ABSTRACT
Recent advances in morphing, simulation, and optimization technologies have enabled analytically driven aerodynamic shape optimization to become a reality. This paper will discuss the integration of these technologies into a single process which enables the aerodynamicist to optimize vehicle shape as well as gain a much deeper understanding of the design space around a given exterior theme.

INTRODUCTION
Efforts are made periodically to understand the aerodynamic potential of a given vehicle theme using designed experiments and physical wind tunnel testing. The physical model is typically constructed from a number modules, as illustrated in Figure 1, in order to support the multiple configurations within the designed experiment. A region such as the greenhouse might be represented by two or more modules. For example, one module representing various windshield angles, a second module to account for modified tumble home, and a third module representing different rear header, rear pillar and backlight angles. This type of physical experiment also requires the multiple variations of each module in order to evaluate different levels of each factor in the design. The design and fabrication of these multiple modules is costly and time consuming. The number of factors that can be evaluated is normally limited by the complexity of the modules and interfaces between modules. These constraints and the cost of wind tunnel test time often limit the extent of the investigation. (i.e.: two level vs. multiple level factor evaluation).

The value of the evaluation is frequently mitigated by the fact that the vehicle theme can evolve beyond the scope of the original test by the time the wind tunnel experiment has been completed. The cost and long lead time associated with this experimental approach coupled with the continuous reduction in vehicle development cycle time over the past decade limit the benefits of this approach.

Computationally based designed experiments and optimization studies have historically also been limited by the cost and time associated with configuration changes and simulation times. The majority of computational studies in the traditional processes have also tended to be sequential in nature as illustrated in Figure 2.

Figure 1. Typical Test Vehicle Modular Construction

Figure 2. Traditional Process
More intensive analytically based processes have been attempted in recent years with some success. Most have been limited to somewhat simplified models and/or constrained by the need for manually driven model configuration changes. Recent advances in morphing, simulation, and optimization technologies have opened the door to a new method of aerodynamic shape optimization which is less costly and able to keep pace with reduced vehicle design cycle times. Such a process is illustrated in Figure 3. The goal of the process described in this paper is to deliver an aerodynamic shape optimization methodology capable of investigating the total design space around a particular theme. The process defines the minimum drag attainable from that shape, the optimum range for each factor in the analysis, and provides the aerodynamicist with an interactive tool capable of supporting program trade-off discussions by rapidly evaluating the aerodynamic impact of any combination of factor levels.

Figure 3. Analytical Process

THE ANALYTICAL PROCESS

Both traditional and virtual optimization studies are integrated into this analytical aerodynamic development process. Traditional optimization studies focus on drag reduction for either an exterior component such as the mirror or a particularly sensitive surface region of the vehicle such as the rear header or on some combination of vehicle proportion changes. A limited number of sampling simulations are required to initiate the process. Factor level changes and additional optimization simulations are then driven by the simplex algorithm. This approach generates a reduced drag configuration but provides little understanding of the broader design space of the problem.

The process described in this paper is a more holistic approach that utilizes virtual optimization techniques. This approach requires a larger number of initial samples evenly distributed across the total design space. Design of experiment techniques are used to generate this initial set of samples. Simulations are performed for each sample/configuration. The simulation results are used to generate a response surface describing the mathematical relationships between factors under evaluation. The response surface is valid for any configuration whose factor levels are within the range of the initial designed experiment. A virtual optimization (using standard optimization algorithms) is then performed in which alternate vehicle configurations are evaluated based on the relationships defined within the response surface. The accuracy of the response surface is a function of the initial sampling distribution.

The general process involves 8 steps. The first step is the creation of the analytical model and identification of the factors to be studied. Step 2 is the development and application of the morphing strategies to the base model. The third step focuses on the design of the experiment. Step 4 is the performance of the simulations for each configuration. Step 5 uses the data from the numerical experiment to generate a response surface. The sixth step utilizes the response surface as the engine to perform a virtual optimization. A simulation is performed in Step 7 to confirm the performance of the optimized configuration predicted from the response surface. The data analysis required to understand the physics driving the Cd reduction is performed in Step 8.

The process is totally automated and shown in simplified form in Figure 4. Overall process integration and optimization algorithms are provided by the ModeFrontier software application.

All model configuration changes are automatically generated from a single initial model surface mesh using morphing strategies developed at the beginning of the project. The morphing strategies are developed within ANSA. Each morphing strategy is checked for the quality of mesh generated before it is incorporated into the process. The sequencing of morphing combinations is also checked to ensure quality meshing. Each morphing strategy created is cataloged and available for deployment on future vehicle programs. The morphing strategies are deployed in batch mode during the process.

The process is not dependent upon a particular computational solver. This is definitely an advantage. It enables the process to be deployed early in a vehicle program using a steady state solver (faster simulation times but less accurate) or later in the vehicle program with a transient solver (longer simulation times with increased accuracy).

The Enliten software application is used to generate dynamic (ELS) images for each configuration simulated. These images are useful in communicating potential surface changes to other attributes such as styling and package engineering.
STEP 1: ANALYTICAL VEHICLE MODEL

Front end opening size & location is not typically known at the beginning of a vehicle program. At this point in the program closed front end models have typically been used. This makes it difficult to accurately predict the flow split around the vehicle. To address this issue the closed front end models now incorporate boundary condition mapping. In this process closure surfaces are first created for both the front end openings and the bottom of the engine bay. A mass flow boundary condition is mapped onto the front end closure panels and set of velocity boundary conditions are mapped onto the engine bay closures. This approach results in a more realistic flow split prediction without the additional computational expense incurred by detailed under hood geometry modeling. This does, however, prevent the inclusion of under hood components as factors within the study. All models include fully detailed underbodies including suspension, exhaust, etc. This process has been successfully applied at Ford Motor Company across a broad range of vehicle topologies including trucks, cross-over utility (CUV) vehicles, B-cars, and sedans as illustrated in Figure 5.

Each study typically targets up to 14 proportionality factors. This upper bound is strictly a function of available computer resources and vehicle program timing requirements. Typical factors are shown in Table 1. Examples from a recent truck application are included in this paper for illustrative purposes. Factors specific to the truck study are identified in Table 2.

**Table 1. Common Design Factors**

<table>
<thead>
<tr>
<th>Windshield Angle</th>
<th>Front End Plan View Sweep</th>
<th>Decklid Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof Height</td>
<td>Rear Pillar Curvature</td>
<td>Greenhouse taper</td>
</tr>
<tr>
<td>Tumblehome</td>
<td>Spoiler Length</td>
<td>Hood Length</td>
</tr>
<tr>
<td>Hood Height</td>
<td>Truck Box Plan View Taper</td>
<td>Side View Roof Taper</td>
</tr>
<tr>
<td>Hood Angle</td>
<td>Body side lateral position</td>
<td>Plan View Roof Taper</td>
</tr>
<tr>
<td>Rear Header Curvature</td>
<td>Rear Overhang</td>
<td>Box Cover</td>
</tr>
<tr>
<td>Tailgate Spoiler Length</td>
<td>Truck Box Height</td>
<td>Box Length</td>
</tr>
<tr>
<td>Box Width</td>
<td>Ride Height</td>
<td>Box Cover Length</td>
</tr>
</tbody>
</table>

Figure 4. ModeFrontier Process Workflow

Figure 5. Example vehicle applications
Table 2. Truck Specific Design Factors

<table>
<thead>
<tr>
<th>Design Level 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced Box Length</td>
</tr>
<tr>
<td>Reduced Box Height</td>
</tr>
<tr>
<td>Increased Cab Height</td>
</tr>
<tr>
<td>Increased Hood Height</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design Level 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased Tumblehome</td>
</tr>
<tr>
<td>Reduced Cab Header/Pillar Chamfer</td>
</tr>
<tr>
<td>Increased Curvature of Box Rear Corners</td>
</tr>
<tr>
<td>Reduced Box Width</td>
</tr>
<tr>
<td>Increased Windshield Angle</td>
</tr>
<tr>
<td>Increased Box Cover Length</td>
</tr>
</tbody>
</table>

STEP 2: MORPHING STRATEGIES; AUTOMATED MODEL CONFIGURATION CHANGES

Automated morphing is a critical part of the analytical process. It requires some amount of development time at the beginning of a new study but ensures consistency in approach across all configuration changes. The strategies are then also available to rapidly generate any configuration defined during the virtual optimization phase of the process.

Strategies initially developed are applied to the base model and the quality of the morphed meshes is evaluated across the full level range of each factor. Several iterations are typically required to ensure consistently high quality mesh morphing. The morphing strategies developed are archived and available for reference/application on future programs. The combined morphing strategies for truck are shown in Figure 6.

Dynamic images (Enliten .els images) are created of each configuration in the designed experiment during the morphing stage of the process. The images have zoom capability and can be rotated. This provides a method for quick inspection prior to the performance of any simulations. It also serves as a good visual communication tool with the vehicle program development teams. The images specifically exclude all underbody components and focus on the upper body where the morphing was performed. An example of such an image is shown in Figure 7.

STEP 3: DESIGNED EXPERIMENT

A well designed experiment tries to balance 3 criteria. It is desired to minimize the number of required simulations, minimize the correlation between factors, and generate sufficient data to enable a reliable statistical analysis including RSM. Establishing the criteria for a well designed experiment is a compromise. In industrial applications cost and timing concerns lead away from pure academic criteria and toward a more subjective approach. For example, although zero correlation between factors would be the ideal
situation, a less demanding value of 0.2 is normally accepted. The acceptability of this value has been established through a number of confirmation simulations.

**Latin Hypercube**

A number of sample generation schemes were evaluated during the development of this process. The Latin Hypercube approach was selected based on its ability to consistently generate the most even distribution across the design space while providing reasonable independence between factors.

This process begins with a Latin Hypercube design with a total sample size of approximately 20 times the number of factors in the study. The initial sample set is subjectively checked for distribution and factor independence. Reduction of the initial data set is performed manually using tools within ModeFrontier. The reduced data set is visually checked for distribution and factor correlation. The size of the initial data is typically set at 200 for a ten factor designed experiment and randomly reduced to 150, 100, 75, 50 and 25. A sample set of 50 for a 9-10 factor experiment has been found to be the minimum required to generate a reasonable quality response surface (RSM). The quality criteria for the response surface are based on equivalent directionality as compared to the 200 sample case. The Scatter Matrix shown in Figure 8 provides a graphical depiction of the design space distribution, the numerical correlation value between factors, and histograms of factor level distributions.

The size of the models used during a transient analysis typically ranged 50 and 75 million cells. Simulation times were on the order of 24 hours running across a 96cpu cluster. Post-processing for each simulation is performed automatically as part of the overall process.

The size of the models used during steady state simulations ranged from 25 to 40 million cells. Typical simulation times were 5 hours running across a 64 cpu cluster. Post-processing for each simulation is performed automatically as part of the overall process.

All post-processing is performed automatically and provides the aerodynamicist with images of flow structures, pressure distributions, velocity distributions, surface flow lines, and drag development plots. In addition, the relative significance on vehicle drag of each factor in the study is quantified in a Factor Correlation Table as shown in Table 3 below.

**Table 3. Correlation of Factors to Drag Coefficient**

<table>
<thead>
<tr>
<th>Design Factor</th>
<th>Correlation Factor to Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>0.844</td>
</tr>
<tr>
<td>Tumblehome</td>
<td>-0.003</td>
</tr>
<tr>
<td>Box Rear Corner</td>
<td>0.827</td>
</tr>
<tr>
<td>Cab Rear Header Chamfer</td>
<td>-0.803</td>
</tr>
<tr>
<td>Plan View Sweep</td>
<td>0.579</td>
</tr>
<tr>
<td>Plan View Taper</td>
<td>0.742</td>
</tr>
<tr>
<td>Hood Vertical</td>
<td>-0.545</td>
</tr>
<tr>
<td>Front Corner X Position</td>
<td>-0.318</td>
</tr>
<tr>
<td>Box Height</td>
<td>-0.047</td>
</tr>
</tbody>
</table>

**STEP 5: RESPONSE SURFACE METHODOLOGY**

A quality response surface serves as the engine for virtual optimization studies which minimize (vs. a traditional optimization approach) the total number of required simulations.

The analytical process described in this paper uses the Radial Basis Function for response surface generation. This approach was selected for its ability to best fit to the underlying data. The maximum expected error range for predicted Cd values based on empirical results is on the order of 0.002. The validity of this approach has been established through a number of confirmation simulations. In these confirmation studies, CFD detailed simulations of the design configurations associated with the RSM predicted minimum and maximum Cd values are performed and the results compared against the RSM predictions.
Graphical User Interface

A graphical user interface (GUI) was developed specifically to support this process. The GUI is totally interactive and provides the aerodynamicist with a tool for rapid evaluation of design alternatives within the original design space. The GUI is divided into two major sections. The first section, shown in Figure 9, presents a function plot for each of the factors (a total of 10 in this case). The function plot acts as a sensitivity indicator. The vertical axis of each function plot shows the range of each factor in the study. The horizontal axis shows the corresponding range of potential Cd changes. Each set of function plots is valid for a single point (configuration) within the design space. Relative sensitivity of a given factor at one point in the design space will vary versus other points in the design space.

![Figure 9. Response Surface GUI Function Plots](image)

The second section of the GUI, shown in Figure 10, is the user interface. It is in this section that the user interrogates the design space by adjusting individual factor levels. The effect on Cd of any configuration change is calculated and immediately available for review by the engineer or program team members.

![Figure 10. Response Surface GUI User Interface](image)

STEP 6: VIRTUAL OPTIMIZATION

As stated earlier, this process utilizes virtual optimizations in lieu of traditional optimization approaches. Time, cost, efficiency and a desire to understand the entire design space are the main drivers in selecting the virtual optimization approach. A number of optimization algorithms are available within ModeFrontier. Non-dominated Sorting Genetic Algorithm II, (NSGAII) has been applied with a good level of success. The virtual optimization is only as accurate as the underlying response surface. The response surface is an approximation of the relationships between the factors under study. It provides direction in terms of factor levels and approximate Cd values. Virtual optimization is deployed early in the vehicle development process when directionality is more important than absolute accuracy of predicted Cd. Virtual optimization has shown itself capable of providing very good directionality. Confirmation simulations are ultimately used to provide accurate Cd predictions for specific configurations of interest to the vehicle program.

There are three major deliverables from this process as shown in the flow chart in Figure 11. Those deliverables are:

1. Determine the minimum Cd attainable within the given design space
2. Quantify the optimum ranges for each factor
3. Provide a GUI to support trade-off discussions across vehicle attributes

![Figure 11. Process Flow Chart](image)

The GUI was described previously. The minimum attainable Cd and the optimum range for each factor are determined from the parallel coordinates plot. A typical parallel coordinates plot is shown in Figure 12.
Figure 12. Parallel Coordinates Chart

The plot defines the factor levels and Cd values for each configuration evaluated during the virtual optimization. Factors are identified across the horizontal axis. Factor level ranges are identified along the vertical axes. Cd values corresponding to each configuration evaluated are plotted on the far right vertical axis. Each configuration is represented in the plot by a single unique curve formed by connecting the factor levels for that configuration. The NSGA II optimization algorithm evaluates an additional 100 generations from each of the configurations in the original designed experiment. This algorithm would thus evaluate 10,000 additional configurations from a 100 configuration designed experiment. Optimum ranges for each factor are identified by areas of clustering in the parallel coordinates chart. The effect of the clustering can also be visually enhanced by filtering the Cd values. The ability to define optimum ranges rather than a point target for each factor level is important. It provides the aerodynamicist with multiple factor level combinations that can all generate a minimized Cd. This is a valuable tool in trade-off discussions.

The minimum attainable Cd value appears as the lowest value shown in the far right hand axis. Filtering can also be applied to any and all vertical axes to evaluate potential Cd reductions under any combination of factor constraints.

STEP 7: CONFIRMATION SIMULATION

Confirmation simulations, as stated earlier, are an important component of this system. The response surface is capable of accurately predicting Cd directionality and relative values only. It is not used for absolute vehicle Cd predictions. Confirmation simulations are ultimately required to provide accurate Cd predictions for specific configurations of interest to the vehicle program.

STEP 8: ANALYSIS OF RESULTS

One of the strengths of CFD is the ability to analyze the flow physics and understand the driver behind predicted Cd changes. A series of images illustrating flow structures, pressure distributions, surface flow visualizations, and Cd development are automatically generated as part of the overall process. An abbreviated set of comparison images for two different design levels from a recent truck optimization study are presented below for illustration purposes.

Geometry

Cd Development Curves

The Cd development curves plot cumulative Cd on the vertical axis against vehicle position on the horizontal axis. Comparison of the plots shows a significant difference in Cd occurs at the rear of the cab.
Surface Pressure Distributions

The surface pressure distributions show a significantly lower pressure on the back face of the cab and along the rear header and pillars of the cab in design level 9.

Flow Structures

Iso-surfaces of total pressure show wake structure differences between design levels but the effect of these differences on Cd can be difficult to quantify.

Flow Field Pressure Distributions

A lower pressure region directly behind the cab in design level 9 is clearly seen in these centerline slices and supports the differences in the two design levels highlighted in the Cd development curves.

SUMMARY/CONCLUSIONS

A process has been developed that is capable of:

1. Determining minimum Cd attainable within a specified surface envelope at the beginning of the vehicle program
2. Quantifying effect on Cd of key upper body surface parameters and establishing optimum ranges for each.
3. Providing a graphical user interface enabling rapid evaluation of the effect on Cd of any configuration within the specified surface envelope.
   ◦ Rapid feedback to Design Studios
   ◦ Supports program trade-off discussions

That process has been successfully deployed in support of vehicle aerodynamic development in a production environment. The process continues to evolve and improve with each new vehicle application.

REFERENCES


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DEFINITIONS/ABBREVIATIONS

CFD
Computational fluid dynamics

Cd
Coefficient of drag

GUI
Graphical User Interface

DOE
Design of Experiment

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper.

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