Evaluating the Interaction Between Material Substitution and Part Sharing in Product Design: A Case Study of Automotive Lightweighting

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Abstract

Firms seek to create a product that are both desired by consumers, and also minimize costs. These goals come into conflict, as minimizing costs leads firms toward mass production, and meeting consumer needs leads firms toward product differentiation. One strategy to resolve these conflicting goals is to share component parts across distinct product variants allowing firms to maintain differentiated products while obtaining some of the economies of scale. In this way, part sharing reduces the cost burden of maintaining multiple product variants. However, part sharing also reduces product differentiation by resulting in some feature sharing, as the requirements of component parts differ across different product variants. Though some sharing may add desirable features, there may also be negative impacts, such as unnecessary mass from overdesign, referred to as "scar mass." In products where low mass is an important feature, this scar mass may deter designers from implementing part sharing. A common way of reducing mass in products is to exchange the material used for a lighter-weight alternative. However, lighter materials may be more expensive to use due to higher unit price or more complicated forming.

This research investigates combined part sharing and material substitution strategies and their implications on cost and product weight. Specifically, it seeks to evaluate whether there exist situations in which 1) the cost savings from part sharing outweigh the increased cost from material substitution, while simultaneously 2) the mass savings from material substitution outweigh the scar mass penalty from sharing. To address this problem, this research develops a framework for modeling the implementation of different part sharing and material substitution strategies. In this framework, design changes to products from material substitution and part sharing are estimated using equivalent structural performance. The cost implications of these design changes are then calculated using a Process-Based Cost Modeling approach. This framework is then used to address a case of a hypothetical generic product and finally is applied to a real case. The real case is based on three real vehicle bodies that share a common platform.

The research findings identify situations in which material substitution and part sharing strategies can be combined to produce lower mass and lower cost products. Automotive manufacturers may benefit from using these findings to implement cost-effective lightweighting policies to help them meet fuel efficiency standards.

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1. Introduction

A firm's major goal is two-fold: create a product that will be desired by consumers, all the while minimizing costs. These two goals come into conflict when the standard approach to reduce costs diminishes the firm's ability to meet divergent consumer needs. The minimum cost solution for many products is mass-production, increasing the production volume to spread the fixed costs of a product. This is especially true when there are significant economies of scale to capture. Though designing and mass-producing a single standard product in this case is the most cost-effective approach, it is limited. When designing a single product, firms must choose which features to implement and therefore which consumers to target, alienating some in the process.

Firms can appeal to a larger population by creating variants of their product tailored to the specific needs of distinct consumer groups. Firms may segment a market into subgroups of like consumers, and implement features in their product variants that meet the needs of these subgroups. This differentiation of products increases consumer utility and the prices firms can charge (Desai et al. 2001). However, such increased variety increases the complexity and cost of the firm's operation through increased manufacturing costs, development effort, manufacturing overhead, delivery times, and inventory (Salvador, Forza, and Rungtusanatham 2002; Desai et al. 2001).

1.1 Part Sharing Across Vehicles Creates Economies Of Scale That Can Improve Economics Of Product Design

One way that firms can continue to provide differentiated products while bounding the complexity of their operation is by sharing a subset of components across their products. There are many slightly different approaches that firms have used to implement such a sharing strategy, though these approaches can be grouped into three main types of sharing. One approach is to create a collection of subsystems used as the basis from which derivative products are made, called a product platform (Robertson and Ulrich 1998). Another approach is the modular strategy, which creates functional groups of parts into modules that can be mixed and matched to form product variants. A final approach is the sharing of individual parts across products. This last is done to some extent in most products – using a single common screw instead of many different screws, each optimized to its exact role in the product. In this thesis, I will refer to part sharing and component commonality to mean any kind of sharing strategy, and the findings are intended to inform decision-making under all three types of sharing schemes.

This part-sharing solution allows firms to achieve economies of scale from high production volumes of shared components, while still allowing for differentiation in unshared components to meet the divergent needs of different consumer groups. Though there are clear advantages to using a part-sharing scheme, a firm must consider many factors before choosing to implement such a strategy.

1.1.1 Part Sharing Costs and Benefits

Part sharing reduces the burden of maintaining multiple product variants. One strategic effect of part sharing is the reduction of fixed costs. By sharing a component part of a product, a firm spreads the investment of the equipment and tooling used to manufacture and assemble that part over a larger production volume, thereby reducing the portion of the fixed costs that are attributed to each individual product. This reduction of fixed costs is especially attractive in products that have high fixed costs relative to their variable costs, where the decrease in fixed costs will have a significant impact on the product's overall cost.

Part sharing also has the potential to impact a firm's potential revenue through the perception of a product's brand. Component sharing has been shown to improve products' reliability as larger production volumes translate to increased experience with a component (Kamalini Ramdas and Randall 2008; Akamphon 2008). Still, the effects of part sharing on a firm's brand perception are not necessarily all positive. If a defect were found in a common component, for example, it would taint all products that shared this component. Such a wide-reaching defect would surely have large negative impacts on a firm's brand perception and therefore threaten future revenue.

Part sharing can have further impacts on a product's economics. Platforms and other part sharing schemes have been shown to reduce a product's time-to-market (Martin and Ishii 2002). With shrinking product lifetimes, increasing the time that a product is on the market relative to the time spent in development can give a product an edge over its competition (Akamphon 2008). However, supply chain considerations from part sharing may threaten this advantage. Transportation and coordination costs may increase if the products sharing components are geographically separated. Huang et al (2005) emphasize the importance and difficulty of configuring supply chains that integrate part sharing, manufacturing processing, and supply sourcing. They also find that increased commonality will result in decreased inventory costs.

A host of other considerations in the decision to share parts stems from the unintended sharing of product features that occurs as a result of component commonality.

1.1.2 Unintended consequence and feature sharing

Even as firms seek to maintain distinct product variants, part sharing inevitably results in some sharing of features across variants. This sharing of features stems from the fact that shared components may have different functional, structural and mass characteristics than they would have had if they were not shared (Nelson, Parkinson, and Papalambros 2000; Robertson and Ulrich 1998). Feature sharing across product variants can result in both positive and negative outcomes: improving product quality and enabling desirable traits but limiting savings and increasing the product mass.

Some feature sharing from component commonality may be desirable. Part sharing may be a means of enabling penetration of new or expensive technologies, those that would otherwise be available only in the high-end products, in less expensive products by "subsidizing" a feature that is desirable in multiple product variants through the extraction of rents on the higher end product. Indeed, Desai et al (2001) demonstrate that in this way component sharing may increase the average quality of a firm's products. Similarly, Heese and Swaminathan (2006) show that increased commonality may lead to more attractive product lines.

Some feature sharing is less desirable, limiting the economies of scale that can be achieved from part sharing. As stated above, a primary reason to employ a part-sharing scheme is to improve the economics of a product. However, the savings from the economies of scale from sharing are limited by the need to maintain distinct product features across product variants. Though savings from part sharing would continue to increase as more components across products were made common, increased sharing would, at the limit, result in identical products. Even without going to such extremes, sharing will result in some loss in product differentiation (Robertson and Ulrich 1998). Reduced differentiation of products increases the risk of cannibalization of one variant's market by another variant (K. Ramdas and Sawhney 2001). Cannibalization occurs when consumers perceive similarity in attributes of products, and purchase one product when they would otherwise have purchased another product from the same firm. This is especially detrimental to firms when consumers opt for the product with the lower price premium, thereby lowering firm profits. This is likely to occur when component sharing is visible to consumers, distorting consumer perception and potentially creating "look-alike" products (Robertson and Ulrich 1998). Even sharing of parts that are not visible has been shown to reduce consumer perception of quality if the sharing impacts an attribute that consumers feel strongly about (Desai et al. 2001). Consequently, feature sharing limits how much part sharing can be practically achieved.

Finally, feature sharing may result in increased product mass. This increased mass can result from having different structural requirements across variants of a component of a product. In order to share such a component, the shared part must meet the strictest structural criteria across all variants. This often results in the presence of an oversized, overdesigned part in all products except that product which had the strictest requirements. In all other products, there is unnecessary structural capacity, which translates to unnecessary mass. This unnecessary, unused mass is sometimes referred to as "scar mass". Scar mass can occur in non-structurally constrained components as well. The cause is much like the need to meet different structural requirements, but in this case the requirements are functional. If one variant requires an additional feature of a part—perhaps an extra tab, extra threading, or an extra port—then a shared part will force this feature onto all variant products, increasing the product's mass. Scar mass from part sharing can be significant, and such an increase in mass has the potential to negate the savings from part sharing.

1.2 Material Substitution is Effective but Costly

For reasons of performance, portability, and cost, minimizing mass is important in many products. For products such as automobiles, airplanes, and bicycles, additional mass increases the energy required for travel and reduces speed, sacrificing performance. Other products such as laptops, camping gear, and cookware are only useful to consumers if they can easily be transported from place to place. Additional mass in any of these products could make them un-usable and undesirable by consumers. For still other products, raw materials are sufficiently expensive that mass must be minimized to keep the product cost down.

Products with high material costs may not be good candidates for part sharing. In products where the material cost is very expensive relative to the fixed costs, added materials cost from scar mass will quickly erode savings from part sharing. However, low materials costs are not a sufficient condition for a product to be a good candidate for part sharing. Even in products where materials are relatively inexpensive, if consumer utility is significantly reduced when additional mass is incurred, cost savings from part sharing may not be realized.

One way that firms may choose to counteract increased mass from part sharing is by removing mass in their products through material substitution. Changing a product's material has been demonstrated to effectively reduce product mass (Bjelkengren 2008; Cheah et al. 2009; Patton, Li, and Edwards 2004). This mass reduction can be achieved by substitution in materials with lower densities than that of the original material, so that components will weigh less for the same volume of material used. However, often when substituting to a less dense material, more volume will be necessary to ensure that structural requirements are maintained. As long as the volume increase is less than the density reduction, however, mass can be reduced. Additionally, firms can use materials with higher structural performance that require less material to achieve the same structural goal (Ashby 2010). Such material substitutions have the potential to not only remove mass, but also to create more performant products in the processes.

However, changing a product's material comes at a financial cost. The lighter, more performant materials often cost more than traditional materials leading to higher materials costs. This is not because lighter materials are necessarily more expensive than heavier materials. Rather, the fact that a heavier material is currently used is an indication that it is "superior" to the alternatives in some aspect, usually cost. If there were a lighter material that met all structural requirements that also cost less, substitution to this material would already have occurred and the entire market would have switched or be in the process of switching. Additionally, these may be more difficult to form, resulting in more complicated manufacturing processes and leading to higher processing costs as well (Michael DeShawn Johnson 2004). Further, material substitution may impact processes that are performed after part forming, such as assembly and painting. Changes in these processes have the potential to lead to cost increases.

1.3 Research Question

As described above, part sharing has the potential to reduce costs, but may increase product mass. Conversely, material substitution has the potential to decrease product mass, but may increase costs. The work presented in this thesis investigates the effects of implementing these strategies simultaneously. Specifically, this thesis asks the question: Are there situations in which the effects of material substitution and part sharing strategies align to produce lighter and more cost effective products?

To answer this question, I developed a framework for modeling the implementation of different part sharing and material substitution strategies. I then used that framework to address a hypothetical case and finally applied it to a real case. The research findings presented herein show that there are indeed some situations in which material substitution and part sharing strategies can be combined to produce lower mass and lower cost products. The findings also show that the benefit of incorporating part sharing to material substitution is specific to the material being substituted, as well as the structural requirements that most constrain the component parts of the product.

The automobile is a particularly interesting product to study in this context due to its high fixed costs, competitive market, and need for low mass. As described above, in order for the economies of scale on the fixed costs from part sharing to result in significant savings for firms, the products must have high fixed costs relative to their variable costs. The fixed costs in the automotive industry are indeed quite high, with approximately 60% of vehicle body-in-white[1] cost coming from equipment, tooling and building costs (M. Johnson and Kirchain 2009). Additionally, there is great pressure for automotive manufacturers to keep their costs as low as possible, as there is much competition in the industry. For these reasons, automotive manufactures already implement some part sharing strategies, and there is data available to use in an analysis of part sharing. Further, maintaining low vehicle mass is very important to automotive manufacturers. The automotive industry faces increasingly stringent fuel efficiency

[1] The body-in-white (BIW) of a vehicle is its metallic frame and body panels. For a detailed description of BIWs, see (Han and Clark 1995)

standards that require manufacturers to find new ways of removing mass from vehicles. As a result, vehicles are sensitive to the scar mass penalty that occurs from part sharing, yet this effect of part sharing is not well studied in the industry. The use of lightweight materials in automotive manufacturing is increasing as new computational tools allow for the simulation of dynamic loads that the vehicles will need to withstand, allowing manufacturers to test many design alternatives within their products. However, the cost implications of such material changes are not well captured in these exercises.

This research therefore aims to address the more specific question: Can material substitution be used in combination with part sharing in the automotive industry to manufacture more performant and less costly vehicles? The first step to answering this question was to develop a method of measuring the impacts of material substitution and part sharing.

2. Methods: Measuring The Impacts Of Material Substitution And Sharing

In order to understand the effects of implementing a joint part sharing and material substitution scheme, it is necessary to identify the changes these approaches will have on product design and manufacturing. Once these changes are recognized, it is possible to quantify the financial impacts of such changes separately and together. Modeling the effects of sharing and material substitution on product design can help to evaluate the different design options.

Limited experiential data makes modeling an attractive approach to answering the question of the impact of combined material substitution and part sharing. Historical cost and design data may be limited due to the novel nature of the materials and design approaches. Even in situations where some data is available, there remains a problem of not being able to observe different permutations: a given material substitution will occur at a set level of sharing. Yet, this research is interested in looking at the full spectrum of combinations of different sharing and material substitution approaches. Collecting data for this kind of combinatorial study is not feasible.

Luckily, there are established modeling approaches that facilitate the implementation of such a case study. The methods I apply in this case study are described below. First, methods to model the design impacts of material substitution and part sharing are described, followed by the method used to estimate cost implications of these design changes.

2.1 Design Impact of Material Substitution: How Can One Calculate Design And Mass Implications Of Changing a Product's Material?

Changing the material that a product is composed of can have significant practical implications, potentially greatly changing the design and mass of the product. This is largely due to the innate properties of different materials: a material's strength, stiffness, ductility or other properties may change the amount of material required, or the shape required of a product and its component parts. Additionally, different materials may require different forming techniques. For example, the lid of a disposable cup may be made through an injection molding or thermoforming process depending on the plastic that it is made of. These different manufacturing processes used to form a product's components may enable or restrict feasible shapes. For example, the injection molding process may enable a smaller radius of curvature than would a thermoforming process. Additionally, some manufacturing techniques may be better suited than others for part sharing (Michael DeShawn Johnson 2004). Assembly processes for joining components of different materials may also differ. A drawer made of metal may be welded together, but one made of wood must be glued or fastened with nails or screws. Just as there are many potential changes to design that may result from material substitution, there are differing approaches to evaluate these design changes.

A thorough means of evaluating a product's design changes from material substitution would involve the redesign of its component parts. Such a redesign would likely be performed using Computer Aided Design (CAD) software. This approach would allow for rigorous simulation of part performance to maintain structural and aesthetic integrity of the product. However, full CAD redesign of all of a product's parts would be extremely time consuming, data-intensive, and would require intimate knowledge of the product and its requirements. Additionally, in order to study the impacts of multiple material changes, it would be necessary to perform multiple CAD redesigns of a product to evaluate the impact of different material substitutions. For all these reasons, for the purposes of this research, a CAD redesign approach is therefore not feasible.

This research shows that such a detailed analysis may not be necessary to make observations about the design behavior of a product under material substitution. To answer the research question at hand, I associated a material change to a measurable design change that is reasonably true to life. Once the change to part design was established, it was possible to assess the impact on the product's mass as well as its manufacturing and assembly processes. With this knowledge it was finally possible to determine a cost of producing the modified product. With product mass and cost information, it was possible to evaluate different material changes, and begin to study their interaction with part sharing.

2.1.1 A Simplified Approach: Applying Different Structural Criteria

An established approach to connect material changes to measurable changes in design and mass makes use of structural criteria. Based on a paper by Chang and Justusson (1976), this approach focuses on ensuring that the product performance is held constant throughout a material substitution. This is done by considering the most restrictive structural criteria put on the component parts of the product, and using knowledge about the properties of the material to set the geometry of the part such that the value of this structural criterion is the same after a material change as it was before the change.

The approach of maintaining structural criteria provides insight necessary to address the research question of this thesis, but some limitations should be acknowledged. The first is that this part-by-part redesign approach is not necessarily the optimal approach to getting the biggest weight savings from material substitution. For some products, in order to realize the full mass savings from material substitution, a full product redesign would be necessary (Roth, Clark, and Kelkar 2001). This is in part because changing material part-by-part does not consider part consolidation gains, and larger scope geometry changes that may be had from using new materials. This implies that the structural criteria approach may be a conservative estimate of the mass reduction potential of material substitution.

Another limitation of this approach is that it is only applicable to structural components of products. Not all parts of a product are necessarily designed for structural purposes; the geometry of a given part may be set by aesthetics or for user interaction or another non-structural purpose. For such a part, changing geometry to maintain the level of a given structural criteria is unimportant and may even result in a part that no longer met the other, non-structural requirements. For these reasons, the study is limited to structural components of products only. This limitation does not greatly impede the approach to answering the research question, however, as the large majority of materials used in products are designed to bear mechanical loads of some kind (Ashby and Johnson 2009).

In addition to being appropriate for the purposes of this research, this approach could also be used by product designers as a means of screening different material substitutions. Since this approach does make some simplifying assumptions about important design features, it is still valuable for designers to go through the exercise of creating a full CAD design of the redesigned product. If the structural criteria demonstrated a promising material substitution, a designer may then opt to perform a full CAD redesign.

2.1.2 Maintaining structural criteria

As discussed above, a material change can impact design in many ways. In order to limit the redesign of the parts due to material change to a single measurable variable, the shape of the part is held constant during the material change. Meanwhile, the thickness of part is adjusted to meet the same level of a defined structural characteristic.

Different parts of a product are designed with different structural criteria governing their design. To take a simple example, a barstool is made of two part types: the seat and the legs. The legs must be resistant to buckling, so that the stool does not collapse under the weight of a user. The top of the stool, however, is unlikely to fail by buckling, but must be resistant to deflection. If one were to redesign this stool for a different material, in order to maintain the same performance of the product it would be important to ensure that the new legs met or exceeded the previous values for resistance to buckling. The top, however, would not necessarily need to maintain the same resistance to buckling; it would need to maintain the same resistance to deflection.

Of course, a part may need to meet several of the different structural criteria at once. Sometimes, these different criteria result in competing goals. A column that is primarily designed to resist failure by compression will also have some secondary resistance to tension or other modes of failure. However, as these secondary modes are not the most critical, the resistance to them is set indirectly as a result of the resistance to the primary failure mode. The compression resistance requirements “design” the part, and the other structural criteria follow as a result of that designing. As a result, the part may be overdesigned with respect to these secondary failure modes. Maintaining these excessive levels of performance is not necessary.

Using the equations for resistance to different failure modes, and the assumption of identical part shape, it is possible to create ratios of necessary part thickness with a new material for a given structural criteria. A selection of these ratios is listed in Table 2-1 below. The approach used to calculate the ratios divides parts into two broad categories: panel members, and thin-walled beam members. The ratios and the relevant structural criteria for these two types of parts differ somewhat. However, many of the thickness ratio equations are quite similar.

Structural Characteristic	Ratio of Structural Characteristics	Thickness Ratio Required for Equal Structural Characteristics	Notes
Denting Resistance, D	$\frac{D_n}{D_o} = \left(\frac{\sigma_{yn}(\dot{\varepsilon})t_n^2}{\sigma_{yo}(\dot{\varepsilon})t_o^2}\right)^{.5} \frac{S_o}{S_n}$	$\frac{t_n}{t_o} = \frac{\sigma_{yo}(\dot{\varepsilon})}{\sigma_{yn}(\dot{\varepsilon})}\left(\frac{E_o}{E_n}\right)^{\frac{1}{2}}$	Panel Members
Oil Canning Resistance (Stiffness), S	$\frac{S_n}{S_o} = \frac{E_n}{E_o}\left(\frac{t_n}{t_o}\right)^2$	$\frac{t_n}{t_o} = \left(\frac{E_o}{E_n}\right)^{\frac{1}{2}}$	Panel Members
Torsional Stiffness, S^t	$\frac{S_n^t}{S_o^t} = \frac{G_n}{G_o}\frac{t_n}{t_o}$	$\frac{t_n}{t_o} = \frac{G_o}{G_n}$	Thin-Walled Beams, Closed Section
	$= \frac{E_n}{E_o}\frac{t_n}{t_o}$	$\frac{t_n}{t_o} = \frac{G_o}{G_n}$	Thin-Walled Beams, Open Section
Buckling Resistance, B	$\frac{B_n}{B_o} = \frac{E_n}{E_o}\frac{t_n}{t_o}$	$\frac{t_n}{t_o} = \frac{E_o}{E_n}$	Thin-Walled Beams
	$= \frac{E_n}{E_o}\frac{1-\upsilon_o^2}{1-\upsilon_n^2}\left(\frac{t_n}{t_o}\right)^3$	$\frac{t_n}{t_o} = \left(\frac{1-\upsilon_n^2}{1-\upsilon_o^2}\frac{E_o}{E_n}\right)^{\frac{1}{3}}$	Panel Members
Local Buckling Resistance, L	$\frac{L_n}{L_o} = \frac{E_n}{E_o}\frac{1-\upsilon_o^2}{1-\upsilon_n^2}\left(\frac{t_n}{t_o}\right)^3$	$\frac{t_n}{t_o} = \left(\frac{1-\upsilon_n^2}{1-\upsilon_o^2}\frac{E_o}{E_n}\right)^{\frac{1}{3}}$	Thin-Walled Beams
Crippling Resistance, C	$\frac{C_n}{C_o} = \left(\frac{E_n}{E_o}\frac{\sigma_{yn}}{\sigma_{yo}}\right)^{.5}\left(\frac{t_n}{t_o}\right)^{1.75}$	$\frac{t_n}{t_o} = \left(\frac{E_o}{E_n}\frac{\sigma_{yo}}{\sigma_{yn}}\right)^{\frac{1}{3.5}}$	Thin-Walled Beams
Stress Yield Factor, Y	$\frac{Y_n}{Y_o} = \frac{\sigma_{yn}(\dot{\varepsilon})}{\sigma_{yo}(\dot{\varepsilon})}\frac{E_o}{E_n}\frac{\bar{S}_n}{\bar{S}_o}$	$\frac{\bar{S}_n}{\bar{S}_o} = \frac{E_n}{E_o}\frac{\sigma_{yo}(\dot{\varepsilon})}{\sigma_{yn}(\dot{\varepsilon})}$	

Table 2-1: Thickness Ratios for Selected Structural Criteria[2]

For the purposes of this study, two structural criteria were chosen to capture a range of different design behaviors under material change. In order to obtain results on different types of material substitution behavior, two criteria with dissimilar thickness ratios were selected. These two criteria are resistance to local buckling, and resistance to crippling.

2.1.1.1 Buckling

Buckling failure occurs when a member under axial compression deflects laterally and deforms such that it can no longer perform its intended function (Collins 1993).This is depicted in Figure 2-1. The thickness ratio for resistance to buckling differs across different part types. As shown in Table 2-1 a panel-type part has a buckling resistance

[2] Adapted from a paper by Change and Justusson. The material properties used in the table are Young's Modulus (E), Poisson's Ratio (υ), yield strength (σ_y), and Shear Modulus (G). Other variables are Strain Rate ($\dot{\varepsilon}$), and the part's thickness (t). The subscript n represents the new material, whereas the subscript o represents the original material. For derivations of these formulas, see (Chang and Justusson 1976).

thickness ratio of $\frac{t_n}{t_o} = \left(\frac{1-\upsilon_n^2}{1-\upsilon_o^2}\frac{E_o}{E_n}\right)^{\frac{1}{3}}$, while a beam has a buckling resistance thickness ratio of $\frac{t_n}{t_o} = \frac{E_o}{E_n}$.

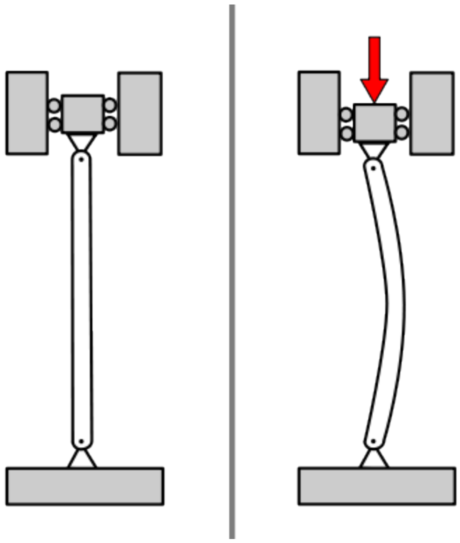

Figure 2-1: Schematic of Buckling Failure on a Column

2.1.1.2 Crippling

Crippling is a local buckling failure that occurs under compression, resulting in a part collapsing on itself. Crippling typically occurs in short members, or along the short axis of a longer member, as long members do not have the stability required for crippling to occur. Long members under compressive loads will buckle before crippling can occur. Figure 2-2 below depicts the typically crippling behavior.

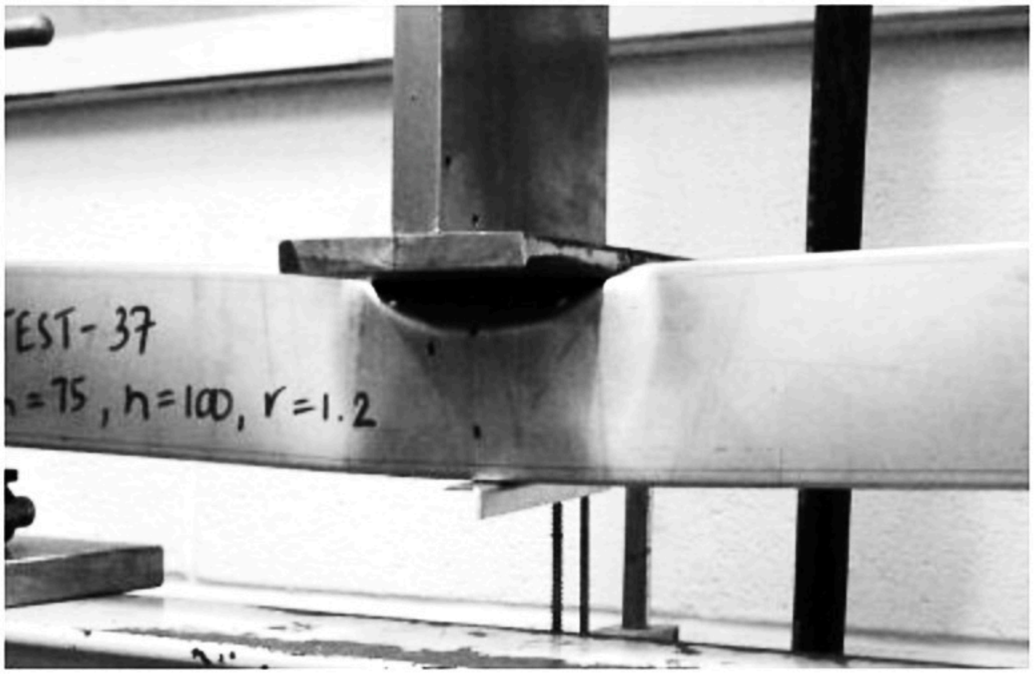

Figure 2-2: Example of Crippling Failure on a Thin-Walled Beam Structure[3]

The thickness ratio for crippling resistance is $\frac{t_n}{t_o} = \left(\frac{E_o}{E_n}\frac{\sigma_{yo}}{\sigma_{yn}}\right)^{\frac{1}{3.5}}$, as is shown in Table 2-1. As this formula demonstrates, resistance to crippling depends on a material's yield strength as well as its modulus of elasticity. For more information on crippling, see (Macdonald et al. 2011; Kassapoglou 2011; Ziemian 2010; Metals 2003).

2.2 Design Impact Of Sharing Parts: How Can One Calculate Design And Mass Implications Of Sharing Parts Across Products?

The previous section detailed the methods that were used to evaluate the design impacts resulting from material changes made on a product. This section goes through a similar exercise for part sharing. Again we are considering methods for evaluating design changes. In order to evaluate the potential for part sharing and material substitution to be used jointly for improved product results, we must quantify the effect that part sharing will have on a product's design. However, before we can quantify these effects, we must understand how a part changes when it is made common.

Across different products, some parts are identical but many are different. Prior research in this area calculated the cost implication of part sharing, but assumed that parts

[3] Picture from (Macdonald et al. 2011)

were unchanged regardless of whether or not they were shared (Michael DeShawn Johnson 2004). Evaluating this sharing led to interesting conclusions, but assuming identical parts across products is not representative of most product design. In reality, the individual optimized product will differ from the collectively optimized family of products that share component parts. Indeed, a component used across multiple products must meet the criteria of the most demanding product. Meeting this criterion will likely lead to the creation of a part that is overdesigned, exceeding the requirements of the other products in which is it used. This leads to an interesting design problem of designing a common part if parts differ across products.

2.2.1 Designing a Common Part

There is no single approach to determine what a shared part will look like. One very rigorous approach, detailed by Nelson et al (2000), involves performing multi-criteria optimization on the product family. This approach ensures that all parts meet their necessary requirements with minimal overdesign and performance reduction. It also allows for differing objective functions specific to different market niches. However, this requires *a priori* knowledge of all products that would be sharing parts, which may not be possible. Some part sharing is done across time, with previous parts held constant from prior designs into new products. In addition, such an approach would be extremely data intensive, as it would require full part-level descriptions of all products in a product family. Such an intensive approach is neither practical nor necessary to quantify the effects of part sharing for the purposes of this thesis.

It is possible to reasonably approximate design changes from sharing through use of structural characteristics. When sharing a single part across multiple products, we want to ensure that the shared part will satisfy the structural requirements that are required in each product variant. There are different ways that one could model a shared part that meets the criteria of all products. One way is to select some attribute of the part—the width, length, thickness, mass, etc.—and to select the part, from the different products, that has the most robust value for that attribute. Another approach is to create an amalgamation of the different parts, with the most robust values from each of the unshared parts in the different products combined into one shared part. This second approach is somewhat dangerous, as the way a part's attributes are defined across products may be inconsistent. For example, what is considered the "width" dimension on one part may be recorded as the "length" of another. So, their amalgamation may result in a part that did not resemble the real parts in any product. To avoid this, I chose to create a shared part based on a single attribute that would be uniquely defined: the part's mass.

When modeling a shared part to substitute the unique parts across different variants, I chose the heaviest of the unique parts to serve as the new, shared part. To illustrate, if two bicycle variants—a men's and a smaller women's bike perhaps—were to share a kickstand, I would select the heavier of the two kickstands from the bicycle variants to be the modeled new shared part. This approach assumes that the heaviest part will perform better on the structural requirements than an otherwise equivalent lighter part. This is not necessarily always the case, as clever design of part shape can reduce mass while improving structural performance. However, if we assume that all individual products were designed equally well initially, then the assumption that a heavier part is more structurally performant is reasonable.

2.3 Estimating Costs for Alternate Materials and Shared Designs

In order for designers to make well-informed decisions regarding the tradeoffs of different design choices, they must be able to attribute a cost to their various options. There are many different approaches to estimating costs of a design, and their benefits are well documented. In this research, I implement a process-based cost modeling approach to estimate costs of design changes. An abbreviated introduction to this kind of modeling is included below. For a more detailed discussion of process-based cost modeling and its alternatives, see (Kirchain and Field 2001; Field, Kirchain, and Roth 2007).

2.3.1 Process-Based Cost Modeling

Process-Based Cost Modeling (PBCM) is a cost estimation strategy that attempts to relate process requirements with costs. The approach to PBCM taken by MIT's Material System's Laboratory uses limited design information to predict those process requirements. Such an approach is essential for this work, as detailed process considerations are not available for the product designs to be analyzed. Therefore, it was necessary to select a method that would first predict these process variables and then estimate costs.

As shown in Figure 2-3, the PBCM can be broken into three sub-models: the process model, the operations model, and the financial model. Each of the sub-models contains statistical relationships based on previous vehicle manufacturing experience as well as relationships derived from first principles.

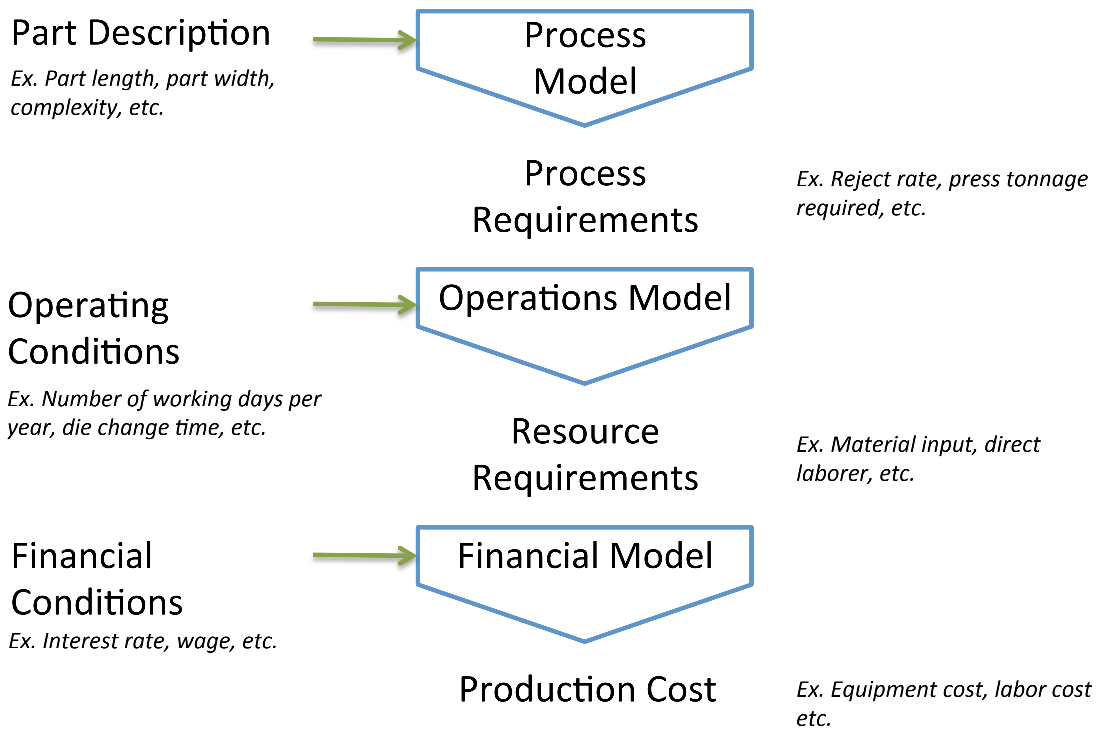

Figure 2-3: Process-Based Cost Model

The process model takes as input the description of the component parts of a product, in this case a vehicle's part's dimensions. The process model then uses these dimensions to estimate the process requirements that will be necessary to produce the parts, such as the size of the press that the part will be run on. The operations model then takes as input these process requirements as well as the operating conditions under which the part will be made. These operating conditions may include the number of days per year the production plant will be in operation and the amount of time it takes to change a manufacturing die set up. Using the process requirements and operating conditions, the operations model then calculates the resources that will be necessary to manufacture the part, for example the amount of material that will be needed to form the part. Finally, the financial model takes these resource requirements as well as some inputs of the financial conditions (wage, interest rate, etc.) and calculates the costs of producing the part.

The model outputs can be grouped into distinct cost elements, both fixed and variable. The variable cost elements are material, labor, and energy. The fixed cost elements are equipment, tooling, and building costs.

2.3.1.1 Modeling Material Changes in PBCM

The material substitution will impact final product costs largely through material costs, but also through different processing costs. A material substitution will often change the amount of material that is required for the product. This may be the result of structural requirements, or of differing scrap amounts associated with that material. Additionally, different materials will have different unit costs. Together, these effects will result in a marked change in materials cost from material substitution.

A material substitution will have financial implications beyond materials costs, however. Different materials, due to their physical properties, will require different processing. For example, a material that is harder to form may require a slower line rate than one that is more easily formed. This material may also require more complicated tooling, and may require additional press hits to form the same part. Additionally, a material that is particularly tough may require more frequent tool replacement rates as tooling wears out faster. Other materials are more prone to defects, resulting in higher reject rates. These impacts of material substitution are all included in the cost model and are visible through changes to labor, energy, and tooling cost.

2.3.1.2 Modeling Sharing in PBCM

Part sharing will impact both fixed and variable costs in opposite ways. Part sharing reduces fixed costs by increasing the effective production volume. This spreads the investment costs such as equipment, building, and tooling costs over more products. Meanwhile, the variable costs will increase due to the increased mass of the shared parts from scar mass. This will translate to additional energy and material costs.

The reduction of fixed costs from sharing is most impactful through the spreading of costs of dedicated equipment. There are two types of investments modeled. Dedicated investments are those that are specific to a given part and can only be used to manufacture that specific part. A part's mold is an example of dedicated investment. In contrast, non-dedicated investments are those that can be used for the production of many different parts. For example, the press that holds the mold and is used to stamp a part. These investments can be shared across multiple dissimilar parts, and so part sharing does not as greatly impact these costs. It is therefore the dedicated investment that most directly generates savings from implementing part sharing.

3. Generic Product Case

In this chapter, I describe the creation and results of a case study for a generic product. The purpose of performing such a study is to explore changing product attributes under different material substitution and part sharing schemes. The product is kept non-descript to enable general observations about such schemes that apply to a broad range of products. In the following chapter, a similar study is performed with features specific to the automotive industry. Before diving into the details of the generic product case study, I first elaborate the goals of such a study.

3.1 More Detailed Research Questions

As described previously, the broad objective of this thesis is to determine if there are benefits to jointly implementing part sharing and material substitution in product design. In order to fully explore this topic and answer the research question at hand, I have developed several sub-questions. These questions provide context for some of the decisions made in the case study framing.

Do Positive Interactions Exist? The first of these sub-questions is most central to the research. Are there favorable cost and mass outcomes that can be reached through combined part sharing and material substitution that could not otherwise be achieved? In order to answer this question, I need to demonstrate the presence of win-win scenarios in which the benefits of part sharing and material substitution outweigh their costs.

Does Degree of Sharing Matter? The second question pertains to the degree to which products share parts. Does the amount of sharing impact how favorable part sharing and material substitution schemes appear?

I have explained that sharing has a practical upper bound due to a need to maintain differentiable parts. This is not a clear or predetermined cut-off, but a region of trade-off between gains from reduced fixed costs and losses from cannibalization and perceived quality. Since there is no one definite cut-off, it is valuable to evaluate the entire range of sharing possible. If favorable changes in product attributes from sharing and material substitution are only observable at extremely high levels of sharing, we may not practically be able to attain the benefits. Therefore, we are interested in evaluating changes in the behavior that result from the amount of sharing.

Does the Material Matter? Are the interactions more favorable for some material substitutions than others? This question attempts to shed light on the impact of different material properties.

A material's properties will impact the design and cost of a product. These properties will determine the allowable thickness and mass of parts as they undergo material substitution. Additionally, a material's unit cost may have a large influence on the product's overall cost. This question asks whether these effects are sufficiently large to decide whether a hybrid material substitution and part-sharing scheme is a good design option or not.

Does the Structural Criteria Matter? Finally, I investigate the importance of structural requirements. Does the presence of favorable behavior depend on the structural criteria that the product's component parts must maintain?

The design impact from material substitution is closely linked to the structural requirements. The structural requirement informs the necessary part thickness and part mass after a material change has been made. As a result, the structural requirements are expected to play a large role in design and cost impacts from material substitution. With this question, we investigate whether this impact is the same or different for different structural criteria. We would like to observe whether favorable interactions between part sharing and material substitution are more favorable in parts constrained by one structural requirement than another. Finding evidence of different behavior across structural criteria may be cause to explore a fuller range of mechanical failure mechanisms and structural criteria that guard against those failures.

3.2 Description of the Generic Product Case

The general product case study is performed on two fictitious generic products. The generic products have 9 parts each of varying size, mass, and complexity. Using these two products, I observe the effects of the full range of sharing, from completely distinct products that share no parts to identical products with all parts shared between the two. I then look at the effects of a range of material substitution, starting from a product of a single baseline material to one with all parts of a lightweight material. Finally, I look at the range of the effects together by increasing sharing while simultaneously implementing material substitution.

In order to capture the effects of scar mass from sharing, it was necessary to start with products with different requirements. To incorporate such an effect, I assigned one product to be 20% heavier than the other. This additional mass is distributed evenly across all parts, with each part from the heavier product weighing 20% more than the corresponding part in the lighter product. In order to isolate the effects of scar mass, other than the difference in mass, the parts in the two products were completely identical.

In order to observe the entire spectrum of sharing, I increased the number of parts that were common across products one at a time. One-by-one, parts went from having different masses across the two products, to having the same mass in both products. As described in Section 2.2.1, the heavier of the two parts is made common across both products when shared. For this simple case study, that meant that one-by-one, parts in the lighter vehicle were replaced by parts from the heavier vehicle. An example of such sharing is depicted in Figure 3-1 below.

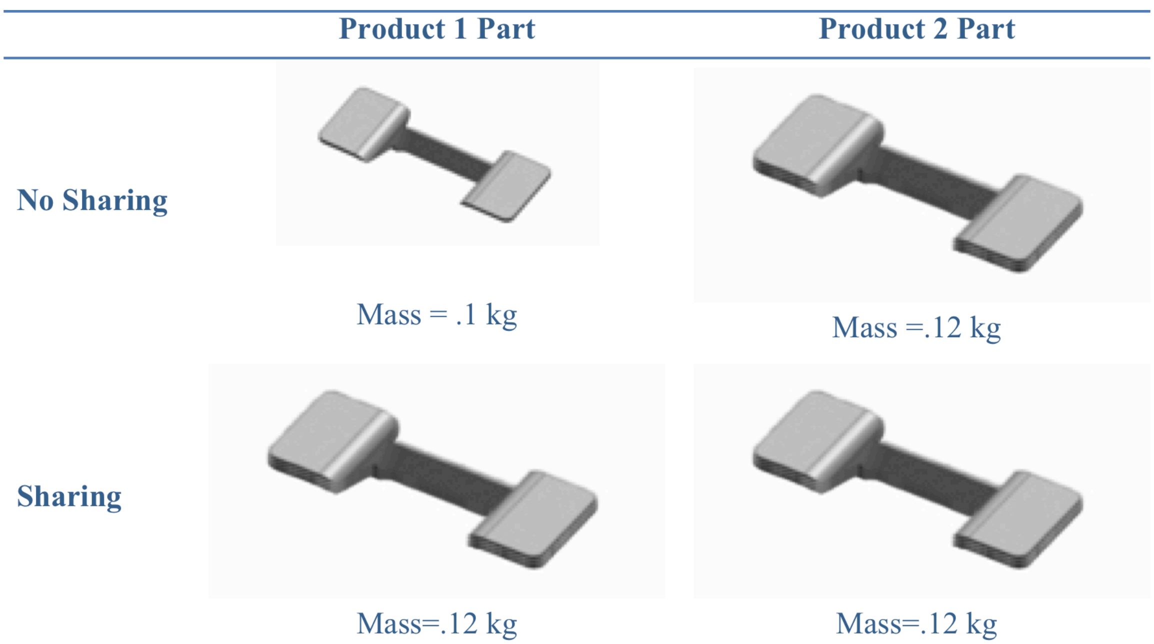

Figure 3-1: Example of Scar Mass Implication of Part Sharing in Generic Product Case Study

To observe the impacts of increasing use of lightweight materials, I assigned the products a baseline material of mild steel, and then upgraded to lighter materials. In order to reduce the number of variables that were impacting the design changes to parts due to material substitution, I chose materials that could all be formed using the same manufacturing process. Since my eventual goal was to create a case study for the automotive industry, a stamping process was a logical choice. Only a subset of engineering materials can easily be formed using stamping. These are, by and large, metals and their alloys. Of the metals, mild steel is very common, easy to form, and relatively inexpensive compared to its alternatives. For these reasons, I set mild steel to serve as the baseline material for the generic product case study.

The mild steel is replaced, one part at a time, for a different material that has physical properties that may enable mass reduction. Three materials that differed in physical properties were selected as the substituting material. These materials are aluminum, high strength steel, and martensitic steel. Their relevant physical properties are listed in Table 3-1. Aluminum was selected for its low density, while high strength and martensitic steels were selected for their high yield strengths. The difference in physical properties is important to capture changes in processing such as different reject rates, line rates, and tool lifetimes.

Material	**Density** (g/cm^3)	**Yield Strength** (MPa)	**Young's Modulus** (GPa)	**Crippling Mass Factor**	**Buckling Mass Factor**
Mild Steel	7.85	175	200	1	1
High Strength Steel	7.85	380	200	.80	1
Martensitic Steel	7.85	1198	200	.58	1
Aluminum	2.7	100	69	.55	.24

Table 3-1: Material Properties

Concurrent with these material changes, the thickness of the part is adjusted to maintain the same level of a measure of structural resistance prior to the material change. The original thickness from the mild steel part is multiplied by a ratio that corresponds to a specific structural requirement. The equations used to calculate these ratios are listed in

Table 2-1. The change in part thickness produces a corresponding change in mass. The resultant mass factors for the three different materials for each of the structural criteria are listed in Table 3-1. Based on first principles, these factors represent theoretical best-case mass reduction, and in some cases may be overly optimistic estimates of the actual mass reduction expected from material substitution.

The part sharing and material substitution schemes are then implemented simultaneously. To do this, I change the material of a part when it is made common across the two products, and make the corresponding thickness and mass adjustments.

3.3 Mechanisms

In order to make statements about the impact of the degree to which a product implements sharing or material substitution, I establish an order for the change done to parts. Parts are ordered by decreasing proportion of investment to total cost (M. D. Johnson and Kirchain 2010).

All parts have different levels of potential for savings from sharing and substitution. The sharing of some parts is more beneficial than the sharing of others. Sharing a part with very high fixed costs from dedicated tooling and low variable costs has a lot of potential to save money. Conversely, sharing a part with low fixed costs but high variable costs will have little benefit, and may result in additional costs if scar mass results in sufficiently high increased materials costs. Similarly, changing the material of some parts will have more beneficial impacts than others. A part with very high material costs relative to other costs may be a poor choice for material substitution if that substitution will result in increased material cost. As a result, simply identifying a percent value of sharing or of substitution is not sufficiently descriptive.

To remedy this ambiguity, I ordered parts by a ratio of their fixed costs to total costs. Specifically, I took the ratio of the total investment per part divided by the sum of the investment cost and the material cost per part. Investment costs included the equipment cost, tooling cost, and building costs. Due to scar mass and mass reduction concerns, material costs are the most relevant of the other, variable costs to monitor. There are two reasons to order the parts in this manner. This order maximizes economies of scale from sharing, and minimizes the potential for increased cost from material substitution.

3.3.1 Ordered Sharing: Maximizing Economies of Scale

As described above, those parts with the highest fixed costs relative to variable cost are the best candidates for sharing. I order the parts by how good a candidate the part is estimated to be. The parts with the highest ratio of investment to total cost are shared before parts with lower values of this ratio. This ordering ensures the sharing of components that will achieve the most economies of scale before sharing of those components with smaller potential savings.

3.3.2 Ordered Substitution: Minimizing Impact of Material Price

Lightweight materials tend to be more costly than their heavier counterparts. If materials cost is a small component of total cost, than substitution to a material with a higher price will not greatly impact total cost. Thus, the mass reduction from material substitution can be achieved at a lower change in cost. For this reason, we prefer to substitute for lightweight material in parts that have lower materials costs as a ratio of total cost. Thus, we first change the material of the parts with the higher ratio of investment cost to investment plus material cost to minimize impact of increased material price.

3.4 Generic Product Case Results

Before considering the interaction effects of part sharing and material substitution, we observe the products' behavior for a range of sharing. We find that part sharing has measurable impacts on both product mass and product costs.

The product mass behaves as expected. As seen in Figure 3-2, as sharing across products increases, the cumulative mass of the two products increases. This increase in mass is due to the scar mass from overdesigned parts. Due to the pre-defined 20% difference in mass in the two products, we see a mostly linear increase in mass with increased sharing. The curve is not perfectly linear because the parts are of various sizes and masses. The measure of sharing shown is purely a measure of the shared part count, so the sharing of some parts leads to larger increases in mass than other parts do. Graphing product mass against a sharing metric that measured the amount of mass shared shows a slightly different, smoother curve.

The products' cost behavior is more interesting. We find that the cost of the products initially decreases with increased sharing before flattening and beginning to rise again.

Looking at Figure 3-3 we see that the total cost of the generic products is minimized at around 40% part sharing. The decrease in cost up to this point is due to the savings from sharing the fixed costs of products. At the minimum cost, we reach a point beyond which savings from investment sharing and economies of scale are dominated by increased costs from overdesign and scar mass. The increase in cost beyond 40% part sharing is due to increased importance of material cost. Though we can see from Figure 3-2 that the additional mass from sharing is no larger after the minimum cost point, the scar mass from sharing beyond this point has a higher cost penalty than the extra mass did under 40% sharing. Observing the standalone trends of mass and cost for the range of part sharing is interesting, but is not best suited for decision-making.

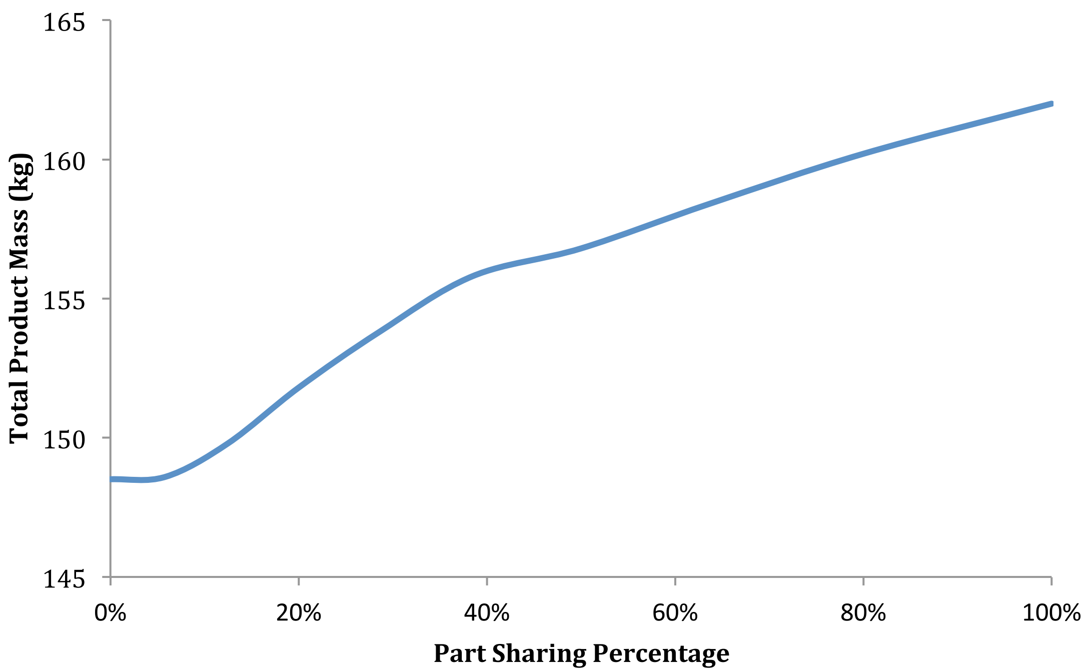

Figure 3-2: Impact of Part Sharing on Generic Product Mass

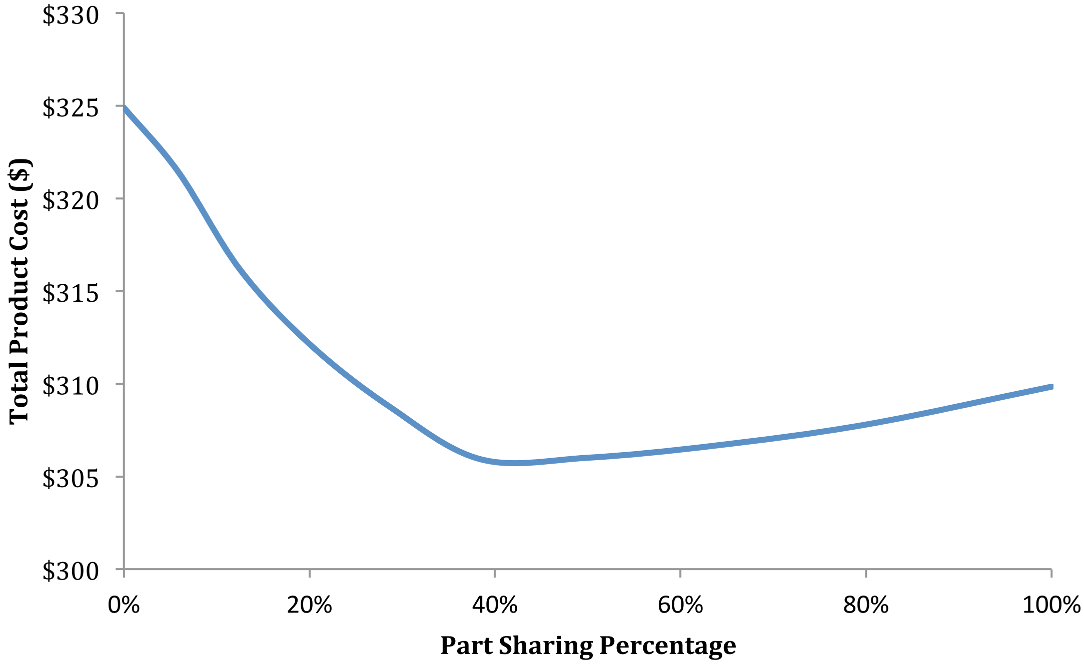

Figure 3-3: Impact of Part Sharing on Generic Product Cost

Looking at the mass and cost together allows for a more complete picture of the design options. For example, a product designer may be willing to incur some additional mass to save on product cost. In order to look at these effects together, I match the cost and mass results for each level of sharing. Looking at the range of possible cost and mass combinations on Figure 3-4 would allow one to make a decision based on his own preference for mass versus cost.

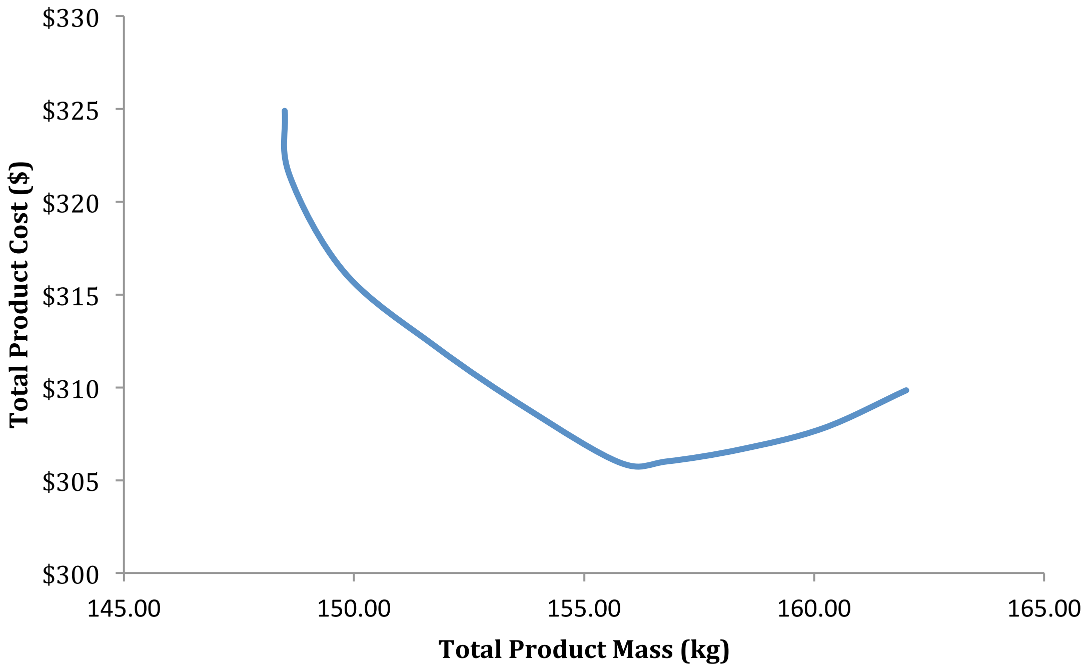

Figure 3-4: Full Spectrum of Attainable Mass and Cost Results from Part Sharing in Generic Product

Before discussing results from combined implementation of sharing and material substitution, it is important to illustrate the implication of location on a mass vs. cost graph such as the one above. The area of the graph can be divided into four quadrants, as depicted in Figure 3-5. The origin of these four quadrants, highlighted with an orange circle, is the default product state. This point represents the cost and mass of the product if a designer takes no action.

Two of the quadrants are regions that represent design trade-offs. In these trade-off regions, represented by grey shading, it is possible to reach points of either reduced mass or reduced costs, but not both. The part sharing results from Figure 3-4 and repeated in Figure 3-5 below are an example of this. It is possible to move from the origin at the left to points of increased sharing down along the curve, reducing costs but increasing product mass. Whether the points in these two quadrants are desirable depend on the preferences of the consumer of the product and the utility derived from products with low cost compared to those with low mass. Not all points within such a region are equally desirable, however. An example of this is depicted by the outcomes to the right and left of the red dot on Figure 3-5. Moving rightward away from the origin by increased sharing enables reduced costs while increasing mass. However, increasing sharing beyond the point of minimum costs results in marginally less beneficial outcomes. Costs to the right of the red point are lower than the origin position, but higher than some points to the left of the red point, and at higher masses.

The remaining two quadrants are more definitely good or bad. One quadrant is a lose-lose quadrant, represented by red shading. Moving from the default product to anywhere in this quadrant results in inferior product outcomes. Product designers should avoid implementing strategies that fall into this quadrant, as the product outcomes in this region only increased costs and increased mass from the original. Finally, there is the win-win quadrant depicted in green. Moving away from the original product characteristics at the origin and into this quadrant reduces costs and reduces product mass. Design options that lie in this quadrant are very desirable and should be sought after by product designers.

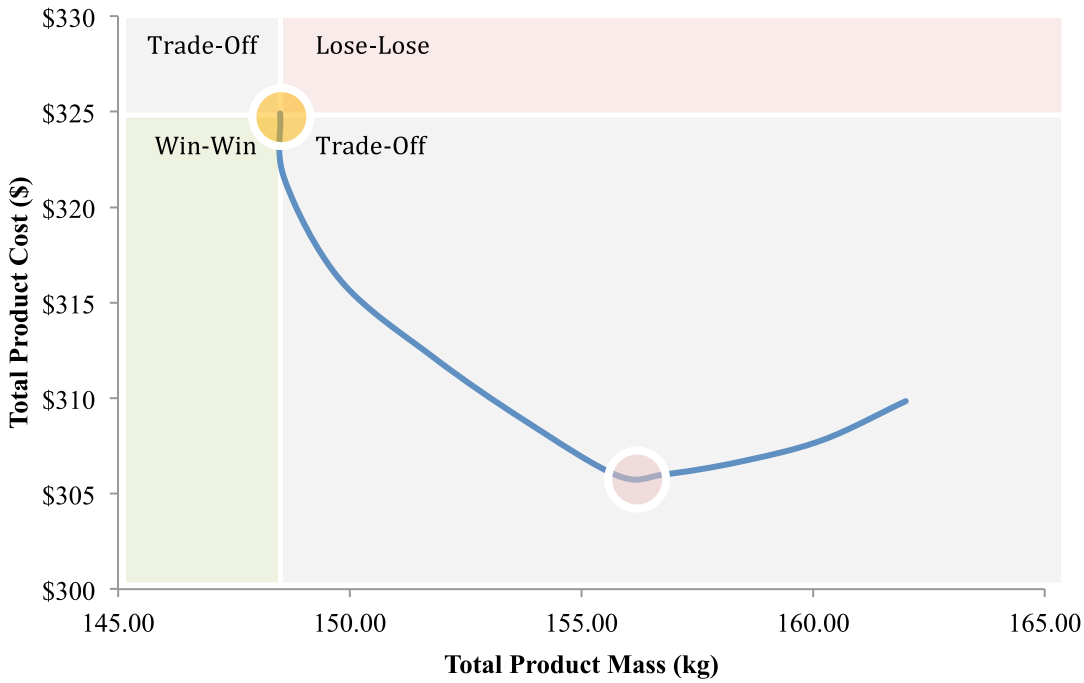

Figure 3-5: Depiction of Quadrants within Cost vs. Mass Space

Moving forward, I use the quadrants to assess the merit of different design options. I evaluate the outcomes of different material substitutions and combined material substitution and part sharing approaches in addition to the standalone part sharing design option. Results are separated by the structural criteria used to calculate mass impacts of substitutions.

3.4.1 Combined Analysis: Crippling Resistance

I first discuss the outcomes from material substitutions using the criteria of crippling resistance. I examine the mass and cost outcomes of substitution from mild steel to aluminum, martensitic steel, and high strength steel. I additionally examine the combined part sharing and material substitution results for each material.

The analysis of substitution to aluminum shows evidence that the degree to which parts are shared and their materials are substituted impacts how favorable combined part sharing and material substitution is relative to other design options. Figure 3-6 shows that material substitution to aluminum, shown by the darker, red curve, is in a quadrant of tradeoffs. It is possible to reduce mass from the original design, but to do so requires incurring additional costs. This is done by operating at a point on the red curve further to the left, away from the origin. As depicted by the lighter, pink curve, at low levels, combined part sharing and material substitution allow for reduced mass at a lower cost than material substitution alone. As the amount of part sharing and material substitution increase, however, there is a switch. At upper extremes of material substitution and part sharing, represented by the left-most edge of the curves, reduced mass is attained at a lower cost through material substitution alone.

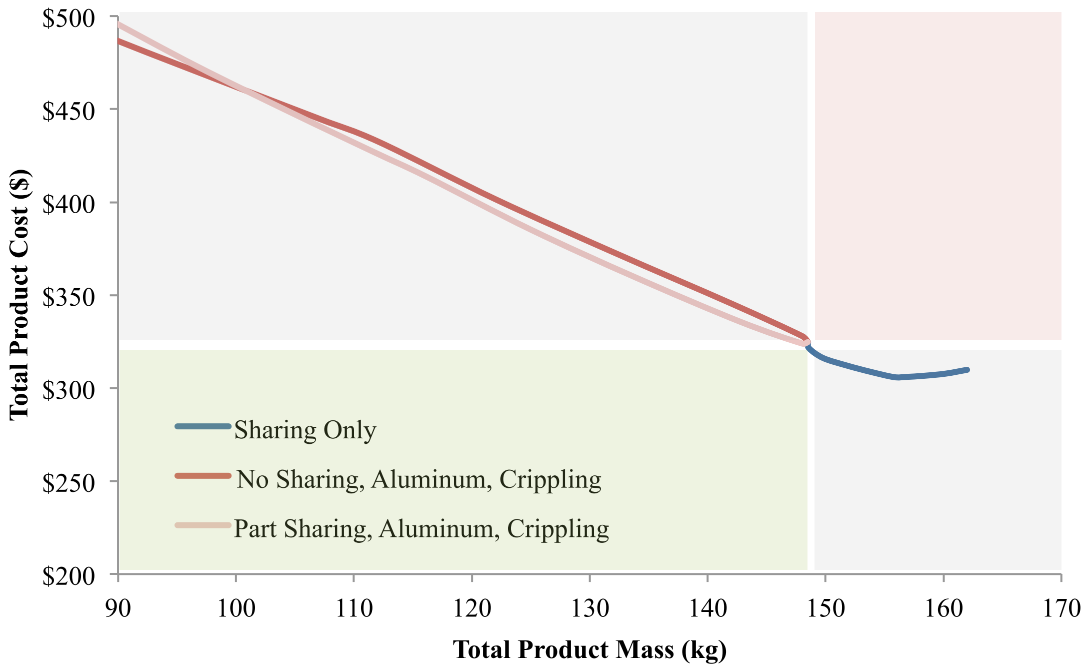

Figure 3-6: Generic Product Cost and Mass Results from Part Sharing and Substitution to Aluminum with Crippling Resistance as Dominating Structural Criteria

Analysis of substitution from mild steel to martensitic steel demonstrates how combining with part sharing can shift a borderline design option to a decidedly appealing one. The darker green line in Figure 3-7 depicts the substitution of mild steel to martensitic steel with no part sharing. Until approximately 40% of the product is substituted to martensitic steel, substitution results in lower mass but at an increased cost. Beyond 40%, material substitution to martensitic steel alone can achieve reduced mass while simultaneous reducing costs. However, these results are based on optimistic estimates of mass reduction. The fact that the results from material substitution alone are so close to the boundary may dissuade a designer from implementing such a strategy if low cost is an important design goal. The results of combined implementation of part sharing and substitution to martensitic steel are decidedly in the win-win quadrant. This is therefore a good example of the benefit of combined implementation of sharing and material substitution. Material substitution and sharing alone have their benefits, but at a cost. Combined, these approaches can lead to reduced mass and cost simultaneously.

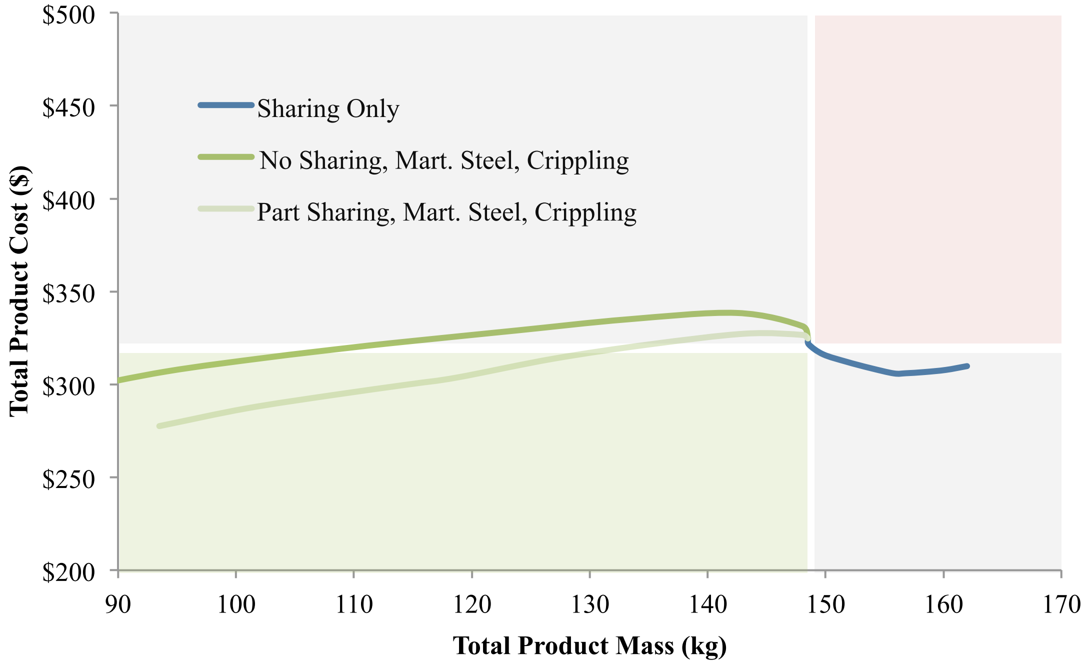

Figure 3-7: Generic Product Cost and Mass Results from Part Sharing and Substitution to Martensitic Steel with Crippling Resistance as Dominating Structural Criteria

The analysis of substitution from mild steel to high steel illustrates how part sharing can make an already good design option even more appealing. As shown in Figure 3-8, material substitution to high strength steel in a part that is constrained by resistance to crippling results in lighter and less costly products. Some of the low levels of mass can be reached even lower costs when material substitution and part sharing are implement jointly, as seen by the lower position of the curve representing the combined scheme. However, jointly implementing the material substitution and sharing reduced the potential mass savings, as scar mass effects erode some of the lightweighting effects of using high strength steel in the place of mild steel. The minimum mass attainable by the combined approach is about 10% higher than that the material substitution alone.

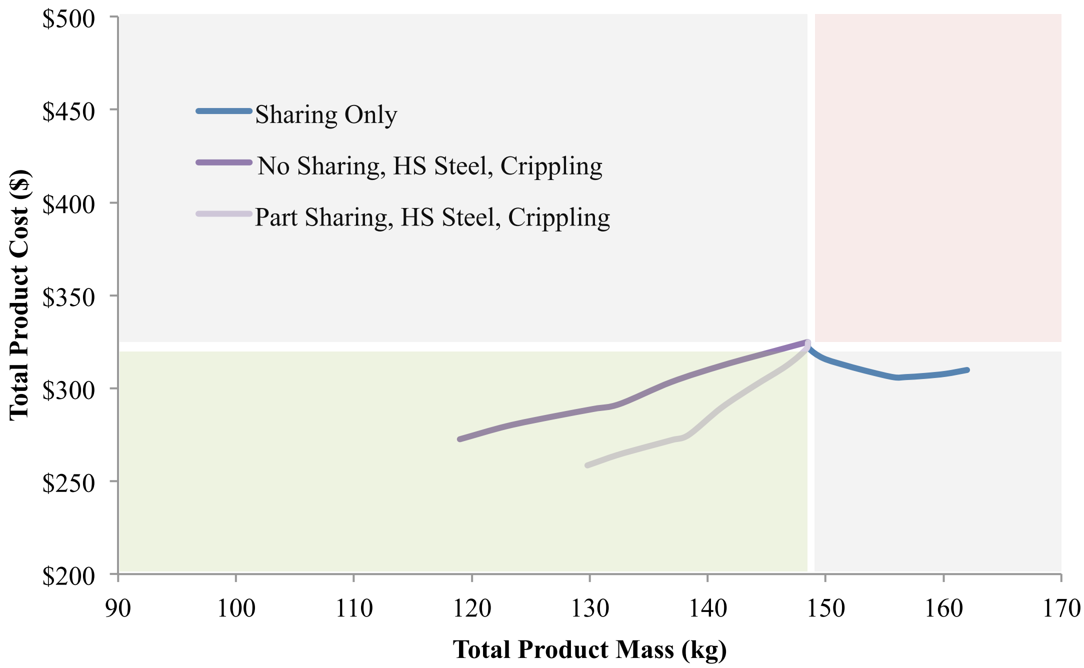

Figure 3-8: Generic Product Cost and Mass Results from Part Sharing and Substitution to High Strength Steel with Crippling Resistance as Dominating Structural Criteria

Looking across at the different analyses, it is clear that different material substitutions will lead to different product attributes. Generally, implementing sharing and material substitution together resulted in more desirable outcomes than either did separately. However, as demonstrated by the analysis of the substitution to aluminum, in some cases the degree to which a product is shared will change which design option is most attractive.

3.4.2 Combined Analysis: Buckling Resistance

I now consider the same material substitutions and part sharing combinations, with buckling as the constraining structural criteria.

The first material substitution is from mild steel to aluminum. This material change, as shown in Figure 3-9, is at the edge of the "win-win" quadrant. It is interesting to note the huge mass savings that are possible from substitution of mild steel to aluminum when buckling is the limiting structural criteria. For some products, such as vehicles, it is unlikely that many of the component parts will be most constrained by buckling resistance. Nevertheless, this large mass reduction potential makes substitution to aluminum very desirable in parts that are constrained by buckling. Part sharing combined with material substitution allows mass reduction to be achieved at lower product cost, but the difference is small with maximum cost savings of about 5%.

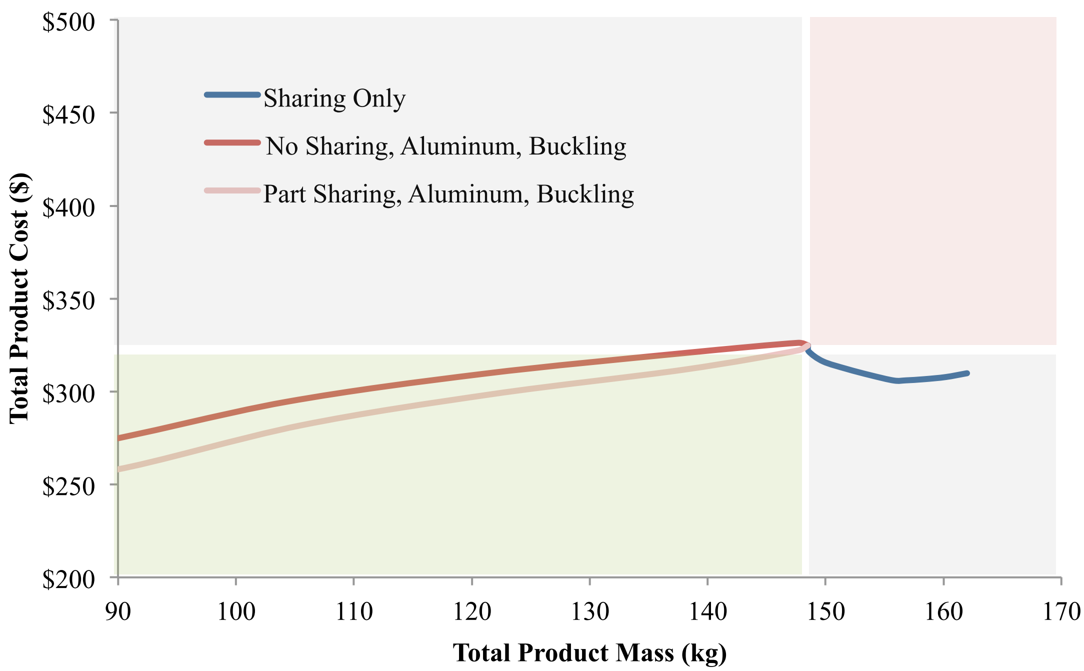

Figure 3-9: Generic Product Cost and Mass Results from Part Sharing and Substitution to Aluminum with Resistance to Buckling as Dominating Structural Criteria

Both material substitutions to martensitic and high strength steels with buckling as the structural criterion show no reduction in mass. This is a product of the fact that buckling resistance is a measure of stiffness and not of strength. Martensitic and high strength steels are stronger than mild steel, but all three have the same stiffness, measured by their modulus of elasticity. The unchanged mass, in combination with increased use of more expensive material that is more difficult to form, means substitution to either martensitic steel or high strength steel leads to increases in total product cost.

The combination with part sharing is different for martensitic steel than for high strength steel. As shown in Figure 3-10, substitution to martensitic steel combined part sharing is well into the lose-lose region. This should be avoided if at all possible. In this combined sharing and material substitution scheme, we observe increased costs and increased mass.

Substitution to high strength steel combined with material substitution does not yield such bad results as substitution to martensitic steel. This substitution is not as expensive, as high strength steel is a less expensive raw material, and is easier to form than martensitic steel, with lower reject rates, faster line rates, etc. As a result, though there is still no mass reduction from material substitution, there is not very much increase in cost. Therefore, when material substitution is combined with part sharing, there is only a small increase in price from the part sharing only. However, this combined part sharing and material substitution should still be avoided if possible. The cost savings from part sharing are reduced with the material substitution for no gain in resistance to buckling, and therefore no mass savings. Therefore, if a designer wished to reduce costs, implementing a part sharing strategy only, without material substitution, would be a better approach.

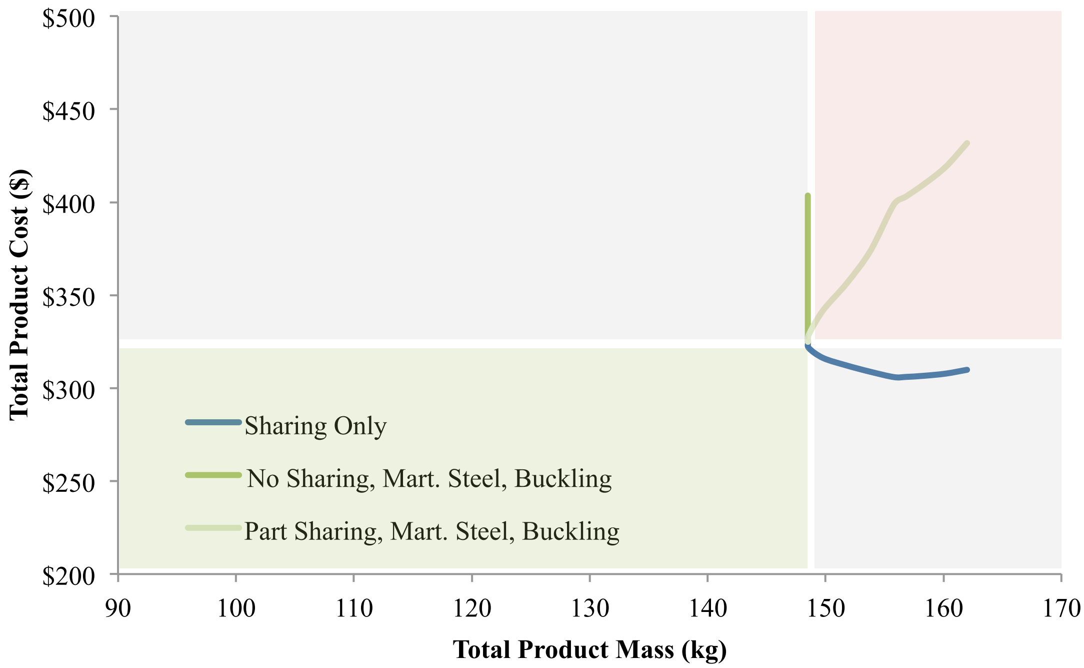

Figure 3-10: Generic Product Cost and Mass Results from Part Sharing and Substitution to Martensitic Steel with Resistance to Buckling as Dominating Structural Criteria

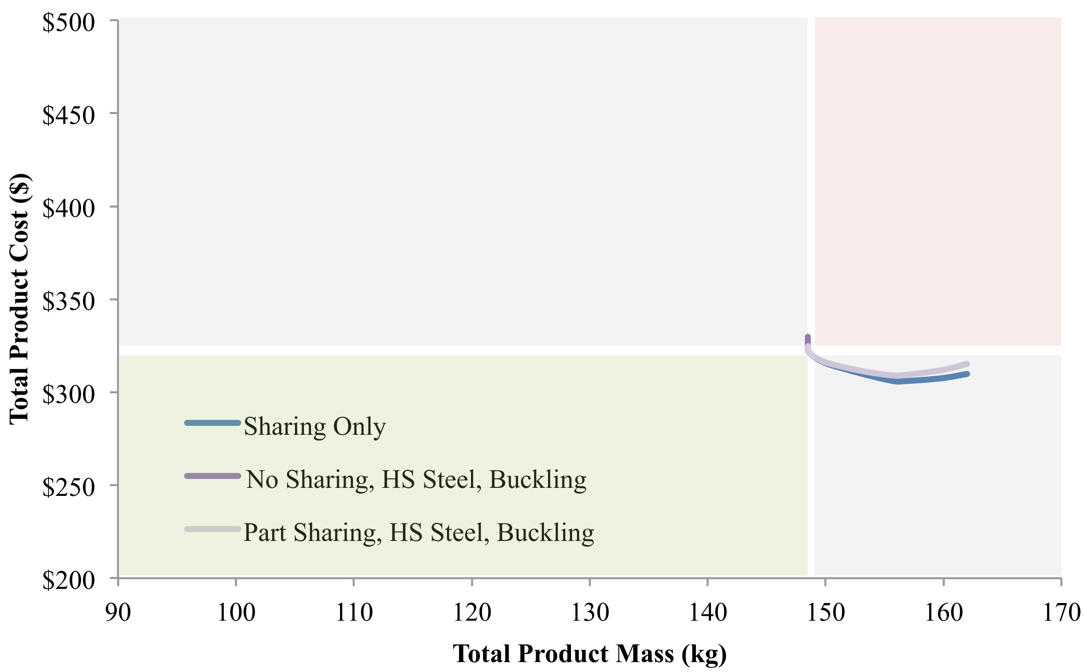

Figure 3-11: Generic Product Cost and Mass Results from Part Sharing and Substitution to High Strength Steel with Resistance to Buckling as Dominating Structural Criteria

From these analyses, we learn that in some cases, for parts that are constrained by buckling failure, any material substitution from mild steel to another steel will not reduce mass. Combining part sharing with these material substitutions does not lead to desirable product attributes, and so these schemes should be avoided.

Material substitution to aluminum has the potential to reduce mass dramatically in parts constrained by buckling. In these parts, combined approaches of material substitution and part sharing are preferred, resulting in reductions in mass at lower cost.

3.5 Cross Criteria Discussion and Conclusions

The analysis of the generic product case demonstrated that there are several situations where jointly implementing part sharing and material substitution will lead to products with lower mass and reduced costs. These occur under the crippling resistance constrained material substitution to high strength and martensitic steels, as well as under the buckling constrained material substitution to aluminum.

The generic product case also demonstrated that the benefits from jointly implementing sharing and substitution may depend on the degree to which sharing occurs. In the crippling resistance constrained substitution to aluminum, the joint material substitution and part sharing approach attains lower mass for less cost than does sharing alone for lower level of sharing, but as sharing increases, this trend reverses.

Additionally, the case highlighted the different product attributes that can be achieved by substituting mild steel to different materials. All materials had slightly different outcomes, though some were more dramatically different than others. For example, the substitution to different steels while maintain equivalent buckling resistance demonstrated no change in product mass, while a change to aluminum under the same constraint showed vast reductions in mass.

Comparing the results from the buckling constrained and the crippling constrained parts analyses illustrates how dramatically the dominating structural criteria can change product outcomes. An example of this is the dramatically different shape of cost vs. mass curve for material changes to aluminum from crippling and buckling. This implies that design strategies should be specific to the structural requirements of different parts when it comes to implementing sharing and material substitution.

Further, parts that fail by different structural mechanisms may be intrinsically different in things like size, scrap rate, and press type. Therefore, a direct one to one comparison may not be the most representative of the reality. It is possible that the effects are being amplified, or diminished by assuming no difference between parts that fail by buckling and parts that fail by crippling. This is left as an exercise for future work.

4. Specific Implementation in Automotive Case

In the previous chapter, a case study of two fictional generic products illustrated possible changes in product attributes results from part sharing and some material substitutions. In this chapter, we perform a similar analysis on real products—three vehicles with a common platform—to evaluate how these findings apply when the complexity of real products are accounted for.

The number of parts, the specific types of parts and number of those types of parts add complexity to the analysis that was not present in the analysis of the generic product. Additionally, looking at real products allows us to observe the true scar mass penalty that is incurred from sharing. Only with real products can we see how functionally equivalent but physically distinct parts will differ, and how much scar mass will be incurred by sharing the part with the higher structural requirements.

4.1 Description of Case

The analysis is performed on three real vehicle models of the same automotive make. These are the make's entry-level sedan, high-end sedan, and cross-over vehicle. These three vehicles were selected for analysis because they are predominately manufactured with stamped mild steel and already share some parts between them. The analysis is done on a subset of the vehicles parts, and is limited to the body-in-white of each vehicle. A summary of the three vehicles and their attributed used in the study are listed in Table 4-1. All three vehicles are assumed to have the same production volume of 75,000 parts per year. This and other assumptions about the operating conditions are listed in Section 7.1 in the Appendix.

	Entry Level Sedan	Cross-Over Vehicle	High End Sedan
Part Count	269	282	280
Mass (kg)	398.5	568.7	402.2
Total Cost ($)	1074.97	1515.02	1078.41

Table 4-1: Summary of Vehicle Data With Costs Estimated Using PBCM

The analysis on the vehicles is very similar to that done on the generic products. As was described in Chapter 3, I first observe the range of sharing and material substitution impacts separately, and then observe the combined range of sharing and material substitution impacts. One large difference from the generic products and the vehicle case is that the cars already share parts across the different variants. The three vehicles have a total of 13% of parts common across all three vehicles. The two sedans have by far the most commonality, with 27% of parts common across the two sedans. The entry-level sedan and the cross-over vehicle have the lowest amount of parts shared, at only 6% sharing across the two. The sharing levels are depicted in Figure 4-1 below. For a description of different methods of measuring sharing, see (Michael DeShawn Johnson 2004; M. D. Johnson and Kirchain 2010).

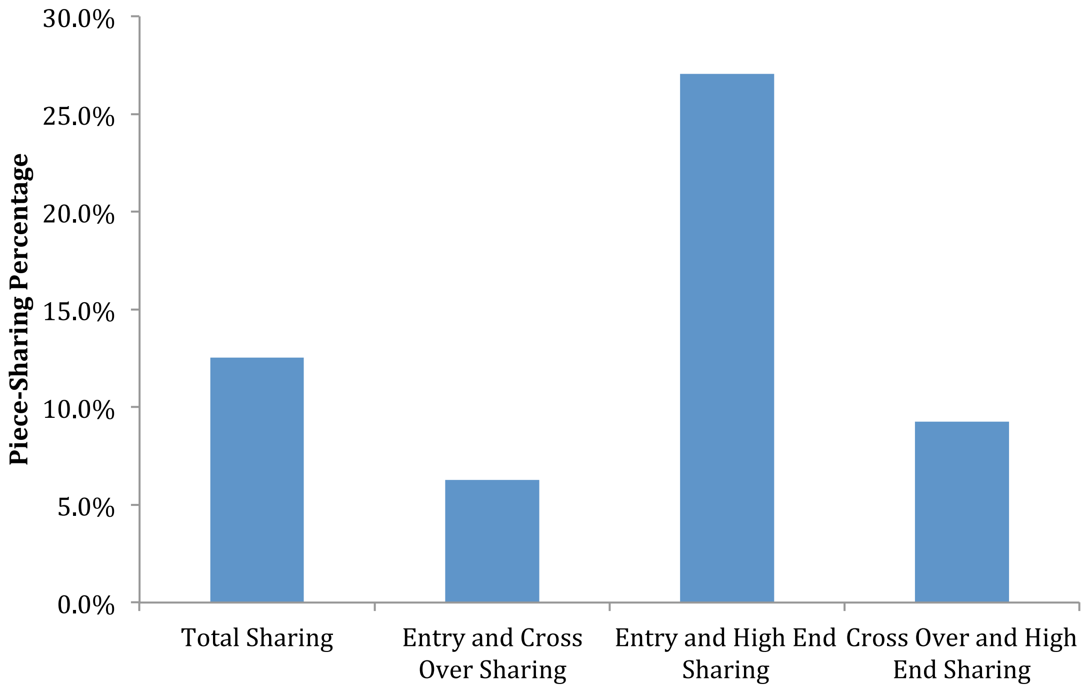

Figure 4-1: Part Sharing Across Vehicles in Automotive Case Study

The sharing of parts validates the idea that these products are good candidates for sharing. However, they limit the ability to observe a full range of sharing options. To get around this, I developed a mechanism to “un-share” the parts.

4.2 Case Specific Mechanisms

The nature of using a set of real vehicles with a predetermined number of parts shared across vehicles raises a challenge that did not occur in the generic analysis. This is a problem of not being able to observe the counter-factual. It is impossible to know the exact characteristics that the shared parts would have had if they had not been shared. However, since we are interested in evaluating the impact of the amount of sharing, it is necessary to “un-share” these parts.

I used the ratios of the different vehicle masses to approximate the characteristics the parts would have had if they had not been designed to be common across multiple vehicles. To do this, I assumed that the heaviest of the three vehicles, the cross over vehicle, had the most stringent structural requirements of its component parts. Accordingly, the high-end vehicle had the second most restrictive requirements. Further, I assumed that the shared part is overdesigned in all but the most restrictive vehicle. Based on these assumptions, to "un-share" the common parts, I would need to remove the unnecessary mass from over design from all but the most constrained part. However, it was necessary to determine what amount of mass to remove.

I created factors that reduce a part's mass to approximate removing the portion of the shared part's mass that was due to scar mass. I did this by summing, for every vehicle, the masses of parts that were shared across only two vehicles, and the parts that were not shared across any of the vehicles. Of this later group, I discounted the parts that did not have exact matches across the three vehicles, as parts with no corresponding parts in the other vehicles may have some intrinsic difference from sharable parts that would bias the results. Using the summed and weighted totals for each vehicle, I calculated the factor that would be necessary to reduce the mass from the cross over vehicle to the other vehicles. Additionally, as it was also necessary to "un-share" parts that were shared across the two sedans only, I calculated the factor required to reduce the mass of the high-end sedan to that of the entry-level sedan. These mass reduction factors for each of the less restricted vehicles are summarized in Table 4-2.

		Most Restrictive	
		Cross Over	High End
Less Restrictive	Entry	.758	.960
	High End	.789	

Table 4-2: Mass Factors for Lower Requirement Vehicle Based

With these ratios, I removed the scar mass penalty from the common parts of the less restricted vehicles. For example, if there is a part common to both the luxury sedan and the entry-level sedan, the luxury sedan has the most restrictive requirements and the less restrictive vehicle is the entry-level sedan. So, to un-share the common part, a new part is created and assigned to the entry-level sedan with a mass that is 96% of the common part.

With all of the originally common parts un-shared, it was possible to proceed with analysis laid out in Chapter 3.

4.3 Case Results

Results from the part sharing analysis demonstrate that vehicle part sharing alone can lead to dramatic reductions in cost. As shown in Figure 4-2, increasing part sharing by moving right-ward away from the leftmost "default" point reduces costs while increasing product mass. At maximum sharing—the rightmost point on the curve—cumulative vehicle costs are approximately half of what they are with no sharing.

The shape of the part-sharing curve is different for vehicles than it was for generic products. In the vehicle case, the cost is monotonically decreasing with increased sharing. At upper extremes of sharing there is less of a cost reduction from additional sharing, but the cost of sharing does not increase with increased mass at any point. Thus, the increased cost from scar mass does not overwhelm savings from reducing fixed costs. There are, however, some significant increases in mass from sharing. At maximum sharing, total mass of the three vehicles is approximately 20% higher than the no sharing case. This increased mass from sharing can be tempered with lightweighting effects of material substitutions.

The shape of this curve is somewhat sensitive to production volume. At higher production volumes, there is less of a cost savings from part sharing as economies of scale are already achieved in the production of the individual vehicle bodies. As cost savings become less important, the scar mass penalty becomes more important, and eventually at very high production volumes the cost is no longer monotonically decreasing with increased sharing. Rather, the costs begin to rise again at high sharing. This change in shape at different production volumes is depicted in Figure 7-2, in the Appendix.

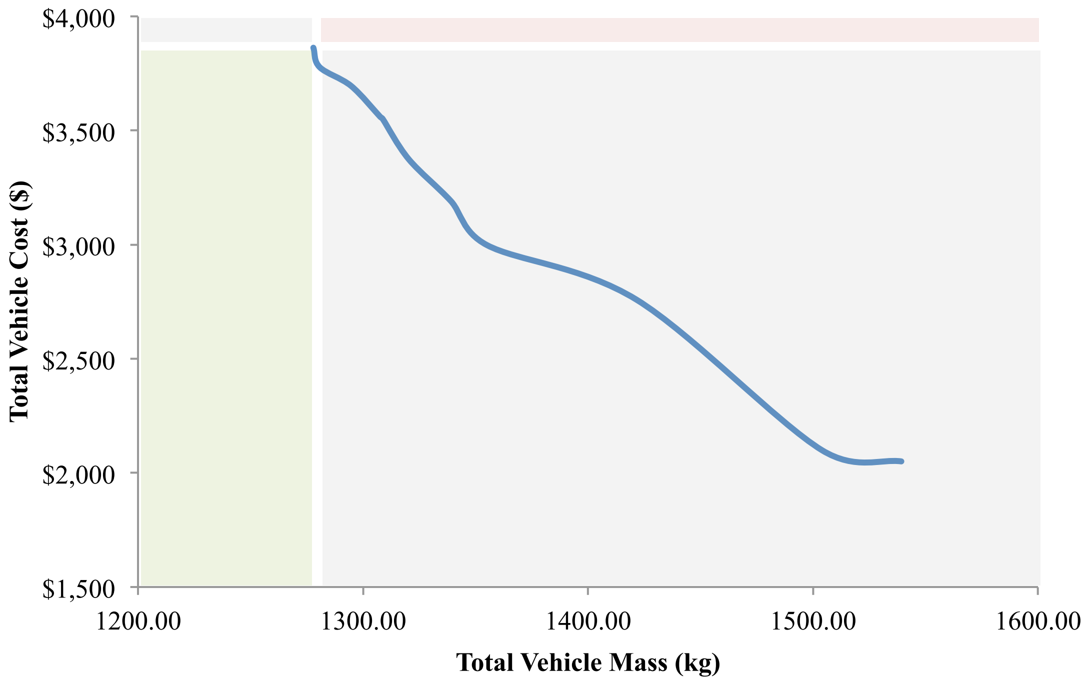

Figure 4-2: Full Spectrum of Attainable Mass and Cost Results from Part Sharing in Vehicles

When crippling resistance is the dominant structural criterion, the improvement in product attributes from combined part sharing and material substitution to aluminum and to martensitic steel is dramatic. Standalone material substitution to aluminum and to martensitic steel substantially reduced vehicle mass, but result in a large increase in cost. When combined with part sharing, however, these material substitutions result in reduced mass and reduced cost.

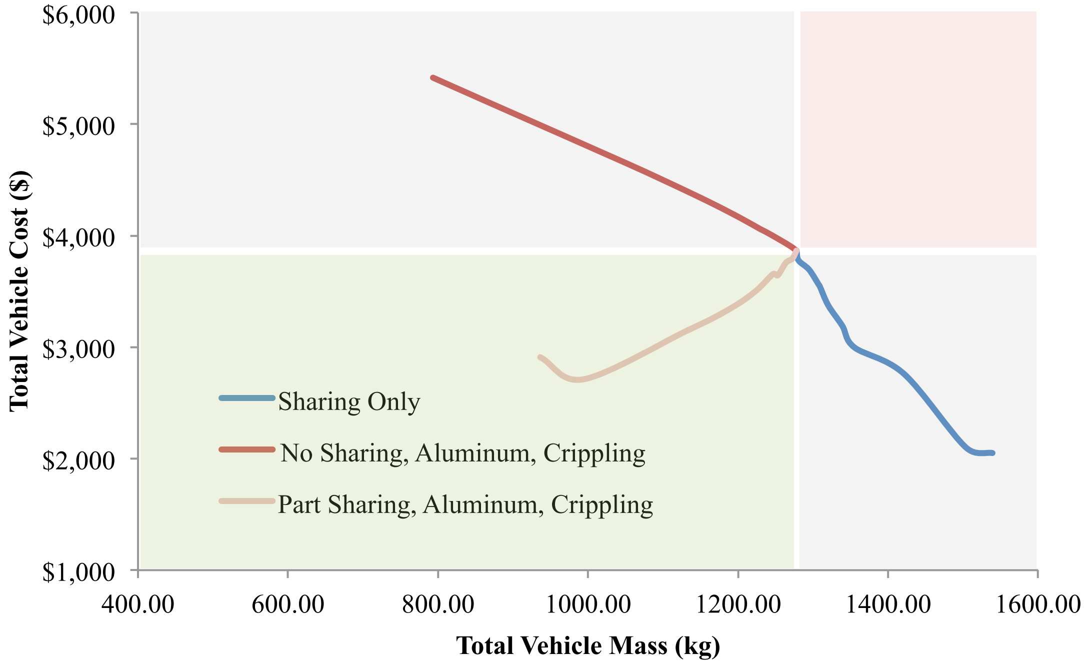

Figure 4-3: Vehicle Cost and Mass Results from Part Sharing and Substitution to Aluminum with Crippling Resistance as Dominating Structural Criteria

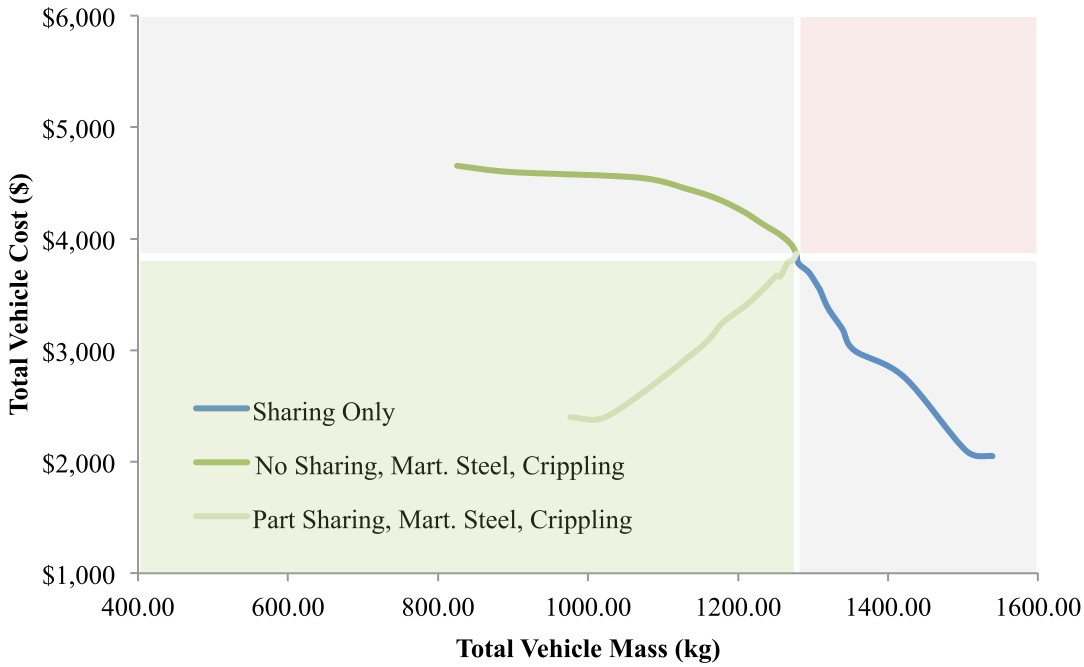

Figure 4-4: Vehicle Cost and Mass Results from Part Sharing and Substitution to Martensitic Steel with Crippling Resistance as Dominating Structural Criteria

The benefits of combining part sharing and substitution to high strength steel are less clear. Depending on the goal of the designer, a design approach of combined part sharing and substitution to high strength steel may be attractive. Such a combination, depicted in Figure 4-5, allows for dramatic reductions in cost with little change in mass. If cost reduction is the objective, this is superior to either the part sharing or the material substitution scheme alone. However, if mass reduction is important to the designer, than such a combined scheme may not be attractive, as the scar mass from sharing cancels out and slightly overwhelms the mass savings from material substitution when the schemes are implemented simultaneously.

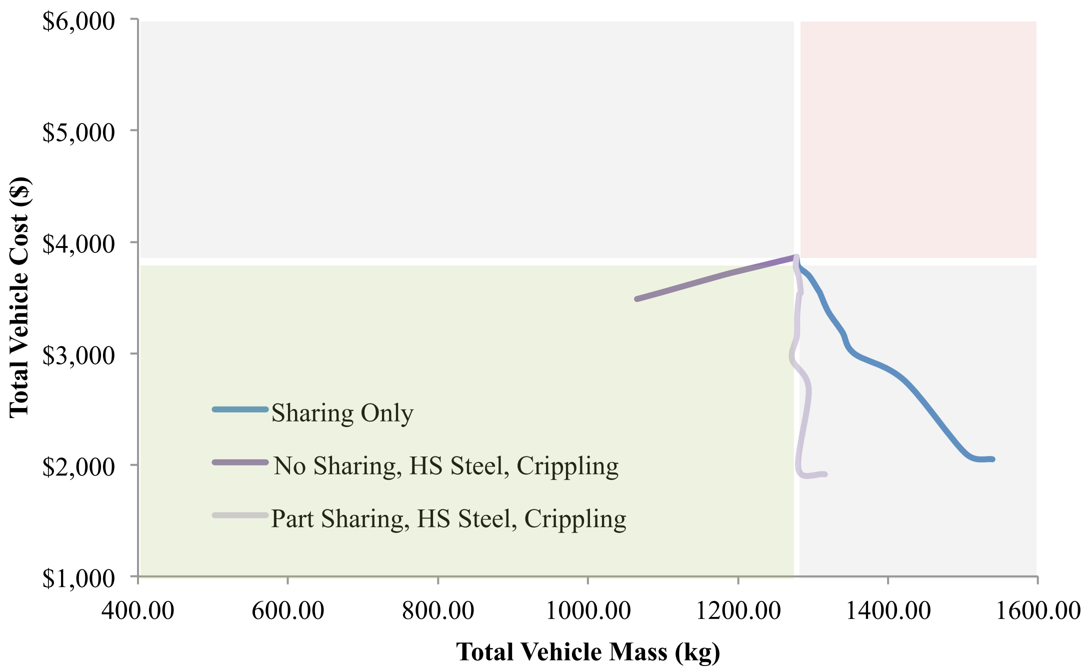

Figure 4-5: Vehicle Cost and Mass Results from Part Sharing and Substitution to High Strength Steel with Crippling Resistance as Dominating Structural Criteria

As it did under a crippling resistance constraint, combined part sharing and material substitution to aluminum under a buckling resistance constraint results in cheaper and lighter vehicles. Figure 4-6 shows that material substitution to aluminum can reduce the mass of the three vehicles from a combined mass of over 1200 kg to approximately 466 kg. The large reduction in mass translates to some small savings in cost, despite the higher material price of aluminum. However, such a large mass reduction is likely a very optimistic estimate. Previous studies of material substitution estimate that mass savings of 40 to 60% are possible from substitution (Cheah 2010). It is likely that the mass savings from substitution to aluminum would be more modest, and as a result have a higher cost. Thus, the design option of material substitution to aluminum is not necessarily desirable if maintaining product cost is vitally important. When combined with part sharing, however, the material substitution to aluminum results in clearly reduced cost with reduced mass. This outcome is plainly desirable.

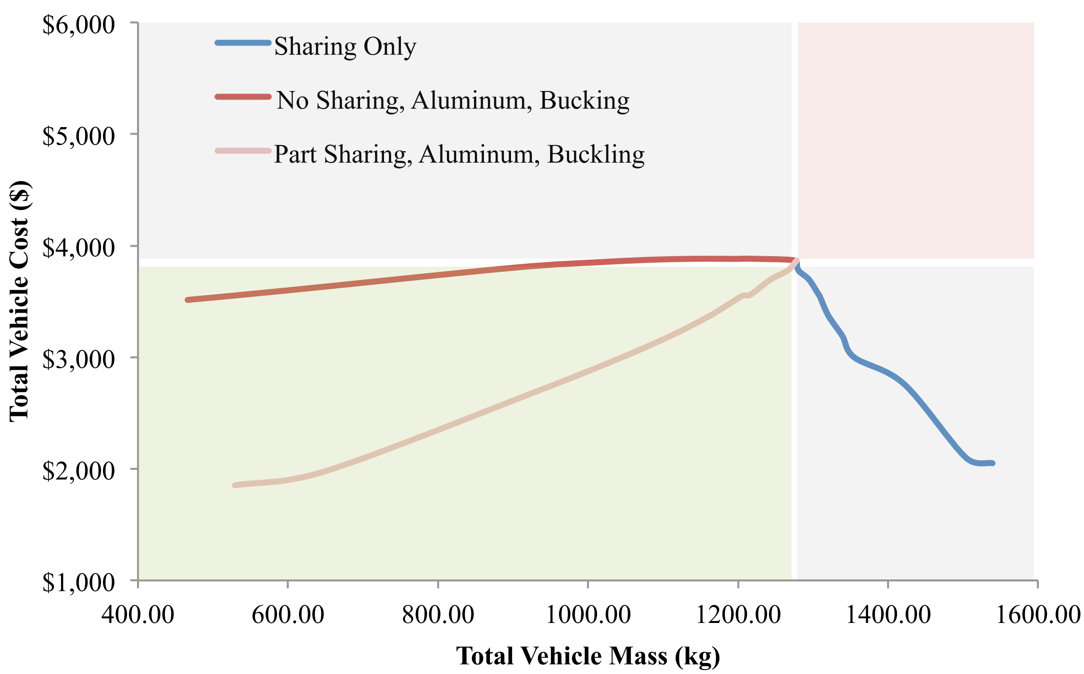

Figure 4-6: Vehicle Cost and Mass Results from Part Sharing and Substitution to Aluminum with Resistance to Buckling as Dominating Structural Criteria

Unlike substitution to aluminum, substitution to martensitic and high strength steels in parts where buckling is the limiting structural criterion results in clearly inferior vehicle attributes. As seen in Figure 4-7 and Figure 4-8, such material substitutions lead to increased cost and no reduction in mass. In both martensitic and high strength steel substitutions combined with part sharing, cost savings from part sharing outweigh the increased costs from material substitution, but even this combined approach is not desirable. If cost reduction is a design objective, then part sharing alone allows for more dramatic reductions in cost for the same increase in mass. If mass reduction is the objective, however, neither part sharing nor material substitution to a higher strength steel is desirable.

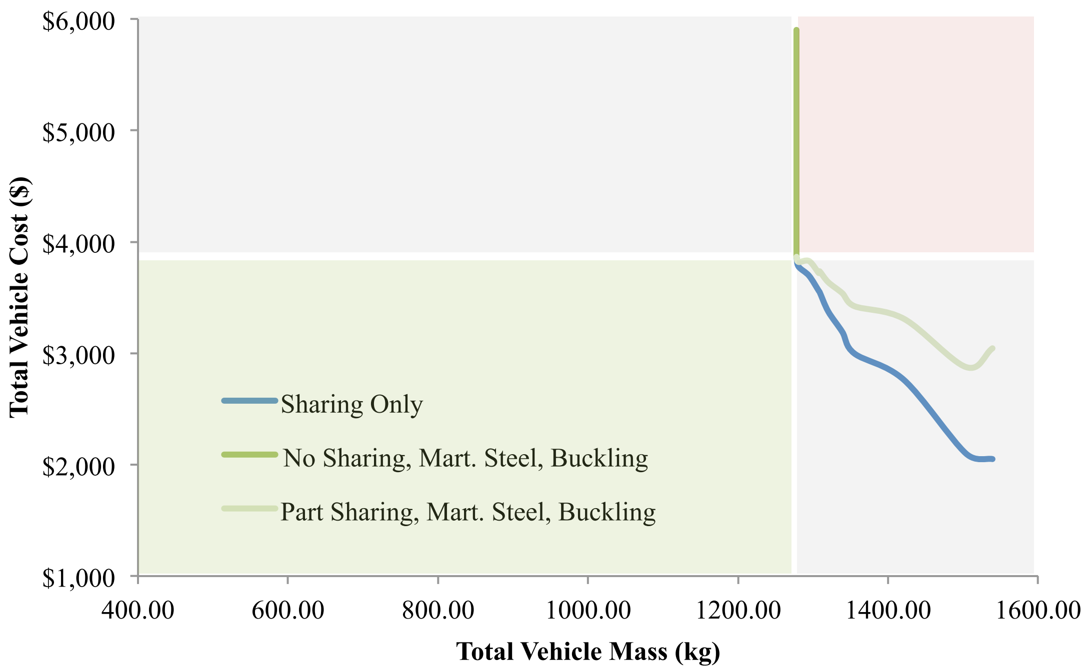

Figure 4-7: Vehicle Cost and Mass Results from Part Sharing and Substitution to Martensitic Steel with Resistance to Buckling as Dominating Structural Criteria

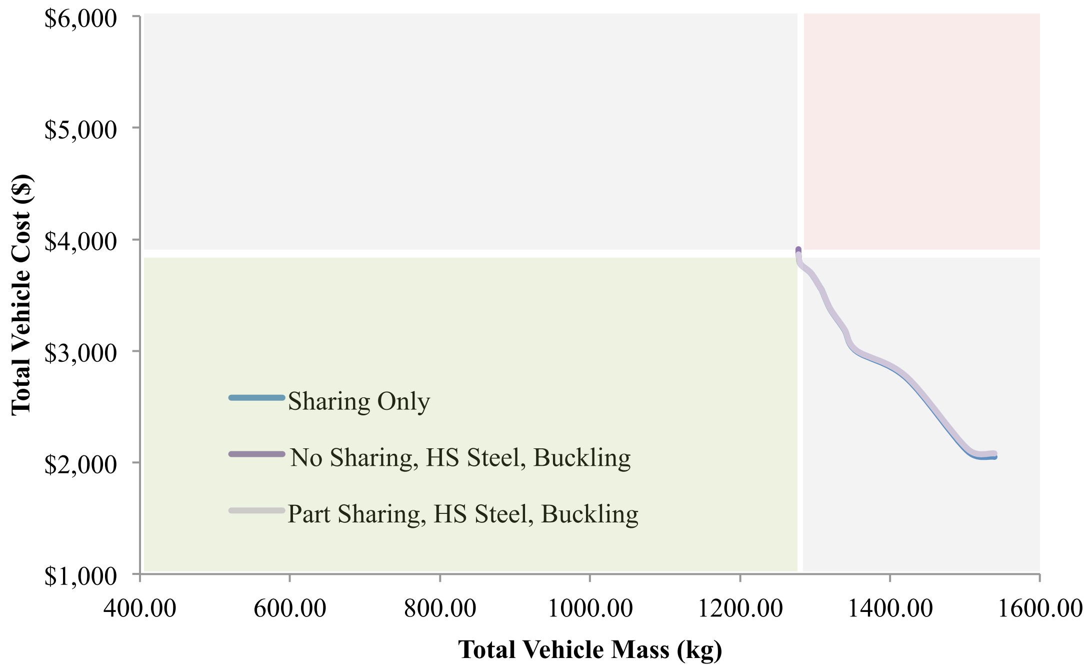

Figure 4-8: Vehicle Cost and Mass Results from Part Sharing and Substitution to High Strength Steel with Resistance to Buckling as Dominating Structural Criteria

4.4 Overall Vehicle Case Results

The analysis of the three vehicle bodies demonstrates that combined implementation of part sharing and material substitution schemes can lead to lighter and less expensive cars. Material substitution to aluminum in both crippling resistance and buckling resistance constrained scenarios demonstrated large benefits from joint implementation with part sharing. Additionally, simultaneous part sharing and material substitution to martensitic steel in crippling resistance constrained parts lead to lighter and less expensive vehicles than did sharing or material changes alone.

Combined part sharing and material substitution does not universally result in superior attributes in cars, however. In the case of part sharing and substitution to high strength steel, it is possible to substantially reduce costs, but the increased mass from part sharing eliminates the mass savings from material substitution. This leads to a potentially attractive design option if cost is the most important design criteria, but if reducing mass is important, combined sharing and material substitution is not necessarily better than material substitution alone. It is clearly better than part sharing alone, however, as reduced costs can be achieved with little change in mass.

Some cases of joint part sharing and material substitution are more definitively undesirable. Part sharing combined with material substitution constrained by buckling to martensitic and high strength steel produces vehicle attributes that are clearly inferior to part sharing alone. The increased cost from higher material cost and more costly forming processes lead to lower savings from part sharing.

5. Discussion and Conclusions

In the preceding chapters, I described the results of various material substitutions in combination with part sharing within a pair of generic products, and three real automotive bodies. The study of both the generic and vehicle cases aim to address the question of whether there are situations in which combining the sharing of parts across product variants and the substitution of baseline materials for those that are lighter weight will result in lighter and less expensive products. I now compare the results of both cases and identify scenarios in which the most favorable design option is to implement concurrent part sharing and material substitution. I then describe how these findings could impact the internal policy making of manufactures.

5.1 Comparing Results from the Generic Product and Automotive Cases

Comparing the case of the generic products and that of the vehicle bodies is helpful in separating the kinds of conclusions about part sharing and material substitution that can be made about a wide range products, and those that are specific to automotive manufacturing. However, as the generic product case was designed with automotive manufacturing in mind, some of the general conclusions may not be universally applicable. Products that are dramatically different from automobiles may not follow the same rules of thumb that the "generic" products exhibit. Despite being loosely based on vehicle body-in-white production, the generic case has results that differ from those of the vehicle case.

One major difference between the cases of the generic product and vehicle body-in-white is the amount of scar mass incurred from sharing. The scar mass in the generic product was set explicitly by the decision to create one product that was 20% heavier than its lighter counterpart. The scar mass in the vehicle case was set implicitly by the selection of the three vehicle bodies. The additional mass from overdesign in the shared vehicles was determined by the different masses of parts with the same function across vehicles. Additionally, whereas the scar mass from sharing was constant at 20% in the generic product case, the amount of scar mass incurred from sharing vehicle components differed from part to part. When implementing sharing, these differences in scar mass affect the resultant total mass of the products as well as their costs.

The impact of unaccompanied sharing (the sharing of parts across the product variants without any material substitution) on the product cost and mass differs in the two cases. In generic product, total cost decreases to a minimum and then rises again as more parts are made common across product variants. In the vehicle bodies, total cost is monotonically decreasing with increased sharing. Increased costs from scar mass can reduce and eventually eliminate savings from sharing, but won't overwhelm the savings as they do in the generic case.

The magnitude of the impact of unaccompanied sharing on cost and mass differs dramatically across the two cases. At maximum sharing, the cumulative mass of the generic products increased 9% from the original, no sharing value. In contrast, vehicle part sharing lead to a 20% increase in mass from the no sharing instance to maximum sharing. Cost differences from sharing were also very different from case to case. The generic product case showed a 6% decrease in total cost from full sharing, while the vehicle case had a huge 47% decrease in cumulative cost at full sharing. These large differences in cost and mass had implications throughout the analyses.

The effects of the differences in cost and mass implications of sharing across the vehicles can be seen in the improvements in cost and mass observed from combining part sharing and material substitution. The cost and mass reductions from concurrent sharing and substitution are much larger in the vehicle case than they in the general product case. However, despite the difference in magnitude of impact, the decision about which design option is preferred is often consistent between the generic product and the real vehicle. There are several instances where the two product cases do not agree on which design option is preferred, however.

In some instances, the superior design decision may differ across the different cases. The scenario where mild steel is replaced with aluminum under a crippling resistance constraint is one in which the preferred design decision is different in the vehicle and generic cases. The generic product case only shows a very slight improvement in cost and mass when part sharing is combined with material substitution over substitution to aluminum alone. Since there is some uncertainty inherent in such a comparison, it is difficult to state which of the design options is preferred. In the vehicle case, however, the combined part sharing and material substitution approach is very clearly preferred to the substitution to aluminum alone. Substitution of mild steel for high strength steel under the constraint of crippling resistance is also a case in which the preferred option may change. In the generic vehicle case, it is possible to reduce mass at a greater savings when material substitution and part sharing are applied jointly. As a result, the combined scheme is likely to be the preferred design approach. In the vehicle case, however, combined material substitution and part sharing does not reduce mass, and only can reduce costs. This may or may not be desirable, depending on how a designer values reduced cost versus reduced mass. Since the substitution to high strength steel under crippling combined with part sharing is not the clearly preferred design option in the vehicle case, this does not match the results of the generic product.

In other instances, the superior design decision remains constant across both cases. For substitution to martensitic steel in a crippling constrained scenario, combined part sharing and material substitution is the best design option in both the generic and the vehicle cases. In substitution to aluminum in a buckling constrained scenario, simultaneous part sharing and material substitution is the favored design option in both cases. In the case of the generic product, however, the difference between unaccompanied sharing and joint sharing and substitution is small. In buckling constrained substitutions to martensitic and high strength steels, the best option is to do no material substitution at all.

Measuring uncertainty within the results of these analyses would help decision-making in cases where differences between design approaches are small. Some of the apparent benefits of combined implementation are small, and may not be statistically significant. Uncertainty may arise from many places, from the input characteristics of the parts and operating conditions to the models used to calculate costs. For example, the inputs of labor, energy, and raw material costs are likely to change over time and may depend on region of production. Also, there is some uncertainty in the definition of a material; the exact yield strengths, moduli of elasticity, and other metrics defining a material are not truly a single constant value, but rather fall within a range. Additionally, there is some uncertainty from using ideal mass factors based on ideal thickness reduction to maintain structural criteria in material substitution. In reality, these low mass factors may not be possible to attain, but the exact values that will be attained from material substitution is not certain. The importance of a metric of uncertainty can be seen in Figure 3-6, where substitution to aluminum and combined part sharing and substitution to aluminum have nearly identical effects on mass and cost of generic products. In this situation, it is difficult to make a conclusion about which of the design options is best. Incorporating a measure of uncertainty is not included in this thesis, and is left as a suggestion for future work in this area.

5.2 Design Suggestions

Some of the results across the analyses appear generally applicable for many products, while other results were specific to vehicles. The results of both case studies exemplify the importance of choosing a design approach that is tailored to the structural criteria of the components under consideration. Parts with different structural requirements benefit differently from a combined part sharing and material substitution approach. As a result, it is important to identify the structural criteria of a part and apply a design strategy that is appropriate for the structural criteria.

It is important to note that these findings are based on the rough capital to materials cost ratio of stamping (in the generic case) and stamping explicitly in the auto case. As a result, the conclusions may not apply to other production technologies, such as casting or extrusion. Exploration of these other production technologies is left as an exercise for future work.

5.2.1 General Design Suggestions

The first design suggestion is to incorporate part sharing when making substitution to aluminum. Combining part sharing to material substitution to aluminum appears to improve outcomes, reducing cost while still enabling reduced mass. This finding is especially true at lower levels of sharing, though the improvement from a material substitution only approach is not always very significant. This suggestion applies for both parts that were most constrained by crippling as well as those that were constrained by buckling. This approach of combining part sharing with substitutions to aluminum is very promising, and has been demonstrated to be effective for both crippling and buckling. However, it should not be applied universally without further investigation of other structural requirements.

A second design suggestion is limited to those parts that are most restricted by their resistance to crippling failure. For parts that fail by crippling, an approach of combined substitution from mild steel to martensitic steel is recommended. The increased strength of martensitic steel and its similar density to mild steel allows for substantial reduction in material usage in a part undergoing this material substitution. This reduction in material requirements translates to a reduced part mass that can overwhelm the scar mass from sharing.

The last design suggestion that applies generally across the range of products studied is specific to parts that are most constrained by their resistance to buckling failure. For parts that fail by buckling, substitution to material with equal stiffness will not change part mass. As a result, substitution to any material that equal stiffness but is more expensive or more difficult to form will increase costs without buying any reduction in mass. These material substitutions should be avoided. Combining such a material substitution with part sharing may result in costs lower than the default position, but not as substantially as would part sharing alone. In these cases, if reducing costs is an important design feature, part sharing may be a desirable design option. However, if increased product mass must be avoided and only substitution to more expensive materials with equivalent stiffness are possible, the preferred design option for a buckling constrained part will be to take no action.

5.2.2 Vehicle Specific Design Suggestions

The suggestions for automotive design from this research include those applicable to general products described above. The suggestion of combining material substitution to aluminum and part sharing holds even more strongly in the vehicle case than for products in general. The benefits of this combined approach are dramatic, with substantial cost and mass savings. As was the case for products in general, any material substitution to martensitic or high strength steel should be avoided if buckling is the constraining criterion. However, in the case that crippling resistance is the dominant structural criterion, substitution to martensitic steel combined with part sharing is recommended.

However, some design suggestions are specific to automotive manufacturing. Substitution to high strength steel alone is a good way of reducing vehicle body costs and mass if crippling resistance is the constraining structural requirement. Combined part sharing and substitution to high strength steel under crippling resistance is demonstrated to be an effective means of reducing costs with little change in total vehicle body mass. Therefore, implementing this material substitution combined with part sharing is recommend if cost reduction outweighs mass reduction as a design objective.

5.3 Policy Implications

The findings of this research have the potential to impact manufacturing policy, especially for products for which low mass is a key design feature. In particular, automotive manufacturers could apply these research findings to help them meet fuel efficiency standards by reducing the mass of their vehicles in a cost-effective manner.

5.3.1 Manufacturing Policy

There are many industries, including automotive manufacturing, whose internal policies may benefit from the findings of this research. Specifically, these are the industries producing products for which low mass and low cost are important design restrictions. Many of the manufactures in these industries could benefit from strategic application of combined part sharing and material substitution schemes.

These firms may instigate policies that directly apply the findings in this research. To do this, firms would put in place policies of implementing part sharing and material substitution where they are demonstrated to be beneficial. As many of the recommendations above are specific to the governing structural criterion of a part, in order for firms to benefit from part sharing and material substitution schemes, firms must put in place policies identifying the structural criteria on the component parts of their products.

Firms may also implement policies of research and development based on the findings. Since there is a demonstration of the importance of structural criteria on the benefits of part sharing and material substitution, firms may develop policies furthering research about the benefits of part sharing under more requirements. Additionally, as firms see the huge impact of spreading tooling costs, demonstrated by the gains from part sharing, they may implement new policy directives investing in tooling that is more flexible and can manufacture different parts. Finally, they may wish to invest in technical improvements that can reduce material price and other production costs through research and development and develop internal policies to meet these objectives.

Though these policy implications are applicable to the automotive industry, there is a greater need for vehicle manufacturers to implement policies guided by the findings in this research. Automotive manufacturers have to meet fuel economy standards, and strategically implementing combined part sharing and material substitution may be a key policy in doing so.

5.3.2 Using Cost-Effective Vehicle Lightweighting to Meet CAFE Standards

All vehicles manufactured for sale in the United States have to meet the fuel efficiency requirements set jointly by the National Highway Transport Safety Administration (NHTSA) together with the Environmental Protection Agency (EPA). These requirements, called the Corporate Average Fuel Economy (CAFE) standards, compel manufacturers to increase the fuel economy (measure in miles per gallon) of their vehicle fleet. For a detailed description of how CAFE standards are set and the regulatory history of CAFE, see the Appendix.

In order for manufacturers to meet the increasingly stringent fuel economy standards they will face with the new CAFE standards and others in the future, they need to pursue fuel-saving technologies, and among them, vehicle lightweighting. There are many different possible fuel-saving technologies that manufacturers consider when trying to meet CAFE standards. These different technologies save fuel by reducing the amount of energy that is discarded through heat and other losses, and maximizing the amount of fuel that is turned into useful output energy. Vehicle lightweighting, or the reduction of a vehicle's mass, improves fuel economy by reducing the amount of energy that is required to overcome the forces opposing the forward acceleration of the vehicle. These forces include rolling and inertial resistance, as well as air resistance (known as drag).

Lightweighting has been shown to create significant improvements in fuel performances. Research demonstrates that a 10% reduction in vehicle mass results in a 5-7% reduction in fuel consumption[4] (Alonso et al. 2012; Bjelkengren 2008; Cheah 2010).

[4] The fuel savings from mass reduction will depend on whether the intention of doing the reduction is to improve or maintain a vehicle's performance. Fuel savings are larger when performance is maintained rather than improved, but requires some vehicle redesign and

In some cases, mass reduction is performed to offset the increased mass of other fuel-saving technologies. For example, advanced powertrains that improve fuel economy also significantly add to vehicle weight. In these situations, it is complicated to isolate fuel savings due to the lightweighting effort, but it is irrefutably assisting in improving fuel economy.

For vehicle lightweighting, the body-in-white (BIW), is the logical place to maximize impact. On average, a vehicle's BIW comprises about 27% of its total mass (Roth, Clark, and Kelkar 2001). Additionally, much of the other components of the vehicle have already undergone significant lightweighting from substitution to plastics and other lighter materials. This makes the BIW an important area to focus on mass reduction.

As discussed above, minimizing mass is an important design objective for vehicle manufacturers. There is an important bound on this objective, however, that the vehicle must still meet the crash criteria and the static and dynamic load requirements determined by safety standards in the industry. Thus the objective of the designer becomes to reduce vehicle mass as much as possible while still meeting these requirements.

Another important objective stems from the fact that the vehicle manufacturers are in the business of making a profit selling cars. Thus, it is important that they minimize their costs as much as possible, while maintaining high revenue. In this they are bound by aesthetic and practical constraints. A set of such constraints is imparted on the vehicle optimization group by the aesthetic designers, who set the vehicle envelope, as well as the "look" and "feel" of the vehicle. Further, the optimization team must maintain distinct

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so is more complex and can be implemented less frequently. The simpler situation is to improve performance, as it does not require redesign. If manufacturers reduce vehicle mass, for example by the substituting some steel parts for aluminum, and they make no other change, then the vehicle's engine will spend less energy overcoming resistive forces and instead deliver more power directly to the wheels. This kind of mass reduction has only modest fuel consumption improvements; a 10% reduction in mass will result in about 3-4% fuel consumption reduction in fuel consumption. The performance remains the same, however, if the mass reduction is followed by a corresponding reduction in engine size. This provides much greater fuel consumption improvements; a 10% reduction in mass will result in about 5-7% fuel consumption reduction in fuel consumption.

vehicle designs to avoid cannibalization of one of their products onto another too similar design.

Vehicle design teams work to minimize cost and mass while meeting safety constraints and aesthetics guidelines. Traditionally, this optimization was relatively straightforward, as removing mass from a predominately stamped steel vehicle reducing production costs. Therefore, the optimal solution was to remove as much mass as possible while still meeting the load and crash requirements.

With the advent of more advanced lightweighting technologies, however, the optimization process has become much more complicated. For example, the substitution of traditional steels for lightweight materials can dramatically reduce mass, but these materials come at an increased cost. Further, the manufacturing processes that are used to form these materials may be dramatically different from conventional stamping techniques, which can lead to additional complexity and costs. These increased costs are difficult to estimate early in the design stage when part characteristics and process decisions are uncertain. As a result, vehicle designers are very interested in improving their understanding of the cost implications of materials substitutions.

This research outlined some heuristics for material selection in the context of part sharing for lightweighting. The results from applying different combined material substitution and part sharing approaches highlight some scenarios that result in lighter and less expensive automotive BIWs. Following these guidelines may help vehicle designers meet the challenges set forth by the CAFE standards.

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7. Appendix

7.1 Cost Modeling Inputs

EXOGENOUS PARAMETERS		
Annual Production Volume	75000	parts/yr
Days per Year	235	days/yr
Wage (including benefits)	$35.00	$/hr
Unit Energy Cost	$0.07	$/kWhr
Interest	8%	
Equipment Life	13	yr
Indirect workers/ Direct Worker (part fabrication)	0.250	
Indirect workers/Line (part fabrication)	1.000	
Building Unit Cost	$1,500	$/sqm
Production Life	5	yrs
Building Life	40	yrs
Downtimes:		
No shifts	0	hrs/day
Worker unpaid breaks	1.5	hrs/day
Worker paid breaks	2.3	hrs/day

Table 7-1: Exogenous Parameters for Cost Estimation

Stamping - Blanking Parameters		
Workers / Blank Line	4	#/line
Blanking Unplanned Downtime	1.5	hr/day
Blanking Maintenance Percent	5%	
Material Loss Percent	1.00%	

Table 7-2: Part Fabrication Inputs for Blanking

Stamping - Press Line Parameters		
Press Line Unplanned Downtime	1.5	hrs/day
Press Line Average Lot Size	5150	parts/lot
Press Line Average Die Change Time	14.5	minutes
Low Volume Tool Life	250,000	hits
Press Line Maintenance Percent	10%	
Press Line Fixed Overhead	15%	% fixed

Table 7-3: Part Fabrication Inputs for Stamping

7.2 Vehicle Cost Modeling Results

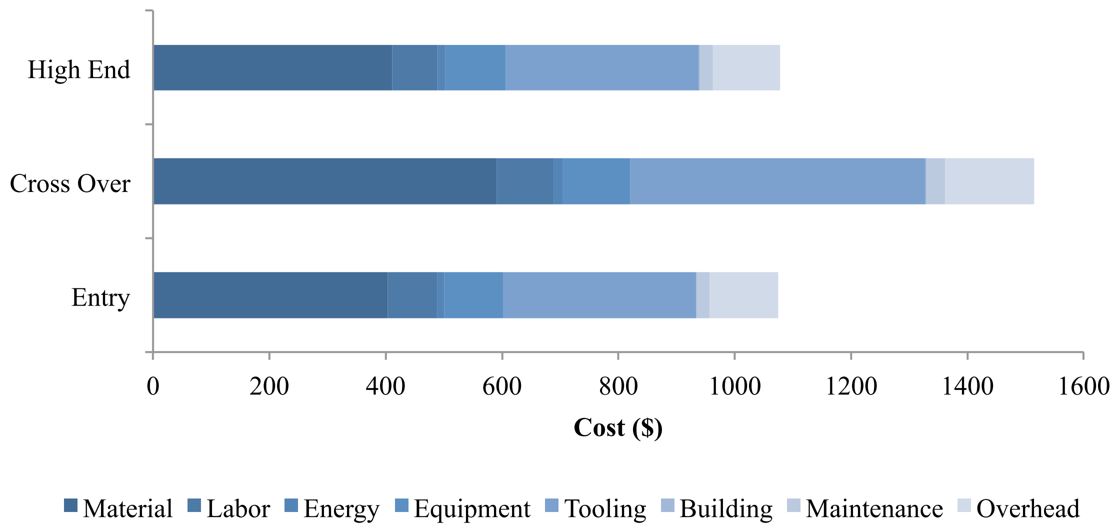

Figure 7-1: Cost Breakdown of Three Automotive BIWs

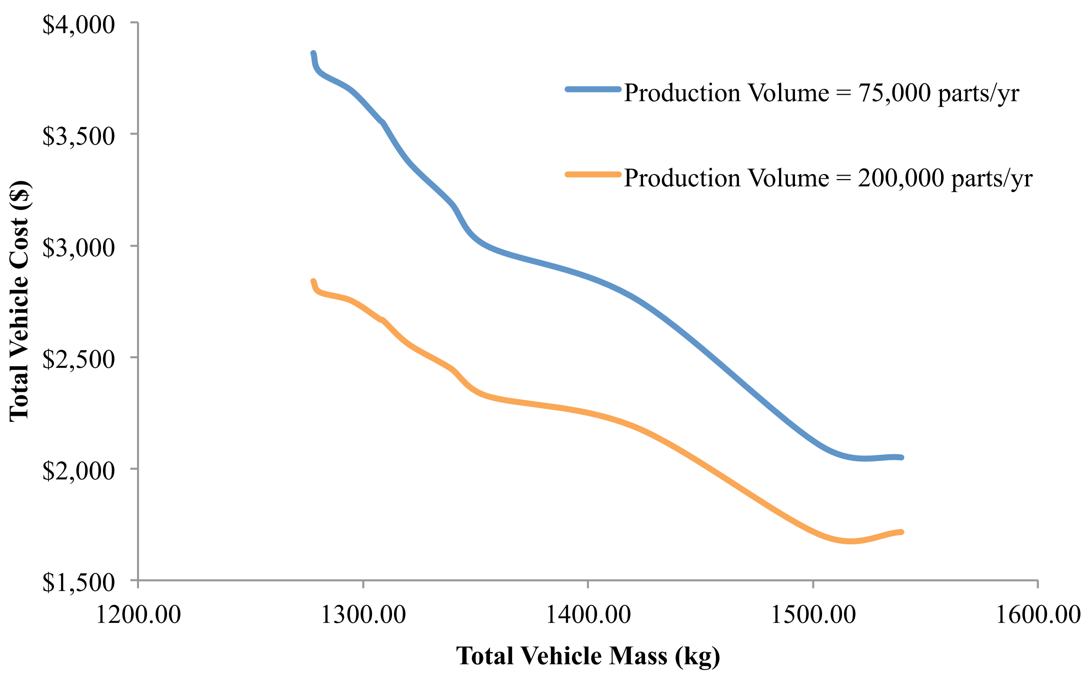

Figure 7-2: Cost And Mass Results From Part Sharing Under Different Production Volume

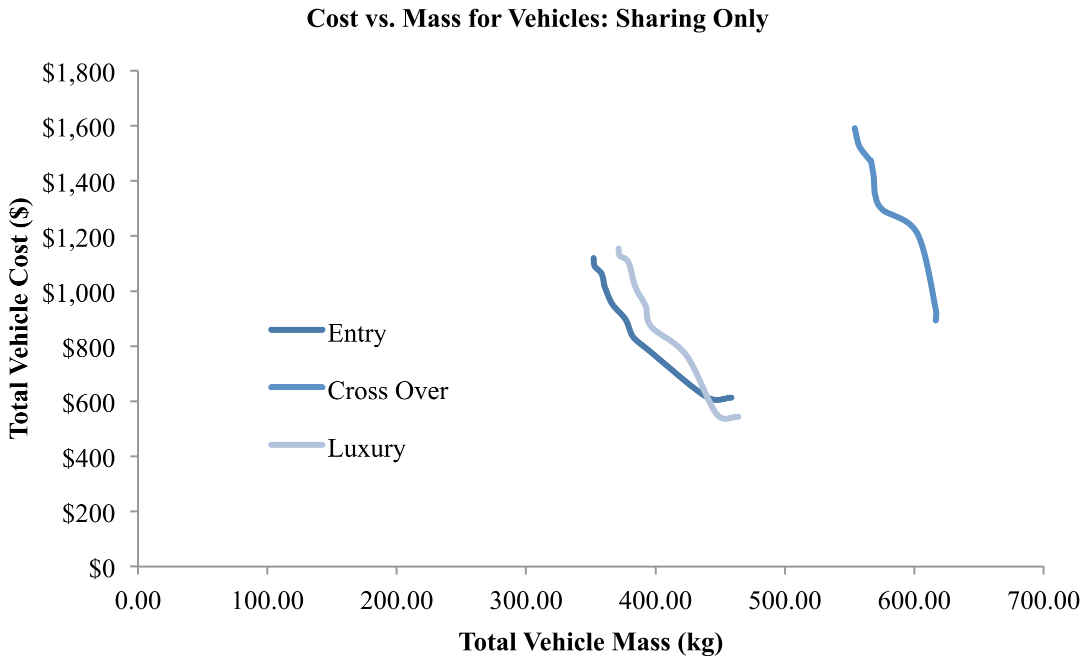

Figure 7-3: Cost and Mass Results from Part Sharing for Three Vehicle BIWs

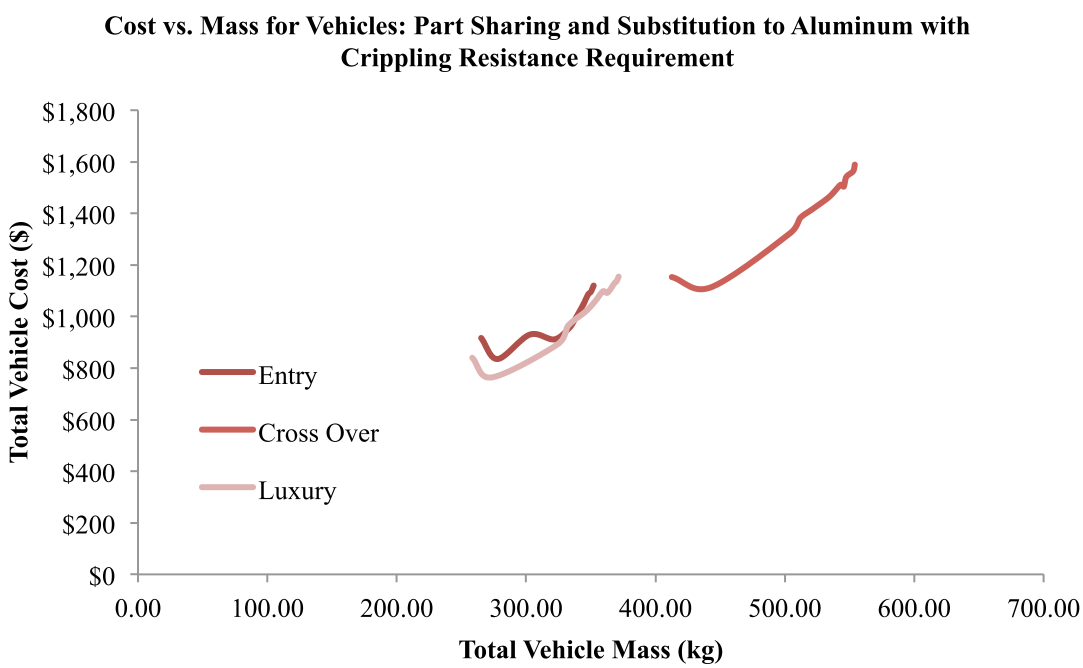

Figure 7-4: Part Sharing and Substitution to Aluminum under Crippling Resistance for Three Vehicle BIWs

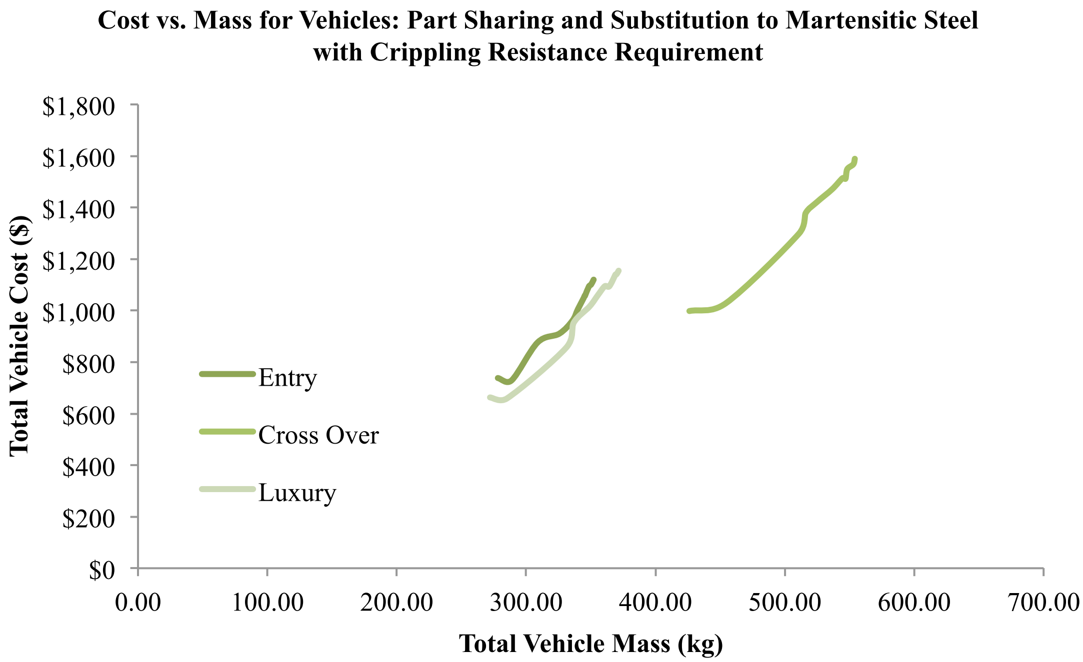

Figure 7-5: Part Sharing and Substitution to Martensitic Steel under Crippling Resistance for Three Vehicle BIWs

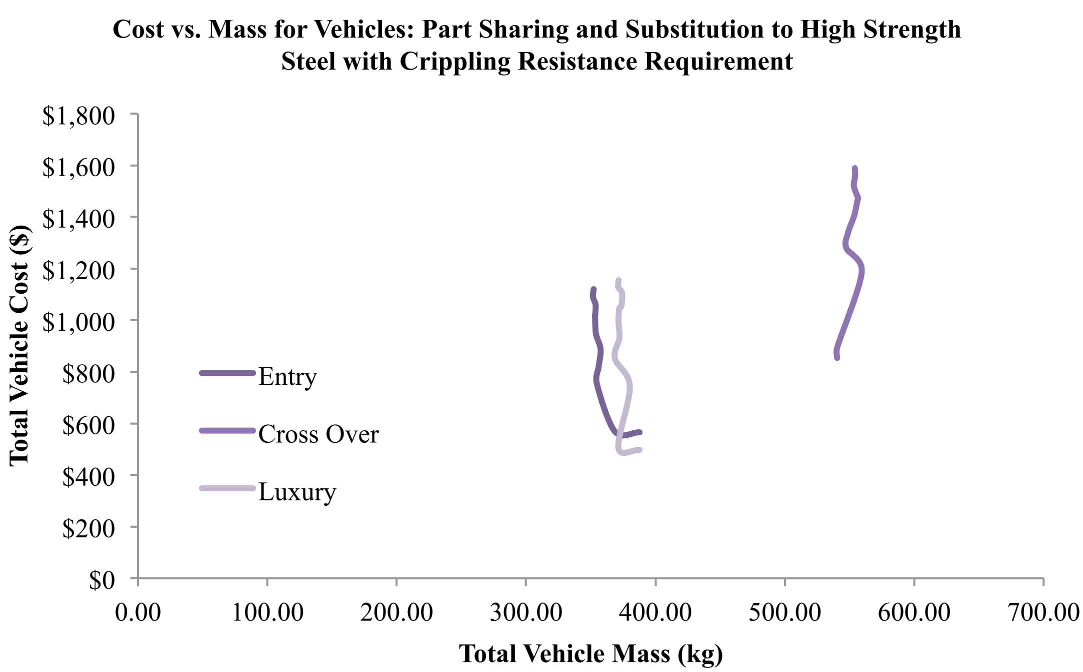

Figure 7-6: Part Sharing and Substitution to High Strength Steel under Crippling Resistance for Three Vehicle BIWs

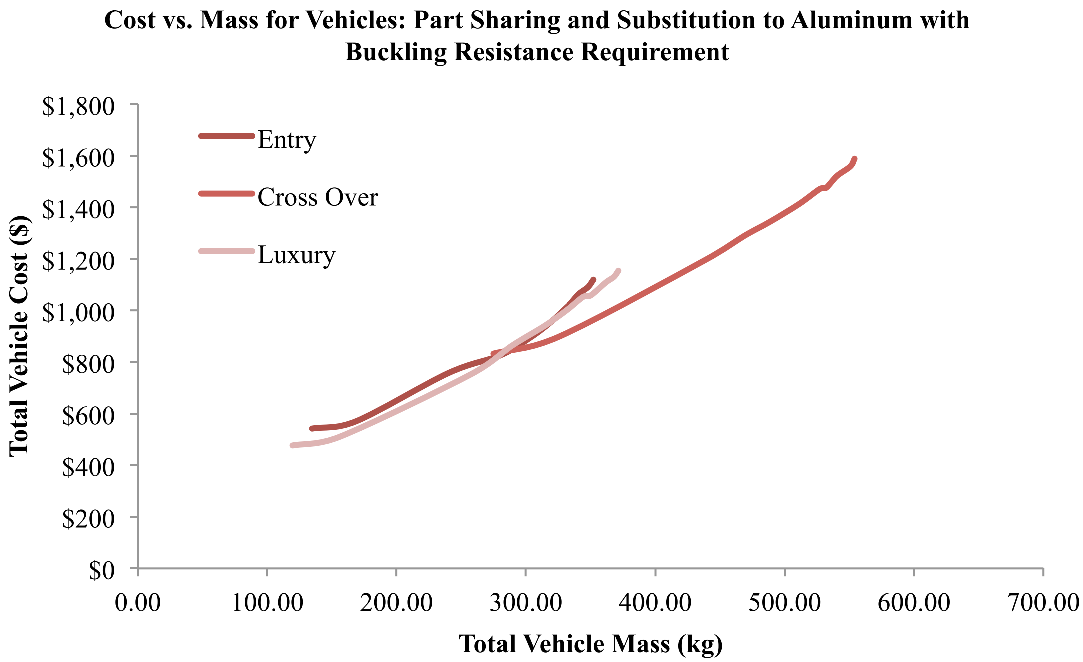

Figure 7-7: Part Sharing and Substitution to Aluminum under Buckling Resistance for Three Vehicle BIWs

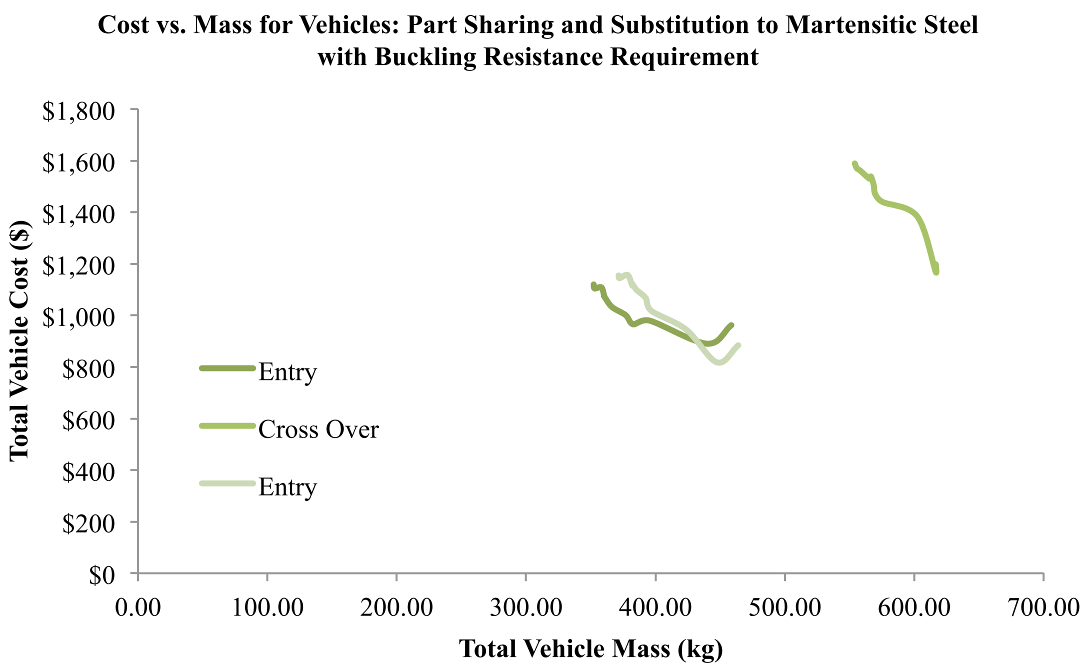

Figure 7-8: Part Sharing and Substitution to Martensitic Steel under Buckling Resistance for Three Vehicle BIWs

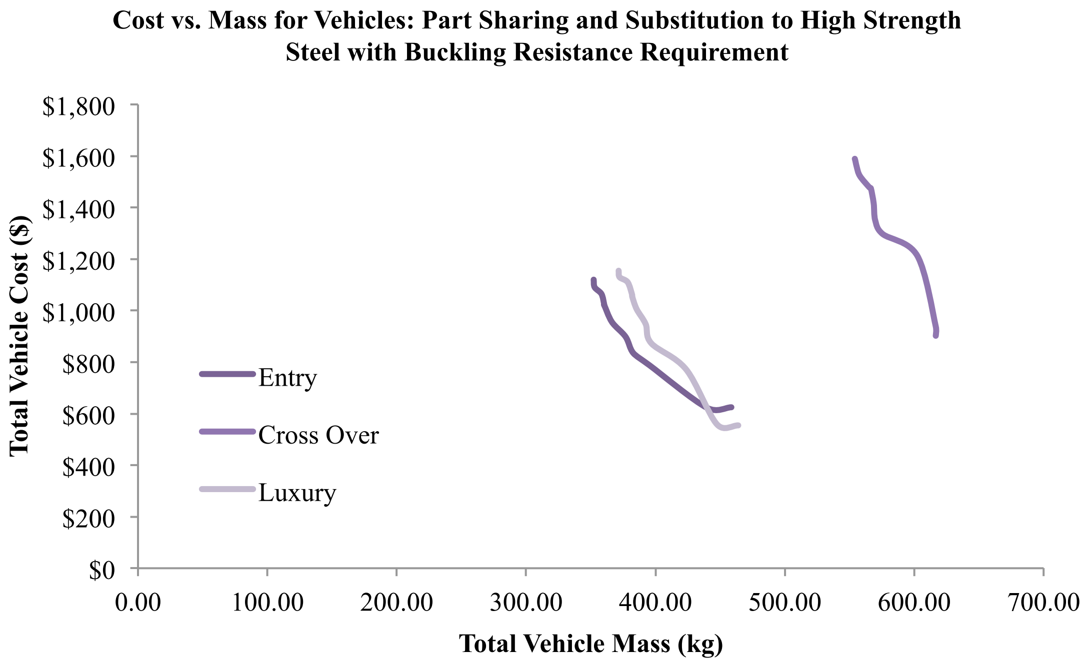

Figure 7-9: Part Sharing and Substitution to High Strength Steel under Buckling Resistance for Three Vehicle BIWs

7.3 Political Economy Analysis and CAFE Standards

When deciding whether or not to drive to, drivers consider two main costs: the time they will spend on the road, and the cost of the gas their trip will consume. The decision these drivers make has greater cost implications than they are incorporating into their decision-making however. As a result of their travels, carbon monoxide, nitrogen oxides, and hydrocarbons will damage local air quality; green house gas emissions will contribute to global climate change; the US government will spend a portion of its middle east military spending on ensuring regional stability to protect domestic oil consumption; drivers will lose many productive hours in traffic; traffic accidents will result in injuries and deaths; the aging highway infrastructure will be worn down further. By leaving these costs out of the equation, the government is *de facto* subsidizing the decisions to drive.

In general, taxes and other forms of government intervention in the free market are justified by the existence of some form of market failure that prevents the free market from achieving the Pareto optimal outcome. In the case of vehicle use, the major source of market failure is in the form of negative externalities—when the costs of a transaction are not fully internalized within that transaction, and instead are borne by some external party. Vehicle use has been associated with many negative externalities (Parry, Walls, and Harrington 2007). The costs of these externalities range from local to global, from smog and noise creation to climate change. The different nature of each of the externalities calls for different types of government intervention.

There are many regulatory interventions that have been proposed that seek to address one or more of the negative externalities associated with vehicle. Of the policy options, there is substantial literature suggesting that the gasoline tax is the best economic instrument to internalize the externalities of vehicle use (Karplus 2011; Austin and Dinan 2005; Portney et al. 2002). Despite its supporters in the academic world, the gasoline tax has not been used extensively. Instead, the regulatory efforts to address the negative externalities of vehicle use show a preference for fuel economy standards. The implication of this preference is that the burden of addressing these externalities is placed upon the vehicle manufacturers in the form of minimum fuel efficiency requirements, and as a result on consumers in the form of increased vehicle costs. In the United States, the fuel economy standards are known as the Corporate Average Fuel Economy, or "CAFE" standards.

CAFE standards were created in 1975 as part of the Energy Policy and Conservation Act. These fuel economy standards and were partially presented as an alternative to the increasingly politically infeasible gasoline tax as a means to reduce gasoline demand. CAFE standards were created in response to increasing security concerns surrounding oil dependence, notably the Arab oil embargo and energy crisis of 1973.

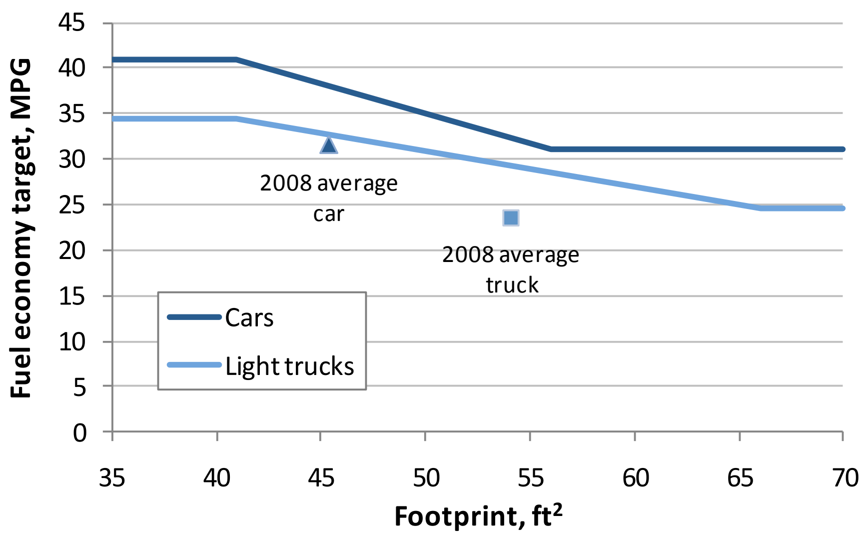

Figure 7-10: Most Recent (MY2016) CAFE Standards Curve[5]

Explicit environmental goals for CAFE standards were added in 2007 with the passing of the Energy Independence and Security Act. The efficiency levels were successfully increased in 2007, again in 2010, and most recently in 2012. The Energy Independence and Security Act of 2007 requires NHTSA to set up attribute-based standards of fuel economy. Though it has changed in the past, the attribute that the most recent CAFE standards are based on is the vehicle's footprint. A vehicle's footprint is the product of the distance between its front and rear axels and its track width—roughly the area of the rectangle connecting its four tires ("H.R. 6-- 110th Congress: Energy Independence and Security Act of 2007" 2007).

The way the standards are set, vehicles with smaller footprints have more stringent requirements for their fuel economy than do vehicles with larger footprints, as we see by the downward sloping curve in Figure 7-10. We can also see from Figure 1 that the line of fuel economy target vs. footprint does not extend all the way from a zero footprint or to zero miles per gallon—it follows a constrained linear mathematical function.

[5] Figure adapted from (Cheah 2010)