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CFD OPTIMIZATION OF SMALL LIVESTOCK TRAILERS (ECCOMAS CFD 2010)

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Abstract. *Increasing public and governmental concern about the potential threat to animal welfare during transport has prompted research into the factors affecting the micro-climate experienced by animals during transit. This paper presents a formal optimization study of the design of small livestock trailers, within which the majority of animals are transported to market in the United Kingdom. The benefits of employing a headboard fairing are investigated by parametrising it in terms of three design variables and CFD solutions of the non-isothermal air flow and moisture transport equations, for flow past the trailer and towing vehicle, are obtained for combinations of design variables defined by an Optimal Latin Hypercube Design of Experiments. These are used to construct metamodels of the drag coefficient and volume-averaged Temperature Humidity Index inside the trailer which are used to identify combinations of fairing design variables which provide desirable low drag and temperature humidity index characteristics.*

1 INTRODUCTION

Increasing public and governmental concerns about the potential threat to animal welfare during transport have stimulated research into the factors affecting the ventilation of animals during transit. A small number of studies have considered the influence of aerodynamics on the micro-climate within large transportation vehicles[1], however far fewer have considered the flow in and around small livestock trailers, within which the majority of animals in the UK are transported to market[2]. These trailers are towed by off-road vehicles such as pick-up trucks and are mainly designed to maximise the internal space available for carrying animals. Ventilation of the internal environment is achieved passively by virtue of vehicle movement which leads to air exchange between the internal and external flows through a series of rectangular apertures on either side of the vehicle. Animal welfare considerations dictate that there should be adequate ventilation of the internal environment.

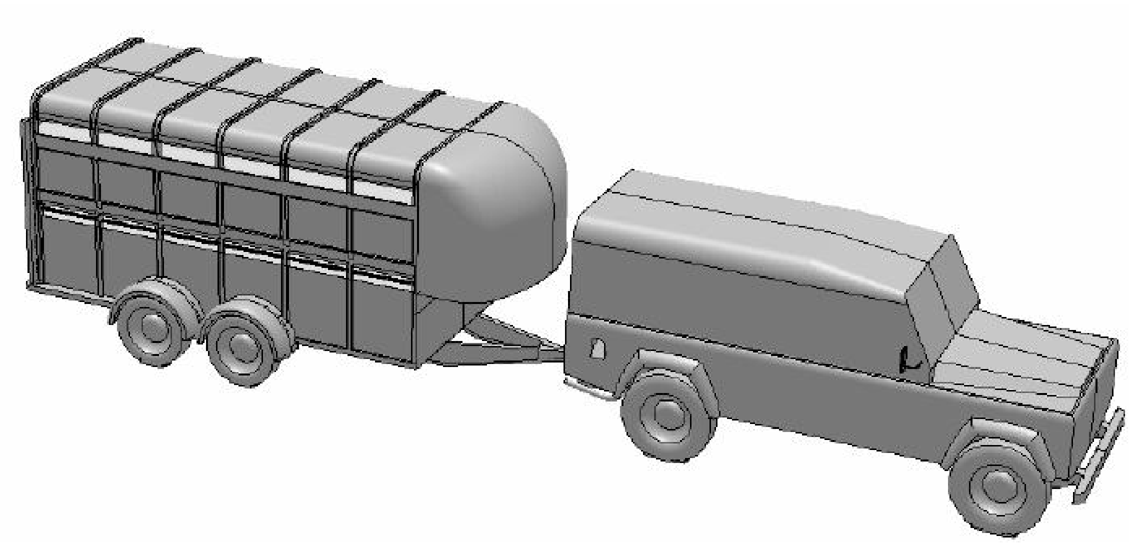

Figure 1: A typical livestock trailer and towing vehicle

The bluff form of these vehicles leads to highly separated flows and significant levels of form drag[3] and current designs appear to have been taken little consideration of aerodynamics. Since previous studies have shown that almost half of the trailer drag is attributable to the headboard of a livestock trailer[2] the benefits of using a drag-reducing fairing on the front of livestock trailers is investigated. Such fairings do not interfere with day-to-day operation and could be implemented in a retro-fitted manner such that the trailer itself and the manufacturing techniques involved would remain largely unchanged. This paper presents a formal optimization study of the design of small livestock trailers aimed at reducing drag and improving the animals' micro-environment inside the trailer.

2 PROBLEM FORMULATION

The optimization process involved a number of steps. Firstly, a CFD model of the non-isothermal external and internal air flow past the trailer was developed that could provide accurate and reliable predictions of the key indicators of the drag and animals' micro-environment within a given trailer design. Next, a region of the trailer was chosen for optimization and this was parametrized in terms of three geometric design variables. An Optimal Latin Hypercube (OLH) Design of Experiments (DoE) consisting of 50 points was then used as training data for a metamodel constructed using the Moving

Least Squares method. Each data point involved a computationally expensive CFD solve of the flow past a specific geometry characterised in terms of the three design variables. The resulting metamodel was then refined using further CFD results to identify the optimum configuration. Each step of the process is described briefly below.

2.1 CFD model

The CFD model of the flow is based upon a CAD representation of a long wheelbase Land Rover and an actual livestock trailer and, due to the computational expense of each problem, a symmetry plane was used to reduce the computational requirements. The CFD model used here is based on that developed using the commercial CFD package Fluent 6.3.26 to solve the non-isothermal Navier-Stokes equations for the coupled external/internal air flow past the livestock trailer[2]. This employs over 6.6 million grid cells and uses the Spalart-Allmaras turbulence model, a moving ground plane and moving boundaries on the wheels, with appropriate rotational speeds[4]. The predictions of this model have been shown to agree well with complementary wind tunnel experiments of a model-scale livestock trailer[3].

The animal welfare indicator used here is based on the following temperature humidity index (THI)[5]:

$$THI = (1.8T_{db} + 32) - [(0.55 - 0.0055rh)(1.8T_{db} - 26.8)] \qquad (1)$$

where T_{db} is the dry-bulb temperature in Celsius (i.e. dry air) and rh is the relative humidity given as a percentage. It has been suggested[6] that values with 75 $\leq$THI $\leq$ 80 indicate mild thermal stress and for values THI $\geq$ 80 moderate to severe thermal stress is likely. Humidity levels throughout the domain were predicted by coupling the moisture transport equations into the Navier-Stokes solver. The thermal boundary conditions were specified by setting the temperature on the inlet and outlet of the domain and prescribing the animals' heat generation rate and core body temperatures. Boundary conditions for moisture transport took the form of prescribed mass fractions on the inlet and outlet of the domain, taken from a psychrometric chart, and moisture generation from the sheep was incorporated using source terms in each deck to represent perspiration. It was assumed that the action of cutaneous loss (i.e. sweating) involved water only and any further chemical species were neglected.

2.1 Optimization methodology

Initial results from the baseline configuration (i.e. the standard trailer case) showed that 39% of the total trailer drag acted on the headboard, with 34% attributable to the tailboard and the remaining 27% due to the wheels and other minor surfaces[2]. Consequently, it was decided to focus the optimization on the identification of a headboard fairing which would not interfere with day-to-day trailer operation. Previous relevant studies into the use of fairings for Heavy Goods Vehicles have been successful in reducing the drag, while more generic bluff-body drag reduction has highlighted the importance of the size of the edge radii[7]. With this in mind the fairing was parametrized in terms of three design variables, namely the side radius, D_1, the lower edge extension, D_2, and the central extension of the fairing, D_3, see Fig. 2. The variable D_2 dictates the rake angle of the device whilst D_3 determines the level of curvature in the fairing when viewed from above. In order for the fairing to integrate successfully with the existing trailer, D_1 and D_2 were both assigned a range of 175-600mm, with a smaller range of 0-200mm for D_3.

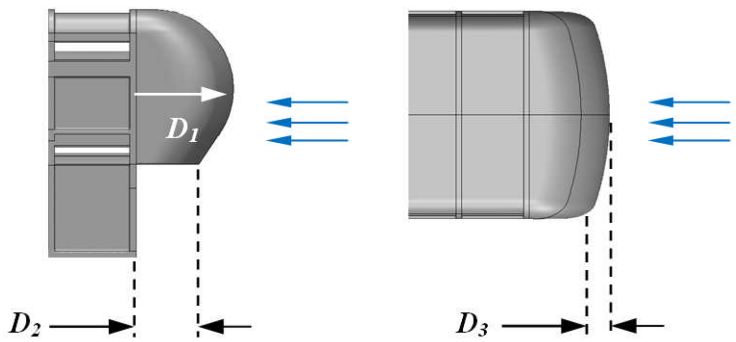

Figure 2: Parameterisation of the headboard fairing: (a) side view, (b) aerial view.

The CFD model was used to study the effect of fairing parameters on the drag coefficient, C_D, for the two vehicles combined and a measure of the state of the animals' micro-environment inside the trailer. Finding a measure of the latter, that is suitable for optimization, proved to be problematical. Previous work identified that the ventilation rate on the bottom deck is significantly lower than on the upper one[3] and hence an initial, isothermal optimization took the drag coefficient C_D as the objective function to be minimized, subject to the constraint that the total flow rate through the lower deck, Q, is not reduced by more than 30% compared to the baseline trailer design[8].

For the initial drag optimization, an Optimal Latin Hypercube (OLH) Design of Experiments (DoE) was employed to fill parameter space with 50 different fairing designs using combinations of the parameters, D_1, D_2 and D_3. The input parameters corresponding to each DoE point were used to systematically generate a CAD model for each of the 50 designs. CFD post-processing carried out on all 50 fairing designs provided the responses for the metamodel building, which was based on the Moving Least Squares method with a quadratic base function and a Gaussian weight decay function, w_i:

$$w_i = \exp(-\theta\, r_i^2)\,. \qquad (2)$$

The parameter r_i is the Euclidean distance from the ith DoE point whilst θ denotes the user defined "closeness of fit" parameter. The latter can either be specified *a priori* or optimized to produce the best fitting metamodel for the given training data.

The metamodel was built in three stages. An initial metamodel was constructed from the 40 point build DoE and the corresponding CFD response values. The 10-point validation DoE then acted as a guide for tuning θ to minimize the RMS error between the metamodel prediction and the CFD responses at the validation locations. Finally, the optimal value of θ was used to re-build the metamodel on the 50-point merged DoE and the associated CFD responses. The validation DoE also served to validate the initial metamodel to ensure adequate accuracy of the final metamodel.

Having identified a series of low drag designs, the optimization problem was reformulated to take account of the state of the animals' micro-environment inside the trailer. A series of initial optimizations were carried out which maximized the flow rate Q subject to a drag coefficient constraint. The numerical noise associated with the flow rate Q translated into inaccuracies in the metamodel constructed during the optimization process. In order to avoid this problem, the present study uses an alternative formulation where the objective function to be minimized is the volume-averaged THI on the bottom deck, THI_B. The initial 50-point DoE was merged with a further 8 design points generated during the problem reformulations so that the final metamodel was constructed using CFD results for a total of 58 fairing designs.

3 RESULTS

CFD solutions were obtained for each of the fairing designs specified by the DoE and the resulting CFD response values fed into Altair's commercial optimization package, Hyperstudy (version 8), to construct a metamodel for C_D and THI_B. The use of THI_B led to much less noisy response surfaces with the result that the maximum discrepancy between the CFD predictions and metamodel values of C_D and THI_B was less than 1%. Optimization was carried out to find the fairing design which minimized THI_B and this was carried out in two stages. Firstly, a Genetic Algorithm (GA) containing 20 individual chromosomes was applied to the metamodel to search for the global minimum. This was performed several times with different initial populations until the termination criteria were achieved. Secondly, the Sequential Quadratic Programming (SQP) technique was used to refine towards the global minimum. The resultant optimized design is summarized in Table 1, together with the corresponding metamodel and CFD predictions.

Design Variables (mm)			C_D			THI_B (°C)		
D_1	D_2	D_3	MLS	CFD	δ (%)	MLS	CFD	δ (%)
213.7	175	0	0.4984	0.4990	0.12	86.14	86.23	0.11

Table 1: Comparison of the metamodel prediction and the corresponding CFD result for the proposed minimum THI_B fairing design.

The CFD results for the DoE points showing the resultant predictions of C_D and THI_B are shown in Figure 3.

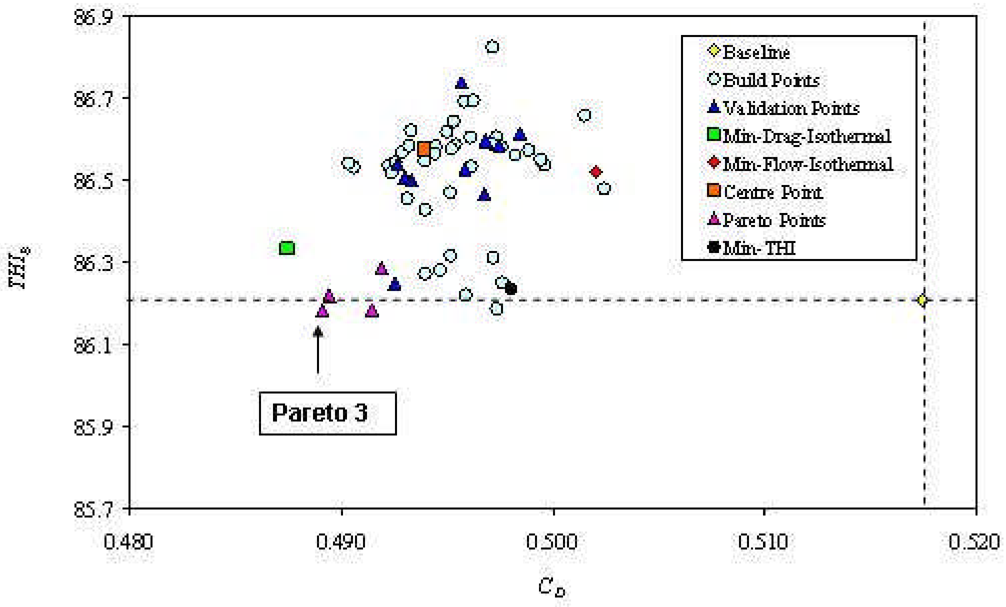

Figure 3: CFD predictions of C_D and THI_B.

In Figure 3 the value of THI_B generated by Pareto point number 3 from the isothermal study[8] gave the best performance of all 58 fairing designs tested. The drag reduction realised by this fairing is very close to the minimum drag design which implies it is a very good overall candidate for the trailer. The fairing represented by Pareto point 3 has the design variable D_2 close to the minimum allowable value. A more detailed study of both the upper and lower decks[4] shows that a small value of D_2 appears to be the key to improving the animals' micro-environment on both decks of the trailer.

More detailed analysis of the design space can provide valuable additional engineering insight. Figures 4 and 5 shows how D_1 influences C_D and THI_B respectively.

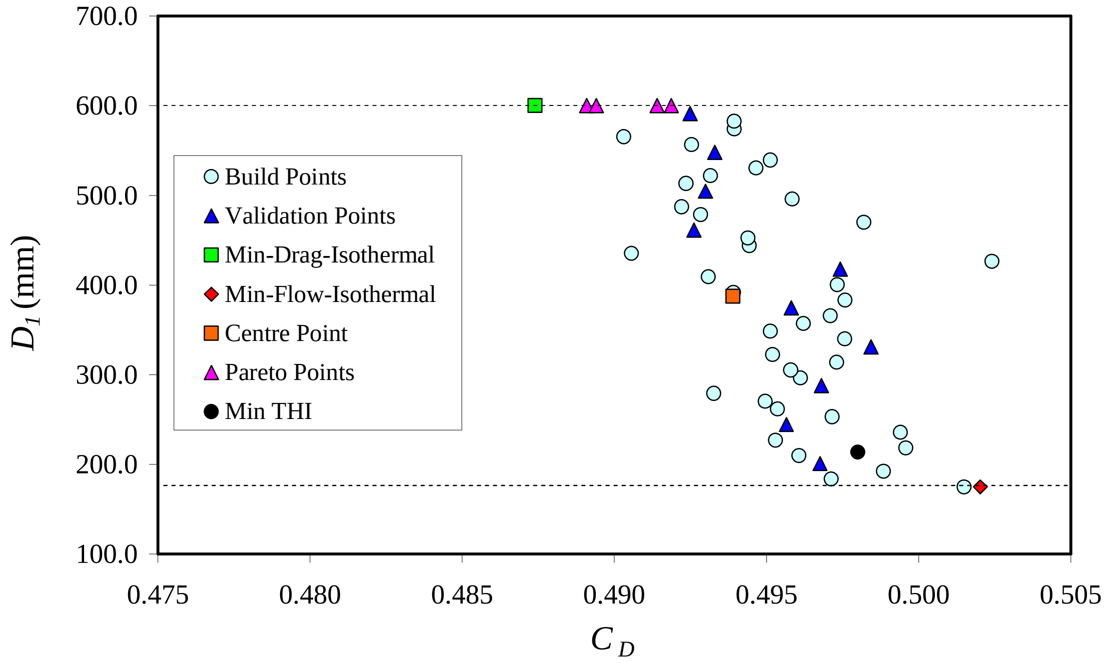

Figure 4: Plot showing correlations between D_1 and C_D..

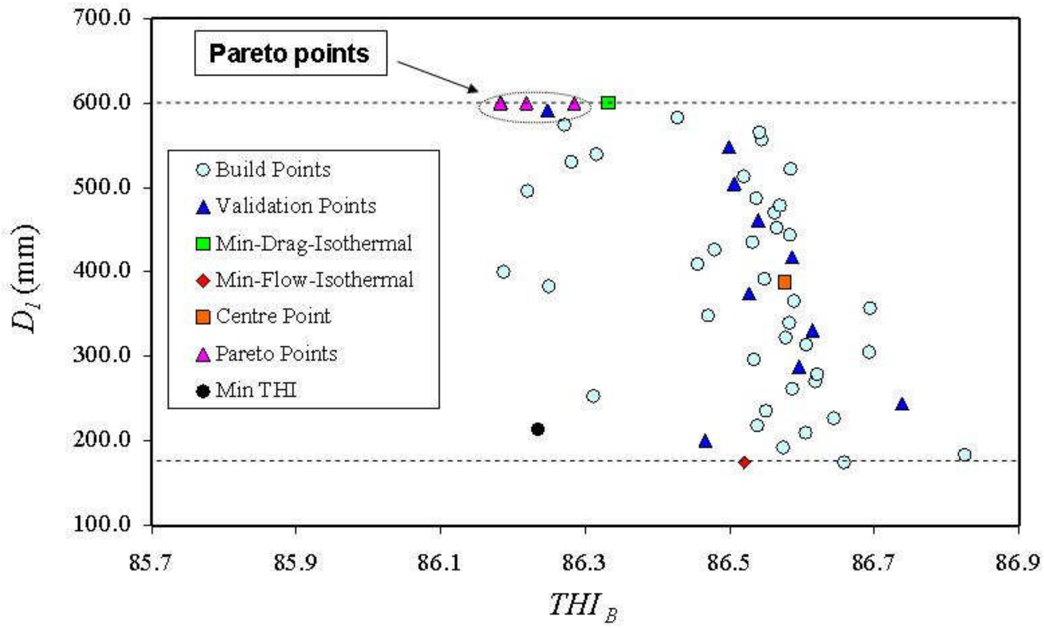

Figure 5: Plot showing correlations between D_1 and THI_B.

The most obvious trend is that as the leading edge of the fairing, D_1, increases C_D decreases. Many of the lowest values of THI_B resulted from the four Pareto points circled in Figure 5. However the Pareto points were obtained for headboard fairings composed of the largest value of D_1 (600mm), whereas the minimum-THI_B point occurred for D_1=213.7mm. Hence no clear trend is apparent between D_1 and THI_B. Similar plots can be obtained for the other design variables[4]. These show that as D_2 is reduced there is a general tendency for C_D to decrease and small values of D_2 lead to the lowest THI_B inside the trailer. This is unsurprising since it follows that for small D_2 the flow accelerates faster around the bottom fairing (or separates), which induces more extraction of heat and moisture from the lower vents, thereby lowering THI_B.

Plots for design variable D_3 show that it is far less influential on the flow field. This is also unsurprising since it influences the shape of the front of the fairing, which is largely hidden by the towing vehicle immediately ahead of it. However enough of the fairing is exposed to the free-stream for the drag to be minimised for the largest possible D_3. In summary, the optimization data shows that minimum drag is dependent on large values of D_1 and D_3 whereas minimum THI_B correlates with small values of D_2 and D_3.

4 CONCLUSIONS

This paper has shown that combining accurate CFD modelling with formal optimization techniques can be used to identify the geometrical characteristics of headboard fairings with the potential to improve the drag and ventilation characteristics of small livestock trailers. Although low drag fairings are reasonably straightforward to identify, optimizing the ventilation rates and thus the animals' micro-environment inside the trailer is more challenging due to the numerical noise associated with the metamodels constructed during the optimization process. This paper has shown that a measure, based on a volume-averaged THI inside the trailer, is much more amenable to optimization compared with surface-averaged ventilation rates. Results from the optimization studies show that large, curvy and bulbous fairings guide the airflow around the trailer headboard with smaller pressure gradients and stagnation areas. In contrast, fairings with smaller radii tend to reduce the temperature and humidity inside the trailer either through separated or accelerating flow, both of which encourage extraction of heat and moisture through the front vent apertures.

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