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Drag Reduction of Truck and Trailer Combination with Different Passive Flow Control Methods

Cihan BAYINDIRLI [1, *], Yahya Erkan AKANSU [2], M. Sahir SALMAN [3]

[1] *Nigde Omer Halisdemir Üniversitesi, Niğde Teknik Bilimler MYO, Motorlu Araçlar ve Ulaştırma Teknolojileri Bölümü, Merkez, 512000, Niğde, Türkiye*
[2] *Nigde Omer Halisdemir Üniversitesi, Mühendislik Fakültesi, Makine Mühendisliği Bölümü, Merkez, 512000, Niğde, Türkiye*
[3] *Gazi Üniversitesi, Teknoloji Fakültesi, Otomotiv Mühendisliği Bölümü, Teknikokullar 06500, Ankara, Türkiye*

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* *Corresponding Author*
e-mail: cbayindirli@ohu.edu.tr

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ORCID Numbers in author order:
0000-0001-9199-9670
0000-0003-0691-3225
0000-0000-0000-0000

ABSTRACT

In this study, drag force and surface pressure measurements were conducted on a 1/32 scaled truck-trailer combination model. The experimental tests were carried out between the ranges of 312×10^3- 844×10^3 Reynolds Numbers in a suction type wind tunnel. The aerodynamic drag coefficient (C_D) and distribution of pressure coefficient (C_P) were experimentally determined for the truck and trailer combination. The regions with a large amount of pressure coefficients were determined on the truck-trailer by using flow visualizations. The aerodynamic structure of truck-trailer combination models was improved by passive flow control methods on 4 different models. By using a newly designed spoiler on Model 1, the drag coefficient was reduced by 10.01 %. On Model 2, after adding a trailer rear extension with a spoiler, the reduction was obtained at 11.35 %. For the model 3 which is obtained by adding a side skirt to model 2, the improvement reached 18.85 %. The model 4 was composed of model 2 and a bellow between the truck and trailer. The drag force improvement was obtained at 22.80 % for model 4.

Çekici Römork Kombinasyonunda Sürükleme Kuvvetinin Farklı Pasif Akış Kontrol Yöntemleri İle Azaltılması

MAKALE BİLGİSİ

Anahtar Kelimeler:
Sürükleme kuvveti
Rüzgar tüneli
Pasif akış kontrolü
Kamyon-treyler
Sürtünme katsayısı

ÖZET

Bu çalışmada, 1/32 ölçekli çekici-römork kombinasyon modelinde sürükleme kuvveti ve yüzey basıncı ölçümleri yapılmıştır. Deneysel testler, emme tipi rüzgar tünelinde 312x103- 844x103 Reynolds Sayısı aralığında gerçekleştirilmiştir. Çekici ve römork kombinasyonu için aerodinamik sürükleme katsayısı (C_D) ve basınç katsayısı dağılımları (C_P) deneysel olarak belirlenmiştir. Çekici ve römork üzerinde büyük miktarda basınç katsayısına sahip bölgeler akış görselleştirmeleri kullanılarak belirlenmiştir. Kamyon-treyler kombinasyon modellerinin aerodinamik yapısı, 4 farklı modelde pasif akış kontrol yöntemleri ile iyileştirilmiştir. Model 1'de yeni tasarlanan spoiler kullanılarak sürükleme katsayısı % 10,01 oranında azaltılmıştır. Model 2'de, spoylerli bir treyler arka uzantısı eklendikten sonra sürükleme katsayısı % 11,35 oranında azaltılmıştır. Model 2'ye yan etek eklenerek elde edilen Model 3'te iyileştirme % 18,85'e ulaşmıştır. Model 4, model 2 ve kamyon ile treyler arasında bir körükten oluşuyordu. Model 4 için sürtünme kuvveti iyileştirmesi %22,80 olarak elde edildi.

NOMENCLATURE

C_D	Drag coefficient	A	Frontal area of model vehicle, m^2
C_P	Pressure coefficient	F_D	Drag force, (N)
Re	Reynolds number	Exp.	Experimental
CFD	Computational fluid dynamics	$U\infty$	Free flow velocity, m/s
Afc	Active flow control	s	Spoiler
Pfc	Passive flow control	s+re	Spoiler+rear extension
Fsv	Free stream velocity	s+re+ss	Spoiler+rear extension+side skirt

INTRODUCTION

The control of flow around of ground vehicles is the main research and development subject of automotive designers and researchers. The aerodynamic properties of vehicles are directly related to fuel consumption, energy balance and emissions. It is very important to examine the flow structures around the vehicles using both experimental and numerical methods and to optimize the vehicles in terms of aerodynamics. Aerodynamic drag force is directly proportional to vehicle speed. Therefore, drag force is of great importance in terms of fuel consumption, engine performance and emissions in vehicles that drive at high speeds. The subject of this study was used at high vehicle speeds between the cities and drove thousands of kilometers in a year. Aerodynamic drag force in trucks and trailers is mainly due to pressure. It is very advantageous in terms of production cost and time to determine the aerodynamic situation, flow separations, forces and moments that act on the vehicles quickly, easily and at a low cost, without producing the prototype of the vehicles in real dimensions by using computer software based on digital fluid dynamics or in a wind tunnel. The summaries of some experimental and CFD studies in the literature are presented below. The drag force which is based on pressure forms a large percent of total drag force particularly on the front surface of road vehicles (Bayindirli et al. 2015). Vehicle performance, energy consumption and traction exhaust emissions are directly related to aerodynamic specifications. Moreover, ventilation, vehicle noise, engine life, and heating and cooling systems of vehicles have been affected by aerodynamic forces (Bayindirli et al. 2016, Wahba et al. 2012, Gilhaus, 1981 and Chowdhury et al. 2013) Vehicle speed is the critical factor determining aerodynamic force (Miralbes, 2012, Cengel and Cimbala, 2008 and Sahin, 2008) . Therefore improving of aerodynamic force of heavy vehicles is very important for transportation costs. 60% of engine power is spent to overpower drag forces at 100 km/h for a passenger car (Wood and Bauer, 2003). Thanks to flow control methods in vehicles, remarkable improvement rates in fuel consumption have been achieved (Bayindirli et al. 2020, Hu and Wong, 2011 and Lokhande et al. 2003). There are two approaches to flow control around vehicles. Perzon and Davidson (2000) obtained a 4-7% aerodynamic improvement in a study. The coefficient was reduced by 7% by using a chassis skirt. 1/24 scaled model cars model were investigated in wind tunnel. The drag coefficients of cars were found between the rates of 14%-7.8% deviation according to real car models (Solmaz, 2010). The influence of windshield angle on drag coefficient was investigated in a study. As angle increased coefficient decreased on a commercial vehicle (Sari, 2007). The C_D of a truck trailer mode was reduced by 12.5% and 28% using vertical and horizontal spoiler by Modi et al (1995). The C_D value of the truck and trailer was determined 0.6 in another study (Mccallen et al. 2000). This result supports the accuracy of this experimental study. 20% drag minimization be obtained by flow control on trucks and trailers (Ogburn and Ramroth, 2007) The effect of spoiler design as a passive flow control element on aerodynamic drag coefficient was investigated on a 1/8 scale truck- trailer model by CFD method and wind tunnel experiments. The aerodynamic drag coefficients were improved up to 19% in the 5.5×10^5 Reynolds number by different spoiler models (Jeong et al. 2017). The C_D values of a truck model were calculated under an average 7.1° yaw axis experimentally and numerically. They used MATLAB Simulink program as a numerical calculation method. The drag coefficient was calculated on average at 0.77 after the result of the numerical analysis and 0.805 after the experimental method (Barden and Gerova 2016). Pickup and sedan cars were analyzed under laminar flow, turbulent flow, and boundary layer flow at different wind angles (Liu et al. 2016). The drag force and flow structure of a truck-trailer combination were examined in CFD. The C_D value of the truck trailer was decreased by 21% with some pfc components which are spoiler, afterbody and vortex generator (Chilbule et al. 2014). Pfc includes modification of vehicles or attachment of some parts to decrease the drag force. They have significant advantages compared to afc because they are cheaper and consume no energy from the engine (Altaf et al. 2014). The large drag force due to the vehicle geometry forms pressure-based drag which is the main contributor to total drag. According to Hucho and Sovran (1993), about 50% of vehicle's the fuel consumption results from this pressure-based drag at high vehicle speeds. CFD analysis was made of SUV model and ~~it~~ it was modified by attaching some kinds of pfc parts such as a lip kit to the bumper. According to the base model car, the pressure increased by about 3.5%, the velocity by 3%, the lift force 50.6% and the drag force by 5.8% in the modified SUV ground vehicle model (Yadav et al. 2021). In another study, dimples on a bus model were carried out numerically and experimentally. The dimple position, dimple number and, dimple orientation were tested to understand their effect on drag. It has been recommended that this method is effective in decreasing of drag force (Chen et al. 2021). In another study, the superior aerodynamic structure of tuna was investigated using an experimental method. 3 types of bionic surfaces were produced by inspired tuna fish. The effect of these surfaces reduced drag force. It was seen that a 7.22% drag reduction was achieved on the dual structure coupling surface. Using jet devices such as afc is a promising approach for reducing drag for vehicles. A CFD study was performed for afc around the Ahmed body model. Comparing three different actuation strategies was researched according to the height of the vehicle. It was shown that variations in the shear layer occured during the blowing phase. The change in flow topology occurs with synthetic jets and suction. Because of this situation, rear-back pressure substantially advanced (Edwige et al. 2022).

This study focuses on reducing of C_D of truck-trailer combinations. Various unique pfc components were developed to obtain lower F_D. The effect of these parts on the F_D was experimentally investigated. Between the rates of 10.01% and 22.80%, drag reduction was achieved. The original part of the study is the drag reduction with the original developed parts and its effect on fuel consumption. The main difference of this study from the studies in the literature is the aerodynamic improvement rate provided by the passive flow control parts developed for this truck model produced in Türkiye. In addition, the study recommends factors to consider when choosing a trailer for a truck model and reveals the possible impact of the improvement in aerodynamic drag force provided by passive flow control methods on the country's fuel imports.

MATERIALS AND METHOD

Experimental setup

The aerodynamic tests were conducted in a suction type wind tunnel as seen in Fig. 2a-b. The size of the test area is 40cm x 40cm x 100cm. The free stream speed was controlled to in the test area with a frequency inverter. It runs between 0Hz and 50Hz and 0.1 Hz steps. The 4000 W-powered fan axial fan motor was used to obtain fsv. A six-component load cell was used to measure Fx and Fy forces up to ± 32N and Fz force up to ± 100N. The load cell measures moments (Mx-My-Mz) in the range of ± 2.5Nm. In studies, turbulence intensity was lower than 1% in the wind tunnel. The maximum fsv was 28 m/s. To ensure kinematic similarity, the blocking rate was 6.31% in test area. The experimental setup and wind tunnel were presented in Fig. 1.

In wind tunnel tests, the model vehicle was positioned on a solid stable ground. This plate is fixed on airfoil legs, 5 cm above the ground. It is connected to the load cell by a shaft. Thus, the vehicle is affected by the free flow velocity in the fully developed flow region. The drag force acting on the plate at each test speed was determined and this value was subtracted when calculating the net drag force values of the vehicle.

Fig. 1. Experimental setup

As seen in Fig. 2a and 2b total of 32 taps were formed on symmetry axis of the truck trailer. 13 taps were on the truck and 19 taps were on the trailers to conduct pressure measurement.

Fig.2a. The locations of the pressure probes on model vehicle

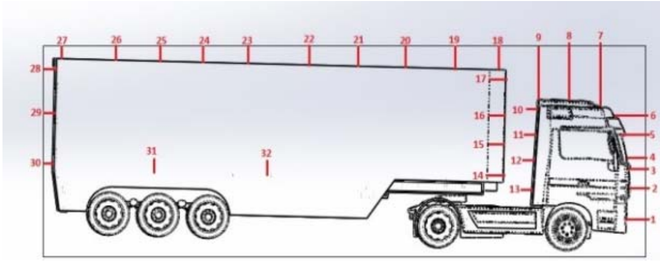

Fig.2b. The locations of the pressure probes on model vehicle

The tests of pressure measurements were made between the range of 89 000 - 286 000 Re for the truck. It was carried out in the range of 253 000 - 794 000 Re for the truck-trailer combination. The dynamic pressure was measured from the pressure taps at the inlet and outlet of the contraction cone of the wind tunnel. Two differential-type pressure converters were used in the tests. It was an Omega PX163-2.5BD5V model. The output voltage of 0V-5V detection time was 1 millisecond. The pressure transducers were calibrated before the pressure measurements. 800 values were taken in a second to calculate surface pressure. These values are below the pressure transducer detection time capacity (1000 Hz). In total 16384 values were taken for each measurement in 20.48 seconds. The dynamic pressure is the difference between the static pressure and the total pressure (Bayindirli et al 2016).

$$P_{dyn} = P_{total} - P_{st} \tag{1}$$

$$P_{dyn} = \frac{1}{2} \rho V \tag{2}$$

$$C_P = \frac{\Delta P}{\frac{1}{2} \rho V^2 A} \tag{3}$$

In wind tunnel tests, room temperature, the pressure of the atmosphere, the dynamic pressure and fsv were gauged with digital micromanometer (Manoair 500 model).

The C_D is expressed with the parameters of fsv (V) force (F_D), air density (ρ), and frontal area of the vehicle (A).

$$C_D = \frac{F_D}{\frac{1}{2} \rho V^2 A} \tag{4}$$

The force measurement tests were conducted on 6 different free stream velocities (5, 10, 15, 20, 25, and 27 m/s). The 2 results were calculated per second in 1 minute. The C_D values were calculated based on these 120 results.

Similarity Conditions

Three similarity conditions must be provided to ensure the accuracy of test results. In this study, a licensed model car was used to obtain geometric similarity. The kinematic similarity is related to the blockade ratio in the wind tunnel test area. It is explained as the ratio of vehicle frontal area to test section surface area. The blockade ratio was 6.31%. As seen in this experimental study, and it is recommended in literature that it must be below the 7.5 % (Cengel and Cimbala, 2008). As shown in Fig.3, Reynolds independency tests were conducted to provide dynamic similarity with this study. The fully turbulent free stream velocities were determined, and related tests were carried out after Reynolds independency.

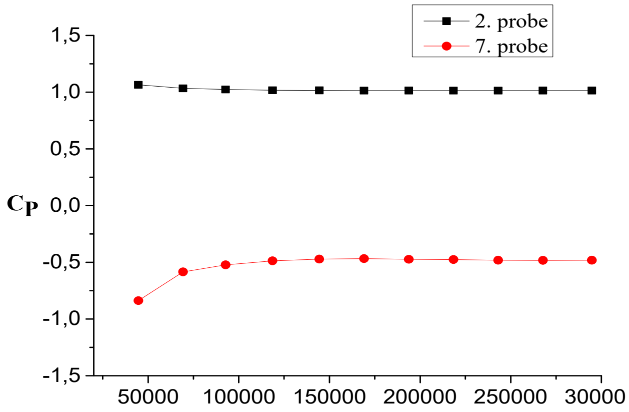

Fig. 3. Reynolds independency in tests (Bayindirli et al. 2016)

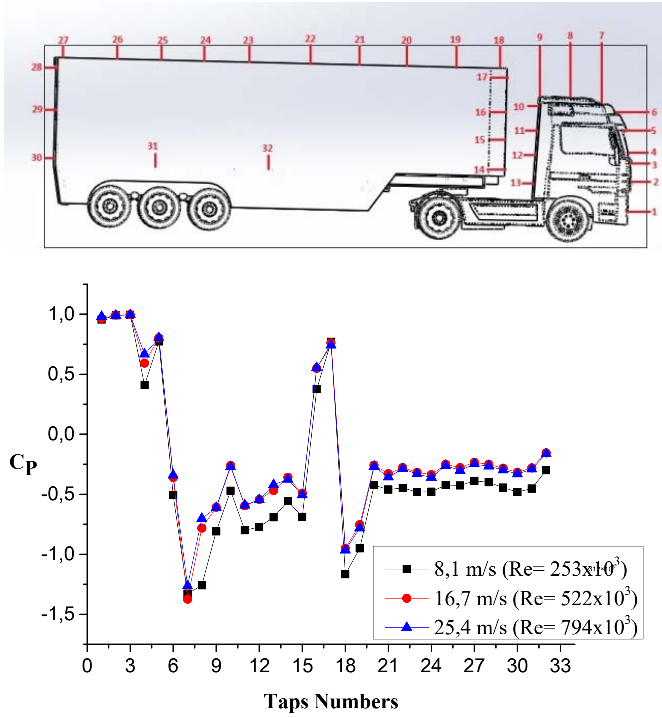

Fig. 4. The CP distributions on base model truck-trailer (Bayindirli et al. 2016)

Uncertainty Analyses of Measured Parameters

Uncertainty rate of Reynolds number was obtained as 3.87% in Eq. 5.

$$u_{Re} = \frac{w_{Re}}{Re} = \left[(u_\rho)^2 + (u_{Pitot})^2 + (u_H)^2 + (u_\mu)^2\right]^{1/2} \quad (5)$$

The drag force uncertainty was acquired as 4.5% in 10 m/s and 312×10³ Reynolds Number in Eq. 6.

$$\frac{w_{F_D}}{F_D} = \left[\left(\frac{w_{X_1}}{X_1}\right)^2 + \left(\frac{w_{X_2}}{X_2}\right)^2 + \left(\frac{w_{X_3}}{X_3}\right)^2 + \left(\frac{w_{X_4}}{X_4}\right)\left(\frac{w_{X_4}}{X_4}\right) + \left(\frac{w_{X_5}}{X_5}\right)^2\right]^{1/2} \quad (6)$$

The uncertainty value of C_D was calculated as 4.7% by writing related parameters such as F, ρ, and A arguments in Eq. 7.

$$u_{C_D} = \frac{w_{C_D}}{C_D} = \left[(u_{F_D})^2 + (u_\rho)^2 + 4(u_{pitot})^2 + (u_A)^2\right]^{1/2} \quad (7)$$

The C_P uncertainty was calculated as 2.11% in Eq.8.

$$u_{C_P} = \frac{w_{C_P}}{C_P} = \left[(u_{\Delta P})^2 + (u_\rho)^2 + 4(u_{pitot})^2\right]^{1/2} \quad (8)$$

RESULTS AND DISCUSSION

The CP distribution on model vehicle

The aerodynamic force of the base truck trailer was determined by Bayindirli et. al. (2016). This study aims to improve the drag force of the base model truck trailer. Take into consideration the pressure coefficient (C_P) distributions in Fig 4. Passive flow control parts were developed to decrease pressure-based drag force. There is a negative pressure area at the rear between the truck-trailer and the rear of trailer.

The drag force measurements

The average C_D of the base model was determined to be 0.704, as seen in Table 1 and Fig 5. The addition of the trailer to the truck increased the drag coefficient (C_D) by 15.8%. The C_P is very high on 17th and 18th probes. There is a huge amount of pressure-based drag force in that area. The aerodynamic structure of model vehicle and flow separation were determined by flow visualization in Fig 6.

Table 1. The C_D values of base model /Bayindirli et al. 2016)

Re	Aerodynamic Drag Force (N)	Base Model C_D
3.12×10⁵	0.467	0.707
4.69×10⁵	1.036	0.697
6.25×10⁵	1.889	0.714
7.81×10⁵	2.917	0.706
8.44×10⁵	3.359	0.697

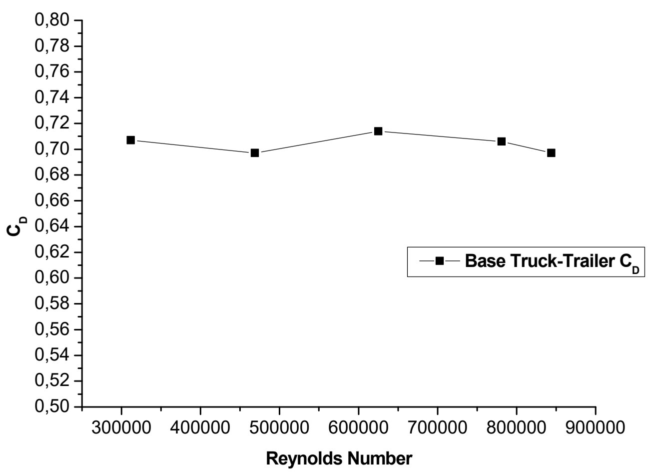

Fig. 5. C_D graph of base truck-trailer model according to Reynolds Number

Fig.6. Flow separations around base model truck-trailer (Bayindirli et al. 2016)

Passive flow control technique

A certain flow structure prevails around the object in the flow medium. The process of removing this flow structure from the normal flow structure is called flow control. Depending on the amount of energy consumed there are two methods flow control. These are named pfc and afc. In pfc method, there is no energy consumption from the vehicle, and this situation provides a big advantage compared to afc. Generally, the geometry of vehicles is optimized with some parts in order to gain better aerodynamic structure in pfc.

Drag reduction with spoiler (Model 1)

After the pressure coefficient distributions were determined that the C_P value was found to be high for the tap number of 17. The vehicles with the standard spoiler pressure coefficient in this region (15., 16., and 17. taps) were obtained to be close to the stagnation pressure like on the front bumper.

A spoiler model was produced with 30° inclination angle to reduce drag force in this area. The truck and trailer combination with newly designed spoiler is given in Fig.7. As shown in Table 2. the wind tunnel tests were conducted in 5 different Re numbers and average C_D was calculated as 0.633 of model 1 (truck and trailer). The C_D of the base truck-trailer model was 0.704.

Fig. 7. Model 1 truc k-trailer

Table 2. The C_D values of Model 1

Re	Aerodynamic Drag Force (N)	Model 1 C_D
3.12×10^5	0.57	0.613
4.69×10^5	1.332	0.65
6.25×10^5	2.338	0.637
7.81×10^5	3.579	0.63
8.44×10^5	4.222	0.638

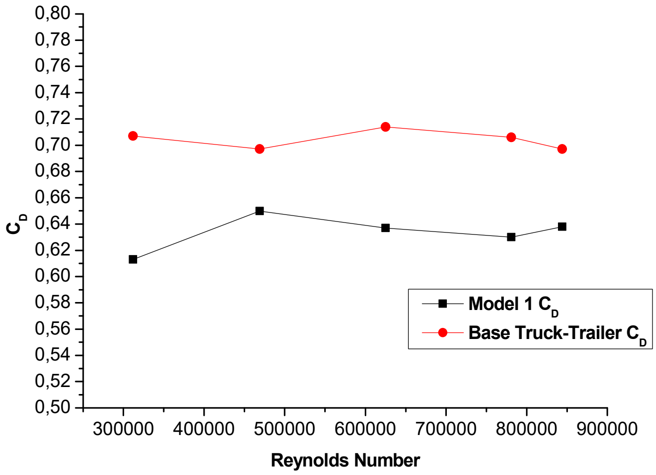

Fig. 8. C_D graph of base truck-trailer model-Model 1 according to Reynolds Number

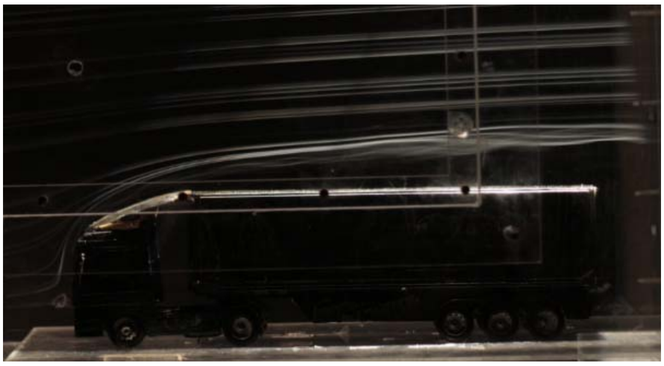

Fig.9. Flow visualization of model 1

As seen in Fig. 4, the flow that affects the upper front region of the trailer (17. taps) was redirected to upper part of the trailer (18., 19., and 20. taps) by the newly designed spoiler. Hence pressure-based drag force was reduced by 10.01% on average.

Drag reduction with spoiler and trailer rear extension (Model 2)

A large amount of negative pressure occurs in rear of the trailers. In truck-trailer combinations, a significant amount of total aerodynamic originates from this negative pressure area. In model 2, it was aimed to create a smaller negative pressure area behind the trailer. A rear trailer extension is designed and added to model 1 truck trailer to obtain aerodynamic improvement. Model 2 truck-trailer and designed rear trailer extension are given in Fig.10.

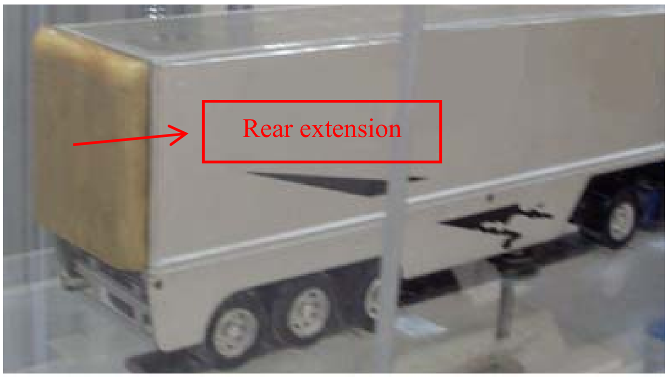

Fig. 10. Model 2 truck-trailer

As seen in Table 3 and Fig 10, the C_D was obtained as 0.624 for model 2. The obtaining aerodynamic improvement obtained was 11.35% with the newly designed spoiler and rear trailer extension (model 2). The aerodynamic improvement gained was 1.35% for rear trailer extension only.

Table 3. The C_D values of Model 2

Re	Aerodynamic Drag Force (N)	Model 2 C_D
3.12×10^5	0.405	0.612
4.69×10^5	0.928	0.624
6.25×10^5	1.672	0.632
7.81×10^5	2.573	0.623
8.44×10^5	3.034	0.630

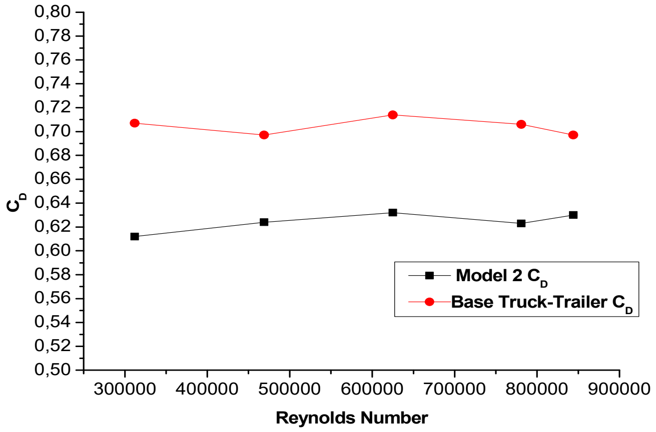

Fig. 10. C_D graph of base truck-trailer model-Model 2 according to Reynolds Number

Drag reduction with spoiler, trailer, rear extension and side skirt (Model 3)

The wheels may cause 5% of the total drag on the truck-trailer combination (Bayindirli et al. 2015). The trailer wheels of model 2 vehicle were closed with side skirt as presented in Fig.11.

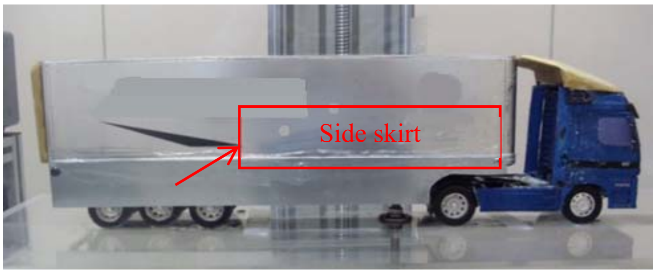

Fig.11. Model 3 truck-trailer

As shown in Table 4. and in Fig 12, the C_D was reduced to 0.571 in model 3 truck and trailer. Consequently the aerodynamic improvement attained was18.85% by of the newly designed spoiler. rear trailer extension and side wind skirt (model 3). By using only side skirt, a 7.5% aerodynamic improvement was obtained.

Table 4. The C_D values of Model 3

Re	Aerodynamic Drag Force (N)	Model 3 C_D
3.12×10^5	0.387	0.586
4.69×10^5	0.842	0.566
6.25×10^5	1.482	0.56
7.81×10^5	2.298	0.556
8.44×10^5	2.832	0.558

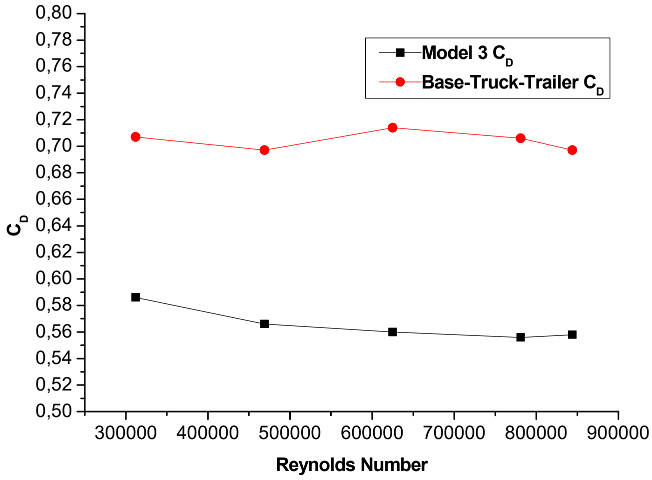

Fig. 12. C_D graph of base truck-trailer model-Model 3 according to Reynolds Number

Drag reduction with spoiler, trailer rear extension and bellow (Model 4)

In experimental studies, negative pressure was formed in the gap between the trailer and the truck. As presented in the Fig.13, gap between the truck and the trailer of model 2 was closed with a bellows in this aerodynamic improvement study. It was aimed at providing an aerodynamic improvement by using bellow to prevent inflow between the truck and the trailer.

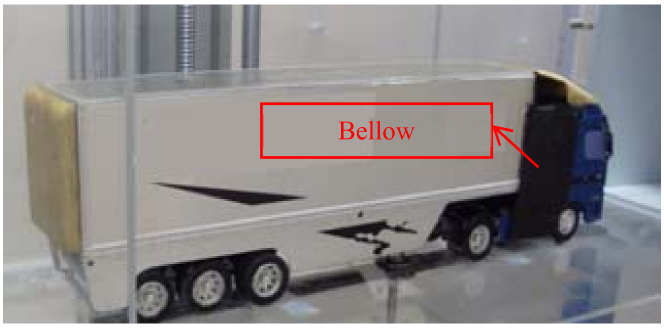

Fig. 13. Model 4 truck and trailer

The C_D value was calculated as 0.543 for model 4 truck-trailer as shown in Table 5 and Fig 14. According to the base model total aerodynamic improvement was 22.80% with a spoiler, trailer rear extension and bellow. The aerodynamic improvement rate achieved was 11.45% by only adding bellow.

Table 5. The C_D values of Model 4

Re	Aerodynamic Drag Force (N)	Model 4 C_D
3.12×10^5	0.36	0.544
4.69×10^5	0.821	0.552
6.25×10^5	1.422	0.538
7.81×10^5	2.249	0.544
8.44×10^5	2.602	0.54

The aerodynamic modification of vehicle geometry ensures drag reduction. It contributes to decreasing of fuel consumption of vehicles. Vehicle body outlines, spoilers, after-body parts, diffusers, side skirts etc. are examples of body modification in vehicles. These applications on vehicles improve stability and increase downward forces (Marklund et al. 2013).

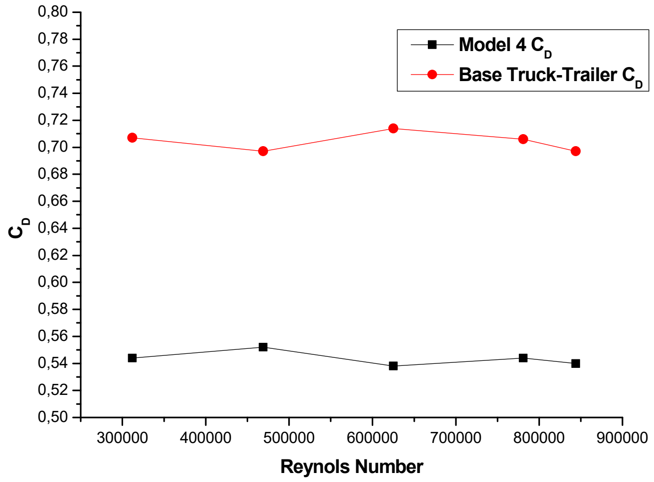

Fig. 14. C_D graph of base truck-trailer model-Model 4 according to Reynolds Number

Keeping the flow at the surface, delaying flow separation, and reducing the negative pressure area reduce the pressure-induced drag force (Yanqing et al. 2023, Edwige et al. 2022 and Altaf et al. 2022) As seen in Fig.15., by using 4 different passive flow control parts respectively 10.01%. 11.35%. 18.85%. 22.80%, respectively, aerodynamic improvement was obtained.

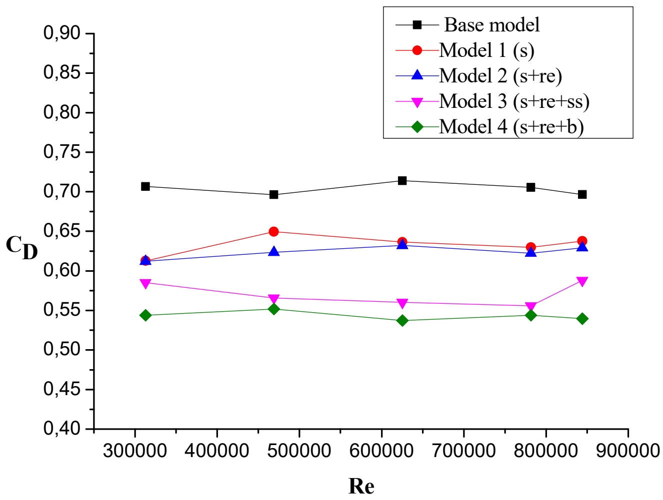

Fig.15. The C_D comparison graph of base model, model 1, model 2, model 3, model 4

When the C_D was reduced by 2% and fuel consumption was reduced by 1% at high speeds for road vehicles. Trucks and trailers are extensively used in intercity freight transportation. These vehicles drive at high speeds. Aerodynamic forces are of great importance when the vehicle speed exceeds 50 km. The vehicle's engine consumes extra fuel to overcome this aerodynamic force. These vehicles also travel many kilometers each year. The maximum drag reduction rate was 22.80% in this study. The 22.80% aerodynamic improvement can reduce fuel consumption by 12%. Assuming that, a truck trailer travels an average of 100.000 kilometers annually and consumes 25 liters for every 100 kilometers. The annual fuel consumption of a vehicle will be 25.000 liters. Thanks to the aerodynamic improvement provided by these passive flow control methods, this vehicle can consume 12% less fuel per year. This means that each car will consume 3000 liters less fuel annually. This aerodynamic improvement will reduce transportation costs and reduce exhaust emissions from engines.

CONCLUSIONS

A summary of this wind tunnel experiments was presented below.

- ✓ A standard trailer addition on the truck model increased the drag coefficient of the truck (C_D) by 15.80%.
- ✓ In model 1, a 10.01% drag reduction was obtained by the newly designed spoiler. This drag reduction rate reduces fuel consumption by 5%. This result has revealed the importance of suitable spoiler selection and design in truck trailers.
- ✓ The C_D was reduced by 11.35% with the newly designed spoiler and rear trailer extension in model 2.
- ✓ 18.85% drag reduction was obtained by the newly designed spoiler, rear trailer extension and side skirt in model 3.
- ✓ The maximum aerodynamic improvement ratio was 22.80% in model 4. According to the literature, this drag reduction rate can reduce fuel consumption of truck trailer by about 12 % over at 96 km/h.

It is recommended, as a result of this study that 4 pfc methods can be applied at the same time to aerodynamically improve of the truck-trailers

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