

A Simple Two-Dimensional Computational Modelling Study of Platooning Phenomenon

K.Mosata¹, T.Phologolo², N.Subaschandar^{3,*}

¹4th year undergraduate student, ²Master's student, ^{3,*}Associate Professor

Department of Mathematics and Statistical Sciences, Botswana International University of Science and Technology, Palapye, Botswana.

*Corresponding author email : raos@biust.ac.bw.

Abstract

Platooning is a technique where two or more vehicles align in a line reducing the overall drag exploiting the lead vehicle's slipstream. Platooning can reduce the overall average energy consumption. In this study, Computational Fluid Dynamics principles have been exploited to analyse the platooning phenomenon. Because of limited resources, the study was done using idealized two-dimensional rectangular geometries. Number of trucks is limited to four. The distance between the trucks is varied equally. Drag force is calculated for two, three and four truck platooning systems as well as a single isolated truck. Preliminary results suggest that platooning is possible. The reduction in drag of trailing trucks continues, up to a gap of 8-truck lengths, although with gradually reducing benefit. This study shows that with ground effect, the drag reduction for four trucks ranges between 69% for no gap and 5% for a gap of 8 truck lengths. The drag reduction for four trucks without ground effect ranges between 69% for no gap and 0% for a gap of 8 truck lengths.

Keywords: Platoon, Drag, Turbulence Model, Fuel Consumption, transportation, CFD

1. Introduction

Transportation is vital for the community, economy and highway goods movement by trucks accounts for about 60% of total road cargo transportation¹. The requirement for surface cargo transference is estimated to grow to surge in the future. As presented in the American Trucking Association report², the freight transport business includes close to 80% of about \$1330 Billion shipment and logistics commerce in the USA. But lots of fuel expenditure and greenhouse gas production are incurred. For example, road shipping constitutes nearly 27% of the energy utilization of the Europe³. Therefore, the environmental degradation occurring during the course of transportation need to be reduced immediately. Fuel expenses represented approximately 30% of the total expenditure of possessing and running a truck⁴. As per the American Transportation Research Institute report⁵, fuel is considered as the second biggest expenditure, while the largest was the expenditure on personnel. Besides a huge number of trucks and the ever increasing requirement for highway transport, it may be forecast that even slight improvements in fuel reduction may result in significant cost cuts. It is also advantageous to attain the target of ecological security due to reduced gas emission. Therefore, it has been of huge advantage to increase fuel saving, and how to improve fuel efficiency during driving has become a common subject of many scientific investigations in the recent past years. The advent of transport systems have aided means to improve the energy efficiency of transportation arrangements. An encouraging method to deal with the issue was to decrease the distance between trucks on the highway, which is frequently known as truck platoons. Truck platoon, referred as convoy too, is a group of trucks making a road train by moving tightly in single lineup to encounter decreased drag due to air flow. Platooning can meaningfully decrease fuel expenditure because nearly 25% of the fuel utilization is connected to aerodynamic drag⁶. Apart from reductions in fuel consumption, vehicle convoys may add to a surge of highway capacity and can alleviate traffic overcrowding because of lesser distances between trucks.

In the past few years, through the growth of autonomous vehicle movement technology, trucks are fitted with many sensors which allow the trucks to watch their environments and determine instantaneously in real time what action ought to be implemented and such vehicles are called “autonomous vehicles” or “driverless vehicles.” Autonomous trucks are capable of synchronizing themselves when moving, and they can move in a platoon with lesser gaps to decrease fuel expenditure. Besides, when moving autonomously in a convoy, it will be likely to diminish the chances of back-end crashes and also to increase traffic safety. Because of the huge benefits stated above, truck convoys have drawn the notice of several governments agencies and research establishments. As a consequence, numerous research studies connected to platoons had been planned. During one such research project⁷, an experiment was performed with two automobiles linked through an “Electronic Tow Bar” for calculating the fuel efficiency. California PATH program commenced its study on heavy vehicle convoys where all trucks were completely automated, even the lead truck⁸. The research report “KONVOI” dedicated to truck convoys, in which a group of German researchers established a convoy of four heavy duty vehicles to decrease fuel consumption and buildup the highway capability⁹. SARTRE is an European Commission co-financed FP7 research¹⁰, where the lead trucks were driven manually, while the trailing vehicles were driven automatically both in lateral and longitudinal directions without any change to the infrastructure, like dedicated lanes. In this research, a platoon of 3 fully synchronized vehicles was studied and the trucks were driven at a speed of 80km/h, with a 10-meter distance between the trucks, on an highway before community use¹⁰. The study reported in¹⁰, stated, using modeling and road investigating methods, that a three-truck platooning at 80km/h with 10-meter gap between trucks could increase fuel efficiency upto an average of about 14% with the lead vehicle undergoing about 7.5% decrease and the trailing truck undergoing about 16% decrease. A comprehensive overview of the benefits of platooning phenomenon is given in the report¹¹.

Platooning involves a sequence of trucks which are deliberately driven maintaining a very small gap between the trucks so as to decrease aerodynamic drag of the vehicles¹². Aerodynamic drag is a force which the oncoming air applies on a moving object like a truck. The lead vehicle at the front of the convoy directs the tailing trucks and they follow each response made by the lead truck like-sudden braking, acceleration and other movements are quickly emulated by the trailing trucks. The report¹³ adds that improved automotive aerodynamics leads to a decrease in fuel expenditure, helping drivers save money and thus lessening carbon dioxide emissions. Truck platooning also improves transport by means of roads more efficiently by reducing traffic clogging and therefore delivering commodities faster. According to the studies^{14,15}, vehicle automation is an encouraging technology to decrease fuel usage, and the platooning arrangements of heavy-duty trucks are probably to be the first measure regarding approval for truck automation. A report from the New Energy and Industrial Technology Development Organization of Japan stated with road experiments that a convoy of four vehicles keeping a 4-meter gap between trucks and 80km/h speeds reached about 15% average advancement in fuel efficiency¹⁶.

Recent research studies^{14,17,18}, have shown that convoy system would be successful in decreasing the aerodynamic drag of the trucks in the line, including even in the lead trucks. The largest aerodynamic drag decrease, however, happens for the trucks between the first and last truck. According to the study¹⁹, inter-vehicle spacing is a factor in the average drag reduction of platoons and it is settled that the smaller the truck gap of a convoy, the greater is the fuel saving.

Following the reports^{20,21}, the savings in fuel expenditure may be related to the reduction in drag as follows.

$$\frac{\Delta(\text{fuel consumed})}{\text{fuel consumed in isolation}} = \eta \frac{(C_{D\text{iso}} - C_{D\text{tandem}})}{C_{D\text{iso}}} \quad (1)$$

where $C_{D\text{iso}}$ is the drag coefficient of a truck travelling in isolation and $C_{D\text{tandem}}$ is the drag coefficient of the truck moving in tandem. The percentage reduction in fuel expenditure was linearly proportional to the reduction in drag. The sensitivity coefficient, η , varies upon several parameters like the rolling resistance, vehicle mass, and the cross-sectional area facing the oncoming air^{20,21}. Typical values of

η remain in the range $\eta=0.6$ for a fully loaded vehicle moving at 70 MPH (31m/s) and with a drag coefficient in isolation of 0.6, to $\eta=0.8$ for the same vehicle without any load. For steady movement (no acceleration/ deceleration, no braking), about 25% total drag reduction could provide about 15-20% fuel reduction subject to the vehicle load. These reports are perhaps very positive, because moving at a uniform speed on a highway for extended distance or time is nearly impossible and it should be remembered that the above Eq.(1) was developed using a two-truck platooning study²⁰.

Platooning has been getting momentum as a competent way to improve highway volume and decrease truck fuel expenditure, as several research reports have suggested^{7,22-26}. One of the important issues causing the decrease in fuel expenditure was the connection between gap between the trucks and the drag forces. In the report²⁷, researchers presented an experimental study on Light Duty Vehicle(LDV) platoons. The experiment was carried out using a 1/8th scale of an actual model of the 1991 General Motors Lumina All Purpose Vehicle in an open-circuit wind-tunnel set-up with drag force measurements upto a gap of 3 and 2 truck lengths in the two and three-vehicle convoy respectively. The research demonstrated a drag decrease of upto about 15% for the lead truck and upto about 30% for the trailing vehicle for the two-vehicle convoy with a gap of 0.5 vehicle length. When gaps were smaller than 0.5 of a vehicle length, these results were swapped, and the lead truck produced a larger decrease in the drag force related to the trailing vehicle. The research presented in²⁸ confirmed this performance at smaller gaps by carrying out a full-scale road experiment. For the bus platoons, a research study²⁹ was carried out on a 1:20 scale of a cylindrical bus-shaped objects in an open-circuit wind-tunnel with drag measurements upto gaps of 5 bus lengths. The tests revealed a drag decrease of upto about 10% for the lead vehicle and upto about 60% for the trailing bus in a two-bus convoy with a 10-metre gap between the buses. The precise modeling of the drag interface between trucks renders the controller design more effective when it is about attaining the optimal control by means of either vigorous or model predictive methods³⁰⁻³³ and decreases the ambiguity in the model³⁴.

Few investigations examined the influence of the number of vehicles in the convoy on the drag reduction of platoons and the aerodynamic drag reduction effects of platooning. There has been no systematic study on truck platooning. Most of the studies have been empirical road tests or wind tunnel experiments. It is important to conduct more studies on the numerical evidence of truck platooning. The present study was started with an aim to answer the question, by a systematic mathematical research, whether platooning phenomenon is possible. We studied, in the current research, platooning of up to 4 trucks and the impact of the lead truck on the trailing trucks with varying gap G , between the trucks to observe the effect on the overall drag. Preliminary results of this study had been presented at the Central Botswana Mathematics and Statistical Sciences Conference (CBMSSC II)³⁵.

2. Geometrical Modelling

In this section, the research work that has been carried out in this study, has been described. A simple idealized configuration has been chosen because of availability of limited resources and time constraints. Research was carried out using up to 4 trucks calculating the impact of the leading truck on the trailing trucks. The gap(G) between the trucks was changed to study the effect of increasing the gap between the trucks on the drag of the trucks. Computations have been carried out with and without ground effect.

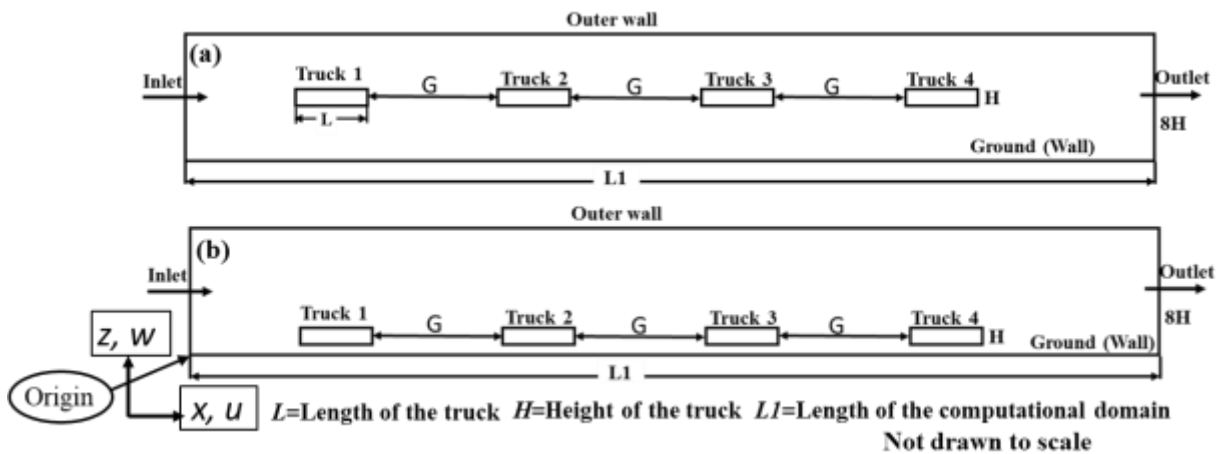


Figure 1. Computational domain (a) without and (b) with ground effect

Figure 1 presents the computational domain without (a) and with (b) ground proximity. L is the length of the truck, H —height of the truck, $L1$ is the length of the computational domain and G is the gap between the trucks. The inlet velocity is kept constant at 40m/s which is about 150kms per hour. Reynolds number calculated using this speed and the length of the truck is about 2.6×10^6 . At this Reynolds number the flow is completely turbulent. Standard $k-\epsilon$ turbulence model has been utilised to capture turbulence parameters. The computational domain is two-dimensional and the fluid is air. Steady, incompressible, single phase, fully-developed, constant fluid viscosity and constant fluid density assumptions have been made. External applied body forces, buoyancy and temperature impacts have been ignored. The friction between the tyres and the road, which occurs in real situation, has not been counted as this friction is common to all geometries and assumed to be equal for all trucks and cases studied here. Drag due to the tractor and other external attachments like rearview mirrors are not considered here.

3. Mathematical Modelling

The transport equations are described by means of Cartesian coordinate system where x and z coordinates are taken as representing the independent variables. The coordinate system, origin, x & z direction, u & w velocity components are described in the Fig.1.

2.1. Governing equations

The Reynolds Averaged Navier-Stokes equations describing the mean flow development in the calculation domain are given by³⁶⁻³⁸:

Horizontal component:

$$\frac{\partial}{\partial x}(\rho u^2) + \frac{\partial}{\partial z}(\rho uw) = \frac{\partial}{\partial x}\left(\Gamma \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial z}\left(\Gamma \frac{\partial u}{\partial z}\right) - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\Gamma \frac{\partial u}{\partial z}\right) + \frac{\partial}{\partial z}\left(\Gamma \frac{\partial u}{\partial x}\right) - \frac{2}{3} \frac{\partial}{\partial x}(\text{div} \vec{V}) \quad (2)$$

Vertical Component:

$$\frac{\partial}{\partial x}(\rho uw) + \frac{\partial}{\partial z}(\rho w^2) = \frac{\partial}{\partial x}\left(\Gamma \frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial z}\left(\Gamma \frac{\partial w}{\partial z}\right) - \frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left(\Gamma \frac{\partial w}{\partial z}\right) + \frac{\partial}{\partial z}\left(\Gamma \frac{\partial w}{\partial x}\right) - \frac{2}{3} \frac{\partial}{\partial z}(\text{div} \vec{V}) \quad (3)$$

In the above equations, p [N/m²] is the pressure. The diffusion coefficient is defined by:

$$\Gamma = \mu + \mu_\tau \quad (4)$$

where μ [Ns/m²] is the dynamic viscosity and μ_τ is the turbulent eddy viscosity.

Continuity Equation:

The mass conservation or continuity equation, is given as follows:

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial z}(\rho w) = 0 \quad (5)$$

2.2. Turbulence modelling

In a turbulent fluid flow, flow parameters (like fluid velocity, fluid pressure, etc.) display oscillations about a mean value. The calculation of the instantaneous values of these parameters is very expensive with presently available computing methods and resources, because of large temporal and spatial frequencies which define turbulent fluid flows and, therefore, the mean values only are computed. The average values and the turbulence parameters are calculated using the standard k- ϵ turbulence model in the current study, which is described below.

The standard k- ϵ turbulence model:

The standard construction of this turbulence model is described in^{36,39,40}. The turbulent eddy viscosity is defined as:

$$\mu_t = C_\mu \frac{\rho k^2}{\epsilon} \quad (6)$$

The turbulence kinetic energy, k , and its dissipation rate, ϵ [m^2/s^3], have been computed by solving two transport equations which are described below:

$$\frac{\partial}{\partial x}(\rho u k) + \frac{\partial}{\partial z}(\rho w k) = \frac{\partial}{\partial x} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x} \right] + \frac{\partial}{\partial z} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial z} \right] + P_k - \rho \epsilon \quad (7)$$

$$\frac{\partial}{\partial x}(\rho u \epsilon) + \frac{\partial}{\partial z}(\rho w \epsilon) = \frac{\partial}{\partial x} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x} \right] + \frac{\partial}{\partial z} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial z} \right] + \frac{\epsilon}{k} (C_1 P_k - C_2 \rho \epsilon) \quad (8)$$

The term P_k is the rate of production of turbulent kinetic energy due to the velocity gradients:

$$P_k = \mu_t \left[2 \left(\frac{\partial u}{\partial x} \right)^2 + 2 \left(\frac{\partial w}{\partial z} \right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 \right] \quad (9)$$

The remaining model constants are given below:

$$C_\mu = 0.09 \quad \sigma_\epsilon = 1.3 \quad \sigma_k = 1.0 \quad C_1 = 1.44 \quad \text{and} \quad C_2 = 1.9 \quad (10)$$

This set of governing transport equations (Eq.(2) to Eq.(10)) was solved, along with suitable boundary conditions for the calculation domain, by means of numerical procedures.

The boundary conditions are

$$u(0, z) = U_\infty, w(0, z) = u(x, 0) = u(x, +\infty) = w(x, 0) = w(x, +\infty) = 0.$$

$$\text{At } x = L_1, \quad \frac{\partial u}{\partial x} = \frac{\partial w}{\partial x} = \frac{\partial k}{\partial x} = \frac{\partial \epsilon}{\partial x} = 0 \text{ for all } z.$$

$$\text{At } x = 0, k = \left(\frac{3}{2} I \mu_\infty^2 \right), I = \text{Turbulence intensity}, \epsilon = \left(\frac{C_\mu^{0.75} k^{1.5}}{H_1} \right), \text{ for all values of } z.$$

$$H_1 = \text{Inlet height } (=8H).$$

The near wall handling of momentum and turbulence transport equations implemented in EASYCFD³⁶ follows the suggestions described in⁴¹. The basic idea behind the automatic wall functions is to modify from a low-Reynolds number procedure to a wall function constructed on the mesh nodes close to the wall. The first order upwind scheme has been employed to discretize the two momentum(velocity) and two turbulence model equations. The Semi-Implicit Method for Pressure-Linked Equations-Consistent (SIMPLEC) technique has been applied for the pressure velocity interactions^{36,42}. At the inlet plane of the calculation region, a constant velocity condition has been applied. At the exit plane, pressure outlet condition was imposed. On the walls and on the geometric models, the zero mean velocity condition was enforced. The two-dimensional CFD software, EASYCFD³⁶, has been used to carry out the computations and for data processing for all configurations. EASYCFD³⁶ is an incompressible fluid flow solver built on finite volume

discretization technique. The transport equations, also called Navier-stokes equations, governing the mean velocity components and turbulent-transport equations of k- ϵ turbulence model, are solved simultaneously and iteratively. The computational fluid dynamics software EASYCFD³⁶ has been chosen because of its lower cost, ability, ease and user-friendliness. The calculations are taken to be converged if the normalized residue values for mass, momentum and turbulence model equations are less than 0.0001.

3. Results and discussion

3.1. Validation of mathematical modelling and numerical method

A two-dimensional calculation domain was created. The commercially available computational fluid dynamics software EASYCFD³⁶ has been used for creation of the computational domain and geometric models for the present computations. The calculation procedure and current flow modelling have been validated by using the methods given below.

- Comparing the present calculated results with available earlier results.
- Carrying out a grid independence study.
- By maintaining the mass flow rates balance at the inlet and exit planes.

A mesh independence analysis was done in the computational domain to exclude the impact of the mesh size (number of nodes in the computational domain. Also known as the grid size) on the computed results. The drag coefficient (C_D) was used as the parameter to evaluate the performance of various mesh sizes.

$$C_D = \frac{F_D}{(0.5 * \rho * H * U_\infty^2)} \quad (11)$$

where C_D is the drag coefficient, F_D is the force component on the truck in the x-direction(also called the drag), H is the height of the truck, ρ is the density of air and U_∞ is the inlet velocity of air.

Table 1. The drag coefficient (C_D) of a rectangular cylinder with mesh size

Mesh Size No.	Mesh size	C_D	% Difference in C_D
1	29440	1.0851	
2	32445	1.1081	2.2
3	35052	1.1231	1.5
4	38110	1.1467	0.9
5	40860	1.1500	0.3
6	44515	1.1512	0.1

From the Table 1, it can be seen that the difference in the value of C_D for the 5th and 6th grid sizes is very small. Hence a grid size of minimum of 45000 nodes was maintained for all configurations studied here. The mesh size was increased significantly as the number of trucks and the gap between the trucks were increased. The grid size in the calculation domain varied from about 45000 nodes with a single isolated truck to about 78200 nodes with 4 trucks and $G/L=8$ and without ground effect. The grid size in the computational domain varied from about 49500 nodes with a single isolated truck to about 84200 nodes with 4 trucks and $G/L=8$ and with ground effect.

Table 2. The drag coefficient (C_D) of a rectangular cylinder with aspect ratio of 5

The experimental and computational results reported in the studies⁴³⁻⁴⁸ are utilised to compare the results of the current computational research. Table 2 gives the results of current computational study along with results of several earlier studies, including an experimental study, on the drag coefficient of a rectangular cylindrical model of aspect ratio (length to height ratio) of 5. The last column in the Table 2 shows the percentage difference in the drag coefficient (C_D) values between the present study and earlier studies. It can be seen from the Table 2 that the presently computed and earlier results (both computational and experimental) agree reasonably well. The matching is not 100% because of the following probable three major causes. (i). The calculation domain built in the current research is a two-dimensional domain but in the other works, including the experimental research, were carried out in three-dimensional domains; (ii). At the inlet plane, uniform velocity condition has been enforced instead of a fully developed mean velocity distribution which is more realistic; (iii). The Reynolds number, in the present study, is very high compared to other studies⁴³⁻⁴⁸. The validation of current modelling technique was, also, done by checking the residuals throughout the calculations and having equilibrium of the mass flow rates at the inlet and exit planes. At the end of the calculations, the mass flow rate disparity between the inlet and the outlet planes is less than 0.001% which is very low.

3.2. Mean velocity contours

Figure 2 shows the contour plots of streamwise component of mean velocity in the calculation domain with number of trucks upto four are presented with (R) and without (L) ground effect with varied distances between the trucks. The mean velocity contours, displayed in the Fig. 2, show that the mean velocity in front of the trailing trucks is low when the gap between the trucks is small, signifying that the drag on the trailing trucks is low. But as the gap between the truck increases, the mean velocity in front of the trailing trucks keeps increasing. By the time the gap is 8 truck lengths ($G/L=8$) the mean velocity in front of the trailing trucks is almost equal to the mean velocity in front of the lead truck. This signifies that when the gap between the trucks is 8 truck lengths, the lead truck has no or low influence on the trailing trucks and the trucks are almost independent of each other's presence. This means that the drag is almost the same for all the trucks. When the gap between the trucks is nearly zero, the drag is low for trailing trucks.

3.3. Turbulent kinetic energy contours

Figure 3 shows the contour plots of turbulent kinetic energy in the calculation domain with number of trucks upto four with varied distances between them with (R) and without (L) ground effect

Reference	Model/Method	Reynolds Number	C_D	% Difference in C_D
Present study	2-D RANS k- ϵ	2.6×10^6	1.1512	
Subaschandar ⁴³	2D RANS SST	2×10^5	1.1389	1.1
Yin et al. ⁴⁴	2D RANS SST	2×10^5	1.1105	2.5
Dahl ⁴⁵	2D RANS k- ϵ	5×10^5	1.1008	3.3
Bruno et al. ⁴⁶	3D LES	4×10^4	1.0500	7.8
Mannini et al. ⁴⁷	3D LES	2.6×10^4	1.0290	9.6
Schewe ⁴⁸	Experiment	2×10^4	1.0300	9.6

respectively. Fig. 3 shows the existence of large turbulent kinetic energy region (high turbulence region) in front of the lead truck and the large turbulent kinetic energy difference between the front and back of the lead truck. However, the high turbulent kinetic energy region is not seen in front of the trailing truck. The turbulent kinetic energy in front of the trailing truck is very less compared to the front of the lead truck. Also, it can be seen from the Fig. 3 that by 8 truck lengths gap the turbulent kinetic energy contours behind every truck resembles that of behind a single isolated truck and the

turbulent kinetic energy has dissipated. This means that the effect of platooning is less, and the trucks behave almost independently.

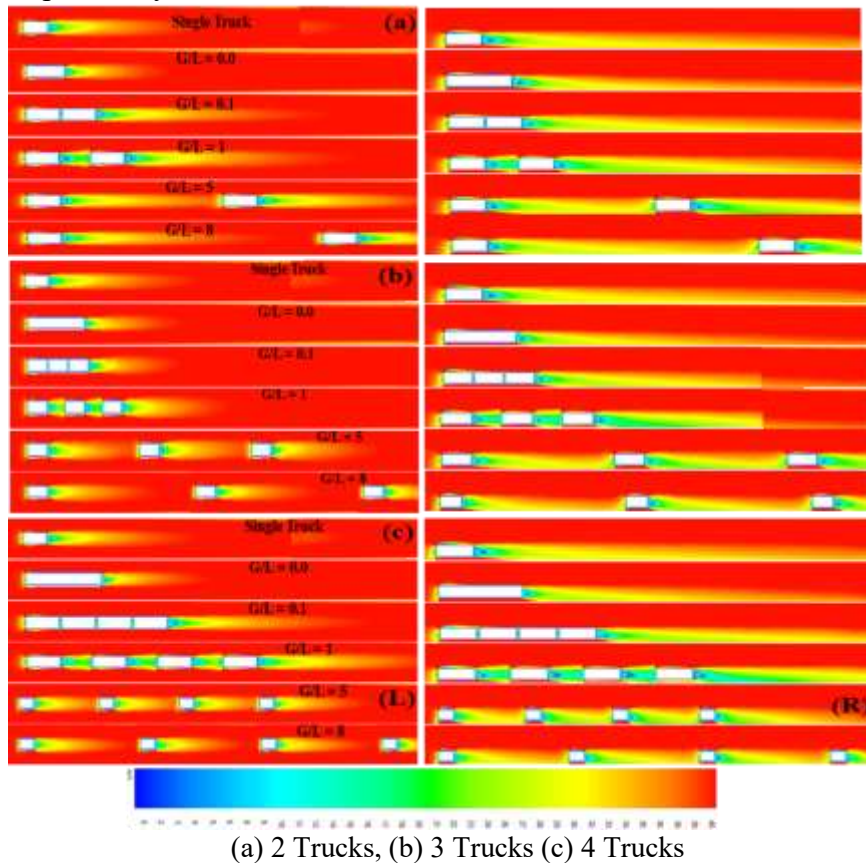


Figure 2. Mean velocity contours without(L) and with(R) ground effect

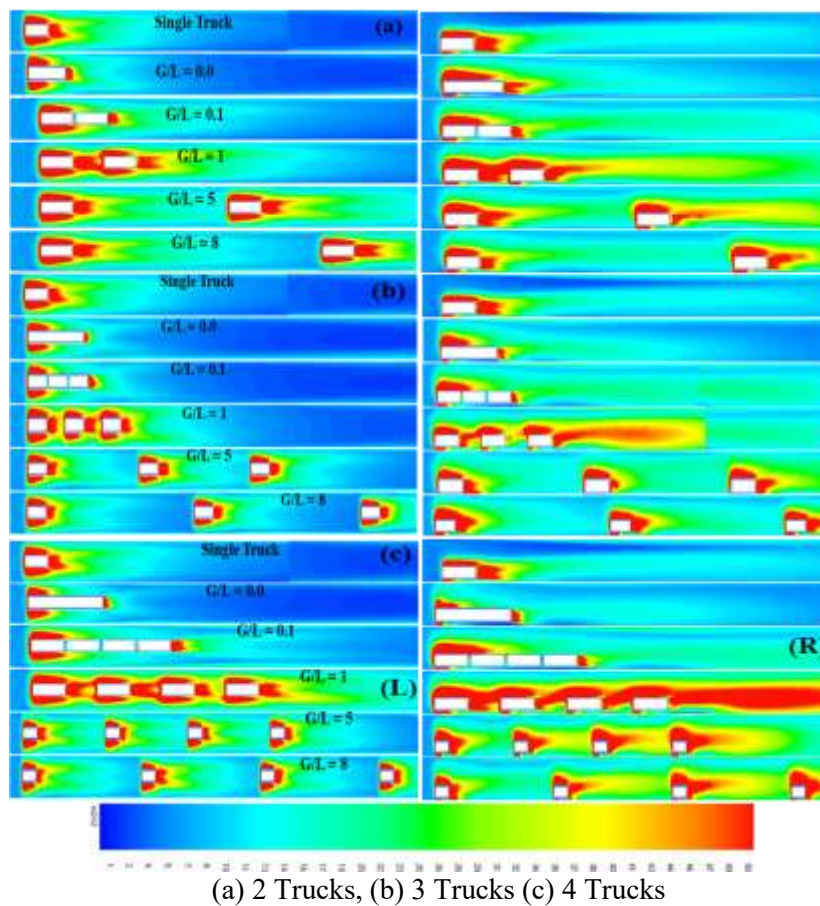


Figure 3. Turbulent Kinetic Energy contours without(L) and with(R) ground effect

3.4. Drag coefficient results

In this section, computed drag coefficient variations in the current computational study are presented for up to four trucks with gap varied upto 8 truck lengths. Figure 4 shows the drag coefficient variation with gap for two trucks without(a) and with(b) ground effect. From the Fig. 4, it is observed that the drag coefficient of the lead truck initially increases slightly and then starts becoming constant as the gap increases. It is seen to increase up to a value almost equivalent to the drag coefficient of a single isolated truck which is about 1.15. Also, seen in the Fig. 4, is that the drag of the trailing truck is very low when (G/L) is small and it increases as the gap between the trucks increases. The drag value of the trailing truck reaches the drag value of the lead truck when the gap (G) reaches 8 truck lengths, upto which the present research has been carried out. Upto $G/L=8$ the drag of the trailing truck is less than the drag of the lead truck, signifying that the trailing truck had the potential to save fuel.

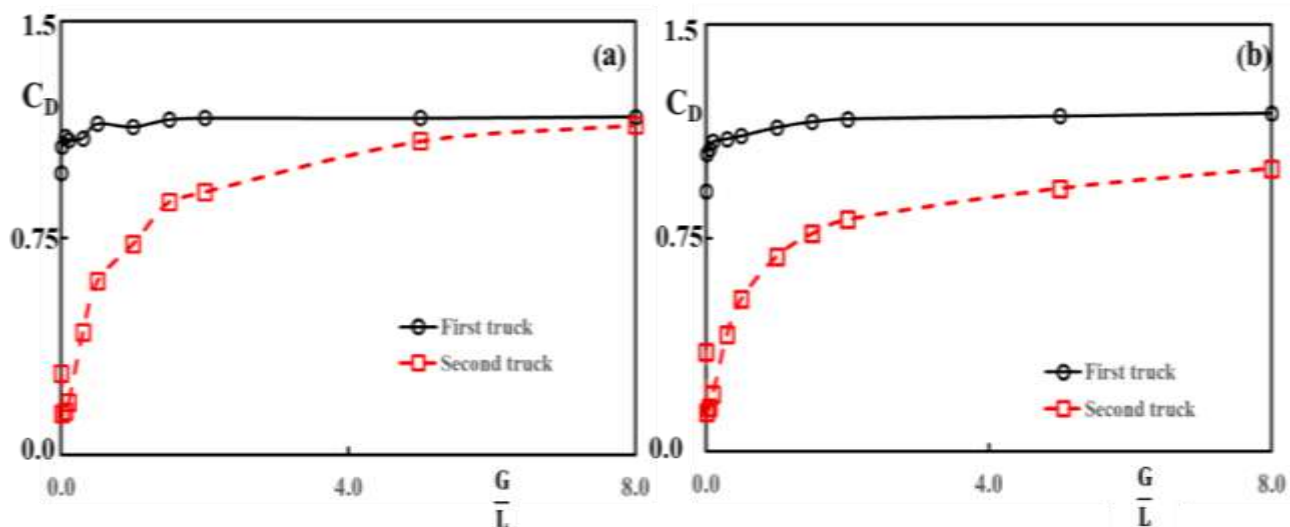
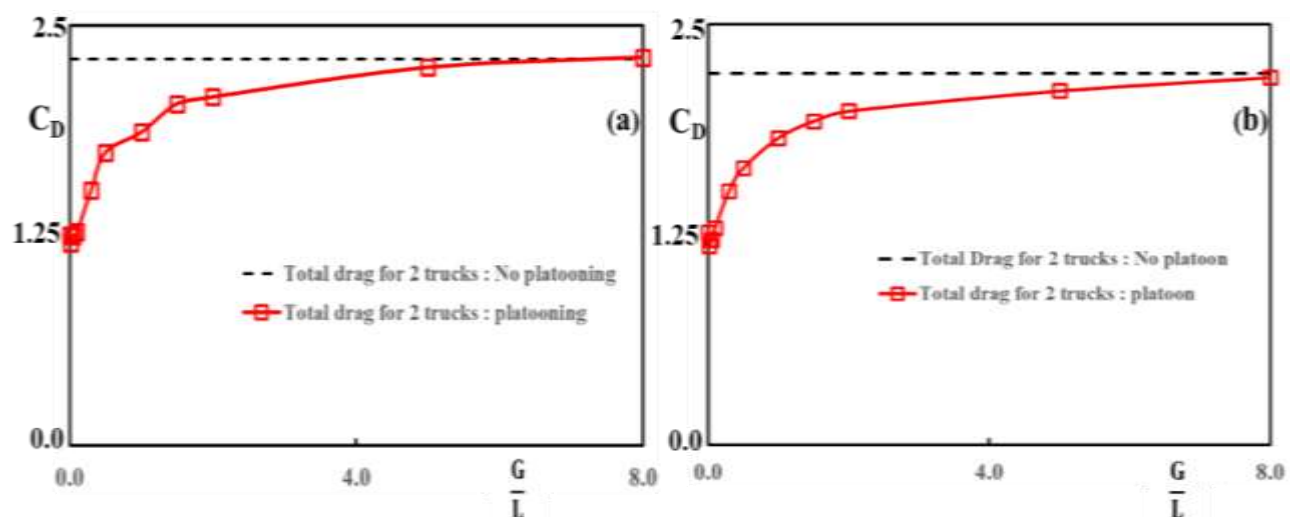
**Figure 4.** Drag variation with gap (a) without and (b) with ground effect for two trucks**Figure 5.** Total drag variation with gap (a) without and (b) with ground effect for two trucks

Figure 5 presents the total drag coefficient variation with gap for two trucks without(a) and with(b) ground effect. For no platooning case, the total drag coefficient is obtained by adding the drag coefficients of two individual trucks. For platooning case, the total drag coefficient for two trucks is obtained from the total drag force experienced by both the trucks using the Eq. (11). From the

Fig. 5, it is observed that the total drag coefficient for two trucks increases with gap(G/L) up to a value almost equal to two times the drag coefficient of a single isolated truck. Tables 3 and 4 present the drag reduction results for two-truck platooning situation. The results are presented for the cases without ground effect (Table 3) and with ground effect (Table 4). From the results given in Tables 3 and 4, it is seen that the lead truck experiences a very small reduction in drag, where as the trailing truck experiences a large reduction. The total drag for both trucks is also reduced significantly. This reduction in total drag slowly diminishes as the gap between the trucks is increased.

Table 3. Drag reduction for two trucks without ground effect

G/L	First Truck	Second Truck	Total Drag Reduction
0	15%	76%	45%
0.01	7%	88%	48%
0.05	4%	87%	46%
0.1	5%	84%	45%
0.3	5%	63%	34%
0.5	0%	48%	24%
1	1%	37%	19%
1.5	-1%	24%	12%
2	-1%	21%	10%
5	-1%	6%	2%
8	-2%	1%	0%

Table 4. Drag reduction for two trucks with ground effect

G/L	First Truck	Second Truck	Total Drag Reduction
0	17%	68%	43%
0.01	5%	88%	47%
0.05	4%	86%	45%
0.1	1%	82%	42%
0.3	0%	63%	32%
0.5	0%	52%	26%
1	-3%	38%	17%
1.5	-5%	31%	13%
2	-6%	26%	10%
5	-7%	16%	5%
8	-8%	10%	1%

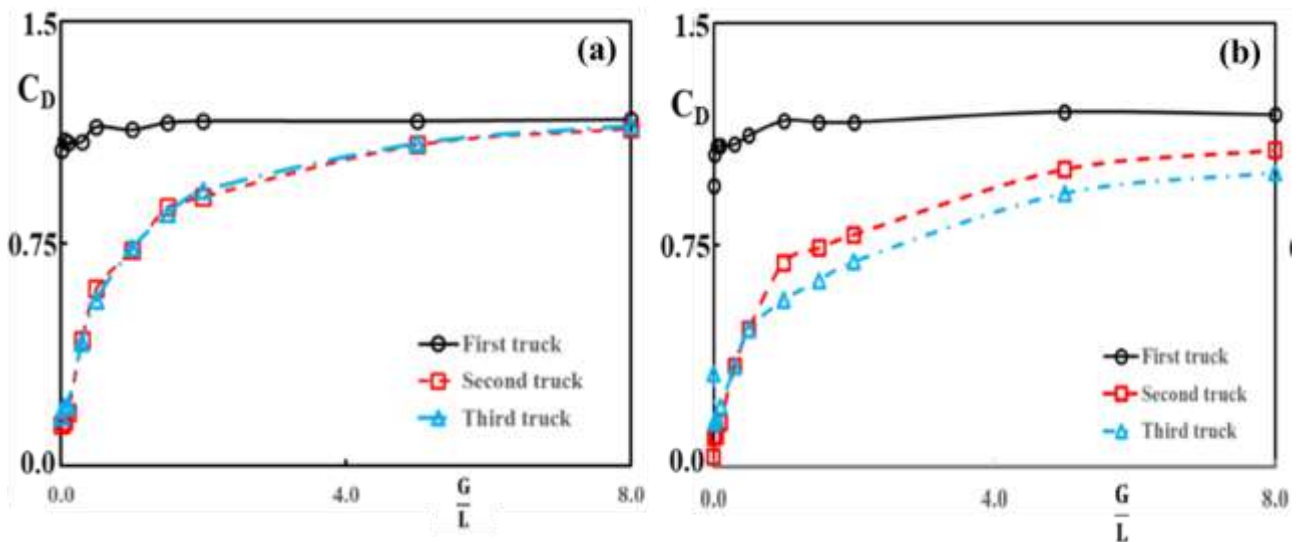


Figure 6. Drag variation with gap (a) without and (b) with ground effect for three trucks

Figure 6 shows the drag coefficient variation with gap for three trucks without (a) and with (b) ground effect. From the Fig. 6, it is seen that the drag coefficient of the lead truck initially increases slightly and then starts becoming constant as the gap increases. It is seen to increase up to a value almost equivalent to the drag coefficient of a single isolated truck which is about 1.15. Also, seen in the Fig. 6, is that the drag of the trailing trucks (second and third) is very low when (G/L) is small and it increases as the gap between the trucks increases. The drag of the trailing trucks (second and third) reaches the drag value of the lead truck when the gap (G) reaches 8 truck lengths, upto which the present research has been carried out. Upto $G/L=8$ the drag of the trailing trucks (second and third) is less than the drag of the lead truck, signifying that the trailing trucks (second and third) had the potential to save fuel.

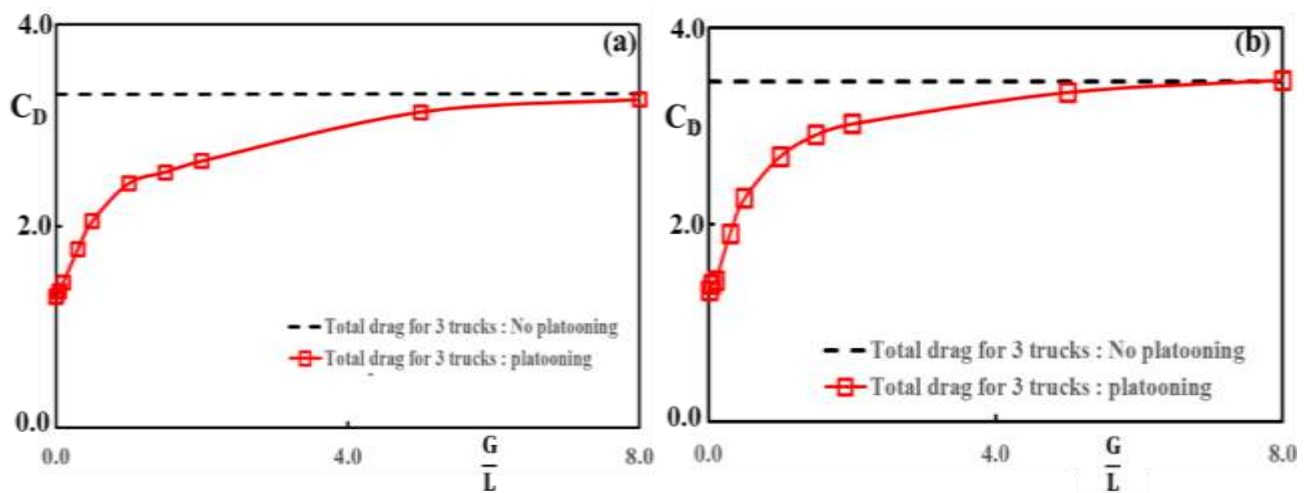


Figure 7. Total drag variation with gap (a) without and (b) with ground effect for three trucks

Figure 7 presents the total drag coefficient variation with gap for three trucks without (a) and with (b) ground effect. For no platooning case, the total drag coefficient is obtained by adding the drag coefficients of three individual trucks. For platooning case, the total drag coefficient for three trucks is obtained from the total drag force experienced by all three trucks using the Eq. (11). From the Fig. 7, it is seen that the total drag coefficient of the three trucks increases with gap up to a value almost equal to three times the drag coefficient of a single isolated truck. This reduction in total drag slowly diminishes as the gap between the trucks is increased.

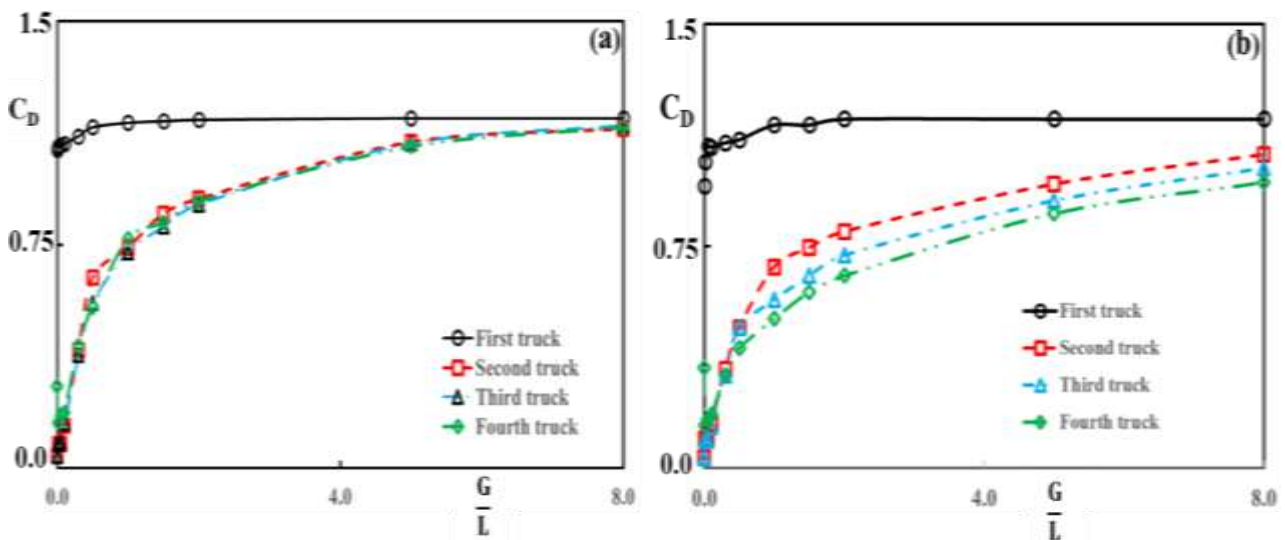


Figure 8. Drag variation with gap (a) without and (b) with ground effect for four trucks

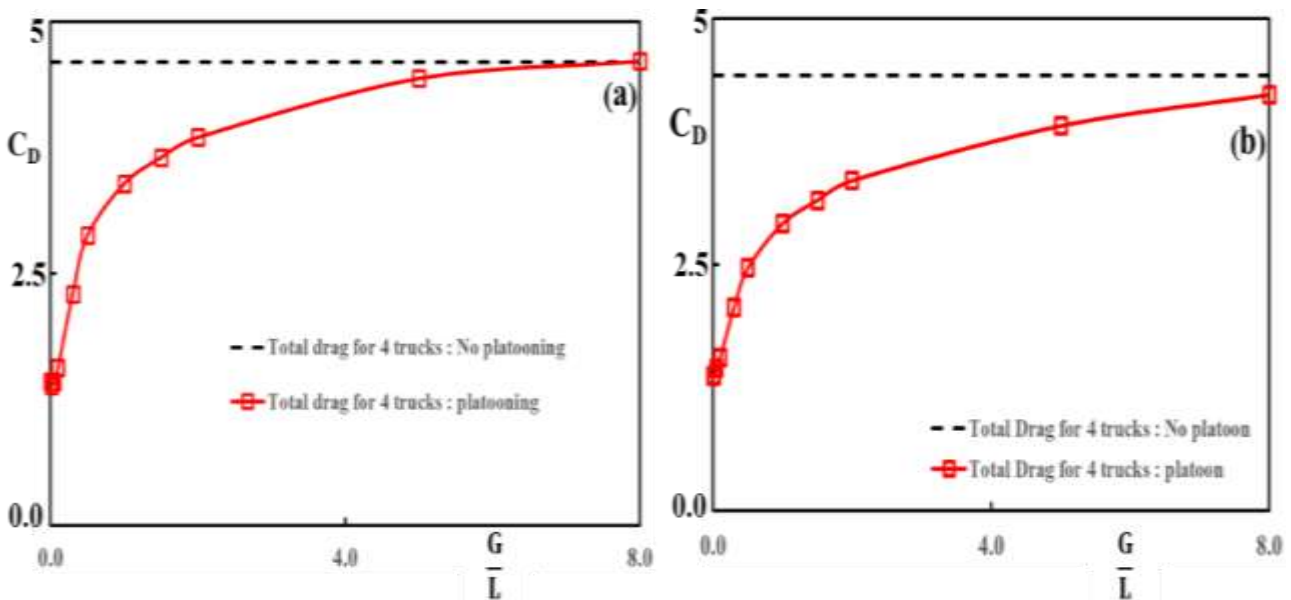


Figure 9. Total drag variation with gap (a) without and (b) with ground effect for four trucks

Table 5. Drag reduction for three trucks without ground effect

G/L	First Truck	Second Truck	Third Truck	Total Drag Reduction
0.0	12%	94%	87%	62%
0.01	6%	93%	86%	61%
0.05	5%	91%	83%	60%
0.1	4%	89%	82%	58%
0.3	4%	65%	64%	44%
0.5	1%	50%	51%	34%
1	-1%	31%	36%	22%
1.5	-2%	23%	26%	16%
2	-2%	20%	19%	12%
5	-1%	5%	5%	3%
8	-2%	0%	0%	1%

Table 6. Drag reduction for three trucks with ground effect

G/L	First Truck	Second Truck	Third Truck	Total Drag Reduction
0	14%	97%	71%	61%
0.01	5%	91%	86%	60%
0.05	2%	90%	85%	59%
0.1	2%	86%	81%	57%
0.3	1%	69%	69%	47%
0.5	-1%	58%	58%	38%
1	-6%	38%	49%	27%
1.5	-5%	33%	43%	24%
2	-5%	29%	37%	20%
5	-9%	9%	16%	6%
8	-8%	3%	10%	2%

Tables 5 and 6 present the drag reduction results for three-truck platooning situation. The results are presented for without ground effect (Table 5) and with ground effect (Table 6). From the results given in Tables 5 and 6, it is seen that the lead truck experiences a very small reduction in drag, whereas the trailing (second and third) trucks experience a large reduction. The total drag for all three trucks is also reduced significantly. This reduction in total drag slowly diminishes as the gap between the trucks is increased.

Figure 8 shows the drag coefficient variation with gap for four trucks without (a) and with (b) ground effect. From the Fig. 8, it is seen that the drag coefficient of the lead truck initially increases slightly and then starts becoming constant as the gap increases. It is seen to increase up to a value almost equivalent to the drag coefficient of a single isolated truck which is about 1.15. Also, seen in the Fig. 8, is that the drag of the trailing (second, third and fourth) trucks is very low when (G/L) is small and it increases as the gap between the trucks increases. The drag of the trailing trucks (second, third and fourth) reaches the drag value of the lead truck when the gap (G) reaches 8 truck lengths, up to which the present research has been carried out. Up to $G/L=8$ the drag of the trailing trucks (second, third and fourth) is less than the drag of the lead truck, signifying that the trailing trucks (second, third and fourth) had the potential to save fuel. Figure 9 presents the total drag coefficient variation with gap for four trucks without (a) and with (b) ground effect. For no platooning case, the total drag coefficient is obtained by adding the drag coefficients of four individual trucks and the total drag coefficient for four trucks is obtained from the total drag experienced by both the trucks using the Eq. (11). From the Fig. 9, it is seen that the total drag coefficient of the four trucks increases with gap up to a value almost equal to four times the drag coefficient of a single isolated truck. Tables 7 and 8 present the drag reduction results for four-truck platooning situation. The results are presented for the cases without ground effect (Table 7) and with ground effect (Table 8). From the results given in Tables 7 and 8, it is seen that the lead truck experiences a very small reduction in drag, whereas all the trailing trucks experience a large reduction. The total drag for all four trucks is also reduced significantly. This reduction in total drag slowly diminishes as the gap between the trucks is increased.

Table 7. Drag reduction for four trucks without ground effect

G/L	First Truck	Second Truck	Third Truck	Fourth Truck	Total Drag Reduction
0	7%	97%	97%	76%	69%
0.01	6%	93%	93%	87%	70%
0.05	6%	93%	93%	85%	69%
0.1	5%	88%	87%	84%	66%
0.3	3%	66%	67%	64%	50%
0.5	0%	44%	52%	53%	37%
1	-1%	36%	37%	33%	26%
1.5	-1%	26%	30%	28%	21%
2	-2%	21%	23%	22%	16%
5	-2%	5%	5%	6%	3%
8	-2%	1%	0%	0%	0%

Table 8. Drag reduction for four trucks with ground effect

G/L	First Truck	Second Truck	Third Truck	Fourth Truck	Total Drag Reduction
0	14%	97%	97%	69%	69%
0.01	6%	91%	91%	87%	69%
0.05	1%	91%	91%	85%	67%
0.1	2%	86%	87%	84%	65%
0.3	0%	70%	71%	71%	53%
0.5	0%	57%	57%	63%	44%
1	-5%	38%	48%	54%	34%
1.5	-5%	33%	41%	46%	29%
2	-7%	28%	35%	41%	24%
5	-7%	13%	18%	22%	12%
8	-7%	4%	8%	13%	5%

The results presented above, show the drag coefficient variation with gap with and without ground effect for two, three and four trucks. These results show that, the trailing trucks experience less drag compared to the lead truck. It is, also, seen that the drag coefficient of the trailing trucks is low initially for small gap and then starts increasing. The present computations were carried out up to a gap of 8 truck lengths. The drag coefficient of the trailing trucks keeps increasing even up to a gap of $G/L=8$ and seems to increase further. This has to be investigated further. This means that the influence of the lead truck on the flow over the trailing trucks keeps diminishing as would be expected to happen. Another interesting note is that for very small gap between the trucks, the flow treats all trucks (up to four trucks) as a single entity.

Table 9. Wake width variation for four trucks configuration without ground effect

G/L	B/H
0	1.552
0.01	1.469
0.05	1.429
0.1	1.379
0.3	1.352
0.5	1.375
1	1.419
1.5	1.445
2	1.482
5	1.533
8	1.551

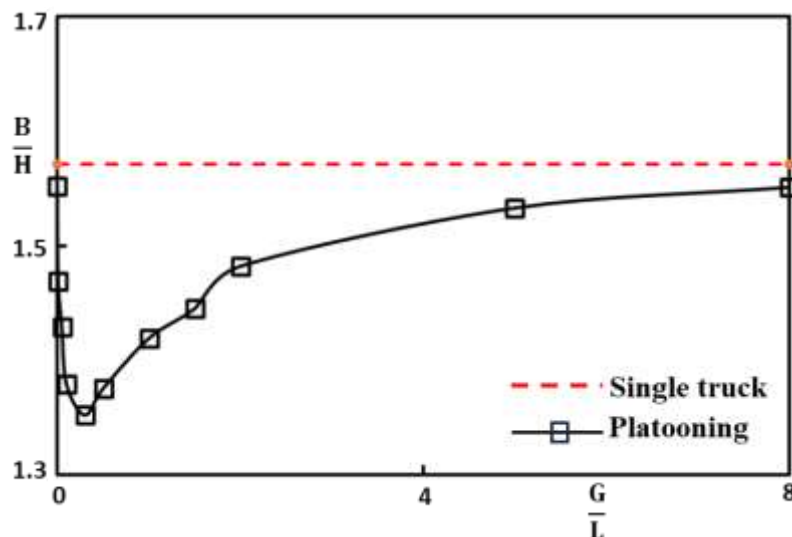
**Figure 10.** Wake width variation with gap without ground effect in platoon formation

Figure 10 and Table 9 present the variation of wake width(B) at one location behind the last trailing truck with gap(G/L). The wake width is described as the location in the z -direction where the value of mean velocity is 99% of the undisturbed freestream velocity from the centreline of the wake and it is computed based on the streamwise component of mean velocity. The wake width is non-dimensionalised using the height(H) of the truck. The wake width results presented in the Fig. 10 and Table 9 are for the case of 4-truck platooning without ground effect. The wake width is calculated at the streamwise location 4-truck lengths distance downstream of the 4th truck. It can be seen from the Fig. 10 and Table 9, that the wake width reduces as the gap between truck increases upto a gap of about $G/L = 0.3$ and then starts increasing with gap though still remains lower than the wake width of a single isolated truck until a gap between the trucks of 8 truck lengths. Similar trends in the results of wake width for 2 and 3 truck platoons cases were obtained, and hence, not presented here. Since it is accepted that the size of the wake width is related to the drag experienced by the object⁴⁹, it can be understood that platooning does provide drag reduction benefits.

4. Conclusions

In this paper numerical fluid mechanics analysis of benefits of platooning phenomenon in trucks is carried out. Computations have been carried out on idealized two-dimensional rectangular geometries to represent trucks. A two-equation $k-\varepsilon$ turbulence model has been utilised with air as the fluid medium. The $k-\varepsilon$ turbulence model was selected mainly because it is a standard and widely used model in solving wide variety of fluid flow problems. From this simple computational modelling study, it has been shown that the platooning phenomenon is possible. Studies were carried out up to 4 trucks and 8 truck lengths gap ($G/L=8$) between the trucks. The present computational results show that the drag coefficient of the lead truck is not affected very much by the presence of trailing trucks. The trucks trailing the first truck experience less drag. This is true up to four trucks. The drag coefficients of the trailing trucks keep increasing as the gap between the trucks increases (up to 8 truck length gap ($G/L=8$) and up to 3 trailing trucks). Velocity in front of the trailing trucks is low for small G/L and increases as G/L increases and eventually becomes equal for region for a single isolated truck. The wake width behind the last trailing truck reduces as the gap between trucks increases upto a gap of about $G/L = 0.3$ and then starts increasing with gap though still remains lower than the wake width of a single isolated truck until a gap between the trucks of 8 truck lengths. From this study, is found that with ground effect, the drag reduction for four trucks ranges between 69% for 0 gap and 5% for 8 truck length gap. The drag reduction for four trucks without ground effect ranges between 69% for no gap and 0% for a gap of 8 truck lengths. It is also shown that, up to 4 trucks, the total drag of platooning trucks is less than total drag of all independent trucks. This continues to be so until 8 truck lengths gap ($G/L=8$) between the trucks. It is shown that for small gap between the trucks, the flow treats all trucks (up to four trucks) as a single isolated entity. Similar trends in drag coefficient were found with and without ground effect. Since this study has been carried out using idealized two-dimensional geometries, it is recommended that further studies be carried out with more trucks (with more realistic geometries) and varying gap between trucks in a three-dimensional domain to confirm this phenomenon.

Acknowledgements

Authors thank the Department of Mathematics and Statistical Sciences and the Botswana International University of Science and Technology, Botswana for encouraging this research work.

Funding sources

This research study did not receive any specific grant from funding agencies in the public, commercial, private, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they do not have any competing financial interests or personal relationships that could appear to influence the work reported in this paper.

Authorship contribution statement

K.Mosata: Simulation, Formal analysis, Methodology, Investigation, Writing-Original Draft; **T.Phologolo:** Validation, Writing-review & editing; **N.Subaschandar:** Conceptualization, Supervision, Formal analysis, Final version of manuscript.

References

1. Zhang L, Chen F, Ma X. A literature review of fuel economy in truck platoons. Proc. of the 23rd Inter. Conf. of Hong Kong Society for Transportation Studies (HKSTS), Hong Kong, 2018, 39–46.
2. American Trucking Association. ATA American Trucking Trends 2015. Richmond, USA, 2016, <http://www.trucking.org/article.aspx?uid=d62a253d-b830-4fa3-b069-f7f8ff5d40df>.
3. EC-European Commission. EU Transport in Figures—Statistical Pocketbook. Publications Office of the European Union. Brussels, Belgium. 2013. https://transport.ec.europa.eu/facts-funding/studies-data/eu-transport-figures-statistical-pocketbook/statistical-pocketbook-2013_en.
4. Schittler M. State-of-the-art and emerging truck engine technologies for optimized performance, emissions & life cycle costs. USA, 2003, <https://www.osti.gov/servlets/purl/829810>.
5. Torrey IV, Ford W, Murray D. An Analysis of the Operational Costs of Trucking: A 2014 Update. American Transportation Research Institute, Atlanta, GA, USA, 2014: <http://atri-online.org/2014/09/24/an-analysis-of-the-operational-costs-of-trucking-2014-update-report-request>.
6. Turri V, Besselink B, Johansson KH. Cooperative look-ahead control for fuel-efficient and safe heavy-duty vehicle platooning. IEEE Trans. on Control Systems Tech., 25(2017), 1, 12–28. DOI: 10.1109/TCST.2016.2542044.
7. Bonnet C, Fritz H. Fuel consumption reduction in a platoon: experimental results with two electronically coupled trucks at close spacing. SAE Tech. Paper 2000-01-3056, USA, 2000. DOI: 10.4271/2000-01-3056.
8. Browand F, McArthur J, Radovich C. Fuel Saving Achieved in the Field Test of Two Tandem Trucks, UC Berkeley: California Partners for Advanced Transportation Technology. California PATH Research Report UCB-ITS-PRR-2004-20. 2004. <https://escholarship.org/uc/item/29v570> mm.
9. Bae R, Ramakers R, Henning K, Jeschke S. Organization and operation of electronically coupled truck platoons on german motorways. Proc. of the Automation, Communication and Cybernetics in Science and Engineering 2009/2010, 1(2011), 427–439. Springer Berlin, Heidelberg, Germany. DOI: 10.1007/978-3-642-16208-439.
10. Tsugawa S, Kato S, Aoki K. An automated truck platoon for energy saving, Proc. of the 2011 IEEE/RSJ Inter. Conf. on Intelligent Robots and Systems. 2011, 4109–4114. San Francisco, CA, USA. DOI: 10.1109/IROS.2011.6094549.
11. Bergenhem C, Pettersson H, Coelingh C, Englund C, Shladover C, Tsugawa S. Overview of platooning systems. Proc. of the 19th ITS World Congress, Vienna, Austria. 2012. https://publications.lib.chalmers.se/records/fulltext/174621/local_174621.pdf.
12. Vohra V, Wahba M, Akarslan G, Ni R, Brennan S. An Examination of Vehicle Spacing to Reduce Aerodynamic Drag in Truck Platoons. 2018 IEEE Vehicle Power and Propulsion Conference (VPPC), USA. 2018, 1-6, DOI:10.1109/VPPC.2018.8604977. DOE OSTI Report 1561786, <https://www.osti.gov/pages/servlets/purl/1561786>.
13. Pandian N. Drag Reduction: The Pursuit of Better Fuel Economy. Illumin Magazine, XIV (2011), No. 1, Univ. of Southern California, USA. <https://illumin.usc.edu/drag-reduction-the-pursuit-of-better-fuel-economy/>.
14. Lammert M, Duran A, Diez J, Burton K. Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass. SAE Int. J. Commer. Veh., 7(2014), 2, 626-639. DOI:10.4271/2014-01-2438.
15. Zhang L, Chen F, Ma X, Pan X. Fuel Economy in Truck Platooning: A Literature Overview and Directions for Future Research. J. of Adv. Transport., 2020, (Article ID 2604012), 1-10. <https://www.hindawi.com/journals/jat/2020/2604012/>.
16. Ashley S. Truck Platoon Demo Reveals 15% Bump in Fuel Economy. SAE International, 2013. <http://www.sae.org/11937>.
17. Smith J, Mihelic R, Gifford B, Ellis M. Aerodynamic Impact of Tractor-Trailer in Drafting Configuration. SAE Int. J. Comm. Veh., 7(2014), 2, 619-625, DOI:10.4271/2014-01-2436. DOI: 10.4271/2014-01-2436.
18. Johansson KH. Cooperative driving for road goods transportation: Optimization and control. Proc. of the 33rd Chinese Control Conference, Nanjing, China, 2014. DOI: 10.1109/CCC32826. 2014.
19. Davila A, Aramburu E, Freixas A. Making the best out of aerodynamics: Platoons. Proc. of the SAE Tech. Paper Series, USA. 2013. DOI:10.4271/2013-01-0767, 2-s2.0-84881211488.
20. Sovran G, Bonn M. Formulae for the Tractive-Energy Requirements of Vehicles Driving the EPA Schedules. SAE Tech. Paper 810184. 1981. DOI:10.4271/810184.
21. Sovran G. Tractive-Energy-Based Formulae for the Impact of Aerodynamics on Fuel Economy Over the EPA Driving Schedules. SAE Tech. Paper 830304. 1983. DOI:10.4271/830304.
22. Alam AA, Gattami A, Johansson KH. An experimental study on the fuel reduction potential of heavy duty vehicle platooning. Proc. of the 13th Inter. IEEE Conf. on Intelligent Transportation Systems, 2010, 306–311. DOI:10.1109/ITSC.2010.5625054.
23. Liang KY, Martensson J, Johansson KH. Heavy-duty vehicle platoon formation for fuel efficiency. IEEE Trans. on Intelligent Transportation Systems, 17(2016), 4, 1051–1061. DOI: 10.1109/TITS.2015.2492243.
24. Humphreys H, Batterson J, Bevely D, Schubert R. An Evaluation of the Fuel Economy Benefits of a Driver Assistive Truck Platooning Prototype Using Simulation, SAE Tech. Paper 2016-01-0167, 2016. DOI:10.4271/2016-01-0167.

25. Tsugawa S, Jeschke S, Shladover SE. A review of truck platooning projects for energy savings. *IEEE Trans. Intelligent Vehicles*, 1(2016), 1, 68-77. DOI:10.1109/TIV.2016.2577499.
26. Gnatowska R, Sosnowski M. The influence of distance between vehicles in platoon on aerodynamic parameters. *EPJ Web of Conferences. EDP Sciences*. 2018, 180(02030),1-5. DOI: 10.1051/epjconf/201818002030.
27. Zabat M, Stabile N, Farascaroli S, Browand F. The Aerodynamic Performance Of Platoons: A Final Report. UC Berkeley: California Partners for Advanced Transportation Technology. 1995. <https://escholarship.org/uc/item/8ph187fw>.
28. Hong P, Marcu B, Browand F, Tucker A. Drag forces experienced by two, full-scale vehicles at close spacing. Univ. of Southern California, California Partners for Advanced Transportation Technology, California Path Research Report UCB-ITS-PRR-98-5.1998. <https://escholarship.org/uc/item/50q2p3sn>.
29. Hucho WH. Aerodynamics of road vehicles: from fluid mechanics to vehicle engineering. Elsevier Science, ISBN 9781483102078, 2013. <https://books.google.co.bw/books?id=psP8B AAAQBAJ>. DOI:10.1016/C2013-0-01227-3.
30. Zheng Y, Li SE, Li K, Borrelli F, Hedrick JK. Distributed model predictive control for heterogeneous vehicle platoons under unidirectional topologies. *IEEE Trans. on Control Systems Technology*, 25(2017), 3, 899–910. DOI: 10.1109/TCST.2016.2594588.
31. Richards A, How JP. Robust distributed model predictive control. *Inter. J. of control*, 80(2007), 9, 1517–1531. DOI: 0.1080/00207170701491070.
32. Calafiore GC, Fagiano L. Robust model predictive control via scenario optimization. *IEEE Trans. on Automatic Control*, 58(2013), 1, 219-224. DOI: 10.1109/TAC.2012.2203054.
33. Li H, Shi Y. Robust distributed model predictive control of constrained continuous-time nonlinear systems: A robustness constraint approach. *IEEE Trans. on Automatic control*, 59(2014), 6, 1673–1678. DOI: 10.1109/TAC.2013.2294618.
34. Mayne DQ. Model predictive control: Recent developments and future promise. *Automatica*, 50(2014), 12, 2967-2986. DOI: 10.1016/j.automatica.2014.10.128.
35. Koontse MD, Mosata K, Phologolo T, Subaschandar N. Platooning By Trucks–Is It Possible?. Central Botswana Mathematics and Statistical Sciences Conference II, Palapye, Botswana. 2022.
36. EASYCFD: A Two-dimensional Computational Fluid Dynamics software Manual Version 4.4.4. www.easycfd.net. 2020.
37. Batchelor GK. An Introduction to Fluid Dynamics. Cambridge University Press, U.K. 1967. ISBN 978-0-521-66396-0.
38. White FM. Viscous Fluid Flow. 3rd Ed., McGraw-Hill Publication. ISBN 978-0-07-124493-0. 2006. <https://books.google.co.bw/books?id=fl6wPwAACAAJ>.
39. Launder BE, Spalding DB. Mathematical Models of Turbulence. Academic Press, London and New York, 1972. ISBN 0-12-438050-6.
40. Launder BE, Spalding DB. The Numerical Computation of Turbulent Flows. *Comp. Meth. in App. Mech. and Engng*, 3(1974), 3, 269-289. DOI: 10.1016/0045-7825 (74)90029-2.
41. Menter FR, Kuntz M, Langtry R. Ten Years of Industrial Experience with the SST Turbulence Model. *Turbulence, Heat and Mass Transfer 4*, ed: K. Hanjalic, Y. Nagano, and M. Tummers, Begell House, Inc., 2003; 625–632.
42. Menter FR, Kuntz M, Langtry R. The SST Turbulence Model with Improved Wall Treatment for Heat Transfer Predictions in Gas Turbines. *Proc. of the International Gas Turbine Congress*. 2003, Tokyo.
43. Subaschandar N. Prediction of Turbulent Flow past a Rectangular Cylinder. *J. of Xi'an Univ. of Archi.&Tech.(JXAT)*, China, XIV(2022), 1, 370-380. DOI:10.37896/JXAT14.01/314437.
44. Yin G, Monaci T, Ong MC. Numerical simulation of flow around two 5:1 rectangular cylinders at a high Reynolds Number. *IOP Conf. Series: Mat. Sci. and Engng*. 700(2019), 012010-012019. DOI:10.1088/1757-899X/700/1/012010.
45. Dahl SM. Unsteady RANS Simulation of Flow around Rectangular Cylinders with different Aspect Ratios at High Reynolds Number. Master's thesis, Institutt for Marin Teknikk, NTNU, 2014.
46. Bruno L, Fransos D, Coste N, Bosco A. 3D flow around a rectangular cylinder: a computational study. *J. of Wind Engng and Indus. Aerod.*, 98(2010), (6-7), 263-276. DOI:10.1016/j.jweia.2009. 10.005.
47. Mannini C, Šoda A, Schewe G. Numerical investigation on the three-dimensional unsteady flow past a 5:1 rectangular cylinder. *J. of Wind Engng and Indus. Aerod.*, 99(2011), 4, 469-482. DOI: 10.1016/j.jweia.2010.12.016.
48. Schewe G. Reynolds-number-effects in flow around a rectangular cylinder with aspect ratio 1:5. *J. of Fluids Struc.*, 39(2013), 15-26. DOI:10.1016/j.jfluidstruct.2013.02.013.
49. Son O, Cetiner O. Drag Prediction in the Near Wake of a Circular Cylinder based on DPIV Data. *J. of App. Fluid Mech.*, 9(2016), 4, 1963-1968. DOI:10.18869/acadpub.jafm.68.235. 246 63.