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Impact of heavy goods vehicles with different payload on crashworthiness of safety barriers

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Abstract

In TRANSFORMERS, a recent co-funded EC project, different configurable and adaptable trucks and trailers were developed for optimal transport efficiency. These new vehicle configurations might have an influence on infrastructure and need to be analyzed with regards to their impact on road equipment. For traffic safety reasons the mechanical impact on different types of safety barriers have been assessed by using numerical simulations (instead of expensive crash tests). Finite-Element models of H4b safety barriers were developed. Investigations showed that the selected safety barriers are just able to contain common heavy goods vehicles with different distributions of payload. But high centers of gravity of the payload have been identified as a critical issue with regard to the risk of rollover in crashes with safety barriers. If the trend in heavier optimally laden vehicles continues, additional requirements for payload positions are highly recommended in a further amendment of Directive 2015/719/EC. Alternatively or in addition a potential amendment of EN 1317 might improve the crashworthiness of safety barriers by introducing other vehicle configurations and/or other containment levels.

Keywords: transport safety; virtual testing; safety barriers; heavy goods vehicles (HGVs); new vehicle configurations; payload; risk of rollover; EN 1317; Directive 2015/719/EC

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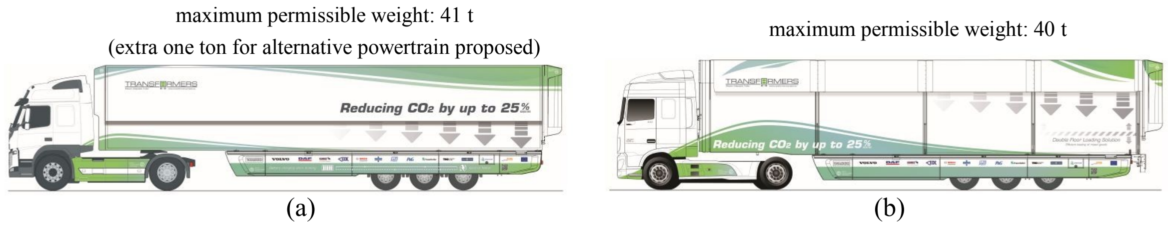
1. Introduction

Road equipment is an essential part of the road and includes all equipment and measures on roads which ensure traffic safety, control and routing. Important elements of road equipment are safety barriers, road markings, road signs, signposts, traffic lights and street lightings. This paper focuses on the impact of the changing vehicle fleet on crashworthiness of safety barriers and investigates the mechanical impact of new vehicle configurations on different types of safety barriers with regard to traffic safety.

Safety barriers are usually made out of steel or concrete and designed to redirect and/or contain errant vehicles safely, for the benefit of the occupants, other road users and third parties. They should help to reduce fatalities and serious injuries in case of an accident. Especially on bridges or roads with high embankments, and in the median of highways the main objectives of safety barriers are the prevention of a breakthrough and/or a rollover of vehicles. While being fit for heavy vehicles, the limitation of accident severity for small vehicles has also to be taken into consideration. EN 1317 (2010) contains the requirements for impact tests with vehicles against safety barriers to determine the performance data of a barrier under impact.

In TRANSFORMERS, a recent co-funded EC project, different configurable and adaptable trucks and trailers were developed for optimal transport efficiency, to reducing energy by up to 25% per tonne km of goods transported. These new vehicle configurations (see Fig. 1) with different total weight might have an influence on existing infrastructure and safety barriers which needs to be analyzed. Both vehicle concepts use innovative aerodynamic measures with a supplementary trailer mounted electric driveline in the Energy Efficiency resp. Hybrid on Demand (HoD)-Trailer which is explained in detail by Nitzsche et al. (2018) and a second cargo floor in the Load Efficiency Trailer.


maximum permissible weight: 41 t

(extra one ton for alternative powertrain proposed)

maximum permissible weight: 40 t

Fig. 1 (a) HoD-Trailer: Curtainsider with fully standard and one segmented fixed roof and supplementary trailer mounted electric driveline; (b) Load Efficiency Trailer: Rigid trailer with box body and 4 segmented roof; Both roofs can be lowered at front AND rear.

The performance of safety barriers is checked and verified by crash tests with different types of vehicles and vehicle weights up to 38 t in different test setups defined in EN 1317-1/2. The articulated heavy goods vehicles (HGVs) developed in TRANSFORMERS with different distributions of payload are not covered by test setups defined in EN 1317. In order to identify the influence of these vehicle configurations on the performance of safety barriers under impact, numerical simulations instead of expensive and time-consuming crash tests have been conducted within TRANSFORMERS.

Methods and results of these simulations are described in chapter 2. Based on the simulation results conclusions are drawn in chapter 3. Some recommendations for necessary adaptions of standards and regulations are summarized in chapter 4. Further and detailed information is also available in public Deliverable D5.3 (2017).

2. Methods and results

Safety barriers are assigned to different containment levels depending on the vehicles that can be contained in crash tests (e.g. level H2: 13 t bus, H4b: 38 t articulated heavy good vehicle). These containment levels are requested in tenders and are selected based on national regulations considering the existing traffic and type of hazards along the road. The national directive RPS (2009) regulates the use of vehicle restraint systems in Germany. At the moment safety barriers with a containment level of H2 are common for medians of German highways. Safety barriers with a containment level of H4b are used in the median of highways in exposed places where the risk and the negative impacts are very high.

Considering a containment level of H4b (38 t truck) and covering a wide range of stiffness, the following safety barriers made of concrete and steel have been selected for the investigations in TRANSFORMERS (see Fig. 2).

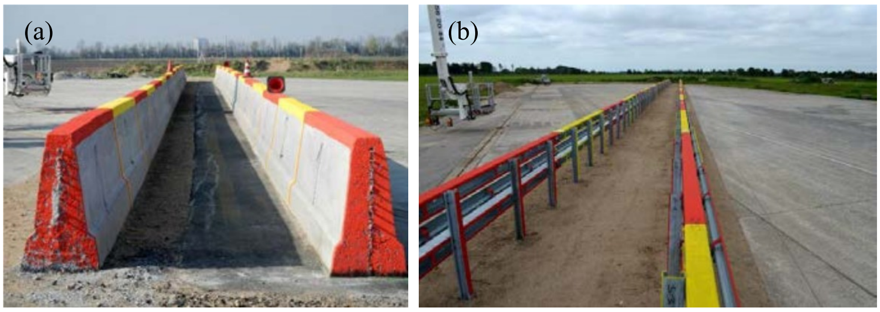


Fig. 2 (a) concrete wall; (b) steel guardrail,
both in double-row installation at test facility; figures published by Jungfeld, I. et al. (2017)

2.1. Crash Tests according to EN 1317 and test setups for containment level H4b

For the assessment of the performance of H4b safety barriers two crash tests (TB11 and TB81) have to be conducted (see Fig. 3). Dynamic deflection and working width of a safety barrier as well as vehicle intrusion are usually determined in a crash test with a heavy vehicle (containment test) whereas the impact severity is measured with a light vehicle representing the worst case for the injury of occupants (impact severity test).

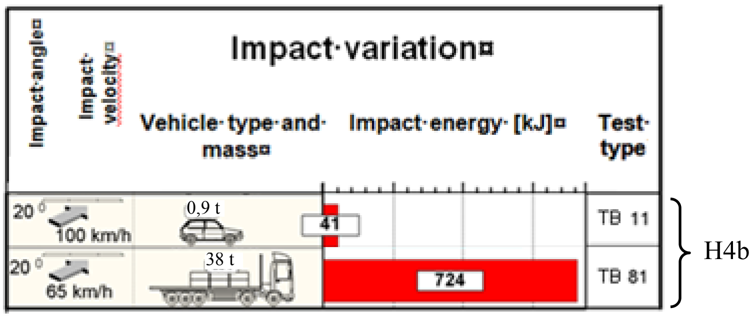


Fig. 3 Impact test parameters for containment level H4b – standardized in EN 1317

Some important requirements for vehicle specifications of TB81 test setup are listed in table 1.

Table 1. Requirements for vehicle specifications of TB81 test setup

Vehicle specifications	Requirement	Limit deviations
Number of axles of articulated HGV	1 steering axle + 3/4 other axles	-
Total weight [t]	38 t	± 1.1 t
Wheel track (front and rear) [m]	2.00 m	± 15%
Wheel radius (unloaded) [m]	0.55 m	± 15%
Wheel base (between extreme axles) [m]	11.25 m	± 15%
COG_x (longitudinal distance from front axle) [m]	6.20 m	± 10%
COG_y (lateral distance vehicle center line) [m]	-	± 0.10 m
$COG_{z,\ payload}$ (height above ground) [m]	1.90 m	+ 15%, -5%

It has to be noted that the center of gravity of the payload ($COG_{z,\ payload}$) in EN 1317 is defined quite low compared to the actual payload positions transported on European roads. It seem to have been chosen as a worst case condition in view of a breakthrough of a median barrier in two-lane motorways, but it is not a worst case concerning vehicle behaviour, e.g. for assessing the risk of rollover during and after the impact.

Figure 4 shows requirements for vehicle and safety barrier behaviour during and after impact and necessary measurements of performance data.

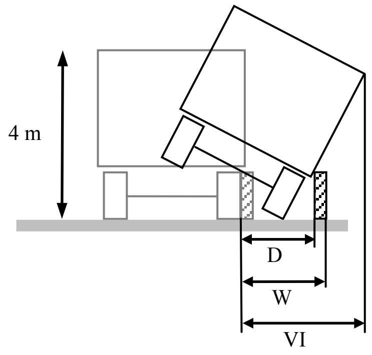
• Safety barrier shall contain the vehicle without complete breakage of any of the principal longitudinal elements. • No more than one of the wheels of the vehicle shall completely pass over or under the safety barrier. • Vehicle shall not roll over (including rollover of the vehicle onto its side).	
• Dynamic deflection D to be measured (accuracy: ± 0.1 m) • Working width W to be measured (accuracy: ± 0.1 m) • Vehicle intrusion VI to be measured (accuracy: ± 0.2 m)	

Fig. 4 Requirements for vehicle and safety barrier behaviour and measurements of performance data acc. to EN 1317

The investigations in TRANSFORMERS are based on a TB81 test setup: truck with a total weight of 38 t impacting a safety barrier with an impact velocity of 65 km/h and an impact angle of 20°. Vehicle configurations developed in TRANSFORMERS are articulated HGVs with a tractor and a semi-trailer, but deviate from vehicle specifications in table 1. The impact of these and other new vehicle configurations on safety barriers have been analyzed by numerical simulations which are described in the next paragraph.

2.2. Finite-Element simulations, verification and validation requirements

In TRANSFORMERS it was not possible to conduct real impact tests according to EN 1317. The developed vehicle configurations are prototypes and have not been available for crash testing. That is reason why non-destructive Finite-Element simulations have been used.

Finite-Element simulation is a well-known and wide-spread numerical method for different kinds of technical processes. It is an approximate solution of a technical process defined by differential equations. For simulation of crash tests with non-linear plastic deformations highly dynamic mechanical analyses have to be conducted.

For Finite-Element simulations in TRANSFORMERS the explicit Finite-Element solver LS-DYNA was used which was developed by Livermore Software Technology Corporation (LSTC).

In order to raise confidence in the simulation results simulation models should always be validated with real test results available for the selected H4b safety barriers. The verification and validation requirements depend on the intended purpose of the simulation model and are documented in CEN/TR 16303, Part 4 (2012) for type approval and certification applications.

Due to time and budget constraints in the TRANSFORMERS project, LS-DYNA Finite Element simulation models for the selected safety barriers and vehicle configurations described below have been developed for investigations in relative terms. They do not intend to be fully validated based on real impact tests and have been combined in simulation models with test setups according to EN 1317. The validation status of the combined simulation models is described in paragraph 2.5 in order to show strengths and weaknesses of the models and to strengthen confidence in the simulation results.

2.3. Development of simulation models for selected safety barriers and vehicle configurations

For the numerical simulations a deformable steel guardrail and a stiff concrete wall have been modelled in single row installation. Figure 5 shows sections of the simulation models of the selected safety barriers (see also Fig. 2).

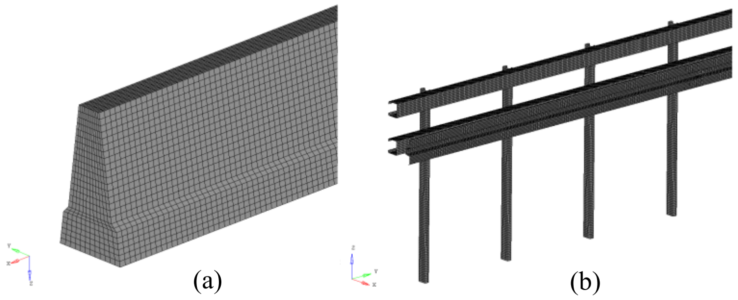


Fig. 5 Developed simulation models for (a) concrete wall; (b) steel guardrail

The double-sided concrete wall (b = 0.6 m, h = 1.1 m) consists of concrete C30/37(LP) and reinforcement BSt 500S and is built directly on an asphalt layer (not anchored). It has a mass of ~1t/m. The single-sided steel guard rail (b = 0.5 m, h = 1.15 m) consists of various parts (posts, rails, box profiles and deformation tubes) made of steel S235JR and fasteners. It has a mass of ~71kg/m. The posts of the steel guard rail are driven into the ground every 1.33 m. Both construction methods are very common for safety barriers in Germany.

The concrete wall simulation model has a length of 80m and consists of 566,746 nodes, 480,000 solid element and 12,800 beams. The mesh size is between 17 mm and 50 mm. The connection between steel reinforcement beams and concrete solid elements is defined by a "Lagrange in Solid" constraint. For the reinforced concrete an elasto-plastic material law including failure is used.

The steel guard rail simulation model has a length of ~79 m and consists of 554,491 nodes, 522,703 shell element and 1,299 beams. The mesh size is between 5 mm and 45 mm (shells) resp. 3 mm and 63 mm (beams). Bolt connections are modelled by beams with a simplified Johnson Cook´s material law including failure criteria. For all parts made of steel S235 JR a strain-rate independent elasto-plastic material law without failure is used.

The vehicle configurations developed in TRANSFORMERS were modelled by adapting a publicly available Finite-Element truck model. This basic model was developed by Politecnico di Milano, Italy and represents a tractor with a semi-trailer fulfilling all vehicle requirements in table 1. The total weight is ~38 t. The linkage between tractor and trailer (king pin) is modelled without failure criteria because it does usually not fail in crash tests. This simulation model of the trailer has been slightly adapted and further enhanced. The visualized payload has been evenly distributed on the trailer. The enhanced truck model has a length of 16.162 m, a height of 2.815 m and a width of 2.486 m and consists of 53,338 nodes, 46,831 shell elements, 2,508 solid element and 110 beams. The mesh size is between 2 mm and 148 mm (shells) resp. 15 mm and 320 mm (solids).

Figure 6 shows this simulation model which is the basis for the numerical investigations.

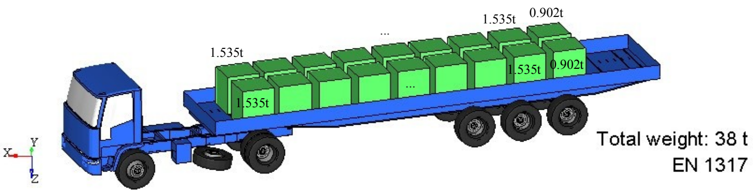


Fig. 6 Enhanced and adapted simulation model acc. to EN 1317 requirements

Figure 7 shows the simulation model with the "Hybrid on demand Trailer" concept. Extra masses in rigid cubes (displayed in red) were added for the electric components. Aerodynamic measures are not taken into account.

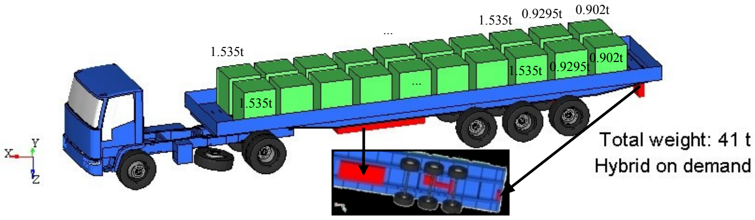


Fig. 7 Developed simulation model for truck with Hybrid on Demand Trailer

The simulation model adapted to the "Load Efficiency Trailer" concept includes both, aerodynamic measures and a second floor (see Fig. 8). Additional masses in rigid bodies for the aerodynamic measures (displayed in orange) and for the second floor (displayed in dark green) have been implemented in the model.

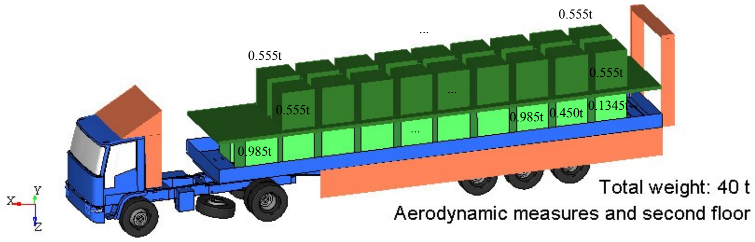


Fig. 8 Developed simulation model for truck with Load Efficiency Trailer

2.4. Simulation matrix

Different simulation models with vehicle configurations and safety barriers were setup and analyzed. Selected simulated cases and important vehicle characteristics are summarized in table 2.

Table 2. Simulated cases and vehicle characteristics

Simulated cases	0D	1	2
Description	simulated crash-test TB81	Hybrid on Demand Trailer	Load Efficiency Trailer
Impact velocity [km/h]	65	65	65
Impact angle [°]	20	20	20
Total weight [t]	38	41	40
Curb mass of tractor and trailer [t]	11.64	11.64	11.64
Extra mass on tractor [t]	-	-	0.135
Extra mass on trailer [t]	-	1.14	0.3 + 1 = 1.3
Payload [t]	26.36	28.22	16.92 + 10 = 26.92
Wheel track (front/rear) [m]	2.021/2.094	2.021/2.094	2.021/2.094
Wheel radius (unloaded) [m]	0.534	0.534	0.534
Wheel base (between extreme axles) [m]	12.226	12.226	12.226
COG_x (longitudinal distance front axle) [m]	6.814	7.181	7.219
COG_y (lateral distance vehicle center line) [m]	0.001	0	0.001
$COG_{z,\text{ vehicle}}$ (height above ground) [m]	1.522	1.514	1.853
$COG_{z,\text{ payload}}$ (height above ground) [m]	1.810*	1.810*	2.256

* lowest position according to EN 1317

Each case is simulated up to 3.5 seconds with both safety barriers (concrete wall and steel guardrail). Deformations of the safety barriers and different vehicle behaviour are investigated and compared in order to study the impact of new vehicle configurations (case 1 and 2) developed in TRANSFORMERS.

2.5. Simulation results

Case 0D simulates a crash-test acc. to EN 1317 with TB81 test setup and represents the reference run for case 1 and 2. For validation purposes simulation results of these reference runs conducted for both safety barriers are compared to corresponding real crash test results. Table 3 gives an overview of the validation status of these reference runs for selected performance data which is open to the public for the safety barriers used.

Table 3. Validation status of reference runs (Case 0D)

Performance data (see fig 4)	Safety barrier	Simulation results (Case 0D)	Real crash test result (EN 1317)	Difference	Tolerances	
					acc. to CEN/TR 16303-4: 2012 *)	amended/ under discussion **)
Dynamic deflection [m]	concrete	0.65	0.99	-0.34	± 0.15	± 0.20
	steel	2.64	2.1	+0.54	± 0.26	± 0.31
Working width [m]	concrete	1.24 (W4)	1.6 (W5)	-0.36	± 0.21	± 0.20
	steel	2.73 (W8)	2.4 (W7)	+0.33	± 0.29	± 0.31
Vehicle intrusion [m]	concrete	3.2 (VI8)	2.4 (VI7)	+0.8	± 0.29	± 0.40
	steel	4.0 (VI9)	2.4 (VI7)	+1.6	± 0.29	± 0.51

*) diff < ± (0.05 m + 0.1 x (measured value))

**) $|D_m - D_{VT}| \le (0.1 + 0.1 \times (D_m))$, $|W_m - W_{VT}| \le (0.1 + 0.1 \times (D_m))$, $|VI_m - VI_{VT}| \le (0.3 + 0.1 \times (D_m))$

The simulation model of the concrete wall is under predicting for displacements and over predicting for vehicle intrusion which represents a worst case scenario for vehicle behaviour regarding rollover. The simulation model of the steel guardrail shows over predicting simulated values. The validation status of simulation models does not fulfil the requirements of CEN/TR 16303, Part 4 (2012) resp. the amended tolerances. For that reason the assessment of simulation results described below is limited to a certain extent and is made in relative terms.

2.5.1. Concrete wall

Simulations have been conducted for 3 cases as described in table 2 and an additional run with a backfilled/fixed concrete wall which cannot dissipate impact energy. Figures 9 - 12 show the simulation results in back view.

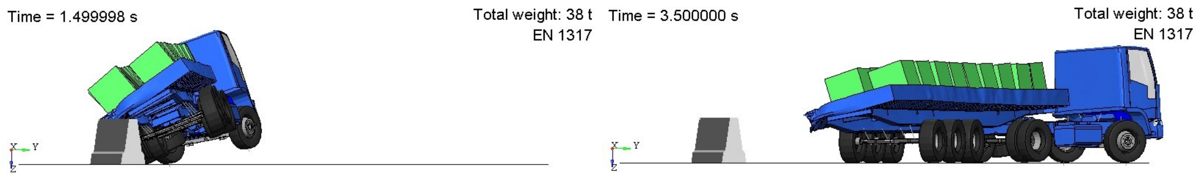


Fig. 9 Case 0D (EN 1317 crash test) with sliding concrete wall after 1.5 and 3.5 s

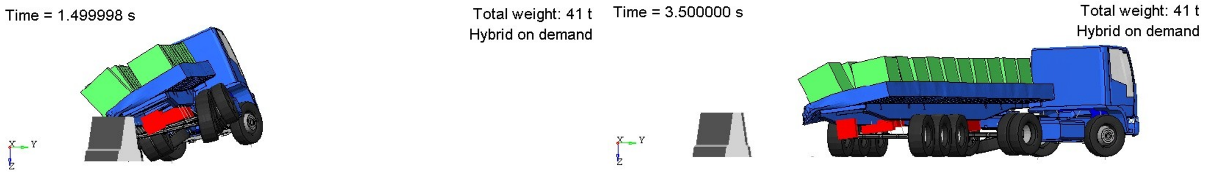


Fig. 10 Case 1 (Hybrid on Demand Trailer) with sliding concrete wall after 1.5 and 3.5 s

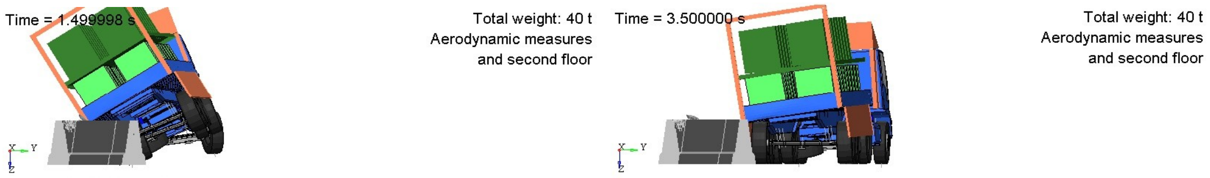


Fig. 11 Case 2 (Load Efficiency Trailer) with sliding concrete wall after 1.5 and 3.5 s

The safety barrier does not fail in cases 0D and 1. It redirects the truck safely. The roll angle of the trailer after 1.5 s is comparable (hardly any risk of roll over). The dynamic deflection and working width (slightly) increase from case 0D to case 1. In case 2 the reinforcement of the safety barrier fails, but the truck is still redirected. The roll angle of the trailer is slightly increased (compared to case 1). The simulated deformation values and roll angle have to be treated with caution because of invalidated assumptions for material failure.

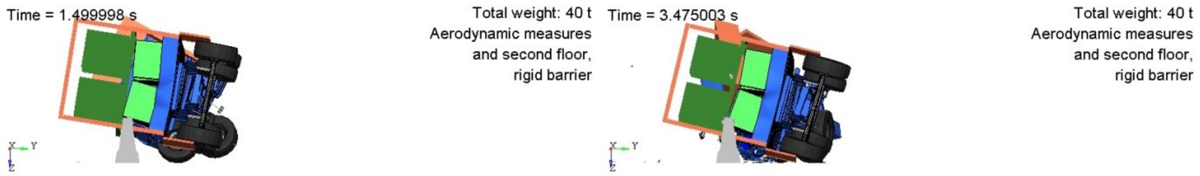


Fig. 12 Case 2 (Load Efficiency Trailer) with backfilled/fixed (rigid) concrete wall after 1.5 and 3.475 s

The backfilled/fixed safety barrier does not redirect the truck safely. The roll angle of the trailer with a high center of gravity exceeds its limit and the truck starts to roll over onto its side. This shows that the risk of roll over is also strongly dependent on the stiffness of the concrete wall.

2.5.2. Steel guardrail

Simulations have been conducted for 3 cases as described in table 2. Figures 13 - 15 show the simulation results in back view.

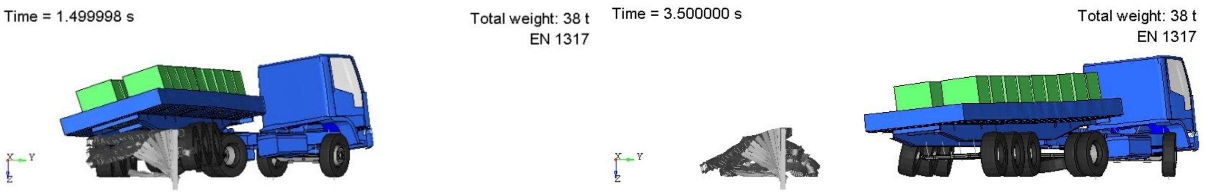


Fig. 13 Case 0D (EN 1317 crash test) with steel guardrail after 1.5 and 3.5 s

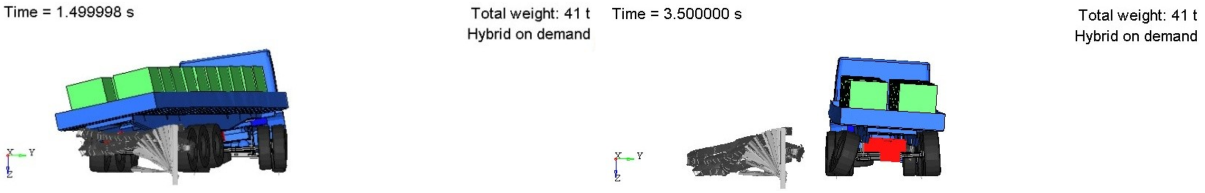


Fig. 14 Case 1 (Hybrid on Demand Trailer) with steel guardrail after 1.5 and 3.5 s

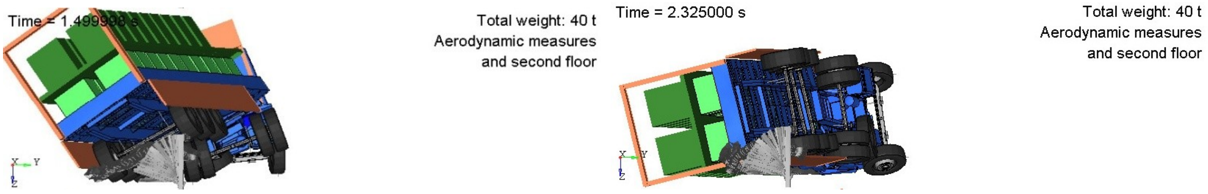


Fig. 15 Case 2 (Load Efficiency Trailer) with steel guardrail after 1.5 and 2.325 s

The safety barrier does not fail in case 0D and 1. It redirects the truck safely. The roll angle of the trailer after 1.5 s is comparable (hardly any risk of roll over). The dynamic deflection and working width slightly increase from case 0D to case 1. In case 2 the safety barrier does not fail, but does not redirect the truck safely. The roll angle of the trailer exceeds its limit and the truck starts to roll over onto its side. Case 2 stopped with an error due to numerical instabilities. The root cause might be rigid material properties used for the aerodynamic measures. This issue could not be solved within the TRANSFORMERS project.

However, investigations showed that the selected safety barriers with the highest containment level (H4b) available on the market are just able to contain common HGVs with different distributions of payload not least because of their double-row installation.

2.6. Additional studies

In the recent past the Federal Highway Research Institute of Germany (BASt) carried out many research activities with regards to extra long heavy load vehicles and their impact on infrastructure published by Irzik, M. et al. (2016). Results of those research activities which are related to safety barriers are described in detail in a paper presented at the last TRA by Jungfeld et al. (2016) and Deliverable D5.3 of TRANSFORMERS (2017). Besides real impact tests against a concrete wall and a steel guardrail, additional simulations have been done with a total weight of 22 t and different payload distributions which confirm the results described in this paper.

3. Discussion and Conclusions

The objective of Finite-Element simulations described above was the evaluation of the mechanical impacts of vehicle configurations developed in TRANSFORMERS on different types of safety barriers. The new vehicle configurations are comparable to 40 t reference trucks authorized by existing legislation and less aggressive than 44 t trucks (for intermodal transport). HGVs with a total weight of 60 t were out of scope of the investigations. The containment level H4b and the test setup TB81 (38 t, 65 km/h, 20°) provides the most severe crash test conditions described in the harmonized standard EN 1317 so far.

Based on the simulation results, vehicle configurations with the TRANSFORMERS Hybrid on Demand trailer does not seem to have a negative impact on accidents with safety barriers. The battery and the electric engine installed below the trailer floor slightly reduce the center of gravity of the trailer and reduce the risk of roll over. High centers of gravity of the payload instead have been identified as a critical issue with regard to the risk of rollover in crashes with safety barriers. This becomes particularly obvious in the assessment of the vehicle configuration with a second floor in the trailer which raises the center of gravity of payload significantly and is also valid for existing trailers which are double stacked with pallets. The additional masses for aerodynamic measures are estimated to have only a minor influence on the crash performance. Their influence has not been evaluated in a separate simulation run.

Investigations showed that the validation status needs to be improved. For the development of validated and numerically stable simulation models further investigations are needed on sliding phenomena, ground modelling and contact interfaces. For realistic failure prediction of concrete walls further researches are also needed on enhanced material laws for concrete and reinforcement. More realistic deformable materials for the aerodynamic measures are recommended and should be applied on numerically instable simulation models in a next step.

4. Recommendations

Generally in terms of road safety, high centers of gravity of payload should be avoided, also in the sense of optimized vehicle dynamics. Up to now there is no legal requirement for the center of gravity of payload in z-direction. In European Regulations (Council Directive 96/53/EC and Regulation (EU) 2015/79) the requirements are related only to maximum permissible vehicle weights and maximum permissible axle loads. Requirements for load positions (e.g. limits for the center of gravity of the payload) are highly recommended in a further amendment of Directive 2015/719/EC. Alternatively or in addition a potential amendment of EN 1317 might improve the crash performance of safety barriers by introducing other vehicle configurations and/or other containment levels contributing to more realistic crash test conditions.

The maximum vehicle mass of 38 t implemented in EN 1317 represents neither the maximum permissible total weight according to the existing legislation in Europe nor the maximum weight for intermodal transport. Contrary to worst case assumptions it covers most cases in the European traffic mix which are not loaded to the maximum and considers technical capabilities of crash test laboratories in Europe. Only one common truck/semitrailer combination is covered by the standard at the moment due to expensive crash tests. Consequently the safety barriers with containment level H4b are designed for this specific truck/semitrailer combination with low center of gravity of payload. But this low center of gravity of payload is not the worst case to assess the risk of rollover during and after the impact. A breakthrough or a vehicle rollover might not be avoided for all cases and with all existing and new vehicle configurations for the above mentioned reasons. A risk assessment needs to be done regularly by road authorities based on future vehicle fleet and current infrastructure which naturally evolve slowly.

If the trend in heavier optimally laden vehicles continues and the percentage share of those vehicles exceed certain limits, a further amendment of EN 1317, Part 2 and national regulations regarding the use of safety barrier might be necessary. Safety awareness with regards to the cargo positioning and securing might also contribute to road safety. Further research and adaptions of regulations and standards are needed to cover all existing and future vehicle configurations and to minimize risks for road safety. In addition to the monitoring of the axle loads carried out on European roads in-depth accident analyses and studies on proper cargo securing are needed. Furthermore, an optimized center of gravity of the payload and necessary limits should accompany and support the ongoing cargo optimization process. Software or web applications on electronic devices already used for the organization of the loading process are usually calculating axle loads and should be amended by an additional target value for an optimized center of gravity in z-direction which contributes to crash performance without roll over and improved vehicle dynamics.

Acknowledgements

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