

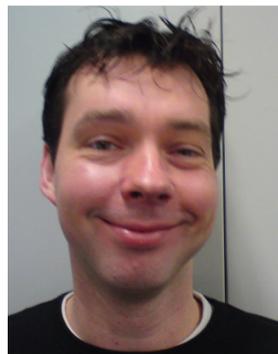
AN INTEGRATED TESTING AND MODEL BASED DESIGN APPROACH FOR SEMI-TRAILER WEIGHT REDUCTION



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Abstract

The paper discusses the derivation of test data for three tractor-semitrailer combinations, to be used for strength and durability analysis of semi-trailers with the ultimate goal to reduce the semitrailer mass. Mathematical relationships have been used to transfer these data to representative loading data for the semi-trailer, in terms of forces and moments in all directions at the axles and king-pin, being used to optimize weight without compromising the vehicle resistance to fatigue.

These activities have been the starting point of a follow-up project FORWARD (Fuel Optimised trailer Referring to Well Assessed Realistic Design loads) including now eleven different trailer manufacturers, and the Dutch Chassis and Body work association FOCWA. FORWARD will extend the previous approach with the objective to lower the trailer weight in order to improve the ratio of payload to fuel consumption. FORWARD consists of the following steps (1) a testing program, the larger part of which corresponds to normal use for a representative period, (2) to apply these data to validate a vehicle model allowing the derivation of representative loading data, and exploration of the effect of design changes on these loading data, (3) to apply these loading data for further FEM analysis of the global chassis and of local critical points.

Keywords: Tractor-semitrailer, testing, design loading, weight reduction

1. Introduction

The contribution of road transport to CO₂ emissions has been steadily growing to 20 % in recent years. Heavy vehicle road transport is taking a fair share of this. The growth in number of commercial vehicles on the road exceeds the average growth rate for road vehicles, and this is not likely to change, in spite of our present economic recession. From 2000 to 2020, freight transport is expected to grow by 50 %, exceeding the economy growth rate, see [1]. From 1995 to 2006, the GHG (Greenhouse gas) emissions due to freight transport has grown by 35 %, see [2]. This trend can be attributed to our increasing standard of living as well as globalization. The transport sector is paying a price for this in terms of tolling, tax and other, clean environment motivated charges. Consequently, this sector is challenged to come up with innovative sustainable solutions to reduce the fuel to payload ratio, which also will lower the ratio of transport cost to payload. The weight of the vehicle contributes to these ratios. Reducing the weight means that a higher payload can be carried for the same fuel costs. As a result, for the same total transport demand, CO₂ will be reduced and, at the same time, there is an economic profit by lowering the fuel costs, which will give both the transport company and the vehicle manufacturer a competitive advantage.

Reduction of a semi-trailer mass requires a redesign of the vehicle for which information about representative loading has to be available. In general, this loading refers to long term repetitive loading, i.e. with emphasis on possible fatigue problems. This means that representative loading is used to analyze the structural behavior of the vehicle under this loading, leading to a prediction of fatigue lifetime for the most critical spots. This prediction depends not only on the local design but also on the global structural performance of the trailer, the different materials in the design, the variation of stiff and flexible parts of the chassis, etc. In general, however, these aspects may be easily neglected. If a vehicle shows fatigue damage somewhere, this means loss of production for the transport company. Consequently, there will be a significant time pressure to solve the problem, with most emphasis on the critical spot without consideration of the representative loading cases, the overall trailer design and the stiffness variations in the trailer chassis. For example, adding more steel to the trailer at such a spot may solve the problem locally, but might induce more severe stiffness differences in the design which may lead to problems at other locations. And this will definitely not lead to a lighter trailer.

There are various attempts to reduce trailer weight by application of special materials, such as composites, aluminum, high strength steel. We refer to [3], [4] for examples such as the ROADLITE and the ColdFeather project and its successor, the GIGA lightweight trailer, all focussing on the use of composite materials for weight reduction. In [5], materials such as aluminium, sandwich material or high strength steel (HSS) are addressed in the context of trailer design.

Design loads for a trailer should not be chosen too small, because of the uncertainty of the occurrence of loading during the trailer life. On the other hand, taking the safety margin unrealistically high will obviously limit the potential weight reduction. Having more information about the loading, for example through testing, will avoid these mistakes, and will support the manufacturer to select realistic design loads at axles and fifth wheel in all directions, for the circumstances being representative for the total life of the vehicle combination at hand. It is thereby important to combine loading at different parts of the trailer in a way as they occur in practice, i.e. accounting for their combination at a certain moment in time in case of for example severe cornering, passing thresholds or extreme braking. Selecting conservative fixed loads for trailer axles and king-pin separately, and using these loads

together in one analysis without regarding their origin, may even underestimate the stress levels in the trailer.

Summarizing, there is a need for more testing, for identification of representative loading and for a design approach that links this information to the analysis of the trailer structural performance and fatigue lifetime, with the final goal to reduce vehicle weight. And all of this should be part of the design practice of the manufacturer. It means that tools such as test protocols in combination with test equipment, post-processing of test data towards loading data and loading history, should be presented to trailer manufacturers in a way that it fits in their design process. Complex modeling, details about model compilation, instrumentation, and specific mathematical routines should be avoided. And above all, using the tools should be efficient in terms of time and money.

The HAN University has taken up this challenge, in close cooperation with the Dutch Chassis and Body work association FOCWA. In a first step, tests have been carried out with different trailers for three different trailer manufacturers, see figure 1.

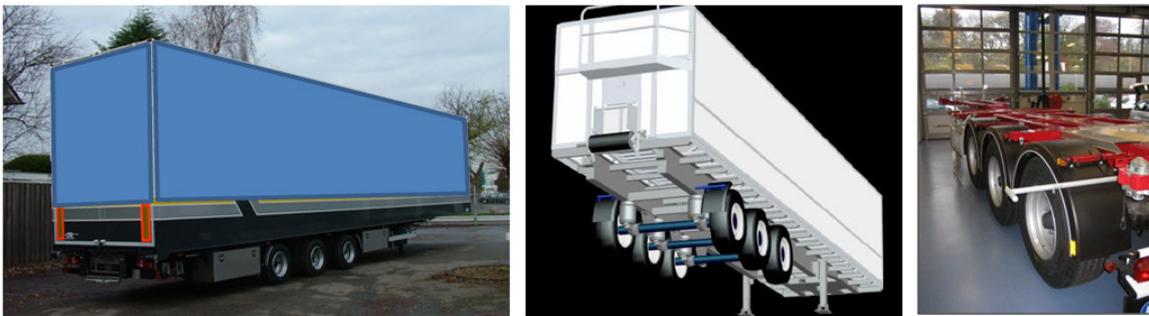


Figure 1.: Three semitrailers being examined for their representative loading

The first one is a box-trailer (volume transport), the second a trailer with a belt unloading system (for transporting potatoes), and the last one a so-called flexi-trailer for container or tank transport. In the next section, the test program for these semi-trailers is discussed. In section 3, we will discuss a simplified approach to transfer these data to loading of each axle and the fifth wheel.

These first tests and follow-up has aroused more manufacturers, resulting in a large research project FORWARD, which has started in 2009 and will last until the end of 2011. FORWARD will cover a more extensive approach (but with equal limited complexity for the trailer manufacturer), accounting for the shortcomings of the first approach. It will also lead to a substantial increase of the data in the trailer loading database which, in itself, will offer more opportunities to derive design practices being valid for a large class of semi-trailer designs. The paper will be closed with an outlook of the effect of FORWARD and some conclusions.

2. Experimental assessment of vehicle data for three different semitrailers

In order to carry out measurements, one first has to decide about the various loading conditions, which will occur during normal practice. This will include braking, cornering, driving over road disturbances, and low-speed maneuvering including cases for 90 degrees articulation angle drive away tests. The tractor mass as well as its CoG position is assumed to be known. In order to derive loading per axle and at the king-pin, the following instrumentation was required.

- Air spring pressures (front and rear most axle) to estimate axle loads in order to determine semi-trailer CoG position, trailer mass and vertical load on the fifth wheel. All tractor-semitrailer combinations have been subjected to accurate wheel load measurements for reasons of calibration of these sensor data
- Wheel speeds, which may be used to estimate yaw rate, but which, in combination with the air spring pressures, can also be used to estimate the roll moment over the trailer axle, i.e. the load transfer during cornering (see [6])
- Vertical acceleration sensors on the chassis and axles, position sensors in the axle systems in order to be able to derive spring and damper forces, and from those the vertical forces at the hinges between axles and chassis (also using the air spring pressures)
- Brake pressures and longitudinal acceleration in order to derive brake forces at the axle, the longitudinal reaction force at the king pin, with pitch effects (longitudinal load transfer) taken into account
- Lateral acceleration, body yaw rate, body lateral speed (trailer body slip angle), in order to derive the total axle side forces, the individual axle side forces (on the basis of the derived slip angles), and the individual wheel side forces by accounting for lateral load transfer.
- Steering angle

An outline of the vehicle instrumentation is shown in figure 2.

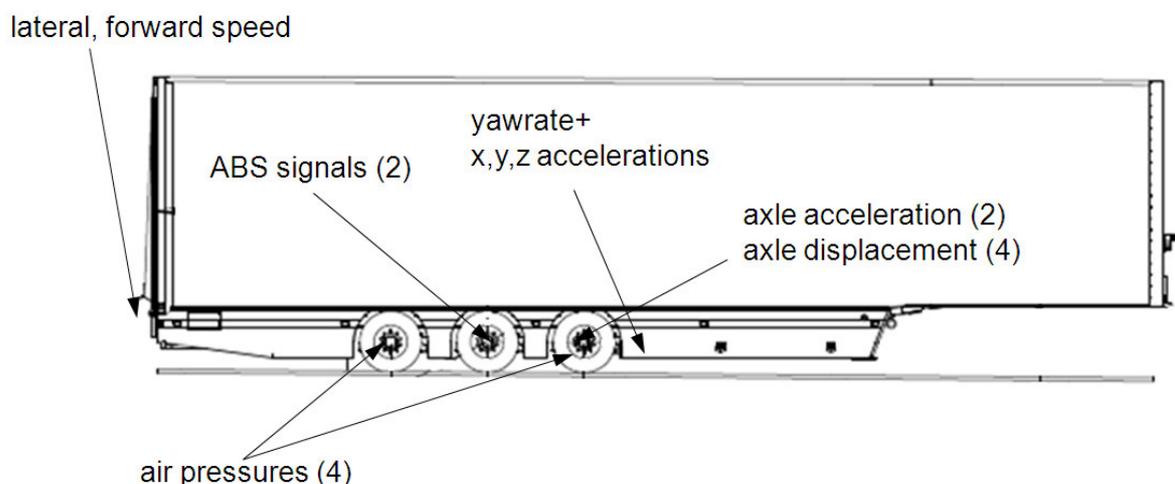


Figure 2.: Layout of instrumentation

This is not the most efficient way of instrumentation, especially with the final purpose in mind that the trailer manufacturer should be able to carry out these measurements within short time and for low cost. One might think then of integrated GPS monitoring systems, and filtering as part of data post-processing to eliminate some of the sensors. These improvements are part of the follow-up project FORWARD. Another remark can be made with respect to the possible need for validation of strength and fatigue analysis on the basis of the derived loads. This would require strain gauges to be included, and that has been done for some of the vehicles. In FORWARD, a standard amount of strain gauges are applied.

3. Representative loading data

All of these test data have been processed to arrive at loading data. We will not discuss all these calculations, but treat two parts of that, our approach to derive the dynamic vertical axle and chassis loading, and the derivation of lateral loading.

In case of non-stationary driving conditions, one has to account for vertical motion of the semitrailer body (low frequency) and of the axles (high frequency). In all other directions, dynamics is considered to be less relevant, for the time being. A proper way to deal with these dynamic loading is to uncouple them from the quasi-stationary loads, or in other words, to subtract the quasi-stationary loads from the total loads. Damper forces and spring forces can be estimated from the relative axle displacements and axle accelerations, as indicated in figure 3. Equilibrium of the axle system in figure 3 will allow us to determine the hinge forces.

The quasi-stationary axle loads may change during braking because of longitudinal load transfer. We estimate the trailer axle brake torque and therefore the brake forces between wheels and road (with wheel dynamics neglected) from the brake pressures.

The longitudinal acceleration gives, together with the brake forces, an estimate of the longitudinal reaction force at the king-pin. The effect of pitching (axle load transfer) on king-pin vertical force and axle loads is derived from the equilibrium in moment around the trailer king-pin, This requires the relationship between brake force and axle load, following from axle characteristics and slip (from vehicle speed, wheel speeds).

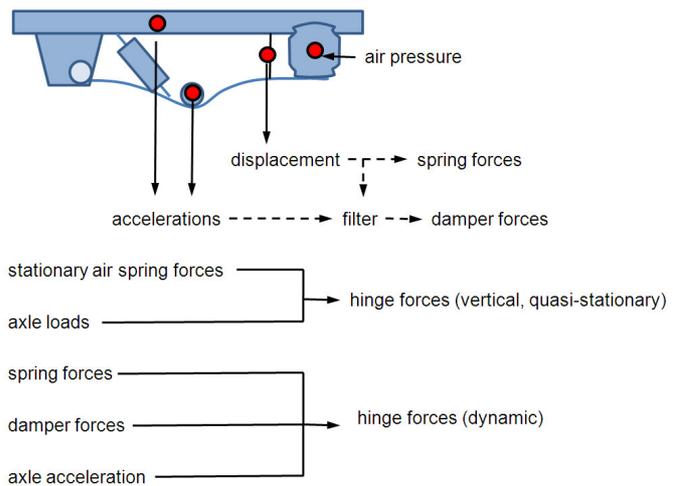


Figure 3.: Vertical dynamic loading

The lateral wheel forces can be derived as follows, see also figure 4. We assume quasi-stationary conditions. In lateral direction, the total side force at all trailer axles plus king-pin reaction force follows from equilibrium in lateral- and yaw-direction.

Assuming the axle side forces to vary linearly in the axle slip angle (the vehicle will likely to roll-over before it reaches lateral nonlinear tyre slip behaviour) we can derive the side forces for the middle axle from linear interpolation (for a three axle configuration). With body slip angle and yaw rate we can then determine the side forces for all axles. Side forces may also be determined during dynamic handling conditions if the effective

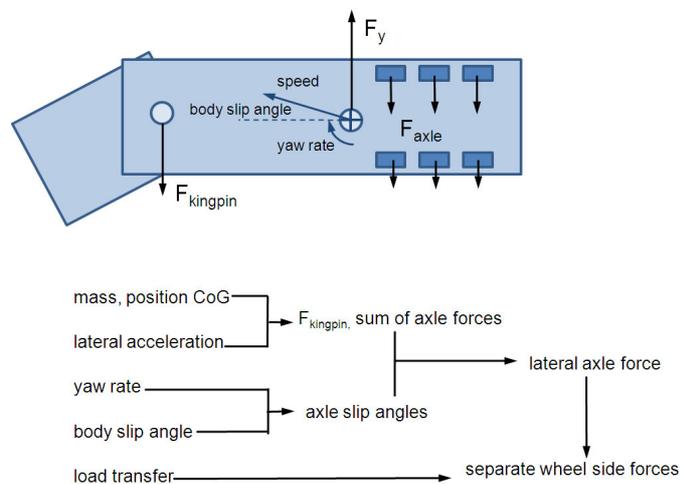


Figure 4.: Tractor-semitrailer during cornering

slip stiffnesses for the rear trailer axles would be known. This information can be derived from steady state cornering conditions, with axle slip angles determined from body slip angle and yaw rate. The lateral load transfer will give further information about the side force per wheel. As indicated above, and discussed in [6], such information can be derived from wheel speeds (more precisely, the deviation of the wheel speeds to the values being determined from kinematic conditions) and/or air spring pressures. This requires calibration beforehand. A simpler way but less general is to estimate the CoG height. During cornering, a torque is acting on the semitrailer due to the different lateral forces per axle.

The payload for the three trailers varied between 24 and 28 ton. The trailer axle loads were in the order of 6 to 8 ton per axle. The maximum decelerations during braking were close to 0.7 g. Maximum lateral accelerations of 0.4 g were obtained. This resulted in a load-range for the trailers as follows

Total brake force on all trailer axles together	: 30 – 40 kN
Longitudinal force at the king-pin	: 60 – 100 kN
Vertical force at the king pin	: 130 – 150 kN
Cornering force over all axles	: 45 – 60 kN
Cornering force king-pin	: in the order of 30 kN
Torque around trailer axle system	: 15 – 20 kNm

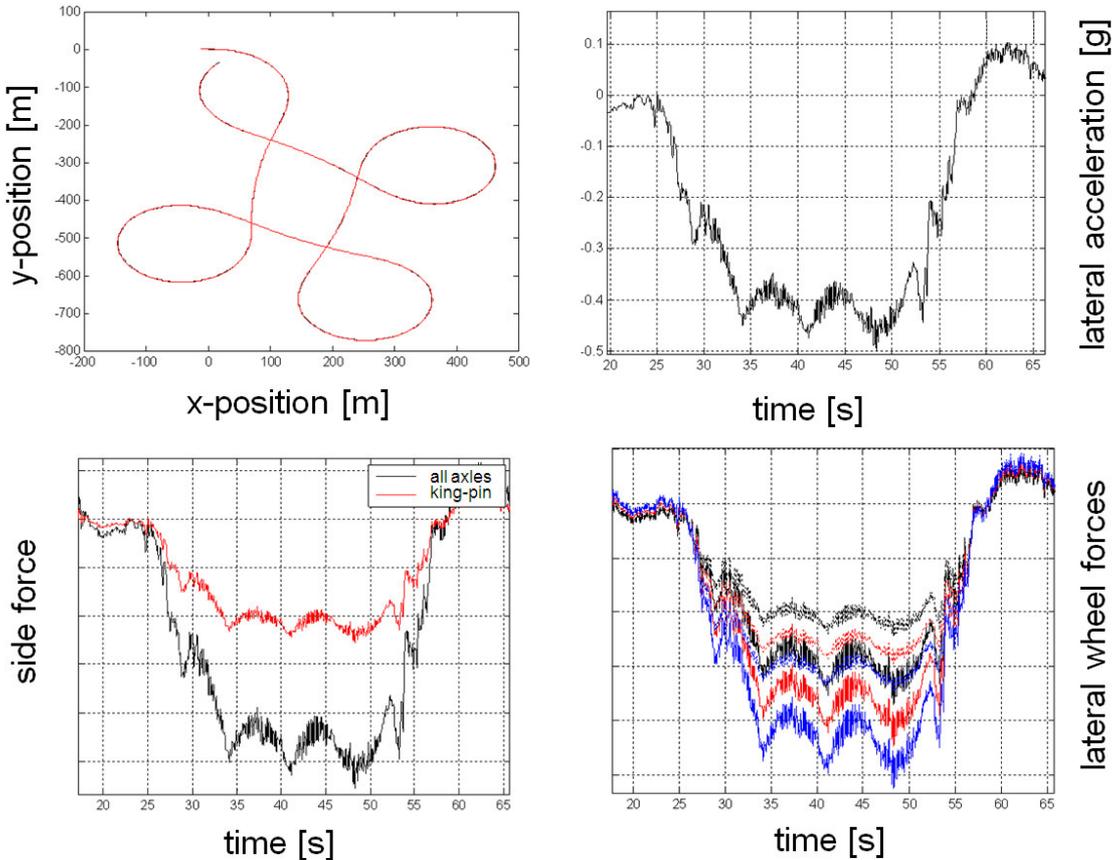


Figure 5.: Side force loading during cornering

Some results are shown in figure 5 for cornering, with a GPS picture of part of the route being followed (intersection of two motorways), the lateral acceleration, the side forces at king-pin

and all axles together, and the separate lateral forces at the six wheels. The large values are related to the outer wheels, whereas the smaller values are related to the inner wheels. As one observes, the side force varies over the three axles with approximately (over all loading history) the maximum force at the last axle being about 50 % larger than the maximum side force at the first axle for this vehicle. Clearly, this depends strongly on the distance between the axles, and the axle position with respect to the trailer CoG.

Another example is braking, where an deceleration of 0.6 g was reached, also resulting in longitudinal and vertical loads on the king-pin. During braking, the ABS system was activated, leading to a low-frequent oscillation of the semi-trailer brake force at the wheels, and therefore also to a similar oscillation in the king-pin forces.

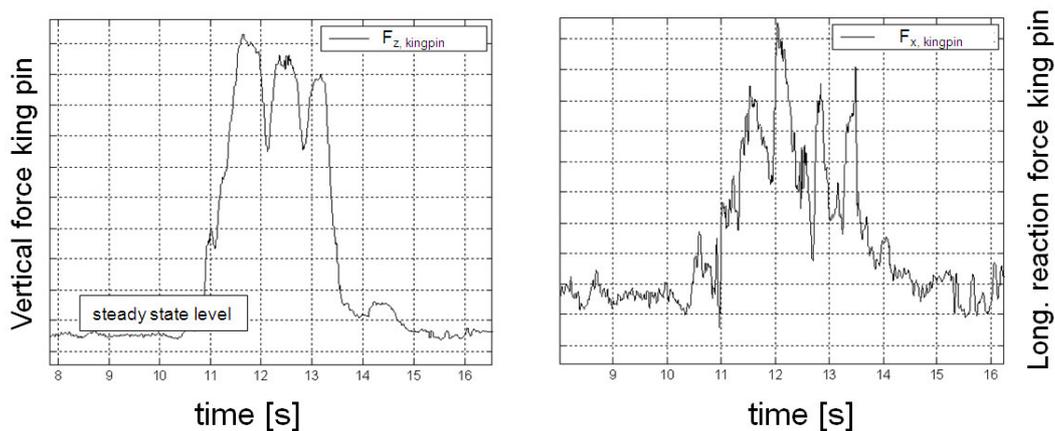


Figure 6.: King-pin loading during braking

Results for the king-pin loads are shown in figure 6. The effect of ABS is clearly shown between 11 and 13 sec. in both plots.

These loads are presently used for FEM analysis of the semi-trailer.

4. The FORWARD extended approach

The first tests plus follow-up, described in the preceding sections, motivated more trailer manufacturers to join this initiative. At the same time, the in-depth discussions with the ‘launching’ trailer manufacturers, showed the need for further improvement of our approach. These improvements were identified as:

- The payload is considered as a rigid part of the vehicle. The tests showed a significant dynamics interaction of payload with the vehicle, The distribution of the payload over the chassis should be accounted for in more detail.
- There is a need to gather more data about the loading of the king pin. In forthcoming measurements, the vertical acceleration at the king pin will be included in the instrumentation plan
- The number of trailers is too small to draw conclusions about more global relationships between design, test conditions, and loading. In FORWARD, at least 11 more trailers are included. There are 7 different vehicle types distinguished in the new batch of vehicles, for which significant differences in response is expected. That includes a tank trailer, a container trailer, bulk transport, a box trailer, a trailer with a double floor at two different heights, and a low loader.

- Further progress in design using FEM analysis requires more validation up to the level of stresses and strains. The standard instrumentation for FORWARD will include strain gauges in the the transition from chassis to fifth wheel.
- Further validation of the dynamic loading requires a tractor-semitrailer model which needs to be validated from experiments. One instrumented tractor will be used for all further measurements.

The aim of FORWARD is to derive representative load cases for analysis of mainly fatigue in order to contribute to a reduction of trailer mass. FORWARD includes testing, transfer of test data to loading data, the derivation of a model environment for this purpose, and FEM analysis (overall and detailed), see figure 7 for some output of FORWARD so far. The first approach starts with (1) road conditions, (2) an existing vehicle and (3) certain test maneuvers (special baseline tests and/or practical use during normal production hours), to result in sets of loading data. The next step should be that the test data are used for validation of a model environment, such that this model can then be used to analyze adjusted vehicle designs. In addition, this model environment will allow more virtual analysis steps, therefore reducing the test effort. The user has the possibility to transfer his test data to loading data using this model, to use the vehicle model to derive these loading data based under realistic test conditions, or, to compare both results in order to validate his model and the model parameters. Discussions with our partners showed that the correct properties of vehicle components (damping, stiffness, inertia, tyre properties,...) are not always available with sufficient accuracy. With their long time experience as a trailer manufacturer, there is always at least a very good guess for these properties, and the comparison between test result and model result is then very useful to tune these parameters.

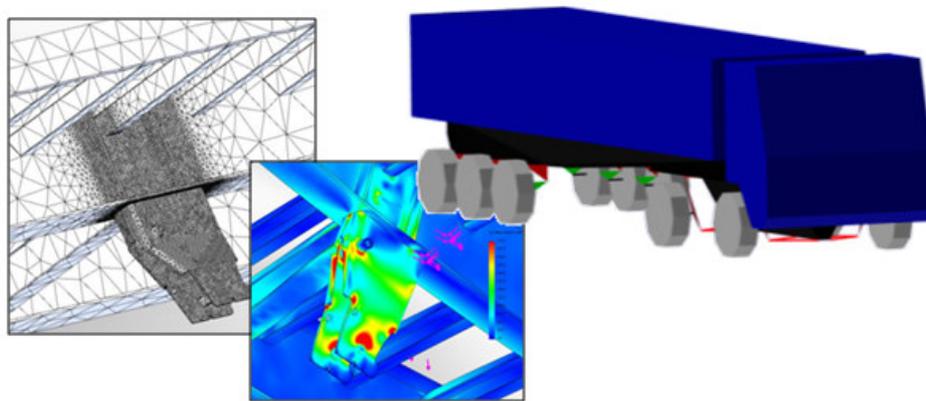


Figure 7.: Some output of the FORWARD project

The FORWARD model environment will have a modular structure, it must be accurate (that means sufficiently accurate to obtain useful results for redesign steps through follow-up FEM analysis), and emphasis must be put on the suspension and axle components. In addition, it should avoid the user to do complex modeling, and it must be easy to compile the model of interest. This requires a user friendly GUI (Graphical User Interface), which allows an automatic model generation in just a few simple steps, with the complete model generation supported by a User's Guide. The different steps in using the FORWARD Model environment can be described as follows:

1. Selection of type of gargo (rigid block container, liquid, pallets, bulk,..)
2. Truck/tractor parameters (CoG, track, wheelbase, inertias, dimensions,..)

3. Trailer parameters (CoG, mass properties, axle positions, number of axles,...)
4. Suspension characteristics (truck & trailer)

These four steps should be sufficient to launch the model generation. As mentioned earlier, model validation can be done through comparison of test results with model results, and tuning each parameter until the match is acceptable. In FORWARD, we carry out a number of specific validation steps on a proving ground for the trailers in the project. That includes steady state cornering for obtaining the lateral tyre properties, straight braking to obtain the tyre longitudinal properties and height of CoG, bump overpass for the derivation of suspension properties, and general handling tests for the overall validation.

5. Outlook and conclusions

A number of first steps is taken to bridge the gap between the derivation of representative measurement data and the structured light weight design of semitrailers. These results, on the basis of three ‘launching’ semitrailer manufacturers, is now continued with an extended consortium and enhanced objectives under the name FORWARD (**F**uel **O**ptimised trailer **R**eferring to **W**ell **A**ssessed **R**ealistic **D**esign loads).

Through the FORWARD project, trailer manufacturers will be able to improve their development and design process, with the aim to reduce vehicle weight without compromising the lifetime of the vehicle. The first test results are accepted well by the trailer manufacturing branch, with an increasing interest of manufacturers (including suppliers of steering and suspension systems) to join the consortium. More partners means gaining more experience with a larger variation in vehicle design. This will result in a more generic approach with potentially new codes of practice in light-weight trailer design.

The different steps in the design process, i.e. testing, derivation of design loads at king pin and trailer axles, virtual design based on validated models derived ‘at the click of a button’, and finally structural analysis aiming at lifetime prediction, are established in a joint effort between the HAN University and the manufacturers. In that way, these steps and the required tools will be optimally adjusted and fitted to the need of these manufacturers.

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