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A CFD Study Investigating Drag Reduction for Different Offset and Inline Distance for Two Trucks Platooning

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Abstract: The automotive industry invests huge resources to improve fuel consumption of commercial vehicles by improving their aerodynamic efficiency. Recently, numerous studies investigating the effect of platooning on aerodynamic drag of semi-trucks have been performed by researchers indicating a positive impact. For the present study, a three-dimensional computational study was performed to investigate the effect of varying offset and linear distance during platooning on the total drag of two semi-trucks. The study was conducted on a full-scale model using Reynold's Averaged Navier-Strokes governing equations for a moving ground simulation using the STAR-CCM+ computational package. Furthermore, for turbulence, the standard *k-ω* SST turbulence model was used for a constant free stream velocity of 70 mph. A baseline study on a full-scale model of a single semi-truck was conducted to compare the results from platooning. Initial findings showed that the inline platooning situation was optimal for drag reduction. However, drag reduction varied with varying offset distances. Drag reduction decreased as the offset distance increased.

Key words: CFD, platooning, drag reduction, trucks aerodynamics.

1. Introduction

In recent years, the increasing threat of global warming due to greenhouse gases has asserted the need of energy efficient vehicles more than ever. Huge investments are being made by manufacturers, universities and governing agencies into developing technologies to improve the fuel efficiency of automobiles around the world. The commercial vehicle sector such as the semi-truck has always emphasized the achievement of higher fuel-efficient vehicles throughout these years. As a result of constant research and development, modern semi-trucks have higher fuel efficiency than ever before. However, due to stricter environmental regulations and increasing threat of climate change, there is a need to improve the fuel efficiency of these vehicles even more. Aerodynamic resistance plays an important role along with mechanical resistance like rolling resistance between road and tires [1].

Over the years a lot of research has been conducted to improve the fuel efficiency of trailer semi-truck by reducing the aerodynamic drag by using various tools and techniques such as trailer caps, side skirts, boat tails and many more [1-5]. It has been reported that for every 2% reduction in drag there is a corresponding 1% reduction in fuel consumption [6]. Most of the research has been performed with speed of 60 mph and over as the aerodynamic resistance becomes dominant over 55 mph [6] which is usually the operating speed for semi-trucks. One such study was performed by Landman [6], where the effect of using a cap on a semi-truck to improve the fuel efficiency by decreasing the aerodynamic drag was studied for a zero degree and 9 degrees crosswind at highway speeds. In the study, the effect of cap on aerodynamic drag was studied with the help of three cases: a baseline case with no aerodynamic devices, with cap at zero crosswind and with cap at a 9-degree crosswind. It was established that there is no significant reduction in drag by using the cap in zero-degree crosswind however, when used in 9-degree crosswind there is a significant reduction in

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drag thus improving fuel consumption.

As mentioned earlier, huge investments are being made in developing newer technologies to improve fuel efficiency of semi-truck. One such technology being prominently researched is platooning. In platooning two or more automated semi-trucks follow each other at set distances apart with the trailing truck(s) operating in the lead truck's slipstream leading to reduced drag and improved fuel efficiency. Extensive studies, largely experimentally-based, were reported by Browand and others starting in the 1990's [7, 8]. Results suggested significant fuel savings, but the technology required to safely implement platooning on the road was perhaps lacking. Recent developments in computer-assisted and driverless vehicle technology have revived interest in platooning.

One more recent study was conducted under a national ITS (Intelligent Transport Systems) program named "Energy ITS" [9] in 2008 which aimed at reducing the impact of global warming. In the study, a platoon of three light trucks operating at a distance of 4 m and at speed of 80 kph was studied to determine the energy efficiency. It was stated that fuel consumption can be reduced by about 13% when the gap was 10 m and the evaluation simulation showed that the effectiveness of the platooning with the gap of 10 m when the 40% fleet penetration in heavy trucks was a 2.1% reduction of CO_2. Another similar computational study was conducted where the aerodynamic drag for two driver assist trucks was studied [10]. The distance between trucks used was varied from 0 feet to 100 feet for the study along with lateral offsets and crosswinds. The results from computational simulation were compared with experimental study and it was found that the drag decreases monotonically with reduction on distances between trucks. Furthermore, the results for lateral offsets suggest a significant reduction in drag for the follower truck while no considerable change for lead truck. Also, the crosswind had an adverse effect on the drag for both trucks. Additionally, similar computational study was performed on multiple trucks in platoon [11] and it was found that for smaller distances both trucks experience a reduction in drag and as the distance is increased, the drag reduction reaches a stagnation point. A similar effect on drag for two trucks in platoon for straight, lateral offset and in yaw was found in another computational study [12, 13].

This study looks to observe the effect of offset distance for a leading and following truck at different follow distances. By isolating the two parameters, the study hopes to provide a direct characterization of drag reduction as a function of offset and follow distance. The three follow distances were 30, 40, and 50 ft. Two offset distances of 1 and 2 ft were run with a benchmark 0 ft offset inline case.

2. Main Section

2.1 Numerical Procedure

2.1.1 Numeric and Geometric Model

A computational fluid dynamics analysis of two automated trucks operating in a platoon was carried out using the computational package Star-CCM+ developed by CD Adapco. Star-CCM+ solves the 3-dimensional Reynolds-Averaged Navier-Stokes equations to model the flow field. The geometries were created using existing models from the Grand Valley State University Computational Fluid Dynamics research group.

Fig. 1 shows an overview of the semi-truck geometry. The geometries were created in SolidWorks 2016 and imported into Star CCM+. Follow distance was measured from the rear doors of the trailer on the

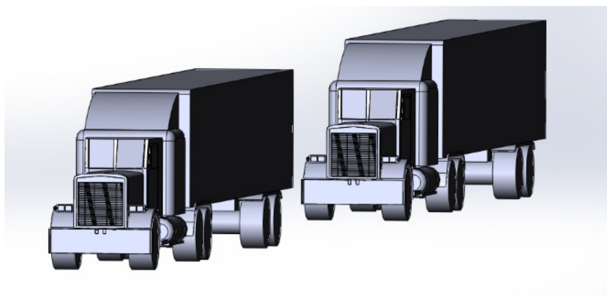

Fig. 1 CAD model of semi-truck geometry used.

front truck to the front bumper surface of the rear truck. When the trucks were satisfactorily placed with respect to each other, complex geometries such as the grill/radiator surfaces were removed. After the geometry was simplified, the fluid volume was generated. The fluid volume length was calculated as 10 times the length from the front bumper of the lead truck to the rear doors of the rear trailer. The height and width of the domain were generated as 10 times the height and width of a single truck cab. The vehicles were centered in the volume and then imported into Star CCM+.

2.1.2 Meshing

The mesh generation was an iterative process starting with a trimmer mesher utilizing hexahedral elements. The resulting meshes produced either unstable simulations terminating in floating point error or oscillating convergence that would not yield a stable solution.

The second major tactic in meshing was using polyhedral meshing. This allowed fewer volumes necessary to produce a stable solution. The mesh settings were kept consistent throughout the test cases. The range of cells in the 9 cases run was 5.6 to 11.2 million cells.

Prism layering on the trucks and ground was utilized to capture flow velocities near the front surfaces of the vehicles. This allowed for capture of flow structure information related to drag.

The volume mesh on the lead truck surface is shown in Fig. 2. The polyhedral mesh proved to be the more consistent meshing regime for this study. The prism layer mesher was modified to adapt to the sharp curvature of the trucks.

The volumetric mesh controls, seen in Fig. 3, were used to cluster the meshing near the trucks and allow coarsening of the mesh at additional places in the domain.

Fig. 4 shows how the far field meshing was coarsened to accommodate the much more refined areas in front, between, and behind the vehicle tandem.

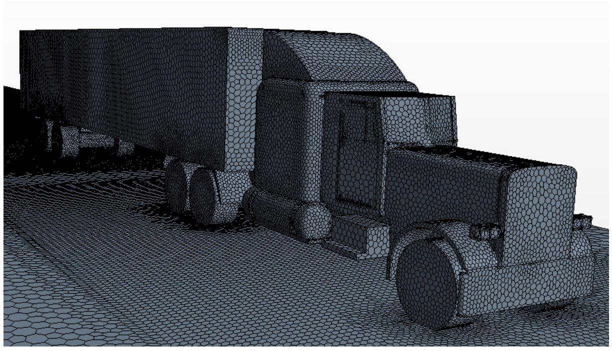

Fig. 2 Volume mesh on lead truck surface.

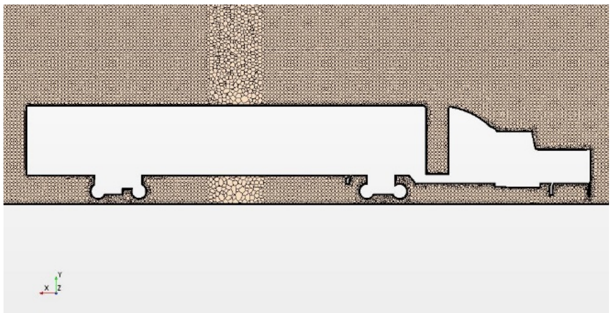

Fig. 3 Front truck mesh profile showing the prism layer clustering.

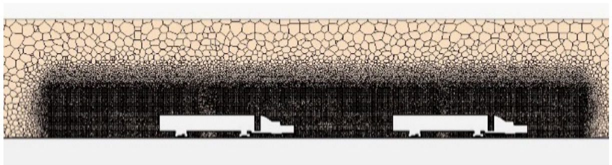

Fig. 4 Overview of the volume domain close to the trucks showing the three instances of the volumetric controls for mesh refinement.

2.1.3 Physics Settings and Boundary Conditions

A 3-dimensional steady state study was performed for each of the cases. Air was modelled as an ideal gas. The segregated isothermal flow regime was used to model the fluid. The fluid domain was used as a free stream set to 70 mph in the x direction, from front to rear with respect to the vehicles. The ground was set to have a tangential velocity of 70 mph in the x direction so as to not create non-realistic flow conditions in the domain. Turbulence was modeled using the k-omega SST Mentor turbulence model, combining the k-epsilon and k-omega models using binary function to avoid discontinuities that each produces.

Cell quality remediation was used to limit the numeric effect of any mesh based discontinuities. Each case was iterated out to two thousand iterations, while the convergence of the residuals and the C_D of each truck were monitored throughout the simulation.

The velocity results around the front truck raised some questions. High pressures at the front of the lead truck with an oscillating low velocity wake following the trailer followed conventional thought. However, asymmetry regarding the velocity surrounding the trailer was a source of concern. Further investigation revealed a geometric asymmetry. The tractor geometry was not centered with the trailer. Fig. 5 shows the asymmetric behavior of the velocity field around the lead truck. Because the asymmetry was consistent with all the cases the study was continued with the issue in-place.

The vertical plane velocity scalar showed a conventional wake surrounding the lead truck. The velocity field in a vertical plane bisecting the lead truck can be viewed in Fig. 6. The vertical field shows the stagnation at the front of the lead truck, wake generation behind the trailer, and when the 30 ft follow distance cases were observed the velocity scalars showed how the frontal blocking area of the truck pair changed with the offset distance increase.

Fig. 7 shows the follow truck in an area of lower velocity air, which contributed to lower stagnation pressures in the lower offset configurations.

At an offset distance of 1 ft, see Fig. 8, the wake of the lead truck moved to allow high speed air in to begin to stagnate at the front of the follow truck.

Fig. 9 shows how significant the offset distance becomes with respect to the speed of air allowed to

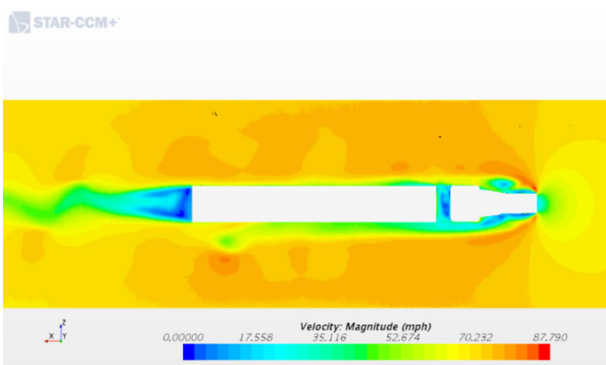

Fig. 5 Horizontal section plane showing velocity around the lead truck.

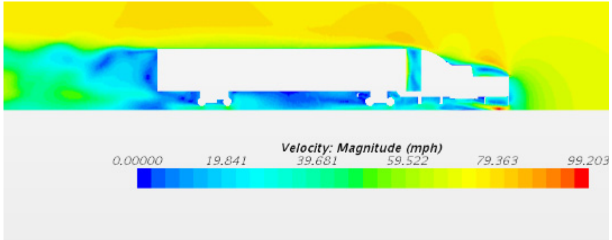

Fig. 6 Vertical section plane showing velocity surrounding the lead truck.

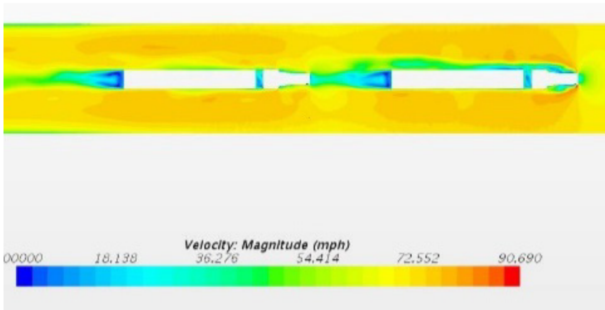

Fig. 7 30 ft follow, 0 ft offset, horizontal velocity plane.

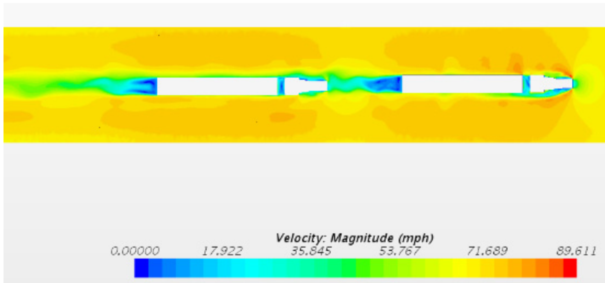

Fig. 8 30 ft follow, 1 ft offset, velocity scalar.

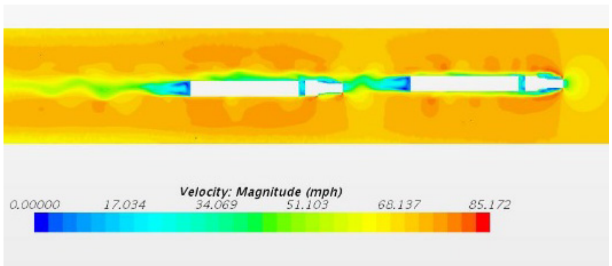

Fig. 9 30 ft follow, 2 ft offset velocity scalar.

stagnate on the follow truck. Figs. 7-9 show how as the truck offsets to the right of the lead truck, and a stagnation point develops on the leading right corner of the tractor. This would lead to an increase in drag on the following truck. The stagnation effect can be seen in the pressure scalars on the offset cases as well.

Fig. 10 shows the increased stagnation on the right-hand side of the follow truck, whereas Fig. 11 shows the inline case pressure scalar.

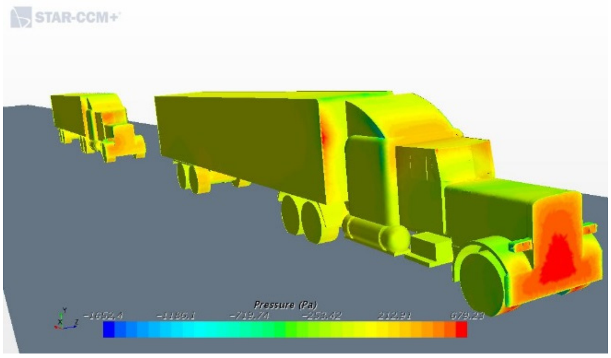

Fig. 10 30 ft follow, 2 ft offset pressure scalar on truck pair.

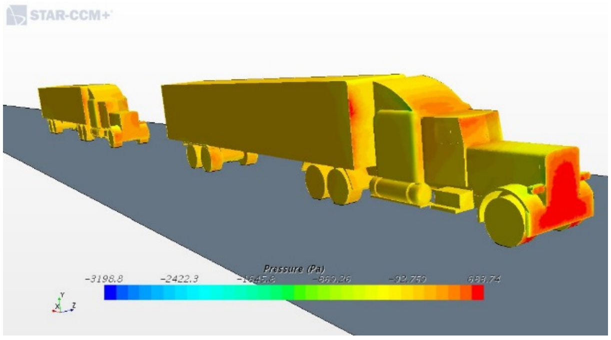

Fig. 11 30 ft inline case pressure scalar on truck pair.

Fig. 11 shows the inline case and a more homogeneous pressure distribution on the leading faces of the following truck. To elaborate further on the effects of the offset on the stagnation pressure of the rear truck the 30 ft case was analyzed further. The pressure contours on the rear truck reveal that as the offset distance increased so did the increase in the maximum pressure on the rear truck.

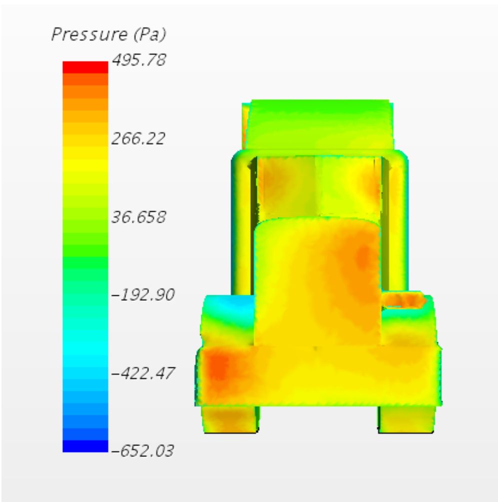

Fig. 12 30 ft follow, 0 ft offset, pressure contour.

Fig. 12 shows the pressure contour on the follow truck in the 30 ft follow and 0 ft offset configuration. While the major areas of pressure appear to be on the front bumper/grill assembly of the follow truck, the maximum value of the pressure is significantly lower than that of the 30 ft follow and 1 ft offset pressure values, as seen in Fig. 13.

The increase in maximum pressure was non-linear. From 0 ft to 1 ft offset distance at 30 ft separation there was a 1% increase in maximum pressure on the rear truck. From 1 ft to 2 ft offset distance at 30 ft there was a 15% increase in maximum pressure on the rear truck, see Fig. 14. This arguably exponential effect of pressure increase as a function of offset distance draws attention to the importance of centering the vehicles during platooning.

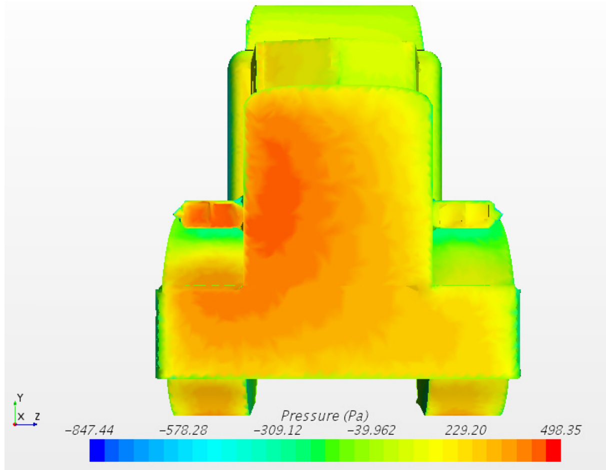

Fig. 13 30 ft follow, 1 ft offset, pressure contour.

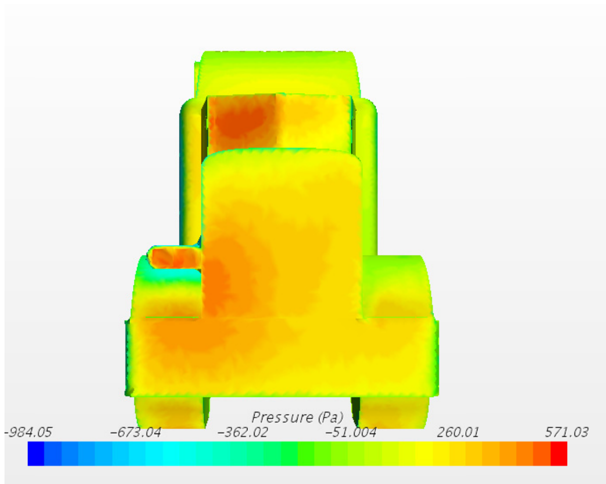

Fig. 14 30 ft follow, 2 ft offset, pressure contour.

The differing pressure contours on the follow truck are directly related to how the wake of the lead truck interacts with the rear truck. Figs. 15-17 show the velocity vector field between the lead truck and rear truck.

Fig. 15 shows how the lead truck wake influenced the velocity profile on the front of the follow truck. The lower velocity air stagnating across the entirety of the follow truck is the major goal of the platooning strategy. Fig. 16 shows how the wake oscillations bring higher velocity air in contact with the follow truck and Fig. 17 highlights how the amplitude of wake oscillations can affect the amount of high speed air involved.

Regarding the three cases shown above, the closer the high velocity flow is to the rear truck the higher the stagnation pressure. As the blocking effect of the front truck is reduced due to the increased offset distance, the average velocity of flow in front of the rear truck increases. Furthermore, the offset leads to less wake-meshing between the trucks and increased turbulence in the wake. This is seen in the 1 ft and 2 ft offset cases where an oscillation in the wake is more pronounced relative to the inline case.

Regarding the degradation of the wake, when a 35 mph isosurface is imposed on the volume, the reduction in blocking effect is shown. Fig. 18 is the ideal case

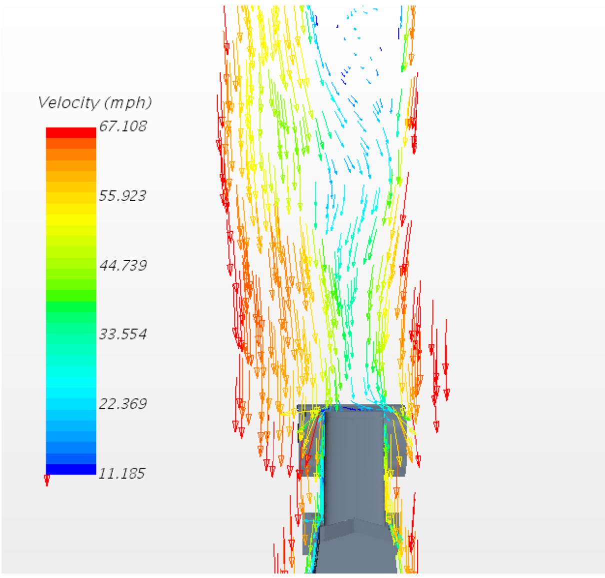

Fig. 15 30 ft follow, 0 ft offset, wake velocity vector field.

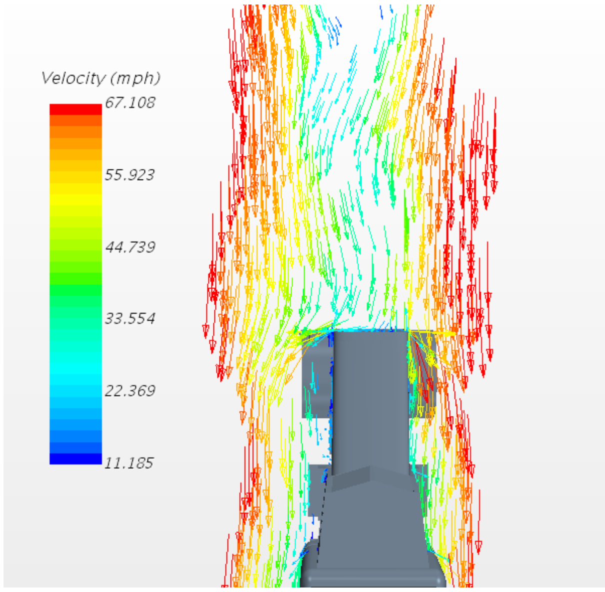

Fig. 16 30 ft follow, 1 ft offset, wake velocity vector field.

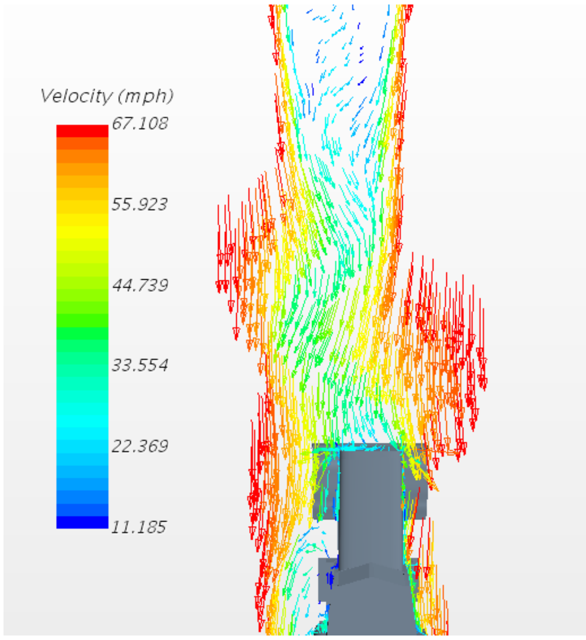

Fig. 17 30 ft follow, 2 ft offset, wake velocity vector field.

showing almost complete coverage of the follow truck by the 35 mph isosurface.

Moving from 0 to 1 ft offset the major change was that the front edge of the follow truck was now exposed to air of velocities above 35 mph, see Fig. 19.

Fig. 20, showing the isosurface for the 30 ft follow and 2 ft offset configuration, shows how far back the 35 mph isosurface had degraded. Furthermore, a more significant portion of the follow truck cab is exposed

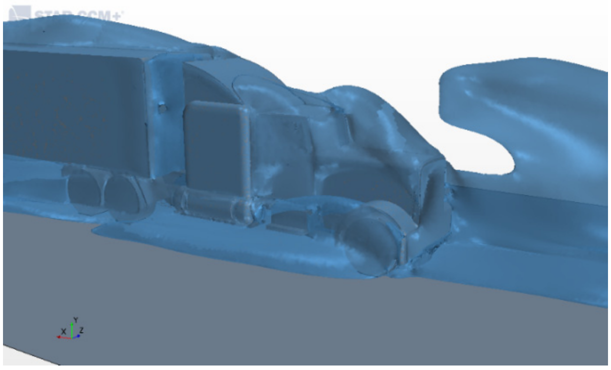

Fig. 18 30 ft follow, 0 ft offset, 35 mph isosurface.

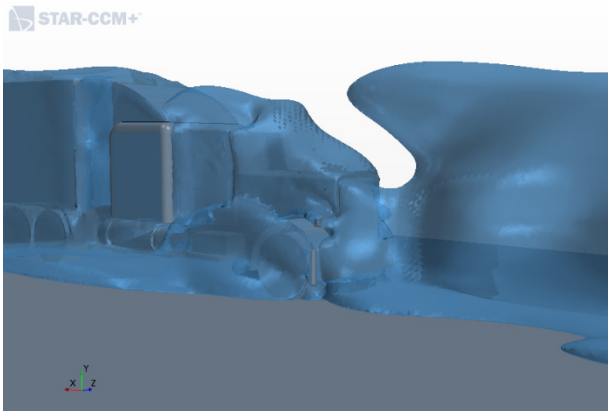

Fig. 19 30 ft follow, 1 ft offset, 35 mph isosurface.

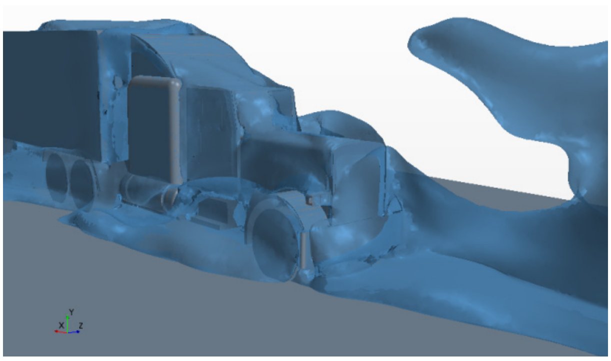

Fig. 20 30 ft follow, 2 ft offset, 35 mph isosurface.

from the isosurface. As the offset distance increases the surface moves closer to the rear truck and wake provides less blocking for the rear truck. Furthermore, the slower moving air from the lead truck is further removed from the rear truck showing increased velocity closer to the rear of the lead truck. That increased velocity is proportional to a decrease in pressure. That volume of reduced pressure behind the lead truck creates a larger drag force on the lead truck as the pressure differential in front and behind the truck

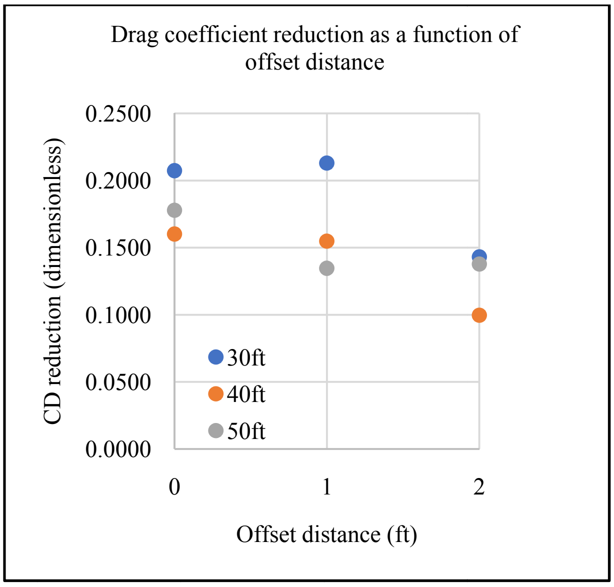

Fig. 21 Drag values plotted as a function of offset distance.

is increased. Therefore, the presence of a rear truck behind the lead truck can decrease the drag for the pair, not just the rear truck.

Unfortunately, the quantitative analysis did not match the qualitative analysis at the completion of this set of simulations.

Fig. 21 shows how the drag values plotted as a function of the two major parameters. As the residuals were converging, the residuals had not reached low enough values to yield accurate drag values. The drag values generally trend downward as offset distance increases, thus following the expected trends of the study.

3. Conclusion

The simulations showed that centering of a vehicle pair in platoon is of the utmost importance. The exponential relationship of maximum stagnation pressure on the rear truck as a function of offset distance relative to the front truck implies this is a critical parameter. Furthermore, the increase in wake degradation between the trucks as offset distance increases shows how stagnation pressure increases for the rear truck, and how the pressure decreases behind the lead truck. This shows how drag reduction can be achieved for both vehicles, rather than just a following truck.

Further study is necessary to create an empirical relationship between maximum rear truck stagnation pressure and offset distance; however, a qualitative understanding has been shown in this study.

Simulations are being iterated further. It is believed that the increased convergence would correct the drag values to acceptable levels of accuracy to characterize the increase in drag coefficient as a function of offset distance. The existing data are promising, and further refinement is already underway.

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