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Modeling Costs and Fuel Economy Benefits of Lightweighting Vehicle Closure Panels

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ABSTRACT

This paper illustrates a methodology in which complete material-manufacturing process cases for closure panels, reinforcements, and assembly are modeled and compared in order to identify the preferred option for a lightweight closure design. First, process-based cost models are used to predict the cost of lightweighting the closure set of a sample midsized sports utility vehicle (SUV) via material and process substitution. Weight savings are then analyzed using a powertrain simulation to understand the impact of lightweighting on fuel economy. The results are evaluated in the context of production volume and total mass change.

INTRODUCTION

The need to improve fuel economy is becoming increasingly important for automakers. Not only has the price of oil—and therefore the price of gas consumers pay at the pump—been increasing over the past several years [1], the public is also becoming more conscious of environmental change and global warming [2, 3]. Vehicle lightweighting represents one of several design approaches automakers are currently evaluating to improve fuel economy. Lightweighting is typically accomplished by downsizing, integrating parts and functions, materials substitution, or by a combination of these methods. The end goal is to reduce vehicle mass, which in turn improves fuel economy as well as vehicle performance.

This work focuses on the methodology behind determining the relative costs and corresponding fuel economy benefits of lightweighting the closure subsystems of a theoretical midsized SUV by substituting lightweight materials and their appropriate processes for stamped mild steel. Manufacturing cost is analyzed by modeling the forming of the entire closure body-in-white subsystem, including inner and outer panels and any reinforcements, and the joining of all its components into a subassembly which can be installed in an automobile assembly plant body shop. The goal of the cost and fuel economy benefit analysis is to identify cost-effective approaches to lightweighting a representative SUV; the preferred approach will depend on the context under which the calculations were performed.

SCOPE

The closure set for a midsized SUV was selected as the design baseline for this study. Closures were chosen because changes in their design have minimal impact on the design of the remainder of the vehicle and because they can be modified later in the vehicle development process than the body structure. The cost of manufacturing and assembling the entire closure subsystem, including panels and reinforcements, was modeled using process-based cost models (PBCMs) [4]. Table 7 in the appendix lists all the parts used in the baseline closure subsystems. The study takes the entire SUV closure set into account—that is, one hood, two front fenders, two front doors, two rear doors, and one liftgate.

To illustrate the methodology for determining the costs and fuel economy improvements gained by lightweighting closures, stamped mild steel closures for the representative vehicle were first chosen as the baseline design. Lightweight designs manufactured from high strength steel, aluminum, and magnesium were then developed by scaling the mild steel baseline design. The cost for each alternative design was then analyzed using PBCMs. Since the new designs employ different materials from the baseline design, manufacturing processes were also changed accordingly. Reinforcements were assumed to be manufactured from an appropriate material—most often the same material as the panel to which the reinforcement was attached. The notable exception is the intrusion beam which was manufactured from extruded aluminum, even for the magnesium designs. Given the reinforcement's material, the most cost-effective manufacturing process for each reinforcement was then chosen. Materials and manufacturing processes included in this study are listed in Table 1. Finally, a powertrain model was used to analyze fuel economy improvement gained from lightweighting.

Table 1 Materials and manufacturing process combinations

Manufacturing Process	**Steel**	**Al**	**Mg**
Stamping	x	x	
Tailor welded blanks	x		
Die casting			x
Extrusion		x	x

METHODOLOGY AND DESIGN ASSUMPTIONS

The baseline SUV used for the study is a representative body on frame production mild steel design. Lightweight design variations used to illustrate the methodology were chosen to incorporate three materials and a variety of processes (Table 2). The first lightweight design, A-HSS, was based on discussions with high strength steel experts and the work of ULSAC and the Auto/Steel Partnership [5, 6]. To accommodate the deep draws required by door and liftgate inner panels and the limited formability of high strength steel sheet, tailor welded blanks (TWBs) of high strength steel for the hinge area and mild steel for the remainder of the panel were assumed. In the stamped aluminum closure set, B-Al, multi-piece designs for the door and liftgate inner panels were used instead of TWBs to deal with the same processing challenge. A four-piece design was used for the front door and three-piece designs for both the rear door and liftgate. Finally, the magnesium die cast design, C-Mg/Al, assumed that a single-piece liftgate inner panel is feasible, but that the door inner panels were cast in two pieces because of the header constraints. These designs, although based on discussions with experts, are simply for the purpose of demonstrating this paper's methodology in a realistic context and consequently are *not* optimized.

Table 2 Summary of closure material and manufacturing processes

Closure Set ID	**Inner panels**	**Outer panels**	**Rein-forcements**
Base	Mild steel stamping	Mild steel stamping	Mild steel stamping
A-HSS	HSS (TWB) stamping	HSS stamping	HSS stamping
B-Al	Al stamping	Al stamping	Al stamping, Al extrusion
C-Mg/Al	Mg die cast, Al stamping	Al stamping	Al extrusion

PANEL AND REINFORCEMENT MASSES AND DIMENSIONS – Design details pertaining to product shape for the mild steel closures came from a theoretical midsized SUV. Corresponding blank sizes were chosen to give a trim scrap percentage target of approximately 40%. Model inputs, including baseline part weights, can be found in the appendix (Table 7).

Lightweighted sheet metal designs for high strength steel (A-HSS), aluminum (B-Al), and magnesium (C-Mg/Al) were scaled from the mild steel design. To maintain bending stiffness, non-ferrous panels and reinforcements were up-gauged according to Chang [7]:

$$t_{LW} = t_{MS}\sqrt{\frac{E_{MS}}{E_{LW}}}$$

E represents Young's modulus and t the panel thickness. A stiffness-only criterion, however, does not permit any down-gauging for high strength steel parts because both mild and high strength steel have approximately the same modulus. Nonetheless, the gauges of panels and reinforcements in the A-HSS design were reduced by approximately 12%, provided they did not fall below 0.65 mm, the minimum gauge used in this study, and they were not the mild steel portion of tailor welded blanks. Panel and reinforcement masses (m) were also reduced accordingly, based on the new panel gauge and the respective densities (ρ) of the baseline and lightweight material; blank size was left unchanged from the mild steel baseline design.

$$m_{LW} = m_{MS}\left(\frac{\rho_{LW}t_{LW}}{\rho_{MS}t_{MS}}\right)$$

Sheet aluminum was used for reinforcements in designs B-Al and C-Mg/Al, with the exception of the intrusion beam and the beam brackets (used to anchor the beam to the door panel) which were extruded. The die cast door inner panels and extruded magnesium reinforcement designs were based on an internal design study.

A summary of panel and reinforcement masses can be found in Table 3; all numbers are for the entire closure set: four doors, two fenders, a hood, and a liftgate. Table 8 and Table 9 in the appendix contain detailed information on closure material, manufacturing process, and mass, broken down by individual part.

CLOSURE ASSEMBLY – Assembly for the lightweight closure designs was also modified to accommodate the use of lightweight materials. For instance, aluminum suffers from cracking when die hemmed because the process only introduces strain perpendicular to the edge of the hem; thus roller hemming was chosen as a substitute process. Additionally, welding methods vary and in some cases, are replaced by other joining methods such as mechanical fasteners or self piercing rivets.

Table 3 Panel and reinforcement mass assumptions breakdown (in kilograms) of closure designs

Closure Set ID	**Inner Panels**	**Outer Panels**	**Reinf.**	**Total Mass**
Base	54.7 kg	52.1 kg	32.5 kg	139.3 kg
A-HSS	53.1 kg	46.8 kg	28.0 kg	128.0 kg
B-Al	41.6 kg	29.8 kg	13.2 kg	84.7 kg
C-Mg/Al	39.2 kg	29.8 kg	7.2 kg	76.3 kg

Table 4 Assembly methods used in the model

Steel assembly methods	**Al / Mg assembly methods**
Spot weld – robot Spot weld – hard auto Pedestal adhesive Die hemming	Spot weld – pedestal Spot weld – robot Spot weld – hard auto Friction-stir welding Laser welding Fastening Riveting Pedestal adhesive Roller hemming

Table 4 presents a summary of assembly processes used by the closures in this model. Comprehensive assembly sequences for the baseline and lightweight designs can be found in Table 10 in the appendix. The assembly sequence is broken down into subassemblies that are done at different stations. For closures, these subassemblies are typically (1) outer panel plus reinforcements, (2) inner panel plus reinforcements, and (3) marriage of the two panels. Using a multi-piece inner panel requires an additional subassembly.

Mild steel assembly welding requirements were based on a review of production assemblies for vehicles of similar size as the SUV used in this case study. Panel marriage was accomplished by die hemming. High strength steel closures were assumed to use the same assembly sequence as the mild steel closures. The assembly for aluminum closures is similar to that for the steel closures but requires 20% more spot welds. Also, roller hemming is used in place of die hemming for both the aluminum and magnesium designs. Sheet magnesium, requires further changes in the assembly processes: instead of welds, a combination of fasteners and rivets are used to join the magnesium reinforcements to the inner panel. Rivets were also chosen to join the outer panel and its reinforcement [8].

COST MODELS

PROCESS-BASED COST MODELS – PBCMs are a systematic way to evaluate the cost of a specific manufacturing process. Each model takes the manufactured part as an input and determines process requirements such as the press tonnage and number of dies necessary to form the part. These requirements in turn are combined with operational conditions for the plant (e.g. number of shifts and downtime) and costs (e.g. raw material price and labor wage) to calculate the unit cost of the input part. The cost models are designed to be predictive, which makes them useful in comparing novel technologies or design concepts that have not yet become standard for a company.

In this study, PBCMs are used to predict and compare the cost of the baseline and lightweight closure subsystems. Cost models are available for the following manufacturing processes:

- Stamping
- Tailor welded blanks
- Die casting
- Extrusion
- Assembly

Although the models strive to be as accurate as possible, several assumptions are required, including reject rate, labor wage, and materials price. Table 5 lists the material price assumptions used in this study. The goal was to choose industry standard numbers. Material-specific process assumptions were also made, such as higher tooling costs for aluminum and high strength steel stamping (20% and 10% greater than that of mild steel, respectively), a slower line rate for aluminum stamping (20% slower), and a higher reject rate for high strength steel stamping (4% vs. 0.5% for mild steel). Experts contacted differed on whether high strength steel stamping required a slower line rate than mild steel stamping; this study elected to assume equal line rates. Finally, individual process steps can be turned on or off according to the material being formed. For example, a large fraction of stamped aluminum outers require finishing in order to achieve a Class A surface, and all magnesium parts require an extra coating step for corrosion protection.

ASSEMBLY MODEL – The assembly model predicts the cost of joining any number of parts when given the joining process for each pair of parts or subassemblies and the "quantity" of that process. Consequently, it employs a different approach to calculating cost from the traditional process-based cost models, which focus on a single manufacturing process with a fixed process flow. Components can often be assembled in various ways and with different levels of automation. The cost to assemble a multi-component subassembly, such as a closure panel, is evaluated using a proposed serial line generated by the model from the inputted joining processes and is dependent on the desired line rate. The model then attaches a cost to the final most cost-effective iteration. Varying the production volume causes the model to generate a revised assessment of the line design and thus a revised cost estimate [9].

Table 5 Raw material and scrap assumptions

Material	**Representative Price [$ / kg]**	**Scrap price [$ / kg]**
Mild steel sheet 140 MPa	$1.00	$0.30
HS steel sheet 210 & 280 MPa	$1.10 - $1.15	$0.30
Al blanks 5000 & 6000 series	$3.75 - $4.50	$1.70
Al ingot	$2.22	$1.51
Mg ingot	$2.53	$1.75

POWERTRAIN MODEL

Powertrain modeling employed a proprietary model to generate curves of fuel economy improvement as a function of weight savings for the representative SUV. Engine map and transmission data from an equivalent vehicle were used as model parameters. This validated model is a powerful tool for simulating performance and fuel consumption [10, 11]. One key advantage this model has over straight line calculation is that it allows the user to tune the engine for fuel economy or acceleration improvement at a fixed weight savings, as well as to see the impact of engine adjustments on both parameters.

ANALYZING DESIGNS

Once the cost and fuel economy are modeled, the cost premium, Δ\$, or the cost difference of using alternative materials, is calculated for each lightweight design. This is, however, an imperfect comparison since while one design may cost more, it may also correspond to higher weight savings and therefore be just as favorable as a less expensive design with lower weight savings. In this light, Δ\$ / Δkg, the cost per kilogram of weight savings, and Δ\$ / Δmpg, the cost per MPG improvement, are more useful metrics for comparing lightweight designs when the ultimate goal is improving fuel economy.

The preferred closure design for lightweighting using this methodology is expected to be context-dependent: for instance, some designs are more favorable at lower production volumes or at lower labor wages. Additionally, the "best" design will depend on the vehicle program's priorities and goals as well as on market dynamics. As a case in point, designers may opt to use more magnesium instead of aluminum if they strongly believe the price of the latter will continue to rise. This illustrates the importance of sensitivity analysis in identifying how changes in process conditions, operational conditions, or factor costs, such as production volume, a higher aluminum price, or lower labor wages, can affect which design is preferred. For the purposes of this study, cost is analyzed as a function of production volume with the PBCMs.

RESULTS

WEIGHT SAVINGS – Table 6 lists the weight savings of each lightweight closure set design relative to the mild steel baseline representative design. The mass of each design was estimated by scaling the baseline parts, as described under Methodology and Design Assumptions. A breakdown of design mass by individual component can be found in the appendix (Table 9).

Table 6 Weight savings (in Δkg) of lightweight designs

Closure set ID	A-HSS	B-Al	C-Mg/Al
Inner panels	1.6 kg	13.1	15.5
Outer panels	5.3 kg	22.3	22.3
Reinforcements	4.5 kg	19.3	25.3
Wt savings	11.4 kg	54.7	63.1
% of baseline wt[1]	8.2%	39.2%	45.3%

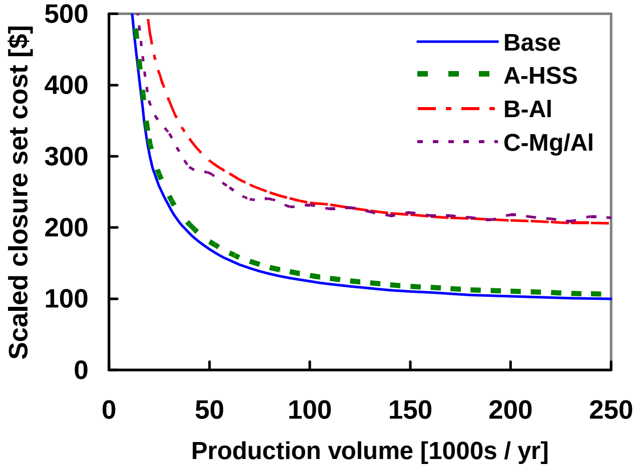

Figure 1 Scaled unit cost of representative closure set as a function of production volume

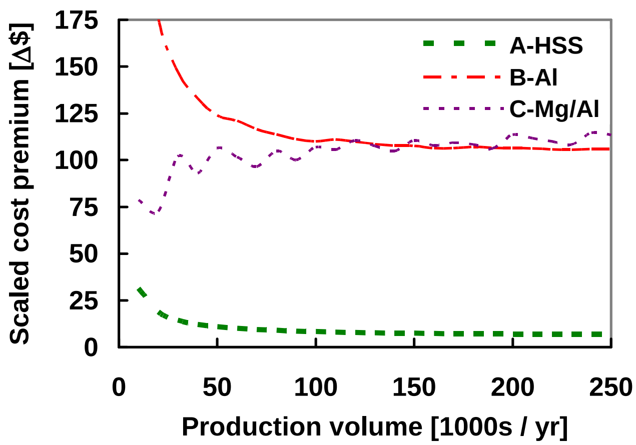

Figure 2 Scaled unit cost premium over mild steel (MS) of representative closure set as a function of production volume

MODELED COST RESULTS – The costs for closure parts were modeled with the appropriate PBCMs and compiled. Model outputs were then scaled and therefore do not represent actual costs; they are useful, however, for comparing the lightweight designs to the baseline mild steel design. Results for the cost and for the cost premium, Δ$, of the entire closure set as a function of production volume are shown in Figure 1 and Figure 2, respectively. A breakdown of the cost by panels, reinforcements, and assembly is shown in Figure 3 and by closure subsystem in Figure 4. The numbers represent the cost for the entire closure set and are shown at annual production volumes of 20,000 / year and 150,000 / year.

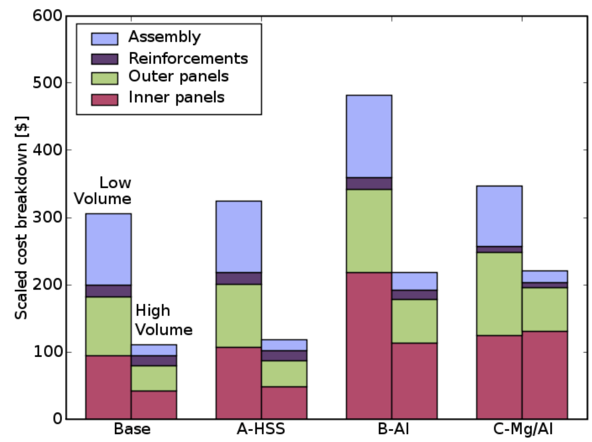

Figure 3 Scaled cost breakdown by part and assembly of a representative closure set at annual production volumes of 20,000 / yr (first bar) and 150,000 / yr (second bar)

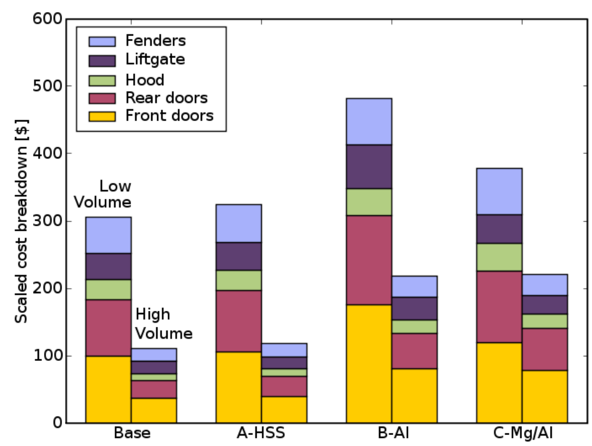

Figure 4 Scaled cost breakdown by subsystem of representative closure set at annual production volumes of 20,000 / yr (first bar) and 150,000 / yr (second bar)

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[1] Closure weight of mild steel baseline is 139.3 kg

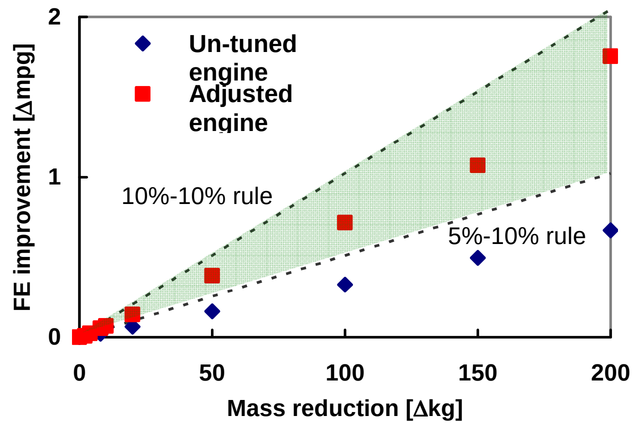

Figure 5 Representative SUV fuel economy improvement as function of weight savings

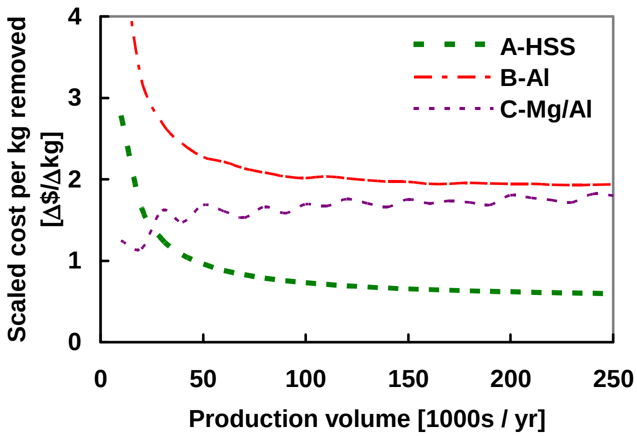

Figure 6 Scaled cost per kilogram removed (Δ$ / Δkg) as a function of production volume for representative designs

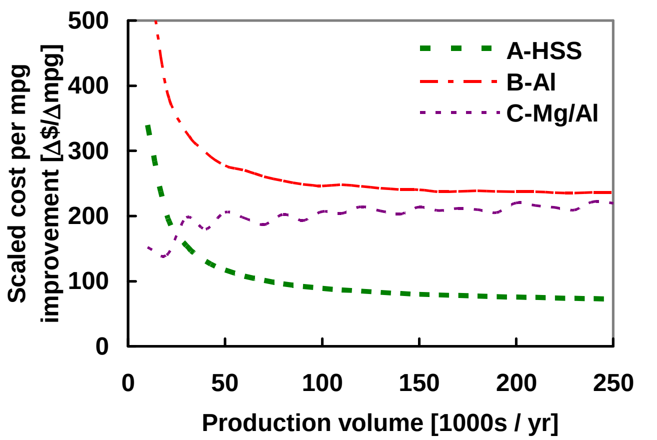

Figure 7 Scaled cost per MPG improvement (Δ$ / Δmpg) as a function of production volume for representative designs

POWERTRAIN MODEL RESULTS – The SUV powertrain model was used to generate curves of fuel economy improvement as a function of weight savings. Figure 5 shows two of these curves: one corresponding to an un-tuned engine for which mass is simply removed from the vehicle, and the other to an engine adjusted so that all the weight savings goes toward improving fuel economy without sacrificing performance. For reference, the lines for the 5%-10% rule of thumb are also included in the plot. This rule of thumb states that a 10% decrease in vehicle mass results in a 5% to 10% improvement in fuel economy [12].

WEIGHT SAVINGS AND FUEL ECONOMY BENEFITS – By combining the cost model results and the weight savings of each lightweight design (Table 6), it is possible to calculate the cost per kilogram of weight savings, Δ$ / Δkg. The results of this calculation for the closure set as a whole are shown as a function of production volume in Figure 6.

Alternately, the cost of each lightweight design can be divided by the amount by which it improves the vehicle's fuel economy and the cost per MPG improvement, Δ$ / Δmpg, calculated. For Figure 7, the fuel economy improvement corresponding to the adjusted engine is used.

DISCUSSION

The weight savings of all hypothetical lightweight designs vary from 11.4 kg for the A-HSS design to 63.1 kg for the C-Mg/Al design (Table 6). The similarity in weight savings between B-Al and C-Mg/Al is partly due to the fact that the two designs share several reinforcements as well as the entire hood and fender subsystems. As for the HSS closures, mass reduction is achieved by reducing gauge and therefore the amount of material needed for a part. However, large blanks were limited to gauges no thinner than 0.65 mm, which constrained the weight savings for some panels. Additionally, the limited formability of high strength steel restricts its use in panels requiring deep draws such as door and liftgate inner panels. Tailor welded blanks of mild and high strength steel resolve this issue, but limit realizable weight savings.

COST MODELS – According to the cost model results for this representative study presented in Figure 1 and Figure 2, the A-HSS design is the least expensive lightweight option at all production volumes. The second least expensive lightweight closure design, however, depends on production volume, along with various other model inputs and assumptions. At low volumes, C-Mg/Al is the second most cost-favorable lightweighting option and B-Al the least favorable. This ordering is partly because die casting allows for part consolidation and therefore requires lower up-front investments. The opposite is true for the stamped inner panels, which were composed of multiple pieces for this study. The latter approach requires additional dies and assembly equipment both of which lead to higher fixed costs. At high production volumes, the two designs switch places. Since B-Al is formed entirely by stamping, it is more preferable at higher volumes for which the up-front investments can be spread over more parts and the parts themselves which can be produced at a faster rate. Die casting, on the other hand, is limited by its cycle time, which is relatively long compared to that of stamping; consequently, its cost rises relative to that of the mild steel design. It should be noted that these hypothetical designs are primarily used to demonstrate the methodology and consequently not validated. If design and cost model assumptions are altered, the relative favorability of B-Al and C-Mg/Al may change.

Figure 3 and Figure 4 breakdown the relative closure set cost at production volumes of 20,000 and 150,000 / year by panels, reinforcements, and assembly, and by closure subsystem. For this example, the majority of the closure set cost comes from the inner and outer panels and, at low production volumes, assembly. The cost difference between B-Al and C-Mg/Al arises mainly from the difference in inner panel and assembly cost. Under these assumptions, B-Al has the highest inner panel and assembly costs because the door and liftgate inner panels are made from multiple pieces. Additionally, C-Mg/Al has the lowest reinforcement and assembly costs because die casting allows for substantial part consolidation.

Ultimately, this methodology illustrates that the preferred lightweight design depends on annual production volume plus a number of model assumptions such as material price, cycle time, equipment and tooling investment, etc. Often the single most important factor in selecting a manufacturing technology is the ability to form the parts required. It should be noted, though that this study does not address the robustness of the designs for manufacturability in the chosen processes; as such is not meant to direct design development, but rather to illustrate how robust designs could be evaluated.

POWERTRAIN MODEL – The powertrain model for the representative SUV predicts that fuel economy increases as weight savings increase (Figure 5). Adjusting the engine displacement is necessary for the fuel economy improvement to conform to the 5%-10% rule of thumb: if the engine is not adjusted, a 10% reduction in mass improves the fuel economy by less than 5%.

WEIGHT SAVINGS AND FUEL ECONOMY BENEFITS – Of the lightweight designs in this report, at very low volumes, C-Mg/Al is the least expensive design per kilogram of weight savings as well as per MPG improvement because of its combination of low cost premium and high weight savings. A-HSS, on the other hand, has both a low cost premium and low weight savings so at low production volumes it performs less favorably on a cost per kilogram basis.

At high production volumes, A-HSS is the preferred design on a cost basis, although its contribution to weight savings is only minimal. C-Mg/Al comes in second ahead of B-Al because of its larger weight savings but nearly identical cost premium. This change in preferred design was caused by shifting the metric from $\Delta\$$ to $\Delta\$ / \Delta$mpg, which illustrates the importance of choosing the appropriate metric when selecting between designs: a different metric can change the preferred design, even when all else is held constant.

LIMITATIONS – This study uses PBCMs to evaluate the manufacturing and assembly cost, and powertrain models to determine the fuel economy improvement of lightweight closure designs relative to a mild steel baseline. Although most of the lightweight designs are scaled from the mild steel design, they should represent a fairly accurate picture of the relative cost and fuel economy improvement attainable with using different materials and serve as an illustration for the methodology.

A second limitation of this study is that only weight savings directly related to using lighter weight materials for closure panels are considered: secondary weight savings are not taken into account. In reality, additional weight savings in other vehicle subsystems and structural components may be possible—leading to further fuel economy improvement.

Finally, the scaled cost of each closure design is sensitive to model inputs so if either process or operating conditions change, the preferred lightweight design may change as well. Also, the favorable design depends on an automaker's objectives. If cost is the only factor that matters, one design will appear better than the others; however, if instead fuel economy improvement or a combination of cost and fuel economy are important, then a different design may be preferable. This study only demonstrates a methodology which evaluates the costs and corresponding fuel economy improvements of various lightweight closure designs.

CONCLUSIONS

1. Developed and demonstrated a methodology combining cost and fuel economy improvement metrics for evaluating alternative lightweighting technologies for representative SUV closure assemblies.

2. The demonstration stresses the importance of choosing the correct metric for evaluating lightweight designs

3. The methodology identified A-HSS as the lowest relative cost lightweighting option for all annual

production volumes but highlighted its drawback of low weight savings and therefore low fuel economy improvement. B-Al, was shown to be relatively low cost for annual production volumes above approximately 130,000 units / year, indicating it is a material-process combination more appropriate for high volume applications.

4. For low volume applications, C-Mg/Al was identified as an advantageous approach to manufacturing closures, especially from a cost to weight savings perspective, and worthy of further consideration.

5. The authors feel this study demonstrates the context-dependence of the preferred material-process combination for a given design and how that design is affected by changes in production volume, raw material cost, design considerations, and an array of other factors.

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APPENDIX

Table 7 Cost model inputs for mild steel baseline representative design closures

				Weight	Blank width	Blank pitch
	Name	**Material**	**Press type**	*kg*	*mm*	*mm*
Front door	Inner panel	mild steel	transfer	6.7	1325	499
	Outer panel	BH steel	transfer	7.7	1735	2063
	Inner beltline reinforcement	mild steel	progressive	2.4	330	1502
	Outer beltline reinforcement	mild steel	progressive	1.05	294	1147
	Window frame reinforcement	mild steel	progressive	0.4	133	547
	Hinge reinforcement (2x)	mild steel	progressive	0.27	149	162
	Intrusion beam	HS steel	progressive	2.54	154	1330
Rear door	Inner panel	mild steel	transfer	5.21	1655	1316
	Outer panel	BH steel	transfer	5.08	1562	1285
	Inner beltline reinforcement	mild steel	progressive	0.6	190	855
	Outer beltline reinforcement	mild steel	progressive	0.65	190	975
	Hinge plate reinforcement	mild steel	progressive	1	170	680
	Intrusion beam	HS steel	progressive	1.32	160	665
	Latch reinforcement	mild steel	progressive	0.4	216	173
Hood	Inner panel	mild steel	transfer	8.4	1828	1350
	Outer panel	mild steel	transfer	10.9	1828	1365
	Hinge reinforcement (2x)	mild steel	progressive	0.21	145	115
Liftgate	Inner panel	mild steel	transfer	9.34	1606	1977
	Outer panel	mild steel	transfer	8.7	1427	1840
	Beltline reinforcement (2x)	mild steel	progressive	3.5	670	592
	Corner reinforcement (2x)	mild steel	progressive	1.1	353	353
	Latch reinforcement	mild steel	progressive	1.1	292	400
Fender	Inner panel	mild steel	transfer	6.56	906	1632
	Outer panel	mild steel	transfer	3.48	1020	1754

Table 8 Material and forming process breakdown of each closure set design by part

	Name / Design	Baseline	A-HSS	B-Al	C-Mg/Al
Front door	Inner panel (face + header)	St TWB	St-HSS TWB	Al stamp	Mg cast
	Outer panel	St stamp	HSS stamp	Al stamp	Al stamp
	Inner beltline reinforcement	St stamp	HSS stamp	Al stamp	—
	Outer beltline reinforcement	St stamp	HSS stamp	Al stamp	Al stamp
	Window frame reinforcement	St stamp	HSS stamp	—	—
	Hinge reinforcement (2x)	St stamp	HSS stamp	—	—
	Intrusion beam	HSS stamp	HSS stamp	Al extr	Al extr
	Beam bracket	—	—	Al extr	—
	Latch reinforcement	—	—	—	Mg extr
	Hinge extension	—	—	Al stamp	—
	Latch extension	—	—	Al stamp	—
	Rocker extension	—	—	Al stamp	—
Rear door	Inner panel (face + header)	St stamp	St-HSS TWB	Al stamp	Mg cast
	Outer panel	St stamp	HSS stamp	Al stamp	Al stamp
	Inner beltline reinforcement	St stamp	HSS stamp	Al stamp	—
	Outer beltline reinforcement	St stamp	HSS stamp	Al stamp	Al stamp
	Hinge reinforcement	St stamp	HSS stamp	—	—
	Intrusion beam	HSS stamp	HSS stamp	Al extr	Al extr
	Beam bracket	—	—	Al extr	—
	Latch reinforcement	St stamp	HSS stamp	—	Mg extr
	Hinge extension	—	—	Al stamp	—
	Latch extension	—	—	Al stamp	—
Hood	Inner panel	St stamp	HSS stamp	Al stamp	see B-Al
	Outer panel	St stamp	HSS stamp	Al stamp	
	Hinge reinforcement (2x)	St stamp	HSS stamp	Al stamp	
Liftgate	Inner panel	St stamp	HSS stamp	Al stamp	Mg cast
	Outer panel	St stamp	HSS stamp	Al stamp	Al stamp
	Beltline reinforcement (2x)	St stamp	HSS stamp	Al stamp	—
	Corner reinforcement (2x)	St stamp	HSS stamp	Al stamp	Al extr
	Latch reinforcement	St stamp	HSS stamp	Al stamp	—
Fender	Inner panel	St stamp	HSS stamp	Al stamp	see B-Al
	Outer panel	St stamp	HSS stamp	Al stamp	

St – steel; HSS – high strength steel; Al – aluminum; Mg – magnesium
stamp – stamping; PF – preform annealing; WF – warm forming; QPF – quick plastic forming;
extr – extrusion; cast – die casting; TWB – tailor welded blank + stamping

Table 9 Breakdown of representative closure weight (in kilograms) by part

	Name / Design	Baseline	A-HSS	B-Al	C-Mg/Al
Front door	Inner panel (face + header)	6.7	6.50	1.93	3.8 + 2.0
	Outer panel	7.73	7.21	4.25	4.25
	Inner beltline reinforcement	2.4	2.16	1.32	—
	Outer beltline reinforcement	1.048	0.94	0.61	0.61
	Window frame reinforcement	0.40	0.36	—	—
	Hinge reinforcement	0.27*	0.24*	—	—
	Intrusion beam	2.54	2.54	1.32	1.32
	Beam bracket	—	—	0.2*	—
	Latch reinforcement	—	—	—	0.19
	Hinge extension	—	—	1.23	—
	Latch extension	—	—	1.48	—
	Rocker extension	—	—	1.05	—
Rear door	Inner panel (face + header)	5.21	6.04	1.93	2.85 + 1.8
	Outer panel	5.08	4.40	2.80	2.80
	Inner beltline reinforcement	0.6	0.52	0.33	—
	Outer beltline reinforcement	0.65	0.60	0.38	0.38
	Hinge reinforcement	1.0	0.243	—	—
	Intrusion beam	1.32	1.32	0.77	0.77
	Beam bracket	—	—	0.2*	—
	Latch reinforcement	0.4	0.32	—	0.19
	Hinge extension	—	—	1.23	—
	Latch extension	—	—	1.48	—
Hood	Inner panel	8.40	8.40	4.89	see B-Al
	Outer panel	10.87	10.09	6.40	
	Hinge reinforcement*	0.21	0.34	0.23	
Liftgate	Inner panel	9.34	9.10	4.6	5.9
	Outer panel	8.69	7.06	5.23	5.23
	Beltline reinforcement*	3.5	2.8	—	—
	Corner reinforcement*	1.1	0.88	0.63	0.03
	Latch reinforcement	1.1	0.88	0.63	—
	Sidewall extension*	—	—	2.0	—
Fender	Inner panel	6.56	5.25	3.76	see B-Al
	Outer panel	3.48	3.23	2.05	
	* Mass shown per piece, but closure design requires 2 pieces				

Table 10 Representative Design assembly model inputs

	Subassembly	Baseline / A-HSS	B-Al	C-Mg/Al
Front door	Components [#]	9	—	6
	Spot welds [#]	38	66	49 (FSW)
	Hard auto welds [#]	24	30	—
	Rivets [#]	—	—	5
	Fastening [#]	—	—	2
	Adhesive [m (#)]	2.6 (4)	2.72 (10)	2.7 (9)
	Die / roller hemming	1	5 m	5 m
Rear door	Components [#]	7	—	6
	Spot welds [#]	34	55	45 (FSW)
	Hard auto welds [#]	20	25	—
	Rivets [#]	—	—	4
	Fastening [#]	—	—	2
	Adhesive [m (#)]	2.2 (4)	2.32 (10)	2.3 (9)
	Die / roller hemming	1	4.5 m	4.5 m
Hood	Components [#]	4	4	see
	Spot welds [#]	30	30	B-Al
	Adhesive [m (#)]	10.4 (11)	12.2 (41)	
	Die / roller hemming	1	5 m	
Liftgate	Components [#]	7	7	4
	Spot welds [#]	32	68	—
	Fastening [#]	—	—	4
	Adhesive [m (#)]	4.72 (4)	4.72 (4)	4.72 (4)
	Die / roller hemming	1	4.72 m	4.75 m
Fender	Components [#]	2	2	see
	Spot welds [#]	18	22	B-Al
	Adhesive [m (#)]	0.88 (1)	0.88 (1)	
	Die / roller hemming	1	0.88 m	

FSW – Friction stir welding

Adhesive shows the length in meters with the number of disconnects in parentheses