

A Parametric Assessment of Skirt Performance on a Single Bogie Commercial Vehicle

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ABSTRACT

A Department of Energy funded research project currently in the final stages of completion has resulted in a web-based tool that gives non-expert users the ability to add aerodynamic devices to a CFD model of a single bogie trailer and generalized tractor model. This model was used to assess the aerodynamic performance of skirt geometries. The skirts were defined using 5 independent geometric parameters and 2 installation parameters. These parameters allow enough freedom in the geometry definition to capture the shape and installation position and angle of a wide number of commercially available skirts on the market today. Using a Design of Experiments approach, the aerodynamic drag response of the truck and trailer to any parametric change in the skirt geometry has been determined across a range of yaw angles. This response surface has then been used to assess the likely range of possible wind averaged drag reduction, and hence fuel economy benefits within the parametric definition of the skirt. The mechanism(s) by which the skirts reduce the drag on the vehicle is also presented.

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INTRODUCTION

Commercial Truck Operators are faced with a bewildering choice of after-market devices aimed at reducing the aerodynamic drag of their fleets. Devices of similar shape, size and installation position often have quite different claims as to the fuel economy savings achievable. Despite updated and/or new standards aimed at improving the experimental test procedures and simulation methodologies, there are still unsubstantiated claims made about the measurable fuel efficiency improvements that given devices can offer.

This paper presents results of a CFD study that assesses the benefits offered by skirt add-on devices. Using a 7 degree of freedom parametric CAD model of a skirt, and a Design of Experiment (DoE) methodology, the aerodynamic drag response to any parametric change in the skirt shape and installation position has been determined, thereby bracketing the maximum and minimum drag benefit such devices are likely to offer.

This work was completed under the LAMP research project being funded by The Department of Energy and administered by NCMS (National Center for Manufacturing Science). It was managed by the Ohio Super Computer Center (Ohio State University)[1] and formed part of a

feasibility study looking into how Vertical Applications might aid in light weight component design for drag reduction in the heavy truck industry. The outcome of the feasibility study was a web-based tool that allows users to place add-on components on a generic truck and single bogie trailer and have a CFD analysis performed across single or multiple yaw angles to calculate a J1252 wind averaged drag. The CFD solvers, meshing rules and post-processing capabilities of this tool are covered in the preceding sections.

CFD MODEL DETAILS

CFD Code - The open source CFD code OpenFOAM was used for this work. OpenFOAM is a free, open source CFD software package (GNU Public License) developed by OpenCFD Ltd at ESI Group and distributed by the OpenFOAM Foundation. It has a large user base across most areas of engineering and science, from both commercial and academic organizations. OpenFOAM has an extensive range of features to solve anything from complex fluid flows involving chemical reactions, turbulence and heat transfer, to solid dynamics and electromagnetics. It offers much of the same functionality as its commercial equivalents and it has been extensively validated and verified for both industrial and

academic flows and has comparable speed, scalability and stability [2].

Truck Geometry

A full-scale version of the SOLUS and ODU Representative Heavy Truck (SORHT) model was used in this study. This is a class 8 heavy truck, with proportions derived from the DOE Generalized Conventional Model (GCM), but with the addition of tires and axles, trailer structural underbody elements, landing gear, mud flaps, and other details. The cab contours are representative of current streamlined commercial models. [Figure A1](#) in the appendix gives a three-quarter view of the geometry together with key dimensions.

Skirt Details

All skirts examined in this study are defined via the five geometric parameters shown in [Figure 1](#). Each skirt was placed on the truck using the two installation parameters shown in [Figure 2](#). The Parameters of interest and their ranges are given in [Table 1](#).

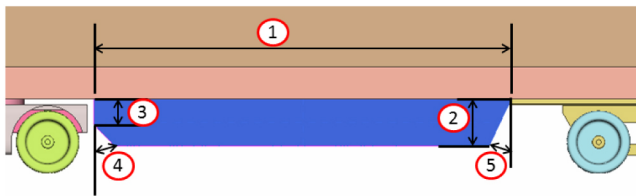


Figure 1. Skirt Geometric Parameterization

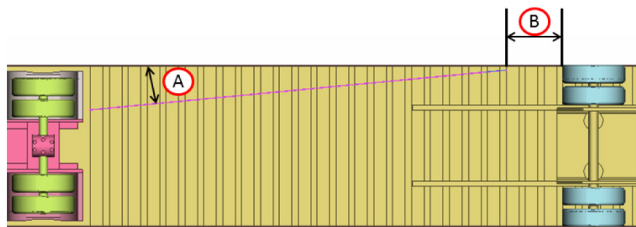


Figure 2. Skirt Installation Parameterization

Table 1. Skirt Parameterization variables and ranges

#	Geometric Parameter	Min value	Max value
1	Length	5486 mm	8534 mm
2	Width	762 mm	940 mm
3	Leading Offset	0 mm	607 mm
4	Leading Angle	0°	80°
5	Trailing Angle	0°	20°
	Installation Parameter		
A	Inset Angle	0°	10°
B	Offset to Rear Tire LE	0 mm	1125 mm

Domain, Mesh and Boundary Condition Details

The CFD model was built to represent a full-size truck running on the open road. The domain was cuboid in shape ([Table 3](#) gives the length, width & height), and extended 3 truck lengths upstream and 5 downstream, with 12 truck widths either side of the centerline. The ground was modeled as moving with its direction of travel aligned to the longitudinal axis of the vehicle. Wheels were modeled with a rotating wall boundary condition, but due to the solid nature of the geometry (no flow through the wheels), a rotating reference frame boundary condition was not applied. A velocity inlet boundary condition was used to set the air speed, with turbulence intensity of 0.2% and a length scale of 0.01m. Yaw was modeled by setting appropriate velocities at the outer domain boundaries, with the adjacent boundaries set as 0 Pa pressure boundaries. The upper boundary of the domain was set as a symmetry wall.

The mesh was built using the snappyHexMesh meshing application provided with the OpenFoam toolset. This is an automated meshing tool that produces a hex-dominant polyhedral mesh compatible with the OpenFoam solver. The mesh is defined by assigning levels to each of the surfaces that make up the truck, these levels correspond to the resolutions given in [Table 2](#). The mesher uses these local surface resolutions, together with proximity and curvature rules and defined refinement regions to build the volume mesh. Y+ values were kept between 30 and 100, with 4 layers in the boundary layer mesh

A mesh refinement study was performed as part of the LAMP project, and the resolutions used here were the best compromise between runtime and accuracy found in that work. The details of that study are not presented here but will be available when that work is formally reported later this year. [Figures A2a, A2b, A2c](#) shows cross-sections through the volume mesh and surface mesh, showing how these levels were applied to areas around the truck.

Table 2. Meshing resolution and distribution

Level	Cell count	Resolution (mm)
0	32268	1600
1	15366	800
2	64566	400
3	338720	200
4	3,515,570	100
5	2,704,230	50
6	9,788,824	25
7	9,297,901	12.5
8	20,857,131	6.25
9	2,124,579	3.125

All data presented here was run using the domain, mesh and boundary condition setup described above. Where comparison is drawn to experimental model scale wind tunnel

data, no attempt was made to model the wind tunnel testing setup i.e. the impact of scale, non-moving ground and the wind tunnel blockage and buoyancy were not included in any of the CFD analyses.

Modeling Details

Two different types of solver were used in this study, a steady state RANS[3] and a transient DES[4], with details on each in [Tables 3 & 4](#). All runs were performed on the Oakley cluster at the Ohio Supercomputer Center. This is an 8238 core machine running Xeon cores[1]. Model sizes and runtimes are also given in [Tables 3 & 4](#).

Table 3. Steady-state solver settings

Solver	simpleFoam
Type	RANS
Turbulence model	k-omega SST
Wall-functions	yes
Domain size	154m x 51m x 25.6m
Mesh size	46.9 million cells
Cores per run	48
Iterations	6500
Averaging period	Last 1000 iterations
Runtime	21 hrs

Table 4. Transient solver settings

Solver	pimpleFoam
Type	DES (transient)
Turbulence model	Spalart-Almaras
Wall-functions	yes
Domain size	154m x 51m x 25.6m
Mesh size	46.9 million cells
Cores per run	48
Flow Time	3.7 s (5 flushes of vehicle length)
Time-step size	1e-4 seconds
Averaging period	0.5 s
Runtime	~250 hrs

Table 5. Design of Experiment Methodology

Spatial filling	Latin Hypercube[5]
Response Surface	Kriging[5,6,7]
Sample size	72 points per yaw angle
# of yaw angles	3
Total samples	216

TEST PROCEDURE, DATA REDUCTION & VALIDATION OF BASELINE MODEL

The CFD model was initially run at 60mph through five yaw angles (0.5, 1.5, 3, 6, 9 degrees) with no skirt (Baseline).

This was done utilizing both the RANS (steady-state) and DES solvers (transient). This is a nominal Reynolds number of 5×10^6 based on trailer width (Re_w). The results are compared against experimental data generated using a 1/4 scale version of the same geometry and run in the Langley Full Scale Tunnel (LFST) fixed ground facility [8]. The nominal LFST test Reynolds number based on trailer width (Re_w) was 1.26×10^6 . Roughness elements were positioned on the trailer sides to force transition in order to match the full-size turbulent boundary layer character at the trailer base. The paper from which the experimental data were drawn makes no comment as to whether blockage, buoyancy or any other corrections were applied to the reported values.

A cubic spline fit was used to allow interpolation between CFD predicted yaw values and those required for calculation of wind averaged drag coefficients using SAE J1252 [10], assuming a wind speed of 7mph. All forces for negative yaw values presented here are duplicates of their positive counterparts. This assumption has been made based on the symmetric nature of the geometry about the longitudinal axis of the vehicle. The results of these calculations are presented in [Figure 3](#) and [Tables 6&7](#).

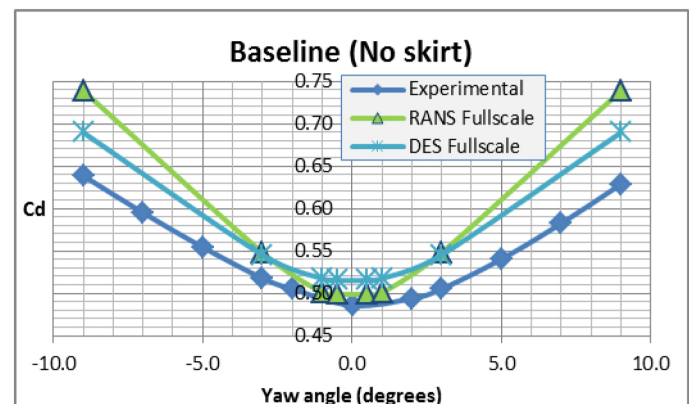


Figure 3. Skirt Parameterization variables and ranges

Table 6. 55mph Wind Averaged Drag Coefficients with No Skirt

	$C_{dwave(55)}$	Δ to experiment	% difference
Experiment	0.554	-	-
RANS	0.611	0.057	10.3%
DES	0.594	0.040	7.2%

Table 7. 65 mph Wind Averaged Drag Coefficients with No Skirt

	$C_{dwave(65)}$	Δ to experiment	% difference
Experiment	0.538	-	-
RANS	0.587	0.049	9.1%
DES	0.575	0.037	6.9%

Comparing the RANS data to the experimental results shows a reasonably good agreement in the low yaw angles

(2.5% difference to experiment), however as the yaw angle increases, the RANS predicted drag increases at a faster rate than the measured data. This rate of change, or gradient, gets steeper the higher the yaw angle becomes, with 9 degrees yaw giving a difference of 17.5%. This variable error across the yaw range results in wind averaged drag coefficients at 55mph & 65 mph that are 10.3% and 9.1% higher than experiment respectively. The higher error at 55mph is because the higher yaw angles (which have the greatest difference to experiment) have a greater impact on the wind average calculations at lower vehicle speeds.

This trend is not exhibited by the transient DES data, which shows a very similar rate of change of drag with yaw angle when compared to the experimental data. However the DES prediction does show an almost constant offset to the experimental data across the yaw range (7.2% & 6.9% difference to wind averaged experimental data at 55mph and 65mph respectively). It is not known how much of this offset are errors in the CFD predictions, or are a result of the differences between the experimental and CFD setup i.e. wind tunnel geometry and boundary layer onto the model, fixed ground vs rolling road, Reynolds number etc. There is also at least one geometrical difference in that the experimental model did not include the mirrors - this accounts for approximately 2% of the total vehicle drag in the CFD model, and is not insignificant when assessing the sources of the discrepancies. The author plans to visit this correlation in more detail in the near future to better understand what factors are contributing to the differences between the measured and predicted data.

Figure A3 shows the steady-state pressure field of the RANS and the time-averaged DES pressure field on the body of the Baseline truck at 0.5 degrees yaw in the form of a static pressure coefficient (C_p).

$$C_p = \frac{P - P_\infty}{1/2 \rho V_\infty^2} \quad (1)$$

These results show broadly similar pressure distributions on both the truck and trailer. However if we look in more detail by examining the difference in the predicted static pressure coefficient (ΔC_p) between the two computational methods we see a different picture (Figure A4).

$$\Delta C_p = C_{p_{case1}} - C_{p_{case2}} \quad (2)$$

The pressure field over the hood, windshield, bumper and A-pillar of the tractor are quite different. The stagnation pressure on the hood is deeper in the DES runs, and the DES is also showing a stronger acceleration over the bumper, which is resulting in stronger suction and hence more thrust from this area. By and large, the trailer is exhibiting similar pressures, except at the base where the pressure for the DES cases is lower. Both the tractor and trailer wheel surface pressures and the area in their immediate vicinity are quite different between RANS and DES. It is the combination of

the different stagnation on the tractor and the base pressure on the trailer, together with the wheel differences, that is giving the difference in the predicted drag between the two methods.

If we look at where the pressure field is most transient using a function called pPrime2Mean (Figure A5) we see that this correlates well with areas where the ΔC_p is different. pPrime2Mean looks at the variance[9] of the instantaneous pressure at a given point on the model to its time-averaged mean.

The similarity of the ΔC_p and the pPrime2Mean plots imply that the pressure differences seen between RANS and DES are generally a function of the local flow transience. More importantly, areas of low transience are exhibiting very similar pressure fields implying that the RANS model does a reasonable job of getting the flow mechanisms in these areas correct despite the steady-state approach adopted and the corresponding offset in loads. The caveat to this is that if the mechanism that is generating the drag change is transient in nature, then the RANS approach may not give reliable drag deltas.

Figures A6 & A7 show the pressure field for a 0.5 degree yaw angle and a 9 degree yaw angle for both the RANS and DES data for the Baseline truck. Oilflow has also been included on these plots to help visualize how the air is moving close to the surface of the vehicle. The same generic changes to the surface flow are seen in both methods, but with magnitude of the flow features being different between the RANS and DES. This is best illustrated by the separation off the tractor's A-pillar at high yaw, where the RANS prediction is showing a much bigger and deeper separation than the DES data (larger recirculation area). The ΔC_p plot for this yaw change (Figure A8) shows that this difference in the predicted separation results in reduced thrust on the A-pillar in the RANS solutions, which may help explain why the RANS cases are showing significantly more drag than both DES and experimental data at the higher yaw angles. Looking more broadly at the plot we see that in general both computational methods show the yaw change affecting the same areas of the vehicle, but that the magnitude of the changes are different. This implies that the flow changes that are impacting the pressure distribution on the vehicle when going from 0.5 degree yaw to 9 degree yaw are the same, but the impact of those flow changes are stronger or weaker depending on the flow feature in question. This would appear to be a much bigger effect on the tractor as the trailer is showing very similar magnitudes of pressure change for both methods. Again the areas that show the biggest difference are areas that exhibit the most transience in the DES solutions.

SKIRT EFFECTS

In addition to the Baseline truck, as part of the model sensitivity analysis two skirt geometries (Skirt A and Skirt B) were constructed utilizing the parametric definition described in Figure 1 & 2. These were run through a 5point yaw angle

sweep both RANS and DES. These results are presented in Figure 4 & 5 with wind averaged data presented in Tables 8 & 9. These curves exhibit the same trends seen above in the Baseline data, with the RANS data showing higher drag predictions at the higher yaw angles than the DES.

This consistent over prediction of the drag at high yaw angles by the RANS model gives some confidence that this can be treated as a systematic error, and that relative changes between skirts can still be measured by the RANS approach. This is somewhat validated by the wind-averaged data in Tables 8 and 9, which shows that for the ranking of the two skirts is unchanged by the method used. However this is far too small a sample set to draw definitive conclusions from, and further datasets need to be added to those presented here to fully validate this assumption.

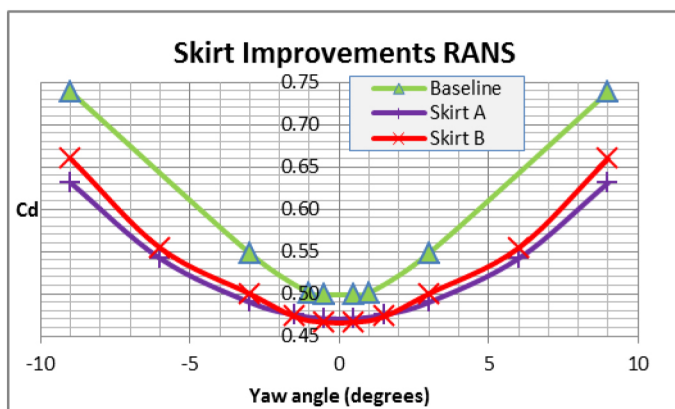


Figure 4. Cd vs yaw angle for 2 skirt changes - RANS

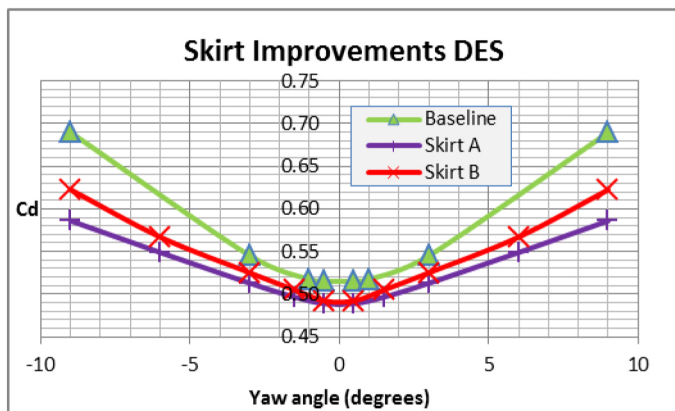


Figure 5. Cd vs yaw angle for 2 skirt changes - DES

Table 8. 55mph Wind Averaged Drag Coefficients for 2 Skirts

	C_{dwave}	Δ to No	%
Skirt A -	0.531	0.080	13.0%
Skirt B -	0.541	0.070	11.5%
Skirt A - DES	0.542	0.074	12.1%
Skirt B - DES	0.558	0.058	9.4%

Table 9. 65mph Wind Averaged Drag Coefficients for 2 Skirts

	C_{dwave}	Δ to No	%
Skirt A -	0.514	0.073	12.4%
Skirt B -	0.522	0.065	11.0%
Skirt A - DES	0.531	0.067	11.2%
Skirt B - DES	0.544	0.053	8.9%

Figures A9, A10 & A11 show the pressure field on the vehicle with and without Skirt A for the RANS data, together with a cross-section through the trailer just ahead of the rear wheels in Figure A12. These plots show that the skirts change how the flow under the trailer behaves. The primary mechanism appears to be to reduce the amount of cross flow between the tractor's rear wheels and the rear wheels of the trailer, effectively shielding the rear wheels from the high total pressure of the free stream. This is best understood when looked at in conjunction with the ΔC_p plots showing the change in pressure across the vehicle for adding the skirt (Figures A12 & A13). This data shows that the primary effect of the skirt is to change the pressure distribution on rear wheels, and that this change is stronger at the high yaw angles. A more negative pressure is seen on the wheels indicating that the stagnation pressure has been reduced, thereby reducing the drag. There is also a small increase in the base pressure behind the wheels, which also adds to the drag reduction. The skirts themselves generate drag, with a positive pressure seen on the outboard face for both the windward and leeward skirts (Figures A10 & A11). This demonstrates that there is a drag transfer between the wheels and the skirts, i.e. the wheels lose drag, the skirt carries drag, but the overall effect is a net drag loss.

SKIRT PARAMETERISATION RESULTS AND DISCUSSION

To better understand the relationship between the shape of the skirt and the drag benefit, a surrogate modeling approach was adopted. The philosophy here is to use the RANS CFD model to generate drag data for lots of different skirts, and then use this data to build a mathematical model of how each parameter, and combination of parameters, changes the drag at a given yaw angle. If an accurate enough mathematical model can be built, then the drag effect of any skirt that falls within the parameter set can be predicted with a high level of confidence without having to physically build and run a CFD model of that skirt. This model can be used to understand the sensitivity of each parameter, allowing, for example, different skirt designs to be ranked against one another or to optimize the skirt shape for minimum drag at specific vehicle speeds and yaw angle ranges.

The RANS model was used in preference to the DES model as the approach used requires in excess of 200 different models to be explicitly built and run to capture the aerodynamic response to an adequate level. This was not

feasible with the DES model as the computational requirements for this number of runs was outside the budget of the work. However it is the authors intent to build this dataset over the coming months to allow direct use of the DES in the surrogate modeling or through some advanced co-kriging technologies [6].

The skirt was defined using the 5 geometric parameters and 2 installation parameters outlined in Figures 1 & 2. Maxima and minima were set for each of these (Table 1), such that the CAD model had enough freedom to capture the majority of shapes and installation configurations seen in the market today [10]. In all cases the skirts were kept planar. A Latin Hypercube space filling algorithm [5] was used to define the initial DoE, and was constrained to limit the initial dataset to 59 points per yaw angle. These 59 skirt designs were run at 0.5, 3 and 9 degrees yaw giving 165 runs in total. This is fewer yaw angles than ideal for J1252, but was a necessary compromise to keep the computational budget to an acceptable level (using the data from Figure 4, the impact of reducing the number of points from 5 to 3 when fitting the cubic spline required for J1252 showed an increase in the wind averaged drag at 55 mph of 0.7%) The drag response was then fitted to this data for each yaw angle using a kriging approach [5,6,7]. Using the results of the krig, the design space was further refined by choosing 5 parametric designs predicted by the fit. These were biased to the upper end of the drag reduction response as this was the deemed the area of most interest. These new designs were drawn in CAD and then run explicitly on the CFD model, added to the DoE at each yaw angle and then re-krigged. This sample and test approach was then repeated one more time, resulting in a response surface (surrogate model) built of 72 points per yaw angle (216 in total).

A further 8 validation points were selected, built and run explicitly. Comparing this final batch of explicit runs (Table 10) to the predicted performance from the surrogate model (Table 11) shows errors of the order of 1% for a wind averaged drag (Table 12). This was deemed accurate enough to determine the importance of each parameter and the range of drag reduction achievable within the constraints of the parameterization. The data also shows that the model accuracy varies with the amount of yaw, with the low yaw angles showing better than 1% accuracy, but the high angles up to 2% accuracy. This would imply that the high yaw angle aerodynamic behavior is more complex than the low yaw angle behavior and that the surrogate model needs a greater number of explicit high yaw angle datasets to capture the aerodynamic response to similar accuracy to low yaw angles.

Figure 6 shows a histogram of wind averaged drag change at 65mph for each of the three krig fits used in the building the final surrogate model. This plot was generated by randomly choosing 2300 parameter combinations, effectively giving 2300 unique skirt geometries. For each of these skirts, the drag response was calculated from the surrogate model of each yaw angle. These were then used to calculate the wind

averaged drag coefficient and the corresponding improvement over the Baseline (no skirt).

Table 10. Explicit RANS Drag Coefficients for the 8 random skirts

	Yaw angle			
	0.5	3	9	$C_{dwave(65)}$
Skirt 1	0.479	0.505	0.651	0.534
Skirt 2	0.479	0.501	0.654	0.531
Skirt 3	0.469	0.489	0.635	0.518
Skirt 4	0.473	0.505	0.676	0.539
Skirt 5	0.466	0.500	0.660	0.531
Skirt 6	0.467	0.495	0.655	0.526
Skirt 7	0.477	0.517	0.690	0.551
Skirt 8	0.465	0.491	0.634	0.519

Table 11. Surrogate Model Drag Coefficients for the 8 random skirts

	Yaw angle			
	0.5	3	9	$C_{dwave(65)}$
Skirt 1	0.476	0.504	0.649	0.533
Skirt 2	0.475	0.496	0.645	0.525
Skirt 3	0.470	0.496	0.638	0.524
Skirt 4	0.472	0.507	0.676	0.540
Skirt 5	0.465	0.499	0.658	0.531
Skirt 6	0.470	0.499	0.651	0.529
Skirt 7	0.477	0.509	0.676	0.542
Skirt 8	0.465	0.489	0.633	0.518

Table 12. % Error between Surrogate Model and Explicit RANS data

	Yaw angle			
	0.5	3	9	$C_{dwave(65)}$
Skirt 1	-0.46%	-0.29%	-0.25%	-0.28%
Skirt 2	-0.78%	-1.05%	-1.31%	-1.11%
Skirt 3	0.20%	1.35%	0.36%	1.22%
Skirt 4	-0.12%	0.30%	0.06%	0.27%
Skirt 5	-0.32%	-0.12%	-0.27%	-0.14%
Skirt 6	0.62%	0.93%	-0.60%	0.66%
Skirt 7	-0.03%	-1.44%	-2.02%	-1.61%
Skirt 8	0.01%	-0.28%	-0.24%	-0.28%

The plot shows that the initial fit predicted a histogram shape similar to a classical Gaussian distribution, the so-called Normal Distribution. As more explicit points were added to the fit, the high performance end of the plot pulls back resulting in a more skewed distribution. This is expected as the additional points added to the set were biased to the high performance part of the design space, therefore there is more information available for the krig to capture the subtler