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Platooning for Improved Safety and Efficiency of Semi-trucks [PISES]

PI: Venkatasubramanian Viswanathan

https://orcid.org/0000-0003-1060-5495

Students: Varun Shankar, Shashank Sripad

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PI: **Venkatasubramanian Viswanathan**
Students: Varun Shankar, Shashank Sripad

Department of Mechanical Engineering,
Carnegie Mellon University, Pittsburgh, Pennsylvania, 15213, U.S.A.

Abstract

With inexpensive sensor technologies and integrated control systems becoming widespread in the automotive industry, platooning has emerged as a viable method for reducing fuel and energy consumption of vehicles, particularly within the heavy-duty trucking sector. In this report, we computationally analyzed the effect of platooning on semi-trucks with regards to aerodynamic drag using computational fluid dynamics. We examined two-truck platoons at various spacing intervals to pinpoint reductions in drag for each truck in the platoon relative to the baseline single truck. Two turbulence models, Reynolds Averaged Navier Stokes (RANS) and Detached Eddy Simulation (DES), provided mean relative drag reductions from 20% to 35% for spacings of 1.0-0.15 vehicle lengths. The lead truck saw reductions of up to 15% with RANS and 25% with DES, while the trail truck saw reductions of up to 60% with RANS and 45% with DES. Based on the proportion of aerodynamic drag to total power, strategic platooning could result in total energy savings of 20%.

Introduction

Electrification of the transportation sector is a rapidly growing field in both research and industry, as concerns over the environmental impact of current fossil-fuel usage rise each year. Transportation accounts for the largest contribution to US greenhouse gas emissions by sector at 29% of total emissions. Within transportation, medium- and heavy-duty trucks contribute to 23% of transportation emissions.[1] As such, the interest in reducing emissions through electrification and other fuel-saving measures is at an all-time high.

Platooning of semi-trucks has been highlighted as a key component to reducing transportation costs and emissions. At highway speeds, the aerodynamic drag forces on a heavy-duty truck can consume 60-70% of total brake power.[2] Improvements in the drag of these large vehicles can have a massive impact on energy consumption of the vehicle. While newer generations of truck cabs are being designed with more care taken toward vehicle aerodynamics,[3] platooning is a method of reducing drag any truck on the road can exploit. In a platoon, trucks drive directly behind one another, benefiting aerodynamically from driving in the anterior trucks wake. Less drag leads to diminished energy requirements, reduced fuel consumption in diesel trucks, and more viable, longer range electric trucks.[4]

In the process of implementing these technologies, we aim to understand the impact they will have, particularly revolving around the aerodynamics, safety, and operations of electric and diesel trucks and platoons. Using our high-performance computational infrastructure, we have set up high-fidelity computational fluid dynamics models to simulate the aerodynamics of platooning. These models were built using the ANSYS Fluent software package, and performance benchmarked using standard simulations. Reductions in energy consumption were calculated and validated using data from full-scale platoon tests, and results extrapolated to suggest ideal strategies.

Methods

Using a standard force balance, the instantaneous power requirement for a vehicle in motion is given by Eq. 1.

$$P = (\frac{1}{2}\rho C_D A v^3 + C_{rr} mgv + t_f mgvZ) \cdot \frac{1}{\eta_{bw}} + ma^+ v \cdot \frac{1}{\eta_{bw}} + ma^- v \cdot \eta_{bw}\eta_{brk} \tag{1}$$

The equation includes aerodynamic, rolling friction, road grade, and inertial terms, where the last term on the right is for regenerative braking in electric vehicles. η_{bw} is battery- or engine-wheels efficiency and η_{brk} is associated with regenerative braking efficiency.[5] Of particular interest is the aerodynamic term, $\frac{1}{2}\rho C_D A v^3$. ρ, the density of air, and A, the projected frontal area, are taken to be constant, so we specifically analyze the drag coefficient C_D using computational fluid dynamics (CFD).

CFD is a class of methods used to numerically solve the Navier-Stokes equations, the set of non-linear, partial differential equations that describe fluid flow. The solution takes the form of a velocity vector field and scalar pressure field, used to calculate total force on an object. The equations for incompressible flow, given below, include a mass balance (Eq. 2) and a momentum balance (Eq. 3).

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = \frac{\mu}{\rho}\nabla^2 \mathbf{u} - \frac{1}{\rho}\nabla p + \mathbf{f} \tag{3}$$

The difficulty in finding a solution lies in the nature of the advective term in the momentum balance, $(\mathbf{u} \cdot \nabla)\mathbf{u}$, which tends to evolve large and unpredictable fluctuations, i.e. turbulence. There are a number of different models used to predict turbulence, each with varying degrees of assumptions, complexity, and computational cost. In this study, we employ two turbulence models: Reynolds Averaged Navier Stokes (RANS) and Detached Eddy Simulation (DES).[678]

In the steady-state RANS formulation, instantaneous variables are rewritten in their Reynolds decomposition, which contains an average term (overbar) and a fluctuating term (prime):

$$u_i = \overline{u_i} + u_i'$$

Plugging in to the momentum equation:

$$\rho\left[\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right]=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}$$
$$\rho\left[\frac{\partial(\overline{u_i}+u_i')}{\partial t}+(\overline{u_j}+u_j')\frac{\partial(\overline{u_i}+u_i')}{\partial x_j}\right]=-\frac{\partial(\overline{p}+p')}{\partial x_i}+\frac{\partial(\overline{\tau_{ij}}+\tau_{ij}')}{\partial x_j}$$

and averaging:

$$\rho\left[\frac{\partial\overline{u_i}}{\partial t}+\overline{u_j}\frac{\partial\overline{u_i}}{\partial x_j}\right]=-\frac{\partial\overline{p}}{\partial x_i}+\frac{\partial\overline{\tau_{ij}}}{\partial x_j}-\rho\overline{u_j'\frac{\partial u_i'}{\partial x_j}}$$
$$\rho\left[\frac{\partial\overline{u_i}}{\partial t}+\overline{u_j}\frac{\partial\overline{u_i}}{\partial x_j}\right]=-\frac{\partial\overline{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\overline{\tau_{ij}}-\rho\overline{u_i'u_j'}\right)$$

The quantity $-\rho\overline{u_i'u_j'}$ is termed the Reynolds stress tensor. RANS methods close the problem using one or two more equations to model the Reynolds stress tensor. In particular, we use the two-equation realizable $k-\epsilon$ model, which relates the turbulent kinetic energy k and turbulent dissipation rate ϵ. RANS provides a relatively accurate averaged solution at a low computational cost.

The transient DES approach functions similarly to RANS, but results in much higher-fidelity solutions. DES is a hybrid approach to turbulence modeling and borrows from both RANS and Large Eddy Simulation (LES). In LES, instead of averaging the equations like RANS, the equations are filtered to remove the highest frequency fluctuations in both space and time. This results in directly resolving the larger scales of turbulence, while modeling the smallest scales. DES combines the two by using RANS close to the walls in the boundary layer and switching to LES further away. The computational cost here is much higher than RANS, but not quite as much as LES.[9]

Problem Setup

To estimate the drag coefficient of trucks in a platoon, we simulated steady flow over platoons at various spacing intervals and calculated the aerodynamic force on each truck. Additionally, a base single truck case was also simulated, and a relative drag coefficient obtained in order to minimize simulation error.

The computational domain consisted of the fluid around the truck(s), extending to a finite distance in the front, sides, rear, and top of the vehicle. The domain was also halved lengthwise with regards to the truck, given that the truck model used was symmetric. The boundary conditions are shown in Fig. 1, and the road was given a moving wall condition, also at 25 m/s. Lastly, the domain was discretized (Fig. 2) using tetrahedrons with a maximum 0.5 m cell size, refined to 0.1 m around the vehicles.

The truck model used was a relatively geometrically simplified cab-over style semi-truck. We performed RANS $k-\epsilon$ and DES simulations on a single truck, as well as two-truck platoons at

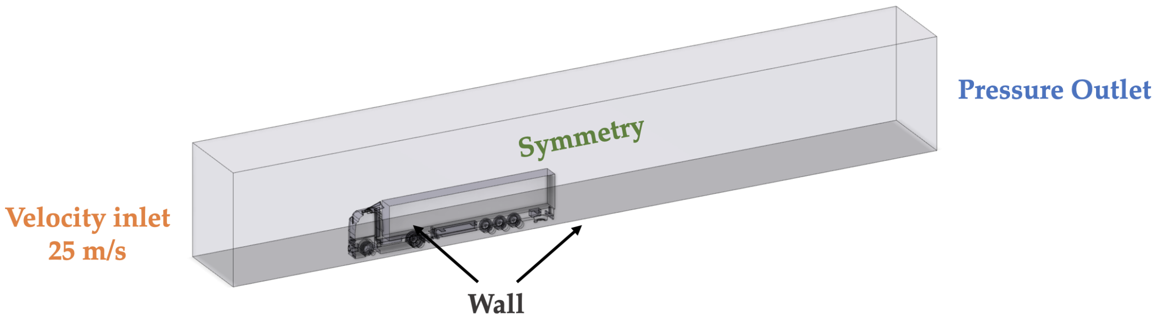

Figure 1: A schematic of the CFD model with a velocity inlet and pressure outlet boundary condition. The walls are shown, planar symmetry is employed and the road is a moving wall.

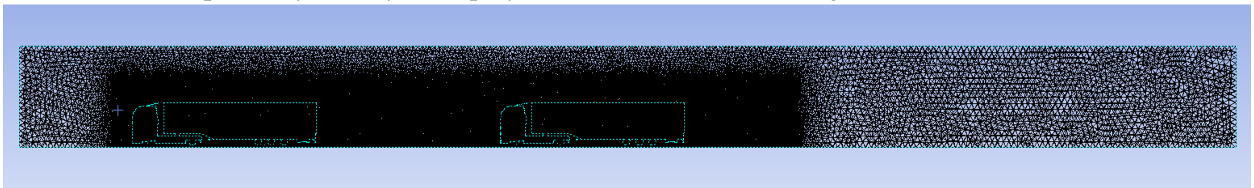

Figure 2: An example of the mesh used for a 2-truck platoon at 1 vehicle length distance. The meshing scheme is adaptive, tetrahedral with a maximum cell size of 0.5 m, refined to 0.1 m close to the vehicle.

spacing intervals of 1.0, 0.75, 0.5, 0.25, and 0.15 vehicle lengths. In our case, one vehicle length was 16.4 m. The ANSYS Fluent software package was used to perform the simulations on a parallelized computing architecture of 64-128 cores.

Results and Discussion

RANS and DES simulations of the base single truck case at 25 m/s resulted in drag coefficients of 0.57 and 0.62 respectively. These values were used to find relative drag coefficients of the two trucks in platoon simulations.

RANS and DES relative drag coefficient results as a function of vehicle spacing are shown in Fig. 3. Additionally, results are compared and validated with an experimental full-scale study with two similar semi-trucks.[10] We found that both leading and trailing trucks experienced reductions in drag, even at the largest spacing of 1.0 vehicle lengths. In the RANS simulations, we saw reductions ranging from 10-15% and 30-60% for the lead and trail trucks respectively. DES calculations reported savings of 10-25% for the lead truck and 30-45% for the trail truck.

In general, DES values for relative drag coefficient were less than the values calculated by the RANS simulations for the lead truck, but greater than RANS values for the trail truck. Particularly, RANS and DES values deviate most significantly for the trail truck at spacings less than 0.5 vehicle lengths. This is typically where we would expect to see more turbulent behavior, and thus where the higher fidelity of DES may outperform RANS.

Fig. 4-5 show contours of velocity magnitude, pressure, and turbulent kinetic energy (RANS) or RMSE velocity magnitude (DES) for a two-truck platoon at 0.5 vehicle length spacing. From the velocity magnitude, both simulations clearly show the second truck driving fully in the first trucks

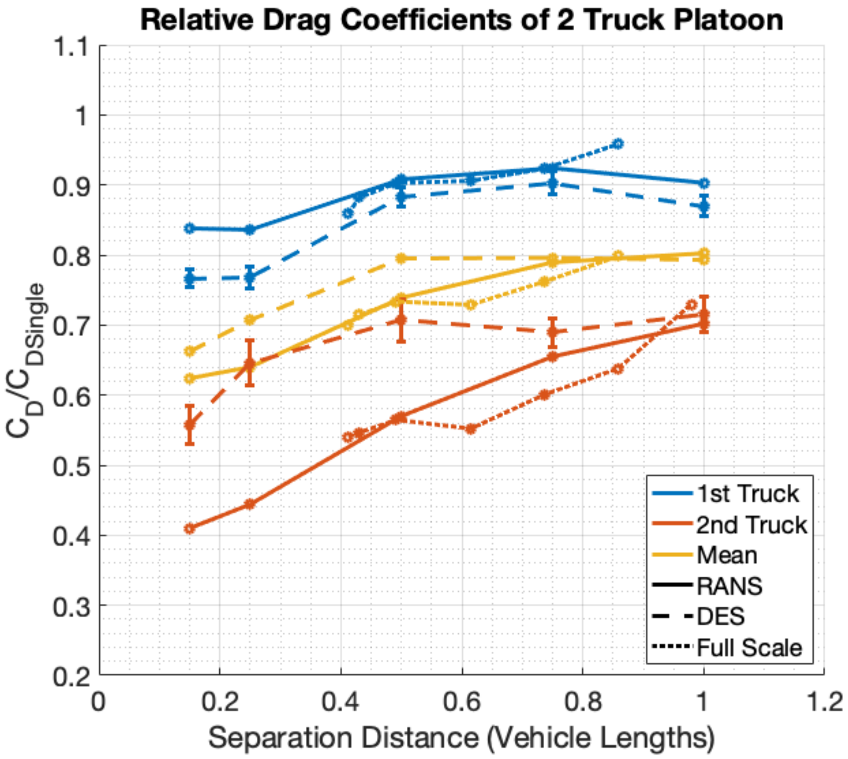

Figure 3: A plot of relative Drag (drag of a platoon normalized to single truck drag) as a function of separation distance. We find aerodynamic gains leveling off at close to 1 vehicle length.

wake. The pressure contours illustrate the effect of this on the pressure head; the second truck experiences a drastically reduced pressure differential across the front and rear as compared to the first truck, resulting in the reduced drag. Finally, we can see representations of turbulence in both simulations, peaking in front of the trailing truck, with another local maxima in the wake of the trailing truck.

Conclusions

We computationally simulated flow around a semi-truck and platoons of two trucks, extracting drag coefficients to determine the aerodynamic advantage of platooning at varying spacing intervals. We found significant savings for both the lead and trail truck, with savings increasing as spacing decreased. Average drag reduction across both trucks at the smallest spacing totaled 35%, equating to around 20% total energy savings for the semi-trucks at highway speed. These considerable savings make platooning a viable strategy for significantly reducing fuel and energy consumption of heavy-duty trucks, aided by the ease of implementation without major changes to truck design.

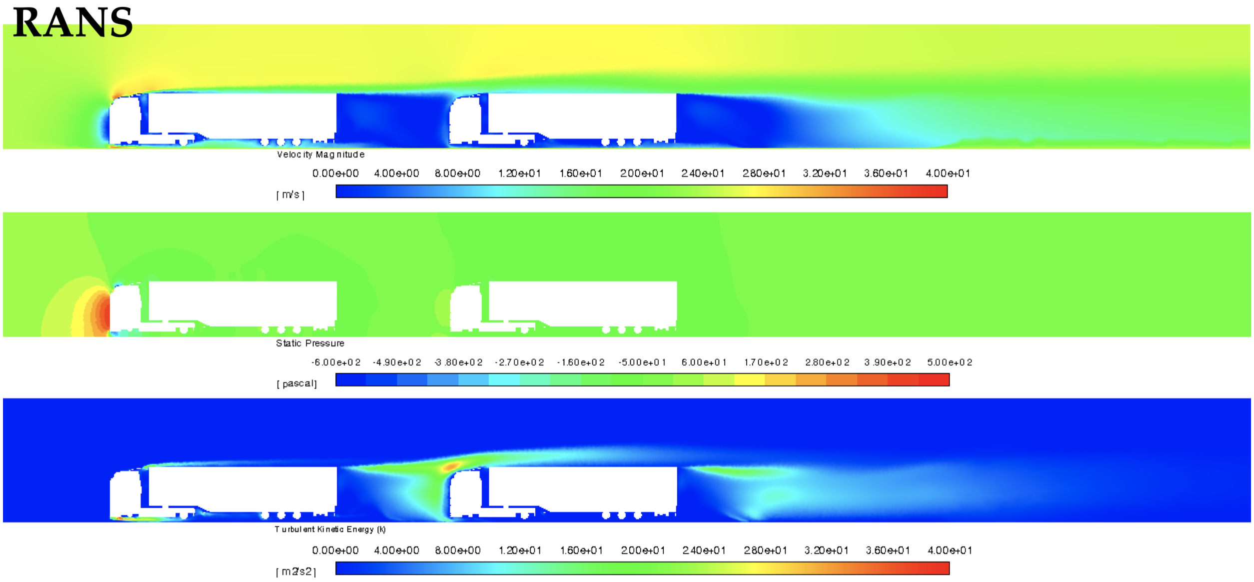

Figure 4: Contours of velocity magnitude, pressure and turbulent kinetic energy (TKE) for the 2-truck platoon case at 0.5 vehicle length spacing simulated using RANS equations.

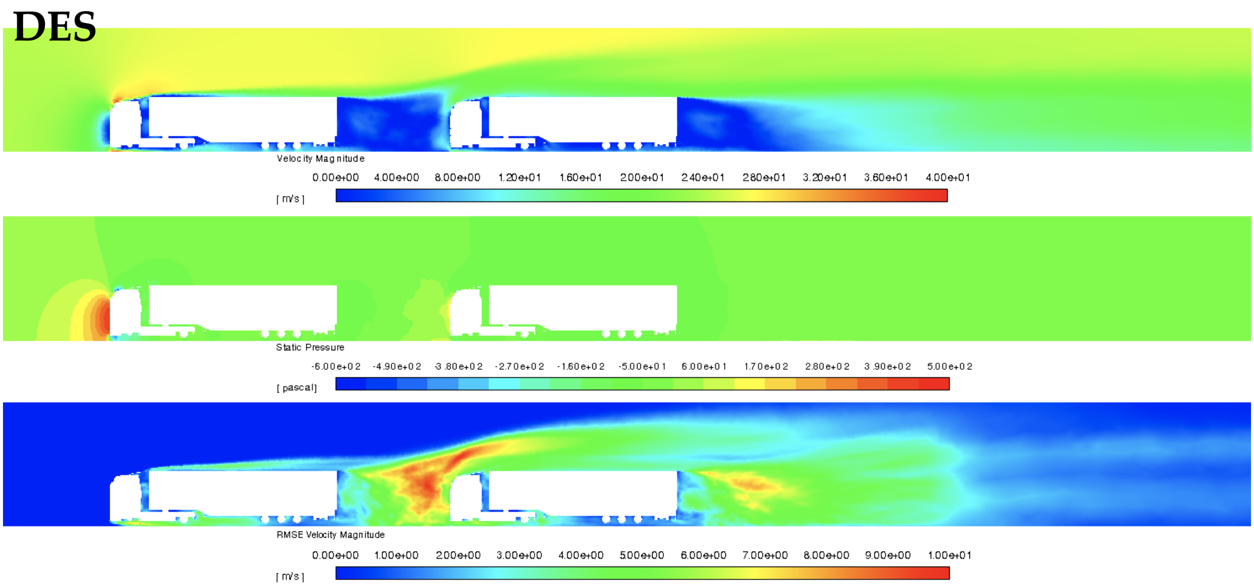

Figure 5: Contours of velocity magnitude, pressure and RMSE velocity magniture for the 2-truck platoon case at 0.5 vehicle length spacing simulated using DES.

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