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(former **LMS International NV**)

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MODRIO

"D3.1.4 – Use of state estimation methodology for virtual measurement channels and advanced data processing"

"WP3.1: Continuous systems"

"WP3: State estimation and system monitoring"

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Executive summary

The idea behind model-based testing is to use the knowledge embedded in models to get more information out of physical testing. By using experimental measurements together with model information, one can implement a 'virtual channel' that can 'virtually measure' signals that cannot be measured directly (for instance, as no sensor can be added at a certain location, or as a direct measurement of a certain quantity is not possible for another reason).

An important challenge that must be overcome is the post processing phase of huge amounts of test data. To address this, one can use state estimation methodologies to reduce the number of measurement channels and to increase the accuracy of the results. In this deliverable, this rationale is explained on the basis of a relevant industrial case: the measurement of the forces acting in the interface between the body and suspension of car. A 1D simulation model is adopted to implement a virtual channel to measure the body corner forces, which are relevant to be able to assess the handling performance of a car. It has been shown that these forces can be estimated using the 1D model and data from sensors that are typically mounted on a car when performing handling maneuvers on a test track.

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1. Development of a state estimator for the identification of the forces acting in the interface between the body and suspension of car

1.1. Introduction

It is well known that the flexibility of a car body has an influence on vehicle dynamics performance. The importance of body flexibility during handling maneuvers has already been shown in several studies; see e.g. [1], [2] and [3]. However, there are still many unknowns in the relation.

In order to get more insight in the relation, a unique test based procedure has been developed for identifying the individual forces acting in the body-to-suspension interface. In addition to computing the forces acting in the interface, the procedure also yields the deformations of the body. The procedure has been applied in several commercial projects for car OEM's (Original Equipment Manufacturers). The OEM's were very enthusiastic about the results obtained so far, but are now hesitant to order new projects due to the high cost and the long time-frame of the projects.

Because of these disadvantages of the existing test-based approach, there is a high interest in the development of a new approach which could reduce the time and cost needed for the force identification. This document presents a first step in the development of such an approach.

1.2. Shortcoming of the existing test-based approach

The existing test-based approach makes use of strain gauges to measure the deformation of the car body. The advantage of strain gauges over e.g. DC accelerometers is that they are capable of accurately measuring the quasi-static body-deformations (the frequency range of interest for vehicle dynamics is 0 to 5Hz), while the signals are not saturated by the rigid-body movement which occurs during a maneuver. When using DC accelerometers, on the other hand, the signal would be dominated by the rigid-body motion and the information about the deformations would be "hidden" inside this signal.

The procedure consists of three steps, see Figure 1:

- The first step is performed in so-called trimmed-body conditions, which means that the suspension needs to be removed. The car body is instrumented with strain gauges and forces are applied at the connection points between body and suspension. Transfer functions from the force inputs to the strain responses are determined. All the transfer functions are assembled in a huge FRF (Frequency Response Function) matrix which needs to be inverted for use in the second step of the procedure.
- In the second step, the car is first brought back in its original conditions without removing the strain gauges. Next, handling maneuvers are performed on a test-track using either a test pilot or a test robot. During the maneuver, strain data is recorded. With the measured operational strain data and the inverted FRF matrix from the previous step, the time-domain forces acting in the body-to-suspension interfaces can be estimated.
- In the final step, the car body is instrumented with accelerometers and a modal model of the car body is derived by applying force inputs at the connection points and measuring FRF's from these force inputs to accelerations. Next, the forces identified in the previous step are applied to the modal model. In this way, the deformation of the body during the maneuvers can be computed and visualized.

More details about the procedure can be found in [1].

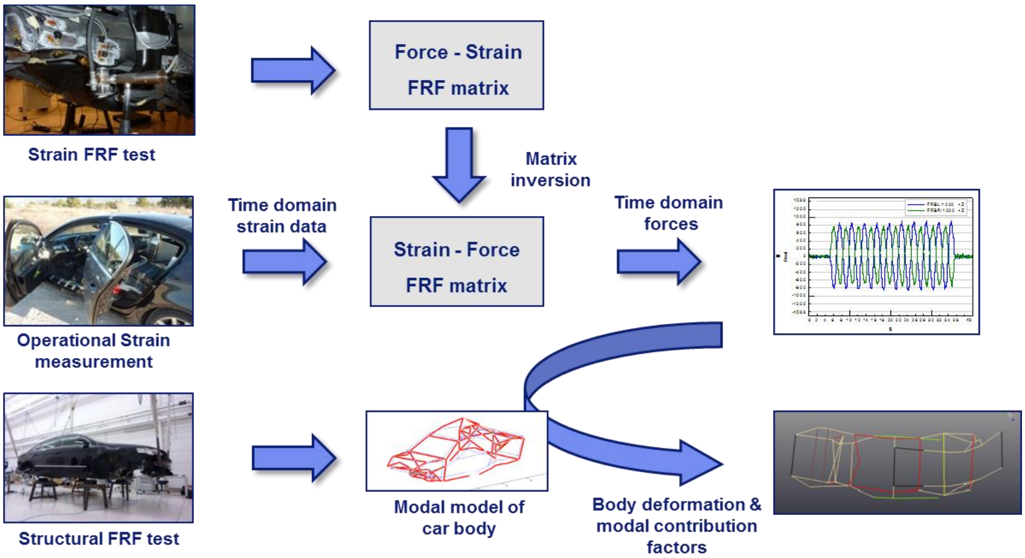


Figure 1: Overview of the test-based procedure used to identify the forces acting in the body-to-suspension connection points.

Although the procedure yields a lot of insight in the effect of body flexibility on ride and handling, there are a number of shortcomings:

- To obtain reliable results, an over-determination with a factor of at least 3 to 5 is needed, i.e. the number of strain gauges to be instrumented equals 3 to 5 times the number of forces to be identified.
- The instrumentation is very expensive. A first reason is because strain gauge instrumentation is very time consuming (approx. 10 gauges a day, per person). Additionally, the number of channels is very high (200 and more) because of the over-determination.
- Despite the over-determination, the matrix inversion methodology turns out to be ill-conditioned, giving results with a limited accuracy (10%).

As already discussed, car OEM's were very enthusiastic about the results obtained so far, but are now hesitant to order new project due to the high cost involved and due to the fact that the time frame for doing such a project doesn't fit anymore in their development cycles that always become shorter.

1.3. A state estimation approach to corner force identification

As discussed before, there is a high interest in the development of a new approach which could reduce the time and cost needed for the force identification. The major line of thought for achieving this is by replacing the strain gauges by other sources of information. In the remainder of this section, a first step towards such an approach is considered. We do not address the identification of the full set of forces acting in the interface between the body and suspension, but a simpler problem: the identification of the four so-called corner forces. The relation between the individual forces acting in the body-to-suspension interface and the corner forces is as follows: a corner force (e.g. the front left one) equals the sum of the individual interface forces over a corner of the vehicle (e.g. the front left corner).

The approach considered here is based on state estimation. The state estimator will employ a full vehicle model developed in LMS Imagine.Lab Amesim (discussed in more detail in the next section). The corner forces in the Amesim model are known nonlinear functions of the state variables. Hence, the estimation of the corner forces boils down to a nonlinear state estimation problem.

One of the major objectives of this research is to determine the type of sensors that are needed by the state estimator in order for the corner forces to be observable. In addition to this, also the required sensor accuracy will be investigated.

On the longer term, the objective is to extend the approach to the estimation of the individual forces acting in the body-to-suspension interface. This will require a more complex vehicle model which includes the individual interface forces.

1.4. The full vehicle AMESim model

Figure 2 shows the AMESim full vehicle model under consideration. It consists of a chassis model, simple suspension models (spring and damper), Pacejka 92 tire models, and road adherence models. The chassis model is devoted to longitudinal and lateral vehicle dynamics and is in fact a simple multi-body model consisting of 10 bodies: 1 body for the steering rack, 4 for the spindles, 4 for the wheels and 1 for the car body. All the 10 bodies are modeled as rigid. Taking the relative motion between the 10 bodies into account, the model has 15 degrees of freedom, see Figure 3:

- The car body has 6 degrees of freedom: roll, yaw, pitch and translation in X, Y and Z direction
- The steering rack has one degree of freedom: translation along its axis
- Each of the 4 spindles has one degree of freedom: vertical lift
- Each of the 4 wheels has one degree of freedom: rotation.

As a result, the model has 31 state variables: 2 state variables per degree of freedom (one “position” and one “velocity” state variable) and 1 dummy state variable.

The parameters of the chassis model are masses and inertias of the different bodies, and kinematic tables describing the variation in steering angle, wheelbase, track width, camber angle and self-rotating angle as function of vertical wheel lifts and steering rack displacement. These parameters were determined based on measurements performed on a real car during a maneuver. The parameters of the suspension, tire and road adherence models were not determined based on measurements, but yet realistic values are used.

The body-to-suspension interface is modeled in low detail in the AMESim model. The model does not yield the individual forces acting in the body-to-suspension interface, but is limited to the four corner forces.

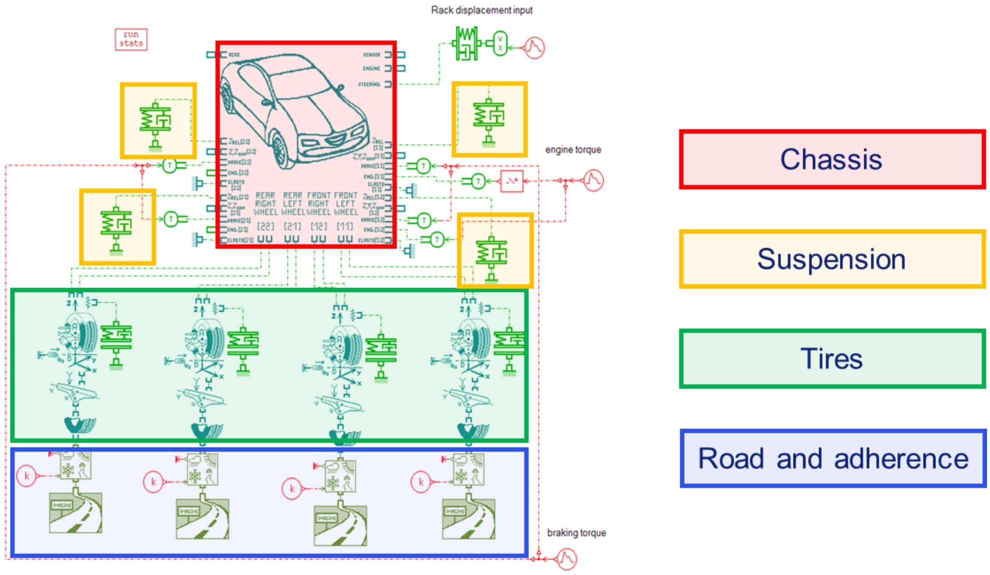


Figure 2: full vehicle AMESim model used for identifying the corner forces.

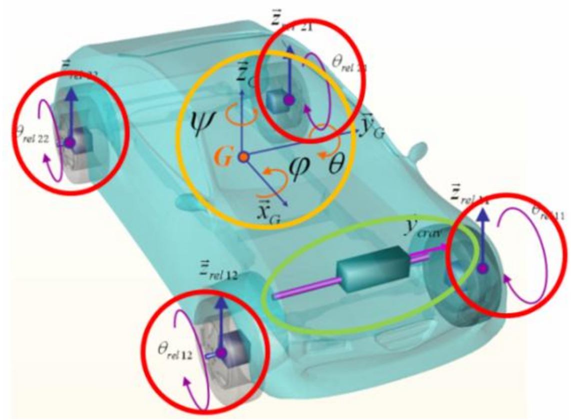


Figure 3: Degrees of freedom of the AMESim model

1.5. Implementation of the state estimator

This section discusses the implementation of the force estimator. As shown in Figure 4, it was decided to use a Kalman filter which is a recursive algorithm consists of two steps: the so-called "time update" and "measurement update".

Since the Amesim environment does not provide any libraries or other capability for implementing a state estimator in the tool, it was chosen to implement the Kalman filter in Matlab. However, for the simulations of the full vehicle model during the time update, it was explicitly chosen to use the AMESim solver. Another option would be to extract the equations – ODEs (ordinary differential equations) or DAEs (differential algebraic equations) – from the model and solve these equations in Matlab. However, this has as drawback that the equations are not solved in their native tool.

The traditional usage of the AMESim solver (i.e. the usage for which it is optimized), consists in performing one long model simulation or a batch of long simulations. During the Kalman filter process, the solver is used in a different way. It will be called during each time update with the same model to perform a simulation covering only a very short time period. Assume for example that measurements are acquired at a sampling rate of 100Hz. If the Kalman filter needs to process the measurement data acquired over a time span of one second, the AMESim solver will be called 100 times, each time with the same model, but a different initial state and performing a simulation covering only 0.01s. Those many short simulations of the same model that need to be performed by the AMESim solver are fundamentally different from the traditional usage of the AMESim solver. It was found that the AMESim solver is not optimized for performing such simulations: it checks the license and loads the necessary data files at the start of each simulation, which yields a huge overhead.

Since the AMESim model is nonlinear, an Extended Kalman filter (EKF), which makes use of model linearizations, will be used. Besides an estimate of the state, the Extended Kalman filter also propagates the so-called error covariance matrix. In order to propagate this matrix, a linearized model in state-space form is required. AMESim allows extracting such a model.

It is clear from the previous discussion that communication between AMESim and Matlab is needed in order to implement the EKF. Figure 5 presents the required communication. The existing AMESim-Matlab interface was used to implement the communication. This interface allows setting the initial state of the AMESim model, calling the AMESim solver to perform a simulation, and extracting the final state and linearized state space model from within the Matlab environment. In this interface, the communication is performed by writing to / reading from files. Notice that communication between Matlab and AMESim is needed two times per recursion step of the Kalman filter: at the start and at the end of each model simulation. Since writing and reading to/from files is extremely slow compared to writing/reading to/from memory, this adds a lot of overhead to the computation time of the Kalman filter.

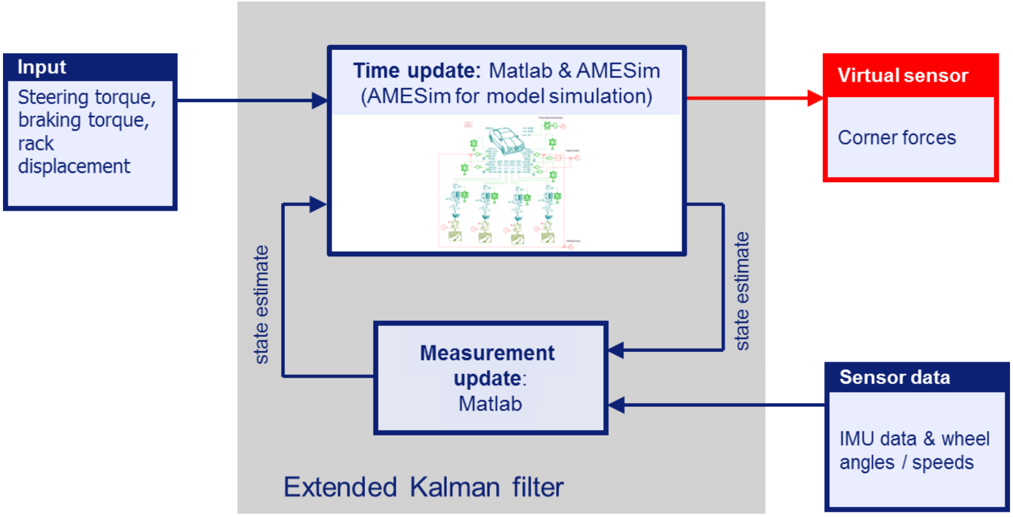


Figure 4: Schematic of an Extended Kalman filter for corner force estimation. The Kalman filter is implemented in Matlab, except for the simulation of the full vehicle model, which is performed using the AMESim solver.

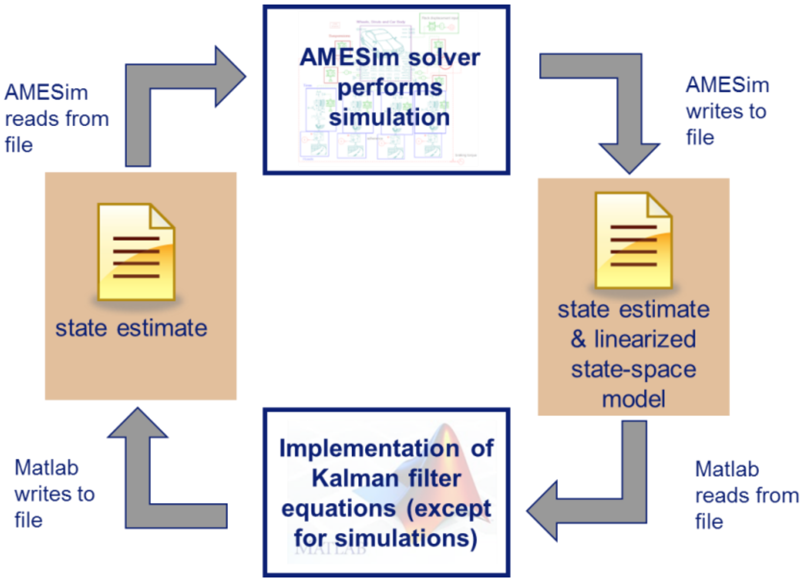


Figure 5: Communication between Matlab and AMESim.

The measurements to be used by the Kalman filter and their accuracy were determined by experimenting with different combinations of possible measurements. Only measurement data that can be easily acquired in a real car was considered. For each combination, observability of the linearized state-space model was checked. It was concluded that the following set of 10 measurements yields linearized state-space models which are observable in each time step:

- X, Y, Z position of the car-body,
- Yaw, roll, and pitch angle of the car body,
- Rotation angles of each of the four wheels.

These measurements can indeed be acquired in a real car. For the measurement of the position and orientation of the car body, an inertial measurement unit can be mounted in the vehicle.

1.6. Simulation setup

The feasibility of the Kalman filter for estimating the corner forces was assessed using simulations. The following procedure was used:

- In a first step, profiles for the inputs of the AMESim model (engine torque, braking torque and steering rack displacement) were defined. These profiles were defined such that the resulting maneuver of the car is a slalom maneuver at a constant speed. Next, the AMESim model was simulated using these inputs. During the simulation, the time history of the four corner forces, the position and orientation of the car body and the rotation angles of the wheels are recorded and written to a file. These corner forces are considered to be "truth" and are to be estimated by the Kalman filter. The position and orientation of the car body and the rotation angles of the wheels will be used as measurements by the Kalman filter. Noise was added to the measured variables in order to mimic a real sensor. The noise was chosen as zero-mean white noise with a normal distribution. The standard deviation was chosen based on the accuracy of a real high-end inertial measurement unit: the Inertial+ system from Oxford Technical Solutions (http://www.oxts.com). This system combines data from a GPS receiver with inertial data. The measurement accuracy of the system together with the standard deviation of the measurement noise derived from it, is shown in Figure 6.
- In the second step, the Kalman filter is employed to estimate the corner forces. The same inputs as in the previous step are applied to the AMESim model. In order to make the simulations more realistic, a slightly different model is used as in the previous step. One of the most difficult parts to model in a vehicle is the tire. Tire models are empirical and contain a lot of parameters that need to be estimated. Hence, tire models are typically error-prone. Therefore, the values of some tire parameters were altered with respect to their values used in the first step. Next to a slightly different model, also the initial state of the model was chosen differently. This is done to mimic the fact that the initial state is in practice never exactly known.

Specification - Typical for RTK GPS

Parameter	Inertial+
Positioning	GPS Receiver Dependent
Positioning Accuracy	0.02m
Velocity Accuracy	0.05km/h RMS
Acceleration – Bias – Linearity – Scale Factor – Range	10 mm/s² 0.01% 0.1% 100 m/s² (Optional 30G)
Roll/Pitch	0.03°
Heading	0.1°
Angular Rate – Bias – Scale Factor – Range	0.01°/s 1s 0.1% 1s 100°/s
Update Rate	100Hz
Calculation Latency	3.9ms
Power	9–18Vdc, 15W
Dimensions (mm)	234 x 120 x 76
Weight	2.2 kg
Operating Temperature	–10 to 50°C
Shock Survival	100G, 11ms
Internal Storage	2 GB
Dual-Antenna	See: Inertial+2

Note: The definitive specifications depend on the attached GPS receiver. These specifications apply to a Novatel RT2 GPS card.

Measured variable	Unit	Standard deviation of measurement noise
X,Y,Z position of car body	[m]	0,01
X,Y,Z velocity of car body	[m/s]	0,1
Yaw, Pitch, Roll angle of car body	[deg]	0,01
Yaw, Pitch, Roll angular velocity of car body	[deg/s]	0,1
Wheel angles	[deg]	1

Figure 6: Specifications of a high-end IMU and standard deviations of the measurement noise derived from it.

1.7. Simulation results

The estimation results of the Extended Kalman filter are shown in Figure 7 and Figure 8. The terminology is as follows:

- "True" refers to the results of the AMESim simulation used to generate the measurement data.
- "Estimated" refers to the results of the EKF which uses an AMESim model with slightly different tire parameters as "True" and starts from a different initial state as "True".
- "Modified" refers to the results of an AMESim simulation using the same model and initial state as in "Estimated". This would be the same as applying a Kalman filter, and performing only time updates and no measurement updates.

The error of "Modified" / "Estimated" is computed as the difference between "Modified" / "Estimated" and "True". The performance of the EKF is assessed from the difference between the error of "Modified" and the error of "Estimated". As can be seen in Figure 7, the error of "Estimated" is in general smaller than that of "Modified". This is especially true at the time instant that the force is most rapidly changing (due to the maneuver). The error in "Modified" shows higher peaks at these time instants. The same conclusion can be drawn from Figure 8, in which the average error for "Modified" and "Estimated" are compared for all four corner forces.

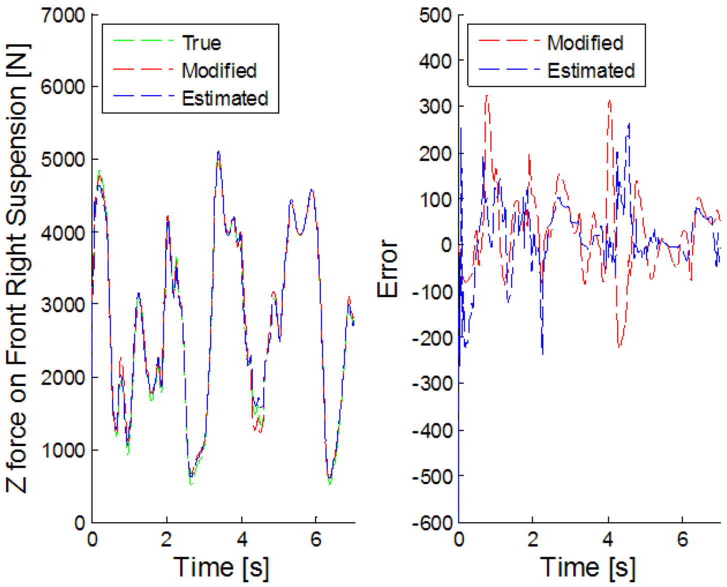


Figure 7: Corner force estimates obtained using the Extended Kalman filter.

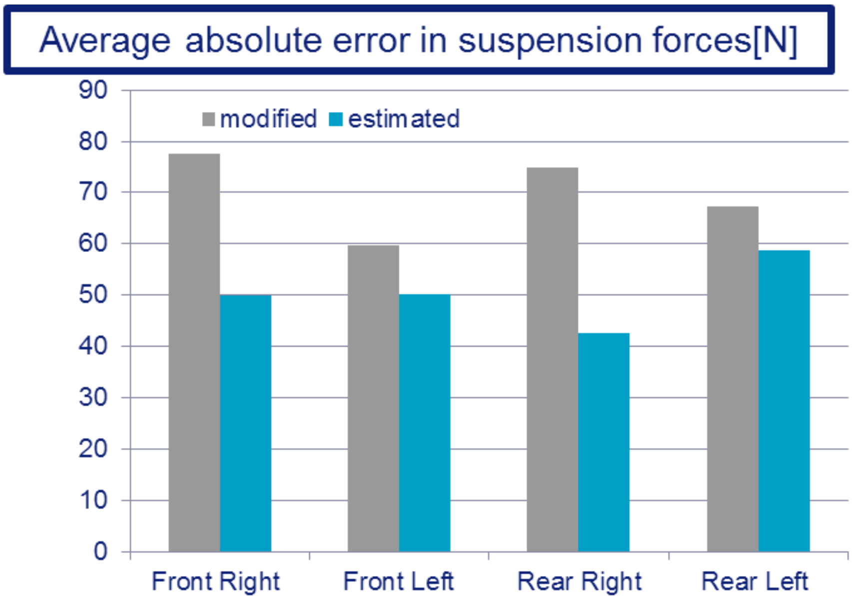


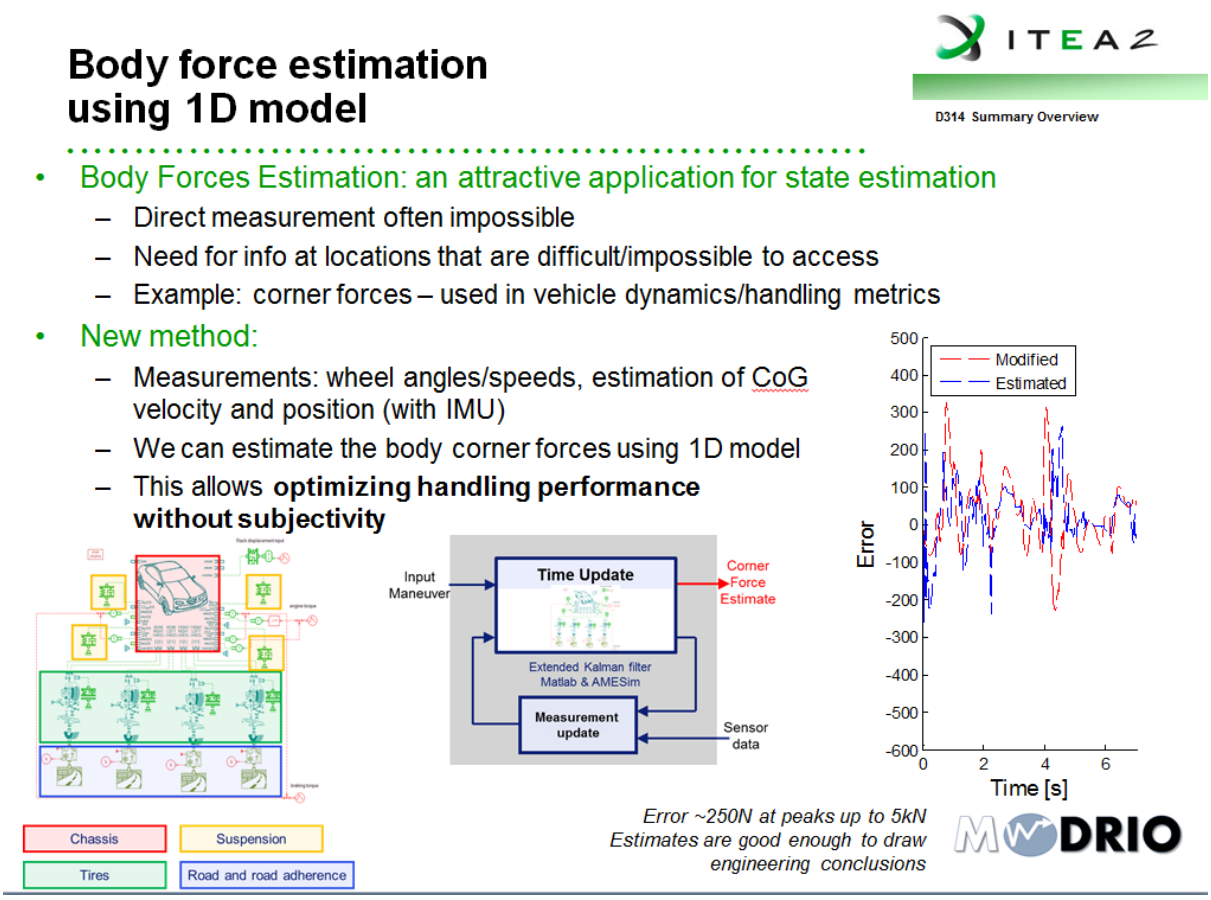
Figure 8: Average absolute error in the estimates of the corner forces.

2. Conclusions and Discussion

In order to assess and optimize vehicle handling performance, automotive OEMs make use of subjective evaluation by humans. Such tests require highly experienced test drivers (typically 1 or 2 senior experts per company). The approach developed here allows assessing handling performance in an objective manner. Indeed, the corner forces estimated by the Kalman filter yield indispensable information about the handling of a vehicle. In addition, the approach does not require more sensors to be mounted in the vehicle. The wheel angle/speed sensors and the inertial measurement unit employed by the Kalman filter are also instrumented when performing a subjective evaluation of handling performance.

The Kalman filter makes use of a first-principles full vehicle model in LMS Imagine.Lab AMESim. This model is integrated using the AMESim solver during the time-updated of the Kalman filter. It was found that the AMESim solver has on the one hand beneficial features for use in the Kalman filter loop, but on the other hand also shortcomings. The major beneficial feature is that the solver can compute a linearized model that can be used for updating the error covariance matrix of an extended Kalman filter. The major shortcoming is that the AMESim solver is optimized for performing one simulation over a long time interval. For each run, some time is required to initiate the model. When performing many simulations over a short time interval, as is the case for a Kalman filter application, the weight of this initialization impact for each run becomes prohibitive. R&D efforts are ongoing to address this initialization performance in the Kalman loop.

Although the body force estimation method has not been tested yet with data measured on a test track, computer simulations indicate that the method delivers forces estimates with an error of less than 5%. This is accurate enough for drawing engineering conclusions.



3. References

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