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Original Research Article

Investigation of the effect of the use of top deflectors on aerodynamic performance in vehicles with CFD analysis

Haydar Kepekçi[1, *]

[1, *] Mechatronics Engineering Department, İstanbul Gelişim University, 34310, İstanbul, Türkiye.

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* Corresponding author
hikepekci@gelisim.edu.tr

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ABSTRACT

Carbon-containing waste gases from vehicle exhausts are one of the main causes of climatic disasters. This problem is tried to be solved by reducing the amount of energy consumed by vehicles while they are in motion. To reduce fuel consumption, it is necessary to reduce the effect of aerodynamic drag force, which is the resistance on the solid surface in motion. It is known that high aerodynamic drag force increases fuel consumption. Reducing aerodynamic drag force is important not only for fuel consumption but also for wind noise and roadholding. Heavy vehicles such as trucks have high drag forces due to the width of their surface areas. However, this situation can be minimized with changes to be made in vehicle designs. In this study, the effect of the use of top deflectors on the drag force for trucks has been investigated. In this theoretical study, separate calculations have been made for different vehicle velocities and the results have been compared among themselves. In this study, which has been carried out using the computational fluid dynamics method, k-e has been preferred as the turbulence method. As a result, it has been concluded that the use of top deflectors reduces drag force, which in turn reduces fuel consumption.

Keywords: Aerodynamics, Computational fluid dynamics, Drag force, Top deflector.

1. Introduction

With the increasing dependence on technology in the rapidly globalizing world, energy requirement has increased at the same rate. Owing to the recent Covid-19 pandemic, it has been seen that both education and business life can be carried out remotely online. In the post-pandemic period, some schools and workplaces have decided to continue the remote working model. As a result of this situation, many houses have also started to be used as workplaces and the energy consumption of the houses has increased [1]. Most of the electrical energy is produced from oil and natural gas [2]. As a result, the fluctuation in the prices of one of the energy sources spreads to the other. As a result of the disagreements in the political process that started with the invasion of Ukraine by Russia, the world's largest energy exporter, in 2021, natural gas and oil shipments to Europe came to a halt [3]. The industrial production of the European countries, which experienced fluctuations in energy imports, decreased significantly and the prices of products increased. Countries facing the danger of economic instability have started to seek new energy sources for themselves. It is obvious that the use of petroleum will not be abandoned soon, both because renewable energy sources are not as efficient as conventional fuels and because it will take a long time to abandon vehicle engines that are currently in use. What needs to be done in this case is to reduce the amount of oil used. Petrol, which is an energy type with a wide usage area, is mostly used in the fuel needs of vehicle engines [4].

It is known that if the energy consumption of vehicles is reduced, the use of oil will also decrease. There are different studies on this subject. In addition to modifications that will increase the efficiency of vehicle engines, new designs are also made for vehicle body models. One of the changes made in addition to these designs is the part attachment called the deflector [5]. Parts called deflectors, which are designed to reduce aerodynamic drag, which is one of the energy loss causes of vehicles, also increase driving performance.

Aerodynamic drag is proportional to the geometry of the vehicle. It is recommended to use deflectors to reduce the amount of energy lost by heavy vehicles such as trucks, tractors, trailers, and lorries from aerodynamic drag. Considering that the aerodynamic drag increases as the vehicle velocity increases, it is concluded that it is a priority to revise the geometric models of the vehicles that are frequently used on intercity roads and highways. As a result of the research, it has been seen that the truck drag forces can be reduced by up to 50%. Considering that the annual fuel cost per truck is 20 thousand dollars, the reduction in energy consumption will provide significant economic savings. Deflector parts can be attached to different parts of vehicles. Examples of these are the underbody, the space between the tractor and the trailer, the vehicle wheels, the side mirror, and the vehicle's upper area [6]. In this study, the effect of the deflector part, which will be used in the upper part of the truck, on the aerodynamic performance has been numerically investigated.

2. Literature Review

Numerous academic studies have been conducted on the aerodynamic performance of heavy vehicles such as trucks and lorries. Studies in recent years aim to save fuel by reducing the amount of drag in trucks. Most of the studies have been done with the CFD method. The main reason for the widespread use of the CFD method is that it saves time and money. The CFD method, which eliminates the necessity of setting up an experimental setup for any scientific study, is frequently used both in academia and in the sector [7]. Nabutola and Boetcher investigated the effect of underbody flow deflection of conventional and air-jet wheel deflectors on vehicle drag in their study using the CFD method. As a result of their research, they found that conventional wheel deflectors only reduced wheel drag but increased overall drag by close to 10%. They found that air-jet wheel deflectors, on the other hand, reduced drag by up to 1.5% at velocities of 35 m/s and above [8]. Khosravi et al. [9] investigated the effects of the use of deflectors and cabin blades on heavy commercial vehicle drag. For their study, they modeled the vehicle body structure and made a CFD analysis. As a result, they found that the drag coefficient decreased by 20% when the cabin wing was added to both front edges of the cabin. If a suitable deflector is used in addition to the cabin wing, they achieved a 41% drag reduction compared to the simple model.

McCallen et al. [10], modeled the aerodynamic flow using the tractor-trailer model with the CFD method. They used RANS modeling in their work. They also developed a formulation to calculate aerodynamic flow using the LES model [10]. Miralbes and Castejon investigated boat tails to reduce aerodynamic forces in heavy vehicles and compared the results. They used the CFD method in their studies [11]. Chowdhury et al. [12] investigated the aerodynamic effects of various fuel-saving devices used in a commercial heavy vehicle. In their study with experimental methods, they subjected the 1/10 scale model truck to the wind tunnel test to measure the amount of aerodynamic drag. They used different deflection angles and operating velocities during these experiments. As a result, they found that the devices they used, including the deflector, reduced the aerodynamic drag by approximately 26% on the vehicle model. Gao et al. [13] designed different models of rear air deflectors to reduce aerodynamic drag in commercial trucks and compared these models with each other. In their study using the CFD method, they concluded that the base blades are the most effective design among the tail air deflectors and that approximately 7% drag reduction can be achieved with this design. Marks et al. [14] have studied the effective forces in the aerodynamic drag of trucks. In their experimental study, full-scale trucks moving at 50 mph were used. For models with gap seals and top deflectors, they achieved reductions of up to 35% in zero yaw resistance coefficient and up to 25% in wind average drag coefficient. Chilbule et al. [15] investigated the effect of changes in the profile of trucks on fuel consumption. They used the CFD method in their studies. They compared the coefficient of drag, lift coefficient, and pressure contours between the modified and unmodified truck model profiles. A wind deflector and swirl trap modifications were made in the modified truck model. With these modifications, a 21% reduction in aerodynamic drag was observed. Chowdhury et al. [16] made calculations using the CFD method to investigate the aerodynamic effect of various deflectors used in light trucks used in Bangladesh and Pakistan. As a result, they have seen that they can reduce aerodynamic drag by around 22% in local trucks, which are widely used in their country. They also concluded that with the reduction in drag force, fuel consumption can be reduced by around 12%. Chowdhury et al. [17] conducted experiments in a wind tunnel environment to investigate the effect of deflector use on fuel consumption in locally produced trucks in Bangladesh and Pakistan. As a result, they found that the use of deflectors reduced the total aerodynamic drag by 58% and fuel consumption by 13%. The aim of this study is to examine the airflow around a moving truck and to examine the effect of the top deflector on aerodynamic drag. Truck models with and without top deflectors have been used in CFD analyses for three different velocities. Boundary conditions have been assumed to be the same for each analysis. The obtained drag force values from result of the calculations have been compared and interpreted.

3. Material and Methods

3.1. Theoretical and mathematical backround

The vertical and tangential forces acting on the surface of an object by the air create aerodynamic forces. The most important aerodynamic forces are lift (F_L) and drag (F_d). Lift force is mostly calculated in aviation, while drag force is used in horizontal motion analysis. The drag force acts in the opposite direction to the solid surface moving in the fluid [5]. The calculation of the aerodynamic drag force F_d is shown in Eq. (1).

$$F_d = (1/2) C_d \rho A V^2 \quad (1)$$

where C_d is drag coefficient, ρ is air density, A is the projected frontal area of the body, and V is the truck's velocity [18]. As can be seen from Eq. 1, the drag force is directly proportional to the front area of the vehicle and its velocity. The drag force is especially felt at high velocities. 60% of the fuel of the full truck and 40% of the fuel of the empty truck is spent on drag [6]. Since the front area of the vehicle is directly proportional to the drag force, the effect of this force on fuel consumption in trucks is higher than in automobiles. Another factor affecting the drag force is vehicle roughness. It is necessary to polish the rough surfaces where the drag force is an undesirable force [19]. If the vehicle windshield is inclined, the drag force will decrease. There are academic studies on this subject. The most well-known are the articles on Ahmed body [20]. In this study, analyzes have been made using the computational fluid dynamics (CFD) program. The calculated drag force values have been obtained directly through the codes in the program. There are steps to be done when any analysis is desired in CFD programs. First, the dimensions of the model to be analyzed should be determined and a geometric drawing should be made. Then the drawn geometry is subjected to a meshing process called mesh. The reason for this is to provide the result sensitivity by dividing the structure to be analyzed into smaller parts. Then, the boundary conditions are determined, and the analysis is started. As a result of the analysis, the values and images that are required to be calculated are obtained as output.

The k-epsilon turbulence method has been used in the analysis. The k-epsilon model is one of the most widely used turbulence models, but that doesn't well perform in cases of large adverse pressure gradients [21]. It is a two-equation model, which includes two extra transport equations to represent the turbulent properties of the flow. This allows a two-equation model to account for historical effects like convection and diffusion of turbulent energy. The first transported variable is turbulent kinetic energy, k. The second transported variable, in this case, is the turbulent dissipation, epsilon. It is the variable that determines the scale of the turbulence, whereas the first variable, k, determine the energy in the turbulence [22]. Turbulence kinetic energy and dissipation equations are given in Eq. (2) and Eq. (3).

For turbulent kinetic Energy, k;

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right]+2\mu_t E_{ij}E_{ij}-\rho\varepsilon \quad (2)$$

For dissipation, ε;

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad (3)$$

In Eq. 2 and Eq. 3 u_i is represents the velocity component in the corresponding direction, E_{ij} is represents a component of the rate of deformation, and μ_t is represents eddy viscosity [22].

3.2. Model confirmation

The truck without the top deflector used in the analysis is given in Figure 1, the truck with the top deflector is given in Figure 2 and the dimensioning of the model is given in Figure 3. These drawings have been made using ANSYS Workbench. The drawn geometry is accepted as a one-piece body.

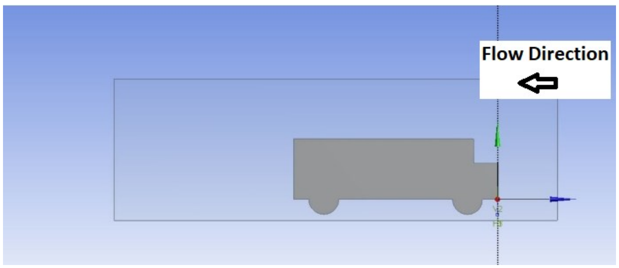

Figure 1. Truck model without deflector

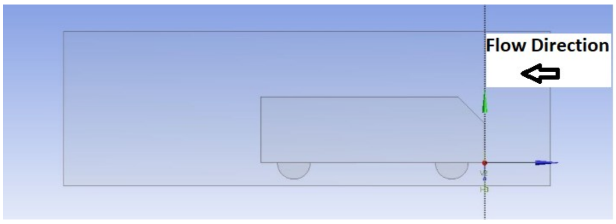

Figure 2. Truck model with deflector

The dimensions of the truck geometry used in the analysis are given in Table 1.

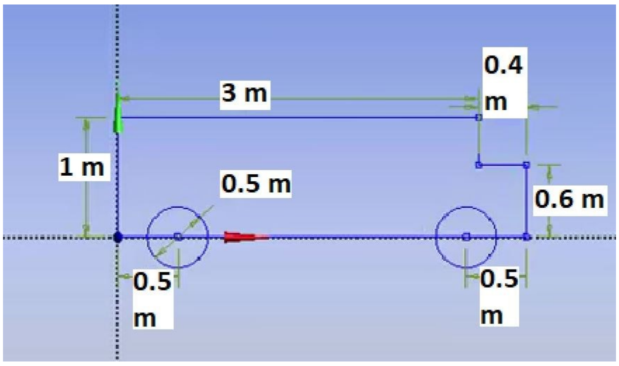

Figure 3. Dimensioning of the truck model

Table 1. Dimensions of the truck geometry

Area	Measure
Truck length	3.4 [m]
Truck height	1 [m]
Truck width	1 [m]
Truck tipper length	3 [m]
Truck front hood length	0.4 [m]
Truck front hood height	0.6 [m]
Truck windshield height	0.4 [m]
Truck front area without top deflectors	0.8 [m^2]
Truck front area with top deflectors	0.565 [m^2]
Truck front area with top deflectors	0.565 [m^2]

To calculate the drag force on the truck, the domain must be created and the air flow around it must be simulated. The created domain is given in Figure 4.

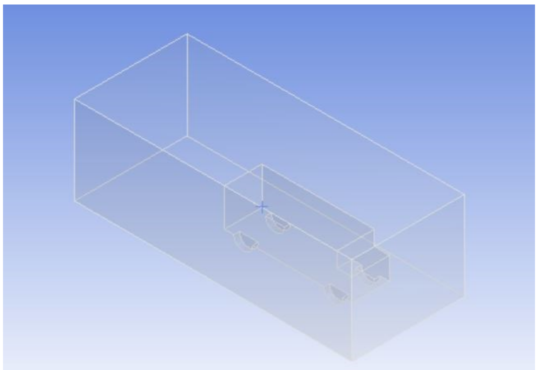

Figure 4. The domain used in the analyzes

Meshing, also called finite element discretization, is required to prepare the created domain for analysis. In the meshing process, the hexahedral and tetrahedral mesh has been used while creating the grids. Different element sizes are used to create a more refined mesh. To increase the accuracy of the results to be obtained from the analysis, the amount of mesh in the front of the truck has been increased and the mesh sizes have been narrowed. The generated mesh file has about 500,000 grid cells. The view of the obtained mesh structure is given in Figure 5.

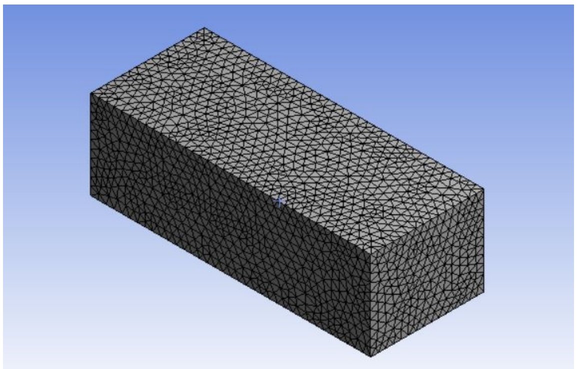

Figure 5. The generated mesh structures

It is assumed that the lateral edges and upper and lower surfaces of the domain are symmetrical. In the analyzes made, the truck velocity has been selected at three different values 50 km/h, 80 km/h, and 100 km/h. The selection of these velocity values is because the trucks have maximum velocity limits in the city, on the intercity roads, and on the highways, respectively. Turbulence intensity and turbulent viscosity ratio have been determined as 1% and 10%, respectively. These values are taken from similar studies in the literature. RANS-based Realizable k-ε model has been chosen as the turbulence method in the analysis. The reason for choosing this model is that it is frequently preferred in aerodynamic force analysis studies in the literature.

4. Results and Discussion

ANSYS Fluent program has been used in the analysis. The drag force and drag coefficient values obtained from the calculations using three different velocity values for the models with and without top deflector of the truck in motion are given in the table below.

Table 2. Drag forces according to different velocity values

Truck model	Velocity [km/h]	Drag force [N]	Drag coefficient
Without top deflector	50	137.590	0.259
With top deflector	50	104.193	0.196
Without top deflector	80	351.066	0.660
With top deflector	80	259.823	0.489
Without top deflector	100	548.295	1.032
With top deflector	100	394.768	0.743

According to the data in Table 1, the use of top deflectors in trucks reduces the drag forces. This will also reduce fuel consumption. The pressure and velocity contours created by the drag force around the moving vehicle in the front areas of the truck models are given in Figure 6, Figure 7, Figure 8, and Figure 9 for the velocity values of 50 km/h and 80 km/h, respectively.

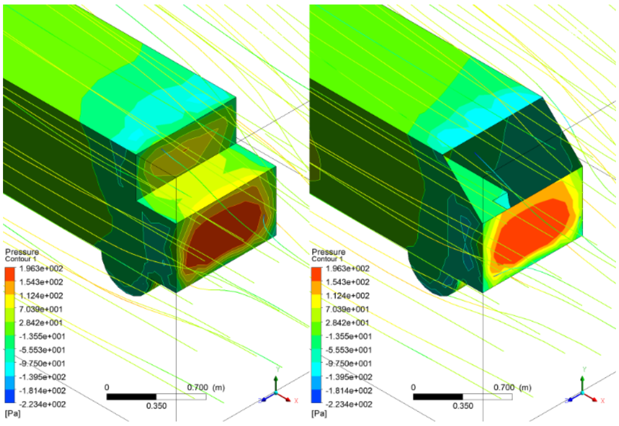

Figure 6. Pressure contours of truck models at 50 km/h

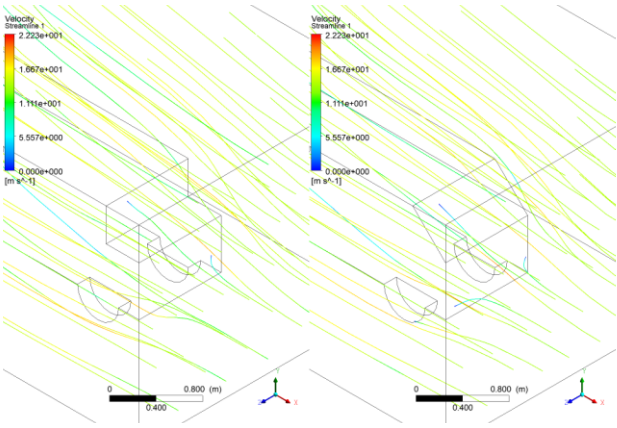

Figure 7. Velocity contours of truck models at 50 km/h

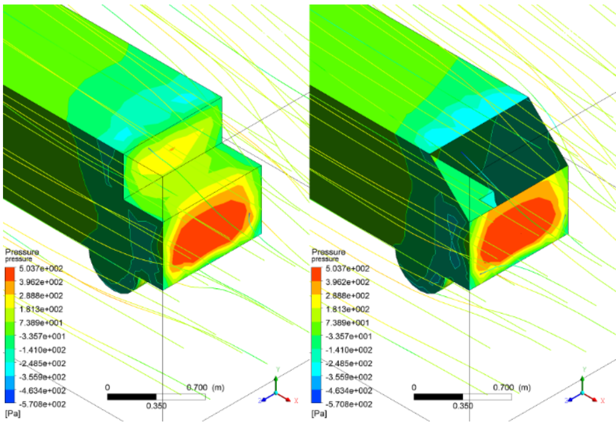

Figure 8. Pressure contours of truck models at 80 km/h

By looking at the contours obtained from the truck models moving at different velocities given in Figure 6, Figure 7, Figure 8, and Figure 9, it can be said that the pressure and velocity values affecting the front area increase with the increase in the velocity of the vehicle. However, it has been observed that increasing pressure and velocity values can be reduced using top deflectors.

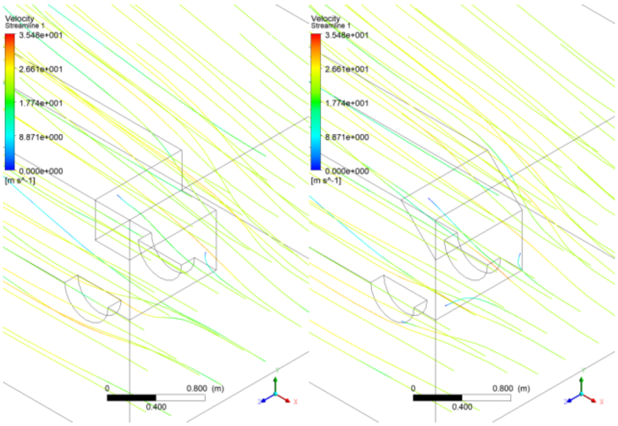

Figure 9. Velocity contours of truck models at 80 km/h

5. Conclusions

It has been observed that as the velocity of a moving truck increases, the drag force increases with or without the use of a top deflector. While the drag force of a truck moving at 50 km/h without a top deflector is 137.590 N and its Cd value is 0.259, when the truck's velocity reaches 80 km/h, the drag force becomes 351.066 N and the cd value is 0.660. It has been determined because of the analysis that the use of top deflectors reduces the drag force. The drag force of the truck with top deflector has been calculated as 137.590 N and Cd value of 0.259, while the drag force of the truck with top deflector has been calculated as 104.193 N and Cd value of 0.196. The drag force of the truck without top deflector, which moves at 80 km/h, is 351.066N and the Cd value is 0.660, while the drag force of the truck with the top deflector is 259.823 N and the Cd value is 0.489. The drag force of the truck without top deflector, which moves at 100 km/h, is 548,295 N and the Cd value is 1.032, while the drag force of the truck with the top deflector is 394,768 N and the Cd value is 0.743. The effect of the use of top deflectors on reducing the drag force is directly proportional to the velocity, but this effect is not linear. The results obtained from the analysis are given in Table 3.

While the use of top deflectors reduced the drag force by 24.27% in the truck moving at 50 km/h, there has been a 26% reduction at 80 km/h and 28% at 100 km/h. Looking at these results, it can be said that the use of top deflectors is more efficient at high velocities. Based on these results obtained from the analysis, it is concluded that the use of top deflectors will reduce fuel consumption. It will be of great benefit to the country's economy if the use of top deflectors is primarily made widespread in commercial trucks and then made compulsory in the future. As a continuation of this study, the prototype of the truck model used in the analysis will be produced and subjected to wind tunnel tests. In the tests to be made, different top deflector geometries will be used, and the ideal top deflector shape will be determined.

Table 3. Numerical results from analysis

Top Deflector	Velocity [km/h]	Drag force [N]	Coefficient of drag (c_d)
without	50	137.590	0.259
	80	351.066	0.660
	100	548.295	1.032
with	50	104.193	0.196
	80	259.823	0.489
	100	394.768	0.743

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