

2nd World Light Electric Vehicle Summit

Rotterdam, 22nd & 23rd November 2017

Concepts and Methods from the Field of Vehicle Dynamics for Safety Considerations of Light Electric Vehicles

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Abstract

Vehicle dynamic considerations regarding the safety of lightweight vehicles need to cover different aspects than those regarding conventional automobiles. New problems and effects require dedicated research and modified methods. The present contribution discusses these new challenges covering aspects like specific vehicle design concepts (e.g. three-wheelers) and the significance of human body mass in relation to the total mass.

Some initial simulation results are presented that were gained with an example design of a three-wheeled two seater vehicle. The results show that the seating position and number of passengers have a significant influence on the stability against rollover. Thus they illustrate that the mass of the human body is of importance for the dynamic behaviour of the overall system.

The article gives a list of further effects like the stiffness and damping properties of the human body and also the influence of the human as part of the system in terms of control engineering. A strategy is suggested which combines computer simulation and road tests. This strategy minimizes the need for costly testbed experiments for optimizing the simulation models. Particularly when simulation is employed in order to reduce the need for sensors that would require complicated structural modification (e.g. force sensors in suspension components). Ideally, sensor application can be limited to inertial sensors and other positioning sensors like GPS.

Keywords: vehicle dynamics, multibody system simulation, parameter identification, model verification, inertial sensors

1 Introduction

Safety of lightweight vehicles requires different considerations than safety of conventional automobiles. This does not only refer to structural strength, but also to the dynamic behaviour, e.g. skidding as a consequence of sudden drop in tire friction, stability against rollover (tipping over), reactions to uneven road surfaces (obstacles, bumps, potholes, etc.). In other words, questions belonging to the field of vehicle dynamics.

It is obvious that results cannot be gained by simply scaling results from conventional automobiles to “smaller” vehicles. The methods and even the questions to be considered have to be defined specifically for the new designs. The main reasons for this are:

- Many light vehicles are based on geometric design concepts that differ fundamentally from the classic four-wheeled car with one of the common suspension concepts; in particular when considering three-wheeled vehicles.
- Lightweight design imposes a number of consequences. In conventional automobile dynamics, the weight of the driver (and passengers) does not make a significant difference to the dynamic behaviour of the vehicle. With light vehicles, driver (and passenger) have a rather significant share in the total mass of the system in motion. However it would be an oversimplified approach to treat human bodies as if they were rigidly attached to the vehicle. Another consequence of lightweight design may be smaller stability threshold with regard to obstacles (curb stone edges) and uneven roads (bumps, ...).

2 Simulation results with an example vehicle

In order to illustrate some basic effects typical for the specific difficulties one might face with lightweight vehicles an example design of a three-wheeled two seater vehicle is examined by means of a multibody systems computer simulation.

2.1 Example vehicle and model

The vehicle chosen for this pre-study is an exemplary design similar to vehicles available on

the market today. The vehicle has three wheels, has an electric drive with approximately 3 kW, is designed for two people and has an unloaded weight of 220 kg. The wheelbase is approximately 1.90 m and the rear wheel track 1.10 m. The design is made for relatively high speeds (approx. 90 km/h) and thus has a relatively low position of the center of gravity (*cg*). The model of this vehicle incorporated in the multibody simulation software “Simscape Multibody” (part of the Matlab / Simulink software family) is shown in Fig. 1.

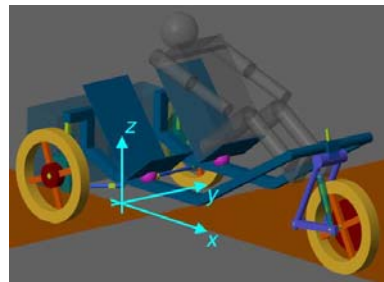


Figure 1: Model of example vehicle in the software “Simscape Mechanics”

2.2 The driving scenario

The showcase effect examined in some detail is the event of a rollover (tipping over) of the vehicle during cornering. The following standardized scenario was defined for a clear and reproducible mathematical description of the scenario:

- target curve radius $\rho=10$ m
- transition from straight travel to the target curve radius within 1 s

The numerical simulation was based on the following assumptions and procedure:

- given initial speed v_0 of the vehicle
- the vehicle is not driven by the motor during the simulated motion

The objective of the simulations was to determine at which critical speed v_{stab} the vehicle would tip over as a consequence of the centrifugal force.

It has to be emphasized that this way of posing the question forces a critical driving situation. Thus it would be a misunderstanding to say that the results would prove that this vehicle is more likely to tip over than any other design including conventional big passenger cars. In order to illustrate how narrow the curve radius in this scenario is, Fig. 2 (left) shows a traffic roundabout in an inner city. This roundabout in an inner city is about the

smallest radius of roundabout that can be found in normal streets. Now the scenario would mean to enter this roundabout at speeds of approximately 30 km/h without reducing the speed, with a quite sudden movement of the steering wheel and without reacting to the tendency of the vehicle to tip over which any average human driver would doubtlessly notice.

Another evidence for the fact that this scenario is quite extreme is a side result of the computer simulations described below: The simulations were carried out with an assumed coefficient of friction of $\mu=0.9$. If the friction coefficient was reduced slightly, to $\mu=0.8$, this would result in the vehicle skidding instead of tipping over.



Figure 2: Curve radius comparison: Left – typical traffic roundabout. Right – Transition phase in comparison to complete turn

Fig. 2 (right) illustrates the time of transition from straight travel to the full steering angle required for the target curve radius. It is given by the red section of the trajectory plot. The trajectory was calculated for a typical speed of 9 m/s.

The method of investigation for this first illustrative study was computer simulation with a software package for multibody system dynamics. This method and the associated software tools are state-of-the-art in automobile dynamics, see [1].

2.3 Simulation results

Whether or not rollover occurs for a given vehicle configuration, depends not only on the curve radius, velocity and the transition time. The parameter which is given a closer look in this study is the configuration in terms of the vehicle load imposed by the driver and potentially the passenger.

Different configurations include:

- person on the left seat
- person on the right seat
- persons on both seats
- person on the left seat, but at a higher and more upright sitting position (100 mm higher than the standard configuration)

The simulation results show that variations in the configuration can lead to quite significant differences in the threshold velocity at which rollover occurs, see Table 1.

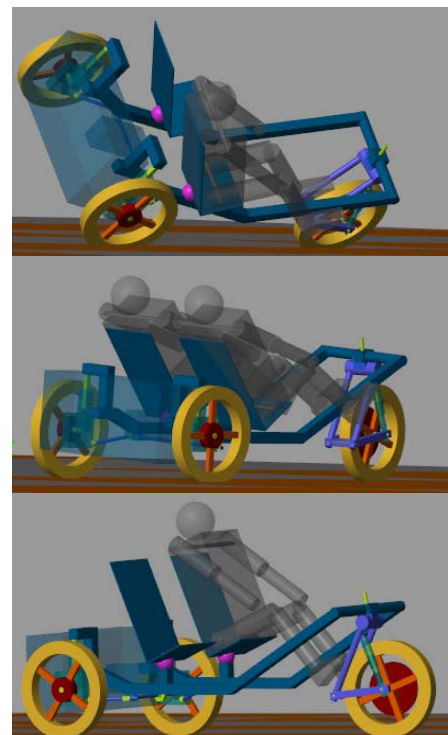


Figure 3: Different configurations studied in the numerical simulation

Table 1: Mass, center of gravity and stability limit for different configurations

configu- ration	mass (kg)	cg coordinates (mm)			stability limit* v_{stab} (m/s)
		x_c	y_c	z_c	
empty	220.0	465.5	-0.2	404.3	---
person left	295.0	491.2	72.3	466.9	$9.2 < v_{stab} < 9.3$
person right	295.0	491.2	-72.6	466.9	$7.6 < v_{stab} < 7.7$
2 persons	370.0	506.5	-0.1	504.2	$8.0 < v_{stab} < 8.1$
person left upright	295.0	512.5	72.3	485.9	$8.8 < v_{stab} < 8.9$

* Stability was tested for different velocities v in steps of 0.1 m/s. The values in the table are the highest v without and the lowest v with rollover.

The critical speed with respect to stability against rollover under the given conditions varies between 7.6 m/s (27.4 km/h) and 9.3 m/s (33.5 km/h). The biggest difference can be found between the configuration with left or right position of the person when a single person is riding the vehicle. Of course, the same comparison can be transferred to the variation between a left or right turn with the driver remaining on the same side of the vehicle. Another result, which might appear surprising, is the fact that the more upright seating position causes less difference than the situation with two persons in the vehicle.

An integral parameter determining the behaviour is of course the position of the centre of gravity, thus its coordinates are included in Table 1 applying the coordinate system defined in Fig. 1. The comparison of the vertical *cg* positions between the configuration “upright seating position” and the configuration “two persons in the vehicle at normal seating position” also illustrates that the latter is the more critical one. Further influences on the results are parameters that were not modified in this study, including vehicle properties such as kinematics and spring constants of the suspension system.

3 Specific approach for vehicle dynamics of light electric vehicles

3.1 Conclusions from the example study

The parameter variations in the above section are relatively simple. Yet they show that parameters that can be neglected (or treated in a simple, uncoupled manner) when studying the dynamics of heavier vehicles are of importance for light electric vehicles.

Nevertheless, the study can only be considered an illustration of this fundamental statement rather than a quantitative study. The most important reason for this is that the person was treated as a rigid body fixed rigidly in the vehicle. Also several of the parameters that were used in this simulation were based on mere assumptions. Particularly important examples are parameters describing the spring stiffness and damping behavior of the suspension system. Of equal importance, and even more difficult to

obtain are parameters describing the contact between road surface and wheels, in particular friction under a wide variety of different loading and environmental conditions. State of the art for including these effects in computer simulation is the well-established magic formula, see [2]. This model is based on empiric data which are at present mainly available for cars and motorbikes. It has to be emphasized that these empirical models are based on observation and cannot quantitatively be derived from basic laws of physics. This is why it is not possible to generalize the parameters known from one type of vehicle to a vehicle with a fundamentally different geometry. For example wheels from bicycles and motorbikes are usually only examined in longitudinal and vertical loading situations, see [3]. But often the same wheels are used in three or four wheeled light electric vehicles. Yet in this application, also lateral loading will occur, therefore further empiric data is required.

Further studies also need to examine different scenarios like sudden braking, collision with obstacles, uneven road surface and many more.

From the considerations above, it is obvious that the challenge cannot be solved by computer simulations alone, since the parameters required for a mechanical model allowing reliable prognosis cannot be gained from the information the design engineer or manufacturer in general have available.

3.2 Conventional approach

The conventional state of the art method for examining vehicle dynamic questions is a combination of computer simulations, test stand experiments and road tests. Of course, it requires an assumed mathematical model for the effect under investigation. In a simplified description, the structure may be described as a linear one:

- design a specialized test setup for identifying the parameters required for the model
- computer simulations, applying the parameters that were determined from test setup
- use road tests to validate the simulation results (and modify the simulation model if necessary)

A very simple example for this strategy is determining the longitudinal friction coefficient. The required steps in the test stand would be:

- apply a specified normal force F_N
- provoke sliding

- measure the tangential force F_T
- calculate friction coefficient $\mu = \frac{F_T}{F_N}$

Even this example, though quite simple concerning the basic idea, proves to be considerably complex. A big variety of side parameters like tire tread, tire pressure, road surface and moisture requires a vast number of experiments. A big expenditure is required to design and built test facilities allowing to adjust all these parameters, see [3].

Advantages of this strategy are reproducible test conditions and relatively simple mathematical relations allowing to determine the parameters from the test stand measurements. Disadvantages are that providing all the test stands for a big variety of parameters is expensive and time consuming. Often it is difficult to match the conditions in the field. Finally, the method has clear limitations when a model is sought for implying human reactions. Such reactions may range from muscle tensioning as a reaction of a critical situation to actions for vehicle control like steering and braking.

3.3 Suggested approach

The suggested approach too, combines computer simulations and experiments. However, the attempt is to reduce the need for test stands by expanding the role of road tests. This approach too, requires an assumed mathematical model for the effect under investigation. The structure of the process for finding the parameters and validating this model is however not as linear as the conventional approach. Steps can be summarized as follows:

- create a multibody simulation model (if possible: check the model with a scenario that does not include the effect under investigation)
- use road tests to quantitatively determine the dynamic behaviour considering the effect under investigation
- identify the parameters by comparison of simulation and road test measurements

Advantages of this strategy are that no hardware test stands are required and that it utilizes testing under true field conditions. Disadvantages are the more difficult mathematical treatment and the fact that it will be more difficult to provide reproducibility in the boundary conditions for the tests.

As an example, we again consider a possible concept for determining the lateral friction coefficient for road to tire contact. The model selected for this is a standard e-bike. The road test experiment (and also computer simulation experiment) selected for determining the parameter under investigation is braking with the front brake only.

Fig. 4 shows the multibody simulation model. The right side of the picture shows the vertical forces and the lateral force of the front wheel. The friction coefficient can be derived from the ratio of lateral and vertical force as in the conventional concept from the relation $\mu = \frac{F_T}{F_N}$.

The basic concept is to adapt the friction parameter in the simulation model such that the vehicle motion determined from simulation matches the vehicle motion determined from a road test measurement.

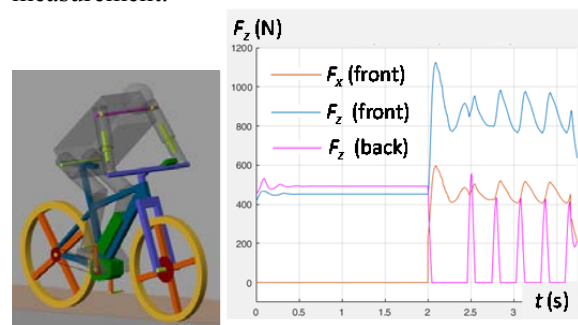


Figure 4: Braking force examination by computer simulation for an e bike

3.4 Sensors and instrumentation

The crucial point and intention of the concept described above is to find an efficient and feasible measurement strategy for the road tests. An efficient strategy should allow to check the matching between computer simulation and road tests without fundamental modifications to the structure of the vehicle. This means in particular, that it should avoid sensor types or sensor positions that require structural modifications of the vehicle. Particularly different are force measurements in structures, they typically require cutting apart the investigated structure in a more or less literal sense. The only alternative in the example would be to position a force sensor in between the wheel and the road surface, which is obviously not feasible.

In contrast, the type of sensors that does not require any relevant modifications of the structure of the vehicle are inertial sensors. The most common sensors in this group are acceleration sensors (accelerometers), but for a full acquisition of a body's motion also gyro sensors (measuring the change rate of angular orientation) are required.

In recent years, sensor systems are available that combine accelerometer for all three axis of the coordinate system as well as gyroscopes for all axes. On a high level of sophistication and precision, these are the so-called inertial measurement units (IMU), meant to allow navigation without requiring satellite signals, often as a backup for temporary interruption of radio contact when a satellite navigation system is used. These systems are big and expensive, typically there would be no more than one such unit in a vehicle. On the other hand, combined sensors are used as so-called motion trackers. These very compact and relatively inexpensive units are often used in biomechanics or entertainment industry for capturing the motion of a human by placing a number of motion trackers on specified positions of the human body, see [4].

Additional information can be gained from other position sensing equipment like satellite navigation or (high speed) video recordings, in particular when synchronized with other measurements.

A possible way to apply this concept to the assumed example of determining the lateral friction coefficient could be to determine the correct friction coefficient by analysing the acceleration signals of both, simulation and road tests. In order to optimize the procedure, it is desirable to use further measurable quantities for cross checks. In this case, such a quantity could be the angular acceleration about the horizontal body axis (pitch angle).

4 Conclusions and future perspectives

The present article has shown that vehicle dynamics can help understanding safety issues of light electric vehicles. Particularly by studying extreme driving situations. It has shown that a number of crucial questions cannot be studied by

applying tools and methods known from vehicle dynamics for conventional types of vehicles.

The suggested approach allows to conduct this kind of investigation and to determine the required system parameters in a cost effective and time saving way.

The following list gives some of the fields concerning light electric vehicles in which specific vehicle dynamic investigations would help improve safety and driving performance. The suggested approach might help to obtain results with relatively small time and cost expenditure.

- Multibody simulation for real vehicle types considering mass distribution, suspension kinematics and parameters. The suggested method could help to validate models and parameters. Computer simulation would provide a cost saving method for studying extreme driving situations.
- Detailed studies on how to apply the known tire models (contact between road surface and tire) on vehicles with non-conventional design concepts. Determination of the parameters of the tire model when applied on these vehicle types
- Modelling of human as a body that does not only include mass and inertia, but also spring stiffness and damping properties. Existing models of the human body for vehicle dynamics usually originate from motor cycle dynamics. Due to differing positioning of the rider and also differing speed range, they can most probably not be generalized to other types of vehicles.
- Analysing the human driver/rider in terms of an active part of the system. In the most simple case by changing the mechanical parameters like spring constants, i.e. by muscle tensioning as a reaction to some situation. But also actions for vehicle control like steering and braking and even misdirected reactions causing critical situations.

Of special importance are fields concerning the dynamics of humans. In this segment, it is obvious that there are significant differences from conventional vehicle dynamics concerned with much heavier vehicles.

A promising approach for these fields is to use motion trackers on both, the vehicle structure and the human body, see Fig. 5 and Fig. 6.



Figure 5: Multi axial inertial sensors (motion trackers) for analysing the dynamics of e bike and rider



Figure 6: Wireless Data Acquisition and Evaluation with a ruggedized laptop computer

The main intention of the approaches described above is analysing dynamic vehicle stability. However, they can also play a crucial role in the further step, which is the development of electronic stability control systems (ABS, ESP and the like) for light electric vehicles.

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