

Utilising the Fine Margins: Enhancing the Aerodynamic Efficiency of a Hyper-efficient Solar Vehicle



By Nathan Lansing

Supervised by Prof. D.B. Sims-Williams

ABSTRACT

For a world far too heavily reliant on carbon emissions, sustainable solutions are quickly becoming a critical consideration for future vehicle development. In particular, aerodynamic design is an essential aspect in increasing vehicle efficiency, accounting for approximately 70% of the power usage of a hyper-efficient solar car. [1] As a result, it was determined that there would be considerable reward in exploring the benefits of a variety of aerodynamic features in order to improve the performance of one such sustainable vehicle, the Durham University Solar Car. A number of components were evaluated in an initial literature review that sought to establish a number of the most realistic opportunities to enhance aerodynamic performance. A baseline assessment of the feasibility and benefits of these components was performed before one particular feature was chosen from the list to be analysed in further detail. This component was then subject to more extensive investigation through computational flow calculations on a 3D model of the most recent Durham University Solar Car, 'DUSC 2023', that was adapted to include the chosen geometry. Ultimately, of the features considered, it was concluded that Wheel Housings, a wheel geometry slightly offset from the tyres, offered the most significant benefit. Consequently, a further investigation was performed on the wheel housings component, in order to establish a more accurate numerical value of their efficacy in reducing aerodynamic drag. Following this process, it was determined that the wheel housings offered a 10.5% reduction in the coefficient of aerodynamic drag for the case with no wheel housings, reinforcing the significance of the benefit that had been established in the initial comparisons.

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1. INTRODUCTION

The growing requirement for new sustainable technologies in the everyday world has fueled a sizeable level of research and development into the renewable transport sector. [2] In particular, a significant portion of this development is centered around improving the efficiency of road vehicles, both in traditional automobiles, as well as a more recent emphasis on renewable alternatives. [3] One prominent solution is found in the development of solar cars – traditional electric vehicles powered by solar energy.

One such solar car, the Durham University Solar Car, has been considered for the duration of this research project. The Durham University Solar Car is a solar powered race car, designed with the purpose of developing renewable technology that has the potential for application in more mainstream production, thus offering an ideal case study to investigate methods of improving the aerodynamic efficiency of a hyper-efficient sustainable vehicle. With a power consumption of less than 1000W, roughly half that of a hairdryer, the solar car relies on near-optimal levels of efficiency, and are consequently heavily reliant on minimizing all forms of drag, ensuring that any reduction in drag can have a monumental effect. [4]

Every other year, the solar car competes at the Bridgestone World Solar Challenge in Australia, a 3000km race from Darwin to Adelaide, and the vehicle is typically designed with these regulations in mind. [5] The most recent Durham University Solar Car design, ‘DUSC 2023’, achieved an impressive 11th placed finish at the 2023 event, becoming the British champions as the best placing British team. [6]

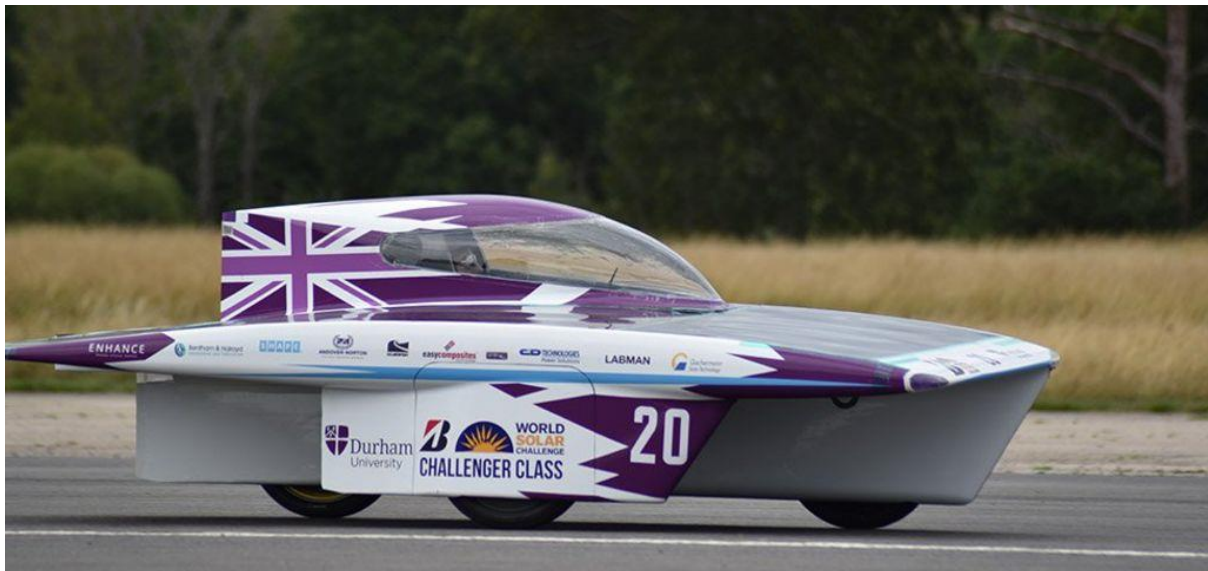


Figure 1: DUSC 2023 in action at the 2023 Bridgestone World Solar Challenge

The primary benefit to be observed is found in the aerodynamic performance of the vehicle; accounting for over 2/3 of the power usage of the vehicle, aerodynamic efficiency is at the forefront of renewable vehicle design. However, due to the increasing prevalence of research into the topic, many techniques to improve the aerodynamic efficiency of a solar powered race car are already well established. [7] Thus, in order to enhance the performance of the Durham University Solar Car, more

distinctive measures must be taken. These measures involve features that are not necessarily of immediate concern when designing a solar car, as well as features that offer benefits specific to environmental conditions.

There is, therefore, a meaningful opportunity to investigate the feasibility of some of these more uncharacteristic measures to alter the aerodynamic efficiency of a solar car. This report hopes to establish a significant benefit for a series of proposed aerodynamic features within the context of solar car racing, which has the potential to in turn provide opportunities for the advancement of aerodynamic efficiency in the wider transport sector.

2. STAGE 1 – INITIAL CALCULATIONS

I. Introduction

In the early stages of the project, a wide range of features were established and evaluated, ranging from active components to be controlled by the driver to more subtle passive methods of establishing an aerodynamic benefit. Each proposed feature was then ranked in terms of the feasibility of developing the respective component on the solar car. Although there was a vast multitude of proposed opportunities for aerodynamic improvement, it was decided that, given the relatively short time frame of the project, only the 3 most attainable components would be given further consideration in the form of a baseline calculation (based on known literature and data). Following a broader discussion with members of the Durham University Solar Car team, these features were established as: a canopy fin, flaps, and wheel housings.

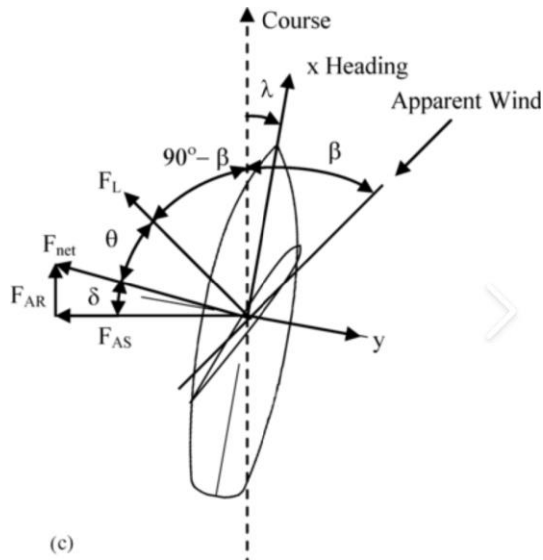
For each of the 3 chosen elements, a calculation was made based on a combination of ideal models and preexisting literature that estimated the aerodynamic benefit for the solar car. These values were then compared with each other to determine the benefits and feasibilities of each geometry in order to decide which solution offered the most beneficial opportunity.

Throughout the report, aerodynamic benefit has been measured in terms of the aerodynamic drag area C_dA . This value is constant, a function of the aerodynamic drag coefficient (C_d) of a body and a defined reference area on which a fluid (in this instance air) interacts. C_dA is the most commonly used measure of aerodynamic drag as it provides a comprehensive overview of the aerodynamic efficiency of a body, taking into account any geometrical variation.

II. ‘Sailing’ Effect

The principal theory behind the expected aerodynamic benefit for the canopy fin and the trailing edge flaps, active aerodynamic components that achieve their benefit in crosswind conditions, is derived from a phenomenon known as the ‘sailing’ effect. [7] The sailing effect is the name given to the propensity of the solar car to generate a thrust force in these crosswind conditions, reducing the effective drag of the vehicle.

In crosswind conditions, the resultant velocity of the wind is not head on; instead, it acts at an angle, known as the yaw angle. As a result, this creates an angle of attack between the direction of motion of the vehicle and the oncoming wind. Symmetrical airfoil geometries generate a lift force at angles of attack, with it being shown that this lift force typically increases linearly up to the point of stall. [8]



With the production of lift, there is also a drag force produced that is related to the amount of lift generated. As shown in Fig. 2, this produces components of lift and drag in the direction of motion of the vehicle – it follows that if the component of lift is greater than the component of drag, there is a positive resultant force in the direction of motion of the vehicle, denoted as a thrust (seen as F_{AR} in Fig. 2). This thrust decreases the value of the negative resultant force acting on the solar car, and can therefore be considered equivalent to a reduction in the drag coefficient of the vehicle.

Figure 2: The forces present on a sailboat sailing into the wind, from which the ‘sailing’ effect for solar cars is derived

III. Yaw Angle Sweep

In order to make the results as useful as possible for Durham University Solar Car specific purposes, each calculation was performed with the specific weather conditions for the Bridgestone World Solar Challenge in mind. In particular, the wind conditions provide a large variation in the performance of the chosen features, so it was essential to establish an outline of the possible wind conditions in which the components would be implemented.

Using historical weather data for Australia, it was possible to generate average yaw angle data for the period over which DUSC 2023 had raced and subsequently develop a weighting that assessed the likelihood of each yaw angle at 5 degree intervals, as displayed in Fig. 3. This approach allowed the possibility of examining yaw weighted CdA as a metric of performance, a result that offered a more realistic value of aerodynamic benefit. These weighted values were developed in conjunction with the rest of the Durham University Solar Car team, and are a standard consideration within wider solar car aerodynamic calculations.

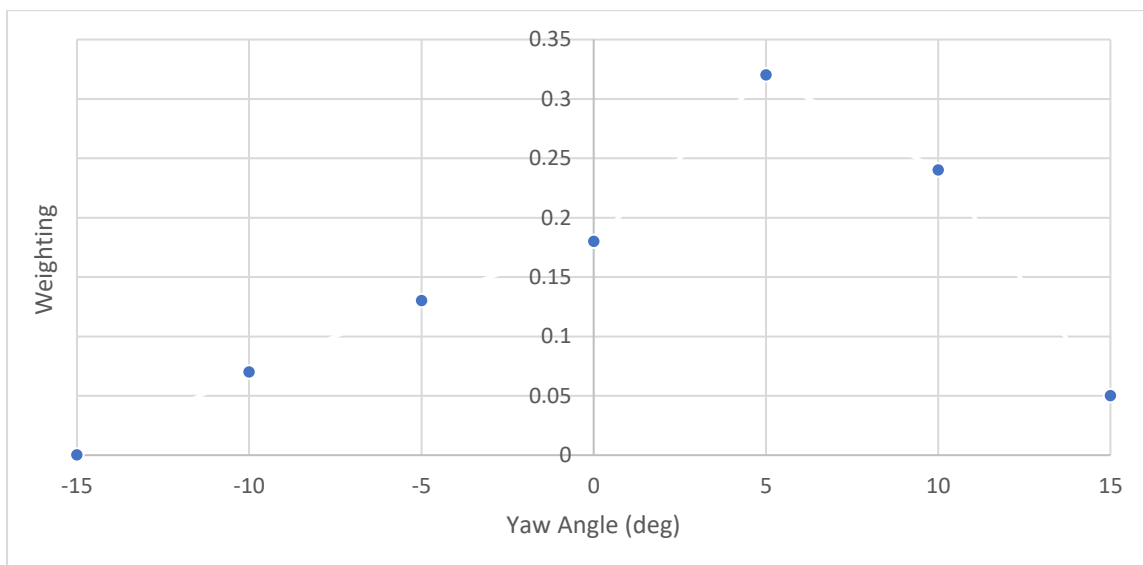


Figure 3: The Historical Weighted Wind Direction for the Bridgestone World Solar Challenge

IV. Canopy Fin

The first of the 3 designs constituted a thin airfoil shape situated on top of the canopy, that could be controlled by the driver in order to harness the benefit of crosswind conditions. It was theorised that the extension of the canopy with a thin elongated airfoil would increase the benefit of the sailing effect by providing a larger area upon which the wind acted and thus increasing ‘sailing thrust’. Furthermore, the canopy fin was designed as an active component, with the ability to sweep through a range of angles, changing the angle of attack relative to the wind direction. This design would allow the driver to choose the optimal orientation of the sailing fin that would maximise the value of the thrust generated. This geometry has previously been implemented in a solar car context but as of time of writing, there has been minimal numerical evidence to support the benefit of the system. [9]



Figure 4: An example of the proposed canopy fin geometry as seen on the 2023 Innoptus solar car [9]

In order to estimate the potential benefit of the canopy fin, a Matlab code was developed that aimed to calculate the increase of thrust of an individual canopy fin geometry. A value of lift coefficient for the airfoil design was calculated for a given rigging angle (the angle at which the fin was set from the x-direction) at a given yaw angle, using experimentally derived relationships between lift and angle of attack. [8] From this value, a resulting drag coefficient could be calculated by taking into account the section drag produced by the 2D geometry of the airfoil as well as the induced drag of the full 3D model. Using the combination of lift and drag components, it was then possible to establish a value of the thrust produced by the canopy fin and deduce the rigging angle that provided the optimum benefit for the given yaw angle.

The canopy fin was modelled as a thin airfoil that had been extended into the third dimension in order to approximate its lift and drag. The canopy fin design was chosen such that the geometry would not only fit on top of the canopy, but also maintain a high aspect ratio, defined as $\frac{Span^2}{Area}$ for the simple airfoil model, to reduce the effect of induced drag on the design.

It has been mentioned that only a certain range of rigging angles was considered – this was a decision made as a result of the effect of stall on an airfoil. Beyond a certain angle of attack, the relationship between angle of attack and lift can no longer be modelled as linear; instead, a reduction in lift is observed with increasing angle, meaning that it is no longer beneficial to increase the angle of the airfoil in relation to the wind. For the chosen airfoil shape, this value has been determined as 12 degrees. [8]

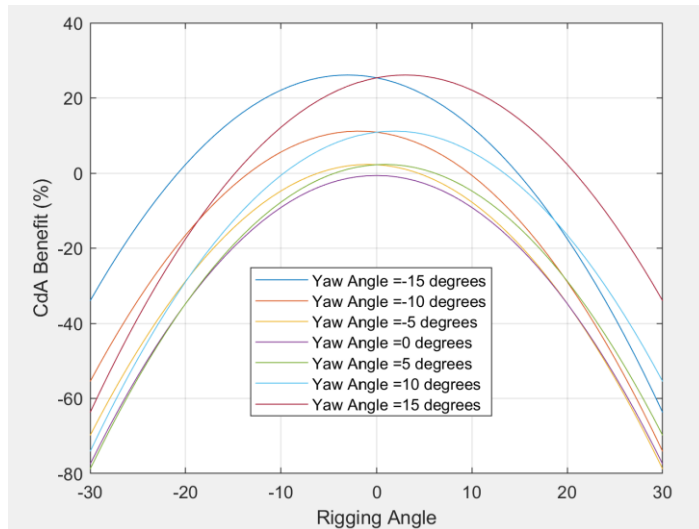


Figure 5: A graphical representation of the aerodynamic benefit, as a percentage of the overall CdA of the solar car, depending on the set orientation of the canopy fin, for the range of yaw angles

Ultimately, it was found that a yaw-weighted aerodynamic benefit of 3% was expected as a result of the canopy fin. Following this conclusion, the aspect ratio was modified to investigate its effect on the calculated benefit. It was expected that, due to its presence in the induced drag term, increasing the aspect ratio would reduce the effective drag coefficient further, but no significant benefit was found within the feasible geometric region.

V. Trailing Edge Flaps

Just as with the canopy fin, the trailing edge flaps relied on the sailing effect in order to generate a thrust and reduce effective drag. Therefore, the flaps were approached in a similar manner, with the generation of a Matlab script with the ability to calculate the benefit. The code functioned in the same way, sweeping through the range of probable yaw angles, but whereas the script for the canopy fin had changed the angle of attack to explore the optimal rigging angle of the design, this new code altered the lift in proportion to the flap angle at the trailing edge.

Just as with the canopy fin, the trailing edge flaps were initially modelled as thin airfoils that had been extended into 3D, but as a result of discrepancies resulting from comparisons drawn between the new code and a control value, an additional coefficient was included in an attempt to more accurately model the component. It was reasoned that due to the presence of the fairings between the array foil and the ground, the true airfoil of the fairings was more ideal than initially depicted, and could be considered more closely to an ideal thin airfoil.

Using an experimental relationship for the change in lift of a symmetrical airfoil with increasing flap angle, it was possible to deduce a value for the lift for each flap angle at a given yaw angle, and therefore, deduce a value of thrust, as with the canopy fin. The remaining geometrical considerations for the flap components were predetermined by the size of the fairings on the ‘DUSC 2023’ car.

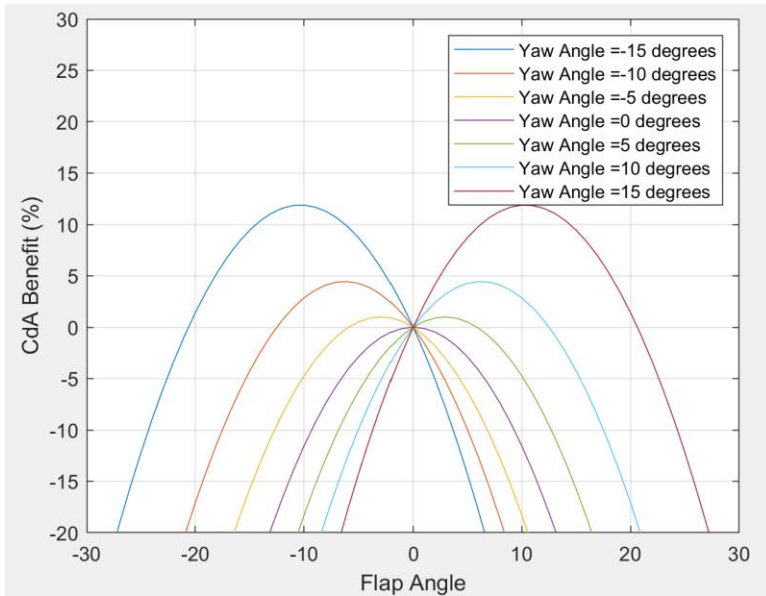


Figure 6: A graphical representation of the aerodynamic benefit, as a percentage of the overall CdA of the solar car, depending on the chosen flap angle for the range of yaw angles.

The baseline calculation for the flaps produced a yaw-weighted benefit of 2.5%.

Following the conclusion of this initial calculation, it was decided that although the initial calculations had not necessarily suggested a significant benefit, there would still be value in a further investigation of their performance following the completion of the report. This was a result of some of the disparities that had arisen when attempting to model the fairing geometry as an ideal component.

VI. Wheel Housings

Where it was possible to generate an initial numerical value of the aerodynamic benefit for the previous 2 components, this was a substantially more difficult task for wheel housings. The canopy fin and trailing edge flaps primarily relied on the effect of sailing, allowing for a simplified calculation of thrust generated by the respective lift and drag forces. By contrast, the wheel housings were affected by an increased number of variables that resulted from the airflow's presence within the interior of the fairings, and as such, could not be approached by examining a simplified geometry.

Consequently, an estimate of the aerodynamic benefit of wheel housings was generated through the reading of relevant literature – of particular usefulness was a masters project that detailed the performance of a wheel housing within a tyre-fairing body. [10]

The results of this investigation established a proposed CdA benefit of 4.1% for an Ultra-Low Carbon Vehicle, such as the Durham University Solar Car, for the housing at an optimal distance as determined in the report. However, this value was calculated for a 4-wheel design, with significantly smaller tyres; as a result, it does not provide an accurate representation of 'DUSC 2023'. Using the reported drag coefficient benefit, it was possible to approximate a numerical value for the CdA benefit for the 'DUSC 2023' tyre dimensions; considering an outer diameter of 558mm and a width of 95mm, and subsequently applying this benefit for each of the 3 tyres, it was possible to estimate a CdA benefit of 16.4% for the most recent Durham University Solar Car design.

VII. Discussion

Upon the conclusion of this initial stage of calculations, an analysis was performed to determine which component offered the most feasible benefit. Following a discussion with the project supervisor, as well as other senior members of the Durham University Solar Car team, the conclusion was made that, due to the high expected aerodynamic benefit, it was most logical to further investigate the wheel housings, with a more specific focus on their design in the recent solar car.

Although the initial reference report had been completed with Ultra Low Carbon Vehicles in mind, it had used a simplified geometry of a single tyre-fairing system in isolation, neglecting the presence of any other drag-inducing bodies, such as the other tyres. Thus, it was decided that a more in depth review would have a significant impact on assessing and improving the accuracy of the initial calculation.

3. STAGE 2 – FURTHER INVESTIGATION

I. *SolidWorks*

In order to further examine the benefits of wheel housings, a 3D model of the new design was generated using Solidworks Computer-Aided Design (CAD) software to include wheel housings. The author had a working knowledge of the design of the ‘DUSC 2023’ car, and, as a result, this existing model was adapted to include wheel housings to establish an analysis that was in line with the most recent solar car design. In order to adapt this model, however, work was needed to be done to redesign the fairings, the most significant of which involved exposing the interior of the model to the exterior in order to more accurately model the internal airflow. Previous designs had simply modelled the lower portion of the wheel as part of the car as one solid body, meaning that this new iteration required substantially more work, both in the 3D model design, as well as computationally, but is believed to have produced more accurate results. The model was then replicated to create a version with and without wheel housings as shown below. Both geometries were then exported into the Pointwise meshing software.

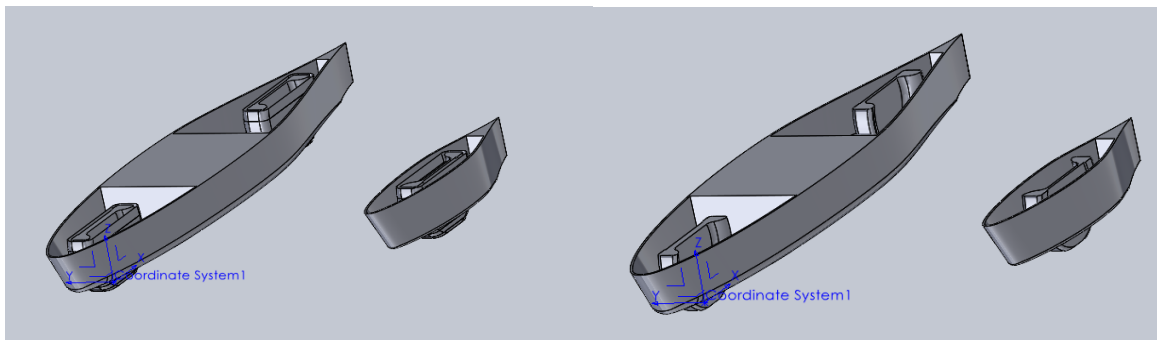


Figure 7: A cross-sectional view of the Solidworks 3D model of the fairing geometry for the modified ‘DUSC 2023’ design with (left) and without (right) wheel housings.

II. *Computational Fluid Dynamics (CFD)*

In order to subsequently calculate the aerodynamic benefit of each of the established models, a CFD solution chain that solved the necessary fluid equations, utilising Fidelity Pointwise and Ansys Fluent software, was used. This method involved the dissection of the 3D model into a large number of smaller cells, within which variables, such as velocity, could be calculated.

Pointwise meshing software was used in order to generate this array of cells to prepare the 3D models for calculation. For both models, a 3 dimensional mesh was generated to create reference points for the airflow around the solar car. A visualization of the mesh is displayed below in Fig. 8.

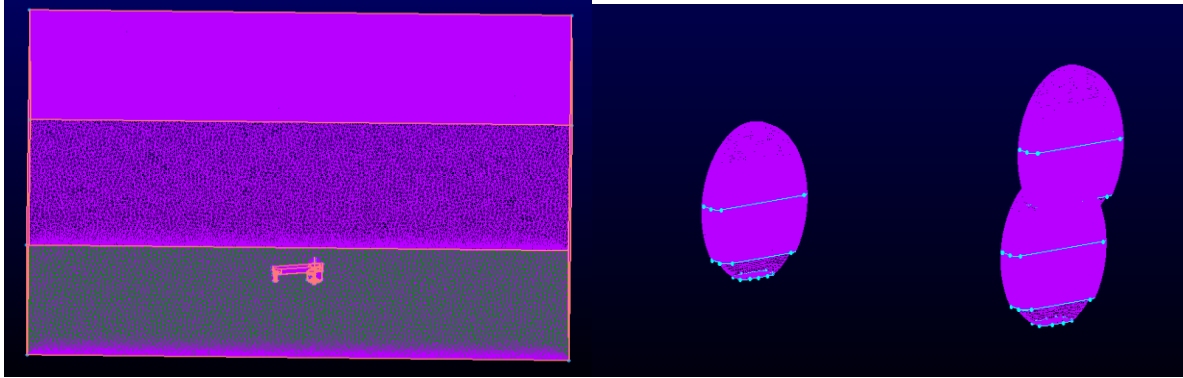


Figure 8: Images of the meshing process of the full car (left) as well as the wheels and surrounding wheel housings (right).

Upon completion, the mesh was imported into Fluent software. Moving wall conditions were used to simulate the movement of the car through the air; the wheel rotation was set at 71 rad/s and the moving ground set at 20m/s to simulate the car moving at 72kph. In order to simulate the various yaw conditions, the left and right walls of the wind tunnel mesh were altered as inlets and outflows where necessary to involve components of the airflow in both the x and y directions.

It is important to note here that the only change between each iteration was the presence of the wheel housings, which were modelled as separate from the existing car body within each iteration of yaw angle. Therefore, although some minor variation between the rest of the car was to be expected due to the somewhat random nature of both the Pointwise and the Fluent software, any change in CdA was almost solely a result of the presence of the wheel housings.

III. Results

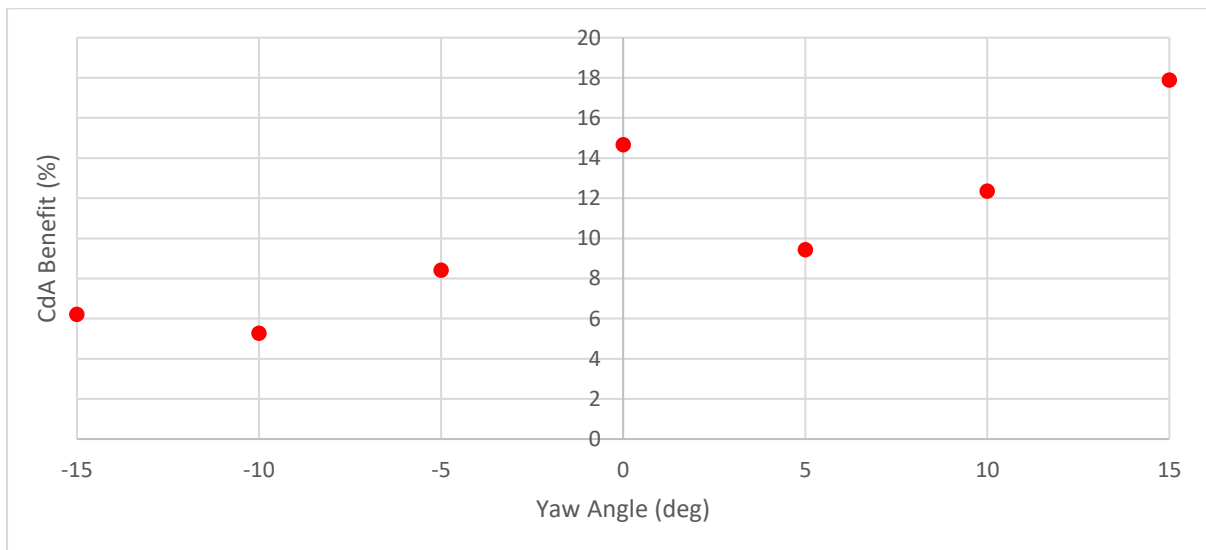


Figure 9: The calculated drag benefit, as a percentage of the control case without housings, that the wheel housings provide for the range of yaw angles.

Fig. 9 shows the final results of the computational fluid dynamics calculations; there is a clear benefit with the presence of the wheel housings, at all yaw angles, suggesting a comprehensive CdA improvement.

In order to consider the accuracy of the initial and more detailed calculations, a comparison was drawn between the proposed benefit established from the Wilderspin report and the calculated benefit

at the 0 degree yaw case. After the more extensive aerodynamic calculation process, a more accurate CdA benefit of 14.7% was found for the Durham University Solar Car, compared to the initial predicted benefit of 16.4%. This value supports the initial prediction with minor variation – any variation is likely a result of variability between the model created in this report and of that used by Wilderspin – and therefore extends a validity to this calculated benefit.

Furthermore, from these results, it has been possible to establish a yaw weighted CdA benefit of 10.5% for the ‘DUSC 2023’ design. This is a significant enough benefit to warrant the production of the wheel housings in future iterations of the solar car, and the author hopes to be involved in the development of this component in the coming years. With further refinement, it is hoped that there could be opportunities to increase this benefit even more.

IV. Further Discussion

Through the use of a post-processing software, Tecplot, it was then possible to develop a 3 dimensional plot of the pressure regions inside and around the car for each yaw case. The purpose of this plot was to examine the changes in pressure along different regions of the car, particularly inside the fairings. Having determined that the most significant benefits of the wheel housings were found at yaw angles of 0 and 15 degrees, with CdA benefits of 14.7% and 17.9% respectively, it was decided to investigate the plots of these extreme cases in more detail in order to better understand this benefit.

Following the examination of the visualization of the 0 degree yaw case, it has been possible to propose an explanation for the numerical benefits observed. From the plots in Fig. 10, it is evident that the wheel housings perform a significant role in restricting the presence of turbulent airflow within the fairing. This internal turbulent airflow is known as pressure drag and results from the separation of laminar flow from a body, and in this case is produced by the interaction of the airflow and the tyre geometry. As the oncoming airflow comes into contact with the tyre and the tyre-fairing gap, this disrupts the smooth laminar flow, creating the observed pressure drag. While solar vehicles are aerodynamically optimized to reduce the existence of pressure drag by maintaining a smooth transition along the body of the car, pressure drag is still evident, particularly around the tyre region, and as a result, any existing pressure drag has a significant negative effect on the efficiency. Pressure drag results in 2 predominant effects – the creation of a low-pressure void, which literally ‘sucks’ the car backwards, and the generation of vortices, which require a lot of energy to create, therefore increasing the power used in overcoming aerodynamic drag. [4] We can, in particular, see evidence of the low-pressure region created in the case without wheel housings, with a considerable amount of turbulent airflow inside the car. By contrast, the case with wheel housings is much clearer; the majority of the turbulent airflow has been bounded inside the housings, therefore reducing the amount of low-pressure volume inside the car, which corresponds directly to the observed numerical benefit.

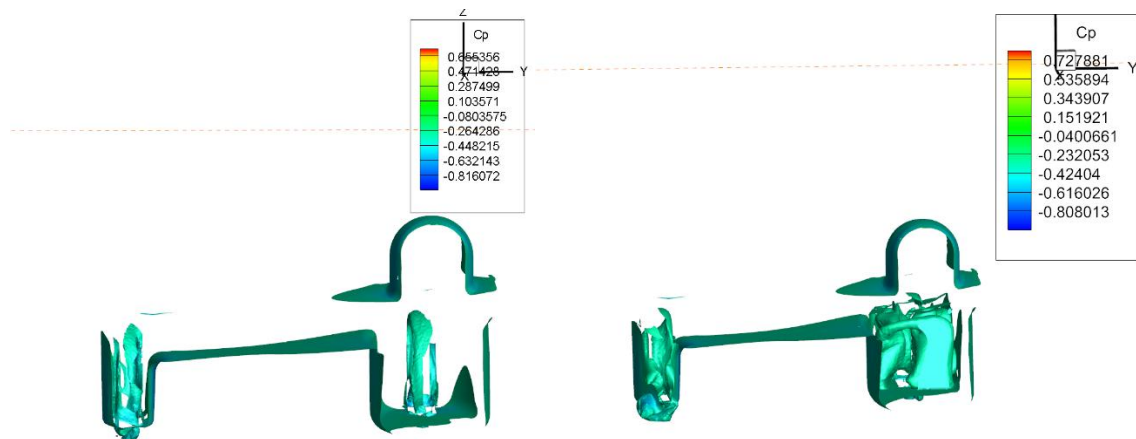


Figure 10: A visualization of the pressure regions inside the fairing geometries for the 0 degree yaw case, both with (left) and without (right) wheel housings.

Furthermore, the generation of vortices, while likely present within the fairings in Fig. 10, is more evident in Fig. 11, seen in the trailing wake of the solar car. Although only minor, there is an observed disparity between the trailing turbulent airflow of the 2 models, with the case with wheel housings having a reduced volume and thickness of the low-pressure wake, seen immediately behind the rear wheels on either side.

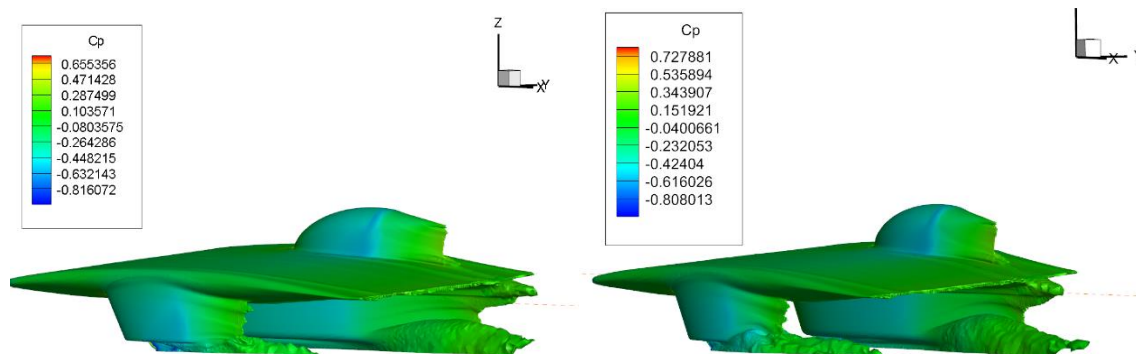


Figure 11: A visualization of the external pressure regions, focused on the trailing wake, for the 0 degree yaw case, both with (left) and without (right) wheel housings.

It is possible to further observe the existence of pressure drag in the more extreme case at 15 degree yaw. Just as with the 0 degree yaw case, there is a significant reduction in internal low-pressure airflow when the housings are present, as displayed in Fig. 12.

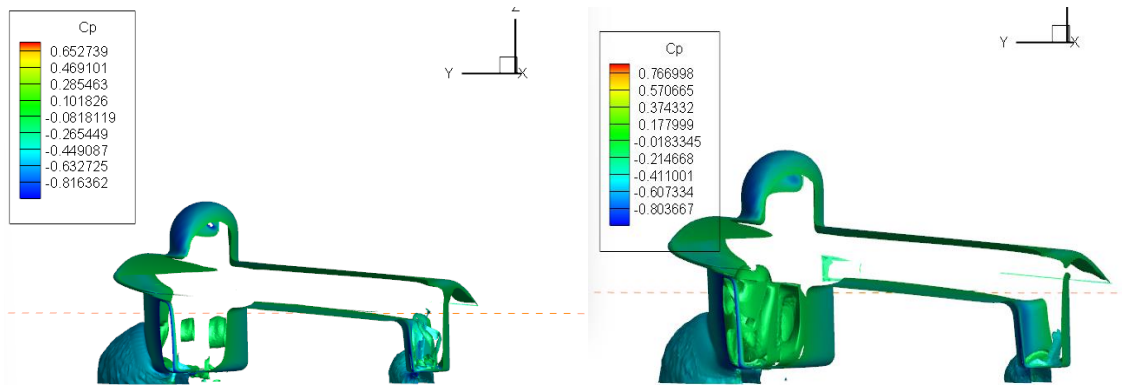


Figure 12: A visualization of the pressure regions inside the fairing geometries for the 15 degree yaw case, both with (left) and without (right) wheel housings.

Perhaps more useful, however, is a consideration of the trailing wake for this yaw condition. Whereas for the 0 degree yaw case the pressure drag produced could be attributed, for the most part, to the low-pressure regions observed above, the presence of the vortices is much more noticeable in this 15 degree yaw instance. The observed vortices are generated in the separation of the laminar flow as it leaves the solar car, both at the trailing edge of the fairing, as well as the tyre. In the case with wheel housings, this vortex is, comparatively, much smaller and less full-bodied than that of the case without wheel housings, posing a significant drag reduction.

Moreover, the calculated relationship between yaw angle and CdA benefit lends credibility to the proposed explanation. Fig. 9 depicts an overall trend that suggests the benefit provided by the wheel housings increases with increasing yaw angle. It is reasonable to propose that this relationship supports the suggestion of pressure drag as the leading cause of drag in the tyre-fairing geometry, a drag which is reduced by the reduction of the internal low-pressure region as with the 0 degree yaw case, or a reduction in the generation of vortices, as with the other yaw cases.

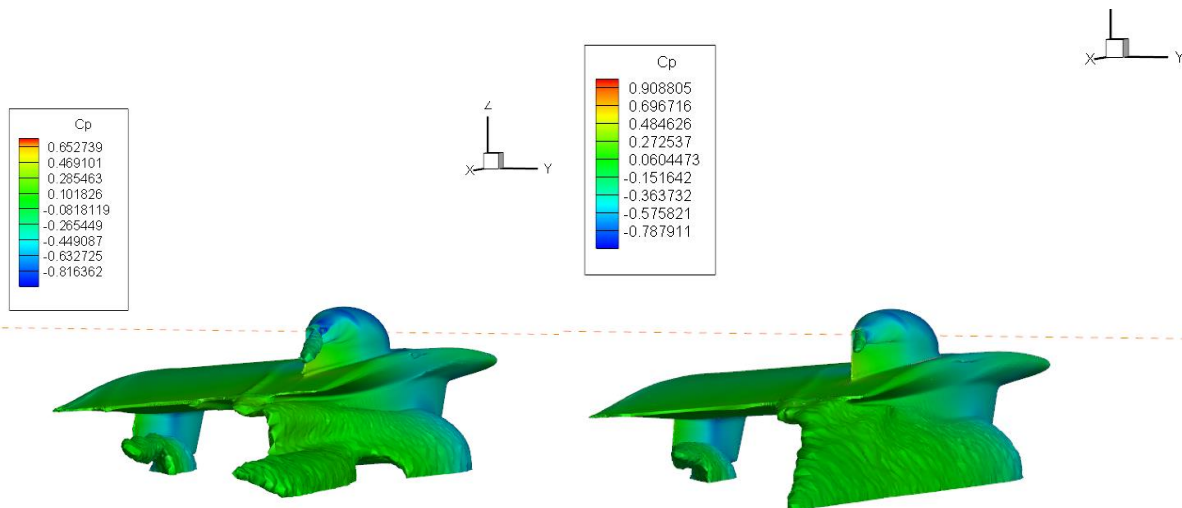


Figure 13: A visualization of the external pressure regions, focused on the trailing wake, for the 15 degree yaw case, both with (left) and without (right) wheel housings.

It is observed, however, that there remains some vortical flow behind the vehicle even in the case with wheel housings; this is due to the existence of induced drag. Although the wheel housings reduce the significance of airflow separation, they do not limit the vortices produced by the pressure differential that arises from the generation of lift, and consequently, there remains a visible turbulent wake, albeit one that is reduced in size.

4. CONCLUDING REMARKS

The baseline assessment of the components produced a numerical value of the benefit for each feature; the most considerable opportunity for aerodynamic benefit was found in the wheel housings component, which were substantially more beneficial than the other features, reducing the aerodynamic drag of the solar car by over 3 times as much as either of the other components.

It can be concluded from the results of the CFD simulations that the Wheel Housings provide a substantial benefit to the aerodynamic efficiency of the Durham University Solar Car, and their inclusion in future iterations of the solar car is more than justifiable. The presence of the wheel housings provided a significant reduction in the yaw weighted CdA of the Durham University Solar Car, of 10.5% , considerably improving the aerodynamic efficiency of the vehicle.

It is reasonable from the results established in the report to further suggest that there would be an aerodynamic benefit in the development of wheel housings for a more conventional road vehicle. The drag reduction provided by the presence of the wheel housings could invoke a significant improvement in efficiency across the range of renewable transport solutions.

Given the possibility for a further exploration of wheel housings in the vehicle, it could prove useful to explore the effect of the height to which the housings extend below the fairings, as it is believed that this will affect the benefit. Furthermore, with additional time and resources, it would be beneficial to confirm the CFD calculated benefit with the development of the components in a wind tunnel model, allowing for a more practical, and perhaps realistic, calculation of their opportunity. Indeed, there is potential to develop the wind tunnel model using the tyre-fairing geometry previously established by Wilderspin [10] as a foundation.

The investigation also explored, at an base level, the benefit achieved by both a canopy fin and trailing edge flaps. Alongside the wheel housings, these other features explored also provided a valuable benefit to the efficiency of the solar car, albeit not to the same extent. There is, therefore, still value to be found in a more detailed examination of their significance, beyond the ideal model, in the context of the full solar car design, and this could be further investigated.

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