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INDUSTRIAL APPLICATION

Designing a family of reconfigurable vehicles using multilevel multidisciplinary design optimization

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Abstract Continuous advancements in technology have resulted in customers expecting enhanced performance across multiple operating conditions. In this paper, the desire to meet a variety of objectives after the system has been deployed is accomplished through the design of reconfigurable systems. However, permitting a system to adapt increases both complexity and cost. If this increase is too large, only a subset of design variables can be made adaptable. A multilevel multidisciplinary design optimization (MDO) approach is presented to determine the core architecture for a family of three reconfigurable vehicles when accommodating a changing number of adaptable design variables. To illustrate this approach, a case study involving a three-driver racing team is introduced. A common architecture is determined for the three vehicle variants, resulting in lap-time performance increases of 2.08%, 3.27%, and 3.67% when compared to the static, optimized baseline vehicle. The results of this study demonstrate the effectiveness of combining reconfigurability with product platforming and MDO.

Keywords Reconfigurable systems · Product family design · Multilevel optimization · Vehicle Design

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1 Introduction

Historically, many customization approaches have been facilitated by research in product platform design. Traditional top-down product platforming, for instance, simultaneously develops platform architectures while reducing redesign costs. However, these approaches (Simpson et al. 2001; Nayak et al. 1999) 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 been identified as a potential solution to this demand for increased performance (Olewnik et al. 2004). These 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 (Siddiqi et al. 2006; Ferguson et al. 2007b). A drawback, however, is that allowing design variables to change during operation results in an increased system cost (Olewnik and Lewis 2006). Therefore, combining reconfigurability with product platform research presents an opportunity to design a family of systems capable of minimizing performance loss across multiple objectives while managing budgetary restrictions and reducing overall design time.

A family of reconfigurable systems will effectively meet customer requirements. However, such design comes at the expense of complexity, as multiple large-scale, multidisciplinary designs must be optimized. Multidisciplinary design optimization (MDO) frameworks have been developed to handle the difficulty of measuring the performance of such complex, large scale systems (Park 2007). Such frameworks decompose the original system into subsystems, generally unique disciplines, which are linked together by couplings signaling information transfer from one subsystem to another. In this paper, a hybrid-hierarchical MDO-style approach is utilized to determine the performance and configuration of a family of reconfigurable systems in relation to their static counterparts. The established concepts of MDO and product platforming are combined under the umbrella of reconfigurable system design to explore the advantages of simultaneously creating products with common architectures and budgetary restrictions. To do this, the amount of reconfigurability is varied in each variant design created.

A case study based on the design of a team of race cars required to traverse multiple racetracks is presented. The three vehicles created represent the three members of a racing team entered into the same race. 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 airfoil planforms are modeled. These airfoils are treated as adaptable airfoils, with changes to surface control points yielding different amounts of aerodynamic downforce. Using this model, a family of reconfigurable vehicles is developed to illustrate the design of reconfigurable systems when operating under budgetary restrictions.

In the next section, background material from the key concepts leveraged in this work is introduced. Section 3 presents an approach for designing a family of reconfigurable vehicles. Results from a case study used to demonstrate this approach are discussed in Section 4, along with the specifics of the vehicle model. Finally, conclusions and future work are presented in Section 5.

2 Background

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

2.1 Reconfigurable system design

Engineering design has primarily focused on the optimization of systems with fixed design variables, where a typical problem formulation is given by:

$$\begin{aligned} &\min f(x) \\ &s.t.\ g(x) \leq 0 \\ &\quad h(x) = 0 \\ &\quad x_{LB} \leq x \leq x_{UB} \end{aligned} \tag{1}$$

where f is an objective function, x is the vector of design variables, g(x) are general inequality constraints and h(x) are general equality constraints. Fixed design variables are 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 (Pareto 1906). 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 when faced with conflicting objectives are a primary motivation for reconfigurable system design.

After deployment, reconfigurable systems 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 (Siddiqi et al. 2006; Ferguson et al. 2007b). For example, a reconfigurable system using a "sliding skin" approach has been proposed by NextGen Aeronautics and is shown in Fig. 1 (Marks 2003). This sliding skin provides the aircraft with the ability to loiter for extended periods of time or gain increased maneuverability. Each of these tasks, however, requires a different airfoil shape or wing cross section for optimal performance.

Utilizing changes in design variables values after deployment allows for the system to respond to changes in system objectives and the operating environment.

Fig. 1 NextGen's morphing aircraft example (Marks 2003)

Current reconfigurable system design research has mainly focused on costing (Olewnik and Lewis 2006), design variable selection (Martin and Crossley 2002; Khire and Messac 2006), transitioning with control theory (Ferguson and Lewis 2006; Siddiqi et al. 2006), and designing tailored missions (Peters et al. 2002; Bowman et al. 2002). These works have demonstrated the enhanced performance of systems given the ability to reconfigure, or morph, when the system objectives change after deployment. While it is seemingly ideal to allow all design variables to 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.

2.2 Product platform design

Creating a family of products has become a major focus of companies striving to reduce costs while maintaining product variety. Two basic approaches to product family design have been identified (Simpson et al. 2001). 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 (Simpson et al. 2006). Black & Decker, meanwhile, has applied the bottom-up approach to redesign or consolidate a group of distinct products in an effort to standardize components and control cost (Lehnerd 1987). Three platform leveraging strategies have been identified by Meyer and Lehnerd (1997) from the market segmentation grid and have been used in engineering design literature (Simpson et al. 2001; de Weck and Suh 2006): horizontal leveraging, vertical leveraging, and a beachhead approach.

Other work has examined how modules influence the development of product platforms (Fujita 2006), and how product families can be extended to the automotive industry (Fellini et al. 2006; Torstenfelt and Klarbring 2006). Similar to the approach presented in this work, Kokkolaras et al. (2002) use a hierarchically partitioned design problem to design a product family using analytical target cascading. Common subproblems are identified based on shared elements and solved using locally introduced targets. A comprehensive discussion of product platforming fundamentals, and research within the field, can be found in (Simpson et al. 2006; Jiao et al. 2007).

Product platform research has demonstrated the ability to provide increased variety with minimized performance penalties. However, resultant designs are still not capable of maintaining optimality when faced with varying system objectives. This paper combines the strengths of reconfigurability and product platforming to meet the performance and cost demands of the consumer. The optimization approach to design such a product family is based upon fundamentals of multidisciplinary design optimization, introduced in the next section.

2.3 Multidisciplinary design optimization (MDO)

Multidisciplinary design optimization is an approach to handle complex design environments comprised of multiple disciplines. These multiple disciplines are treated as subsystems, and are linked through design, function and performance (McAllister et al. 2005). Within each subsystem, objective functions, constraints, design variables, and linking variables are defined as being local or common properties throughout the entire system. Many applications of MDO approaches utilize gradient-based optimizers, heuristic optimization techniques, and response surface modeling to solve such problems.

In a comparison of MDO methods, Yi et al. (2007) identified seven methodologies currently proposed. These methods are classified into either single level or hierarchical (multilevel) approaches. Single level methods use a single optimizer in a nonhierarchical structure with analysis carried out by each discipline. As an example, Global Sensitivity Equations (GSEs) were introduced by Sobieszczanski-Sobieski (1988) to determine objective function and constraint sensitivities of subsystems to allow for efficient optimization of MDO problems.

Multilevel methods reorganize the relationship of the system structure into a hierarchical form. In the Concurrent Subspace Optimization (CSSO) approach (Sobieszczanski-Sobieski 1988), a system-level coordinator is created to ensure system-level feasibility and compatibility amongst the subsystems in problems where system-level design variables and objectives are not defined. Each subsystem is formulated to contain unique design variables and objectives, for which a distinct subspace optimizer is established. Other methods structured in this hierarchical manner, such as Collaborative Optimization (Kroo and Manning 2000), generally contain an optimizer at each level, as shown in Fig. 2. This method differs from CSSO in that the objective of each discipline is the minimization of compatibility constraint violations while a system-level optimizer is created to minimize an overall design objective and handle the passing of coupled variables. This method has also been extended to handle multiobjective formulations (Tappeta and Renaud 1997), robust design and uncertainty (McAllister and Simpson 2003; Giassi

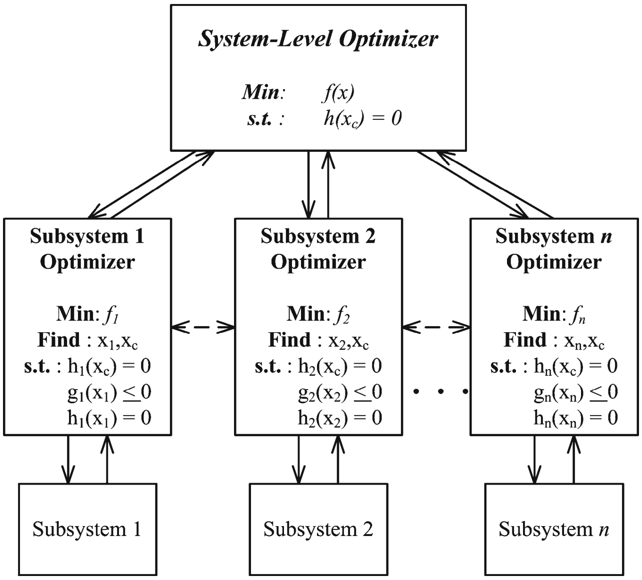


Fig. 2 Multilevel MDO approach

et al. 2004), decision-based design (Gu et al. 2002), high performance computing (Kodiyalam et al. 2004), and goal programming (McAllister et al. 2005).

In this work, the hybrid-hierarchical nature of multilevel MDO methods is leveraged in a case study involving the design of a family of formula-style race cars. Unlike traditional Collaborative Optimization, the subsystems minimize the lap time of each vehicle in the product family, while the system-level optimizer minimizes the combined lap time of the entire racing team. Approaching the problem in this manner facilitates the design of a family of reconfigurable racecars traversing a racetrack that is multiobjective in nature. The next section of this paper details the steps taken when designing a product platform that contains reconfigurable systems.

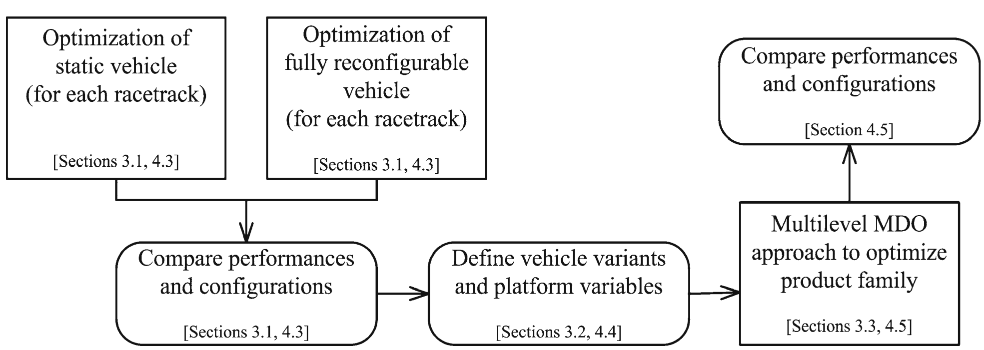
3 Approach for designing a reconfigurable vehicle platform

Imagine the scenario of a race car manufacturer developing a hypothetical next generation Formula One racecar. Current racing restrictions have been removed, allowing the vehicle configuration to change while on the track. Aware that any amount of reconfigurability added to the system will yield faster lap times, the manufacturer is faced with the challenge of creating a vehicle for each member of the three-driver team. A decision has been made to incorporate reconfigurability into each vehicle, rather than improving only the car of the primary driver. The team is working with a limited budget, making a method of platforming necessary to capture performance benefits while maintaining commonality across the vehicles to reduce design and manufacturing costs. While driver preferences and performance capabilities are not modeled, an assumption has been made that the team's primary driver should have the fastest vehicle. However, varying the amount of reconfigurability and determining common components across the entire family of vehicles will ensure the team outperforms the static vehicles of their counterparts. The approach used for designing a family of reconfigurable vehicles is presented in Fig. 3 and discussed in the following sections.

3.1 Optimization of base vehicles

The first step in the approach involves optimizing the performance of both the static and fully reconfigurable vehicles on each racetrack for benchmark comparisons. The optimal configuration of the static vehicle is determined based on the criteria that the vehicle must traverse the track without modification. Next, the fully reconfigurable vehicle is optimized for the corners and straights of each track. In a fully reconfigurable vehicle,

Fig. 3 Approach for designing a reconfigurable vehicle platform



all design variables controlled by the designer are allowed to be adaptable. Adaptability is the ability of the design variables to change their values, and thus the configuration of the system, while the system is deployed. The designer controlled design variables used in this paper are introduced in Section 4. The resulting optimized vehicles—and the difference in their performances and configurations—are compared to ensure that a noticeable benefit for a reconfigurable system exists, establishing a potential need. With the need for a reconfigurable system established, the vehicle variants must be identified.

3.2 Definition of vehicle variants and platform variables

While the performance of a fully reconfigurable system may be significantly increased, the realistic cost of such a design—in design time and implementation—can be quite large. Recalling the scenario on which this approach is built, a racing team is interested in creating three variant reconfigurable racecars. However, the cost of incorporating reconfigurability into the system will likely prevent all design variables from being made adaptable. It has also been mandated that the primary driver's vehicle must have the best performance. Compared to the optimized static vehicle, the two other reconfigurable vehicles must only demonstrate increased performance. Efficient design of these three vehicles requires managing the amount of reconfigurability present in each vehicle while maintaining common characteristics across the family to reduce design time and manufacturing costs.

Creation of a market segmentation grid is the best approach to determine the core architecture that will create the reconfigurable vehicle family. In this approach, vertical leveraging is used to determine the common characteristics of the three reconfigurable vehicle variants. First, the design variables that remain fixed during the operation of the vehicle must be defined. These variables do not change as the vehicle progresses around the track and are common for all three reconfigurable vehicles. This process involves analyzing system design variables to ensure they have a statistically significant impact on the objective function and determining which variables would be the most difficult to modify. As the difficulty of making a design variable adaptable increases, so too does the potential cost, making such design variables prime candidates to remain fixed across all three vehicle designs.

3.3 Multilevel MDO approach to design an optimized product family

Based upon the variant description in Section 3.2, three reconfigurable vehicles must be designed simultaneously. A top-down platforming approach is used to create the vehicles by leveraging the fundamentals behind a multilevel (hybrid-hierarchical) MDO approach, shown in Fig. 4.

The system-level optimizer minimizes the objective function $f(\mathrm{x})$, the overall performance objective by which the product family is evaluated. A genetic algorithm is used to minimize this objective function and determine the optimal value of the platformed variables. Research by Pierret et al. (2007) and Narayanan and Azarm (1999) have demonstrated the effectiveness of such heuristic-based methods when solving MDO-style problems.

Within the system-level optimization are a series of sub-optimizations represented by different subsystems. In Collaborative Optimization, a subsystem traditionally represents a unique discipline or major component of the system being optimized. Here, a subsystem represents one of the three reconfigurable vehicle variants being optimized. As shown in Fig. 4, each vehicle variant appears as a separate subsystem with its own optimizer. These vehicle variants may be evaluated successively or concurrently based upon available high performance computing capabilities. In this formulation, each vehicle variant is responsible for minimizing a unique performance-based objective function. This differs from Collaborative Optimization where subsystems minimize compatibility constraint violations.

In this approach, each vehicle variant uses platformed design variables, x_c, and adaptable design variables, x, to optimize the performance of the vehicle on each segment of the track. Platformed design variables are defined by the system-level optimizer and are passed to each variant. Within each variant, they are treated as static and not allowed to change. The remaining adaptable design variables are capable of changing their value during each segment optimization, signifying a configuration change while the system is deployed.

For each vehicle variant, the on-track performance can be summarized as follows. First, it enters a straight 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 straight the vehicle's velocity is equal to the maximum steady-state cornering

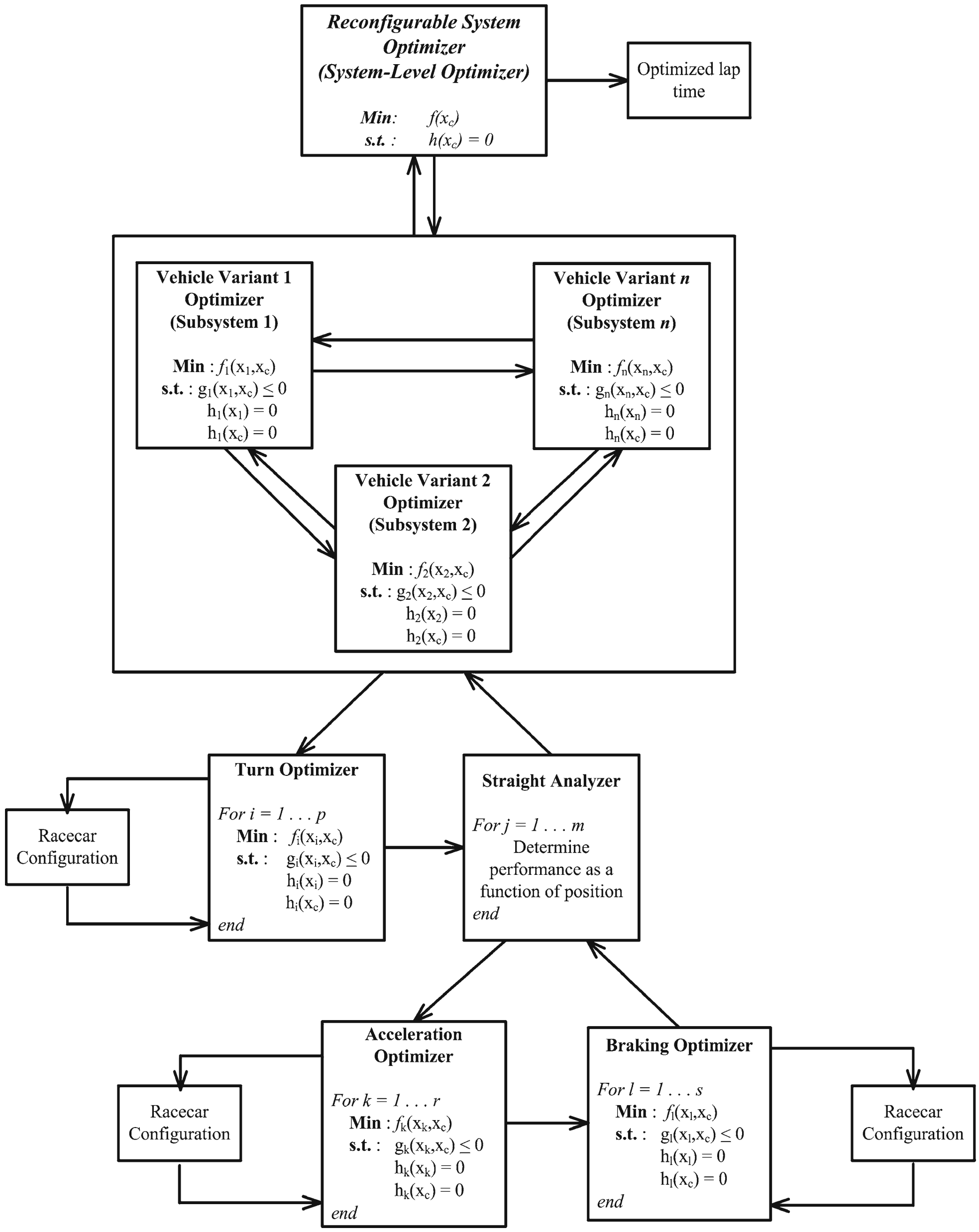


Fig. 4 Multilevel MDO approach to generate reconfigurable racecar family

velocity of the upcoming corner. This sequence repeats for every corner-straight-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. First, the p unique racetrack corners are evaluated separately to determine the maximum steady-state cornering velocities based upon the platformed variables and the optimized values of the adaptable design variables. The maximum steady-state cornering velocities serve as boundary conditions for the m straights that remain to be evaluated. For the evaluation of all m straights, each sub-optimization must be carried out for each second that the vehicle is traversing that segment of the track. The *Acceleration Optimizer* block is first evaluated at a time increment of one second, a total of r times, providing the necessary initial condition for the *Braking Optimizer* block. The *Braking Optimizer* block is then evaluated every second, as necessary, a total of s times. As shown in Fig. 4, this analysis must be completed for each subsystem. Double arrows connecting vehicle variant optimizers represent coupled variables that are shared by each vehicle variant.

Finally, all optimizers are required to interact with the *Racecar Configuration* module. This module defines the overall vehicle configuration based upon the values of the platformed and adaptable variables and allows the performance of the vehicle to be determined. The usage of the *Racecar Configuration* module in this work is further discussed in Section 4.1.

Approaching the problem in this manner allows the utilization of a multilevel MDO approach towards designing a family of three reconfigurable vehicles. The next section of this paper introduces a case study developed to demonstrate the application of this approach. First, the vehicle model used and the disciplines the design variables represent are identified. This model is then applied in the approach above to design a vehicle architecture in which only a subset of the original design variables are adaptable. The performance of the platformed vehicle variants is then compared to demonstrate the effectiveness of reconfigurable systems and the benefits of implementing product platform techniques into the design process.

4 Case study: designing a family of reconfigurable racecars

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. A vehicle's core architecture is traditionally aimed at an optimal compromise that allows a driver to turn fast lap times repeatedly at a particular racetrack. A particular vehicle configuration may be optimal at a certain speed and cornering radius, but sub-optimal on others. Although racetracks have numerous corners with varying radius; 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.

For this case study, the performance of a static vehicle is compared to a family of reconfigurable vehicles designed using the approach introduced in the previous section. Sections 4.1 and 4.2 detail the vehicle model used to design the family of formula-style race cars. Following this, discussion turns to the vehicle's front and rear wing. These wings are created as reconfigurable airfoil planforms, and the manner in which the adaptations are handled is introduced. Identification of the key vehicle model developments provides the foundation for the remaining elements of the case study problem.

4.1 Discipline identification

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 straight, a large turn, or a hairpin turn, the car can adjust variables such as the center of gravity, roll stiffness, and aerodynamic downforce. A brief explanation of the race car model used in this work can be found in (Ferguson and Lewis 2006; Hacker et al. 2000). The design variables currently controlled by the designer in this simplified vehicle model represent three potential disciplines working on the vehicle, whose parameters primarily affect a vehicle's performance (Kasprzak et al. 1999), as shown in Fig. 5.

The three upper-level design variables that determine the vehicle's configuration in this model are the longitudinal center of gravity location (a'), roll stiffness distribution (K'), and the aerodynamic downforce distribution (C'), each normalized between 0 and 1. The normalized longitudinal 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 case study introduces the configuration of 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. For all analysis completed in this case study, a constraint on the airfoil design is that its maximum thickness must be greater than or equal to 4% of the overall chord length.

The performance of this model using only the three upper-level design parameters on variable radius skidpads has been extensively studied (Kasprzak et al. 1999), and a more detailed look at the vehicle analysis can be found in (Milliken and Milliken 1995). McAllister et al. (2005) applied this vehicle model along with goal programming, linear programming, and a

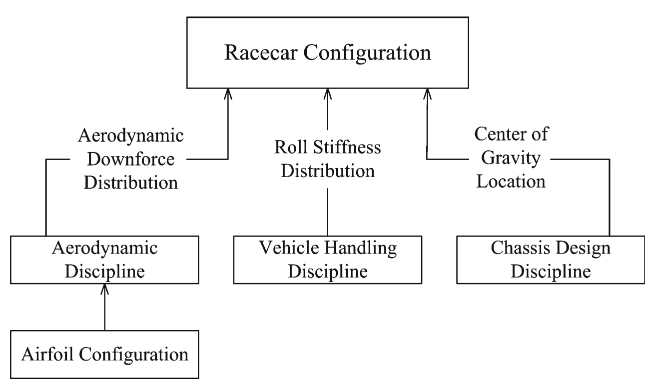


Fig. 5 Multidisciplinary vehicle configuration flowchart

collaborative optimization framework to create preliminary vehicle designs. Further analysis using this model involving the manner in which design variables change in a reconfigurable race car has also been reported (Ferguson and Lewis 2006).

Previous work with this vehicle model has focused solely on the three inputs into the *Racecar Configuration* block in Fig. 5. Further updates to this model have also been made, and can be found in (Ferguson et al. 2007a). To extend this model and further the practical understanding of reconfigurable system design, the configuration of the front and rear airfoils has 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 mph. 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 produce negative lift (downforce) to increase tire capabilities and counteract these high speed instabilities. Aerodynamic downforce is therefore essential in maintaining speed while cornering, and different race courses will place different demands on the aerodynamic setup of the vehicle. The next section describes the approach towards making the front and rear airfoil configuration adaptable.

4.2 Creating adaptable airfoils

The importance of airfoil wing and planform shape is an elementary aspect of aerodynamics and aircraft design. From the standpoints of both structural optimization and MDO, airfoil optimization has been a noted area of research (Li et al. 2002; Gantois and Morris 2004). Research into the design of morphing aircraft and morphing wings, meanwhile, has mainly been focused in two areas: understanding performance implications while designating appropriate mission requirements, and the sizing and control issues in designing a morphing aircraft to meet those requirements (Talley et al. 2004; Ricci and Terraneo 2006; Vale et al. 2006). In this work, determining the overall lift and drag of an airfoil planform is done using panel methods. Panel methods have been used to calculate the velocity distribution along an airfoil for more than 30 years. When designing a racecar, however, a significant amount of downforce is also achieved through the use of ground effect. Details of how ground effect is approximated in this model can be found in (Ferguson et al. 2007a).

Airfoil planforms in this study are comprised of 60 vortex panels, with seven control points selected for the upper and lower surface of the airfoil. Similar approaches to modifying the shape of an airfoil using control points to promote morphing have been seen in (Secanell et al. 2006). In this approach, when a number of control points are selected for adaptation, the y-values corresponding to both the upper and lower surface are allowed to deviate with respect to the constraints in (2), 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.

$$
\begin{aligned}
&0.75y_{CP_{UPPER}} \le y_{CP_{UPPER}} \le 1.25y_{CP_{UPPER}}\\
&0.75y_{CP_{LOWER}} \le y_{CP_{LOWER}} \le 1.25y_{CP_{LOWER}}
\end{aligned}
\qquad (2)
$$

The endpoints of the airfoil, at both the leading and trailing edge, are fixed to the base airfoil design to ensure continuity. As an example, in Fig. 6 four control points (2, 3, 4 and 5), have been modified with respect to (2) to create a new airfoil configuration. In changing the airfoil configuration, however, anywhere from one to seven control points may be changed. With such surface modifications using the control points, panel endpoint locations are determined using a splined approach.

The next section introduces the racetracks used in this case study and compares the performances of the optimized static and fully reconfigurable vehicles.

4.3 Optimization of static and fully reconfigurable vehicles

In this study, performance on two unique racetracks is investigated, and their simplified dimensions are listed in Table 1. The Pocono Raceway in Long Pond, PA, USA, consists of three unique turns and three unique straights. The second racetrack is the oval course at the

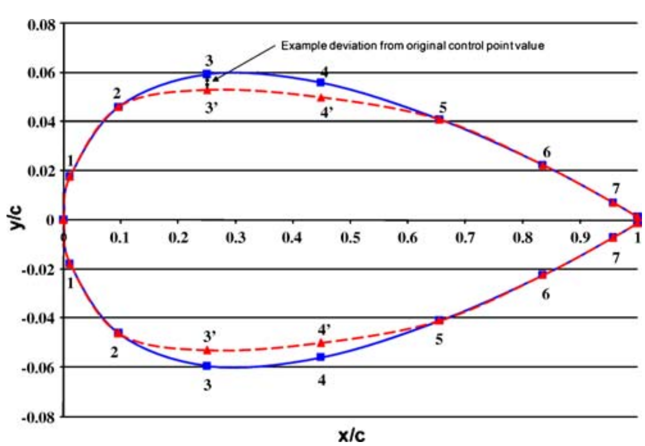


Fig. 6 Airfoil reconfiguration moving four control points

Table 1 Racetrack dimensions

Track	Segment	Bank (°)	Radius (ft)	Distance (ft)
Pocono Raceway	Straight 3	–	–	3,055
	Turn 1	14	602	1,565
	Straight 1	–	–	3,740
	Turn 2	8	760	1,115
	Straight 2	–	–	1,780
	Turn 3	6	736	1,630
Indianapolis Motor Speedway (oval course)	Straight 1	–	–	3,300
	Turn 1	9	840	1,320
	Straight 2	–	–	660

Indianapolis Motor Speedway in Speedway, IN, USA. This course consists of only three unique segments, with a lap consisting of four times around the corner, and twice down each straight.

The multiobjective problem developed by this analysis is defined by the minimization of the time it takes to traverse the n sections of the racetrack, subject to the constraints placed upon the vehicle. The ultimate goal is to minimize the sum of each objective, F_i, 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:

$$\begin{aligned}
&\mathit{Minimize:} \quad \sum_{i=1}^{n} F_i \\
&\mathit{Subject\ to:} \quad 4 * (\mathit{Front\ airfoil\ chord\ length}) \\
&\qquad - (\mathit{Front\ airfoil\ thickness}) \leq 0 \\
&\qquad 4 * (\mathit{Rear\ airfoil\ chord\ length}) \\
&\qquad - (\mathit{Rear\ airfoil\ thickness}) \leq 0 \\
&\qquad 0.10 \leq a' \leq 0.90 \text{ (Normalized center of gravity position)} \\
&\qquad 0.10 \leq K' \leq 0.90 \text{ (Normalized roll stiffness distribution)} \\
&\qquad 0.10 \leq C' \leq 0.90 \text{ (Normalized aerodynamic downforce distribution)} \\
&\qquad 0 \leq \alpha_F \leq 16 \text{ (Front airfoil angle of attack, in deg)} \\
&\qquad 0 \leq \alpha_R \leq 16 \text{ (Rear airfoil angle of attack, in deg)}
\end{aligned} \tag{3}$$

The definition of the optimization problem allows for the configuration and performance of the static and fully reconfigurable vehicles to be determined using a series of genetic algorithms (GA).

When evaluating each turn, a single GA is created to arrive at an optimal solution. A single vector of optimal variable values can be achieved for each turn due to the assumption of steady-state cornering in the analysis of the skidpad. For example, the fully reconfigurable vehicle will adopt a value of 0.4721 in Turn 1 for the normalized longitudinal center of gravity. At Turn 2, this design variable has adapted to a value of 0.4639. This process continues for the remaining design variables, shown in Table 2, as the new values of the variables are adopted during the vehicle's motion along the track.

For the straights, however, this steady-state assumption is not valid. Therefore, an instance of the GA was implemented each second (in racing time) that the vehicle traverses the straight. This assumption allows the vehicle to update and completely change its configuration every second it is on that segment of the track, maximizing the acceleration and deceleration as needed. Table 2 also shows the optimum values for the static vehicle on the Pocono Raceway track. These results show that the fully reconfigurable vehicle is 3.040 s faster per lap than the static vehicle, a 9.53% improvement. This speed increase over the static vehicle is due to the tradeoffs necessary in a multiobjective problem when designing for multiple system objectives.

Figure 7 compares the solution of the static airfoil design (NACA 5147) versus the solution of the reconfigurable front airfoil for each of the corners (NACA 9712, 6212, and 2938). From this figure, the limitations of a static airfoil, when compared to a reconfigurable airfoil, become apparent. For instance, the optimized airfoil for Turn 2 (NACA 6212) produces less lift than the static airfoil, but also reduces the drag produced by the front wing, allowing for faster speeds when combined with other design variable changes.

Table 3 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. A third track, referred to as the *Combined Track*, is also introduced. This track integrates the Pocono Raceway and Indianapolis Motor Speedway tracks end-to-end. This track is

Table 2 Multidisciplinary optimization results for Pocono Raceway

Variable	Static vehicle	Fully reconfigurable vehicle					
		Turn 1	Turn 2	Turn 3	Straight 1	Straight 2	Straight 3
a'	0.4133	0.4721	0.4639	0.4865	Varies to facilitate the reconfiguration between turns		
K'	0.4001	0.2836	0.3198	0.2607			
NACA front	5147	9712	6212	2938			
NACA rear	1260	2510	1319	1521			
AoA front (°)	8.7169	6.1415	4.2410	6.7312			
AoA rear (°)	5.9570	6.7412	9.5882	10.1699			
Time (s)	31.911	4.118	2.864	4.305	7.433	3.919	6.210
		28.871					

comparable to a racecar traveling a more complex course, or engaged in a multi-race season without allowing for modifications to the vehicle's configuration between races. Of particular interest is that on the combined track, the fully reconfigurable vehicle would have a lead of 1,094.680 s over the static vehicle. This is contrasted by adding the time differential between the two vehicles on the individual tracks, which yields a time advantage of 743.280 s. This increased time difference of 351.400 s demonstrates the significance of reconfigurable systems as the number of objectives increases.

The results of this section demonstrate the significance of reconfigurable systems under a number of conflicting system objectives. However, such performance increases come at an increased cost, possibly preventing a fully reconfigurable system from becoming a plausible design. Incorporating platforming concepts and using a scalable number of adaptable variables provides increased performance while maintaining commonality amongst the three vehicles. This is the focus of the next section.

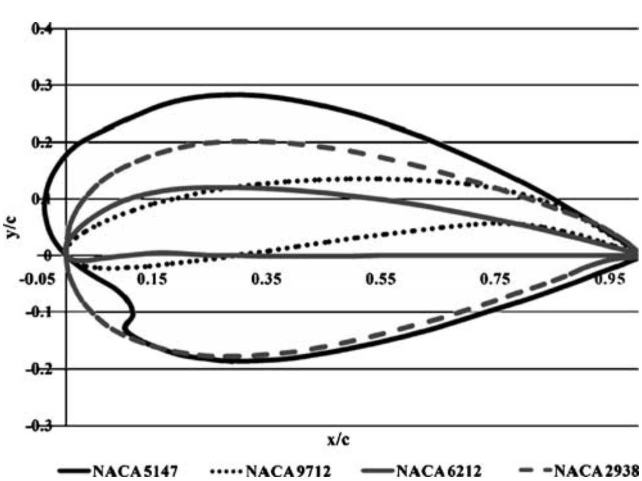


Fig. 7 Comparison of front planforms from Pocono Raceway optimization results

4.4 Defining vehicle variants and platformed variables

The previous section determined the configuration and optimal performance for both a static and fully reconfigurable racecar. As a result, the performance of the fully reconfigurable system was significantly better than the static vehicle; however the realistic cost of such a design would be quite large. For this problem, vertical leveraging is used to design a family of three reconfigurable vehicles and the resulting targeted vertical segments targeted are shaded in the product segmentation grid of Fig. 8.

The product segmentation grid in Fig. 8 has been created to represent the hypothetical desires of the racing team. Assuming that a fully reconfigurable vehicle is outside the team's budget, the performance of the three vehicles must still be greater than that of the static vehicle. It is a requirement that the primary driver's vehicle has the best performance, requiring more reconfigurability/adaptability and a larger cost. Correspondingly, the vehicles for the second and third driver must also implement reconfigurability to ensure increased performance.

As increased reconfigurability results in larger system costs, the racing team plans to mitigate the overall cost of the third vehicle, ensuring the necessary funds for the primary driver's vehicle. This low cost requirement will result in Driver 3's vehicle having less reconfigurability than the other two vehicle variants created.

To reduce overall design time and ensure service compatibility between vehicles, design variables that remain static (non-adaptable) during the race will be common across all three vehicles. If this was not the case, it is very likely the three vehicles variants would have very different design variable configurations, increasing the difficulty of fleet maintenance and part ordering. The commonality of the static vehicles creates the foundation of the vehicle family while providing the ability for increased performance as the amount of reconfigurability is increased. The next sub-sections

Table 3 Vehicle times for each track studied

Track	Static vehicle lap time (s)	Fully reconfigurable vehicle lap time (s)	Time difference after 200 laps (s)
Pocono Raceway	31.911	28.871	608.080
Indianapolis Motor Speedway	31.640	30.964	135.200
Combined track	65.308	59.835	1,094.680

explore the three vehicle disciplines, providing rationale for the selection of adaptable design variables within the vehicle family.

4.4.1 Chassis design discipline

Given the nature of the problem, design variables that are the most difficult to modify are first examined. Adapting the longitudinal center of gravity during the race proves to be the most difficult design variable to change. Chassis design focuses on reducing drag and weight, leaving little room for extra components and creating a tightly packed space. Figure 9 shows the center of gravity initially located at a distance *a* away from the front of the vehicle, with the mass of the vehicle distributed in two segments over the entire length, *l*.

Given an overall mass, *W*, of 41.7 slugs, it can be seen from Fig. 9 that:

$$W = 41.7 \text{ slugs} = W_1 + W_2 \quad (4)$$

and taking the moment about the center of gravity location:

$$0 = W_1\left(\frac{a}{2}\right) - W_2\left(\frac{b}{2}\right) \quad (5)$$

Table 4 uses (4) and (5) to estimate the necessary weight transfer to move the center of gravity a distance of Δa, given as a normalized distance in relation to the overall vehicle length. The results in Table 4 demonstrate the substantial amount of mass that must be transferred to significantly alter the center of gravity location. These results also show that a shift in center of gravity location requires an equal percentage of total vehicle weight transferred. The optimized configurations of the fully reconfigurable vehicle on the Pocono Raceway track in Table 2 shows that the center of gravity would need to shift a minimum of 12.18% of the total vehicle length. Moving that corresponding percentage in overall vehicle weight greatly increases the complexity of the designed system.

In addition, the extra mass from components and hardware needed to exact such changes raises a potentially prohibitive cost barrier. A constraint-based approach was developed in previous work to determine the maximum amount of allowable mass that could be added to a reconfigurable system (Ferguson and Lewis 2008). For various combinations of adaptable and static variables, performance of the reconfigurable systems was compared to an optimized static vehicle to determine the amount of additional mass each variable combination could accommodate. Insights into adaptable design variable selection were presented using this amount of additional mass as a decision-support variable. It was discovered, for example, that if only the center of gravity were to change, the additional hardware needed could amount to no more than 17.39 lb_m, or 1.1% of the vehicle's baseline weight. This work also determined that a reconfigurable vehicle with a fixed center of gravity is able to achieve 91.65% of the performance of a fully reconfigurable vehicle on the same track. Thus, the center of gravity becomes the first platformed design variable, making it common and unchangeable in the three vehicle variants.

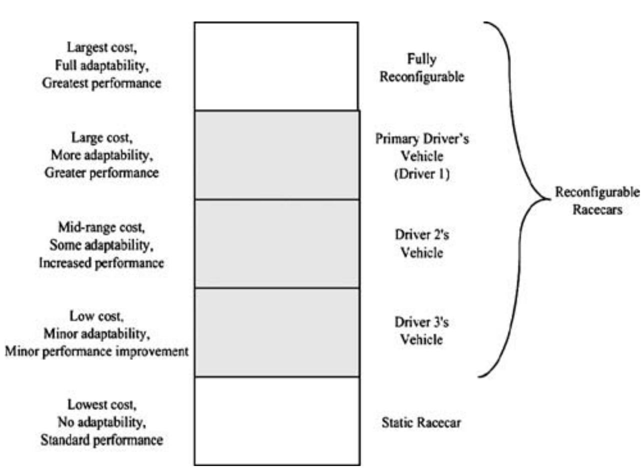


Fig. 8 Product segmentation grid using vertical leveraging

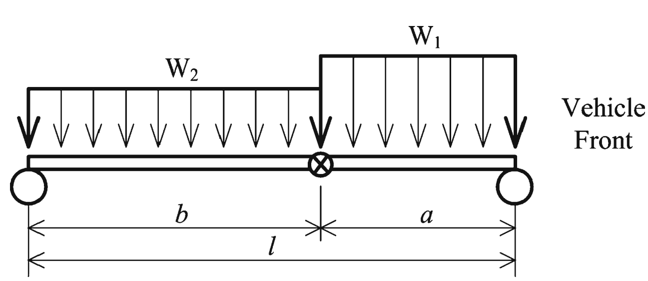


Fig. 9 Longitudinal center of gravity

Table 4 Weight transferred during CG shift

Δa	Mass transfer (slugs)	Percentage of total vehicle weight transferred
0.05	2.085	5%
0.10	4.170	10%
0.25	10.425	25%
0.5	20.850	50%

4.4.2 Vehicle handling discipline

Currently, methods exist within formula-style vehicles to control roll stiffness distribution while the vehicle is in motion. Drivers use hand-cranks located in the cockpit to change the roll stiffness distribution based on experience and personal preference. Analysis of the allowable additional mass for this design variable was completed by Ferguson and Lewis (2008), and it was shown that 25.44 lb_m of extra material is allowed in a vehicle where this is the only adaptable design variable. Such devices are currently designed within this mass constraint while producing a significant performance increase. Therefore, the roll stiffness distribution becomes the first adaptable design variable in the vehicle family.

4.4.3 Aerodynamic discipline

Like roll stiffness distribution, methods also exist for modifying an airfoil's angle of attack. However, current racing restrictions do not allow for the angle of attack 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. Previous work has shown that within the aerodynamic discipline, over 100 lb_m of extra material can be added to the system while maintaining a performance increase (Ferguson and Lewis 2008). Using the fact that approaches of modifying these design variables currently exist, and the large amount of design freedom that exists in additional system mass, these design variables are selected to be adaptable.

The construction of a base airfoil with an optimized selection of control points made adaptable can provide a variety of aerodynamic behavior. Coupled with an adaptable angle of attack, the obvious customization possibilities become apparent. Work in morphing airfoil design has shown that the initial overhead for incorporating reconfiguration capabilities can be expensive, with most approaches relying on actuators and smart materials. This adds additional cost to the airfoil when increasing the number of adaptable control points and the range by which they can change. As these additional costs impact the team's overall budget, this impact must be mitigated across the family of vehicles created.

4.4.4 Definition of adaptable and platformed variables

The creation of design variable selection guidelines in the prior sub-sections permits definition of the vehicle variants. The foundation for these guidelines comes from two of the primary challenges associated with reconfigurability—additional cost and additional mass. As shown in Ferguson and Lewis (2008), if the additional mass increase is too great, the performance advantage of a reconfigurable system is negated. Selection of adaptable design variables in this work is aided by conclusions developed from an analysis of the amount of additional mass allowed for different combinations of adaptable and static design variables.

Designing the three vehicles in a top-down platforming approach allows the increased cost of reconfigurability to be distributed across the entire vehicle family. In this light, the cost of changing the airfoil planform for the team's third vehicle is removed, only allowing the angle of attack to be modified. Furthermore, a common NACA planform is being used by all three vehicles. The team's second vehicle will have four total airfoil control points made adaptable, two for the front and two for the rear, out of a possible fourteen. To improve performance further, the team's primary vehicle will have eight control points made adaptable, further increasing cost. To help minimize design time and manage cost, the control points selected for the second vehicle will be common with those of the primary vehicle, extending the core architecture across the family of vehicles.

Figure 10 shows the final selection of platformed (static) and adaptable design variables. The system-level optimizer controls the platformed variables, determining their optimal value and ensuring component commonality amongst the three designs. Performance differences between the three vehicle variants are obtained by increasing the number of adaptable airfoil control points. The team's third vehicle obtains the lowest cost by preventing a change in the airfoil planform, allowing only the roll stiffness distribution and the front and rear angle of attack to change. Identification of the platformed and reconfigurable variables allows for the vehicle family to be optimized using the multilevel MDO approach from Fig. 4.

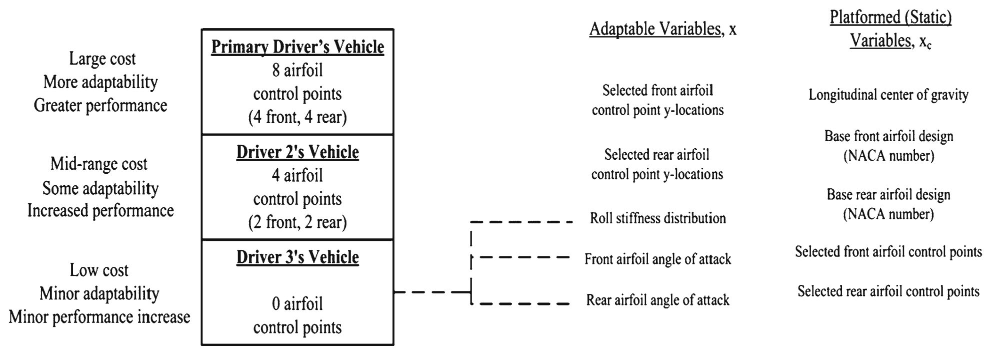


Fig. 10 Product platform description within market segmentation grid

4.5 Multilevel optimization of reconfigurable vehicle family

The results presented in this section are for an optimized family of three reconfigurable vehicles that must race "a season" on the *"Combined Track"* using the approach outlined in Fig. 4. For this case study, the system level objective function $f(\mathrm{x})$ is the combined lap time of each of the three reconfigurable vehicles. As with the static vehicle, the platformed design variables, x_c, for the reconfigurable racecars may not be changed when transitioning between tracks. For each vehicle variant, the minimized objective is the lap time of the individual vehicle, with the control points made adaptable on the airfoils serving as coupling variables. It should 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. Table 5 lists the values of the optimized platformed design variables, common for the three reconfigurable vehicles, for this top-down product platform approach along with those of the optimized static design. For the optimized static vehicle, no airfoil control points are made adaptable.

Examination of the control points in Table 5 show the primary driver's front and rear airfoil have three of the four selected control points 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—with control points 6 and 5 adaptable on the front airfoil, and control points 4 and 1 adaptable on the rear airfoil. Analysis of the effect of each control point on airfoil performance is an identified source of future work.

Using information from the subsystem optimization with the information from Table 5 for the first turn on the Pocono Raceway, the surface modification of the front airfoil planform can be determined, resulting in the airfoil shape in Fig. 11. Here, the base front airfoil planform NACA 3906, shown as a solid line, is modified using control points 2, 4, 5, and 6, to create the modified airfoil planform to maximize the vehicle's cornering velocity on Turn 1 of the Pocono Raceway.

The performance of all five vehicles studied: static, fully reconfigurable, and the family of three reconfigurable vehicles are shown in Table 6. The vehicle family on this combined track shows obvious performance improvement over the static design, demonstrating that full reconfigurability is not needed to obtain significant performance results. These results demonstrate the

Table 5 Platformed variables for reconfigurable race car family

Vehicle	Platformed	Static
Normalized center of gravity	0.3412	0.4133
Base front airfoil (NACA number)	3,906	5,147
Base rear airfoil (NACA number)	9,059	1,260
Adaptable front airfoil control points	6–5–4–2	–
Adaptable rear airfoil control points	4–1–5–2	–

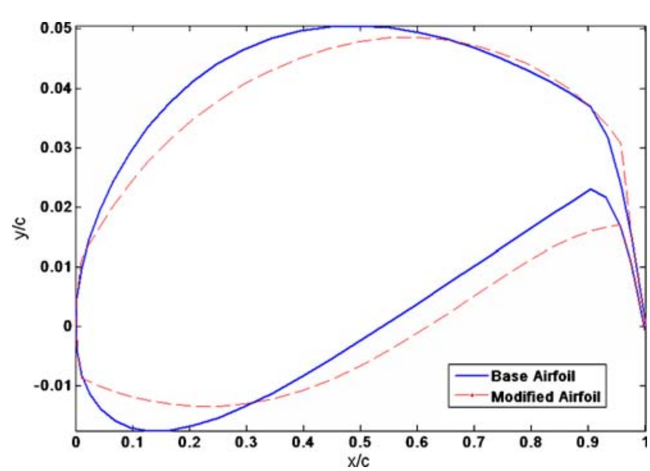


Fig. 11 Modification of the primary vehicle's base front airfoil design for turn 1 of Pocono Raceway

Table 6 Lap times for combined racetrack

Vehicle	Adaptable control points	Lap time around combined track (s)	Time difference after 200 laps (s)	Percent improvement over static design
Static	0	65.308	–	–
Driver 3's vehicle	0	63.950	271.600	2.08%
Driver 2's vehicle	4	63.170	427.600	3.27%
Primary driver's vehicle	8	62.910	479.600	3.67%
Fully reconfigurable	14	59.835	1,094.680	8.83%

potential impact of combining reconfigurability with product platforming, as the vehicle with the least amount of reconfigurability, Driver 3's Vehicle, would be over 4 laps ahead of the static vehicle after 200 laps of the race.

The results in this section illustrate the advantage of combining reconfigurable system design with a core architecture and multidisciplinary design optimization. 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 common architecture can reduce necessary performance tradeoffs while maintaining appropriate budgetary constraints. These results follow previous research which states that system performance improves with increased reconfigurability, albeit at an increased cost. The responsibility of the designer lies in the correct identification of the number of variants desired and the performance/cost impact of each design variable. Ultimately, defining the appropriate amount of reconfigurability desired, at the expense of total cost, is left in the hands of the consumer.

5 Conclusions

This paper presents a methodology for the design and multidisciplinary optimization of a family of three reconfigurable race cars. 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, product platforming, and multidisciplinary design optimization, design solutions are provided that outperform static systems and maintain commonality amongst the vehicle variants, while satisfying budgetary restrictions.

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, is added to the vehicle aerodynamics model to further practical understanding of reconfigurable system design. Adaptable airfoil designs are created through the introduction of seven 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 the 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 is introduced as a means of providing increased performance using a scalable number of adaptable variables while maintaining a common architecture within the family of vehicles. Vertical leveraging is used to identify the three vehicle variants and to select the static (platformed) and adaptable design variables. A solution for the family is generated using a multilevel MDO approach to create the three vehicle variants simultaneously. The results of this study quantify the significant advantages of combining product platforming techniques with reconfigurable system design. All three vehicle variants demonstrate obvious performance advantages over their static counterpart while meeting the hypothetical desires of the racing team.

A source of future work involves studying the results on different combinations of racetracks to understand the effect of course design on performance for a family of 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. This will also permit the development of a method to segment design variables within each of the grids when considering reconfigurability. 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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