Visualising Vehicle Platoon Aerodynamics Using ICFD in LS-DYNA®

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Abstract

Since the fuel crisis in the 1970s, platooning of vehicles has been considered as a method of reducing fuel consumption and improving traffic congestion. Until now, research has primarily considered homogeneous platoons with varying separation distances. Furthermore, the basis of much of the work so far has been experimental instead of computational so fluid flow interactions between the platooning vehicles are not well understood. The Incompressible Computational Fluid Dynamics (ICFD) solver in LS-DYNA provides a powerful method to simulate flow interaction around a body and produce data to be used in understanding the aerodynamic behaviour. This paper shows some of the capabilities of LS-DYNA in visualising fluid flow around complex bodies when in platooning formation. Of interest in this paper is the variation of geometry of the vehicles within a platoon with a set separation distance. This paper considers the ability of LS-DYNA to analyse fluid-structure interaction and explores how this could be of use for future platooning research.

Introduction

Platooning may be defined as the assembling of two or more vehicles in close proximity with the view to reduce total drag acting on the group. The idea of platooning first came about following the fuel crisis in 1970s since it seemed to be a viable solution to both reduce fuel consumption and alleviate traffic congestion. This potential reduction in aerodynamic drag was studied experimentally, with Hucho [1] finding total drag reducing to 80% of the original value for three car platoons, as shown in Figure 1. Initially the concept was held back by a lack of control technology and research, but advances in this area has once again displayed the potential of platooning.

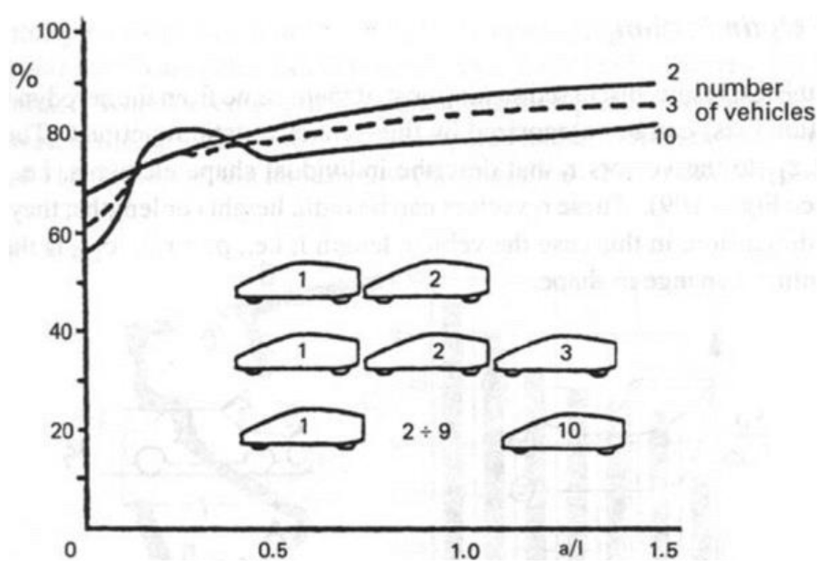

Figure 1: Total aerodynamic drag for platoons with 2, 3 and 10 vehicles by Hucho [1]

Platoon Theory

Figure 2 shows experimental work by Hucho considering platoons of varying isolated drag coefficient. At all separation distances for all cases, the front body experiences a reduction in drag compared to the isolated case. This phenomenon was also shown by work by Hoerner who suggested that this was due to an 'increased static pressure' between the two bodies which effectively 'pushed the first one forward' [2]. Therefore, previous work concludes that the front body in a platoon always experiencing a reduction in drag and so this should be used as a verification tool for ICFD studies.

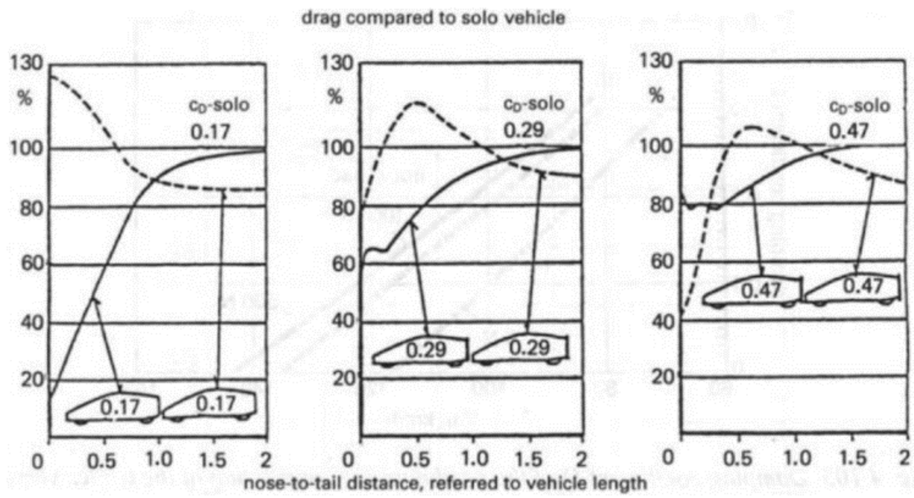

Figure 2: Change in drag coefficient with separation distance for platoons of low, medium and high isolated drag values by Hucho [1]

Studies of Non-Homogeneous Platoons

Work in this area has primarily considered homogeneous platoons with varying separation distance between the bodies. Although this is necessary to determine an optimal separation distance, if platooning was implemented it is likely the geometries of the component vehicles would vary. This was noted by Le Good, Boardman, Resnick and Clough who looked at platoons of three 'Windsor Models' with varying angles for backdrops [3]. Their experimental results found using the Coventry University Low-Speed Wind Tunnel showed a wide variation in the change of drag for the different combinations, displaying the importance of considering non-homogeneous platoons. This dependence on geometry may be explained by Hucho's drawings of characteristic flow regimes for three standard vehicle types, as shown in Figure 3. Clearly the way in which these different geometries are arranged within a platoon will heavily impact the overall flow behaviour and drag associated.

Due to the complex nature of the aerodynamics of platooning, much of the research into it has been experimental rather than computational. This has resulted in work based predominantly on fundamental theory and trial and error, so there is little understanding of the aerodynamic interactions themselves. This paper will present a method to visualise these interactions with the view to improve understanding of platooning behaviour and show LS-DYNA as a tool to aid future research.

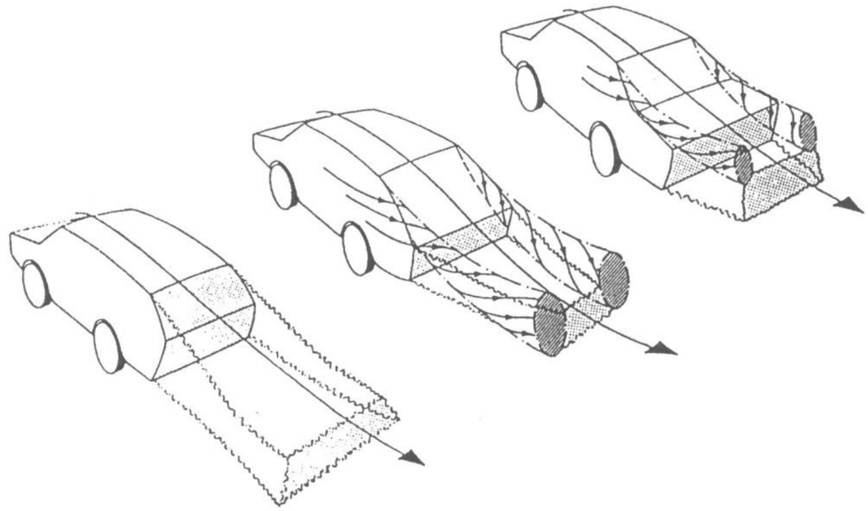

Figure 3: Characteristic flow for estateback, fastback and notchback (left to right) by Hucho [1]

DrivAer Geometry

The aim of this study is to visualise the characteristic flow behaviour within a platoon, so a vehicle model was required which would produce this whilst not overcomplicating the flow with additional vortices. The model also needed to have the capability to vary upper body geometry to represent the three characteristic flow regimes shown in Figure 3.

One model used in work on vehicle aerodynamics is the Ahmed body which was developed by Ahmed, Ramm and Faltin in 1984 [4]. This features interchangeable rear sections which allow the angle of the rear backdrop to be altered to produce each of the characteristic flow regimes. However, the Ahmed model is simplistic in geometry and therefore does not represent the geometry of modern passenger vehicles well, particularly due to its flat front. Le Good, Resnick, Boardman and Clough used a self-designed model they named "MSM" [5]. This closely resembled existing vehicle geometries and, by altering the backdrop shape, provided a proof-of-concept that geometry affects platooning aerodynamics. The MSM model therefore presented a viable choice for this study due to its simple but realistic geometry. However, since the MSM model is new, the only data available is that from this study and so instead a more widely used model was required, which was found in the DrivAer model.

The DrivAer model [6] was developed by the Technical University of Munich (TUM) and is based upon the geometry of the Audi A4 and BMW 3 series. DrivAer offers a model which more closely resembles modern passenger vehicles than simple models previously used. It comes in a wide range of configurations, the choices for which are summarised in Table 1 and shown in Figure 4. These are for each of the three models - estateback, fastback and notchback. To avoid flow vortices produced due to the door handles, these were also removed during meshing. The DrivAer models are free to download and use so there is extensive experimental data available which will be used to determine the accuracy of the LS-DYNA model.

Table 1: DrivAer configurations used in model

Underbody Geometry	Smooth Underbody - **S**
Mirror Configuration	Without Mirrors - **woM**
Wheel Configuration	Without Wheels - **woW**

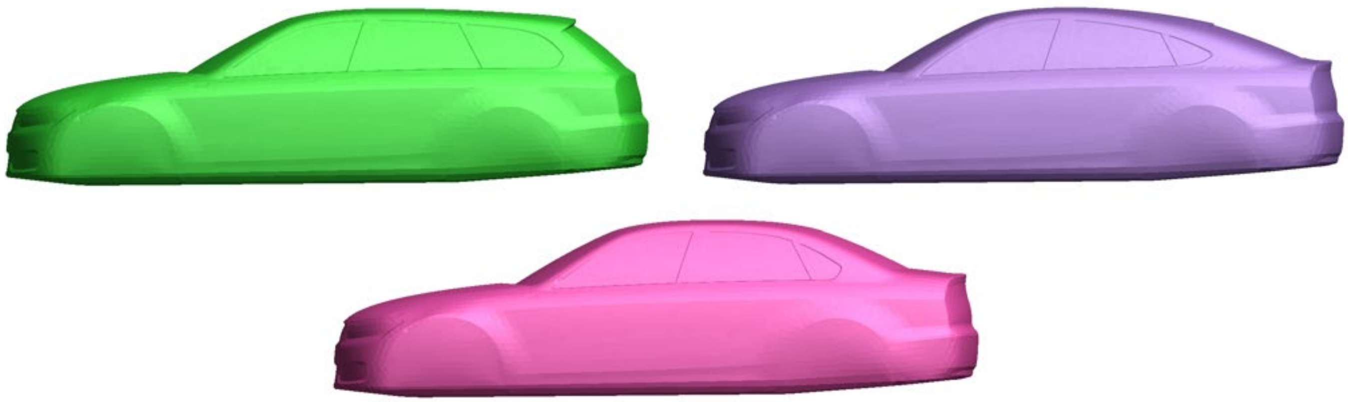

Figure 4: DrivAer models - estateback (top-left), fastback (top-right), notchback (bottom)

Setup and Validation

In Hypermesh, a 50mm mesh was applied to each car surface and a 25mm mesh to areas where high pressure gradients were anticipated, such as around the tops of the side windows and on the rear window. The meshes were exported as Keyword files and read into Oasys PRIMER.

The model set-up for this study is based on that used in *'Fluid Structure Interaction Simulation of Bonnet Flutter'* presented at the 15th International LS-DYNA Users Conference in 2018 by Dilworth, Ashby and Young [7]. Figure 5 shows the domain used for the ICFD study along with the slip boundary applied to the top and side walls, prescribed velocity in of 30m/s and prescribed pressure out of zero. The ground was prescribed a velocity of 30m/s in same direction as the fluid velocity to imitate the vehicle moving relative to the road. A sensitivity study was carried out for the size of the domain and found that the results for an isolated model were independent of its position. The model domain and individual vehicle models were merged within Oasys PRIMER to produce each simulation setup.

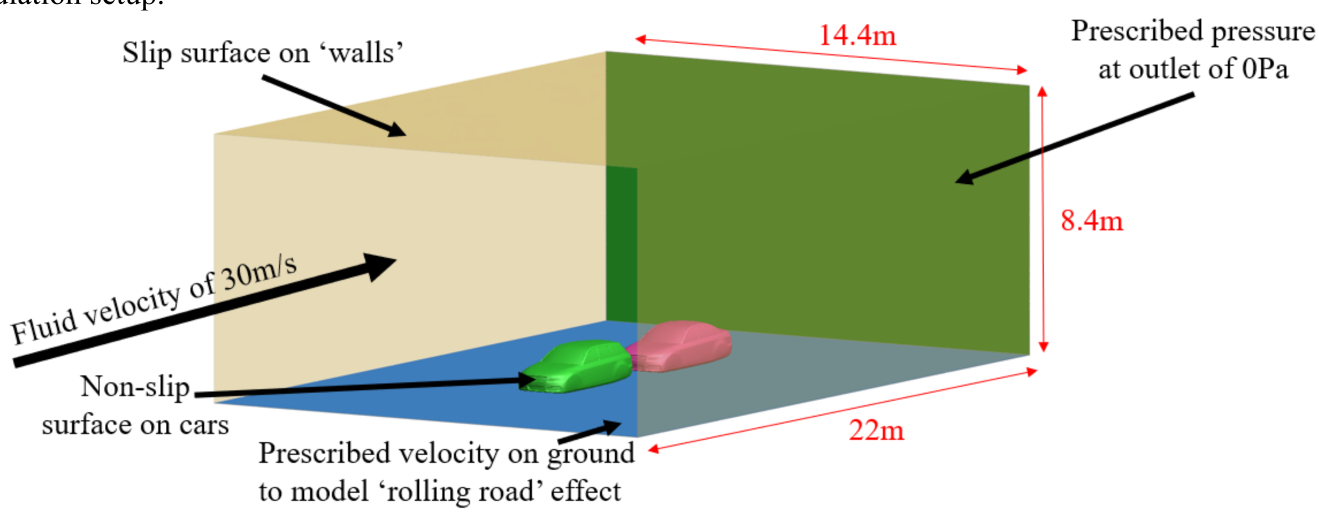

Figure 5: Model set-up in Oasys PRIMER

The volume mesh is generated by the ICFD mesher built into the analysis in LS-DYNA. Using *MESH_VOLUME [8], the surfaces of the vehicles and domain walls are input and the ICFD mesher forms the volume mesh in between. Refined volume meshes are specified around both vehicles as well as the moving ground by using *MESH_BL. *MESH_SIZE_SHAPE was used to create a box around the vehicles, in which the volume mesh elements were set not to exceed 25mm in size. In all simulations, whole cars are modelled to account for non-symmetrical turbulence. A simulation time of one second was chosen so that the simulation had time to reach a steady state. Due to the nature of the turbulent flow creating oscillating vortices, it is then necessary to take the sum average of values between 0.5 and 1.0 seconds of analysis.

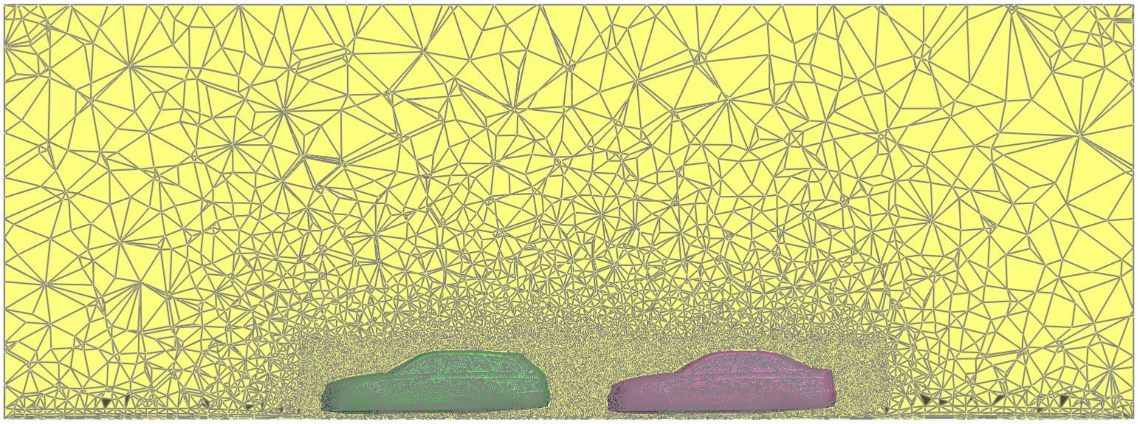

Figure 6: Cut section showing variation in density of volume mesh in Oasys D3PLOT

To validate the model setup in LS-DYNA and ensure the mesh density was adequate, the notchback model was first considered in isolation. Previous publications have used the pressure down the centreline as a method of validation, so this is produced in Figure 7. The trend appears to match the experimental data from TUM well, although it must be noted that there are a few areas where it deviates. The drag coefficient for the notchback model was compared to values published by TUM and Figure 8 shows the agreement between the two. It was therefore concluded that the model was producing expected results and so analysis proceeded to consider the models of other geometries.

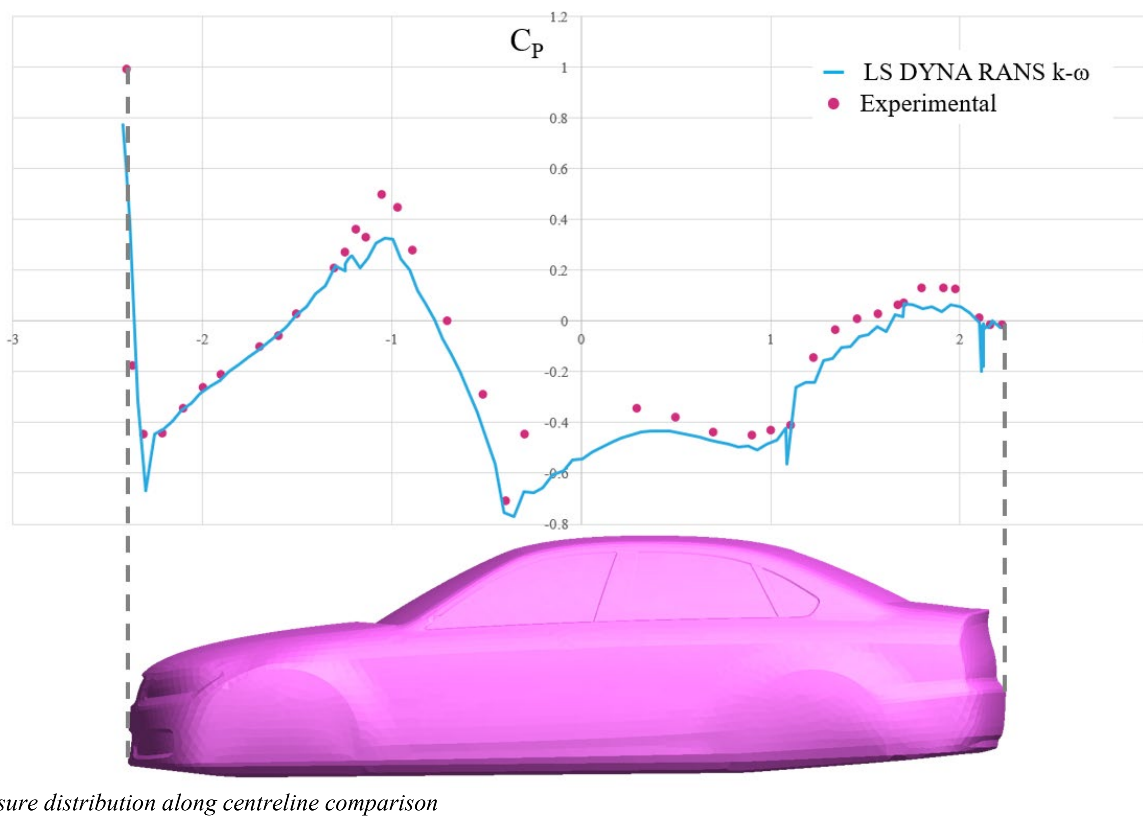

Figure 7: Pressure distribution along centreline comparison

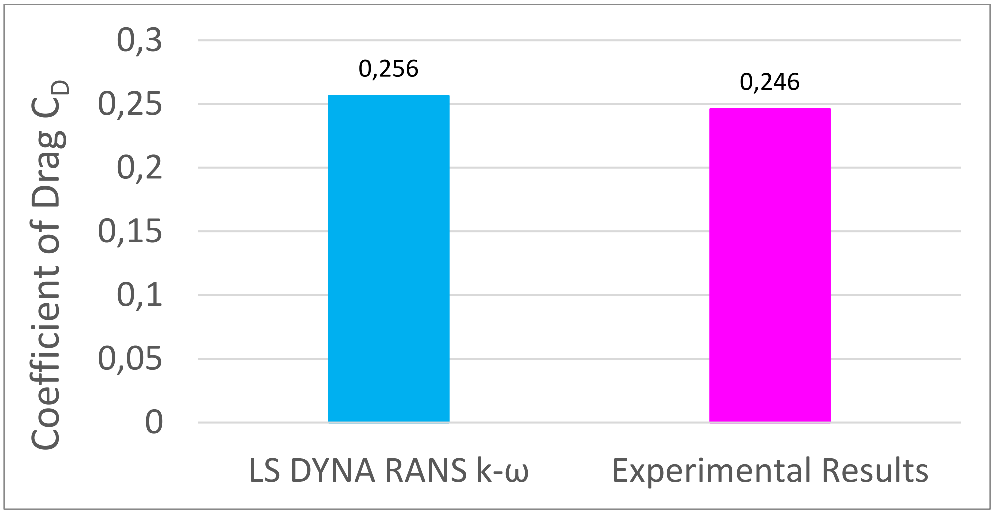

Figure 8: Drag coefficient comparison for notchback

Figure 9 displays the absolute value of the coefficient of drag for each model as well as the percentage error compared to experimental results. The large error in the estateback model will likely be due to the complexity of flow separation at the rear window. One method of reducing this error would be to increase the mesh density around the rear window to better capture the flow separation. A mesh sensitivity study was therefore carried out by using a finer mesh for the DrivAer model. It was found that, although the finer mesh model produced a drag coefficient and centreline pressure profile more representative of the experimental data, the increase in run time was significant.

Another method of reducing the percentage error for the drag coefficients would be to consider a more accurate turbulence model. For this study, the RANS k-ω turbulence model was used rather than the LES turbulence model. In their study, Dilworth, Ashby and Young [7] concluded that the RANS k-ω turbulence model produced a flow field which wasn't as accurate as that produced using the LES turbulence model when comparing to experimental data. However, using the LES turbulence model took almost four times as long as using the RANS k-ω model run in steady state.

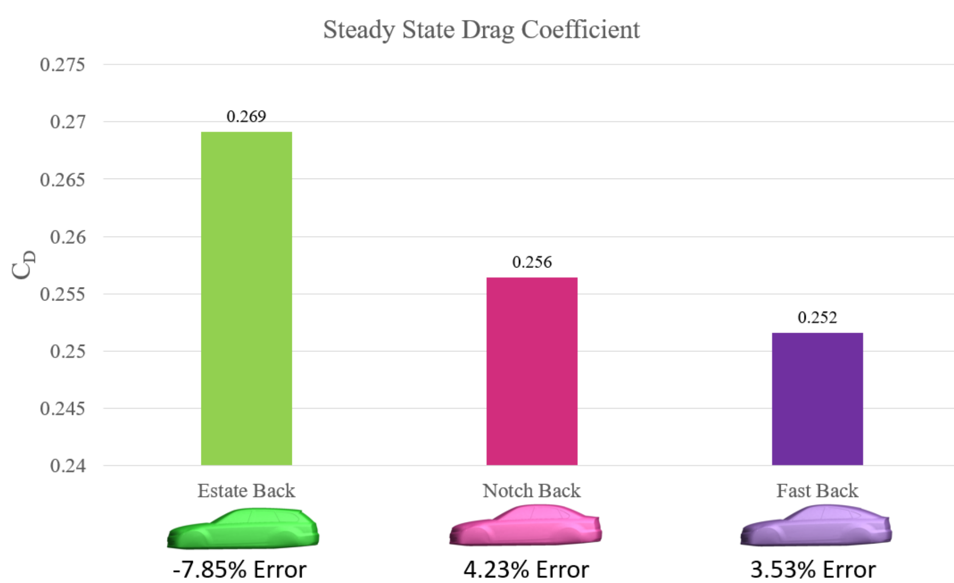

Figure 9: Drag coefficient for each model in isolated study

The key aim of this study is to produce a model which allows the visualisation of the flow behaviour for platooning vehicles. Consequently, trends in data and overall flow behaviours are currently more important than exact numerical solutions to improve understanding in this area. Increasing the mesh density and changing to the LES turbulence model would significantly increase run time while only producing marginally more accurate results. It was therefore concluded that the current setup was adequate in achieving the aims set out for this paper. However, these two methods represent two ways in which the model may be enhanced in the future once the aerodynamic flow behaviour is better understood. The DrivAer model may also be complicated in the future by including wing mirrors, engine bay flow and wheels.

The coupling algorithms available in LS-DYNA provide a method to consider fluid-structure interaction problems whilst using the same simulation solver. This was previously displayed by Dilworth, Ashby and Young when considering the interactions resulting in the phenomena of hood flutter [7]. However, in the context of platooning, this feature is likely to have many possible uses for future research and to aid further understanding. It is therefore clear how LS-DYNA both provides an accurate ICFD solver while having the relevant features in order to enhance future models and analysis.

Two-Car Platoons

To consider the impact that changes in geometry of vehicles in a platoon has on aerodynamics, each model was considered at the front and the rear of a two-car platoon, resulting in nine configurations. These therefore represent all combinations of typical flow regimes with the aim to characterise simplified flow behaviours of passenger vehicle platoons with a separation distance of a quarter of a car length. Figure 10 shows the results for each configuration of platoon in terms of the percentage change in drag coefficient. For each model in the platoon, this percentage change is relative to that same model when analysed in isolation to normalise the results.
The vehicle models used in each platoon are shown above their corresponding data points.

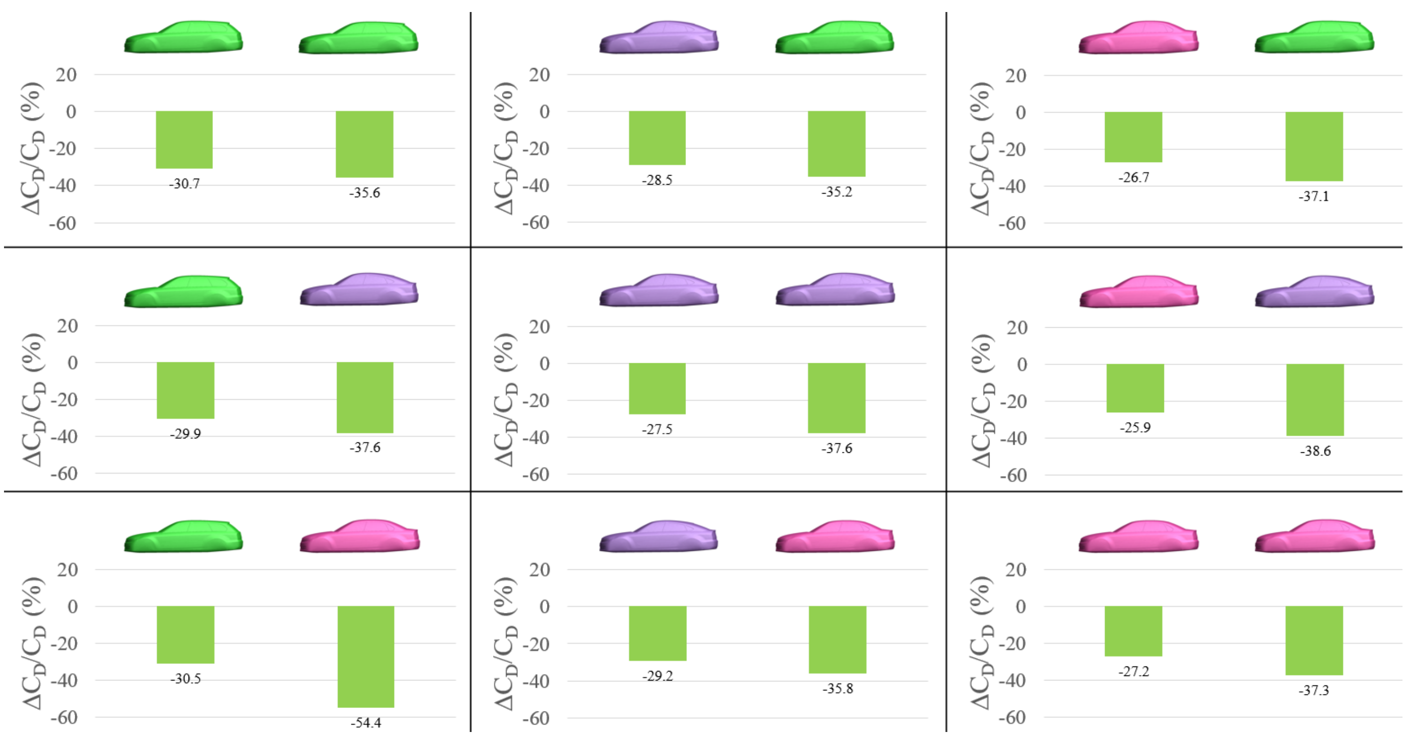

Figure 10: Nine two-car combinations showing percentage change per vehicle compared to same vehicle in isolation

All configurations resulted in a drag reduction for the leading vehicle. This ranged from a reduction of 25.9% for the notchback-fastback to 30.7% for the estateback-estateback. It was expected that the lead vehicle would always experience a drag reduction in a platoon as this is what was shown by the experimental work carried out by Hucho and Hoerner.

Figure 11 displays the pressure distribution down the centreline for the fastback model when isolated and when platooning with an estateback model behind. The blue colouring behind the fastback in the isolated case highlights that there is an area of negative pressure which will be contributing to the drag force. On the other hand, in the platooning case, the green areas highlight a positive pressure acting on the rear of the fastback model. This will be beneficial in reducing the drag acting on the leading vehicle since it reduces the negative pressure force. It must be noted that the magnitude of the pressures is significantly greater than the scale used and are in the magnitude of 500Pa. This scale was chosen to best visualise the areas of high and low pressure around the platoon rather than to reflect quantitative results.

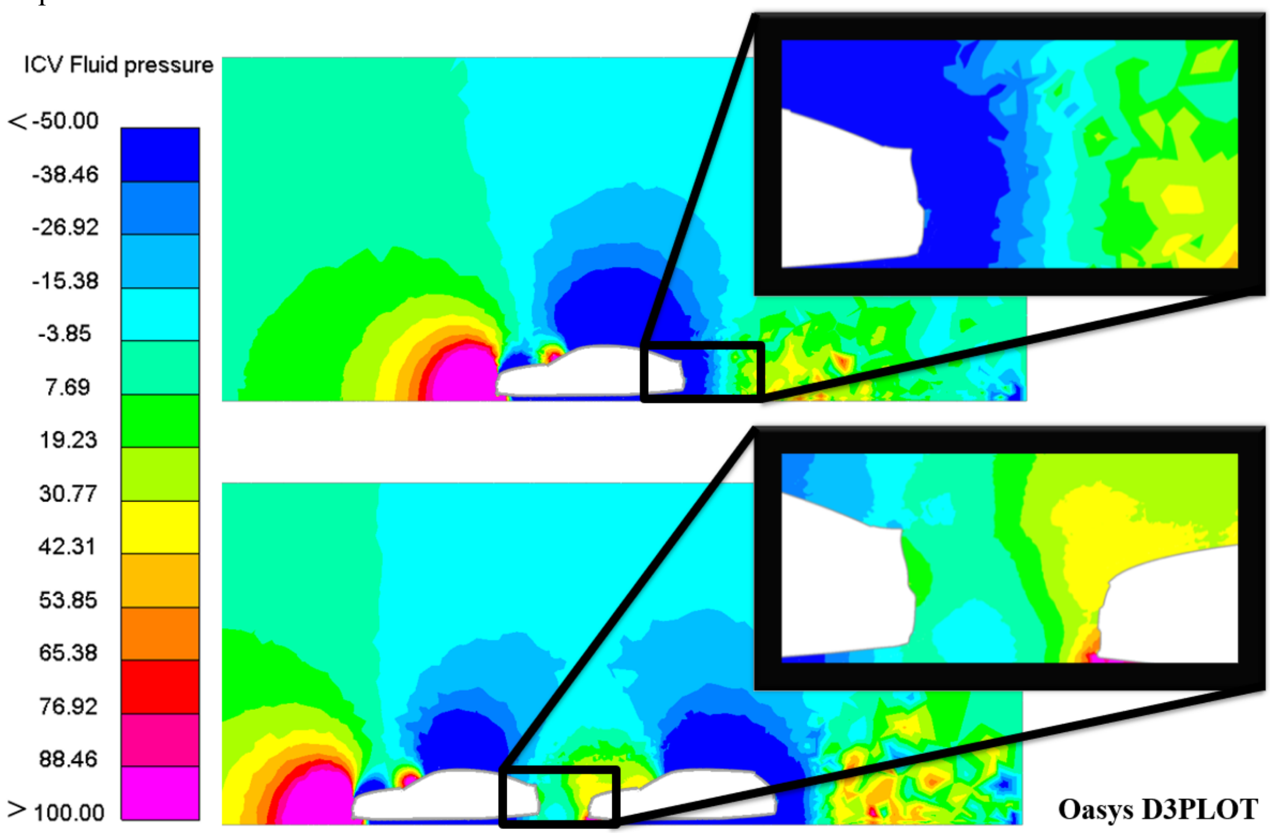

Figure 11: Pressure [Pa] distributions down centreline of isolated fastback (top) and fastback-estateback configuration (bottom) with snapshots showing close-up of pressure behind the fastback models

In all cases, the rear vehicle experiences the greatest reduction in drag and thus the greatest benefit in the platoon. For the cases considered here, these reductions were between 35.2% for the fastback-estateback and 54.4% for the estateback-notchback. It can be seen in Figure 12 that, compared to the isolated case, the pressure acting on the front of the notchback vehicle is significantly reduced when it is placed at the rear of a platoon.

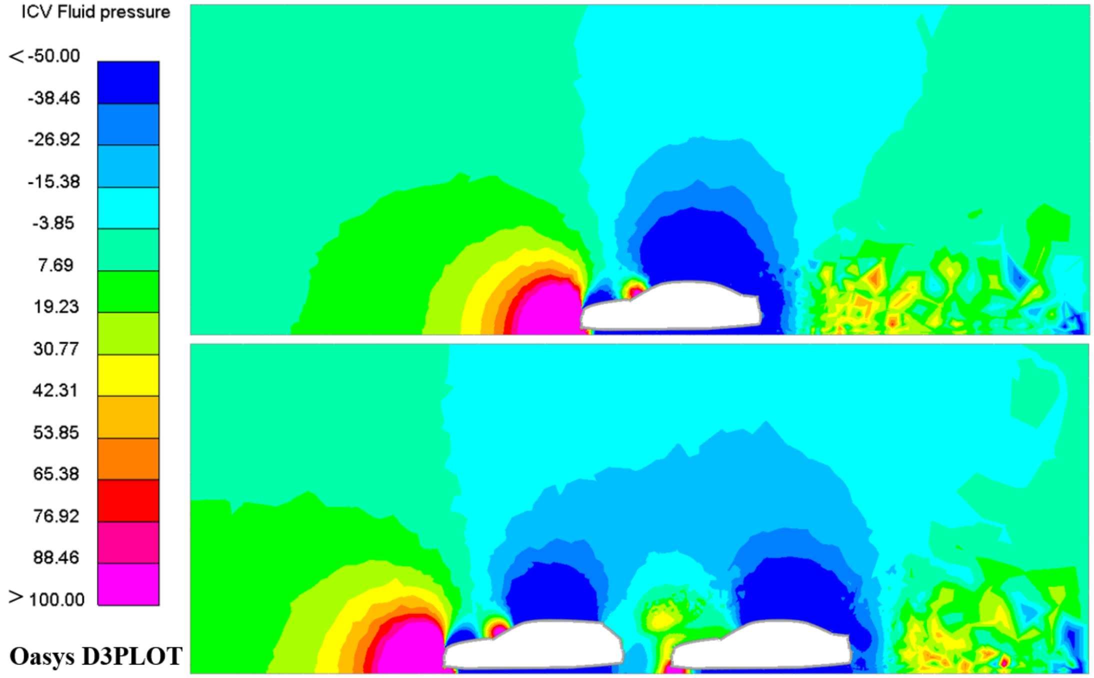

Figure 12: Pressure [Pa] distribution along centreline for isolated notchback (top) and estateback-notchback platoon (bottom)

From Figure 13, the surface streamlines for both the isolated estateback and estateback-notchback platoon can be seen with the colour indicating the velocity magnitude. Relating to the characteristic flow regimes in Figure 3, the streamlines of the isolated estateback show the separation which occurs approximately half a car length behind and between the ground and half way up the car. This therefore introduces the theory that a body which fits into this 'pocket' would experience a significant reduction in drag. The notchback model may be seen to do exactly this since the streamlines appear to be only slightly distorted by its presence. Furthermore, Figure 13 appears to show that the geometry of the rear backdrop of the notchback results in the streamlines ending up in a less separated form than for the isolated case. This may therefore go towards explaining why this configuration resulted in a particularly significant reduction in drag.

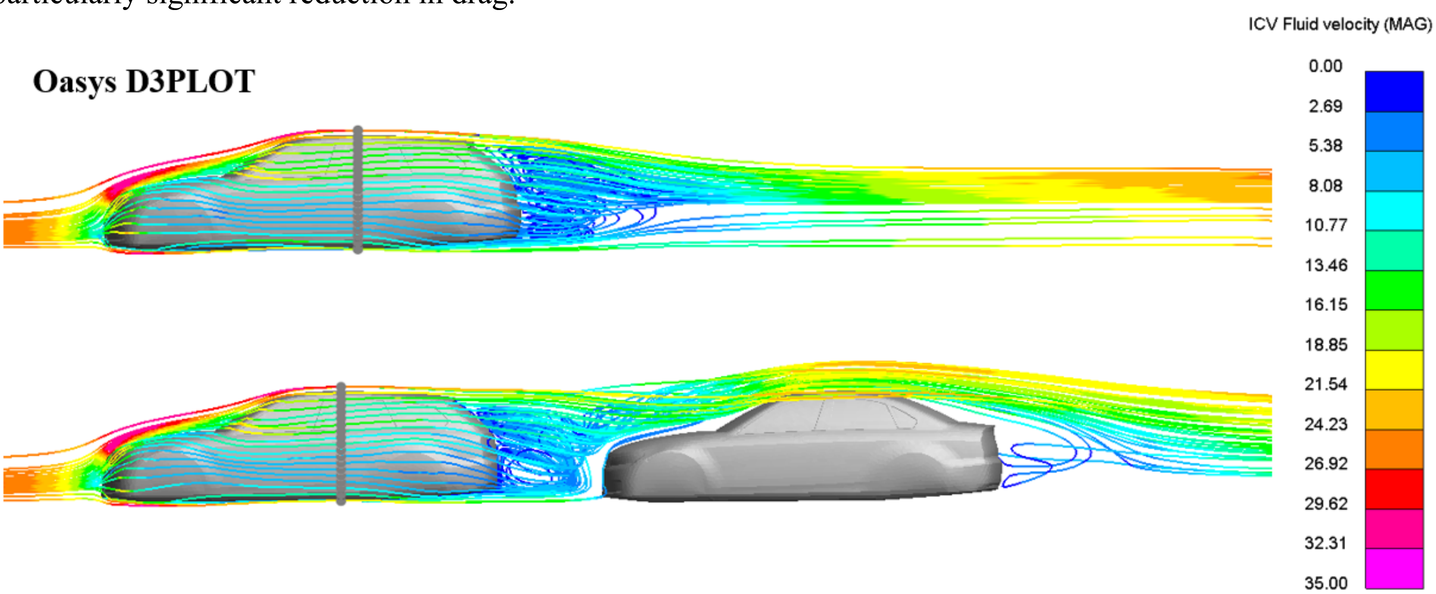

Figure 13: Surface streamlines with velocity magnitude [m/s] for isolated estateback (top) and estateback-notchback platoon (bottom)

Figure 15 shows the distribution of pressure on the Y-Z plane at various cuts along the length of the platoon. These distances are various multiples of one-eighth of a car length which is shown using the reference bar below each diagram, explained in Figure 14. Figure 15 therefore allows the visualisation of pressure distribution at multiple points along the length of the platoon with emphasis here on the quarter car length gap between the two vehicles. One observation is that the distance from the vehicle in the width direction for which the fluid pressure is impacted is quite significant. This can be best seen by the cuts half a car length down both the front and rear vehicle as the dark blue region of low pressure extends up to half a cars width away. Further to this, the low-pressure region appears to extend further for the rear vehicle than for the front vehicle. Although beyond the scope of this study, this low-pressure region on this plane of the model could go on to help the understanding of interactions laterally as well as longitudinally.

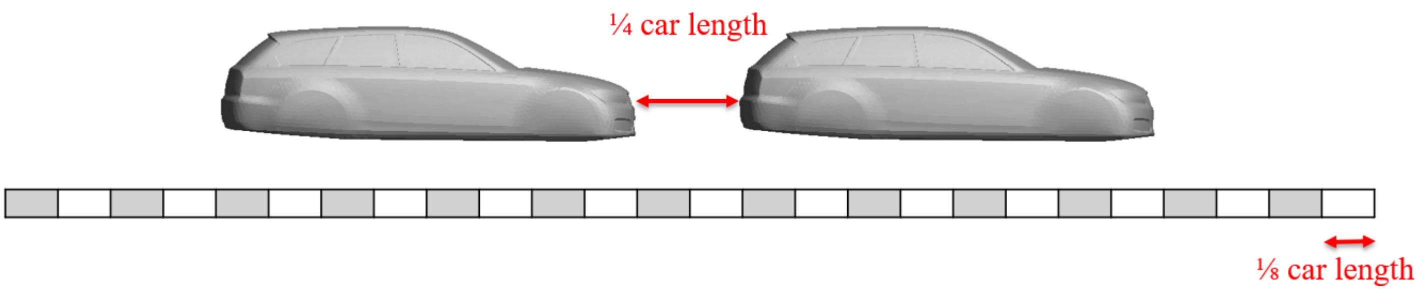

Figure 14: Explanation of reference bar for use with cuts along length of platoon

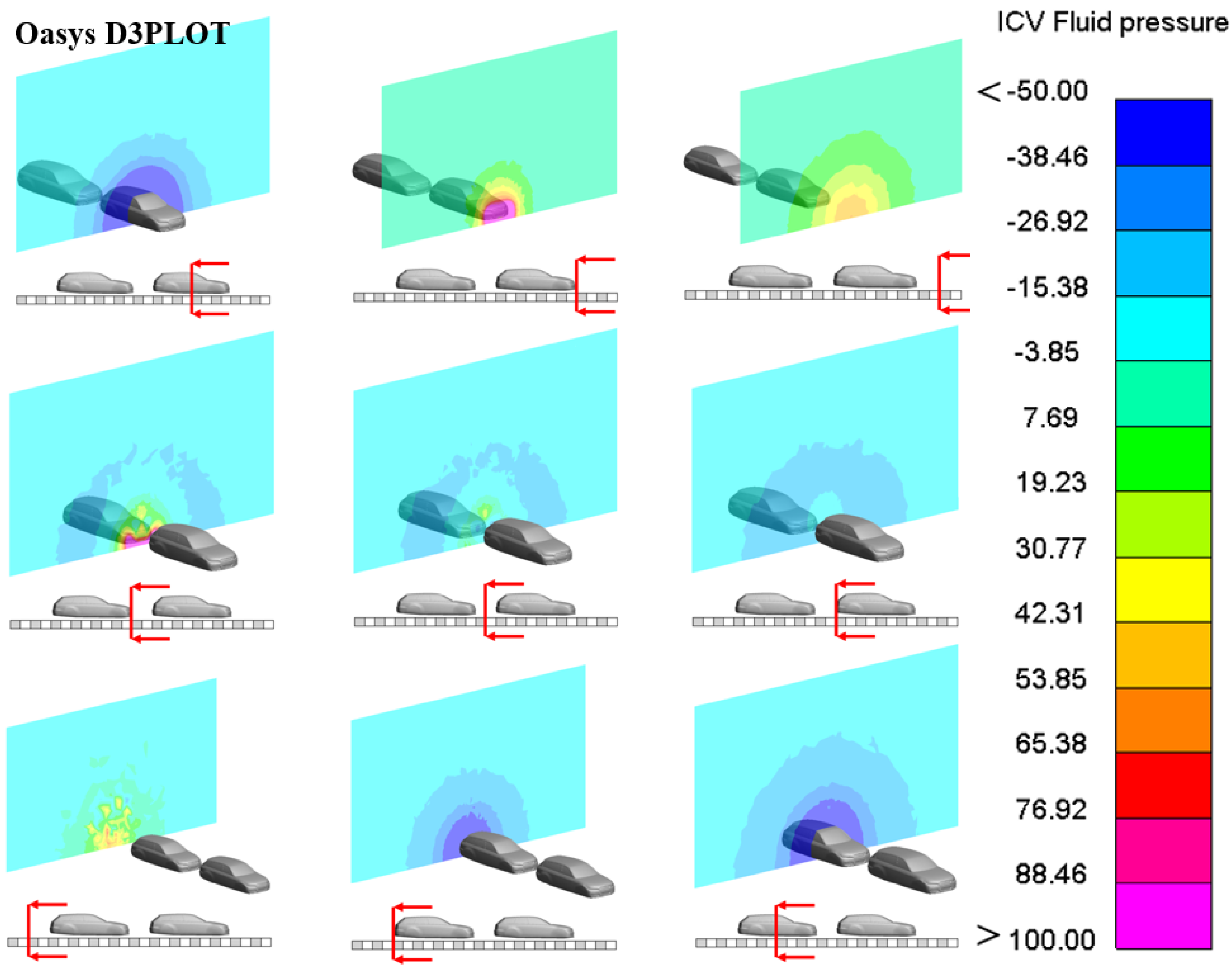

Figure 15: Pressure [Pa] distribution at cuts along length of platoon

Conclusions

The key aim for this paper was to present how the ICFD solver in LS-DYNA may be used to analyse a realistic model and allow the visualisation of platooning interactions. The following key conclusions have been made from this study:

- LS-DYNA offered all features which were required for this study. This included features unique to automotive applications such as the ability to simulate a rolling road and in future analysis could consider rotating wheels. Oasys D3PLOT allows simple extraction of data relevant to platooning aerodynamics such as pressure distributions, streamlines and velocity gradients. Making cuts, blanking parts and changing transparency means that results may be presented clearly. The Oasys software package is exclusively developed for use with LS-DYNA and provides a streamlined method to pre-process models, submit jobs and post-process results.

- The DrivAer model provides a middle ground between basic models such as the Ahmed body and production vehicle models which would over complicate the problem. It has extensive data associated with it due to it being free source and is a known reference model.
- There is a clear benefit in arranging vehicles in some configurations instead of others. This matches the conclusions of the work by Le Good, Boardman, Resnick and Clough [3] and emphasises the importance of considering geometry as well as separation distance when considering platoon analysis.
- This study did not set out to present numerical solutions but instead provide an insight into methods of visualising the aerodynamics of platooning. The model was found to match trends occurring experimentally, with drag coefficients which were comparable. All results for the two-car studies were presented in ways to deter numerical analysis and instead encourage observing trends and characteristic behaviours. The opportunities relating to platooning have been widely considered, with their benefits well documented. However, through improving the understanding of the aerodynamic interactions which are occurring, there are significantly greater gains to be made.
- The ability of LS-DYNA to analyse fluid-structure interaction is likely to be of great use in future research surrounding platooning. The multi-physics functionalities of LS-DYNA provide wide-ranging tools with comprehensive support as industry moves to expand research in this area.

References

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