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ENVIRONMENTAL IMPACT OF AERODYNAMIC OPTIMIZATIONS AT HEAVY DUTY COMMERCIAL VEHICLES

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ENVIRONMENTAL IMPACT OF AERODYNAMIC OPTIMIZATIONS AT HEAVY DUTY COMMERCIAL VEHICLES

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ABSTRACT

The optimization of aerodynamic drag represents an important research area for the fuel consumption reduction of heavy duty commercial vehicles. Today's design of tractor-trailers in the European Community is significantly influenced by legislative boundary conditions regarding the overall vehicle dimensions of the entire tractor and trailer arrangement. This fact in combination with the target of high transport efficiency leads to brick-shaped vehicle outer geometries. In this way, the investigations of aerodynamic optimization at commercial vehicles are restricted to detail measures. Already performed investigations related to this topic are discussed in literature, (6), (7).

The present publication treats the aerodynamic characteristics of general modifications at the outer contour of heavy duty tractor-trailers regarding a reduction of drag resistance and thus a potential reduction of fuel consumption under steady state conditions on highway traffic. The research activities considered the European legislation for maximum vehicle dimensions and weight.

A generic, virtual three dimensional computer aided design (3D-CAD) semi-trailer truck, which displayed the characteristics of market-typical vehicles, served as a basis for several modifications. All geometrical modifications at the virtual reference vehicle were investigated and assessed by three dimensional computational fluid dynamics (3D-CFD) simulations. To get a better conclusion, the fuel consumption of each modified tractor-trailer was calculated in longitudinal vehicle dynamics simulations.

As a result of the present work, different aerodynamic optimization measures were assessed and evaluated in comparison with the reference vehicle under consideration of the transport volume. The research work demonstrates the big potential of aerodynamic optimization by application of general measures at the vehicle outer contour under compliance with the European legislative boundary conditions. As additional conclusion, the present work points out the different areas of a semi-trailer truck with respect to the potential of aerodynamic optimization. The achieved improvements can lead to a reduction of fuel consumption, which encloses both, optimized operating costs for carriers as well as reduced carbon dioxide (CO_2) emissions which support the intentions to environmental friendly road transport.

INTRODUCTION

Road transportation is a main pollution emitter of carbon dioxide. About one third of the CO_2 emissions from road traffic is caused by commercial vehicles, especially from the widely used semi-trailer truck class. This type of vehicle combination is currently dominant in long-distance haulage on road. Reducing the fuel consumption of such commercial vehicles would contribute to a decrease of exhaust emissions from road traffic. Due to the hard business competition between the carriers, it's a requirement to transport goods as cost efficient as possible. In addition, transport efficiency of the applied commercial vehicles is first priority to survive in carrier business. About one half of the entire annual operation costs of long-distance haulage semi-trailer trucks is caused by fuel expenditures. From this it follows, that a reduction of fuel consumption could be one factor to improve the transport efficiency, (1).

An important contribution to increase the transport efficiency can be accomplished by improvements of the aerodynamic characteristics of vehicle combinations. Today's design of semi-trailer trucks in the European Community is significantly influenced by legislative boundary conditions regarding the overall vehicle dimensions of the tractor and trailer arrangement. This fact in combination with the target of high transport volumes leads to brick-shaped vehicle outer geometries which cause high aerodynamic drags. As an example, a 40 tons semi-trailer truck, which drives 85 km/h steady state on a horizontal highway, needs at least 40 percent of the provided driving performance for the aerodynamic resistance (Figure 1). Due to a legislative limitation of the vehicle dimensions, the investigations of aerodynamic optimization at commercial vehicles have been restricted to detail measures so far, (1) (2).

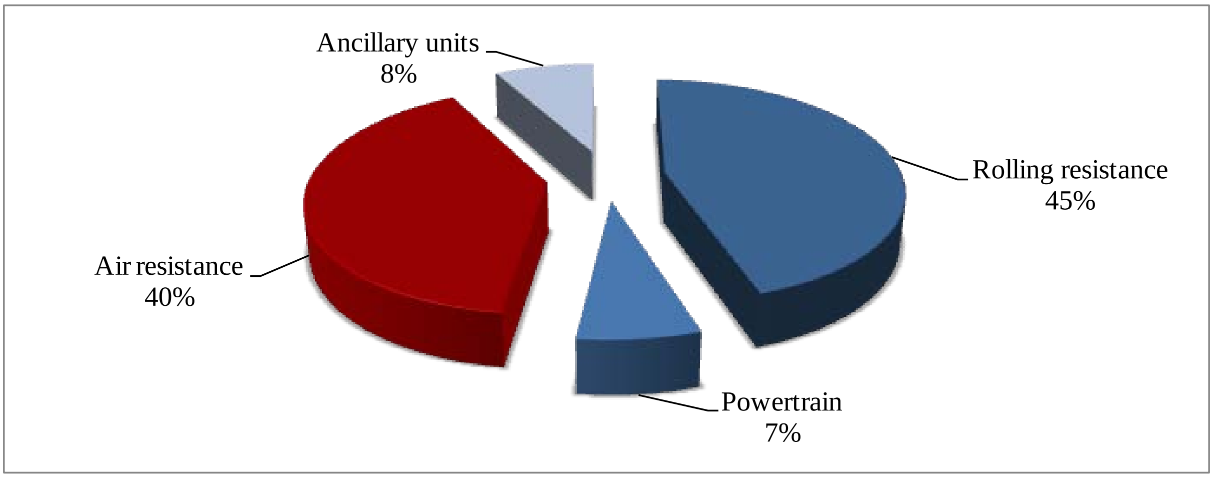

Figure 1: Resistance distribution of a 40 tons semi-trailer truck at 85 km/h, (2)

BASIS OF THE RESEARCH WORK

The aerodynamic studies of the present research work were based on generic virtual semi-trailer truck models. The first step was a geometrical investigation of market-typical European heavy duty semi-trailer trucks for a subsequent derivation of a generic virtual reference vehicle. In this way, several cab-over-engine semi-trailer tractors for long-distance haulage of six European truck manufacturers were evaluated and compared. Out of this investigation the configuration and the dimensions for an average tractor were determined. The same procedure was performed to collect information of typical European curtainsider semi-trailers.

This determined average vehicle combination provided a basis for designing a generic, virtual 3D-CAD reference truck. The design process of this reference model, which displayed the characteristics of market-typical vehicles, was carried out in the 3D-CAD software package CATIA V5, (3). The design phase, especially the creation of the driver's cab, was a big challenge due to the requirement of a neutral styling to avoid any characteristic brandings. For the following aerodynamic research work, two virtual semi-trailer trucks with different levels of detail were created. A generic virtual reference vehicle with a high accuracy was designed to compare the final results with today's market-available vehicles. Besides that, a simplified single-volume-model was created to support the achievement of general findings of aerodynamic influences and to keep the simulation complexity efficient. This simplified single-volume-model represented the most important geometrical characteristics of the mentioned average vehicle combination and demonstrated the basis for the following geometrical investigations.

AERODYNAMIC INVESTIGATION

The aerodynamic semi-trailer truck optimization was carried out according the following investigation process, (Figure 2). This investigation process was split up in two main parts, a coarse geometrical concept study by use of the simplified vehicle model and an accurate study based on the detailed reference truck model.

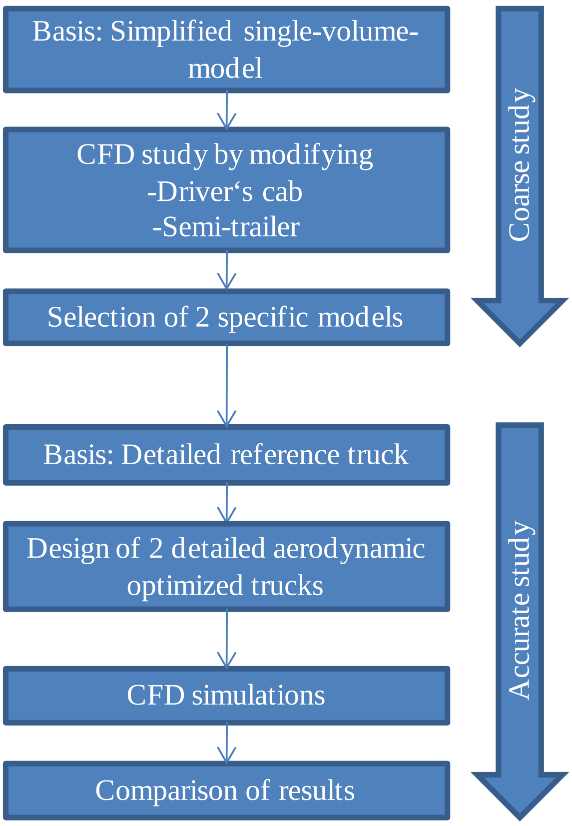

Figure 2: Investigation process

The coarse concept study was based on the simplified reference model. During this study, principal geometrical modifications were performed at the outer contour of the driver's cab and the semi-trailer independently. Following that, the air drag of each model variant was assessed by application of 3D-CFD simulations by use of the commercial software Star-CCM+, (4). In the next step, two characteristic model variants with specific aspects were selected out of the coarse study. The subsequent accurate study was based on the detailed reference truck. The geometries of the two selected simplified models were used as drafts to design two detailed truck models in a high accuracy, which were influenced by the outer shape of the two selected single-volume-models. After finishing the design phase, the aerodynamic drag coefficient c_D of the detailed reference truck and the two detailed optimized trucks were evaluated by accurate 3D-CFD simulations. To achieve a high accuracy in the simulation, the boundary condition at the bottom was modeled as moving ground surface. Finally the results of the optimized truck models were compared and assessed in relation to the characteristics of the generic reference truck model.

Coarse Concept Study

The simplified reference single-volume-model, which is shown in Figure 3, demonstrates the basis for the subsequently performed aerodynamic measures.

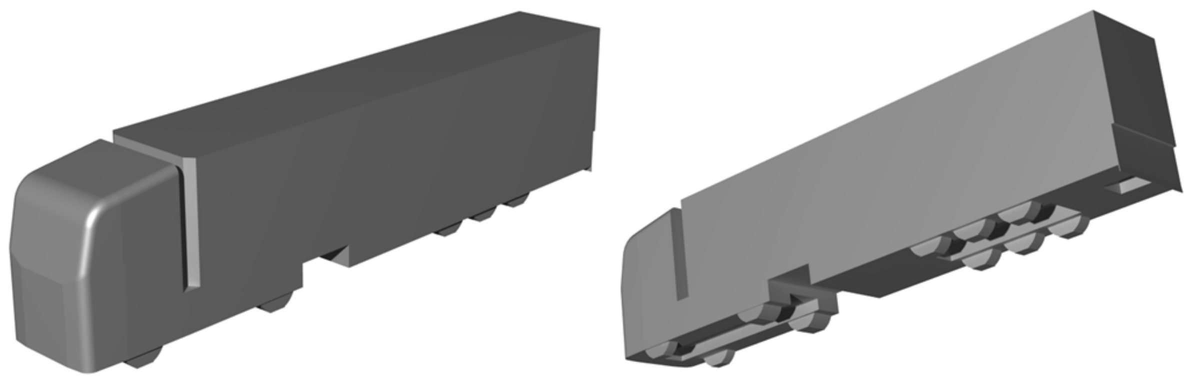

Figure 3: Reference single-volume-model, used as a basis for the coarse concept study

The coarse concept study started with geometrical modifications at the shape of the driver's cab. These principal modifications exceeded consciously the limited vehicle length of the present European legislation to prevent small radiuses and edges at the geometry. The air drag coefficients of every model were calculated in 3D-CFD simulations. Figure 4 represents the different driver's cab variants with the related results in comparison to the reference single-volume-model R. An unexpected outcome of this study was that no coarse geometry modification of the driver's cab could reach a decrease of the air drag. This issue leads to the predication, that the potential to reduce air drag by exclusive modifications of the outer contour in the front of the truck arrangement seems to be low.

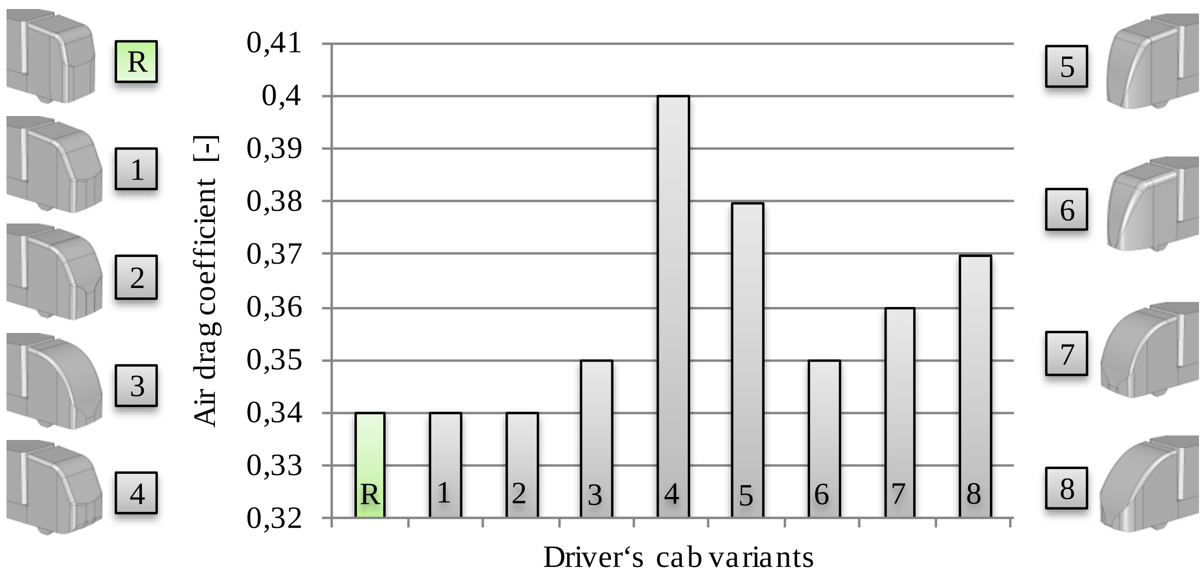

Figure 4: Geometry study of the driver's cab

In the next step of the coarse concept study different geometrical modifications at the semi-trailer geometry were carried out to evaluate the potential in view of drag reduction of the vehicle's rear end geometry. Figure 5 illustrates the results of the 3D-CFD simulations of the semi-trailer study and the impact of different geometrical modifications on the air drag characteristics under consideration of the payload space in comparison to the reference configuration R. The variant models number one to number eight were modified by using different vertical tapers at the semi-trailer. In contrast to those, the semi-trailer variants number nine and ten have been equipped with horizontal boat tails as additional modification. As a result of this study, each geometrical modification led to a decrease of the air drag coefficient, but also to a more or less reduction of the semi-trailer's payload space.

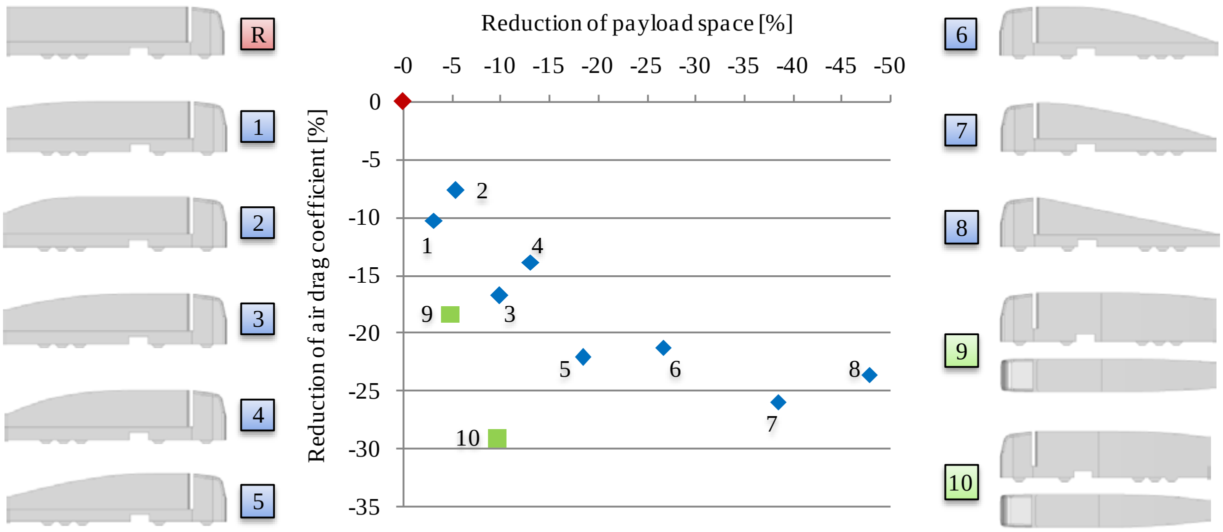

Figure 5: Geometry study of the semi-trailer

As a result of the coarse concept study, two variants with a significant reduction of air resistance were selected for further detailed aerodynamic studies. Due to the fact that no coarse modification of the driver's cab was able to lower the air drag, the detailed studies were carried out with the standard generic cab model of the reference model R. As the coarse study demonstrated, geometrical modifications of the vehicle rear end showed big impact on the aerodynamic resistance, cf. (7). A selection of two representative trailer geometries (model number one and number nine) was chosen for further investigations. Besides the reduction of air drag, these two variants were selected because of their comparative small decrease of payload space.

Accurate Study

This study was carried out to verify the results of the coarse concept study due to higher simulation accuracy and to compare the simulation results with the characteristics of present market-available semi-trailer trucks. The accurate study of the aerodynamic investigation process was based on a generic reference truck with a high level of geometrical detail. Figure 6 displays the 3D-CAD reference truck (left) and its tractor (right) in a typical long-distance transport configuration. The creation of a neutral driver's cab styling with typical air resistance characteristics was a main challenge during the design phase of the project to avoid a deviation from market-available driver’s cabs, having a high level of aerodynamic development. The air drag characteristics of the present generic truck were assessed by use of a 3D-CFD simulation with a higher accuracy and complexity than in the coarse study. The results of this simulation were used as a reference for the evaluation and assessment of the subsequently performed 3D-CFD studies of the aerodynamic optimized truck configurations.

Figure 6: Detailed generic reference truck, used as a basis for the accurate aerodynamics study

In a second step, the geometry of the detailed generic reference truck was modified to create two aerodynamic optimized truck configurations with a high degree of geometrical detail. As mentioned above the selected geometries of the coarse semi-trailer study provided a draft for the 3D-CAD design process. Out of the shape of selected model number one, the optimized Truck A was designed with a vertical taper of 50 cm at the semi-trailer’s rear end and model number nine was used as a template for the accurate designed Truck B, as shown in Figure 7. The difference between the geometries of these two truck configurations was the horizontal boat tail of 25 cm on each side at the semi-trailer of Truck B.

Figure 7: Detailed optimized trucks: Truck A (left) and Truck B (right)

Finally, the aerodynamic drag characteristics of the optimized trucks, Truck A and Truck B, were assessed in detailed 3D-CFD simulations by application of the same boundary conditions as they were applied during the simulation of the generic reference truck. Figure 8 illustrates the flow velocity around the vehicle combinations of the detailed reference truck and the optimized Truck A as a result of the 3D-CFD simulation.

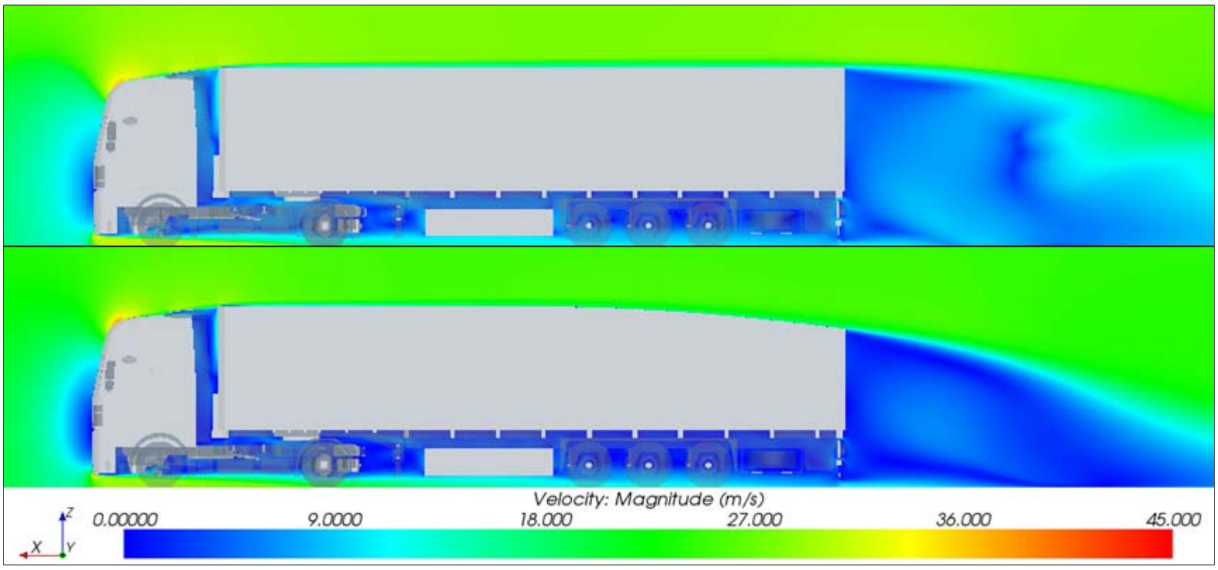

Figure 8: Flow velocity at the reference truck (above) and at Truck A (below)

In contrast to Truck A, the reference truck shows a big irregular dead water area behind the rear end of its semi-trailer due to its brick shaped outer contour. The aerodynamic optimized shape of Truck A enables the fluid a smooth change over to the road surface which leads to a smaller dead water area behind the rear end. In this way the static pressure at the back panel of the reference truck could be increased by the specific geometrical shape at Truck A, which results in a lower air resistance force in driving direction. General information of aerodynamic principles is treated in detail in the relevant literature, e.g. (5).

RESULTS AND EVALUATION

For the support of a clear evaluation, the fuel consumption of each semi-trailer truck variant was calculated in longitudinal vehicle dynamics simulations by use of predefined engine characteristics of a typical semi-trailer truck engine. As illustrated in Figure 9, the aerodynamic optimized semi-trailer trucks, Truck A and Truck B, obtained a declination of the aerodynamic drag coefficient c_D between 15 % and 23 % related to the generic reference truck. The results of these simulations confirmed the issues of the coarse concept study. Due to these significant aerodynamic improvements, a reduction of fuel consumption up to 6.5 % by Truck A and 10.2 % by Truck B could be reached. In contrast to the decrease of fuel consumption, the payload space was comparatively slightly reduced, between 3.2 % (variant Truck A) and 6.1 % (variant Truck B).

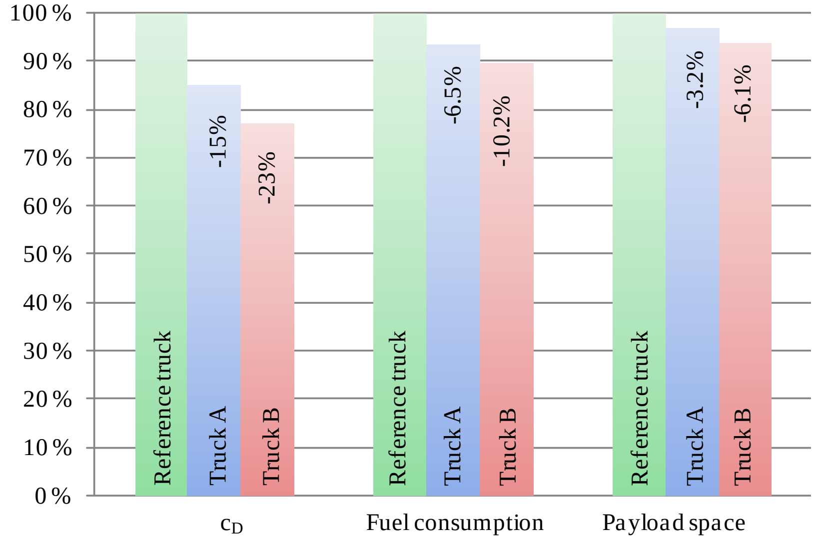

Figure 9: Results of the accurate study, comparison of characteristic values

However, an important aspect for carriers is the amount of operation cost savings by use of aerodynamic optimizations. Figure 10 illustrates an overview of different influencing cost factors of semi-trailer tractors with a capacity of averaged 140.000 kilometers per year. The percentage breakdown of the operation costs is an exemplary extract of corresponding literature, (6). The share of the fuel costs for such a vehicle reaches up about 50 % of the total costs. Due to a possible reduction of fuel consumption, a lowering of the entire annual operation costs of up to 5.1 % for Truck B could be reached.

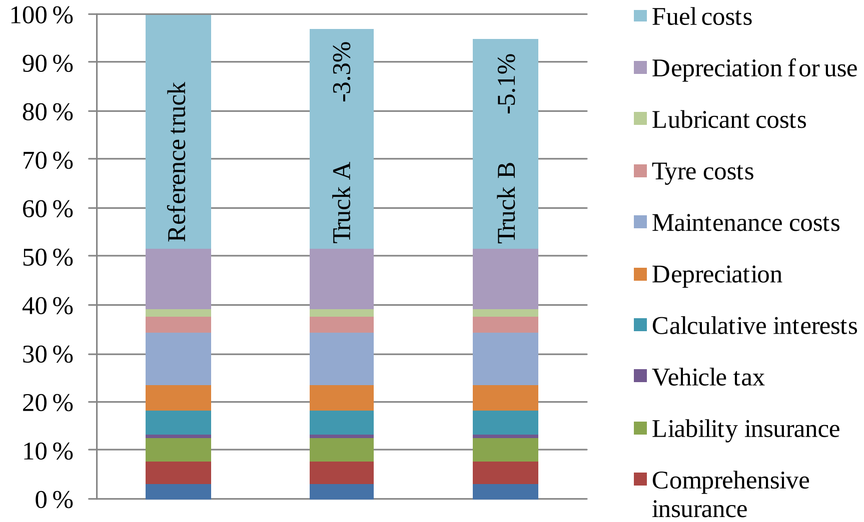

Figure 10: Comparison of the annual operation costs of a typical semi-trailer tractor

TECHNICAL IMPLEMENTATION

The transport efficiency of commercial vehicles depends on their payload and different cost factors. Regarding the results of the two optimized truck configurations with respect to aerodynamics, on the one side a reduction of fuel consumption and thus a decrease of the operating costs could be reached. But on the other side the payload space shrinks, because of the geometrical modifications at the trailers rear ends. In this way an improvement of the transport efficiency depends on the type of payload, more exactly on the freight density. Considering the fact that about every fifth trip of European semi-trailer trucks is without payload, the overall transport efficiency could be raised significantly by application of the proposed design, (1). To ensure a high transport efficiency for the present aerodynamic optimized trucks, a balanced vehicle design, which is able to provide an advantageous outer contour and to achieve a satisfying payload space at the same time is a precondition.

During the present research work some possibilities for a technical implementation of such arrangements have been worked out. Figure 11 represents the trailer shape of the reference truck (above) compared to the shape of the aerodynamic optimized Truck A.

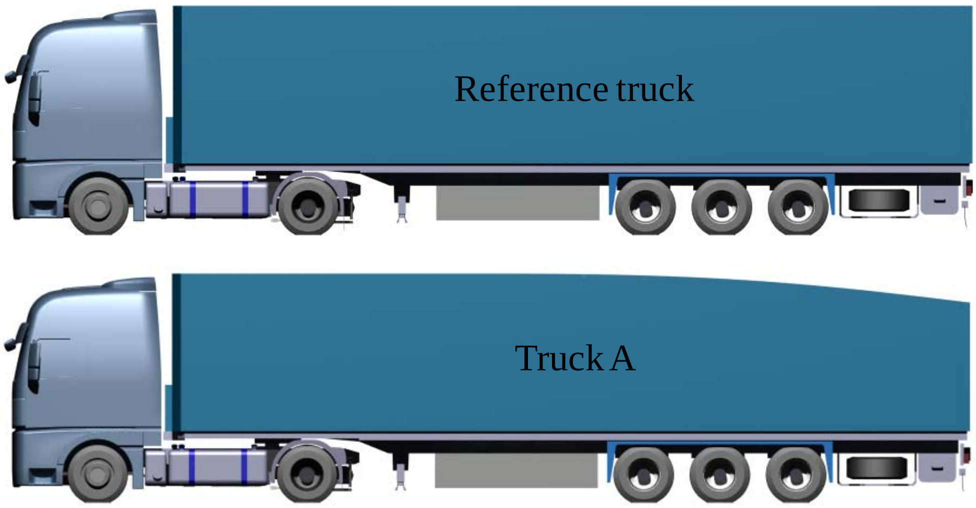

Figure 11: Reference truck (above) and optimized Truck A (below)

The semi-trailer of the reference truck illustrates the standard constellation of today's semi-trailers. A modified shape of the semi-trailer of e.g. Truck A would be able to lower the averaged aerodynamic resistance and consequently the averaged fuel consumption by just a moderately reduction of payload space. This would lead to an increase of the averaged transport efficiency of semi-trailer trucks.

CONCLUSION

The present research project treats the aerodynamic characteristics of general modifications at the outer contour of heavy duty semi-trailer trucks. The aerodynamic drag represents an important influencing factor of the total driving resistances of trucks, and consequently it has an important contribution on the fuel consumption. In the present publication, different geometrical modifications of the vehicle outer contour have been evaluated regarding a possible reduction of aerodynamic resistances and thus a potential reduction of fuel consumption under steady state conditions on highway traffic. The research activities were carried out under consideration of the European legislation for maximum vehicle dimensions and weight.

As a basis for the research work, two types of generic virtual 3D-CAD reference trucks with different levels of detail were created. In a coarse concept study different geometrical modifications at a simplified reference model were investigated and assessed by use of 3D-CFD simulations. Out of this coarse concept study, two specific geometry variants were selected for the creation of two aerodynamic optimized trucks with a high geometrical accuracy. The air drag characteristics of these trucks were calculated in detailed 3D-CFD simulations to verify the results and to compare them with the behavior of market-available vehicles. For the evaluation of the results the fuel consumption of each variant was calculated by use of longitudinal vehicle dynamics simulations under steady state conditions.

The present work points out the potential of different geometrical areas of the entire semi-trailer truck configuration with respect to aerodynamic optimization. The elaborated aerodynamically optimized trucks of this project are able to lead to a reduction of fuel consumption and thus to optimized operating costs for carriers. By introducing such optimized trucks the CO_2 emissions of road transportation can be decreased significantly, which supports the intentions to environmental friendly road transport.

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