Passive and active flow control effects in the platoon and overtaking maneuvers

Karimi, Saber ; Mohammadikalakoo, B.

DOI
10.2514/6.2023-2141

Publication date
2023

Document Version
Final published version

Published in
AIAA SciTech Forum 2023

AIAA SciTech Forum
23-27 January 2023, National Harbor, MD & Online
AIAA SCITECH 2023 Forum
10.2514/6.2023-2141

Passive and active flow control effects in the platoon and overtaking maneuvers

S. Karimi[1] and B. Mohammadikalakoo[2]

Lakehead University, Thunder Bay, Ontario, Canada

Delft University of Technology, Kluyverweg 2, 2629 HS Delft, The Netherlands

P. Schito[3]

Politecnico di Milano, Via La Masa 1, Milano, Italy

The current numerical study is dedicated to investigating the effect of passive, active, and combined flow control techniques on the performance of the vehicles in different maneuvers including, platoon and overtaking on critical highway velocity (70 miles per hour) for a reference bluff body vehicle called Ahmed body. The target passive flow control method is an innovative technique called Rear Linking Tunnels (RLTs), introduced previously by the group of authors. Studying the effect of the Single Dielectric Barrier Discharge Actuator (SDBD) as an active flow control method and its combined effect with RLTs on the drag and lift of controlled vehicles and surrounding vehicles in various maneuvers is one of the main aims of this research study.

[1] PhD student, Mechanical Engineering Department, not a member.

[2] PhD candidate, Aerodynamics Group, Faculty of Aerospace Engineering, not a member.

[3] Assistant Professor, Mechanical Engineering Department, not a member.

Introduction

Lower fuel consumption and stability for heavy vehicles on the highway condition can be achieved by being in the right position. The aerodynamic drag represents around 65% of the total energy consumption for heavy trucks on the road with a speed of 70 miles per hour [1]. The reduction of this drag force could have a decisive influence on fuel consumption, for instance, it is conceivable to reach a 25% reduction in fuel consumption at highway speeds by a 50 % reduction in drag force [1]. Besides fuel consumption, new policies related to global CO_2 footprints create a significant moving force toward aerodynamic drag reduction studies.

Different parameters like vehicle spacing, speed, position, and vehicle mass usually have a significant role in fuel consumption [2]. Aerodynamic forces are mainly dependent on the flow field around and through the vehicle so any change in the aforementioned parameters could affect the fuel consumption and stability of the vehicles. For example, in some positions for the vehicles during the overtaking or platoon maneuver, additional aerodynamic forces start to act on both vehicles due to the interaction between the vehicles' wakes ([3], [4]). These additional forces have destructive impacts on the drag and lift coefficient leading to sudden lateral displacements and rotations around the yaw axis of each vehicle which can yield critical safety situations [3]. So, finding the appropriate situation on the highway condition to reduce drag and lift forces is highly recommended.

Any method to reduce the strength of wake vortices offers the largest potential for drag reduction [5]. The wake behind vehicles is a major source of pressure drag and so reducing the wake size leads to drag reduction and an increase in vehicle stability [6]. This feature has motivated the development of many passive and active flow manipulation methods in order to reach high aerodynamic performance as an efficient solution, especially for the automotive industry [7].

According to previous research studies, the main factor to decrease car drag is creating delay in the flow separation [8]. One of the interesting flow control techniques for separation delay is plasma actuators (SDBD) which have a direct impact on the flow separation leading to a weaker and smaller wake region [9]. In the flow field around the car, there are also streamwise vortices that have an important role to increase the drag and lift of the vehicles [10].

One of the passive flow control methods aimed to control these Streamwise vorticities is called Rear Linking Tunnels (RLTs) introduced previously by [6], which is the starting point for considering the effect of the passive flow control on vehicle aerodynamic performance in the different platoon and overtaking scenarios. The main idea behind this type of passive flow control is inducing momentum into the rear part of a vehicle through specific tunnels linking the high-side pressure side of the vehicle to the rear low-pressure wake region. Therefore, the recirculation cores move away from the rear part of the car model and lose their strength leading to drag reduction.

Based on the experimental and numerical results [6], up to a 5% reduction in the drag force of Ahmed body can be achieved by this type of passive flow control. The typical shape of these linking tunnels is presented in Fig.1 on a reference bluff body model called Ahmed body introduced by [13]. It should be noted that the main geometry used for this study is a slightly modified version of the Ahmed body introduced in reference [5]. The general criterion for Ahmed body dimensions can be seen in Fig.2.

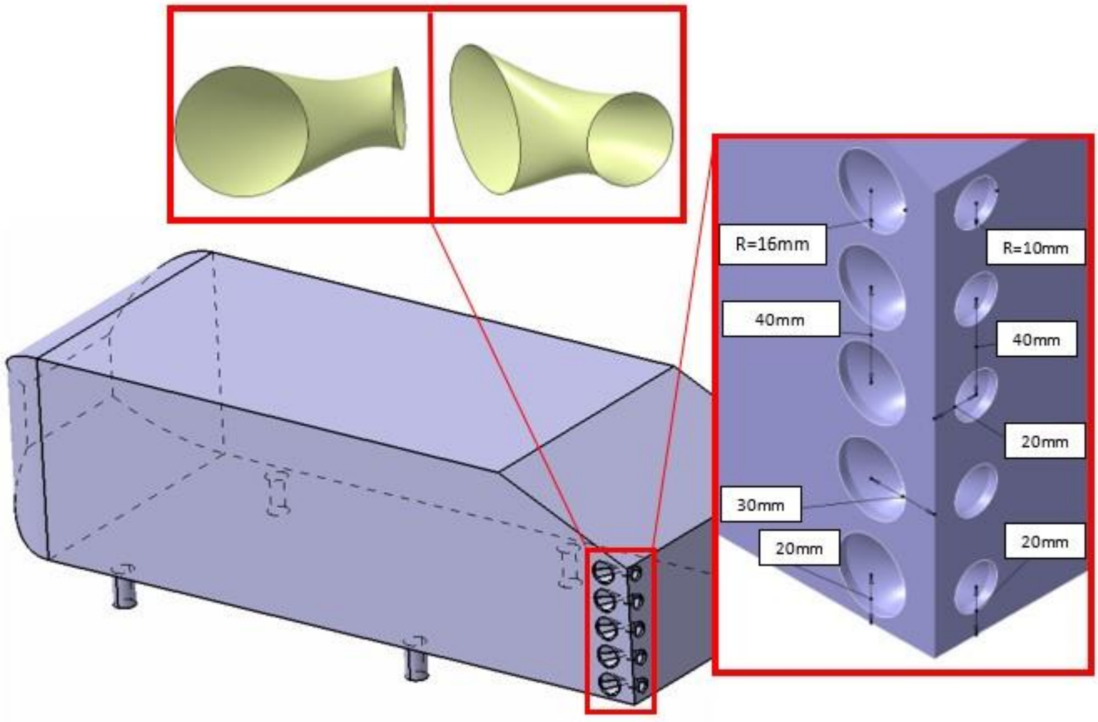


Fig 1. linking tunnels (passive flow control) on a 25° Ahmed body model [6]

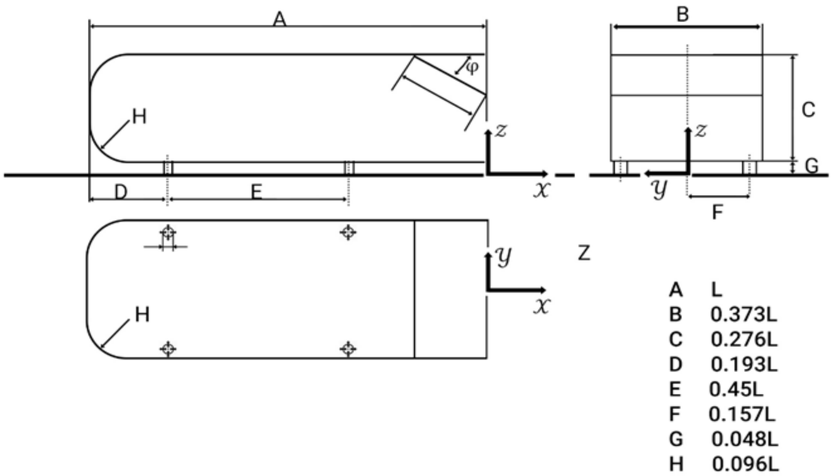


Fig 2. Geometry of the Ahmed Body

There is a study related to investigating the effect of the RLTs on the performance of SDBD actuators as active flow control and combined method of active and passive flow control. [11]. Based on this research, a combination of these flow control devices has a significant influence on the wake region and vorticities around the model, therefore, the power and size of vortices and wake decrease as a direct effect of the flow control.

This study aimed to analyze the effect of the Rear Linking Tunnels (RLTs), active, and combined flow control techniques not only on the controlled car but also on the surrounding cars' aerodynamic performance in two scenarios of five different scenarios of platoon and overtaking introduced in this research (the average cruise velocity on standard roads is 70 miles per hour [1]). In other words, we would like to look at the effect of the flow control techniques from another point of view. Since most of the studies only focus on the local effects of flow control on a single car without considering the real road condition.

Methodology

Numerical setup

ANSYS FLUENT™ as a Computational Fluid Dynamics (CFD) solver with the steady formulations of the Reynolds Averaged Navier Stokes (RANS) has been used to solve the flow field around the cars consisting of large vortex structures, separation, and the boundary layer phenomena. Therefore, k-ω Shear Stress Transport (SST) turbulence model which is able to predict non-equilibrium turbulence was selected. A coupled algorithm to match pressure and velocity fields and a pressure-based solver to solve the equations were used. The pressure equation is discretized using a standard gradient method and other equations are discretized spatially using a second-order upwind gradient scheme. The computational domain shown in Fig 3 was designed so that the velocity inlet and pressure outlet would be always at an appropriate distance from the front of the first car and the rear part of the last car (more than 5 L and 7 L respectively, where L is the model length). In addition, the distances of the cars from the upper and side surfaces are 3 L [3]. Fixed inlet velocity condition for the inlet boundary condition and fixed pressure for the outlet boundary was applied besides the no-slip wall boundary conditions for all the surfaces of the vehicles and road. The computational domain is full scale including two high-resolution subdomains for capturing the flow field characteristics on the slant surface, especially the flow separation and reattachment before and after applying the SDBD actuators. The total number of tetrahedral cells for the grid varies between 5.3 and 8.7 million based on the various case study configurations. The average value of y+ near the walls is less than 5 which is acceptable for k-ω Shear Stress Transport (SST) turbulence model to obtain accurate shear stress and resolve the viscous sublayer [12]. In this research, a specific version of Ahmed body square back has been used in which the upper (roof) edges are rounded with a 40 mm [5].

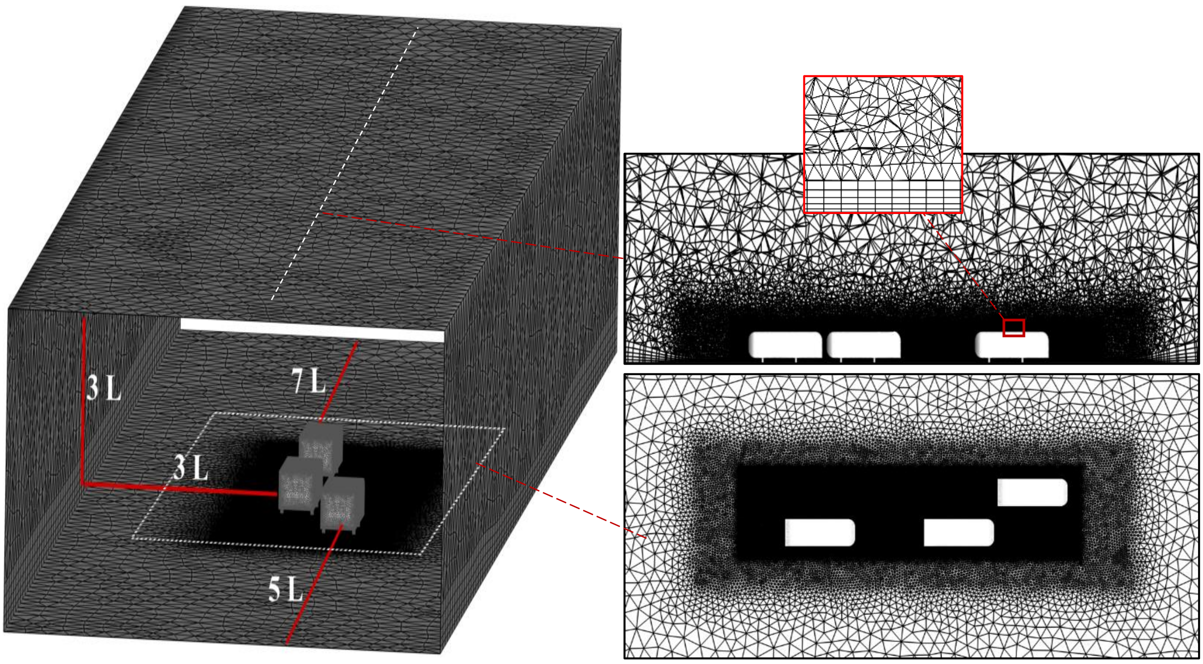


Fig 3. Computational domain and grid visualization

Case studies

The controlled car in the current study has been investigated for five moving modes with four different phases per each mode. Each case considered with passive flow control (RLTs), active flow control (SDBD), and combination of them. All the modes and corresponding phases are presented in Fig 4, and explained in the following: (L is the length and W is the width of the car):

Moving modes:

1- The platoon

2- The overtaking

3- The overtaking with a fixed car located at 0.5L distance from the back of the controlled car.

4- The overtaking with a fixed car located at L distance from the back of the controlled car.

5- The overtaking with a fixed car located at L distance from the front of the controlled car.

Phases:

Phase A: The overtaking car positioned at the 0.5 L distance from the side and back of the controlled car

Phase B: The overtaking car positioned at the 0.5 L distance from the side of the controlled car

Phase C: The overtaking car positioned at the 0.5 L distance from the side and front of the controlled car

Phase D: The overtaking car positioned at the 0.5 L distance from the side and L distance from the front of the controlled car

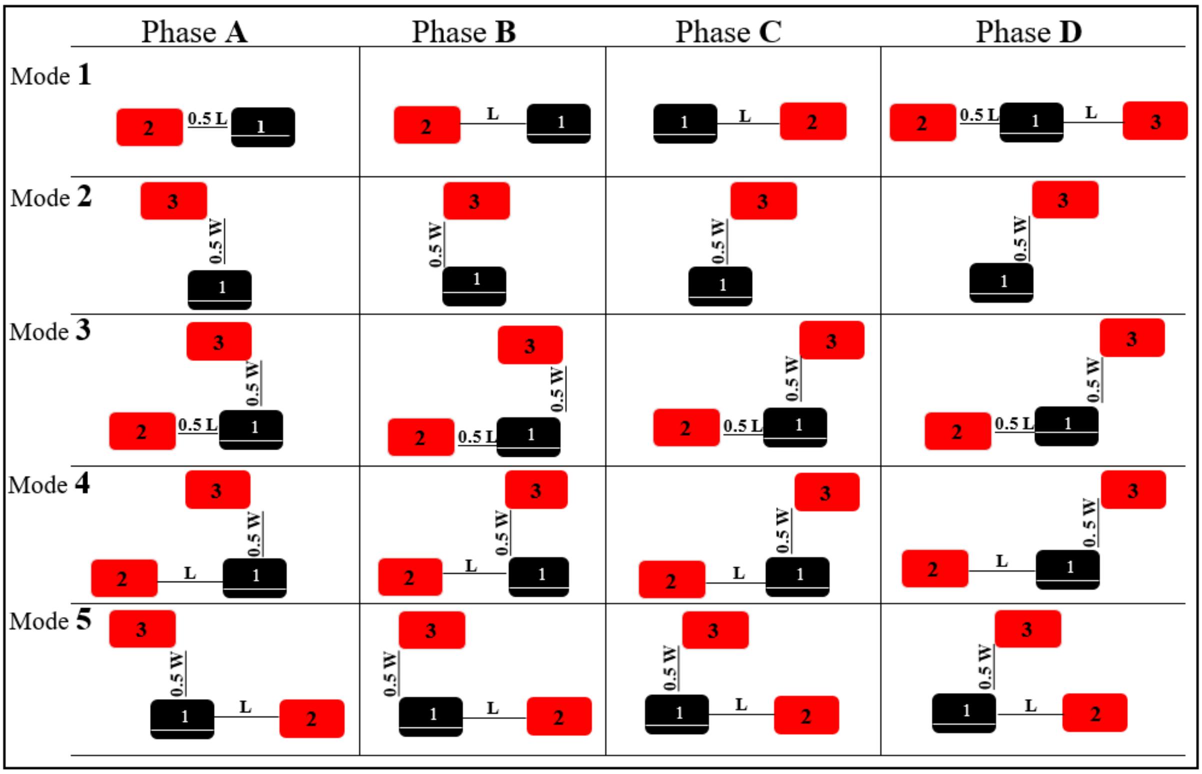


Fig 4. Considered platoons and overtaking maneuverers (Model 1: Controlled car, Model 2: Fixed car, Model 3: Overtaking car)

Results

Based on the explanations in the case study section, there are almost 20 different case studies with 4 specific conditions resulting in 80 different flow field studies. Considering the most critical conditions between those case studies, one of the specific modes (mode 3) will be considered in this report. Analyzing all the remaining modes and conditions is part of our future plan for this research study. Mode 3 with corresponding phases is presented in the next section.

Mode3) The overtaking with a fixed car located at 0.5L distance from the back of the controlled car

In this mode, phase A is the critical condition for the controlled car which experienced a high lift (2.8 times of the basic model without surrounding cars). Based on the previous research studies [3] related to the interaction of several cars in real road conditions in the case of having the overtaking phase of two cars, the flow between two cars usually accelerates which creates a Venturi effect. Therefore, two cars tend to attract each other [4] due to this Venturi effect. The interaction of the two close rear c-pillar vortices of the cars in the middle region is one of the observations which is in good agreement with this suction effect in Fig 5.

It should be noted that the structure of the vortices in the wake region of the cars and their interactions are shown with the help of the lambda2 criterion. The lambda2 isosurfaces with the contour of the velocity are represented for the critical phase A for this mode in Fig 5.

Based on Fig 5, the rear linking tunnels as the passive flow control technique will increase the pressure and momentum inside the region between controlled mode and fixed car leading to enhancing the strength of the Venturi effect between fixed and overtaking cars. This increase in the Venturi effect will create an additional suction effect which tends to attract the flow of the overtaking car toward the fixed car. The suction effect of the Venturi could be perceived easily by comparing the structures of the vortices over the top surface of the overtaking and fixed cars which are completely swept away.

Based on Fig 5 related to the wake structures over the models, deviation of the bottom rear c-pillar vortex of the overtaking car toward the fixed car will create a stagnation region (additional side force) for the flow on the side of the fixed car. This is the high-pressure region represented in Fig 6 for the fixed car which extended to the bottom of the fixed car and leads to creating excessive lift for that model. This increase of the lift and drag force can be seen also in Fig 11 corresponding to the drag and lift coefficient of model 2 which has a noticeably higher lift and drag coefficient compared to the clean model. This phenomenon could create a noticeable issue for the drivability of the fixed car in this mode, especially at high speed. The above pressure increase creates a high-pressure region also between two other pairs of the c-pillar vortices of the cars and repels each other which could be seen in Fig 5.

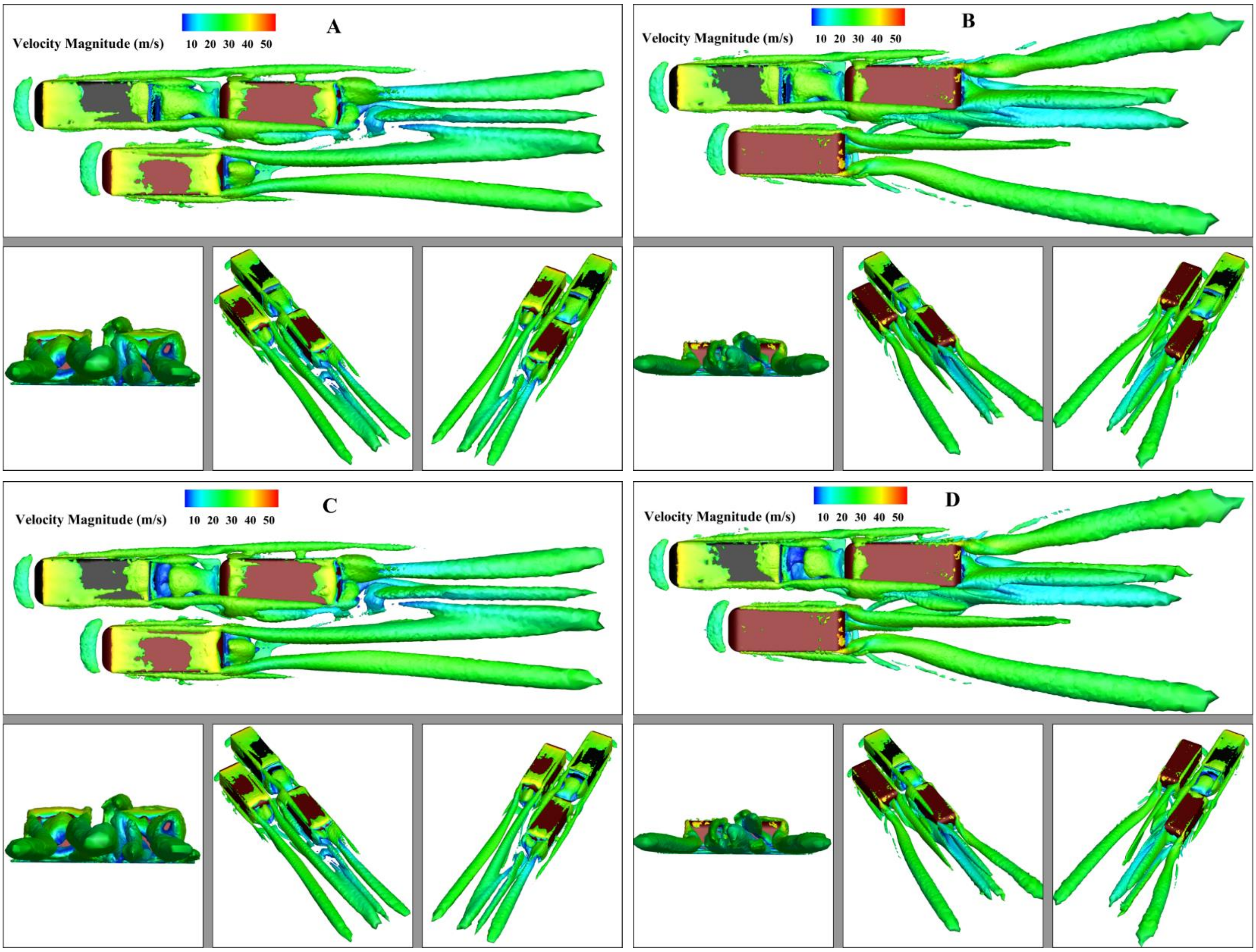


Fig 5. Contour of velocity on the Iso-surface of λ2 for mode 3-Phase A (Black car is the controlled model). A), Without flow Control-Clean B), Passive flow control-RLTs C), Active flow control-SDBD actuator D), Combination of RLTs with SDBD actuator

The repulsion effect of these two vortices will create low surface pressure on the corner sides of the fixed and overtaking cars in a symmetric pattern as can be seen in Fig 7. This low pressure on the rear part of the cars creates a vertical suction component on both overtaking and fixed cars which is the second reason for having a noticeable lift increase for them (3.3 and 2.09 times of clean case for the fixed and overtaking cars, respectively.) These suction sides on the corner have the same negative effect on the drag force (56% and 75% increase in drag for fixed and overtaking cars respectively). In summary, we can conclude that the effect of RLTs on the controlled car in this specific mode (Phase A) is only in favor of the controlled car in terms of 5.76% drag reduction and 25% lift reduction as can be seen by comparing the drag and lift coefficient of the three models in Fig 11 corresponding to phase A.

The physical behavior of the SDBD active flow control is completely different from the RLTs technique which is related to the fact of tangential blowing mechanism in the SDBD actuators compared to the normal blowing of the RLTs. So, this tangential blowing on the top surface of the controlled model increases the momentum over the model and based on the Bernoulli effect creates an additional suction over the top surface. Therefore, we have an increase in the lift force for the controlled car (37%) with some effects on the lift force of the other cars (almost 5% increase). For the effect of the SDBD actuators on the drag force of the cars, almost 10% drag reduction is observed for the controlled car without a noticeable effect on the other two cars. These claims can be confirmed by comparing the red triangle and black circle markers in Fig 11 for all three models corresponding to phase A.

The combination of the passive and active flow control for this mode (phase A) leads to a 16.5% drag reduction and a 43% increase in the lift force for the controlled car. The effect of this combined flow control method on the overtaking and fixed car is the same as the RLTs effects plus minor negative effects due to the presence of the SDBD actuators.

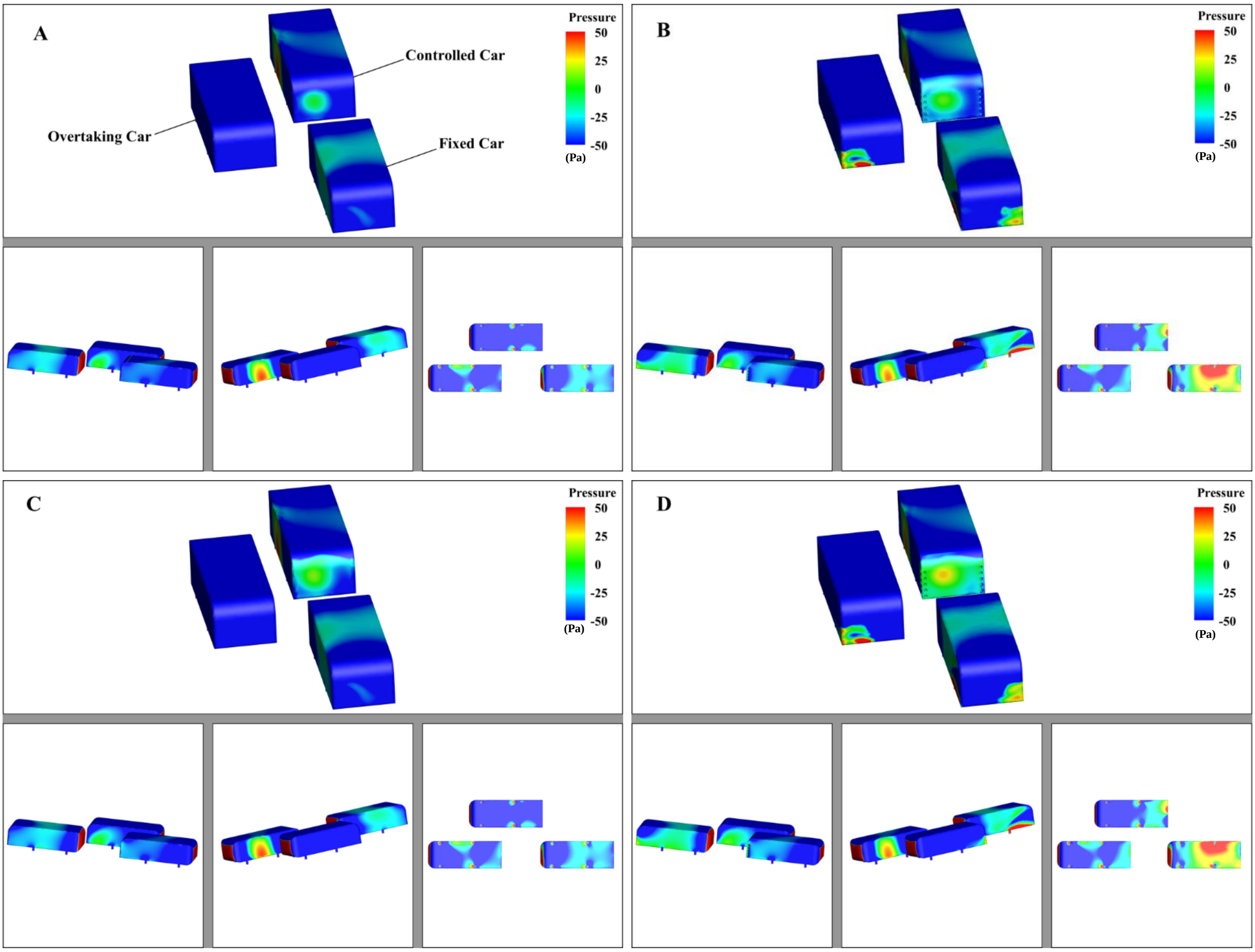


Fig 6. Surface pressure distribution over the cars for the mode 3-Phase A. A), Clean B), RLTs C), SDBD actuator D), Combination of RLTs with SDBD actuator

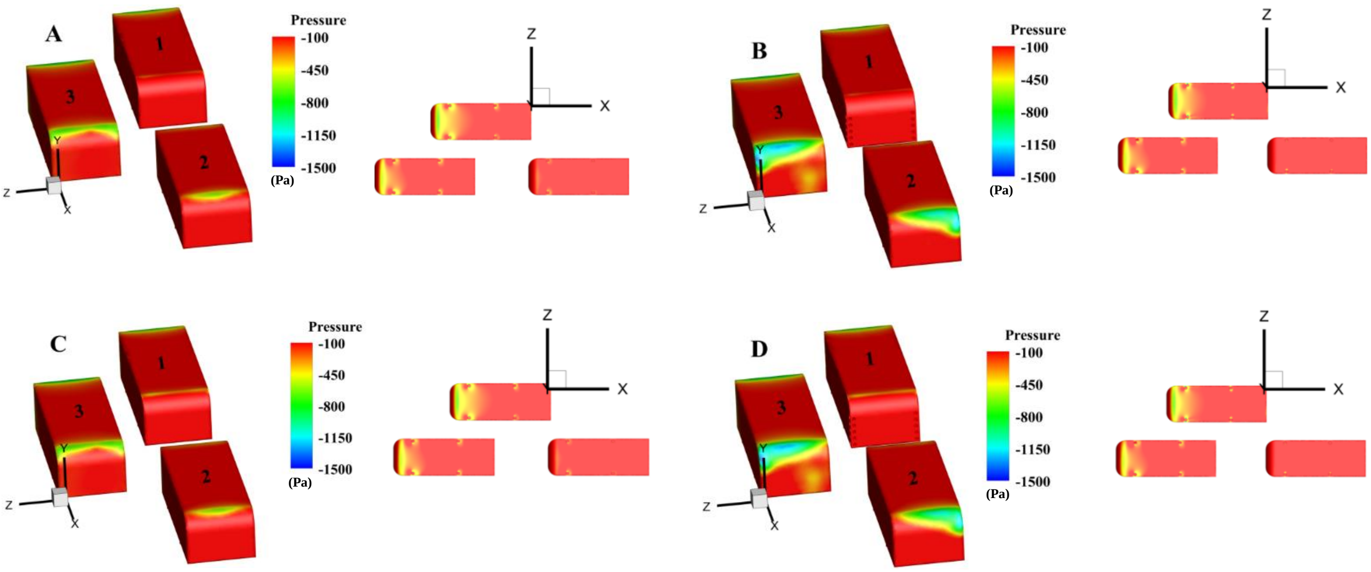


Fig 7. Surface pressure distribution focused at the rear part of the vehicles for the mode 3-Phase A. A), Clean B), RLTs C), SDBD actuator D), Combination of RLTs with SDBD actuator

Considering the noticeable effect of the RLTs on the drag and lift force of the controlled car and also surrounding cars, the overtaking phases of this type of passive flow control could be important to perceive the underlying physics behind these observations. So, the next section is allocated to the four different phases (A-D) of the overtaking modes.

Overtaking phases results

Due to the interesting similarity of the results related to the overtaking phases of modes 2 and 3, this section will be explained based on two modes 2 and 3. The different phases for the overtaking including modes 2-3 represented in the velocity magnitude contours of Figs 8, and 10. It should be noted that illustrating the shape of the wakes and comparing them at different phases are the main aim of these two figures. The aerodynamic force coefficients are also presented in Figs 9, and 11 for all models and phases.

The target phases for this work are the main four different phases described previously (A-D), but there are also some other interesting phases described in the literature, and we will rely on those observations for the sake of brevity. For instance, before phase A when the front part of the overtaking vehicle approaches the rear of the overtaken vehicle, the vehicles repel each other due to the development of a jet flow derived from interactions of the front and rear parts of the moving and fixed vehicles, respectively. Based on Fig 6, the maximum side pressure is in these regions. As discussed before, the positive side force has the maximum amount till phase B due to the Venturi effect between the cars [4]. Based on the drag and lift force results presented in Fig. 9, the tolerated drag and lift force on the overtaking car increases from Phase A to C and then decreases toward phase D in contrast to the overtaken car. Overall, we could say that deviation of the wake due to the suction of the other car leads to the increase in lift and drag force and vice versa.

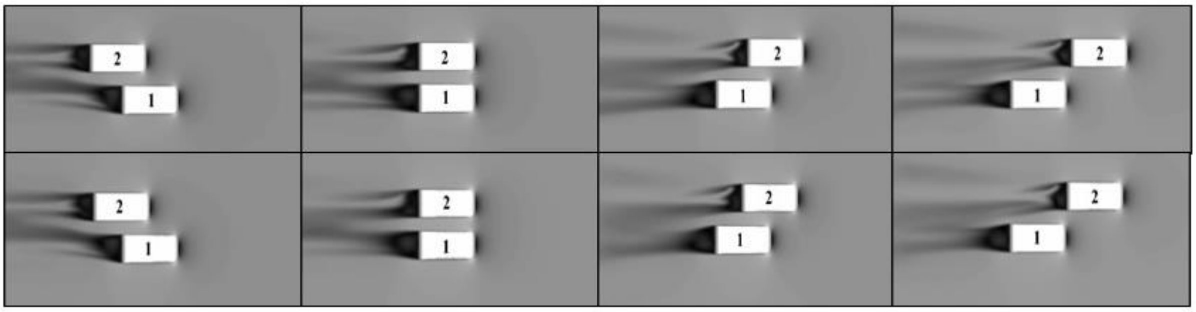


Fig 8. Velocity contour on the overtaking mode (flow direction: right to left) 2. Up), Clean Down), Passive flow control (RLTs).

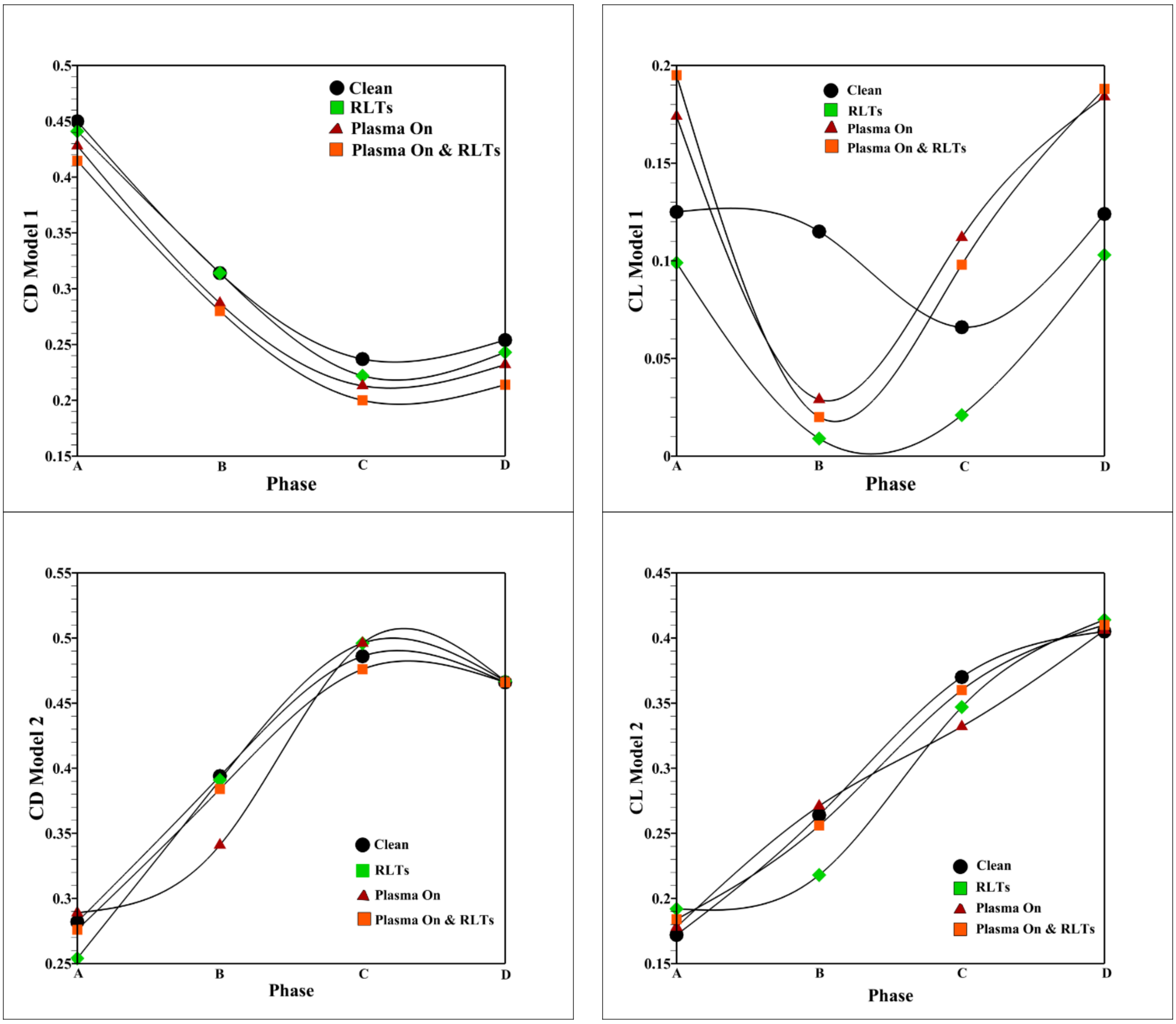


Fig 9. Aerodynamics force coefficients of cars based on overtaking car location for mode 2, Left: Drag coefficient, Right: Lift coefficients

According to the suction and blowing mechanism of RLTs [6], an increase in the drag force of the surrounding cars can be observed when the wake of the surrounding cars is located upstream of the RLTs. This observation is due to additional suction of the rear linking tunnels from the wake of the surrounding cars leading to the wake deviation and increase in drag forces.

On the other hand, when the wake of the surrounding cars is located downstream of RLTs, the increase of momentum due to the blowing effect of the RLTs inside the wake of the controlled model could produce extra momentum even for the downstream ones and this is the main logic behind the drag reduction of the surrounding cars by the passive control on the controlled car.

In mode 3, the drag force is the minimum value between all the modes due to the presence of the fixed car quite close to the rear part of the controlled car (half of the car length distance) which suppress the wake zone of the controlled car increasing the pressure at the rear part of the car and therefore reducing the drag force.

The trend of drag and lift force modification in different phases for this mode with and without RLTs is almost the same as mode 2 with minor differences related to the presence of the additional fixed car near the wake zone of the controlled car which can be perceived by comparing Figs 9 and 11. This issue leads to the presence of a smaller wake zone for the controlled car as the suction source for deviation of the surrounding cars' wake as can be seen in Fig 10. Overall, we could say that the deviation of the wakes and therefore drag and lift forces due to the blowing and suction effects of the RLTs are less noticeable compared to mode 2.

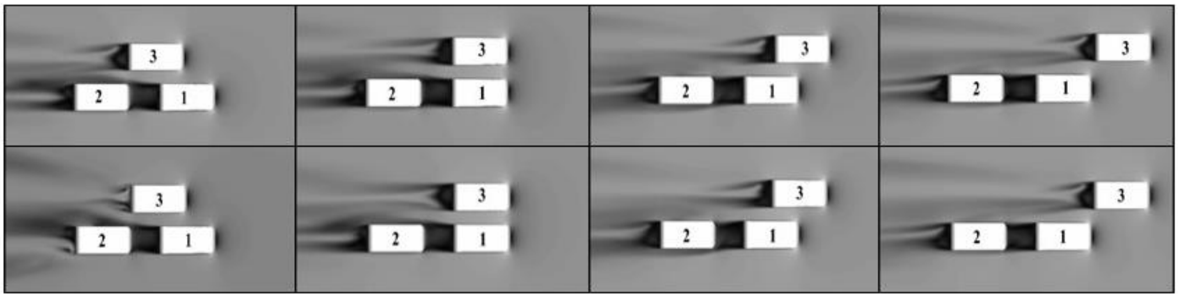
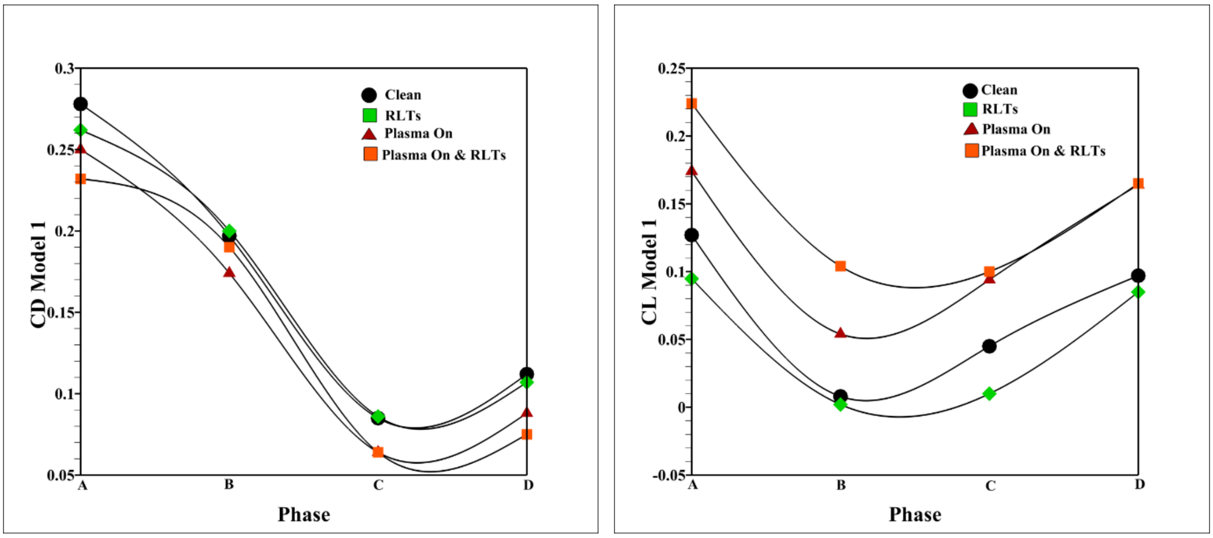


Fig 10. Velocity contour on the overtaking mode 3 (flow direction: right to left). Up) Clean, Down) Passive flow control (RLTs)



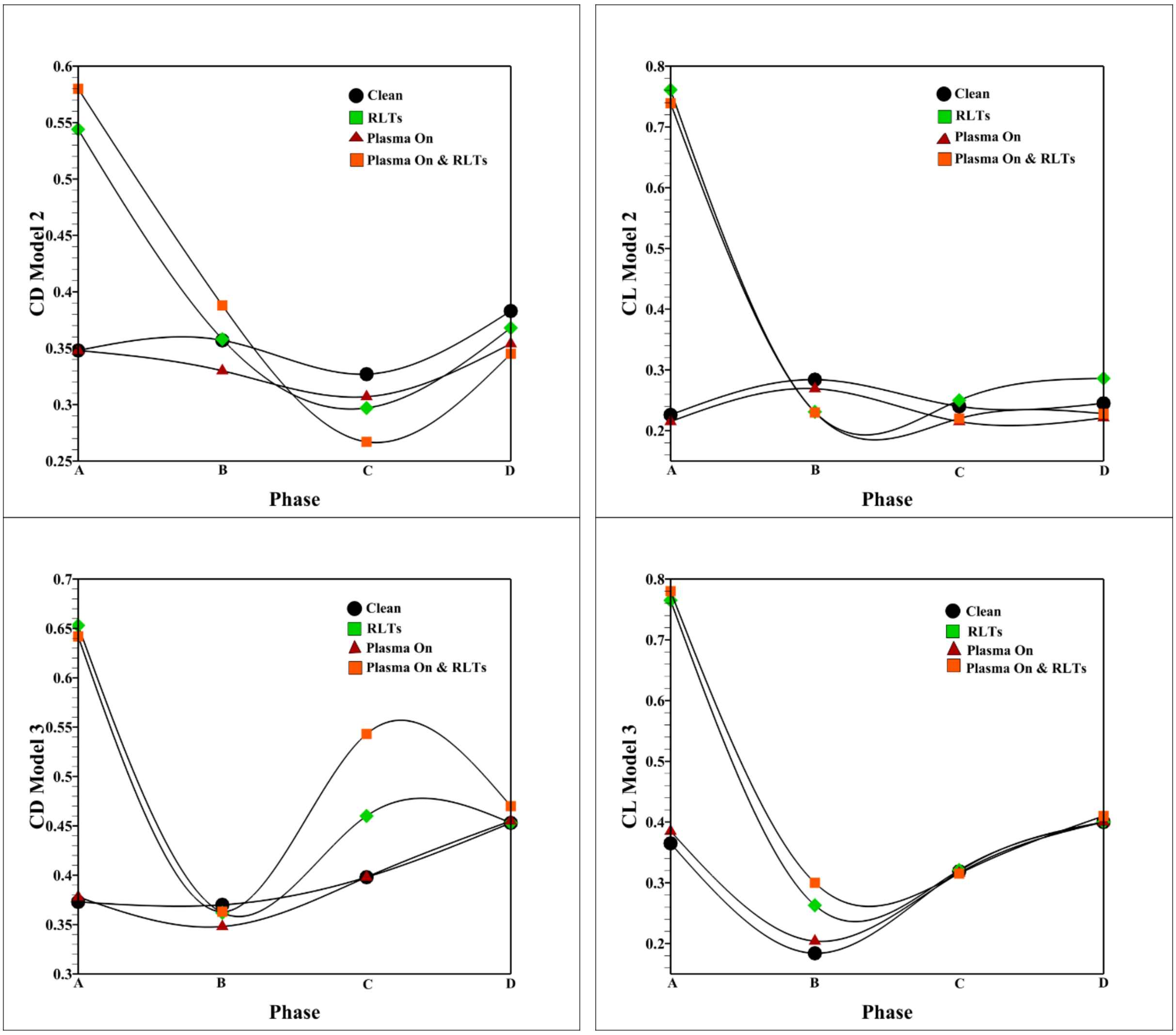


Fig 11. Aerodynamics force coefficients of cars based on manoeuvring car location for mode 3, Left: Drag coefficient, Right: Lift coefficients

Conclusion

This study aimed to investigate the interaction of the flow fields of several vehicles in real highway condition and tried to analyse the effect of passive, active, and combined flow control methods in this condition. The main goal is to look at the flow control techniques from another point of view and see the side effects of the flow control over other surrounding cars rather than just considering the effects on the main controlled car.

In this research study, 20 different case studies (5 motion modes and 4 phases per mode) with 4 specific conditions (clean, passive, active, and a combination of passive and active flow control) have been investigated. Some of them are reported in this paper and the remaining are under study for future works.

Based on the numerical simulation results in this study, several interesting results were reported which can give us valuable insights regarding the application of different flow control techniques in real road conditions. For example, in one specific case study (mode3), the effect of the passive flow control on the surrounding cars is huge in terms of increasing the lift and drag force for other cars while reducing those forces for the main controlled car. An increase of 3.3 and 2.09 times of the clean case in lift force for the fixed and overtaking cars were reported due to the passive flow control on the main car. There is the same negative effect on the drag force (56% and 75% increase in drag for fixed and overtaking cars respectively).

As a conclusion for the RLTs effect on the real road condition scenario, their effect on the controlled car could be only in favor of the controlled car in terms of drag reduction and lift reduction while having a huge negative effect on the surrounding cars. It should be noted that the above claim is related to one of the specific modes and could not be considered as a general rule for all the cases. Other cases and modes need to be investigated further.

There are also some other interesting observations regarding the effect of the RLTs when considering the wake location of the surrounding cars. Due to the different physical behavior of the SDBD compared to the RLTs, the obtained results show the negative effect of the SDBD actuators for the lift of all the cars in most of the phases with a higher effect on the controlled car while having a positive effect on the drag reduction of the controlled car without interesting effects on the drag force of the surrounding cars.

Finally, the combined effect of the passive and active flow control for the target mode and phase reported in this paper is in favor of drag reduction for the controlled model with considerable negative effects on the drag force of the other cars. The negative effect of the SDBD actuators could overcome the positive effects of the RLTs in terms of lift force reduction, therefore, the lift force for all the cars including the controlled car will increase by having combined active and passive flow control in the majority of phases.

There are several interesting future works regarding the effect of passive and active flow control on downforce for high-speed cars which are getting attractive, especially from the safety point of view. We are already working on analyzing the other modes and phases of maneuvering for this case study which are more related to this safety concern and will be published in near future.

References

[1] R. Mccallen, K. Salari, J. Ortega and L. DeChant, "DOE's Effort to Reduce Truck Aerodynamic Drag-Joint Experiments and Computations Lead to Smart Design," in *AIAA Fluid Dynamics Conference*, Portland, OR, United States, 2004, DOI: 10.2514/6.2004-2249.

[2] B. McAuliffe, M. Lammert, X.-Y. L. a. S. Shladove, M.-D. Surcel and A. Kailas, "Influences on Energy Savings of Heavy Trucks Using Cooperative Adaptive Cruise Control," *SAE International; National Renewable Energy Laboratory,* 2018, Doi:10.4271/2018-01-1181.

[3] D. Uystepruyst and S. Krajnovic, "Numerical simulation of the transient aerodynamic phenomena induced by passing manoeuvres," *HAL,* 2014, Doi:10.1016/j.jweia.2012.12.018 .

[4] C. Noger and E. V. Grevenynghe, "On the transient aerodynamic forces induced on heavy and light vehicles in overtaking processes," *Int. J. Aerodynamics,* 2011, Doi:10.1504/IJAD.2011.038851.

[5] B. Khalighi, J. Ho, J. Cooney, B. Neiswander and T. Han, "Aerodynamic Drag Reduction Investigation for a Simplified Road Vehicle Using Plasma Flow Control," *ASME,* 2016, DOI: 10.1115/FEDSM2016-7927.

[6] B. Mohammadikalakoo, P. Schito and M. Mani, "Passive flow control on Ahmed body by rear linking tunnels," *Journal of Wind Engineering & Industrial Aerodynamics,* 2020, Doi.org/10.1016/j.jweia.2020.104330.

[7] M. Metka and J. W. Gregory, "Drag reduction on the 25-deg Ahmed model Using Fluidic Oscillators," *JOURNAL OF FLUIDS ENGINEERING,* 2015, DOI: 10.1115/1.4029535.

[8] S. Karimi, A. Zargar, A. Hemmati and M. Mani, "The Effect of Single Dielectric Barrier Discharge Actuators in Reducing Drag on an Ahmed Body," *Fluids,* 2020, Doi:10.3390/fluids5040244.

[9] M. Matthew, "FLOW CONTROL ON THE AHMED BODY VEHICLE MODEL USING FLUIDIC OSCILLATORS," *IMECE2013*, 2013, Doi:10.1115/IMECE2013-67343 .

[10] T. Heinemann, M. Springer, H. Lienhart, S. Kniesburges and S. Becker, "Active Flow Control on a 1:4 Car Model," *Experiments in Fluids,* 2014, Doi:10.1007/s00348-014-1738-0.

[11] S. Karimi, B. Mohammadikalakoo and P. Schito, "Performance enhancement of single dielectric barrier discharge flow control actuators by means of rear linking tunnels on a reference bluff body using CFD," *Journal of Wind Engineering & Industrial Aerodynamics,* 2020, Doi.org/10.1016/j.jweia.2020.104488.

[12] M. Hassaan, D. Badlani and M. Nazarinia, "On the effect of boat-tails on a simplified heavy vehicle geometry under crosswinds," *Journal of Wind Engineering & Industrial Aerodynamics,* 2018, Doi.org/10.1016/j.jweia.2018.10.013.

[13] Ahmed, S., Ramm, G., and Faltin, G., "Some Salient Features Of The Time-Averaged Ground Vehicle Wake," *SAE Technical Paper,* 840300, 1984, https://doi.org/10.4271/840300.