Effect of underbody diffuser on the aerodynamic drag of vehicles in convoy

Deepinder Jot Singh Aulakh*

Abstract: Presented work is extension to previous studies of convoying where prime focus was to study effect of intervehicular spacing and upperbody geometry of vehicles on aerodynamics of convoy. Current study examines the effect of underbody diffuser on coefficient of drag (Cd) of convoy of two reference car bodies (Ahmed body). CFD analysis of convoy is done using Shear-Stress-Transport model under moving ground conditions. The length of lead body’s diffuser is taken as 0.222 m with diffuser angle (degrees) of 0 (no diffuser), 3, 5, 7, 9, 15, 20, 25 and 30 each at intervehicular spacing of 0.25 and 0.75 Ahmed body length. Each configuration thus resulting was analyzed with lead body backlite angle of 25° (pre-critical) and 35° (post-critical) with follow body’s backlite angle remaining 25°. CFD analysis are conducted after performing two validation analyses from previous studies. To understand the flow features developed on Ahmed body due to an underbody diffuser a preliminary analysis is done on an isolated body with 25° and 35° backlite angles by applying each diffuser angle used in current study. After analysis of convoy, drag on lead and follow vehicles is found to be also dependent on the axial vortices formed due to diffuser in addition to those from backlite surface of lead body. Average drag on cases with diffuser is found to be lesser than the no diffuser cases up to a certain diffuser angle. Thus applying diffuser has a potential for reducing the overall drag on convoy.

ABOUT THE AUTHOR
Deepinder Jot Singh Aulakh is currently working as quality engineer at Heromotocorp Ltd. He has done his Bachelor of Technology in Mechanical engineering from NIT Jalandhar. His key area of interest is dynamics of road vehicles. His work include design of retractable steering column and variable length wishbones for suspension of off road vehicles and converting 3,100 hp diesel engine to 3,300 hp in a project with Indian railways.

Convoying of road vehicles is widely accepted as fuel saving technique by reducing overall aerodynamic drag on vehicles. The research reported in this paper is extension to previous studies on aerodynamics of convoy. Current study explores the effect of installing underbody diffuser to vehicles on overall aerodynamic drag of convoy. The results obtained are quite encouraging as by application of diffuser the overall drag of convoy is further reduced. Thus opening a further prospective of fuel saving.

PUBLIC INTEREST STATEMENT
As consumption of fuel by road vehicles is increasing, many new techniques are being developed to increase their mileage. Convoying is one of these techniques. In this technique, vehicles traveling on road would assume convoy shapes similar to train carriages and thus will experience lesser air resistance. The lesser the air resistance, the lesser the effort vehicles need to travel (power consumed) and lesser the fuel consumption. Studies done in this area are more concerned with studying the air flow around upper body of a vehicle and finding a suitable distance between convoying vehicles for reducing maximum amount of air resistance. The present study expands this horizon further and studies the flow of air under the body of vehicles travelling in a convoy. This resulted in further possibility of reducing air resistance, thus giving a potential possibility of saving more fuel and money.
1. Introduction

In Automated Highway System (AHS), vehicles travelling on highway assume convoy arrangements, thus experiencing the drag benefits by being closely coupled at high speeds. Vehicles are equipped with Intelligent Transport Systems (ITS) which enable them to travel “safely” close together (less than one car length) (Hall, Thakker, Horan, Glazer, & Hoene, 1997).

There is good amount of study done in the area of convoying as, Zabat, Frascaroli, and Browand (1994) studied the effects of inter-vehicle spacing on aerodynamic drag of vehicles using mini-van geometries and found that significant drag savings were experienced by both lead and trailing model at close proximity, with the lead model benefiting greater and the trailing model benefits with evenly distributed trend over the spacing (Zabat et al., 1994).

Watkins & Vino, 2004 conducted experiments to understand the effects of inter-vehicle spacing using two Ahmed car models with backlite angle of 30°. Significant drag increases were found for the rear Ahmed body at close spacing. It was concluded that the effect of the strong vortex system arising from the slant back of lead body was the cause of the drag and lift changes of the rear vehicle (Watkins & Vino, 2004).

Pagliarella (2009) studied the effects upperbody’s geometry on aerodynamic drag of the convoy of two Ahmed bodies by applying pre-critical (25°) and post critical (35°) backlite angle on the lead body i.e. one configuration with 25° lead and 25° follow vehicle and other with 35° lead and 25° follow vehicle. In both cases the trailing model exhibited a rise in drag force above model in isolation values, whilst the leading model exhibited a drag reduction. Net platoon drag was lower than for model in isolation values. Two distinct gap flow phenomena were observed in the intervehicular spacing examined, based on both leading model geometries (Pagliarella, 2009).

As it can be seen from previous studies that most of the literature available in convoying is concerned with exploring the effect of either intervehicluar spacing (Watkins & Vino, 2004; Zabat et al., 1994) or upper body geometry of the vehicles in convoy (Pagliarella, 2009). There is no literature available for studying effect of underbody geometry of vehicles on aerodynamics of a convoy. As underbody flows affect the aerodynamics of road vehicles significantly. Current study aims to fill this gap by exploring the effect of underbody diffuser on the aerodynamic drag of vehicles in convoy of a two Ahmed bodies.

2. Reference model and its flow characters

The most common reference model used by researchers is Ahmed body (Le Good & Garry, 2004). Current study also uses Ahmed body (Figure 1) as reference model as it represents some of the critical flow features (Figure 2) around the vehicle body while maintaining geometrical simplicity (Ahmed, Ramm, & Faltin, 1984). In Ahmed body for backlite angle (φ) less than 12.5° flow on it remains fully attached and longitudinal vortices (c-pillar) are formed and drag coefficient decreases with increase of the backlite angle. Beyond 12.5° a separating bubble is observed on the backlite surface in addition to strengthened longitudinal vortices. Coefficient of drag increases with increasing backlite angle up to angle of 30°. Upon further increasing the backlite angle the flow is completely separated from the backlite surface and longitudinal vortices lose their strength; drag coefficient decreases abruptly (Ahmed et al., 1984).
3. Methodology and scope
There are many variables in study of this kind; these include vehicle geometric configuration (e.g. truck or car, including fastback, notchback, etc.), intervehicular spacing, number of vehicles in convoy, configuration of diffuser (length and angle) and the nature and relative direction of the atmospheric wind. In order to restrict the number of variables, investigation is limited to CFD simulation of representative car geometry in calm conditions (i.e. no yaw angle) with two Ahmed bodies in a row. Two cases; one with backlite angle 25° in lead body and 25° follow body (25°/25°); while in other case 35° lead and 25° follow body (35°/25°) are chosen in order to study effect of pre and post critical lead body configuration respectively. For above two cases lead body's underbody diffuser length ($l_d$) is taken as 0.222 m with variable diffuser angle ($\alpha_d$ degrees) of 0 (no diffuser), 3, 5, 7, 9, 15, 20, 25 and 30. Underbody diffuser is chosen as only representative of the underbody flow because it is primary component affecting it (Cooper, Bertenyi, Dutil, Syms, & Sovran, 1998). It has also been shown in
studies that the diffuser angle play important role in the function of diffuser and wake flow structures (Cooper et al., 1998; Fu Limin, 2006). Therefore various angles of diffuser are taken in order to have detail analysis of flow generated by underbody. Every possible configuration resulting from above was tested at intervehicular spacing of 0.25 and 0.75 model length (x/l) with moving ground. As available study on Ahmed body with diffuser is restricted to 35° backlite angle with diffuser angles up to 9° (Huminic, Huminic, & Soica, 2012). Therefore to understand the effect of 25° backlite angle and higher diffuser angle a preliminary CFD analysis is done on Ahmed body in isolation. The configurations chosen for this analysis are 25° and 35° backlite angles. Diffuser angles (degrees) are varied as 3, 5, 7, 9, 15, 20, 25 and 30.

The ground condition is taken as moving ground because in static ground conditions the boundary layer developed will affect the results flow in underbody thus give erroneous results for coefficient of drag (Hucho, Janssen, & Schwartz, 1975; Wing, 1981).

4. Meshing

The meshing is done in ANSYS workbench. Mesh is divided into 3 zones. First is inflation zone which first aspect ratio is set as 5 at growth rate of 1.2 (Best practice guidelines for handling Automotive External Aerodynamics with FLUENT, 2016). This is done to properly resolve the boundary layer along the surface of Ahmed body. The second is exterior to first zone; named as body of influence. This is done to fully resolve the flow pattern around the Ahmed body. The outermost zone has relatively coarser mesh for saving computational time. The mesh is shown in Figure 3. This mesh has three bodies of influences as shown in Figure 4. The body I and III have 20 mm as size of element and body II is having 15 mm as size of element. These sizes were decided after conducting grid independence studies. The smaller element size in body II is kept to more accurately resolve the flow region between lead and follow body. The resulting number of elements is 1.1 million for isolated body and 1.5–1.7 million for cases with bodies in tandem.
5. Solver settings
In this study, the analysis is done with boundary conditions similar to previous study by Huminic et al. (2012) for ease of validation. These boundary conditions are given as velocity of vehicle body relative to air in x direction (Figure 4) is 40 m/s with 0.2% turbulence intensity.

Shear-Stress-Transport (SST) model (Menter, 1994) is used because accuracy of this model has been proved in various previous studies (Huminic & Huminic, 2009, 2010; Huminic et al., 2012). Second order implicit equations for Pressure, Momentum, Turbulence K. E. and Turbulence Dissipation Energy are used.

6. Solver accuracy
The accuracy of SST model for used mesh and solver settings is validated by comparison with previous studies as following:

(1) Comparison with results of study on Ahmed body with diffuser (Huminic et al., 2012).
(2) Comparison] with experimental results for two Ahmed bodies in convoy (Pagliarella, 2009).

6.1. Validation 1
The CFD results obtained for Ahmed body (diffuser length $l_d/l = 0.212$) are compared those by Huminic et al. (2012). $l_d/l = 0.2$ case of previous study is chosen for comparison because it is close to value of current study i.e. 0.212. The results are conforming well as shown in Figure 5.
6.2. Validation 2
In second validation the CFD analysis is done on two Ahmed bodies in convoy in similar arrangement as experimental study of Pagliarella (2009). This analysis is done with static ground conditions because experiments are done on static ground (Pagliarella, 2009). From results obtained the trend is observed to be similar for both CFD and experiments (see Figures 6a and 6b) the slight over prediction of the computational values is mainly due to the overestimation of the base pressure drop (Gilliéron & Chometon, 1999).

7. Results

7.1. Model in isolation
As seen from vector plot (Figure 7) in the wake of Ahmed body at a distance of 0.2 m from the rear end of body, four axial vortices are formed two from the upper backlite surface and two from the underbody diffuser surface.

The results for variation of drag coefficient (Cd) are shown in Figure 8. The trend of variation of Cd with diffuser angle is similar in both (25° and 35° backlite) cases. The Cd first decreases up to diffuser angle of 9° and flow is fully attached as shown in wall shear × plot Figure 9 (analogous with regime of Ahmed body up to backlite angle of 12.5° (Ahmed et al., 1984) and \( \text{l/l}_{0} = 0.2 \) case of previous study (Huminic et al., 2012). After that drag starts to rise this occurs due to formation of separation bubble.
at the diffuser surface shown by negative wall shear (9° case) in Figure 9 and strengthening of the axial vortices formed by diffuser surface causing both pressure and vortex induced drag (Hucho, 1998) to act. After reaching maxima at about 25° diffuser angle, Cd starts to decrease as flow is fully separated from diffuser surfaces shown by wall shear (for 30° case) in Figure 9. Thus reducing the strength of the vortices resulting in improved pressure recovery (Ahmed et al., 1984).

The case with backlite angle of 35° has lower drag coefficient than that of 25° because of its post critical geometry (35°), the upper vortices have lesser strength (Ahmed et al., 1984) so only underbody diffuser is producing strengthened axial vortices that are generating drag contrary to 25° case where both backlite and diffuser surfaces generate high strength vortices resulting in more drag.

7.2. Models in tandem

7.2.1. Lead model
Axial vortices generated by lead body have two way effect on its aerodynamic drag one is increasing it by producing vortex induced drag (Hucho, 1998) and other is decreasing it by generating feedback pressure at lead body’s base (rear end) after impinging on the follow body (Pagliarello, 2009). The feedback pressure is directly proportional to strength of the vortices and inversely proportional to intervehicluar distance (Pagliarello, 2009).
Figure 9. Wall Shear × plot (35° backlit).
The variation of Cd with diffuser angle is shown in Figure 10. Cd of lead model for each case is lower than isolated values because of feedback pressure developed on the base (rear end) of lead model (Pagliarella, 2009). At intervehicular spacing \( x/l \) of 0.25 the 25° (backlite angle) lead body has lesser drag coefficient than 35° lead body this is due to more feedback pressure (Figure 11) arising at base of former case by two high strength vortices system present (of backlite and diffuser surfaces) as compared to latter where only one strong vortex system is present (of diffuser).

At \( x/l \) of 0.75 effect is opposite i.e. the 25° lead model has higher drag than 35° lead model. Because due to increased spacing in this case the vortices after impinging on follow body are not causing as strong feedback as 0.25 spacing (Pagliarella, 2009). Thus vortex systems have more effect in increasing the drag of lead body (as in isolated) than reducing it by feedback leading to lesser pressure at base of 25° lead than 35° lead (Figure 11).

Also from Figure 10, the trend of Cd at \( x/l = 0.25 \) is different from that of isolated case i.e. drag decrease with increase in diffuser angle, this is because at closer spacing as feedback mechanism is stronger as compared to phenomenon of vortex induced drag; when the diffuser angle is increased more strong vortices are generated from the underbody and more strong feedback pressure is applied on the base of lead body thus decreasing the drag. This decrease continues till diffuser angle of 25° after that Cd increases because after 25° the separation bubble breaks and flow become fully separated at diffuser surface causing axial vortices to lose their strength in result lesser feedback pressure and more drag.

The trend of Cd variation with diffuser angle for spacing of 0.75 (Figure 10) is similar to that of isolated body. This is due to the larger spacing the feedback mechanism is not as strong. Thus leading to behavior like isolated body and can be explained similarly. The only difference is of lesser magnitude of drag than isolated body this is due to presence of follow body which is still causing some feedback pressure.

7.2.2. Follow body
The follow body has higher Cd than isolated cases. This is due to impingement of axial vortices generated by the lead body which increases the pressure at front surface of the follow body (Pagliarella, 2009). Cd vs. diffuser angle for all cases is shown in Figure 12.

At both intervehicular spacings the follow body with 25° backlite angle lead model convoy has more drag than follow body of 35° lead model convoy. This is due to the more pressure generated (see Figure 13) on the front surface of follow body of 25° lead convoy as compared to follower of 35°...
Figure 11. Pressure plot at rear end of lead body.
lead convoy because in 25° lead convoy there are two vortex systems as compared to only one of 35° lead convoy that are striking front surface of follow body.

Also for each backlite angle drag at spacing of 0.25 is more than the corresponding case of 0.75. This is due to the reason that vortices strength decrease as they move farther from the base of lead body which result in more pressure development at the 0.25 distance cases compared to 0.75 cases (Pagliarella, 2009). See Figure 13.

Trends for change of Cd are similar in all cases, Cd first increases with the increase in diffuser angle and after reaching diffuser angle of 25° drag decreases. The reason behind the decrease of drag is that at diffuser angle 25° the shear layers which were forming the axial vortices at lead body are now completely separated from the surface of the diffuser which reduce the vortex strength (Ahmed et al., 1984) and thus causing pressure on the front surface of the follower body to get reduced resulting in lesser drag.

7.2.3. Average drag comparison
To understand the effect of convoying on overall drag coefficient of convoy a comparison of average Cd of bodies in convoy with Cd of isolated geometry of lead and follow body is shown in Figures 14a and 14b.

For models in tandem the average coefficient of drag is less than that of isolated body in all cases except in 25° lead body convoy where the coefficient of drag is more than isolated value for diffuser angles greater than 13°. Thus convoying can also result in larger overall drag depending on the diffuser angle of lead model.

Comparing to no diffuser case (0° angle) average Cd is less for convoy up to diffuser angle of 3° and 5° for cases of 25° lead with spacing 0.25 and 0.75 model length respectively and up to diffuser angle of 3° and 7° for case of 35° lead with spacing of 0.25 and 0.75 model length respectively. From here it can be inferred that applying diffuser to a convoy can further result in reduction of drag as compared to no diffuser case thus opening a further prospective of drag reduction in a convoy.

For diffuser angles greater than 10° Cd increases at greater rate for 0.75 spacing as compared to 0.25 spacing in both graphs. This is due to the increase in Cd of the lead body for 0.75 spacing as compared to reduction in case of 0.25 spacing.
Figure 13. Follow body pressure contour.
8. Conclusions
The drag characteristics of the convoy with underbody diffuser (in lead body) are analyzed in current study. From the analysis of isolated body it is found that drag characteristics arising from the underbody diffuser are similar to upperbody (backlite) surface showing analogous trends for coefficient of drag. The drag characteristics of both lead and follow body of convoy are significantly influenced by axial vortices produced by underbody diffuser.

From the average drag on lead and follow body it is found that drag in convoy can be more or less than isolated bodies depending upon the configuration of convoy. Also up to certain diffuser angles the average drag on convoy is found to be lesser than the case of no diffuser thus opening a newer perspective for further drag reduction in a convoy.

This work can be further expanded by using following recommendations:

- Study is conducted on bluff body without any wheels the further study can include simulations of wheels also for more accurate flow prediction.
- Since this work is based on only Ahmed body which only replicates the flow around a production vehicle. Further study can be done on the actual production models for more realistic results.
- Also as study uses only two vehicle convoy this can be further extended up to more number of vehicles for more practical cases.
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Author details
Deepinder Jot Singh Aulakh
E-mail: deepinderjot@gmail.com
1 Department of Mechanical Engineering, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar, Punjab, India.

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