Design and Optimization of Reconfigurable Vehicle Platforms

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Continuous advancements in technology have resulted in customers expecting enhanced performance across a variety of diverse and changing operating conditions. When multiple system objectives exist, traditional design techniques incorporate tradeoffs to reach a final design. In this paper, the desire to meet a variety of system objectives is accomplished through the design of reconfigurable systems. Reconfigurable systems are capable of undergoing changes to their configuration to meet new objectives, function effectively in varying operating environments, and deliver value in dynamic market conditions. However, permitting such changes to a system increases complexity and cost, from both a monetary perspective and allocation of resources. If this increase is too large, only a subset of design variables can be made adaptable, making the need for incorporating product platforming apparent. The intelligent design of a core architecture to accommodate the changing number of adaptable design variables allows for broader applications when technical and economic constraints are present. To illustrate this approach, a case study involving the design and optimization of a reconfigurable race car is introduced. The performance of this vehicle is assessed on different racetracks, with the overall goal being the minimization of the time required to traverse each track section. The results from this case study demonstrate the effectiveness of combining reconfigurable system design with product platforming techniques to achieve individualized products that meet the many demands of the consumer.

Nomenclature

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a' )</td>
<td>Normalized center of gravity position</td>
</tr>
<tr>
<td>( C )</td>
<td>Chord length, ft</td>
</tr>
<tr>
<td>( C' )</td>
<td>Normalized aerodynamic downforce distribution</td>
</tr>
<tr>
<td>( C_L )</td>
<td>Lift coefficient with ground effect</td>
</tr>
<tr>
<td>( C_{LO} )</td>
<td>Lift coefficient in free air</td>
</tr>
<tr>
<td>CP</td>
<td>Control point</td>
</tr>
<tr>
<td>( f )</td>
<td>Generic objective function</td>
</tr>
<tr>
<td>( g )</td>
<td>Generic inequality constraint</td>
</tr>
<tr>
<td>( h )</td>
<td>Distance from ground to leading edge of airfoil, ft</td>
</tr>
<tr>
<td>( K' )</td>
<td>Normalized roll stiffness distribution</td>
</tr>
<tr>
<td>N</td>
<td>Number of panels</td>
</tr>
<tr>
<td>( x )</td>
<td>Generic design variable vector</td>
</tr>
<tr>
<td>( y_{CP} )</td>
<td>Unitless y-value of control point</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Angle of attack, deg</td>
</tr>
</tbody>
</table>

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I. Introduction

Beginning in the 20th century, design in industrialized economies became based upon the concepts of mass production, mass distribution and mass marketing. Continuous advances in technology and information have impacted all aspects of design. These advances have made it possible to rapidly respond to the unique demands, or requirements, of the consumer. As a result, designers have begun to shift their focus towards variety and customization especially in the aerospace industry. For instance, military aircraft incorporate customer-specific weapons and avionics systems while passenger aircraft are customized by each airline to meet particular requirements.

Such continuous advances have fragmented consumer demand, resulting in a more heterogeneous marketplace where consumers are demanding products that meet their individual needs. As consumer needs become more diverse, it becomes increasingly difficult to provide the market with a single, static product. To meet the demand of these small market niches, companies manufacture a great variety of products. However, a pitfall to this increased variety is heightened confusion and stress, making it difficult for consumers to choose the product that best suits their needs. Therefore, a key aspect of this new design paradigm is meeting consumer needs while maintaining budgetary constraints and not overwhelming the consumer with variety.

Historically, a majority of customization has been accomplished through the development of product platforms. To promote mass production, many top-down platforming approaches aim to simultaneously develop product platform architectures while reducing redesign costs. These approaches create their common cores at the expense of performance, refining a problem to be customer-specific but not alleviating the problem of attaining optimality across multiple, non-simultaneous, operating conditions. Recently, reconfigurable system design has arisen as a potential solution to this demand for increased performance. Costing studies, however, have demonstrated that increased system cost results from the ability for design variables to change during operation. Such costs can occur from both a monetary and resource perspective. Therefore, combining reconfigurable system design with product platform research presents an opportunity to design systems capable of minimizing performance loss across multiple objectives while managing budgetary restrictions.

This paper examines the performance and configuration of reconfigurable systems in relation to their static counterparts, and then quantifies advantages of combining reconfigurability and product platforming. A case study based on the design of a race car required to traverse two different racetracks is presented. Design parameters are taken from three unique disciplines that primarily affect vehicle performance – aerodynamics, handling, and chassis configuration. To accurately demonstrate required changes in the aerodynamic discipline, the vehicle’s airfoils are modeled. These airfoils are treated as reconfigurable airfoils, with changes to surface control points yielding different amounts of aerodynamic downforce. Finally, a family of reconfigurable vehicles is developed to illustrate the design of reconfigurable systems when attempting to reach a range of market segments.

II. Background

This research occurs at the intersection of several technology areas: reconfigurable system design, design and analysis of reconfigurable aircraft / morphing airfoils, and product platform design. This section contains an overview of the relevant material from each of these three areas.

A. Reconfigurable system design

Increased expectations have made today’s products inherently complex, as customers demand enhanced performance to suit their specific, yet constantly changing needs. Work in customization has shown that the mere inclusion of additional features will not guarantee full customer satisfaction. Also, there has also been increased economic and political pressure to develop systems capable of performing multiple roles, or to be “jack-of-all-trades”. Designers are therefore beginning to shift focus from a single product design to a realm of designs that are expected to evolve, perform multiple tasks, and operate under changing operating conditions.

Engineering design has primarily focused on the optimization of systems with fixed design variables, where a typical problem formulation is given by:
\[
\begin{align*}
\min f(x) \\
st. g(x) < 0 \\
x_{LB} \leq x \leq x_{UB}
\end{align*}
\]  

where \(f\) is an objective function, \(x\) is the vector of design variables, and \(g(x)\) are general inequality constraints. The design space is where the designer establishes geometric shape, adds or removes modules, defines possible platforms, and receives variable values from other designers. Fixed design variables are those not allowed to change once the system has been deployed, preventing changes in the system’s state. When multiple competing performance objectives exist, the optimum is no longer a single design point but an entire set of nondominated design points, referred to as the Pareto set\(^{10}\). In this situation, a designer is faced with the challenge of choosing a single point, preferably Pareto optimal, as the final design. Therefore, the inherent tradeoffs needed to resolve issues when faced with conflicting objectives are a primary motivation for reconfigurable system design.

Reconfigurable systems are designed to maintain a high level of performance by changing their configuration to meet multiple functional requirements or a change in operating conditions, within acceptable reconfiguration time and cost\(^{11,12}\). After the system has been deployed, design variables change their physical values, allowing the system to respond to changing operating conditions or system objectives. Modularity and adaptability provide the means toward achieving these configuration changes. Modularity allows modules to be replaced and updated with interfaces that are well defined\(^{13}\). Adaptability characterizes a system’s ability to adapt itself to deliver intended functionality under varying conditions through the design variables changing their physical values through both active (on-line), or passive (off-line), configuration changes\(^{14,15}\).

Utilizing changes in design variables values after deployment allows for the system to achieve multi-ability and respond to changes in system objectives. A reconfigurable system is also able to respond to changing in the operating environment in a manner different than traditional robust design\(^{16}\). A reconfigurable system accepts changes in the operating environment and determines the appropriate adaptation needed to obtain an optimal design. Research into reconfigurable system design has mainly focused on three specific areas: costing, design variable selection, and transitioning with control theory\(^{17-21}\).

A majority of the research to date in reconfigurable system design has focused on developing methodologies and approaches to be used within the context of the design process. Within the last decade, there has also been a movement towards multi-role vehicles and the increased missions they are capable of. Research in the area of multi-role vehicles, such as morphing aircraft, is the focus of the next section.

### B. Morphing aircraft / airfoils

Research into the design of morphing aircraft has mainly been focused in two areas: understanding performance implications and appropriate mission requirements, and sizing and control issues in designing a morphing aircraft to meet those requirements\(^{22}\). These issues tend to go hand-in-hand, as “the suitability of a type of morphing technology that is integrated into an aircraft will be dependent on size, range and flight performance envelope\(^{23}\).” Peters et al.\(^{24}\) discuss an approach to generate and develop missions suitable for morphing aircraft that complement a “push” from device and technology research. Cesnik et al.\(^{25}\) describe a need to develop metrics capable of assessing morphing capabilities by systematically considering the aircraft’s ability to complete the desired roles based on changing its configuration. Such a fleet of aircraft poses economic motivation when contrasted to a fleet of different aircraft types, each optimized for a specific mission, with unique maintenance and support requirements\(^{23}\). A baseline concept to achieve shape change can then be selected to compare the morphing fleet of aircraft against a fleet of fixed architectures\(^{22}\). Solution frameworks combining probabilistic measures of mission success, and multiple missions containing nondeterministic parameters, also have been introduced\(^{26}\).

An approach to developing a morphing UAV was proposed by Rusnell\(^{27,28}\) by designing a buckle-wing airfoil. Martin and Crossley\(^{29}\) studied the variation in design variables associated with the aircraft wing to determine which variables would be the best candidates for morphing actuation. Roth and Crossley\(^{30}\) presented the approach of treating morphing as an “independent variable” in determining which design variables should be changed and by what magnitude. Here, morphing was constrained to the aircraft wing, and changes in shape were represented as occurring instantaneously between mission segments.

Traditional sizing approaches, however, may not be able to address the significant shape changes permitted by morphing aircrafts. Frommer and Crossley\(^{26,31}\) leverage the “morphing as an independent variable” approach to permit the use of continuous optimization techniques to size the resultant aircraft. Ricci and Terraneo\(^{32}\) have
examined how changes in sweep angle and aspect ratio, subject to constraints and aeroelastic behavior, affect the minimum structural weight of morphing wings. Wing shaping, however, may also result in poor lateral control due to the increased difficulty of installing ailerons on membrane wings. Changes in planform and wing section shape through the implementation of extendable spars and telescopic ribs have demonstrated performance advantages of reducing drag. Furthermore, a generalized strategy towards developing wing weight equations using response surface methodology, design of experiments, and finite element analysis, has been introduced.

The performance from morphing wings is not limited solely to the design of aircraft. Race cars use inverted airfoils to product downforce, which allows the vehicle to maintain speed in corners and increase braking effectiveness. Leveraging a concept like morphing will decrease the lap time of a race car with reconfigurable airfoils. The ability of a system to reconfigure, or morph, has been shown to enhance potential performance when the system objectives change after deployment. However, while it is ideal to allow all design variables to adapt and change values, budgetary restrictions may prevent this. Product platform design is an approach to achieving variety while maintaining economies of scale, and is the focus of the next section.

C. Product platform design

Creating a family of products has become a major focus of many manufacturing companies as it reduces costs while allowing for product variety. However, this increase in commonality inhibits the ability to create designs that are fully optimized for performance within their individual market segments. Therefore, the challenge presented lies in determining which components to share when designing the product family while minimizing resulting decreases in performance. Two basic approaches to product family design have been identified. The top-down approach has been used in the development of the Sony Walkman™ and Kodak Quicksnap™, where a company develops and manages a family of products based on a product platform and its variants. Black & Decker has applied the bottom-up approach to redesign or consolidate a group of distinct products in an effort to standardize components and control cost. Three platform leveraging strategies have been identified from the market segmentation grid, as identified by Meyer: horizontal leveraging, vertical leveraging, and a beachhead approach as shown in Fig. 1.

Meyer and Lehnerd discuss advantages and disadvantages of each leveraging approach, and many instances of the product segmentation grid are demonstrated in engineering design literature. Other work has examined how modules influence the development of product platforms, using a fixed modular architecture. Papalambros et al. studied product platforming when considering “mild variants” such that they could be guided by sensitivity information when optimizing their commonality decisions. Fellini developed an optimization problem to maximize commonality subject to performance loss constraints resulting in a single objective optimization problem. This approach was leveraged by the authors in collaboration with General Motors to design a family of vehicles using a technical feasibility model and marketing tools.

Research into product platforms has demonstrated the ability to provide increased variety, but resultant designs are not capable of maintaining optimality when faced with varying system objectives. This paper combines the strengths of reconfigurable systems and product platforming to meet the many demands of the consumer. Now that the theoretical foundation for this paper has been presented, these concepts will be applied to a case study involving the design of a formula-style race car. The next section of this paper details the development of the vehicle model, the manner in which the reconfigurable airfoils are designed, and initial results of the static and fully-reconfigurable vehicle. The results from this section will then be applied in the design of a vehicle architecture when only a subset of the original design variables are allowed to change. The performance results of the platformed vehicle will then be compared to demonstrate the effectiveness of reconfigurable systems and the benefits of implementing product platform techniques into the design process.
III. Case Study Model Development

A. Vehicle Model Development

In the design of a race car, success comes down to the ability of a driver to get the most out of an optimally designed vehicle. The core vehicle architecture is aimed at an optimal compromise that allows a driver to turn fast lap times repeatedly at a particular racetrack. A particular vehicle design may be optimal at a certain speed and cornering radius, but sub-optimal on others. Generally, racetracks have numerous corners with varying radius; however, the design team must choose a single vehicle configuration on race day. Compound this with the fact that the vehicle must be configured for anywhere between 15 and 30 tracks throughout the racing season, and the complexity of such a task comes into focus.

Consider a reconfigurable formula-style (Formula 1) racecar design that is able to optimize its performance as a function of its current track location. Whether on a straightaway, a large turn, or a hairpin turn, the car could adjust variables such as the center of gravity, roll stiffness, and aerodynamic downforce. The amount of detail that can be modeled in a computer-based simulation of an automobile is almost limitless. Although many of the details are unnecessary in the preliminary design stage, it is necessary to model the basics of the vehicle design correctly. A brief explanation of the race car model can be found in Refs.46, 21. The design variables chosen for this model represent three potential disciplines working on the vehicle, whose primary parameters affect a vehicle’s performance47, as shown in Fig. 2.

The performance of this model on variable radius skidpads has been extensively studied47, and a more detailed look at the fundamentals of vehicle analysis can be found in Ref. 48. Further analysis of this model, studying the manner in which design variables change in a reconfigurable race car, has been completed by the co-authors 21. This work also introduced the optimization of a vehicle traversing a straightaway connecting two corners of different radii. In this paper, the following updates to the vehicle model have been made:

- Non-zero bank angle now accounted for in skidpad optimization
- Vehicle is power limited based on a 750 hp engine
- Model for front and rear tires has been updated
- Reconfigurable vehicle is able to change configurations multiple times on track straightaways
- Aerodynamic downforce is now calculated using wing planforms

Previous work with this vehicle model has focused solely on the three inputs into the racecar configuration block in Fig. 2. To extend this model and further the practical understanding of reconfigurable system design, the configuration of the front and rear airfoils have been added as part of the aerodynamic discipline. Up until the 1960s, aerodynamic effects were of secondary concern to powertrain, chassis design, and tire analysis. However, in terms of overall vehicle drag, aerodynamic drag is the dominant factor once a vehicle is moving faster than 60 miles per hour. As the vehicle’s speed increases, the vehicle also becomes more unstable due to a reduction in yaw damping. Airfoils on a modern Formula One car are designed to produce negative lift (downforce) in order to increase tire capabilities and counteract these high speed instabilities. Aerodynamic downforce is therefore an essential component in maintaining speed while cornering, and different race courses will place different demands on the aerodynamic setup of the vehicle. For instance, a road course requires large downforce to maintain speed through the corners and enhance braking, while on a speedway the reduction of drag is a primary concern49. The next section describes the approach towards calculating the lift coefficient for an airfoil planform.

Fig. 2. Multidisciplinary Vehicle Optimization Flowchart
B. Lift Coefficient Calculations for a Planform Shape

Panel methods have been used to calculate the velocity distribution along an airfoil for more than 30 years. Source panels determine the flow characteristics around arbitrarily shaped non-lifting bodies in both two and three dimensions. When circulation is introduced, it is possible to obtain the lifting characteristic for each shape. Distributed sinks and sources can be replaced by vortex panels for which the circulation is included in the formulation. A finite number of vortex panels are used to approximate the body shape of an airfoil, distributed more densely in the leading and trailing edge regions, where the velocity changes rapidly. In the development of this approach, a linear variation of circulation density, $\gamma$, is assumed on each panel. Also, it is assumed that the circulation density is continuous across each panel, as seen in Fig. 3.

![Fig 3. Creating Vortex Panels for an Airfoil Planform (From Ref. 50)](image)

Determination of the pressure coefficient at each control point creates a series of equations allowing for the calculation of the overall lift and drag. When designing a racecar, however, a significant amount of downforce is also achieved through the use of ground effect. While the application of the vortex panel method above does not account for this phenomenon, the next section describes an approach to account for this increased downforce.

C. Determination of Ground Effect

Ground effects allow for a significant increase in the downforce generated by the vehicle, as the flow around the airfoil is significantly modified. In this situation, a wing near the ground may be regarded as interference between the wing and its image in the ground. Complex analysis of ground effect can be completed using a wind tunnel, a moving belt simulating the ground, and a model of the airfoil being tested, as in Refs. 50, 51. For the development of this case study, however, Fig. 4 serves as an approximate estimation of how the sectional lift coefficient is affected by the presence of the ground.

![Fig 4. The lift on a flat plate near the ground (From Ref. 53)](image)

In this figure, $h$ is the distance from the ground to the leading edge of the airfoil, and $C$ is the chord length of the airfoil planform. These values must be selected by the designer along with the angle of attack, $\alpha$, to determine the ratio between the sectional coefficient of lift, $C_{L_s}$, and the coefficient of lift in free air, $C_{L0}$. Further information about the influence and study of ground effect can be found in Refs 51,52. Having explained the manner in which the coefficient of lift is calculated in free stream and modified by ground effect for the front and rear airfoils, the next section will describe the manner in which the airfoils are made adaptable.

D. Creating Adaptable Airfoils

Having presented the necessary material to analyze an airfoil design, attention must now be turned to creating the adaptable airfoils. Figure 5 first shows the panels created for a NACA 0012 airfoil using the vortex panel method with the number of panels, $N = 60$. Seven points at the same x/c location are selected as control points for the upper and lower surface of the airfoil.
Similar approaches to modifying the shape of an airfoil to promote morphing have been seen in Refs. 54, 55. In this approach, when a control point is selected for adaptation, as shown in Figure 6, the $y$-values corresponding to both the upper and lower surface are allowed to deviate with respect to the constraints in Equation 3, where $CP$ refers to the control point selected. These constraints have been generated to prevent unnatural modifications to the planform of the airfoil that cannot be accurately modeled by the vortex panel method.

\[
0.75 y_{CP_{UPEX}} \leq y_{CP_{UPPER}} \leq 1.25 y_{CP_{UPPER}} \\
0.75 y_{CP_{LOWER}} \leq y_{CP_{LOWER}} \leq 1.25 y_{CP_{LOWER}}
\]

The endpoints of the airfoil, at both the leading and trailing edge, are fixed to the base airfoil design to ensure continuity. With such surface modifications using the control points, panel endpoint locations are determined using a splined approach.

Now that the fundamental details behind this model have been presented, the model can be applied to the design of a platformed, reconfigurable formula-style racecar. The next section introduces the design variables, objective functions, and racetracks that the vehicle must complete. The optimal values for the static and reconfigurable systems are presented, with focus on the resultant front and rear airfoil solutions. An opportunity for product platforming is introduced, and the optimization approach to this problem is presented. Finally, a family of reconfigurable vehicles is developed to meet the required market segments and illustrate the benefits of combining reconfigurability and product platform design.

IV. Case Study: Designing a Platformed Reconfigurable Racecar

For this case study, the performance of static vehicles will be compared to a family of reconfigurable vehicles on two racetracks. A race car’s on-track performance can be summarized as follows. First, it enters a straightaway at the maximum steady-state cornering velocity from the previous corner. It will accelerate as hard as possible until, at the last possible instant, it will brake as hard as possible so that at the end of the straightaway the vehicle’s velocity is equal to the maximum steady-state cornering velocity of the upcoming corner. This sequence repeats for every corner-straightaway-corner segment of the track. A simulation is completed by evaluating each portion of the track separately and combining the results to assemble a lap time. Although this simulation includes many simplifications and does not capture every aspect of the vehicle’s dynamics, the results provide enough information to evaluate...
reconfigurable systems and potential product platforming opportunities. In the next section, the problem description will be defined.

A. Problem Description

Imagine the scenario of a race car manufacturer developing a hypothetical next generation Formula One racecar. Current racing restrictions have been removed and the ability for the vehicle to reconfigure itself while on the track is now allowed. However, there is significant variation in the allowable budget of different racing teams, and to capture as much as the market as possible, the vehicle design must be platformed to reach all potential buyers. The approach taken in this case study is shown in Fig. 7. First, a multidisciplinary optimization is completed for a static vehicle on each racetrack. The optimal configuration of the static vehicle is then determined based on the criteria that the vehicle must traverse both tracks, without modification. Finally, the fully reconfigurable vehicle is optimized for each corner and straight of each track. In a fully reconfigurable vehicle, all design variables are allowed to be adaptable. The solutions of the multidisciplinary optimization are then compared to evaluate performance and compare the resulting configurations. The appropriate market segments, using vertical leveraging as in Fig. 1, are then identified, and the appropriate design variables are selected to be platformed. Once these criteria have been defined, the multidisciplinary optimization of the product family is completed and the benefits of combining product platforming and reconfigurability are quantified.

![Multidisciplinary Optimization of static vehicle (for each racetrack)](image1)

The first step in optimizing the configuration of the vehicle is determining the design variables associated with the vehicle layout. As previously shown in Figure 2, the three upper-level design variables that determine the vehicle’s configuration are the center of gravity, roll stiffness distribution, and the aerodynamic downforce distribution, each normalized between 0 and 1. The normalized center of gravity represents the weight distribution on the front axle. Roll stiffness distribution signifies the amount of resistance to vehicle roll the front axle provides relative to the total resistance provided by the front and rear tires. Aerodynamic downforce distribution is the division of the individual aerodynamic downforce acting at the front and rear axles. As this force is generated by the overall shape of the inverted airfoils, this approach defines the airfoil planform NACA number for both the front and rear airfoils. The four digits in the NACA number describe the overall shape of the airfoil. As an example, the first two numbers in a NACA airfoil 6418 defines an airfoil with a maximum camber of 6 percent the chord length, occurring at a distance 40 percent from the leading edge. The last two digits indicate that the maximum thickness of the airfoil is 18 percent the overall chord length of the wing. For all analysis completed in this case study, a constraint on the airfoil design is the maximum thickness of the airfoil must be greater than 0.

In this study, performance on two different racetracks is investigated. The simplified dimensions of the first track, the Pocono Raceway in Long Pond, PA., are listed in Table 1.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Bank (deg)</th>
<th>Radius (ft)</th>
<th>Distance (ft)</th>
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<tbody>
<tr>
<td>Straightaway 1</td>
<td>-</td>
<td>-</td>
<td>3055</td>
</tr>
<tr>
<td>Turn 1</td>
<td>14</td>
<td>602</td>
<td>1565</td>
</tr>
<tr>
<td>Straightaway 2</td>
<td>-</td>
<td>-</td>
<td>3740</td>
</tr>
<tr>
<td>Turn 2</td>
<td>8</td>
<td>760</td>
<td>1115</td>
</tr>
<tr>
<td>Straightaway 3</td>
<td>-</td>
<td>-</td>
<td>1780</td>
</tr>
<tr>
<td>Turn 3</td>
<td>6</td>
<td>736</td>
<td>1630</td>
</tr>
</tbody>
</table>

Table 1. Dimensions of Pocono Raceway
The second racetrack studied is the oval course at the Indianapolis Motor Speedway in Speedway, IN. This course consists of only three unique segments, with a lap consisting of four times around the corner, and twice down each straightaway. The simplified dimensions for this track are shown in Table 2.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Bank (deg)</th>
<th>Radius (ft)</th>
<th>Distance (ft)</th>
</tr>
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<tr>
<td>Straightaway 1</td>
<td>-</td>
<td>-</td>
<td>3300</td>
</tr>
<tr>
<td>Turn 1</td>
<td>9</td>
<td>840</td>
<td>1320</td>
</tr>
<tr>
<td>Straightaway 2</td>
<td>-</td>
<td>-</td>
<td>660</td>
</tr>
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</table>

Table 2. Dimensions of Indianapolis Motor Speedway (Oval Course)

The multiobjective problem developed by this analysis is defined by the minimization of the time it takes to traverse each section of the racetrack, subject to the constraints placed upon the vehicle. The ultimate goal is to minimize the sum of each objective as it relates to the fastest lap time. In standard form, the optimization problem for the static and fully reconfigurable vehicle can be written as:

\[
\text{Minimize: } \sum_{i=1}^{n} F_i \\
\text{Subject to: } \begin{align*}
0.10 &< a' < 0.90 \quad &\text{(Normalized center of gravity position)} \\
0.10 &< K' < 0.90 \quad &\text{(Normalized roll stiffness distribution)} \\
0.10 &< C' < 0.90 \quad &\text{(Normalized aerodynamic downforce distribution)} \\
\alpha_{fa} &< \alpha_f < \alpha_{fa} \quad &\text{(Front airfoil angle of attack)} \\
\alpha_{ra} &< \alpha_r < \alpha_{ra} \quad &\text{(Rear airfoil angle of attack)}
\end{align*}
\]

The definition of the optimization problem allows for the configuration and performance of the static and fully reconfigurable vehicles to be determined. Results of this multidisciplinary optimization are presented in the next section.

B. Racetrack Analysis

The multidisciplinary optimization described in the last section was completed using a genetic algorithm (GA). For each corner, the GA only needed one instance to arrive at an optimal solution. A single value can be achieved due to the assumption of steady-state cornering in the analysis of the skidpad. However, for the straightaways, the steady-state assumption is not valid. Therefore, an instance of the GA was implemented each second (in racing time) that the vehicle was traversing the straightaway. This allowed for the configuration of the vehicle to change and maximize both acceleration and deceleration as needed. The results for the static vehicle and the fully reconfigurable vehicle are shown in Table 3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Static Vehicle</th>
<th>Fully Reconfigurable Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Turn 1</td>
<td>Turn 2</td>
</tr>
<tr>
<td>( a' )</td>
<td>0.3417</td>
<td>0.4251</td>
</tr>
<tr>
<td>( K' )</td>
<td>0.7248</td>
<td>0.5334</td>
</tr>
<tr>
<td>NACA Front</td>
<td>5456</td>
<td>1735</td>
</tr>
<tr>
<td>NACA Rear</td>
<td>1518</td>
<td>0404</td>
</tr>
<tr>
<td>AoA Front (deg)</td>
<td>8.99</td>
<td>9.02</td>
</tr>
<tr>
<td>AoA Rear (deg)</td>
<td>10.398</td>
<td>10.67</td>
</tr>
<tr>
<td>Time (sec)</td>
<td>33.254</td>
<td>4.2986</td>
</tr>
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</table>

Table 3. Multidisciplinary Optimization Results for Pocono Raceway

The results of Table 3 show that the fully reconfigurable vehicle is 1.878 seconds faster per lap than the static vehicle, a 5.65 percent improvement. Given a race on this track of 200 laps, the total time differential between the two vehicles, all else being equal, would be 375 seconds, or roughly 6.25 minutes. This speed increase over the static vehicle is due to the tradeoffs necessary in a multiobjective problem when designing under multiple system objectives. Figure 8 compares the solution of the static airfoil design (plotted in black) versus the solution of the
reconfigurable airfoils for each of the corners. From this figure, the limitations of a static airfoil, when compared to a reconfigurable airfoil, become apparent.

![Front Airfoil Planform](image1.png)

![Rear Airfoil Planform](image2.png)

**Fig 8. Comparison of Front and Rear Planforms from Pocono Raceway Optimization Results**

Table 4 combines the results of the multidisciplinary optimization from the Indianapolis Motor Speedway. While the benefit on this track is not as apparent as the Pocono track, a decrease in time of 0.67 seconds relates to a 2 percent improvement.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Static Vehicle Turn 1</th>
<th>Fully Reconfigurable Vehicle Turn 1</th>
<th>Fully Reconfigurable Vehicle Straight 1</th>
<th>Fully Reconfigurable Vehicle Straight 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a'$</td>
<td>0.4040</td>
<td>0.3647</td>
<td>Varies to facilitate the reconfiguration between turns</td>
<td></td>
</tr>
<tr>
<td>$K'$</td>
<td>0.3628</td>
<td>0.4889</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NACA Front</td>
<td>6124</td>
<td>3061</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NACA Rear</td>
<td>3432</td>
<td>0806</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AoA Front (deg)</td>
<td>9.218</td>
<td>13.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AoA Rear (deg)</td>
<td>2.892</td>
<td>6.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (sec)</td>
<td><strong>31.64</strong></td>
<td><strong>7.248</strong></td>
<td><strong>1.594</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4. Multidisciplinary Optimization Results for Indianapolis Motor Speedway**

Table 5 lists the times of the static and fully reconfigurable vehicle on each of the tracks and the time improvement of the fully reconfigurable system after 200 laps have been completed. Of particular interest is the fact that on the combined track, the fully reconfigurable vehicle would have a lead of 593.6 seconds over the static vehicle. Merely adding the time differential between the two vehicles on the individual tracks only yields a time advantage of 510.2 seconds. This increased time difference of 83.4 seconds demonstrates the significance of reconfigurable systems as the number of objectives a system must be designed for increases.

<table>
<thead>
<tr>
<th>Track</th>
<th>Static Vehicle Lap Time (sec)</th>
<th>Fully Reconfigurable Vehicle Lap Time (sec)</th>
<th>Time Difference After 200 Laps (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pocono Raceway</td>
<td>33.254</td>
<td>31.376</td>
<td>375.0</td>
</tr>
<tr>
<td>Indianapolis Motor Speedway</td>
<td>31.64</td>
<td>30.964</td>
<td>135.2</td>
</tr>
<tr>
<td>Combined Track</td>
<td>65.308</td>
<td>62.340</td>
<td>593.6</td>
</tr>
</tbody>
</table>

**Table 5. Vehicle Times for Each Track Studied**

The results of this section demonstrate the significance of reconfigurable systems when faced with a number of conflicting system objectives. However, such increases in performance will also come at an increased cost, which may prevent a fully reconfigurable system becoming a realistic and plausible design. Incorporating product platform design will provide increased performance using a scalable number of adaptable variables while maintaining a core architecture. This is the focus of the next section.

C. Market Segment and Platform Definition

The previous section determined the configuration and optimal performance for both a static and fully reconfigurable racecar. The performance of the fully reconfigurable system was significantly increased; however,
the realistic cost of such a design would be quite large. Recalling the scenario on which this case study is built, while a small number of racing teams may be able to purchase the fully reconfigurable vehicle, a large portion of the market would remain untapped. Understanding the best way to leverage a core architecture and design a product platform requires the creation of a market segmentation grid. For this problem, vertical leveraging will be used to capture market share from both the low cost customer, and the customer for whom money is not a concern. The market segments targeted in this study are hatched in the market segmentation grid shown in Fig. 9.

Identification of the market segmentation grid is the first step in the design of a product family. Next, the design variables that are to remain fixed must be defined, thereby constructing the foundation of the core architecture. The first step in this process involves analyzing each design variable to ensure that it has a statistically significant impact on the objective function. The results of p-tests and visual examination of the main effects plot demonstrated that each design variable plays a statistically significant role in the vehicle’s lap time.

Given the nature of the case study problem, designing a product family to reduce the cost of the system to the consumer, design variables that would be the most difficult to modify are first examined. To do this, a heuristic approach is applied to select design variables that will be placed in the platform. Currently, methods exist within the vehicle to control roll stiffness distribution while the vehicle is in motion. Vehicles with this ability have a hand-crank located in the cockpit with the driver. Based on experience and personal preference, the driver manually controls this value. Methods also exist to modify the angle of attack for each airfoil. However, these designs do not allow for the value to be changed while the vehicle is in motion. Instead, slats are designed into the system so the angle of attack can be modified by a member of the pit crew. This allows the angle of attack to be changed only when the vehicle returns to the pit for fuel or under a caution flag. Based on the fact that approaches of modifying these design variables currently exist, these design variables are selected to be reconfigurable.

Moving the longitudinal center of gravity during the race on a race car, on the other hand, could prove extremely difficult. Chassis design has focused on reducing drag and weight, leaving little room for extra components. Therefore, the longitudinal center of gravity is the first design variable selected to remain static. As previously shown in Fig. 6, moving only two or four airfoil control points can alter an airfoil’s planform. Based on this ability, construction of a base airfoil, with optimized adaptable control points can provide a variety of aerodynamic behavior. Coupled with an adaptable angle of attack, the obvious customization possibilities become apparent. The final selection of platformed (static) and reconfigurable design variables are shown in Fig. 10. In an effort to capture the three market segments shaded in Fig. 9, increased adaptability is found by allowing for an increased number of adaptable airfoil control points.
D. Product Platform Optimization

Based upon the platform description in Fig. 10, one vehicle for each segment must be created. A top-down approach to product platforming will be used, where the three vehicles will be created simultaneously. To accomplish this, a genetic algorithm is created at the top-level to determine the optimized value of the platformed variables. Within this optimization are a series of required sub-optimizations. Each sub-optimization must be carried out for each vehicle, on each segment of the track. In the case of the straightaways, each sub-optimization must be carried out for each second that the vehicle is traversing that segment of the track. This approach is described in detail in Fig. 11 for Vehicle 2, the vehicle in the second market segment.

The results presented in this section are for a family of reconfigurable vehicles that must race “a season” on the Pocono Raceway and Indianapolis Motor Speedway tracks previously listed. As with the static vehicle, platformed design variables for the reconfigurable racecars may not be changed when transitioning between tracks. It should also be noted that as the number of racetracks included in the study increase, so does the computational expense of each evaluation due to an increasing number of sub-optimizations that must be completed for every design. Table 6 lists the values of the platformed design variables for this top-down product platform approach in comparison to those of the static design.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Normalized center of gravity</th>
<th>Base front airfoil (NACA number)</th>
<th>Base rear airfoil (NACA number)</th>
<th>Front airfoil control points</th>
<th>Rear airfoil control points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platformed</td>
<td>0.3412</td>
<td>3906</td>
<td>9059</td>
<td>6 – 5 – 4 – 2</td>
<td>4 – 1 – 5 – 2</td>
</tr>
<tr>
<td>Static</td>
<td>0.4822</td>
<td>7502</td>
<td>5520</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6. Platformed Variables for Reconfigurable Race Car Family

Examination of the control points from the optimization show that the front and rear airfoil have three of the four selected control point in common. However, the platformed vehicle in the middle target market segment does not have either of the front and rear control points in common. Analysis of the effect of each control point on airfoil...
performance is an identified source of future work. Using information from the sub-optimization algorithm with the information from Table 6 for the first turn on the Pocono Raceway, the surface modification of the front airfoil planform can be determined. The resultant shape of the airfoil design for this corner is shown in Figure 12.

![Fig 12. Modification of Platformed Vehicle 3’s Base Front Airfoil Design for Turn 1 of Pocono Raceway](image)

The three platformed vehicles on this combined track showed obvious performance improvement over the static design, demonstrating that full reconfigurability is not needed to obtain significant performance results. The performance of all five vehicles studied: static, fully reconfigurable, and the three platformed vehicles are shown in Table 7. These results demonstrate the potential impact of combining reconfigurability with product platforming, as the vehicle with the least amount of reconfigurability, Platformed Vehicle 1, would be over 4 laps ahead of the static vehicle after 200 laps of the race had been completed.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Adaptable Control Points</th>
<th>Lap Time Around Combined Track (sec)</th>
<th>Time Difference After 200 Laps (sec)</th>
<th>Percent Improvement Over Static Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>0</td>
<td>65.308</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Platformed Vehicle 1</td>
<td>0</td>
<td>63.95</td>
<td>271.6</td>
<td>2.08%</td>
</tr>
<tr>
<td>Platformed Vehicle 2</td>
<td>4</td>
<td>63.17</td>
<td>427.6</td>
<td>3.27%</td>
</tr>
<tr>
<td>Platformed Vehicle 3</td>
<td>8</td>
<td>62.91</td>
<td>479.6</td>
<td>3.67%</td>
</tr>
<tr>
<td>Fully Reconfigurable</td>
<td>ALL</td>
<td>62.340</td>
<td>593.6</td>
<td>4.54%</td>
</tr>
</tbody>
</table>

Table 7. Lap Times for Combined Racetrack

The results in this section illustrate the advantage of combining reconfigurable system design with a core architecture determined using product platforming approaches. While a fully reconfigurable vehicle can eliminate the need for performance tradeoffs, it does so at the expense of cost and system complexity. Reconfigurable race cars created with a core architecture reduce necessary performance tradeoffs while maintaining appropriate budgetary constraints. These results demonstrate that system performance improves with increased reconfigurability, albeit at an increased cost. The responsibility of the designer lies in the correct identification of the market segments on which the product platform is based. Ultimately, defining the appropriate amount of reconfigurability desired, at the expense of cost, is left in the hands of the consumer.

V. Conclusion

This paper presents a methodology for the design and multidisciplinary optimization of a platformed, reconfigurable race car. Research in product platform design has demonstrated the ability to provide increased variety, but indicated that resultant designs are not capable of maintaining optimality when faced with varying system objectives. Incorporating adaptability allows for the configuration of a system to change, thereby altering the system’s performance, but this is done at an increased cost. By combining concepts associated with reconfigurable system design and product platforming, design solutions are provided that meet individual customer needs and minimize performance loss while satisfying varying budgets.

In the case study, an enhanced vehicle model is combined with airfoil planform analysis to measure the performance and configuration of reconfigurable race cars in relation to their static counterparts. The configuration of the front and rear airfoil, which provide the aerodynamic downforce for the vehicle, has been added to the aerodynamic discipline of this model to further practical understanding of reconfigurable system design. A vortex
A panel method approach is applied to the configuration of the airfoil planform to determine lift coefficient in free air. The influence of ground effects, resulting in a significant increase in the downforce generated by the vehicle, has also been modeled. Adaptable airfoil designs are created through the introduction of 7 control points, used to modify the location of the upper and lower surfaces of the airfoil.

Optimization of a static race car and a fully reconfigurable race car occurred on three racetracks, demonstrating significant performance improvements when faced with a number of conflicting system objectives. However, such improvement comes with an increased cost that may prevent the design, or purchase, of a completely reconfigurable system. Product platforming was introduced as a means of providing increased performance using a scalable number of adaptable variables while maintaining a core architecture. Vertical leveraging was used to identify three target market segments and the static (platformed) and adaptable design variables were selected. A top-down platforming approach was used to create the three vehicles, one for each market segment simultaneously. The results of this platforming study quantified the significant advantages of combining product platforming techniques with reconfigurable system design. All platformed vehicles demonstrated obvious performance advantages over their static counterpart while potentially allowing a wider variety of consumers to be satisfied than the fully reconfigurable system.

A source of future work involves examining the results of this work on different combinations of racetracks to understand the effect of course design on performance for a series of platformed, reconfigurable vehicles. Also, further study of the relationships and interactions of the platformed design variables is essential for the future development of this model, and for more complex engineering systems. Finally, increased details involving the modification of the airfoil planform, enhanced lift coefficient analysis for complex shapes, and further improvements to the vehicle model, are other fundamental avenues of research towards demonstrating the effectiveness and eventual fabrication of such reconfigurable systems.

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References


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