F2010-C-177) (Albers and Düser, Implementation of a vehicle-in-the-loop development and validation platform, FISITA world automotive congress, Budapest, 2010). It offers a methodology for multi domain product development and validation as well focuses on its key hypothesis that validation is the main task in every step of product development process. An open hardware and software platform allows integration of different real components and simulation models as well as the usage of established tools and methods for measurement and validation. The platform is based on a common hardware-in-the-loop System using extended I/O-communication to the vehicle and the test bench. The application is done in C code and Matlab/Simulink so an easy exchange of modular simulation models and test cases is feasible. The architecture of model-, component- and test case implementation simplifies the scalability as well as the modularization. IPEK uses this platform amongst others for its improved fully automated validation environment which allows the optimization of operating time for determination of shifting quality on the chassis dynamometer. The task is to perform several hundred gearshifts under particular reproducible conditions automatically such as engine speed or even battery state of charge, which normally a real driver had to perform on a real test track. Compared to road tests on the rig it is possible to reach time benefits of over 80 % by using a special driver

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model for acceleration (using gas pedal), deceleration (using dynamometer) and gear shifting (using tip signal at steering wheel). Since the vehicle behaviour on the road is constrained to different environmental conditions it is necessary to reproduce these conditions on the test bench accurately. Different resistances affect the vehicles responses such as shifting strategy, acceleration characteristics or fuel consumption which results in altering test results. State of the art for simulating environmental conditions and vehicle characteristics on the chassis dynamometer is the Road-Load-Simulation (RLS) which uses measured vehicle coast downs to map the static resistances of a real car on a real track onto the test bench. These coast downs have to be redone every single time components of the car or the environment changes. In addition, changing resistances during test like air drag due to headwind and rolling drag due to tire temperature or abrasion can't be simulated based on that static coast down. This paper shows an approach for simulating all kind of resistances that can appear and vary during the test such as air drag (wind), road gradient, road friction, curve resistance etc. in real-time. It can be used to drive test cases like the determination of characteristic shifting map in a more realistic way to perform better validated results. Central point is a configurable vehicle and environment model which has to be parameterized with data from the real car and track and then calculates the necessary dynamometer responses. Applied with a four roller dynamometer (two or even four driven axles) it offers the possibility to perform complex all-wheel manoeuvres e.g. such as μ-split or cornering with independent wheel behaviour and slip. Besides the advantages of this approach, an analysis of different influencing factors is shown in this paper.

Keywords Vehicle-in-the-loop · X-in-the-loop (XiL) · Model based testing · Environment simulation · Vehicle simulation · Road load simulation · Chassis dynamometer

1 Introduction

Vehicle testing in early stages of product development became state of the art for new vehicles. Including driving tests on the road, or the chassis dynamometer it got more and more important to know the exact vehicle behaviour, fuel consumption or other characteristic values as soon as possible in the product development process. Because most parameters of the complex system vehicle, which always stands in interaction with environmental influences, still can't be simulated reliable, tests with prototypes or pre-series cars are necessary.

Tests on the road are time-consuming (the prototypes, the staff and all the measuring equipment have to be transported to the test track) and not very reproducible (due to human deficiency in reaching defined operation points, which in consequence causes an higher amount of repetitions as well as weather conditions and curves). On the chassis dynamometer a robot can be used to drive the vehicle reproducible in every situation and independent of many unpredictable environmental influences like temperature, weather or road surface. The measuring equipment can be placed right beside the vehicle on the test bench, which makes special measurement setup in the vehicle dispensable.

However, influences of the environment are highly important for a realistic measurement of parameters like fuel consumption or driving performance, these influences have to be simulated on the test bench. Therefore, the state of the art solutions use static coast down measurements to extract the driving resistances and emulate them on the test bench. The problem with that is the extracted driving resistances are only valid for the exact same car (same powertrain components, aerodynamic form, tire pattern, wheel pressure, etc.) with the exact same environmental influences (same wind direction, road surface, temperature, etc.). If even one parameter changes, the driving behaviour on the test bench changes too, which could make the measured results invalid. So every time a parameter changes a new coast down has to be done, because there is no direct mathematical relation between the parameters of the resistance force curve and the physical phenomenon it's caused by.

A new method has to be found to optimize the determination of driving resistances on the chassis dynamometer without using these static coast downs so that in every vehicle configuration and driving situation the resistances are comparable to the ones on the road. It should also give the operator the possibility to interact with the resistances so he can vary specific resistances, always with the direct physical parameter which influences it.

2 State of the Art

2.1 Driving Resistances on the Road

The most important resistances on the road that influence the vehicle coast down behaviour are:

- air resistance (air drag and wind)
- rolling resistance (wheel contact on the road)
- power train losses (e.g. bearing losses, gearbox losses, motor drag)
- grade resistance (slope of the road)
- curve resistance (course of the road)

The driving resistances on the road are very well known and described in many different state of the art sources (see [1, 2]). Therefore the different resistances are mentioned only for the sake of completeness.

2.2 Driving Resistances on the Chassis Dynamometer

The resistances on the chassis dynamometer differ from the ones on the test track. Because the vehicle is not moving lateral or longitudinal, there is no air drag like on the road, where it has a wide influence. Due to vehicle fixation, all forces caused by air blower or external cooling fans have no influence on the driving behaviour of the vehicle on the test bed.

The roller surface is not plane but curved. That causes a higher rolling resistance for the wheel compared to the (almost) flat road surface. The differing rolling resistance on the chassis dynamometer can be calculated approximately with formula (1), where F_x is the rolling resistance on the road, r the wheel radius, R the roller radius [3].

$$F_{xR} = F_x \left(1 + \frac{r}{R}\right)^{\frac{1}{2}} \tag{1}$$

All the powertrain losses are (nearly) the same for the chassis dynamometer and for the test track. The vehicle uses all the same hardware components in both cases.

Grade resistances can be simulated on the test bed as well as curve resistances. Slopes and curves are not physically existent on the test bed but can be simulated by applying additional forces to the rollers.

2.3 Road Load Simulation

The standard method for transferring the real vehicle behaviour from the test track to the chassis dynamometer is the so called road load simulation (RLS) according to SAE J2264 [4]. It's a fast method for calculation of driving resistances on the chassis dynamometer. It's based on a pre-measured vehicle coast down and uses a simple mathematical approximation for computing-time reduction.

The Pros beside fast calculation and fast closed loop control are simple mathematics, robust and fail safe dynamometer operation and the possibility to simulate road gradients.

The key fact, which makes the big difference to the presented approach, is the way the dynamometers are operated. The road load simulation uses torque resp. force control. That means the output signal of the calculation is the dynamometer torque not the speed. The dyno controller then adjusts the dyno torque, applied to the rollers. That results in a roller speed change corresponding to formula (1), where $M(t)$ is the torque, J is the mass moment of inertia and $\ddot{\varphi}(t)$ is the rotational speed.

$$M(t) = J \cdot \ddot{\varphi}(t) \tag{2}$$

2.4 Approach to Calculate the Required Torque

First of all a coast down curve has to be recorded. Therefore, it is important to use exactly the vehicle which should be tested on the test bench. There must not be any differences in aerodynamics, mass, tires etc. It's clearly visible that changes in one

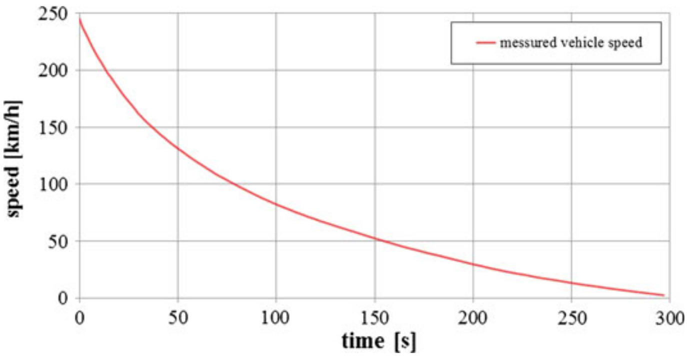

Fig. 1 Measured coast down curve $v(t)$

of these parameters affect the driving resistances (mentioned above) and therefore the coast down curve [5].

In Fig. 1 is shown a coast down curve of a common passenger car. It was measured on the test track with neutral gear position an approximated for high speeds. Some of the cars specs are:

- vehicle mass (with driver) $m = 1600kg$
- drag coefficient $c_w = 0.3$
- reference area $A = 2.05m^2$
- summer tires

With the coast down curve it is possible to calculate the effective driving resistance at each time. That includes air resistance (wind could be included), rolling resistance, rest powertrain resistances (of not uncoupled powertrain components like differential and axle bearings), tire bearing resistances and possible grade resistance (both not effective in this special case) of that specific vehicle configuration.

According to famous formula (1), where $F(t)$ is the sum of retarding forces, m the vehicle mass and $a(t)$ the vehicle acceleration, the reacting Force can be calculated. The acceleration results from differentiating the velocity plot.

$$F(t) = m \cdot a(t) \tag{3}$$

Figure 2 shows the calculated forces plotted over the corresponding vehicle speed $F(v)$.

By using a least square approach, the force over speed curve can be approximated in a wide speed range. As basic function serves a quadratic equation according to formula (1), where $F_0,\ F_1,\ F_2$ are unknown parameters which have to be estimated.

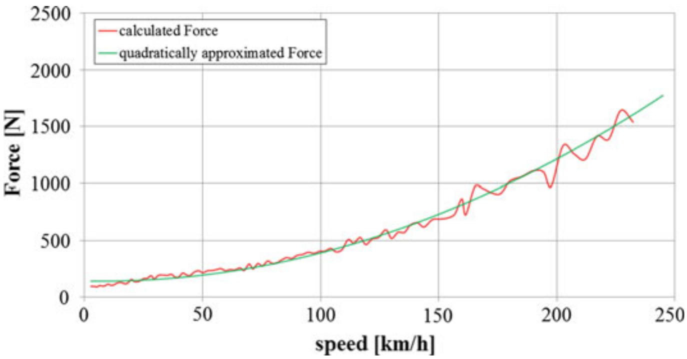

Fig. 2 Calculated and quadratically approximated force in tire contact point

$$F(v) = F_2 \cdot v^2 + F_1 \cdot v + F_0 \tag{4}$$

Applied to the curve shown in Fig. 2, the parameters for the least square approach result in $F_0 = 142$, $F_1 = -0.407 \frac{N \cdot h}{km}$ and $F_2 = 0.0289 \frac{N \cdot h^2}{km^2}$.

These parameters can be used to calibrate the test bench. Before it's possible to drive with the vehicle on the test bench it's necessary to do a parameter correction. The parameters calculated above are valid for the vehicle driving on the real test track. But when the vehicle drives on the test bench some influences on the vehicle coast down behaviour drop out and some come along. For example the air resistance drops out and an additional rolling resistance due to curved roller surface comes along. To adopt these changings it's necessary to measure the difference in coast down behaviour of the vehicle on the track and on the test bench without changing any parameters. This difference is also transformed into another Force over speed curve represented by another set of test bench parameters. In an iterative process these test bench parameters are adopted to match the coast down curve with the vehicle on the test bench with the one from the road.

Finally with these two sets of parameters every speed is attributed to one Force which then can be transformed into a torque resp. force with the radius of the roller. This torque is provided directly to the dynos.

3 Extended Validation Platform

As described above, the state of the art process to apply a road load simulation on the chassis dynamometer is based on a static coast down curve, and an iterative but static parameter adaption.

The here shown method uses a real time based vehicle and environment model to calculate all the driving resistances on the test bed without using a measured coast down. Goal of the model is to build up a simulation which can be parameterized with few characteristic values which are easy to find out and to produce a realistic driving behaviour. For example these parameters could be vehicle mass, tire size, tire type and air drag coefficient. Furthermore it should offer more possibilities to vary the driving behaviour due to different road and vehicle influences and it should be easy to parameterize.

In the paper F2010-C-177 from FISITA 2010 [6] the IPEK introduced the vehicle-in-the-loop platform based on its X-in-the-loop approach. The described platform is now used to build up the simulation of driving resistances. AVL InMotion powered by IPG CarMaker is chosen for the environment and vehicle simulation. In addition a model based on Matlab/Simulink was used for the vehicle which considers all driving resistances but does not use a vehicle model in an environment. The resistances are calculated directly with the corresponding equations.

3.1 Components of the Simulation Platform

At first there's the chassis dynamometer which in this special case is a 4 × 2 roller test bench (4 rollers, 2 driven axles). So it's possible to carry four wheel drive vehicles but the simulation is then limited in its possibilities (see below) compared to a 4 × 4 roller test bench (4 separately driven rollers). The dyno provides a rotary speed which is given by the simulation model. The speed of each driven roller is regulated separately so different speeds can be provided. The dyno controller is running in mode 'speed control', which allows the simulation to regulate the roller speed directly, not by regulating the torque.

The vehicle is mounted on the chassis dynamometer and fixated with a wheel hub fixation. The wheel hub fixation induces the less chassis movement and does not allow much longitudinal movement of the wheel relative to the roller apex. That improves the measurement of the dyno torque which in consequence improves the simulation results. Other vehicle fixations are feasible as well. The resulting chassis movement does not correlate with the one on the road which was neglected in the first step. The here shown tests are done with a front driven vehicle with approximately 66 kW. It has winter tires mounted and regular aerodynamic characteristics.

On the other hand there is AVL InMotion powered by IPG CarMaker [7] which runs the vehicle and environment model and represents the base for maneuver based testing on the chassis dynamometer.

The simulation uses a freely configurable vehicle model (based on the IPGCar [8]) which includes a powertrain, tire, chassis suspension, steering and aerodynamic model beside others. These simple physical models are sufficient for the performed tests what was shown by the received results. The model gets

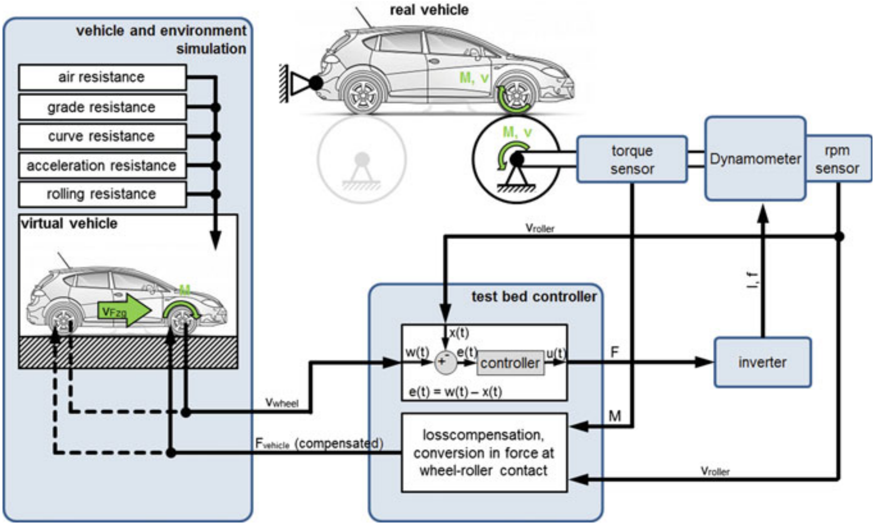

Fig. 3 Components of the simulation environment

parameterized with the parameters from the real car used for the tests. The most important parameters with the greatest influence can all be found very easy in data sheets or on the manufacturer's homepage. Less important parameters have to be measured or can be used from comparable vehicles. For easy vehicle creation, the software provides the so called Vehicle Generator.

The virtual car drives in a virtual environment which induces resulting forces to the car. Beside air drag caused by aerodynamic coefficient and wind, the road has a big influence on the resulting forces. For example a downhill slope causes positive forces, air drag, rolling resistances and steering causes negative forces.

Figure 3 shows the build-up of the simulation environment with its components and interfaces schematically. The build-up is similar for each driven roller but here shown only for one roller. The torque from the dynos torque sensor is measured and serves as input for the simulation. The torque signal is converted to a Force at the wheel contact and the roller losses (bearings) are compensated in the test bed controller.

This measured force is added to the forces at the virtual wheel in the simulation which causes the virtual vehicle to accelerate or decelerate. The resulting new speed from the virtual car serves as set value for the test bed controller. The test bed controller then regulates the speed of the dynos. Based on the virtual car driving curves or occurring wheel slip, the speed of each roller is regulated individually, corresponding to the virtual wheels in the simulation.

Figure 4 shows a comparison of the different approaches. The red graph represents the reference coast down measured on the real test track. The green graph shows the results on the test bench with the Simulink model which was used in the first step. All parameters in the model were taken from the vehicle that was used

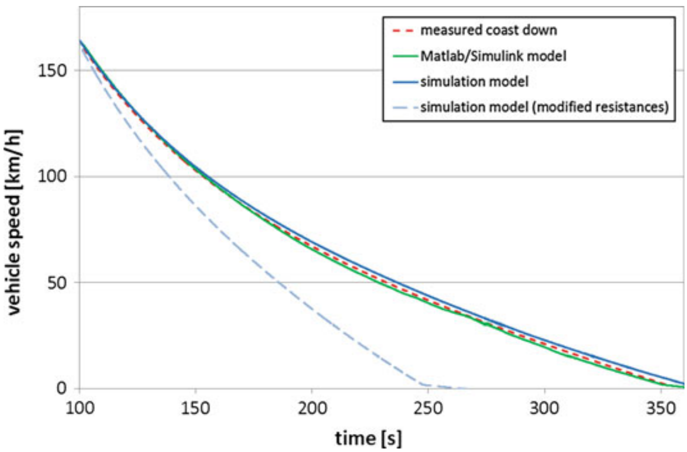

Fig. 4 Comparison of the different approaches and the measured caost down on the road

for the reference coast down. The blue graph shows the new approach using the simulation model for calculating the driving resistances (including vehicle and environment simulation). It matches the reference coast down very good revealing the validity of the presented approach. Finally the light blue graph shows the result with simulation model using slightly modified rolling resistances. Increasing the rolling resistance shortens the coast down and vice versa.

3.2 Characteristics of the Simulation

The new method for simulating the driving resistances has all the functionalities of the state of the art road load simulation and brings along many others. Some are mentioned below.

The virtual environment in which the virtual car is driving gives the information of slope and curves. In case the virtual car is driving uphill or in a curve the simulation raises the torque given to the virtual wheel hub which causes a reduction of the vehicle speed. When driving curves in the simulation the wheel speeds can be calculated independently to realise the different speed of the inner and outer wheels. On a four wheel dyno it is possible to analyse the behaviour of differentials while driving curves without the need to steer (which is not possible on a normal chassis dynamometer).

Because the vehicle model uses a simple air drag calculation (a real fluid simulation is not implemented yet due to performance reasons and the limitations given by the real time environment) it is possible to change aerodynamic parameters like drag coefficient or reference area while the simulation is running and the car driving on the test bed. A change in aerodynamics could be caused by rear spoiler which comes out at 80 km/h on the Porsche 911.

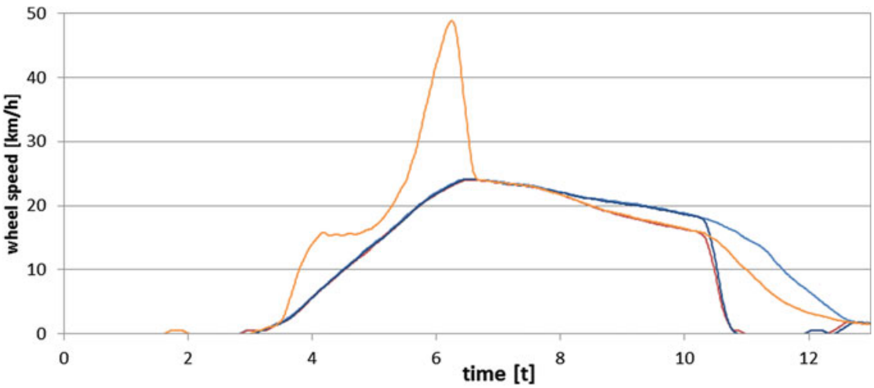

Fig. 5 Acceleration on ice (*left wheels* on ice, *right wheels* on asphalt), *front left wheel* slipping; *curve* to the *left* (with slip) and blocked rear wheels

A wind simulation makes it possible to simulate different wind directions and therefore the varying air drag in driving direction.

The simulation is based on a physical model where parameters like vehicle mass, center of mass or even trailer mass have an influence on the virtual driving behaviour and the real torque applied to the test bed. Because the mass although has an influence on the coast down it can be used to compensate weight influences like measuring equipment or driver which are installed on the test vehicle but should not be considered in the resulting driveability. Simulating trailer load could although be a use case for this simulation.

Many applications on the test bed make it necessary to use special roller tires (e.g. for acoustic measurements). The changed tire pattern causes a differing rolling resistance. To obtain the same coast down curve as with normal tires it's possible to change the tire model in the simulation.

Depending on the roller count, dynamometer power and the roller inertia it is possible to simulate different road surfaces (friction coefficients). These could be caused by changing weather in the environment simulation e.g. rain, snow or ice or other changes of the road surface like asphalt or gravel. It's not possible to simulate the real slip between tire and roller with this method but by allowing high accelerations of the roller the wheel slip can be played to the vehicle ECU. The higher the acceleration of the free spinning wheel is, the stronger the dyno has to be (for the tested car the slipping wheel acceleration on ice is about 10 m/s, see Fig. 1). For Example it's possible to simulate a slipping front axle on a slippery road (in the dynamic limits of the test bench) and use it to analyse the vehicles ESP. On a 4 × 4 roller chassis dynamometer where each wheel is controlled separately, μ-split drive can be simulated as well as blocked wheels (Fig. 5).

4 Summary and Outlook

In the paper was shown a method to calculate driving resistances based on a real time vehicle and environment model and use these to simulate the driving resistances on the chassis dynamometer.

The model is simple to parameterize as it's based on physical correlations and not on a measured coast down. It considers the important driving resistances and has many benefits compared to the road load simulation.

First comparisons of driving test on the road and the chassis dynamometer show good correlations between the results from the test track and the chassis dynamometer. The new simulation approach performs good compared to the measured coast down and the state of the art road load simulation.

Furthermore there's a good usability of this method for many other applications on the chassis dynamometer e.g. analysis as well as optimization of shifting strategies and the corresponding gear shifting quality [9]. Another application could be the use for calibrating or conceptual tests of vehicles using torque vectoring.

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