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The first Self-Propelled Caravan: Design and Validation of Simulation Tools for Powertrain and Safety Feature Development

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Summary

ZF-Friedrichshafen-AG, Erwin-Hymer-Group & FKFS teamed up to provide solutions for challenges mobile vacationing is facing today:

Together we are developing a new type of caravan, featuring an electric axle, battery and control system: This project offers a promising solution to renew caravanning in the EV-age; extending electric towing cars range, increasing conventional vehicles efficiency, while also enabling electric manoeuvring.

Homologation of new vehicle types and the lack of similar vehicles on the market requires thorough research and creates demanding requirements regarding functional safety and design. To aid development, validate vehicle dynamics, and develop safety features, simulation tools were designed.

Keywords: BEV, market development, powertrain, simulation, safety

1 Introduction: A new type of Caravan

In the past, the trend to bigger caravans required increasing car engine power output, leading to the use of larger cars with higher towing capacity. Considering the current development of electric vehicles and the limited space in cities, in the future we expect an increasing number of small city cars and cars with electric drives instead, both lacking towing capacity.

To cope with that trend, we have to design extremely lightweight, aerodynamic caravans as well as use foldable structures or reduce the comfort of a spacey floor plan. The caravan “Coco” of Dethleffs in Fig.1 features the lightweight approach. Nevertheless, even “Coco” comes at a gross vehicle mass (GVW) of about 900 kg, including a payload of about 200 kg. Therefore, we have to think further than only reducing weight.

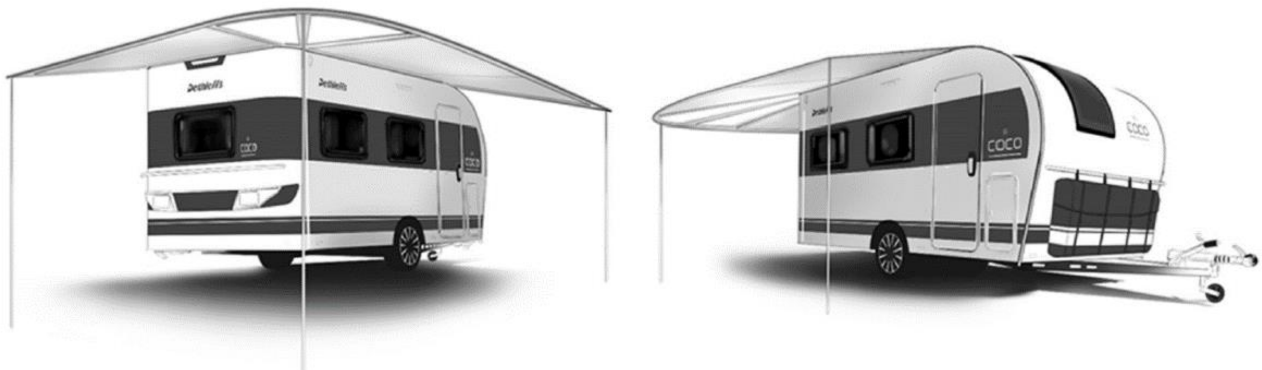


Figure 1: Dethleffs Coco featuring intelligent lightweight design

The suggested solution is to introduce a self-propelled trailer. We present: e.Home Coco, the world’s first caravan trailer with its own electric powertrain (as shown in [1]). In order to add further functionalities, we chose a setup with individual wheel drives. This supports a torque vectoring function for trailer stability, safely allowing high speeds and a low-speed autonomous mover function to handle the caravan on the campground. Since caravans typically are not operated the whole year round, we also developed an approach to integrate the vehicle into the energy grid, allowing for production of solar energy and/or energy buffering via using its integrated battery.

2 Functional System Requirements and System Design

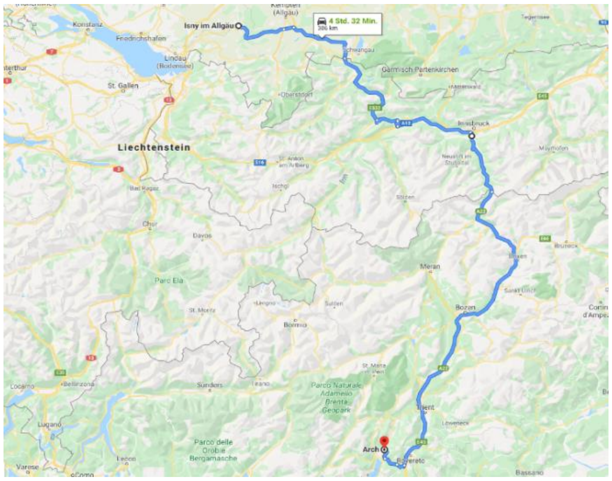
For the development of the e.Home Coco, several functional requirements need to be considered. In the following sections, a brief overview of basic electrical properties, mechanical requirements and driving capabilities including safety features will be presented.

2.1 Electrical Properties

For a caravanning vacation, the designed system shall allow at least about 400-600 km (~250-370 mi) between two main stops for refuelling and/or a longer rest. A topologically typical part of the journey in Europe may be the crossing of the Alps (e.g. passing the Brenner on a trip from the southern part of Germany to Lake Garda in Italy).

A proposed benchmark route, displayed in Fig.2, ranges from Isny, the hometown of Dethleffs (a brand of Erwin Hymer Group), to the Italian city of Arco close by Lake Garda, where a plant of ZF Friedrichshafen AG is located. The route results to a total length of around 400 km (~250 mi), representing a cumulative elevation climb of over 3500 m (~11500 ft) and ascent of over 4000 m (~13100 ft) with up to 6 % inclination. Said topological profile is shown in Fig.3.

This results in very high demands on the drive system in case of the proposed electric powertrain setup. Simulations have shown that the combined energy consumption of car and trailer for this trip will amount to approximately 150 kWh. Once arrived at the destination and depending on the driving strategy and target distance, the battery pack may be able to feature additional long time autarky. Optional solar panels allow for further extension of that timeframe or even an integration into home and/or smart grid energy concepts.



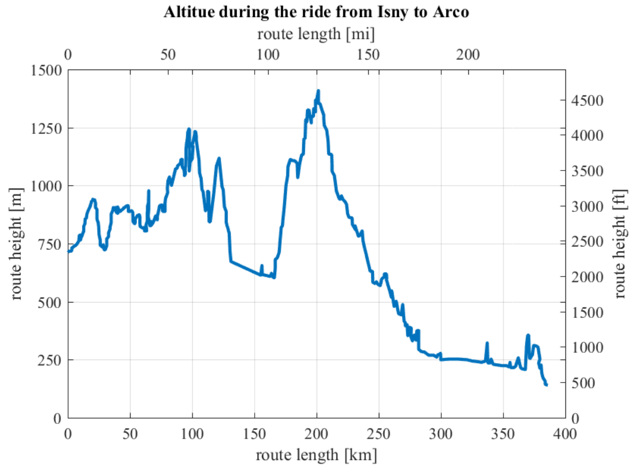


Figure 2: Example route from Isny to Arco, leading over the Alps & Figure 3: Elevation profile from Isny to Arco

2.2 Mechanical properties

Considering the intended long-distance use of the caravan, a high travel speed is necessary to cover the journey in a reasonable time. Factoring in the average speed limit on federal highways and highways in Europe, a top speed up to 100 km/h (~62 mph) is proposed.

When moving fully electrical, without a towing vehicle during manoeuvring on the campground or during parking, the caravan should be able to mount curbs. This results in a standstill wheel torque of 1.500 Nm.

The Chassis and suspension are designed to support an estimated empty caravan weight of around 1800 kg, with a GVW up to 2500 kg.

2.3 Caravan driving capabilities and system safety features

Combining previously described requirements while considering our proposed benchmark route, the electric motors should be able to propel the trailer continuously at speeds around 100 km/h (62 mph) at six percent incline but also be able to generate enough torque to make it over sidewalk curbs at a low driving speed, while always keeping the hitch-forces to a minimum. Additionally, as stated before a wheel-individual drive was chosen. This opens up a completely new range of possible features, including: Autonomous driving capabilities for moving and parking, safety features while driving, including stabilizing torque vectoring, and most importantly a precise target-traction following-function.

Due to compatibility reasons to existing but also future cars, the trailer needs to be able to be used with a standard hitch and trailer connector. This means only a limited set of car signals (most importantly reversing light, indicator and break signal) are accessible to the trailer. In order to execute previously described desired functions the trailer consequently needs to be independent from the car, thus requiring its own control unit and environmental sensors. Said control unit is called Trailer Mobility Control (TMC).

Fig.4 shows a simplified draft of the trailer and the most significant physical parameters. These include mass of the trailer, moments of inertia, velocities, accelerations, resistive forces, driving forces, and most importantly the hitch forces. Described values are measured by IMUs (e.g. accelerations, angular velocities), resistive wire strains (hitch forces) or are derived from measured values (e.g. motor torque from currents). Due to very noisy signals and low signal to noise ratio, it is necessary to implement adequate filters, use observers, and employ state space controls. The TMC now allows for two different operating modes, following mode (while connected to a car hitch) and mover mode (while moving without a towing car).

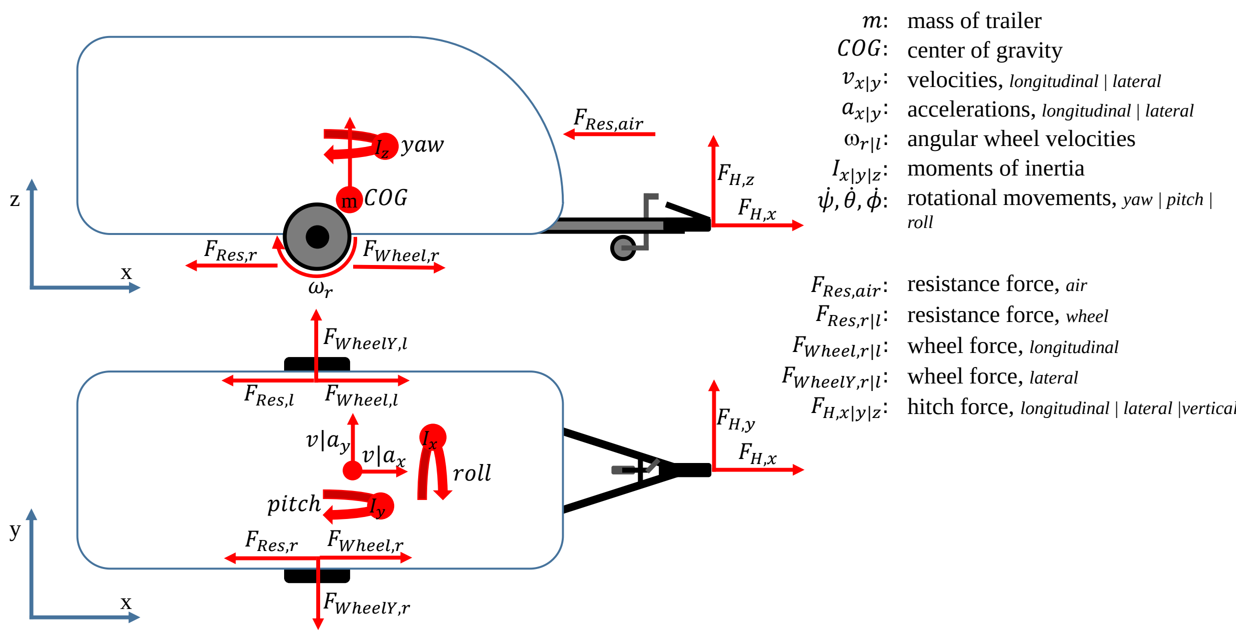


Figure 4: Trailer control system – forces, accelerations, and turning motions

The basic working principle during following mode is displayed in Fig.5. While connected to a hitch, the desired hitch forces act as set point. The idea behind this system now is as follows: The trailer tries to regulate its own wheel torques in such a way that forces attacking the hitch remain within defined boundaries in order to relieve the towing vehicle. Simultaneously, it tries to minimize influx on lateral and vertical forces. Here it is important to note that the trailer may never actively push the towing vehicle, as this may lead to an instable and possibly dangerous driving behaviour.

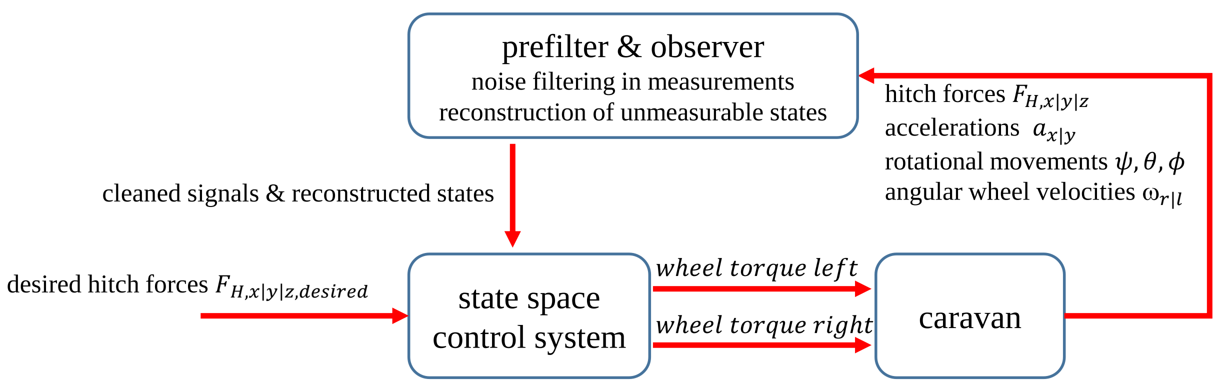


Figure 5: Trailer Mobility Control – following mode

The possibility to set wheel individual torques allows for more complex torque control than just relieving the towing vehicle: During potentially dangerous, highly dynamic maneuvers, e.g. evasive or fast lane changes, an anti-swerve control allows for additional lateral and yaw control.

Similar to following mode, the trailer is also able to move without being towed during mover mode. Fig.6 outlines the basic working principle. Here, the set point sizes are not generated by the applied hitch forces but rather generated internally within the TMC module. A desired path generated (e.g. by a mobile phone app) is used and converted into yaw angle and velocity. Those values are then fed into the control system where needed wheel torques are calculated. During mover mode, it is very important that the trailer speed never exceed the legally permitted value of 6 km/h (~3.7 mph).

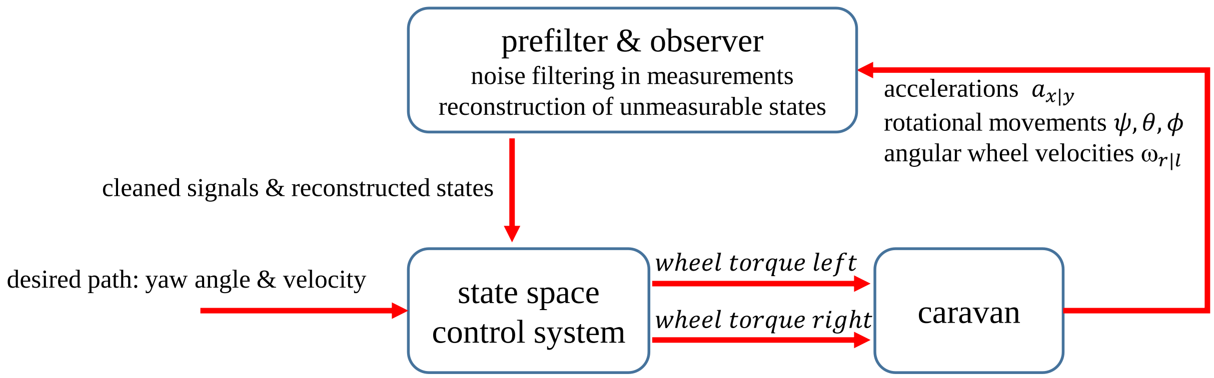


Figure 6: Trailer Mobility Control – mover mode

In addition, several safety functions need to be considered irrespective of the operating mode. This includes the high voltage system and the mechanical parts. In case of failure or a crash, the HV system automatically shuts down to prevent further danger. Absolute threshold values for, for example, motor moments, acceleration or yaw rates are defined, and system reactions were implemented if these boundaries are reached during operation.

3 Model design and validation for power train function development

To speed up the development process of the trailer and especially the powertrain and its control units, a simulation model using CarMaker was built. The program is able to simulate driving dynamics of passenger cars, light-duty vehicles, trucks, and two-wheelers with high precision. External code written in C or models created in Matlab Simulink can be implemented, offering countless possibilities to test and simulate different aspects and functions of street-bound vehicles. Furthermore, CarMaker supports functional mock-up interfaces (FMI), a standardized interface to connect multiple simulation systems, allowing, for example, for testing of control units or software features using a MiL/SiL-approach. Three basic steps, which will be presented in the following sections, were made to create said model:

1. Real world test-drives
2. CarMaker model creation, adjustment, and validation process
3. TMC implementation: Relieving the towing vehicle & stabilizing an evasive maneuver

3.1 Real world test-drives

In order to validate the car-trailer model as described in section 3.2, various test-driving maneuvers were carried out, using a prototype of the trailer. The prototype, still without battery and motors, was loaded with additional lead ballast to compensate for the lower weight due to the missing components. The car used to pull the caravan was an Opel Insignia with up to 184 kW of power and driven by a professional test driver with many years of experience driving highly motorized prototypes and car-trailer vehicle combination.

Quantities relevant to driving dynamics were recorded, a reduced set of which are displayed in Fig.7. These include the driver inputs like the steer angle, brake and gas pedal position, car internal sizes like engine speed and engine torque or physical dimensions like driving speed, three-dimensional accelerations, and three-dimensional rotational movements of both the car and the trailer. Hitch forces and the kink angle between car and trailer were also recorded. All mentioned sizes later serve as a basis for the tuning and validation of the created CarMaker model.

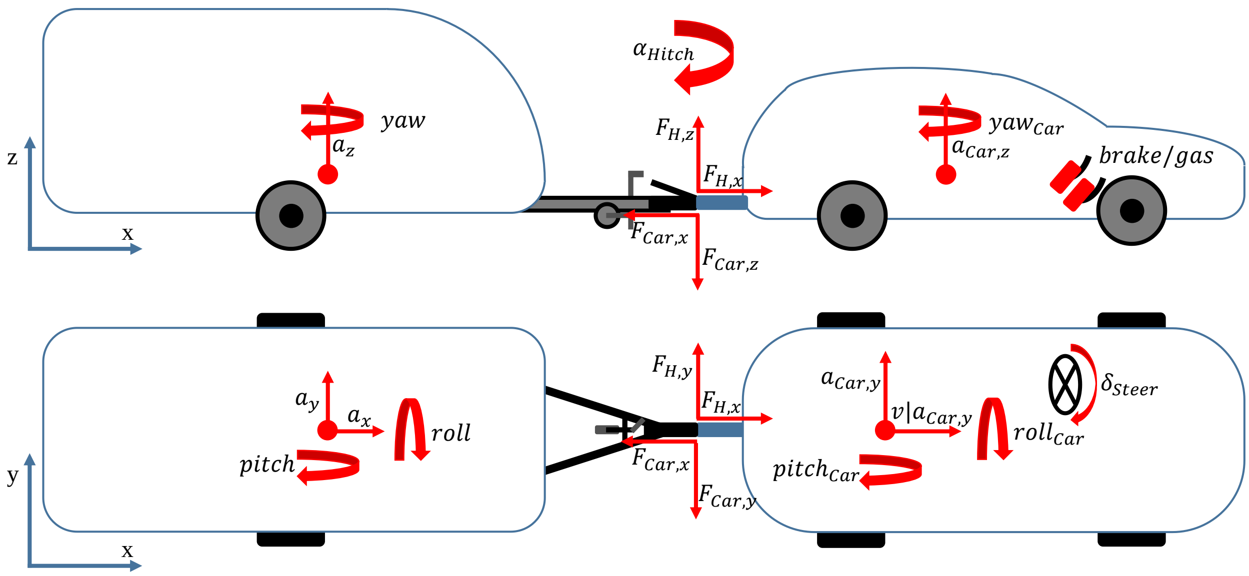


Figure 7: Car-Trailer test setup – set of measured sizes

The real-world driving tests were conducted on a former airport landing strip. This was necessary due to safety reasons. Here, one can find ideal conditions considering the straight, long and flat road without the risk of oncoming vehicles. The tests consisted of a series of separated maneuvers, which were designed for the model validation. In addition, also maneuvers that are needed to gain vehicle type approval, like a fast lane change maneuver, were included compare to [2], [3], [4]. The actual test-drive setup is shown in Fig.8.

Figure 8: Actual test-drive setup, hitch force measurement hardware hidden under cap

The basic design idea was to decouple longitudinal and lateral behaviour of the car-trailer combination. First, the longitudinal behaviour was determined, recording acceleration, braking, and constant speed sections. The driver held the car in the middle of the road while keeping steering input reduced to minimize disturbances.

Second, the lateral behaviour was measured. Instead of a straight driving route, a constant radius circle was followed, again mixing different phases of acceleration, braking, and constant speed.

A final step combined scenarios of both longitudinal and lateral components. For example, the driver followed a sinuous line or drove a steering angle sweep. Measured signals were recorded via CAN using specialized measuring equipment in the trunk of the car, imported into Matlab and pre-processed for later use.

3.2 CarMaker model creation, adjustment and validation process

This section will explain the creation and validation of the CarMaker model. Then, latter will be used as a tool to test powertrain functions and develop safety features.

CarMaker allows for detailed modelling of vehicles. To simplify vehicle parametrization, CarMaker splits vehicles into individual sub-components, which in their function are more or less independent from each other. Fig.9 shows all configurable car and trailer components, of which the most important concerning driving dynamics shall be explained. Using the *Body/Bodies* tabs, the position, weight, size, and moments of inertia of the vehicle body, wheels, suspensions and additional loads can be defined. *Suspensions* allows for configuration of length, position, and constants of springs, buffers, dampers, stabilizers, and parametrization of steering kinematics. Under *steering*, the ratio between rack travel and steering angle and properties of power assist modules can be configured. The *tire* tab offers options regarding the kind of tire model used and basic parameters like circumference, width, stiffness, maximum loads and many more. *Powertrain* contains all information regarding the drive train, including engine, gearbox, differentials, and corresponding control units. Under *aerodynamics*, the size of the vehicles front surface and coefficients for longitudinal and lateral winds can be entered. *Hitch* allows for the configuration of the hitch position, type, and kind of dampening like friction or spring damper elements.

Every component described allows for several different models with increasing level of detail to be used. For example, the ratio between steering wheel angle and rack travel simply can be a constant value or a more complex look-up table, including mechanical spring damper elements and additional steer assist modules.

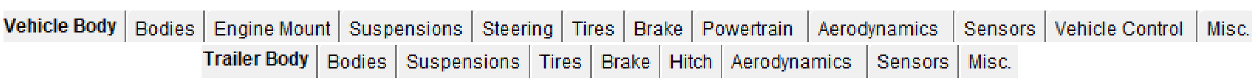


Figure 9: CarMaker car and trailer components

Many initial model values were determined using measurements (e.g. positions, weights) or data given in CAD-files or data sheets (e.g. lengths, spring values, tire data). Some values had to be initially guessed, as their precise identification would be too time-consuming or expensive (e.g. moments of inertia of the trailer or exact position of the centre of gravity).

Eventually in order to validate the created CarMaker model an iterative process as shown in Fig.10 was developed. All test-driving scenarios (longitudinal, lateral and mixed scenarios) were implemented in CarMaker, consisting of a road definition, car and trailer model, driving maneuver, initial and environmental conditions.

The program offers an emulated driver, which is able to control the vehicle during simulation, and allows external data to be imported into to the simulation. This way measurements made during test-driving can be used as set point during simulation. Here, the steering wheel angle, the driving gear, and the velocity were used as inputs. The CarMaker driver regulates its gas and brake pedals in such a way that the simulated velocity profile is as close as possible to the measured data. Our test driver corrected disturbances while test-driving, especially one-sided lateral winds during longitudinal maneuvers. Due to no lateral winds in the simulation, an unmodified steering wheel input would lead to slow drifting of the road. To compensate for this, a slow superimposed steer angle was added to the driver inputs to keep the vehicles in the middle of the road. Additionally, a rawness was modelled onto the road surface to add noise similar to that present in the measurements.

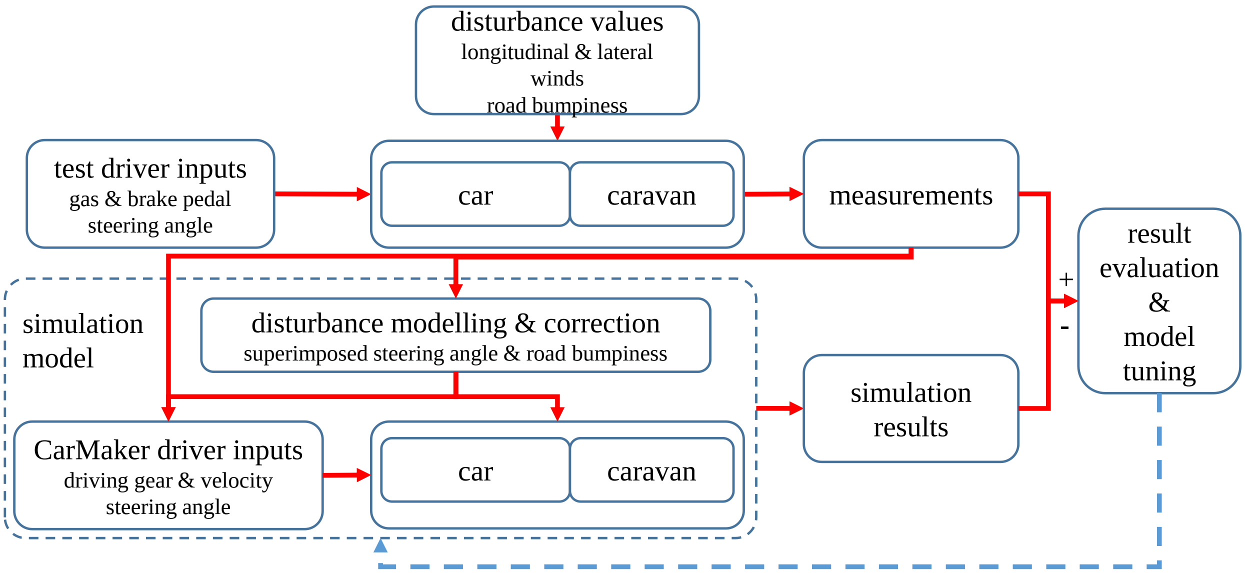


Figure 10: Model adjustment and validation process

After simulations in CarMaker, a Matlab script automatically reads and analyses the generated results. Initially, measurements and simulation results are filtered using a modified median filter. Here the objective was to reduce noise while simultaneously conserve high signal gradients. In a next step, the mean absolute error (MAE) between every pair of filtered signals is calculated which then is normalized by dividing by the range of the measured signal. This process is shown in the left half of Fig.11. The normalized nMAE now indicates how accurate the model behaves concerning the respective analysed size. A value of zero indicates perfect correlation while an increasing value represents an increasing mismatch between model and simulation.

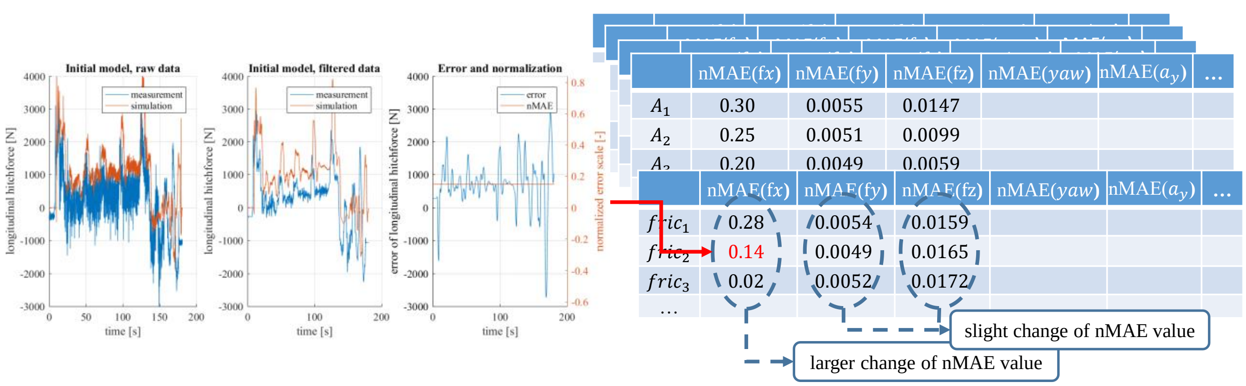


Figure 11: process of filtering, normalization and calculation of nMAE to determine parameter influx

In order to facilitate model tuning, CarMaker, besides a normal simulation with fixed parameter values, also offers the possibility to replace any model parameter by placeholders. This way it is possible to select any model parameter where an influence onto a specific driving behaviour is visible and assign each placeholder an array of values. While tuning the difference between measured and simulated longitudinal hitch force for example, properties like the trailer surface area, aerodynamics coefficient or wheel friction play an important role. After creating an array of values ranging around the initial parameter value, CarMaker then allows for combinatorial testing of each placeholder combination.

Due to exponential growth of total needed simulation time and for each placeholder and each permutation added, it is important to keep the number of simultaneously modified parameters as low as possible. In order to identify the size of influence of each model parameter onto model behaviour, initial simulations with up to 10 changing parameters but only 3 values each were made. If no or just a slight change of the nMAE value was observed this indicated a small influx of the changed parameter (cf. Fig.11 right, changing of the wheel friction leads only to a small change of nMAE(*fy*) or nMAE(*fz*), whereas a significant influence on nMAE(*fx*) can be observed). This allowed identifying which parameter needs to be taken in consideration and which can be ignored, while tuning a certain aspect of the vehicle behaviour. Typically, a set of 1 to 4 relevant variables was found for each signal nMAE. Signals, which predominantly were tuneable by only 1 (or 2) parameters, were tuned first to ease up to later tuning of more entangled signals. In the following, two examples of tuned behaviour shall be presented.

Shown in Fig.12 is the yaw rate of the trailer while driving a constant radius circle with increasing velocity up to 50 km/h (~31 mph). On the left, the simulation results before tuning are shown. In the middle and on the right, the results afterwards are shown. Before tuning, the simulation results continuously show a higher yaw rate with an even increasing difference for higher values than the measurements (red circle). This behaviour indicates a mismatch in the steering system, leading to smaller driven circles in the simulation. When decreasing the steering wheel to rack travel ratio, this leads to an almost perfect match for lower speeds (Fig.12 middle).

Figure 12: yaw rate during constant radius circle maneuver, before and after tuning

When reaching top speed, an extensive oscillation in the simulation can be observed, whereas only a slight oscillation is visible in the measurements (blue, dotted circle). The oscillation at higher speeds is due to swerving of the trailer caused by a low lateral stiffness of the trailer tires. After iterative modifying of this parameter, the trailer remains stable up to top speed showing just a slight swerving as in the measurements (Fig.12 right). nMAE value could be improved from 0.03 to 0.0008.

Shown in Fig.13 is the longitudinal hitch force while driving a straight maneuver at increasing speeds of 50-100 km/h (~31-62 mph). The left figure shows simulation results before and the right after the tuning process. Before tuning, the simulation displays an underestimation of longitudinal forces. Here, tuning of several parameters, including effective trailer front surface, wheel friction and spring/damper parameter of the hitch model had to be tuned. Each parameter has a different effect on the hitch force when tuned, showing a linear or quadratic proportionality or just affecting slew rate. After tuning, the nMAE value decreased from 0.16 to 0.06, whereas the remaining error is due to slight differences in hitch model properties (peaks, red circle) and different behaviour of the overrun break (blue, dotted circle).

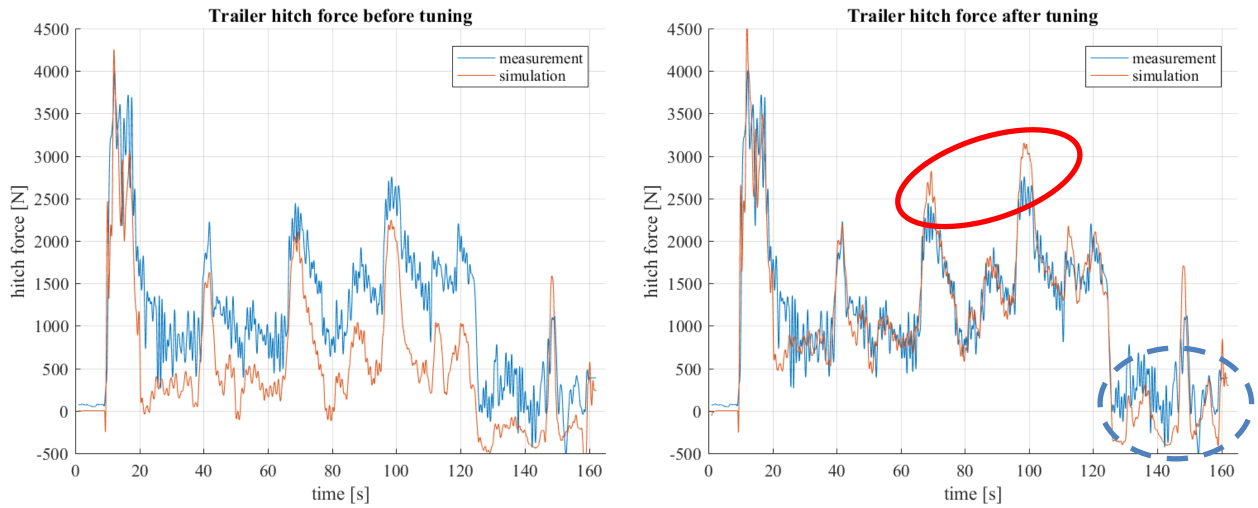


Figure 13: longitudinal hitch force during straight driving maneuver, before and after tuning

Altogether, well over a dozen parameters were tuned. In order to validate the model, especially maneuvers with combined lateral and longitudinal components were tested, as a poorly tuned model would have shown easily in the results. This was not the case as the model here showed a precise simulation-measurement congruence. Remaining simulation-measurement mismatches can be explained by environmental disturbances like oncoming winds, slight incline and bumpiness of the road and difficulties with the hitch force measuring principle.

3.3 TMC implementation: Relieving the towing vehicle & stabilizing an evasive maneuver

After model creation, tuning and validation, the next step is to implement the TMC controller. As a first step a basic TMC variant as a proof of concept, featuring a longitudinal force regulation and a swerve protection was programmed. In addition, the reduced TMC design was necessary in order to early answer upcoming questions regarding trailer movement and hitch force measurement principles in the prototype. A more complex controller model will be developed during commissioning and testing phase.

The programmed TMC force regulation consists of two parts; one is a map-based pilot control, the other is utilizing a PID controller to regulate the remaining hitch force not compensated by the pilot control or created by environmental disturbances. Parallel to the force regulation, the TMCs swerve protection observes the current trailer yaw rate and lateral acceleration and calculates a necessary output moment distribution to reduce lateral vehicle oscillation. The basic working principle of the controller is presented in Fig.14.

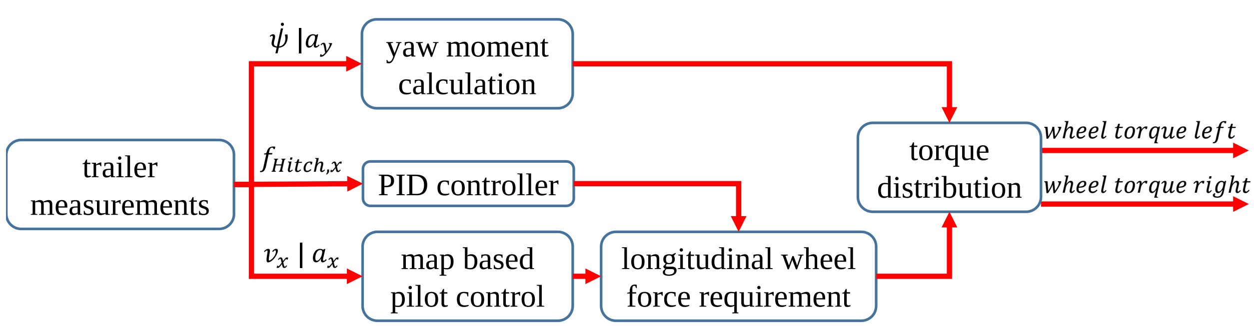


Figure 14: TMC implementation, basic working principle

Finally, simulations made for the validation process were repeated, this time employing the TMC to check the performance of the controller. Fig. 15, left shows the same hitch force as presented earlier in Fig.13 during model tuning without TMC. Fig.15 right shows the results now with active TMC. During driveaway (10 s), a short peak to build up tensile force is visible and the controller begins to regulate wheel torque, presenting an overall good performance with a considerably reduced, homogenous longitudinal hitch force.

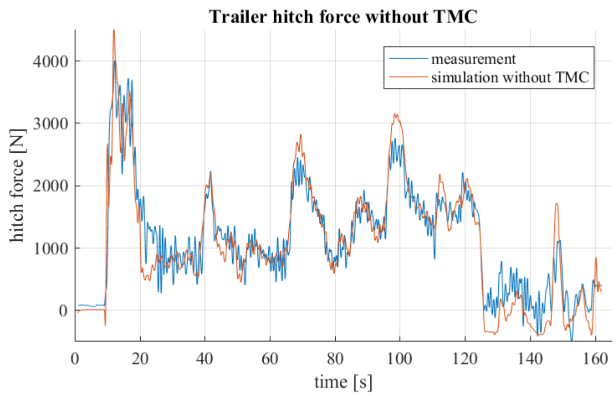


Figure 15: TMC relieving the vehicle by reducing longitudinal hitch force

To test the anti-swerve feature of the TMC, a new test-run was built, consisting of an initial acceleration phase to a velocity of 80 km/h (~50 mph) and then turning into a wide right curve. Fig.16 shows the animated simulation, the brighter, translucent trailer without TMC, the coloured trailer with TMC. A defective truck parked on the right suddenly forces the driver to execute an evasive maneuver onto the opposite lane. Due to the high amplitude and the high slew rate steering movement at high velocity, the trailer loses traction, leading to swerving far into the left lane. When re-entering the right lane, the excited oscillation forces an overshoot far to the right edge of carriageway.

When instead analysing the trailer with TMC, it is possible to see that lurching could be reduced drastically, proving the effectiveness of the system, possibly avoiding a fatal crash with the oncoming orange car.

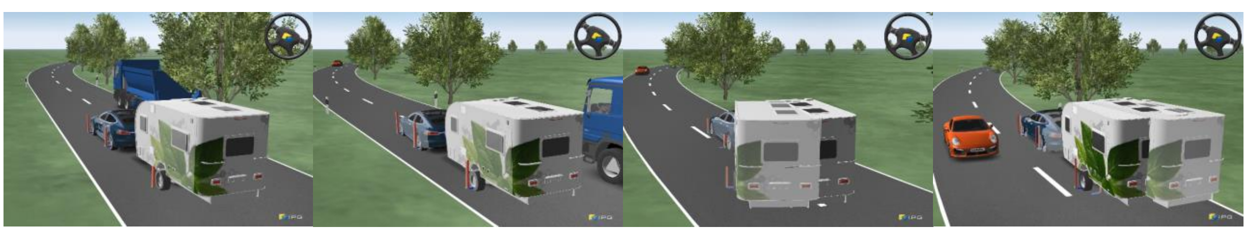


Figure 16: Example – Fast evasive maneuver with and without torque vectoring.

4 Conclusion and Outlook

The development of a new vehicle type is not something done overnight. It involves many steps, provides many challenges and requires a large team to execute necessary tasks. Besides fundamental engineering tasks like dimensioning of powertrain components, creation of packaging concepts for batteries, motors and electronics, and function development and programming of control units need to be thought of. However, even with a working prototype, there are several further hurdles to take, like the introduction of required bills to introduce a new type of vehicle. Most importantly, to successfully gain homologation, aspects regarding functional safety need to be examined thoroughly. In order to start research and development as early as possible, a simulation environment was necessary.

As presented, a simulation model of car and trailer were be designed, tested and validated. Further, as proof of the concept, a simplified version of the TMC, providing longitudinal force control and an anti-swerve feature, was implemented and tested successfully. Next planned steps will include expansion of the TMC to implement a full state controller, adding features and improving safety. During the writing of this paper, the prototype was brought into service and component tests were conducted. By the time EVS33 takes place, a series of real world test-drives should be concluded and results related to TMC performance and safety analysed.

Regarding official approval and homologation, a first bill draft should be written and preliminary work done to initiate the legislation process in Germany and on the level of the European Union.

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References

[1] Rüdiger Freimann, Jeffrey Zhang, Gerhard Gumpoltsberger, Udo Gillich, Ria Kaiser, New Vehicle Concepts for Mobile Vacation, 28. Aachener Kolloquium, Aachen, 2019

[2] DIN ISO 7401:2011, Road vehicles - Lateral transient response test methods - Open-loop test methods (ISO 7401:2011)

[3] DIN ISO 9815:2010, Road vehicles - Passenger-car and trailer combinations - Lateral stability test (ISO 9815:2010)

[4] DIN ISO 3888-1:2018-12, Passenger cars - Test track for a severe lane-change manoeuvre - Part 1: Double lane-change (ISO 3888-1:2018-12)

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