MODIFICATION OF A TRUCK FRONT FOR IMPROVED KINEMATICS IN RUN OVER ACCIDENTS

Michael Hamacher
fka - Forschungsgesellschaft Kraftfahrwesen mbH Aachen
Germany
Sven Fassbender
ika - Institut für Kraftfahrzeuge RWTH Aachen University
Germany
Florian Feist
Jürgen Gugler
Graz University of Technology
Austria
Paper Number 09-0458

ABSTRACT

A major problem of the predominantly flat fronts of trucks used in Europe with respect to accidents involving vulnerable road users are the kinematics of the vulnerable road user after the impact. Contrary to car versus vulnerable road user accidents the flat truck front pushes the vulnerable road user to the road rather than lifting him. This effect causes a high risk of a run over.

The main idea of the presented safety device is to change the flat front to a tapered shape deflecting the vulnerable road user sideways by using the impact impulse. The achieved deflection reduces the risk of a run over. The tapered truck front has been designed and analysed within the EC funded APROSYS integrated project.

For a principal investigation the tapered shape is realised by an add-on structure mountable to the front of a reference truck. Hence, a direct comparison of the flat and the tapered shape is possible. Regarding a practically relevant application of this safety concept with respect to technical and economical feasibility the tapered shape has to be implemented directly in the cabin design. During the development phase of the new front structure a large number of design versions are generated and assessed. The resulting final principal shape is compared to the basis truck in various numerical simulations with different accident scenarios, pedestrian models and parameter settings.

Due to these results it can be concluded that a convex truck front significantly reduces the risk of a run over. It is most effective in accidents with higher speed (> 20 km/h) and the additional deformation space allows to reduce the contact forces at the primary impact. In this regard it has to be discussed whether the implementation of passive safety devices in trucks should implicate a revision of the vehicle length regulation.

INTRODUCTION

Statistics indicate that more than 1400 vulnerable road users in the current EU member states lose their lives every year due to accidents with heavy vehicles. This number is much larger in the Eastern Europe countries. A major problem of the predominantly flat fronts of trucks used in Europe with respect to accidents involving vulnerable road users are the kinematics of the vulnerable road user after the impact. The flat truck front pushes the vulnerable road user to the road, which causes a high risk of a run over. Car versus vulnerable road user accidents show a different characteristic. The primary contact is followed by a flight phase, in which the vulnerable road user is moved away from the car before the secondary impact and the sliding phase occur. A further contact to the car, the so called tertiary impact, is compared to accidents with trucks quite seldom.

Currently there are no existing pedestrian safety requirements for trucks. The main idea of the safety device described within this paper is to change the flat front to a tapered shape deflecting the vulnerable road user sideways by using the impact impulse. The achieved deflection reduces the risk of a run over and the additional deformation space allows to decrease the contact forces at primary impact. Due to the shape of the optimised truck front, there is not only a benefit in scenarios, where the truck is driving straightforward but also in cornering scenarios. The tapered truck front has been designed and analysed within the EC funded APROSYS integrated project [1].

To ensure a direct comparison of the flat and the tapered shape, it is realised by an add-on structure mountable to the front of a reference truck. The reference truck is a MAN LE. Regarding a practically relevant application of this safety concept with respect to technical and economical feasibility the tapered shape has to be implemented directly in the cabin design. However, the results of the add-on device give sufficient implications on the benefits and difficulties to be expected for a tapered truck front in accidents between a truck and a vulnerable road user.

DEVELOPMENT OF A DEFLECTING FRONT SHAPE

The first step on the way to a final design is to determine the most appropriate general design.

Front geometry versions

In total the number of front geometry versions developed and assessed amounts to 90. The differences between the single versions are often only marginal. This approach is reasonable to examine the effect of a specific geometry or to improve positive effects. However some versions show exaggerated shapes. These versions are meant to provide information about the accident kinematics but are not practical for an actual application. An overview of the different development stages is given by the 12 examples shown in Figure 1.

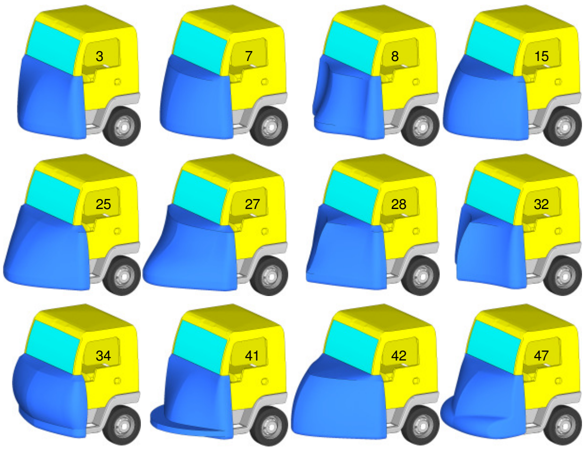


Figure 1. Examples of the 90 front geometry concepts.

Regarding the current regulations a practical front structure solution should be as flat and even as possible. Versions 3, 7 and 8 fulfil these requirements but do not provide a sufficient deflection of the pedestrian. Version 15 shows a highly improved deflection effect. The front structure of the versions 3, 7 and 15 is rather steep, which leads to a straight and direct impact of the pedestrian. An effect that throws the pedestrian slightly upwards can be achieved with the versions 25 and 27, which show a more shallow shape.
Examples of front structures bending sharp to the centre of the front are the versions 28 and 32. The aim of these versions is to deflect the pedestrian even from a centre position sufficiently to the side. Unfortunately, these solutions have not shown the expected effect. In addition they are critical because of the disadvantageous primary impact on the sharp and stiff edge formed by the centreline, which might cause severe injuries of the pedestrian. The idea of design concept 34 is a primary contact of the arms and torso of the pedestrian instead of the lower extremities. Due to its bad test results this design is not regarded in further concepts.

To achieve the effect of throwing the pedestrian up but having a short front version 41 has been designed with a forward reaching plateau at the lower end of the nose. In contrast to this, version 42 shows the maximum geometrical design space regarded within the study. As of a certain length further improvements can not be achieved by extending the nose. Version 47 is an optimisation of version 41 and forms the basis for the remaining 43 versions, where the design is further optimised. This concept can be seen as the summary of all experience gained in the previous designs. The dominant concept idea is the surrounding plateau at the bottom. In addition to the effect of throwing the pedestrian up the plateau improves the compatibility to cars.

Assessment of the front geometries

During the development of the different designs the versions have to be assessed regarding their impact kinematics. Due to the large number of different versions this can only be done by a reduced number of accident scenarios.

The assessment of the different versions comprises six tests, but for most of the versions less tests are conducted if they do not show appropriate results. The complete scope includes three crash-scenarios in a forward-driving and three crash-scenarios in a right-cornering situation. The simulations for the determination of the general shape are carried out with a 50 % male pedestrian model only. Later on for the assessment of the final design more scenarios and pedestrian models will be considered. The assessment only assesses the crash kinematics and the position of the pedestrian after the impact. In this context the two terms run over and roll over are used. Both cases are critical since the pedestrian gets underneath the truck, whereas roll over implies a contact of the pedestrian to the tyres.

Determination of the best front geometry - Regarding the different front geometries the curvature of the plateau along the width of the truck front has an important influence. After all, a curved platform shows better results because of the stronger side deflection of the pedestrian. Additionally, a steeper design of the plateau has a positive effect on the impact kinematics. A slight tapering of the outer edges of the plateau has advantages in the right-cornering scenarios when the impact occurs at the corner of the truck front. Front geometry 84 offers all these positive effects (Figure 2).

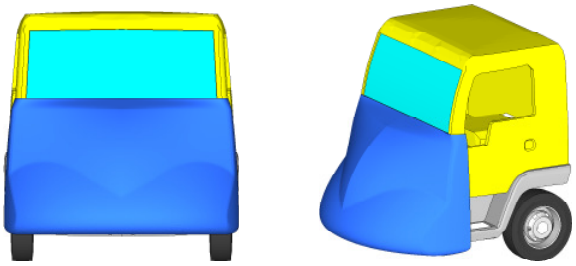


Figure 2. Front geometry 84.

The kinematics of the pedestrian model can be seen in Figure 3. Shortly after the primary impact the pedestrian model looses contact to the ground and turns away from the truck. When touching the ground the right leg is already beside the plateau. The rest of the body is deflected to the side. During the secondary contact the pedestrian model rolls to the side and rests at a sufficient clearance to the truck wheels.

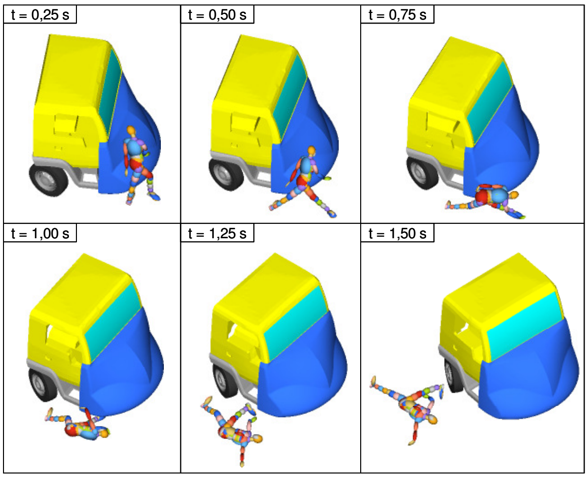


Figure 3. Deflection of the pedestrian in a right-cornering scenario (Version 84).

For the simulation of the run over tests the multi-body simulation software MADYMO (mathematical dynamic modelling) is used.

ASSESSMENT OF THE FINAL DESIGN

For the definition of a run over test procedure the knowledge of typical accident constellations is necessary. This includes the knowledge of the predominant scenarios as well as the knowledge of the most frequent locations of the primary contact in accidents between trucks and vulnerable road users (VRU). Accident scenarios and assessment parameters can be deduced from those results to cover a broad spectrum of real world accidents.

Accident analysis

In countries of the European Union about 1400 pedestrians (year 2006) and cyclists lost their lives after an accident with a truck. Accident experts expect a possible decrease of about 30 % through new design concepts, test methods and development guidelines. The injury severity of a VRU is depending on different aspects. The collision speed plays an important role beside the geometry of the vehicle front and the position during the primary impact. But also age and height of the pedestrian are relevant. At last, the secondary impact has an influence on the severity of the injury.

The results of a previous APROSYS study [2] showed that accidents with pedestrians are more crucial than accidents with cyclists. Especially the danger of a fatal accident by being rolled over is higher. In the APROSYS study 26 truck-pedestrian accidents from the GIDAS (German In-Depth Data Analysis Study) data base and 30 cases of DEKRA have been regarded amongst further in-depth studies. In 94 % of the cases the truck was driving straight-forward. For inner city areas the scenario of a right cornering truck is relevant as well with a rate of 6 %. Accidents with left-cornering trucks do not occur in the studies. The in-depth data show three characteristic situations for accidents between trucks and pedestrians (Figure 4).

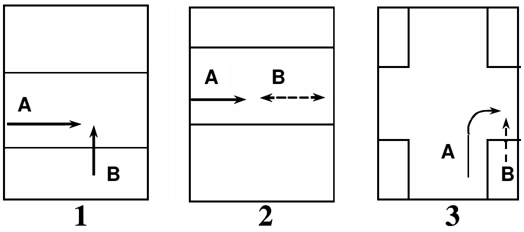


Figure 4. Characteristic situations of truck-pedestrian accidents. [2]

In the first situation a pedestrian tries to cross the road and approaches from the right side. In the second situation the pedestrian walks in or against the driving direction of the truck. Right cornering is the third characteristic situation for an accident. Situations 1 and 3 are typical inner city accident situations whereas situation 2 is more common on non-urban roads.

Regarding the straightforward driving direction of the truck (situation 1 and 2) it is obvious that most impacts occur at the front, whereas the right corner is involved most frequently. The area behind the front axle is not very relevant (only 10 %).

The front right corner of the drivers cabin is also the predominant impact area in situation 3. This scenario is crucial because the affected section is hardly visible or even not visible at all from the drivers seat. As a result the accident partners are rolled over in many of these cases. However the hit pedestrian gets not necessarily underneath the truck in place of the primary impact. Depending on the impact constellation the pedestrian is run over at a subsequent location. 81 % are run over before the right front wheel, 62 % of those are actually rolled over by the front or the rear wheels during the turning process. In contrast to the right side the left side is less relevant. Only 10 % of VRU's impact here and reach under the truck. The results of the accident analysis are used as a basis for the assessment of the optimised front design. [3]

Accident scenarios

Within the APROSYS project the straightforward driving truck turned out to be the predominant accident scenario. Beside this, also the right-cornering situation is relevant. Both situations are regarded for the assessment of the final design. The straightforward driving scenario is comparable to the first situation in Figure 4 with a pedestrian approaching from the right side of the street. The pedestrian model is placed sideways in a walking position in front of the truck. The right-cornering scenario is defined according to situation 3 in Figure 4 but differs in an important aspect. Here the pedestrian model is hit at the entrance of the curve and not at its end as it is shown in the picture. Correspondingly, the pedestrian model is placed in a walking position sideways directly in front of the truck. Because of the curve radius the truck moves also in lateral direction towards the pedestrian. Thereby the position of the pedestrian moves, relatively to the truck, to the front centre. As a result the cornering counteracts a deflection to the right side of the street. This effect has to be compensated additionally (worst case). Both driving scenarios are displayed in Figure 5.

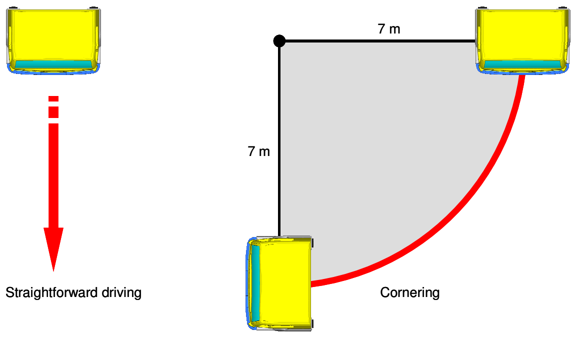


Figure 5. Movement of the truck model.

Another important aspect for the definition of the cornering scenario is the curve radius. The used radius of 7 m is deduced from the turning circle of the MAN LE 2000, which is 14 m in diameter. DEKRA determined radii of 10 to 15 m, but there are also smaller radii of about 6 m, therefore the chosen 7 m radius represents a good estimation and represents the more critical constellation with respect to side deflection.

Pedestrian models - MADYMO offers a full body pedestrian model. The model is available in five different body heights reaching from a three year old child to the 95 % male model. The three year old child model is not regarded in the tests, due to the low protection potential in an accident with a truck. The included models are shown in Figure 6.

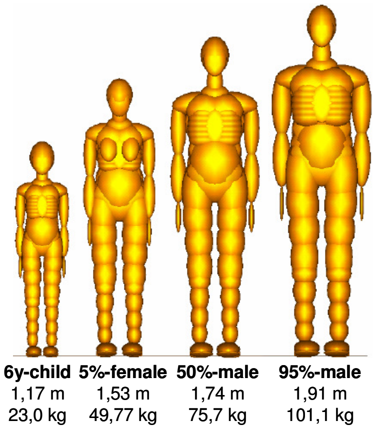


Figure 6. Regarded full body pedestrian models from MADYMO. [4]

The kinematics of the pedestrian models were precisely determined. The legs are able to break at the tibia and the femur. Thereby the impact kinematics can be described more exactly. For the analysis in the tests measuring points record the accelerations, forces and moments. Predictions concerning impact kinematics and the behaviour of throwing the pedestrian up are feasible. Head impact speeds are simulated with a good tendency. Head movements, impact angles and impact points can be simulated accurately. Precise predictions of injuries are not possible. Adequate predictions can be deduced from the measured accelerations.

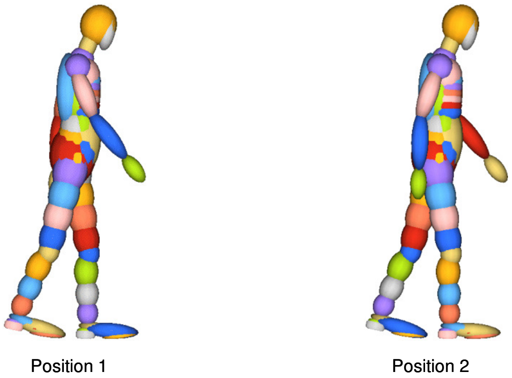
In addition to the kinematics of the human models also the head impact speeds at the primary and secondary impact are regarded within the assessment of the final design. The head impact point of the primary contact is determined to identify the influence of the different body heights.

Collision speed - An essential factor during a crash is the collision speed of both opponents. This speed has to be chosen appropriate to deliver realistic results. Since both regarded accident scenarios occur in urban areas the speed range is limited. For the straightforward driving scenario a truck speed of 40 km/h is chosen, which is about 20 % lower than the inner city speed limit and covers a wide field of possible accidents. This speed corresponds to the speed in several full-scale and component tests.

The truck speed in the right cornering scenario is inevitable lower. 87 % of the trucks collide in a right-cornering situation with a speed of only up to 20 km/h, whereas the speed range in most of the accidents analysed by DEKRA reaches from 11 t o 15 km/h. Regarding the side deflection behaviour a higher speed would reduce the demands for the side deflection as it would contribute to the impulse given by the shape. Therefore a collision speed of 14,4 km/h (4 m/s) is chosen in the right cornering scenario. Together with the narrow turning circle this scenario sets high demands for the new front structure.

Analyses reveal that the pedestrian is in movement prior to the crash. But within the run over assessment the pedestrian model has no initial speed, which correlates with the common procedure. This approach is acceptable as the pedestrian model is set up directly in front of the truck and due to the low kinetic energy of a walking pedestrian.

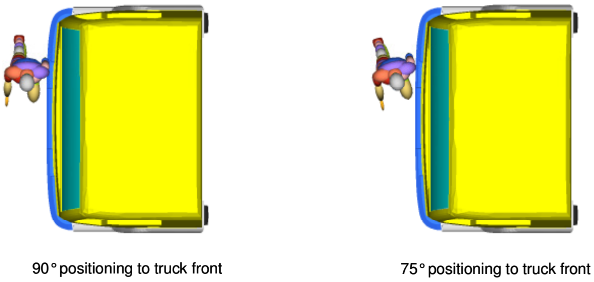
Positioning of legs and arms - The positioning of the legs and arms has an important influence on the accident kinematics. Two different postures are simulated to consider this effect. In position 1 the left leg and the right arm are moved forward (walking position). Position 2 is set contrary. The two postures are shown in Figure 7.


Position 1

Position 2

Figure 7. Positioning of the pedestrian model.

Collision angles - Besides the angles of arms and legs the orientation of the human model in relation to the truck defines the pedestrian positioning and the resulting collision angle. Extensive in-depth analyses of car-pedestrian accidents revealed that in more than 90 % of the accidents the pedestrian crossed the street and was hit laterally. In more than 80 % of these cases the pedestrian was caught in a 3-o'clock or 9-o'clock position by the vehicle front. As the accident analysis records the hit angle with an accuracy of 15°, two different orientations are used for the assessment of the final design. In addition to the 90° orientation of the pedestrian model an angle of 75° is regarded. Both collision constellations are shown in Figure 8.


90° positioning to truck front

75° positioning to truck front

Figure 8. Impact constellations.

Lateral positioning of the pedestrian model - Three different lateral positions of the pedestrian model in front of the truck are defined for each scenario. The classification in right and left front side is carried out in driving direction.

In the straightforward driving scenario the pedestrian is positioned 50 cm left and right of the trucks longitudinal axis. That matches with the respective middle of each front half of the truck. The third position addresses the centre of the truck with an offset of 15 cm to the right of the longitudinal axis. This offset is necessary, because with respect to a side deflection an exactly centred position represents an instable and undefined situation. By the offset the direction of the deflection is predetermined. Furthermore an exactly centred impact is very improbable. The simulation of a corner impact is not necessary for the straightforward driving scenario, because a sufficient deflection can be taken for granted when the pedestrian isn't run over in the first two positions. This has been proven by several simulations.

The focus in the cornering scenario lies on the right front edge of the truck, which represents the predominant impact area for this scenario. For this reason the pedestrian is positioned in a distance of 80 cm and 100 cm from the trucks longitudinal axis. Since the truck is turning right a wheel angle of 25° is defined. The left side is not as critical as the right side in this scenario, because here the truck moves away from the pedestrian. This effect supports the movement out of the critical area. Therefore a position closer to the centre of the truck front is chosen. Corresponding to the value of the straightforward driving scenario the pedestrian is positioned at a distance of 50 cm from the trucks longitudinal axis. All positions are displayed in Figure 9 by vertical lines.

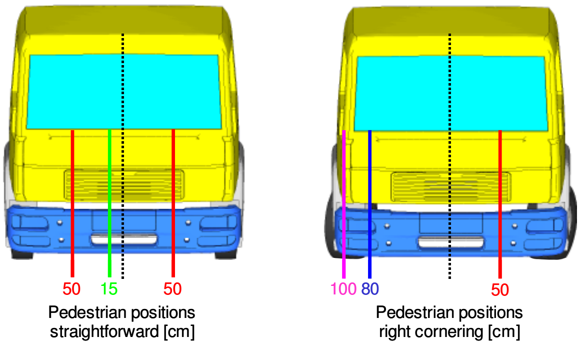


Figure 9. Positions of the pedestrian model relative to the longitudinal axis.

Simulation matrix – The shape of the optimised front has been mainly designed for the 50 % male. The entire assessment described above covers necessarily a much broader spectrum of tests. All tests are also carried out with the basis truck front as a reference. Altogether the parameters defined lead to 192 simulations. The associated simulation matrix is shown in Table 1.

Table 1.
Simulation matrix for the assessment of the final design

Parameters	Test scope	Factor
Crash scenarios	Straightforward driving and cornering	2
Pedestrian models	6 y. child, 5 % female, 50 % and 95 % male	4
Collision speed	One collision speed per crash scenario	1
Positioning of arms and legs	Two postures per pedestrian	2
Collision angle	Two constellations	2
Pedestrian positions	Three positions per crash scenario	3
Truck models	Basic and optimised version	2
Total amount of simulations		192

For the comparison of the improved truck front to the basic design the kinematics, the head speeds and the impact points of the pedestrian models are regarded. Variations of several simulation parameters complete the assessment.

Results of the basis model

The steep front shape of the basis model is representative for existing truck designs in Europe. Only the slight forward reaching front bumper of the MAN LE 2000 is a non-typical feature but is positive for the loads at the primary contact. Nevertheless the steep front shape causes disadvantageous kinematics with the pedestrian rotating to the street.

Accident kinematics - In all scenarios the pedestrian model is thrown straight in front of the truck after the impact and is rolled or run over. Severe injuries are expected in 80 of 96 cases (83,3 %). Only in the 16 cases of the right cornering scenario, where the pedestrian model is positioned on the left side, the results are not as crucial. Here the truck moves away from the pedestrian after the impact. In these cases the essential parts of the body remain in a sufficient distance to the front wheels but still the lower limbs are rolled over. Table 2 gives an overview of the crash characteristics of the basis model.

Table 2.
Overview of the crash characteristics of the basis model for 6 year old child (Ch), 5 % female, 50 % male and 95 % male

Scenario	Position		Ang	Ch	5%	50%	95%
Straight-forward driving	15 cm right	Pos 1	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
		Pos 2	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
	50 cm right	Pos 1	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
		Pos 2	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
	50 cm left	Pos 1	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
		Pos 2	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
Right cornering	100 cm right	Pos 1	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
		Pos 2	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
	80 cm right	Pos 1	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
		Pos 2	75°	🟧	🟧	🟧	🟧
			90°	🟧	🟧	🟧	🟧
	50 cm left	Pos 1	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
		Pos 2	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
🟩	Roll over of outer limbs without life threatening injuries		🟧		Run or roll over of essential body regions		

Fields marked in orange highlight situations where essential body regions of the pedestrian model are run or rolled over. Both effects have to be avoided in respect of an improved pedestrian safety. Only a rolling over of arms and lower legs can be allowed without risking life-threatening injuries. These cases are marked in green.

Despite the missing contact to the wheels a run over implicates a great danger for the pedestrian and is almost as critical as a roll over. Therefore roll and run over of a pedestrian model are rated equally. Besides a roll over can only be determined for the front axle with the available model. Further axles are not regarded and the roll over of pedestrians by the rear axles can not be detected.

Figure 10 shows an example of a run over situation in the straightforward driving scenario. The sequence shows the 5 % female at a collision angle of 75° positioned 50 cm right from the front centre. Arms and legs are in position 1. As a result of the steep front it cannot be avoided that the pedestrian reaches under the truck. In the sequence the model is only run over but in 11 of the 16 cases within this scenario the pedestrian model is actually rolled over. Five of these cases are highly crucial as essential body regions are rolled over.

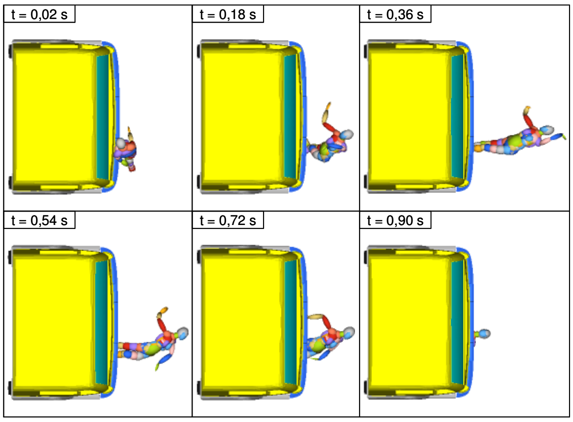


Figure 10. Kinematics of the 5 % female in the straightforward driving scenario.

In the right cornering scenario all cases with an impact at the right truck side result in a run or roll over situation. Figure 11 shows an according crash with a six year old child model.

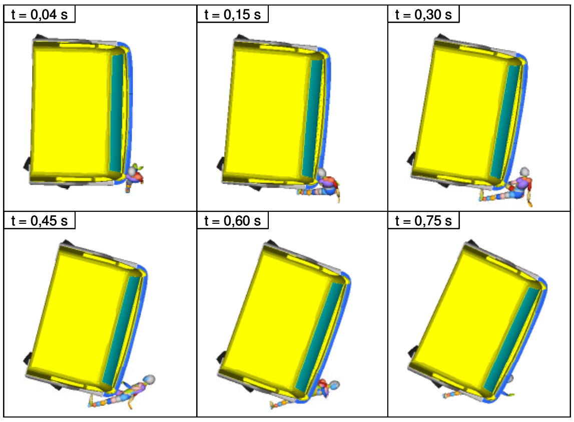


Figure 11. Kinematics of the six year old child in the cornering scenario.

<u>Head impact areas</u> - Body height and collision constellation affect the head impact area. Due to the fact, that the pedestrian models are positioned directly in front of the truck the head impact points are nearly identical to the initial head position. In four cases of the six year old child, a second impact of the head occurs. This happens in the cornering scenario when the model is hit by the edge of the truck. The head strikes the bumper while the model is falling down.

The head impact areas can be seen in Figure 12 divided into straightforward driving and cornering scenario. On the left side impact areas of the six year old child and the 5 % female are illustrated. The right side shows the impact areas of the male pedestrian models. Each mark represents one of the defined scenarios and comprises all impact points of the corresponding model within this scenario. A missing mark indicates, that a head impact has not been detected in all of the four belonging cases.

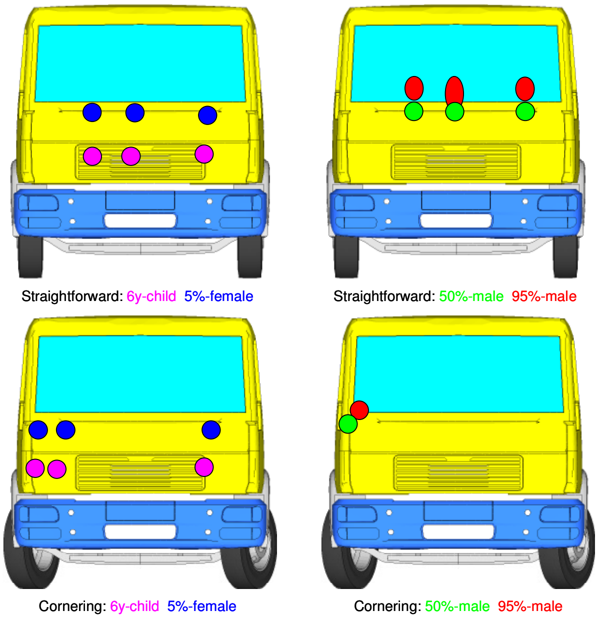


Figure 12. Head impact areas.

<u>Summary</u> - The pedestrian safety potential of the basis structure can be estimated as very poor. All crash situations lead to run or roll over events. The flat front design pushes the pedestrians straight in front of the truck. Regarding pedestrian protection, this is a big disadvantage of today's truck front designs. Measurements, like rounding the edges, that decrease the severity of injuries at the primary impact are not sufficient as long as there is such a high risk for the pedestrian of getting under the truck.

The head impact speeds of the primary impact can be regarded as relatively good, except for the six year old child. In many cases there is even no contact of the head with the front due to the straight impact of the pedestrian model. The simulations reveal high head impact speeds during the secondary impact. The burden on the head is significantly higher compared to the primary impact. In this context it is interesting to what extent the deflection effect of the optimised front shape will influence the speed level of the secondary impact.

Results of the optimised model

The optimised front leads to completely different kinematics compared to the basis truck. Due to the effect of throwing the pedestrian model up with the resulting rotary motion towards the truck a head contact to the front is very probable. So it can be expected that compared to the basis model there will be less cases without a head contact. As before the roll over of non essential body parts like feet, lower legs and arms are regarded as non critical. Nevertheless, the predominant aim of the new front structure is the entire prevention of run and roll over situations.

<u>**Accident kinematics**</u> – Only 16 cases of the basis model fulfil the requirements for a non critical assessment. The optimised model reveals a highly improved behaviour with 84 cases rated uncritical (87,5 %). So in most cases fatal injuries resulting from a run or roll over of the pedestrian can be avoided. Regarding the 12 cases with fatal injuries the 95 % male model is affected six times, the six year old child is involved four times and the 5 % female two times. The right cornering scenario with a position of the pedestrian model 80 cm right from the longitudinal axis shows the highest number of critical cases. Table 3 gives an overview of the simulation results of the optimised front. The results for the 50 % male model are particularly good, because the front geometry has been designed for it.

Out of the three situations of the straightforward driving scenario the impact of the pedestrian model next to the front centre is the most challenging constellation for the new structure. In this situation a maximum deflection of the pedestrian is required. Four critical cases occur, where the deflection is not sufficient. A roll over of essential body parts is identified for the six year old child in both constellations with arms and legs in position 2. Due to the low impact point of the child model the plateau geometry is here mainly responsible for the kinematics. Near to the front centre the plateau shows only a slight curvature. Thus a strong deflection impulse cannot be generated for the child model, although its low weight has a positive influence. A negative effect of posture 2 can also be detected for the other pedestrian models.

Table 3.
Overview of the crash characteristics of the optimised model for 6 year old child (Ch), 5 % female, 50 % male and 95 % male

Scenario	Position		Ang	Ch	5%	50%	95%
Straight-forward driving	15 cm right	Pos 1	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
		Pos 2	75°	🟧	🟧	🟩	🟧
			90°	🟧	🟩	🟩	🟩
	50 cm right	Pos 1	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
		Pos 2	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
	50 cm left	Pos 1	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
		Pos 2	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
Right cornering	100 cm right	Pos 1	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟧
		Pos 2	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
	80 cm right	Pos 1	75°	🟩	🟩	🟩	🟧
			90°	🟧	🟩	🟩	🟧
		Pos 2	75°	🟩	🟩	🟩	🟧
			90°	🟧	🟧	🟩	🟧
	50 cm left	Pos 1	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
		Pos 2	75°	🟩	🟩	🟩	🟩
			90°	🟩	🟩	🟩	🟩
🟩	No run or roll over / Roll over of outer limbs without life threatening injuries			🟧	Run or roll over of essential body regions		

Figure 13 shows an example of a prevented run over situation in the straightforward driving scenario. The sequence shows the 95 % male model in posture 1 with an impact angle of 90°.

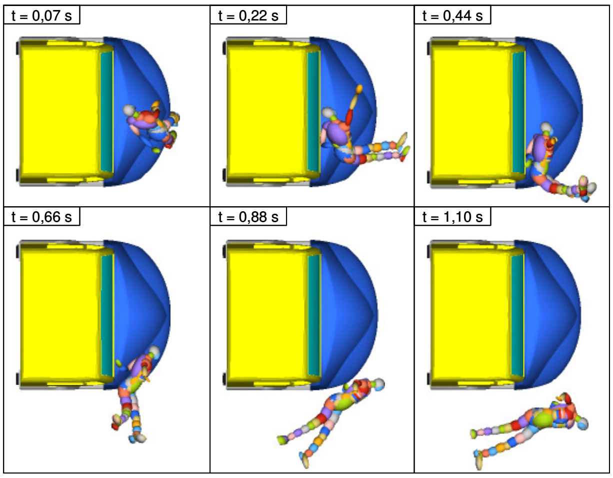


Figure 13. Kinematics of the 95 % male in the straightforward driving scenario.

Although the impact occurs next to the centre of the truck front and despite the height and weight of the 95 % male the model is deflected far enough to the side. This is a good example for the potential of the tapered front structure. With only four critical cases in 48 situations of the straightforward driving scenario its effectiveness can be regarded as good in comparison to the basis model showing a run or roll over of vital body parts in all constellations.

In Figure 14 an example of the right cornering scenario is displayed. It shows the kinematics of the six year old child model with arms and legs in position 2 and a collision angle of 90°. In the illustrated position at 100 cm right to the centre of the truck front only one case is critical. The torso of the 95 % male dummy is rolled over due to a disadvantageous drop behaviour caused by a broken shinbone. In all other cases the kinematics are good.

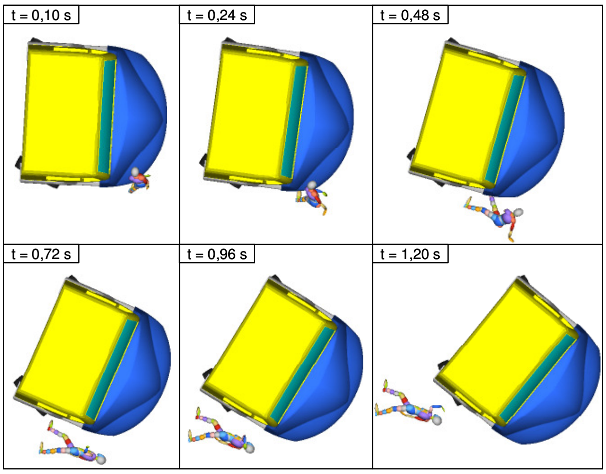


Figure 14. Kinematics of the 6 year old child in the cornering scenario.

In the second constellation (position 80 cm to the right) of the cornering scenario it becomes apparent that the design is optimised for the 50 % male model. The 50 % male dummy is sufficiently deflected to the side in all cases while the 95 % male dummy is rolled over after fractures of the shinbone. The 5 % female shows one critical situation. The kinematics of the six year old child depend on the collision angle. Both situations with a collision angle of 75° show good kinematics without a roll over of body parts. However under a collision angle of 90° the torso is rolled over. The kinematics of the 50 % male for a collision angle of 75° and with arms and legs in position 1 are shown in Figure 15.

No roll over is identified in the third crash constellation of the cornering scenario with the impact on the left front side. This scenario is not as critical as the other scenarios. The basis model has no critical cases in this scenario as well. Nevertheless, the pedestrian safety is improved. In the basis model the lower extremities are rolled over. This can be avoided with the improved front structure

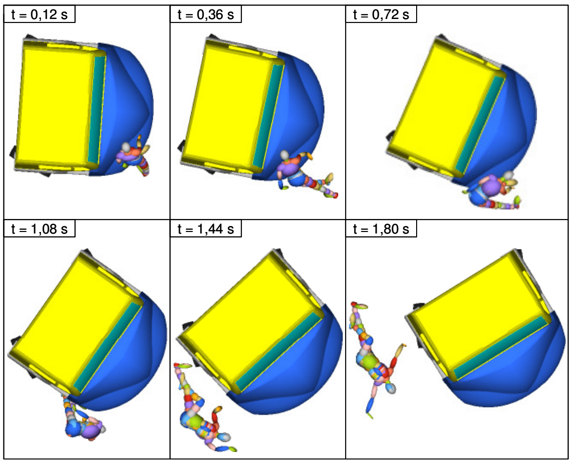


Figure 15. Kinematics of the 50 % male in the cornering scenario.

Eight critical cases are detected in the cornering scenario. That is two times as much as in the straightforward driving scenario but still relatively low compared to 48 cases tested.

<u>Head impact areas</u> – As expected the head impact occurs more frequently with the optimised front. One example is given in Figure 16, where the impact of the 50 % male model next to the front centre is shown for both models. Whereas there is no impact of the head at the truck front with the basis model, the kinematics caused by the optimised shape lead to a head contact.

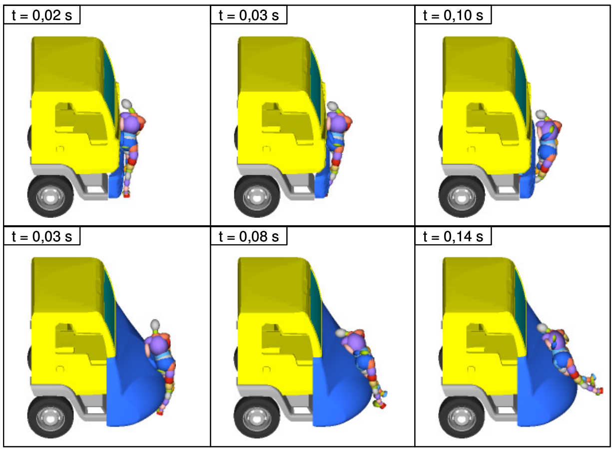
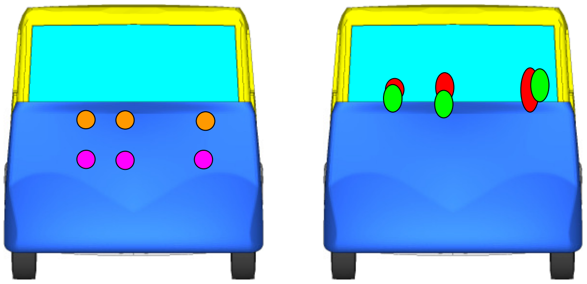


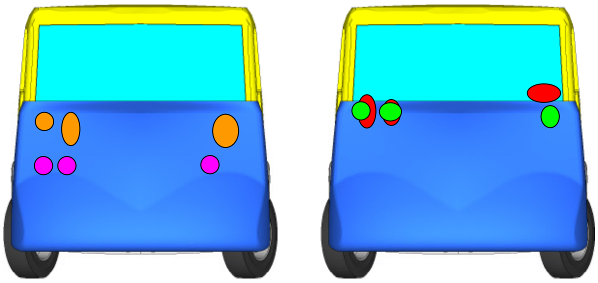
Figure 16. Comparison of primary contact with basis and optimised front (50 % male).

Despite the throwing up effect in three cases still no head impact can be detected for the 95 % male model.

The head impact areas are displayed in Figure 17 divided into straightforward driving and cornering scenario. On the left side impact areas of the six year old child and the 5 % female are illustrated. The right side shows the impact areas of the male pedestrian models. Each mark represents one of the defined scenarios and comprises all impact points of the corresponding model within this scenario.



Straightforward: 6y-child 5%-female Straightforward: 50%-male 95%-male



Cornering: 6y-child 5%-female Cornering: 50%-male 95%-male

Figure 17. Head impact areas.

Head impact speeds - Overall the head impact speeds in the straightforward driving scenario vary only in single cases from the basis model. Positive and negative deviations are found. However the rotary motion of the pedestrian models caused by the optimised shape has a bad influence on the secondary impact. In the regarded constellations the head of the pedestrian hits the road first. As a result high head loads can be assumed. An evaluation within the parameter studies has to show if this effect depends on the truck speed or occurs in general.

In the cornering scenario the kinematics caused by the new front structure have a beneficial effect on the head speeds. Especially the more critical secondary impact shows lower values in most of the cases. However higher speeds are detected for the primary impact due to the effect of throwing the pedestrian up, which makes a contact of the head with the truck front more probable.

Parameter studies - The parameter variations for both accident scenarios are assessed with the 50 % male pedestrian model at a collision angle of 90° and arms and legs in position 1. This corresponds with the constellation during the design phase of the optimised front.

In the straightforward driving scenario a speed of 16 km/h leads to a sufficient side deflection when the model is positioned 50 cm next to the front centre. For positions closer to the side of the truck the speed is even less critical. The rotary motion of the pedestrian, which occurred in many simulations, shows a relevant effect at speeds higher than 30 km/h. At that speed the pedestrian model is rotated so far into a horizontal position, that it hits the road with the back of the head first.

Increasing the speed from 4 to 5 m/s in the cornering scenario leads to bad results for the male models. The shinbone breaks at that speed and looses its supporting function. The model falls right in front of the truck. However, a reduction of speed to 3 m/s is uncritical. Despite the low speed a sufficient deflection is still achieved and a roll over of the pedestrian model can be avoided.

Another varied parameter is the positioning of arms and legs. In the straightforward driving scenario also an upright (not walking) posture provides a sufficient side deflection. A positive effect with this constellation is the missing rotary motion of the pedestrian model. Thus the head is not the first body part which hits the road at the secondary impact. It can be concluded that the rotary motion results from the walking posture of arms and legs. Figure 18 shows the kinematics of the standing pedestrian model. The model is sufficiently deflected to the side and is not rolled over by the truck.

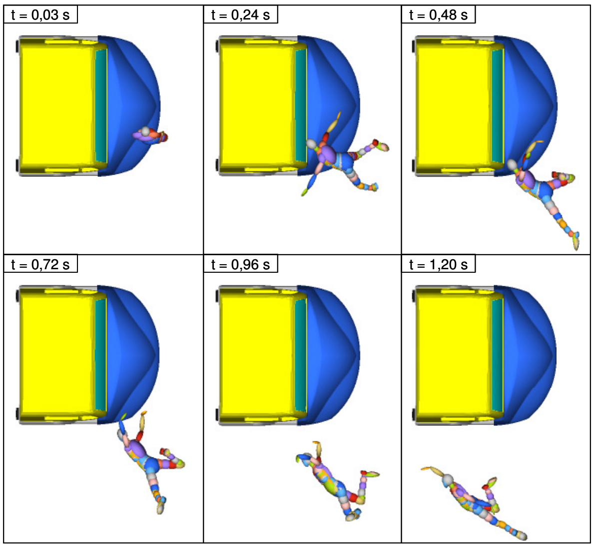


Figure 18. Kinematics of the standing 50 % male model.

In the cornering scenario a sufficient deflection for the upright posture can only be achieved for an edge impact. For the walking postures a position 70 cm right from the longitudinal axis is critical. The pedestrian model is no longer deflected far enough out of this position. It remains within the unsafe area.

Beside the parameter studies also strength and HIC analyses have been conducted with a FE-model of a detailed designed add-on solution. It has been proven, that despite lightweight design such a structure is able to withstand a pedestrian impact. Also the HIC values at primary impact are improved by the optimised front.

<u>Experimental test</u> – A prototype of the optimised front out of EPP foam is tested in a straightforward driving scenario at a speed of 30 km/h. For good control of the impact speed the truck is not driven by its own engine but pulled with a towing device. The driver inside the truck is only steering (Figure 19). [5]

Figure 19. Connection of prototype to the truck. [5]

Due to the risk of possible damage caused by a run over, the pedestrian model used for the test is a simplified 50 percentile dummy without instrumentation and a weight of 75 kg. It is positioned exactly between the centre of the truck and the right truck side in a walking position with the leg that is standing forward facing the truck front. Consequently, the dummy is impacted laterally.

Figure 20 shows a picture sequence of the experimental run over crash test. It can be observed that the pedestrian model is deflected to the side as intended instead of being run over. As a result of the simple pedestrian dummy mainly set up from rigid body parts connected by standard joints the biofidelity is limited. However, the experimental test shows good consistence compared to the simulation of the same accident scenario. The picture sequence of the respective simulation is presented in Figure 21. The good correlation between experiment and simulation shows the principal applicability of numerical simulation for the risk evaluation of a run over.

Figure 20. Experimental test. [5]

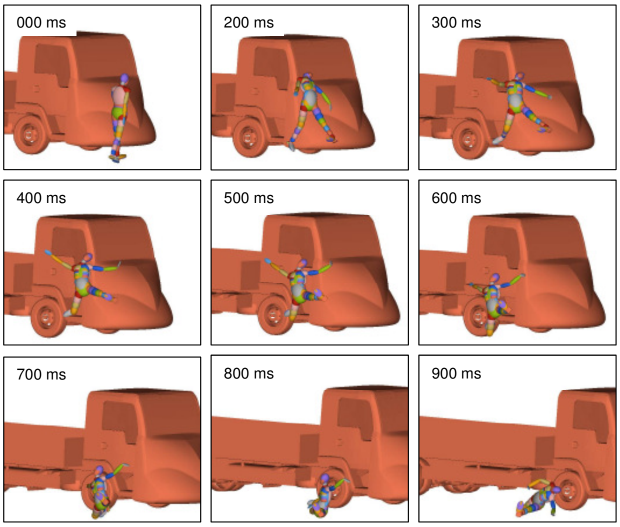


Figure 21. Simulation with parameters of experimental test.

<u>Summary</u> - The results of the performed tests prove the effectiveness of the optimised front. The simulations show that the optimisation of current truck front designs can lead to a significant improvement. The passive safety is enhanced because serious roll over accidents are avoided in 87,5 % of the simulated cases.

In the straightforward driving scenario, according to accident analysis the most important scenario, a sufficient deflection can be guaranteed in a wide range of constellations even for low speeds of the truck. Only an impact very close to the centre of the front is sometimes critical and requires a certain velocity for a sufficient deflection.

The right cornering scenario is more sensitive. Impacts closer than 80 cm to the longitudinal axis lead to run or roll over situations on the right side.

Within the effective area of the front especially the 95 % male pedestrian model shows critical results. On the one hand there are anthropometrical reasons for this but on the other hand a main problem is the fracture of the shinbone at the primary impact. Further tests have to indicate if this issue can be improved by the designated structural foam in the bumper, which has not been regarded within the simulations. In general better results are achieved with an impact angle of 75°. Referring to the real accident this is advantageous, because due to the cornering an impact angle of exactly 90° is rather unlikely.

INTEGRATED DESIGN APPROACH

An add on solution of the optimised front as used for the crash test is not an efficient solution with respect to costs, weight and appearance. In order to fully exploit the benefits of such a design the shape has already to be considered in the early design phase and must be an integral part of the cabin. Figure 22 indicates how such a cabin could look like.

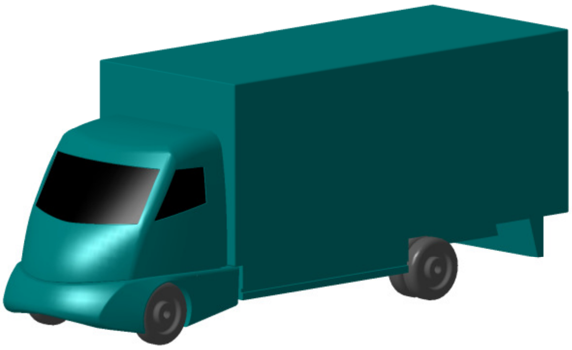


Figure 22. Integrated design approach.

The design study by DAF, shown in Figure 23, could also be considered as a first approach for a design with an improved pedestrian safety.

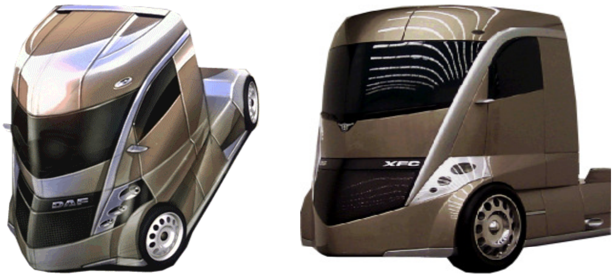


Figure 23. Design study by DAF.

Moreover, with respect to the current European legislation that limits the total length of trucks the market implementation of such a tapered shaped front design is unlikely, since the loading space would have to be reduced. Discussions during the APROSYS final workshop have disclosed that the truck manufacturers are principally supporting the implementation of passive safety devices at the truck front in case legislation allows an increase of the total vehicle length for those measures.

Aerodynamics

Beside the improved passive safety the optimised design seems also to have potential in reducing fuel consumption due to its streamline design. A 1:10 model is used to study the wind resistance of this design versus a flat front design (Figure 24).

Figure 24. Overview of wind tunnel with truck model. [6]

The truck is modelled of wood and foam. The wind tunnel tests are performed with velocities up to 40 m/s. Measurements are forces and moments in all directions. The calculation of the drag coefficients is referenced to the truck width or the cross section area (characteristic dimensions). During the tests the airflow is made visible by artificial fog. This shows clearly the benefits of a homogenous airflow around the vehicle as it is illustrated by Figure 25 and Figure 26.

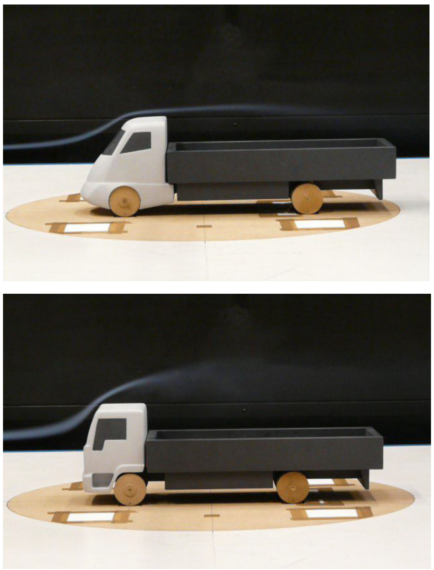


Figure 25. Visualisation of aerodynamics in the wind tunnel for a tipper type truck. [6]

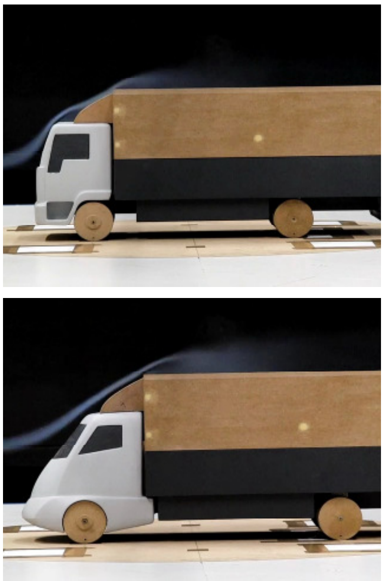


Figure 26. Visualisation of aerodynamics in the wind tunnel for a box truck with spoiler. [6]

The optimised design shows a clearly lower drag coefficient compared to the standard truck. The decrease of the drag coefficient lies between 0.10 and 0.33. This is equivalent (not taking into account the scale of the model) to a reduced fuel consumption of 1.2 to 3.6 litres per 100 km. [6]

CONCLUSIONS

The results of the performed tests prove the effectiveness of the optimised front. The simulations show that the optimisation of current truck front designs can lead to a significant improvement. The passive safety is enhanced because serious roll over accidents are avoided in 87,5 % of the simulated cases.

Numerical simulations and experimental testing have not only shown the relevance of the primary impact for serious injuries. The secondary impact on the ground is just as important as the primary impact. Further studies of enhanced front structures should also consider post-impact kinematics and the secondary impact of the VRU.

In general a tapered shaped truck front is a simple and cost efficient passive measure to reduce the risk of a run over of VRUs by heavy vehicles. Beside this main purpose there are also positive effects on:

- Contact forces at primary impact of the VRU (additional crush space)
- Vehicle to vehicle compatibility (impoved frontal underrun)
- Occupant safety (additional crush space)
- Aerodynamics (streamline shape)
- Package (more space due to longer cabin)

The introduction of an optimised front design for trucks requires a reconsideration of the vehicle length regulations. With the current legislation the vehicles are designed to maximise loading space and payload. Because the main business is to carry freight with the heavy goods vehicles, optimisation is made with regard to maximum loading (volume and payload) under current length. All measures reducing payload or volume are not taken into account. Therefore the allowance for additional vehicle length for the implementation of safety features is a basic requirement with respect to an improved passive safety of current trucks. The presented design is also transferable to other transportaion systems like trams or buses.

REFERENCES

[1] Faßbender, S.; Feist, F.; Niewöhner, W.
Demonstrator module for new design concepts
APROSYS SP2.1 Deliverable D2.1.3, 2007

[2] Mesina, C.T.; Margaritis, D.; de Vries, Y.W.R.; Niewöhner, W.; Ruijs, P.A.J.
Characteristics of Heavy trucks versus Pedestrians and/or Cyclists
APROSYS SP8.3 Deliverable D8.3.5, 2006

[3] Niewöhner, W.; Berg, F. A.
Gefährdung von Fußgängern und Radfahrern an Kreuzungen durch rechts abbiegende Lkw
BASt report F 54
DEKRA Automobil GmbH, Stuttgart, 2005

[4] N. N.
MADYMO Human Models Manual Release 6.3.1
TNO, 2006

[5] Faßbender, S.; Feist, F.
System description of the experimental safety module
APROSYS SP2.1 Deliverable D2.1.5, 2008

[6] Faßbender, S.; Feist, F.; Gugler, J.
Guidelines for integrated design and evaluation of advanced vulnerable road user protection systems
APROSYS SP2.1 Deliverable D2.1.7, 2009