SEPTEMBER

2016

Assessing the Fleet-wide Material Technology and Costs to Lightweight Vehicles

CENTER FOR AUTOMOTIVE RESEARCH

Jay S. Baron, Ph.D.

Shashank Modi

ACKNOWLEDGEMENTS

This study is the result of an industry wide effort. The authors would like to thank the Alliance of Automobile Manufacturers and its members who were instrumental in helping CAR with this study. Frequent meetings with the automotive engineers and leadership would not have been possible without the automakers and Alliance support. The authors would also like to thank our colleagues at the Center for Automotive Research for their assistance. Significant efforts of internal reviews, editing and document production were provided by Lisa Hart, Brian Esterberg, and Denise Zilch. Additional research support was provided by CAR's student interns, Estefania Jurado and Matthew Chess. The authors would also like to thank our corporate and academic colleagues who provided external reviews and commentary throughout the development of this work. Their input contributes significantly to the integrity of this research.

Jay S. Baron, Ph.D.

Shashank Modi

CENTER FOR AUTOMOTIVE RESEARCH

3005 Boardwalk, Suite 200
Ann Arbor, MI 48108
www.cargroup.org

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CAR's mission is to conduct independent research and analysis to educate, inform and advise stakeholders, policy makers, and the general public on critical issu18,000es facing the automotive industry, and the industry's impact on the U.S. economy and society.

CONTENTS

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LIST OF FIGURES

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List of Tables

List of Abbreviations

AHSS	Advanced High Strength Steel
Adv.	Adhesives
BH	Bake Hardened
BIW	Body-in-White
BoF	Body-on-Frame
CAE	Computer Aided Engineering
CAFE	Corporate Average Fuel Economy
CAR	Center for Automotive Research
CFRP	Carbon Fiber Reinforced Plastic
CI/FC	Grey Cast Iron
CP	Complex Phase
CR	Cold Rolled
CS	Cold Stamped
CUV	Cross Utility Vehicle
DP	Dual Phase
DMC	Direct Manufacturing Cost
EDAG	EDAG Engineering Company
FB	Ferritic-bainitic
FDS	Flow Drill Screws
FEV	FEV Engineering Company
FG	Fiberglass
GF	Glass Fiber
GFRP	Glass Fiber Reinforced Plastic
HF	Hot Formed
HS	Hot Stamped
HSLA	High-Strength Low Alloy
HSS	High Strength Steels
HVAC	Heating, Ventilation, and Air Conditioning
IF	Interstitial Free
LW/FW	Laser/Friction welding
LWB	Laser Welded Blanks
LWV	Light Weight Vehicle
MIG	metal inert gas welding
MPa	Mega Pascal
MR	Mass Reduction
MS	Martensitic
NAS	National Academy of Science
NRC	National Research Council
P/GF/CF	Plastic/Glass Fiber/Carbon Fiber
PSF	Plastic Thermoforming
PSS	Plastic Thermosetting
RF	Roll Forming
Riv.	Rivets
RSW	Resistance spot welding
SMC	Sheet Molded Compounds
TIG	Tungsten Inert Gas
TRB	Tailor Rolled Blanks
TRIP	Transformation-induced plasticity
TWIP	Twinning-induced plasticity
UHSS	Ultra High Strength Steel

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I. Estimating U.S. Fleet Lightweighting Costs

The purpose of this study is to provide insight to the technology and cost to reduce vehicle weight for the U.S. fleet of light-duty vehicles. Considerable resources have been expended by the regulators trying to estimate the lowest cost feasible for mass reduction of light-duty vehicles in the United States. Detailed teardown and cost studies, performed by reputable engineering firms, have aggressively approached lightweighting on a handful of vehicles, producing a number of innovative ideas (references: Lotus Engineering/Toyota Venza[1], EDAG/2011Honda Accord[2], FEV/2011 Silverado[3]). However, automakers respond by pointing out that there are risks, business constraints, and customer requirements that these studies do not address. Furthermore, to extrapolate the results from one, or a few studies, to over 1,000 vehicle models for sale in the U.S. market is inappropriate. The fallacy in doing so was recognized by the National Research Council (NRC) study[4] (Finding 6.9, pg. 242) that cautioned extrapolation of any teardown study to the U.S. fleet. Some companies, for example, have developed histories of specializing in certain materials which will bias their options for the lowest cost lightweighting pathway. Lowest cost for one company is not necessarily lowest cost for another one. A company's tolerance for risk, technical knowledge base, modeling software capability, and available supply chain can direct one company toward one material over another. Other barriers that would add cost over ideal conditions were outlined in a Center for Automotive Research (CAR) study[5] published in early 2016. Projected cost estimates from the 2015 NRC study show a range from $0.44/pound to about $1.18/pound for a 10% lighter vehicle. When multiplied by 10% of a 4,000-pound vehicle, this cost estimate ranges from $176 to $472 per vehicle. Perhaps the greatest challenge in estimating the fleet's cost to lightweight is that there are more than 1,000 vehicle models in the fleet with different levels of inherent technology today. **The average baseline of today's lightweighting technology in the U.S. fleet is largely unknown.** The approach taken by this study is to collect automaker data on lightweighting technology for a large sample of vehicles that cover major vehicle segments, use this data to set an estimated baseline for the fleet, and then estimate a representative lightweighting pathway. With a representative baseline and standardized lightweighting pathway (assuming this exists), a cost curve can be estimated.

[1] Light-Duty Vehicle Mass Reduction and Cost Analysis — Midsize Crossover Utility Vehicle, EPA-420-R-12-026 August 2012

[2] Singh, Harry. (2012, August). Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025. (Report No. DOT HS 811 666)

[3] Mass Reduction and Cost Analysis - Light-Duty Pickup Truck Model Years 2020-2025, Technical report, EPA-420-R-15-006, June 2015

[4] National Research Council. *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. Washington, DC: The National Academies Press, 2015. doi:10.17226/21744

[5] Baron J., Identifying Real World Barriers to Implementing Lightweighting Technologies and Challenges in Estimating the Increase in Costs, January 2016

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Figure 1 illustrates the objective of this research study. The cost curve line is conceptually accepted as a general, exponentially increasing curve where cost per pound increases as additional lightweighting technology is added. There are three principal aspects that this study will evaluate:

1. The lightweighting technology baseline is dynamic and advances every year when a new model vehicle architecture is introduced. For competitive reasons, automakers are motivated to introduce cost-competitive lightweighting technologies because vehicle performance improvements (braking, handling, safety, etc.) make vehicles more competitive and desirable, and these vehicles are better able to meet fuel economy regulations. Over time, new technologies (such as advances in materials or joining) are developed and become available without cost implications. This study will evaluate the average 2015 baseline of lightweighting technology and compare this baseline with that from the EDAG/2011 Honda Accord Study.

2. An estimate will be considered for the industry's lightweighting pathway. The independent cost studies developed cost curves, anticipating the availability of new technologies in the future. If the industry expectations are similar to the independent studies, then the cost curves can be similar with adjustments for the baseline and real-world conditions. (Real-world conditions are explained in CAR's Barriers to Lightweighting Study referenced above. The real-world conditions that drive up costs include, for example: material qualification, material modeling, non-robust supply chains, conflicts in the paint shop, and use of non-standardized manufacturing processes which have been traditionally developed for steel).

3. The historical trend of vehicles gaining weight is well established. In spite of the advancement of lightweighting technologies, vehicles have gained weight because of increased regulations and customer requirements, and there is no reason to expect this trend to stop. Consequently, for automakers to apply lightweighting technology to end up X% lighter, they must apply technology for X% plus the amount required to meet regulations and consumer requirements (Y%). Therefore, total weight reduction needed equals X% plus Y%.

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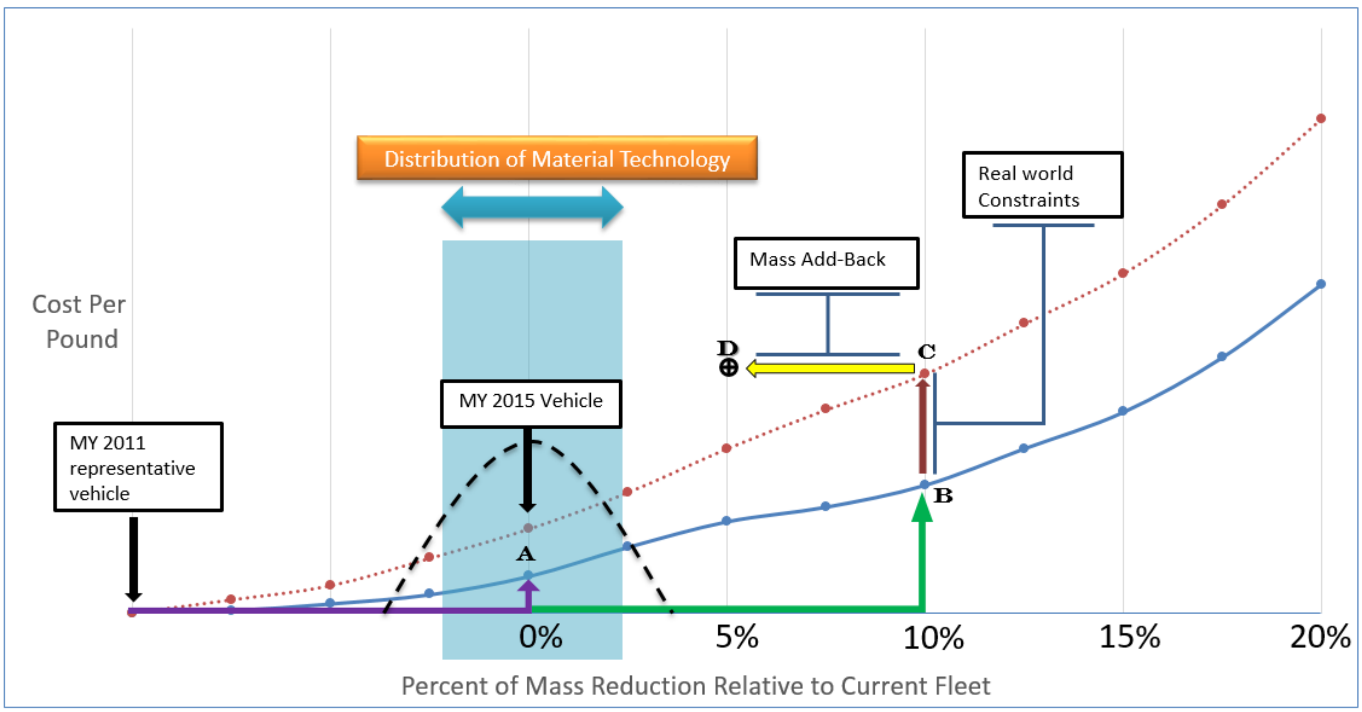
Figure 1 illustrates these three issues using hypothetical percentages. The graph shows a starting baseline for model year 2015 (Point A). There is a distribution of material technology in the MY2015 fleet, no two vehicles are completely alike. Model year 2015 cars possess more technology than a few years ago and are not at the zero starting point (the cost curve was based on those developed for previous model years). In order to achieve a 5% net mass-reduction (Point D), an additional technology of 10% mass-reduction is required from a MY2015 vehicle (to Point B). The cost curve is adjusted to account for real-world barriers not captured in the idealistic curve that ignores business constraints such as initial capital investment in R&D and manufacturing equipment (Point C). Assuming a 5% mass add-back for safety and customer requirements, a net mass-reduction of 5% is achieved from the MY2015 baseline at the cost of 10%.

Figure 1: Generic Cost Curve Illustrating Real-World Barriers, an Alternative Baseline, and Mass-Add Due to Safety and Customer Requirements.



Source: CAR Research

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II. SURVEY INTRODUCTION

Two surveys were developed and sent to 16 automotive manufacturers. A description of participation is outlined in the next section.

The first survey, The General Survey (see Appendix 1) was designed to elicit general automaker lightweighting strategies. Questions were asked to help determine an automaker's technology pathway on top selling vehicles from various vehicle segments. For example, what areas of the vehicle would be targeted with new technology first and offer the greatest opportunity for lightweighting? The six vehicle systems investigated are shown below in Table 1. These questions were independent of the vehicle model, and reflect automaker tendencies. Questions were also asked about mass decompounding[6] opportunities, learning[7] (that leads to cost reductions), and "mass add-back" which is the amount of weight that may be added to a future vehicle due to safety and customer requirements.

Table 1: Summary of Vehicle Sample Items Investigated, General Survey

Closures : e.g., hoods, front doors, rear door, decklid
Body-in-White : e.g., pillars, floor, fenders, shock towers, frame (if light-truck)
Unsprung Mass : e.g., wheels, suspension, brakes
Non-Structural : e.g., shock tower, exhaust system, glazing
Interiors : e.g., seats, trim, instrument panel, switches, electronics
Components : e.g., power-steering, HVAC, electronics, starter motor

The second survey was the Vehicle Model Survey (see Appendix 2), designed to ask questions about specific model vehicles produced by each automaker. The survey questions were vehicle specific up to the trim level, covered the major sub-systems, and the major components comprising the sub-systems. For every component surveyed, the survey asked for the material technology used in the current model year vehicle and the manufacturer's future plans for that specific component (factoring in real-world production, product constraints, and vehicle redesign schedules) if the vehicle weight is to be reduced by 5%, 10%, or 15% plus, by model year 2025. The survey results covered model years 2015 to 2025.

Automakers completed multiple vehicle-specific surveys in different vehicle segments. Detailed lightweighting questions were asked about each of the 20 systems shown in Table 2 below. Strategies for

[6] Mass decompounding is the process by which it is possible to identify further reductions when secondary mass savings result in further reduction of the vehicle weight. The sub-systems primarily targeted include engine, brakes, transmission, and suspension.

[7] Learning reflects the impact of experience and volume on the cost of production.

lightweighting these systems for 5%, 10% and 15% mass reduction helped in identifying the lightweighting pathway. Additional questions were asked about the body-in-white (BIW) because it is the single biggest vehicle system and offers significant lightweighting opportunities.

Table 2: Summary of Vehicle System Sub-Components, Vehicle-Specific Survey

BIW	Closures & Fenders	Chassis	Powertrain	Interiors	Steering	Electrical
A Pillar	Front Door Inner	Engine Cradle	Engine Heads	Instrument Panel Cross Beam	Steering Shaft	Wiring Harnesses
B Pillar	Front Door Outer	Lower Control Arm	Fuel Tank	Seats Frame		
Floor	Hood	Brake Disk/Rotor				
Front Bumper Structure	Decklid	Steering Knuckle				
Roof Panel	Fender LH/RH					

By design, CAR requested surveys for specific vehicle models to insure that different segments would be covered and that a large population of vehicles, based on sales, was represented. All vehicle models surveyed were 2015 or 2016 model-year vehicles. Recognizing that lightweighting pathways (and costs) will depend on vehicle segmentation, the vehicle surveys were parsed into four segments: small car, midsize and large car (combined), cross utility vehicle (CUV), and body-on-frame (BoF). BoF includes light-duty pickup trucks and sport-utility vehicles if they have a frame architecture. The launch year of the surveyed vehicle was requested so the age of the architecture would be known.

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Sixteen automakers are listed below were invited to participate. Nine of the 16 participated in the survey.

- Audi
- BMW
- Fiat Chrysler Automobiles
- Ford
- General Motors
- Honda
- Hyundai/Kia
- Jaguar Land Rover
- Mazda
- Mercedes Benz
- Mitsubishi
- Nissan
- Subaru
- Toyota
- Volkswagen
- Volvo

Nine general surveys were completed in addition to 42 vehicle specific surveys for the 2015/2016 model-year. The proportional sales volume of the represented vehicles is 47% of the U.S. fleet, based on 2015 U.S. sales volumes. The nine automakers represent 88% of the U.S. sales market. The number of vehicles in each of these segments, their representation in the segment, and percentage of overall sales is summarized in Figure 2 and Table 3. Representation in each segment is robust with 65% of body-on-frame market surveyed, 59% of the small car market surveyed, almost half of the mid/large car market surveyed, and a third of the cross-utility vehicle market surveyed.

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Figure 2: Percentage of U.S. Market Covered

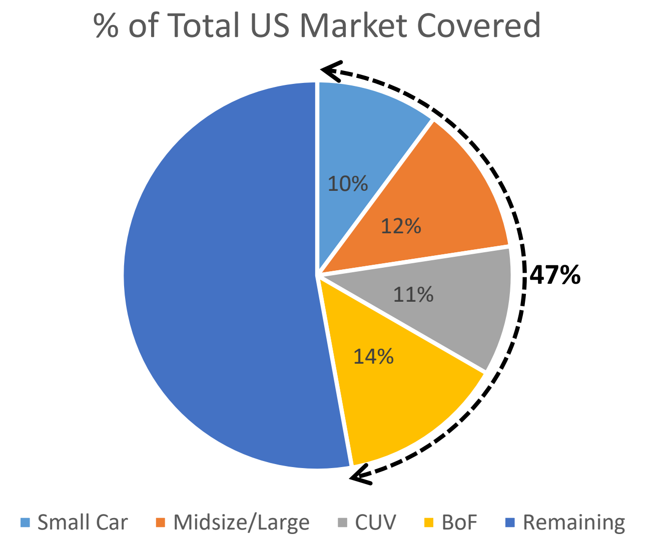

Table 3: Summary of Survey Responses by Segment

Segment	No. of Vehicles	% of Segment	% of U.S. Sales
Small car	12	59%	10%
Midsize & large car	12	48%	12%
Cross utility vehicle (CUV)	12	31%	11%
Body on frame (BoF)	6	65%	14%
Total	42		47%

III. General Responses, Challenges and Opportunities

Lightweighting Priorities by Vehicle Sub-system

Where lightweighting will be targeted is important because it affects material choices, cost and total weight reduction opportunities, especially in the short term. The survey requested information on the vehicle's design year and the year the automaker anticipates the next major redesign for the vehicle. The data suggests that on average there is a 7-year timeframe between major redesigns of a vehicle. Between 2016 and 2025, there will be an opportunity for only one major design change. Body-on-frame vehicles have a much longer timeframe between architectural changes, which can approach 20 years. The results from the general survey regarding where the current lightweighting effort (across the industry) is focused

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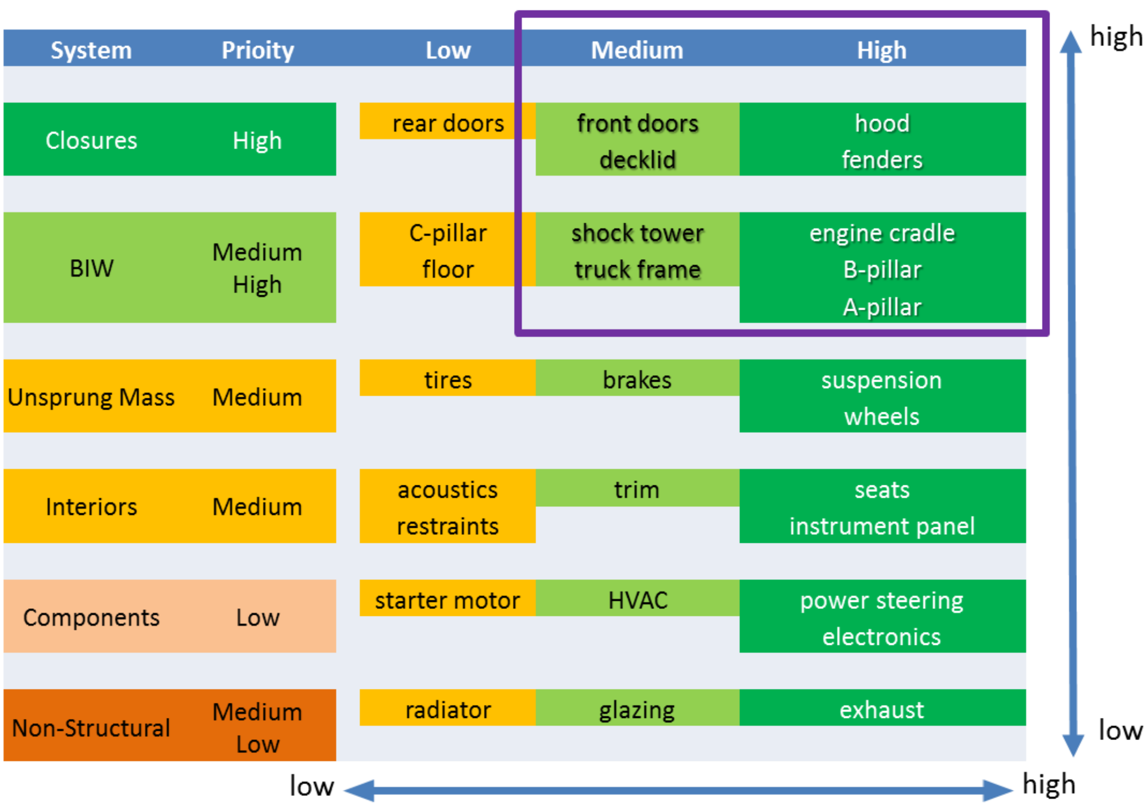
upon is summarized in Table 4. Although the body-in-white (BIW) is ranked number 2 after closures, it offers greater opportunity but with added complexity. Closure panels can be readily bolted onto the structure without the complexity of systems design and integration into the body structure, simplifying new material strategies.

Table 4: Median Rank for Vehicle System Lightweighting Opportunity

Vehicle System	Median Rank
Closures	1
BIW	2
Unsprung Mass	3
Interiors	3
Components	5
Non-Structural	6

Figure 3: Low, Medium, High Prioritization of Vehicle Subsystems for Lightweighting Opportunity



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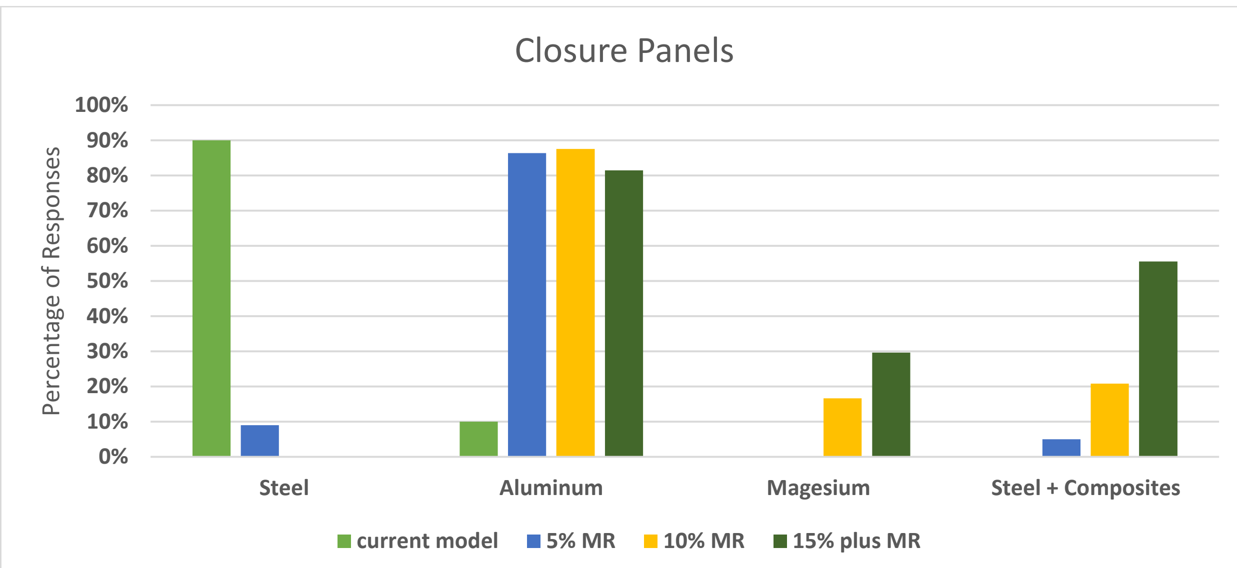
In Figure 3, the priorities for lightweighting combine the vehicle system rank with their subsystems. The highest priority for lightweighting are the hood and fenders (both closures) followed by: front doors, decklid, engine cradle, A and B pillars, and truck frame. The A and B pillars are highly dependent on crash requirements and are an area of the vehicle where some of the most advanced lightweighting technology is seen. The opportunity for truck frames is highly dependent upon the age of the truck in its product life-cycle.

General Material Substitution Trend and Challenges

Figure 4 shows the material substitution that is expected as vehicle manufacturers attempt to reduce the weight of closures. The data shows that, while 90% of the current closures are made from steel, with as little as a 5% objective to lightweight a vehicle will result in an 85% transition from steel to aluminum. Additional efforts to lightweight the vehicle beyond 5% will begin to introduce magnesium and composites, with slightly greater growth in composites.

Figure 4: Closures Material Substitution Trend



The material trend to aggressively lightweight the car body (body-in-white) is more complicated than closure panels – see Figure 5. BIW shows slight growth to higher strength steel (UHSS) over AHSS, but significant growth for aluminum. Composites growth is dependent on aggressive vehicle lightweighting at 10% and 15%. While design optimization and advanced high strength steels (AHSS) are relatively insensitive to lightweighting aggressiveness (from 5% to 15%), increased use of ultra-high strength steels (UHSS), aluminum, and composites increase with aggressiveness. Aluminum has the significant opportunity, growing by about 70% from current use if vehicles are to become 15% lighter. Composite use also grows significantly with the 10% and 15% levels of lightweighting.

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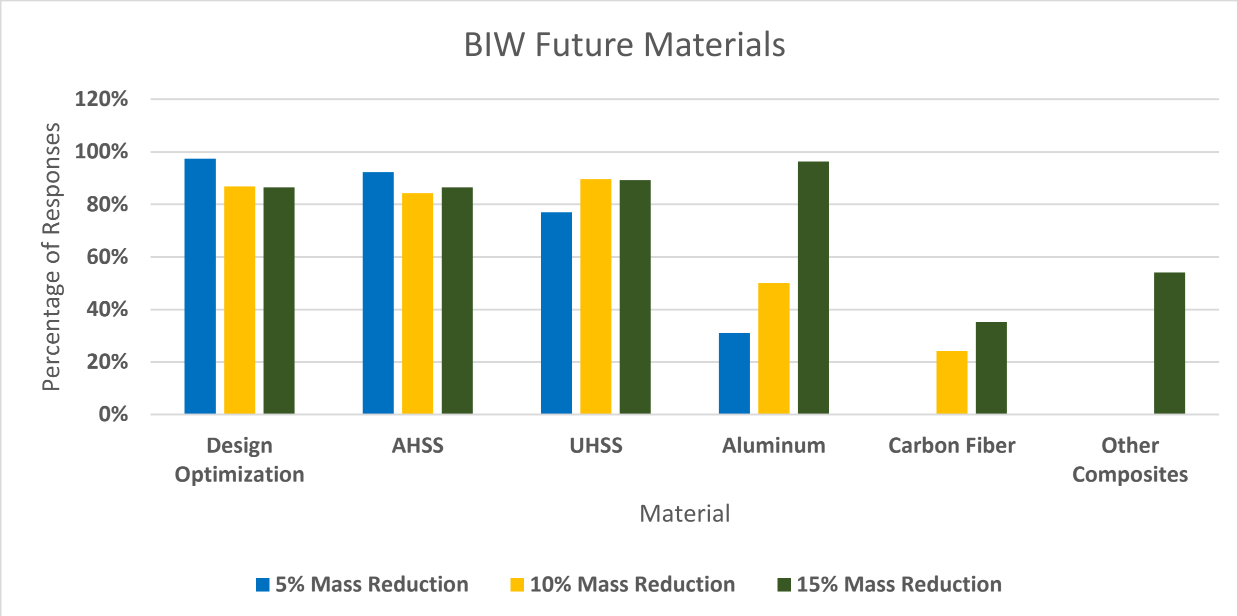
Figure 5: BIW Material Substitution Trend



The rank order of difficulty in using different lightweight materials is shown in Table 5. Each material has unique challenges with increasing complexity and cost implications from steel to aluminum, magnesium, and composites.

Table 5: Rank Order of Materials Seen as Challenging to Introduce into High-Volume Vehicles
Rank: 1 = Most Challenging; 5 = Least Challenging

Material	**Rank**
Carbon Fiber	1
Glass Fiber	2
Magnesium	3
Aluminum	4
Steel	5

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Material-specific challenges identified in the survey:

- **High strength steel**
  - Material characterization – the new material must be computational for CAE analysis. With newer high strength, press hardened steels, additional specifications are often required for simulation.
  - Robust supply base – some of the newer ultra-high strength steels and generation 3 steels do not have a global supply base. Automakers are skeptical about qualifying such a material for global platforms.
  - Formability into usable shapes – higher strength steels generally have low formability which limits their use in deep draw applications.
  - Tendency for thinner grades to corrode.
- **Aluminum**
  - Conversion of the existing steel-based supply-chain infrastructure
  - Paint shop – for example, aluminum has different surface behavior and a different thermal expansion coefficient than steel.
  - Robust supply base – fewer sources of aluminum suppliers
  - Complete re-design of body shop assembly technology
- **Magnesium**
  - Conversion of the existing steel-based fabrication infrastructure
  - Robust supply base – 70 to 80% of magnesium production is based in China and the potential for a supply disruption exists[8]
  - Paint shop
  - Complete re-design of body shop assembly technology
  - High price and volatile material cost
- **Composites**
  - Robust supply base – composites, unlike metals, are not as commonly sold as commodities. Standard products are not commonly available globally.
  - Production cycle times to meet vehicle production rates – the manufacturing rate required to meet the high-volume requirements of car or truck production is generally acknowledged to be one part per minute. It takes 5-10 minutes for traditional composites to crosslink sufficiently to cure. Reducing the cycle time for composites is an ongoing R&D effort at composite suppliers. The production rate of vehicles can be several times faster than component production. Variation in part-to-part fabrication (i.e., quality).
  - Performance modeling and requirements definition – the available CAE software does not perform well for some composite materials because of fundamental differences in

[8] A Closer Look at Magnesium, Zimtu Research (http://www.zimtu.com/i/pdf/2015-07_ZR.pdf)

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material behavior from metals. Also, the composite materials are often branded by the supplier and the material chemistry is protected as intellectual property. This makes it difficult for CAE software companies to create generic simulation models for composites.

- High material and fabrication cost

The largest barrier to lightweighting is capital investment (e.g., to alter infrastructure, the body shop, the paint shop, etc.). See Table 6.

Table 6: Rank Order of Barriers from Introducing More Advanced Lightweight Materials
Rank: 1 = Most Challenging; 5 = Least Challenging

Barrier	**Rank**
Capital Investment	1
Manufacturing Capacity	2
Design	3
Qualification	4
Supply Base Competitiveness	5

Weight Add-Back

Weight add-back estimates (from 2015 to 2025) were provided separately for cars and light-duty trucks, with separate estimates for performance and safety. Mass for safety may be added for crashworthiness and electronics devices such as cameras, sensors, computers, etc. Performance mass might be added for attributes such as improvements in: stiffness, quietness of ride, lowering the center of gravity, equalizing the load distribution, reduction of unsprung mass, etc. According to a Massachusetts Institute of Technology report,[9] required safety and emissions equipment were the source of approximately 62 kg (3.9%) and 24.6 kg (1.5%), respectively in a 2010 vehicle. By comparison, 1975 vehicles, on average, incorporated 31.2 kg (1.7%) of safety equipment, 6.35 kg (0.3%) emissions equipment, and 71 kg (3.9%) of optional features.

The results of the survey indicate that the total mass add-back expected for cars today averaged 4.9% for cars and 4.6% for light-duty trucks. See Table 7.

Table 7: Summary of Mass Add-Back

Cars = 4.9%		**Trucks = 4.6%**	
Safety	Performance	Safety	Performance
2.48%	2.38%	1.74%	2.81%

[9] Stephen M. Zoepf, Automotive Features: Mass Impact and Deployment Characterization, Massachusetts Institute of Technology (MIT) 2010

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Decompounding

The industry recognizes opportunities for mass decompounding, but sees limitations. The automakers, in general, do not accept that a 40% decompounding for cars and 25% for trucks, as suggested in the NAS study[10] is that available with 10% or more lightweighting. Real-world estimates are closer to one-half these NAS estimates. Key limitations include resources and practicality to optimize shared systems. Survey results indicate the following:

- Decompounding can be directed at brakes, chassis (suspension, cradles, tires/wheels) and powertrain (engine/transmission).
- Many systems on a vehicle are shared across the company and not optimized for each model. In addition to cost constraints, there are insufficient resources to optimize every component.
- There are only a limited number of engines available. The manufacturer must choose from the selection of engines that produce the desired performance, fit within the architecture, and match with other systems such as the transmission.
- Decompounding is only practical when the level of weight reduction is high. While a continuous decompounding percentage is desired, actual down-sizing of components can only occur in discrete steps.
- The opportunity to decompound is in the 10% to 20% range (not 40%).
- Opportunities to decompound become more limited when there are multiple models built off the same platform because of the designed utility of different models. It is not practical to uniquely design each vehicle to allow for decompounding.

Learning

Time-based and/or volume-based learning in material technology lowers the cost of the technology in the long run. Mainstream, mature technologies tend to have a lower cost. Also, technologies used in mass-produced vehicles have lower cost in general compared to technologies used in niche market vehicles. The Volpe Model,[11] used by the federal agencies for the final rulemaking to set Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy (CAFE) for 2017-2021 applied learning factors to the mass reduction cost. The Volpe Model applies 3% per year cost reduction (applied to direct manufacturing cost for mass reduction) between 2012 to 2021, 2% per year cost reduction between 2022 to 2027, and 1% per year cost reduction between 2028 to 2030. These percentages were applied to all the vehicle segments uniformly for any material. The draft Technical Assessment Report for the Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025, use similar cost reduction percentages for mass reduction to account for learning. The CAR general survey asked for automakers' opinions on the learning percentages for various materials for two different timeframes, 2012-2021 and 2022-2027. Table 8 shows the average

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[10] National Research Council. Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles. Washington, DC: The National Academies Press, 2015. doi:10.17226/21744

[11] The Volpe Model files are available at: http://www.nhtsa.gov/Laws+&+Regulations/CAFE++Fuel+Economy/CAFE+Compliance+and+Effects+Modeling+System:+The+Volpe+Model

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results from the survey. It can be noted that the learning in terms of cost reduction per year is in the 0.4% to 1.5% range, and also differs significantly by material. Steels have lower learning percentages because the material technology is already very mature. Composites have the highest opportunity as some of the materials in this category are an active area of research. It can be also noted that learning is less in the later timeframe of 2012-2027 because some of technologies are expected to reach maturity by then.

Table 8: Learning Factors

Average % cost reduction/year	**Time Period**	**AHSS/UHSS**	**Aluminum**	**Magnesium**	**Composites**
	2012-2021	1.21%	0.79%	1.08%	1.50%
	2022-2027	0.69%	0.69%	0.42%	1.47%

IV. Pathway Analysis

The need to meet regulations has driven the automakers to aggressively introduce new materials to lightweight vehicles. The material pathways for lightweighting are critical because they directly affect cost. Principal cost differences between parts made from alternative materials are: material costs, design and development costs, tooling and fabrication, assembly and joining, and painting. In every case of using a new material, the total system implementation cost needs to be considered. For example, although higher strength steels cost more than mild steels, less material is required. Looking forward, automakers were asked what material pathways they expect if the vehicle has to be lightweighted by 5%, 10% or 15%. The more aggressive the objective, the more expensive the material pathway becomes to achieve it. For the body-in-white and the closure panels (see Figure 4 and Figure 5), the overall material substitution trend is evident for 5%, 10% and 15% lightweighting:

- Even with modest lightweighting (5%), closure panels are being converted from steel to aluminum. More aggressive lightweighting (10% to 15%) will lead to other materials such as magnesium and composites, but aluminum use will continue to grow.
- At 5% and 10% vehicle lightweighting, the body-in-white will see growth in ultra-high strength steel, including hot-formed boron steels, and significant growth in aluminum.
- Growth in composite materials for the body will be seen as vehicles reach the 10% or greater lightweight objective.

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The individual pathways for 5%, 10% and 15% vehicle curb weight reduction are generalized by component in Table 9 and an overall summary of material trends are shown in Figure 6. These pathways illustrate the progression to higher strength materials for lightweighting, as well as the progression for increased joining complexity. Generalizations of the pathways is complicated because each component has a different starting point (baseline) and business case to determine when to add new lightweighting technology. For example, materials for the A and B pillars are driven by crash requirements and tend to already use very high strength steel. However, thinner high-strength steel can maintain strength but reduces stiffness, which is an important design criterion. When the minimum thickness level is reached for the required stiffness, it cannot be reduced any further. Several vehicles use hot-formed 1500 steel, which is a mainstream technology today.[12] Automakers indicated they would plan to use advanced aluminum (7000 series) or even carbon fiber reinforced plastic if they have to further lightweight the vehicle by 10% to 15%. As the materials become more complex, the joining processes also advance to more challenging technologies. The technologies to join different parts evolve from traditional resistance spot welding (for steel) to also include adhesives, fasteners, and laser welding.

The following generalizations are made summarizing the pathways to lightweighting (see Figure 7), which is similar to the lightweighting pathway followed by the EDAG study:[13]

- Movements from mild steel to high strength steel
- Increasing use of higher strength steels and possibly hot formed steel
- Aluminum closure panels starting with the hood and decklid
- Increasing application of composite components (oil pan, wheel well, etc.)
- Additional aluminum closure panels for the doors
- Mixed materials with aluminum and high strength steels
- Aluminum intensive body (car)
- Aluminum intensive body (truck)
- Aluminum intensive frame (body-on-frame)
- Composites skin panels and some structural panels (pillars and rails)
- Composite intensive vehicle

The difficulty level in terms of technology implementation and cost increases with every step. A typical MY2015 vehicle is on step 3 - an advanced high strength steel body-in-white with mixed steel & aluminum closures.

[12] http://www.automotiveworld.com/analysis/hot-stamping-goes-mainstream-2/ , September 2013

[13] Singh, Harry. (2012, August). Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025. (Report No. DOT HS 811 666)

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Figure 6: Summary of Lightweighting Material Trends

Material	Examples	Typical Usage	Trend
Conventional Steels	Mild steel	High formability parts such as fender, door outer/inner	↓
High Strength Steels (>300 Mpa UTS)	Bake hardened steel	High formability parts	↓
Advanced High Strength Steels (>500 MPa UTS)	Dual phase steels	Structural members	↔
Ultra High Strength Steels (>700 MPa UTS)	Hot formed (boron)	Structural members such as B Pillar, reinforcements	↑↑
Aluminum Alloys	Al 6xxx, 7xxx	Closures, engine components e.g. hoods	↑↑
Magnesium Alloys	Cast magnesium	Closures, instrument panel structure	↑
Composites	Carbon fiber	Structural members, reinforcements, closures	↑

Figure 7: General Lightweighting Pathway

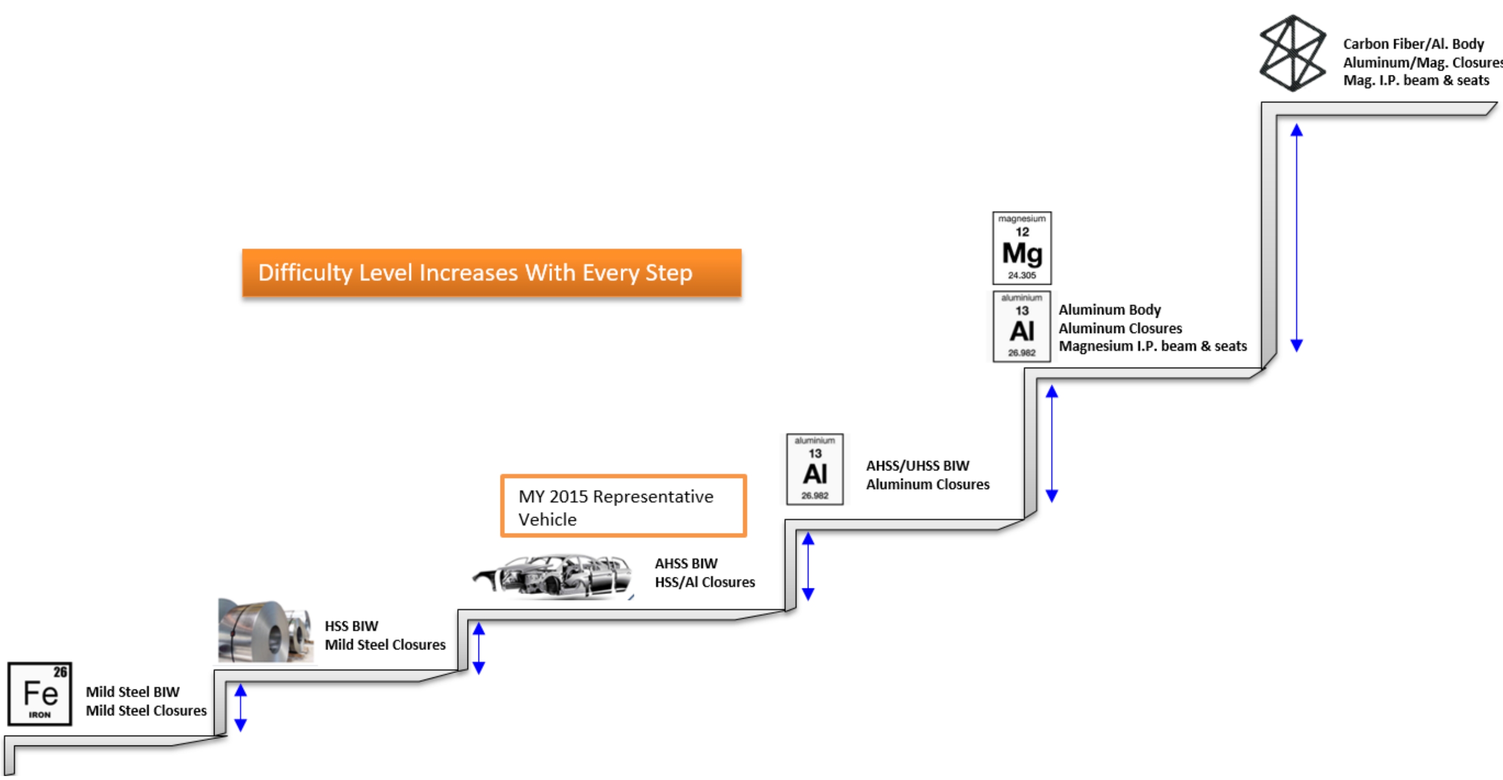

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Table 9: Material Trends for Vehicle Lightweighting by Component

Component/Material	Mild Steel	HSS/AHSS	HF Steel	Aluminum	Plastic/Comp (P/GF/CF)
A Pillar					
Current	140	HSLA/DP	1200/1500	---	---
5% MR	---	HSLA/DP	1800	6xxx	---
10% MR	---	DP	1800	5xxx/6xxx	---
15% MR	---	---	2000	6xxx/7xxx	CFRP
B Pillar					
Current	140	HSLA/DP	1200/1500	6xxx	---
5% MR	---	HSLA/DP	1800	6xxx	---
10% MR	---	DP	1800	6xxx	CFRP
15% MR	---	---	1800	6xxx/7xxx	CFRP
Floor					
Current	140/270	BH/HSLA/DP	---	5xxx	---
5% MR	140	BH/HSLA/DP	1470	---	---
10% MR	---	BH/DP	1470	5xxx/6xxx	CFRP
15% MR	---	DP	---	5xxx/6xxx	CFRP
Front Bumper Structure					
Current	270	HSLA/DP	1100	6xxx/7xxx	---
5% MR	---	HSLA/DP	1470	6xxx/7xxx	---
10% MR	---	---	---	6xxx/7xxx	---
15% MR	---	HSLA	---	6xxx/7xxx	CFRP
Roof Panel					
Current	140	BH/HSLA/DP	---	---	---
5% MR	140	BH/HSLA	---	6xxx	FP
10% MR	140	BH/HSLA	---	5xxx/6xxx	CFRP
15% MR	---	BH	---	5xxx/6xxx	CFRP
Front Door Inner					
Current	140	BH/HSLA	---	5xxx	---
5% MR	140	BH/HSLA	---	5xxx	---
10% MR	140	BH/HSLA	---	5xxx	---
15% MR	---	HSLA	---	6xxx	---
Front Door Outer					
Current	---	BH/HSLA	---	---	---
5% MR	---	BH	---	6xxx	---
10% MR	---	BH	---	6xxx	---
15% MR	---	BH	---	6xxx	---

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Component/Material	Mild Steel	HSS/AHSS	HF Steel	Aluminum	Plastic/Comp (P/GF/CF)
Hood					
Current	140	BH/HSLA	---	5xxx/6xxx	---
5% MR	140	BH	---	5xxx/6xxx	---
10% MR	---	---	---	5xxx/6xxx	CFRP
15% MR	---	---	---	5xxx/6xxx	CFRP
Decklid / Tailgate					
Current	140	BH/HSLA	---	6xxx	P
5% MR	140	BH/HSLA	---	6xxx	P
10% MR	---	BH/HSLA	---	6xxx	P
15% MR	---	Mg/HSLA	---	5xxx/6xxx	GF
Fender					
Current	140	BH/HSLA	---	6xxx	---
5% MR	140	BH/HSLA	---	6xxx	---
10% MR	---	BH	---	6xxx	---
15% MR	---	---	---	6xxx	P/CFRP
Engine Cradle					
Current	---	HSLA	---	---	---
5% MR	---	HSLA/CP	---	6xxx	---
10% MR	---	HSLA/CP	---	6xxx	---
15% MR	---	HSLA/CP	---	6xxx	---
Lower Control Arm					
Current	---	DP/HSLA/CP	---	6xxx	---
5% MR	---	HSLA/CP/FB	---	6xxx	---
10% MR	---	HSLA/FB	---	6xxx	---
15% MR	---	HSLA/CP/FB	---	6xxx	---
Rear Suspension					
Current	CI/270	HSLA	---	---	---
5% MR	---	HSLA	---	---	---
10% MR	---	HSLA	---	---	---
15% MR	---	HSLA	---	6xxx	---
Brake Rotor					
Current	CI/FC220	---	---	---	---
5% MR	CI/FC220	---	---	---	---
10% MR	CI/FC220	---	---	6xxx	---
15% MR	CI/FC220	---	---	6xxx	---

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Component/Material	Mild Steel	HSS/AHSS	HF Steel	Aluminum	Plastic/Comp (P/GF/CF)
Steering Knuckle					
Current	GI500	480	---	6xxx	---
5% MR	CI500	---	---	6xxx	---
10% MR	CI50	---	---	6xxx	---
15% MR	CI500	---	---	6xxx	---
Engine Head					
Current	---	---	---	Xxxx	---
5% MR	---	---	---	Xxxx	---
10% MR	---	---	---	Xxxx	---
15% MR	---	---	---	Xxxx	---
Fuel Tank					
Current	274	BH	---	---	P/PSF
5% MR		HSLA	---	---	P/PSF
10% MR		HSLA	---	---	P/PSF
15% MR		---	---	---	P/PSF
Instr. Panel Cross-Beam					
Current	270	DP/Mg	---	---	PSF
5% MR	270	Mg	---	6xxx	PSF
10% MR	270	---	---	6xxx	PSF/GFRP
15% MR	---	---	---	6xxx	PSF/CFRP
Seat Frame					
Current	---	HSLA/DP	---	---	---
5% MR	---	HSLA/DP/Mg	---	---	---
10% MR	---	HSLA/DP	---	5xxx	GFRP
15% MR	---	HSLA/DP	---	5xxx/6xxx	GFRP
Steering Shaft					
Current	---	CI/340	---	Xxxx	Nylon
5% MR	---	CI/340	---	Xxxx	Nylon
10% MR	---	CI/340	---	Xxxx	Nylon
15% MR	---	CI/340	---	Xxxx	Nylon
Wiring Harness					
Current	---	Copper	---	---	---
5% MR	---	Copper	---	Xxxx	---
10% MR	---	Copper	---	Xxxx	---
15% MR	---	Copper	---	Xxxx	---

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V. Technology Scoring and Industry Analysis

A scoring methodology was developed to assess the inherent level of overall lightweighting technology on the surveyed vehicle, to look at trends, and to compare vehicle technology levels. The inherent level of lightweighting technology, by component, is expressed as a score from 0 to 100. Relevant factors to assigning a score include:

- Expert opinion is used to look at all the material technologies identified in the surveys, by component, and then prioritize them relative to each other based on the material and application. The least advanced material application in this regard is set as the baseline (0) score, and the most advanced is set as 100.
- Materials with higher strength-to-weight ratios tended to be assigned higher scores. Therefore, high yield strength steels received higher scores than mild steels.
- Advanced metal grades for formability (e.g., DP or CP steels over HSLA, or 7xxxx aluminum over 6xxx) received higher scores than less complex materials because this allows for stronger materials to be used in more complex shapes/applications. Steel requiring hot forming receive higher scores than low strength cold stamped steels, as do composites and aluminum.
- The score of the lightweighting technology could be application dependent. Some materials will be introduced sooner to one application than to another one for a variety of reasons. So the same material may be old on one part, but state-of-the-art on another part. The assigned score had to recognize the use of the material on the specific application. Thus, the material assigned the baseline (0) score can differ for each component.
- In order to get a single vehicle score, a weighted average of the individual component scores was computed. The value of the weights assigned to the components depend on level of opportunity for lightweighting and crash sensitivity. For examples, lightweighting a floor will have higher impact on the curb weight of the vehicle than a fender, thus, floor has a higher weight than a fender. Also, crash sensitive structural components like A & B pillars have higher weights assigned.

Two materials that reflect application dependency mentioned above are mild 270 steel and DP 980. Mild 270 is an “old” technology for roof panels, but a middle technology for front door inners and floors. Mild 270’s initial application on the roof was to support dent resistance (e.g., from hail). Later it was applied to door inners and floors for lightweighting. New, state-of-the-art door inner and floor materials are now higher strength than 270. DP 980 was introduced to bumpers for lightweighting, but now is replaced by hot-formed steel and aluminum, so it is a middle technology on bumpers. However, it is now a state-of-the-art material (along with aluminum) for floors. Every component cannot use high strength steel because of formability issues. High strength steels tend to have lower elongation, which limits their application. It should be noted that not all components are driven by strength. For example, many panels are driven by sound transmission, and higher strength steels cannot be used to save mass beyond a certain level.

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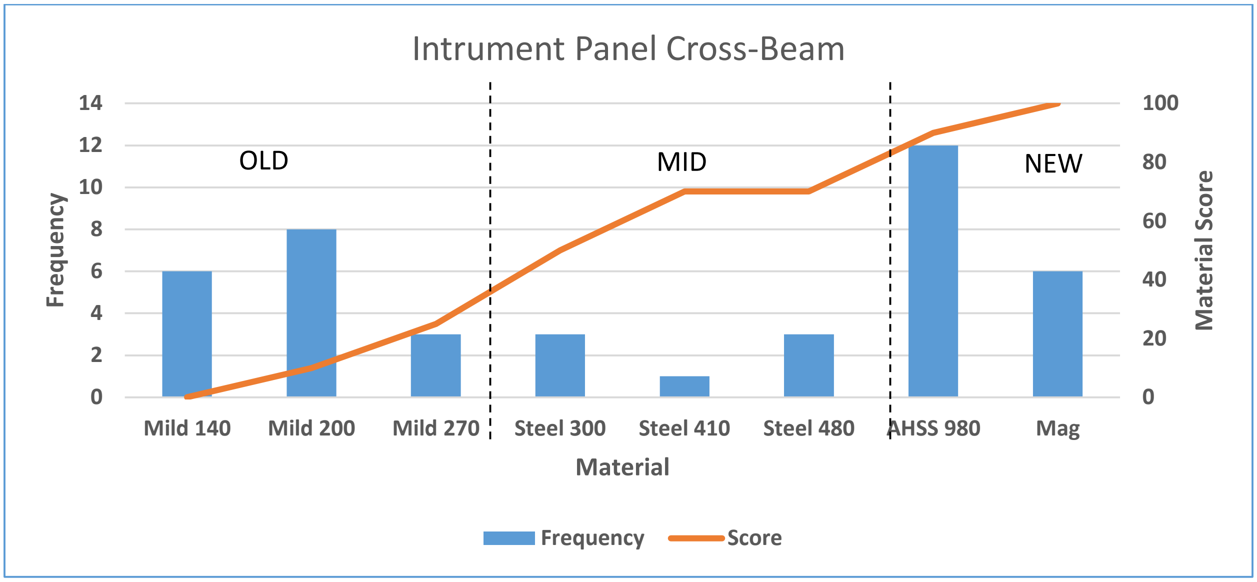
Figure 8: Material Frequency and Score for Instrument Panel Cross-Beam



As an example, Figure 8 shows material frequency (number of vehicles, primary Y axis) and the assigned scores (secondary Y axis) for the instrument panel crossbeam. It is evident that a high number of vehicles in the fleet today use advanced high strength steel or magnesium in the instrument panel cross-beam to save weight. Similar scoring charts for each component are shown in Appendix 3 - Technology Scores and Sample Frequency. The charts show the assigned technology scores for each of the 20 vehicle components and the frequency of occurrences by material type. The material types are also partitioned into three general groups, old, middle and new, based on the relative technology level of the materials used for this application. The higher strength-to-weight materials tend to be newer materials. In general, new materials are recognized as being mainstream materials within the past five years; the older materials would be over 10 years old.

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Figure 9: Lightweighting Technology Scores for 2015/2016 Model Year Vehicles (Small/Midsize/Large Car and CUV Combined; No Body-on-Frame Vehicles) with Comparison to the MY2011 Tear-Down Study Baseline by EDAG.

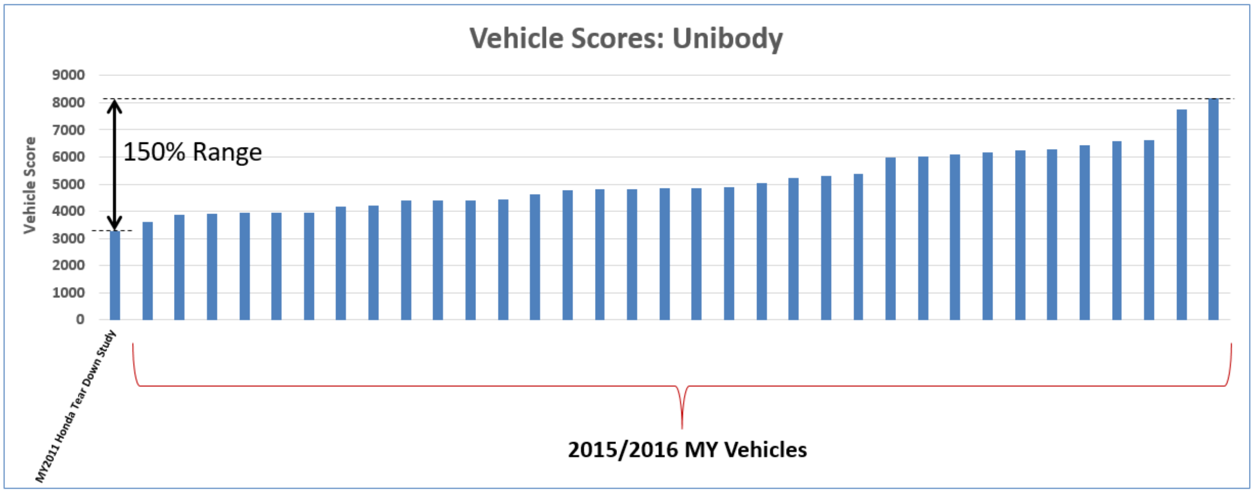

Figure 9 compares the lightweighting technology scores for the cars and crossover vehicles in the survey (excluding the body-on-frame vehicles). All the surveyed vehicle models are 2015/2016 model year. Also shown in the graph are the technology scores for the 2011MY Honda Accord. This vehicle was not in the survey and its score was derived independently by reviewing the materials from the teardown study conducted by EDAG.[14] Two key observations can be drawn from this chart:

- Every 2015/2016 model year car has a higher lightweighting technology score than the 2011MY vehicle. Thus, the 2011 vehicle is not representative of the material technology in the currrent fleet.
- The range in lightweighting technology scores of the surveyed vehicles is over double the score of the lowest vehicle.
- Figure 10 shows the statistical distribution of the vehicle scores. As expected, the distribution is spread out, indicating that the level of lightweighting technology varies greatly among the surveyed vehicles.

[14] Singh, Harry. (2012, August). Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025. (Report No. DOT HS 811 666)

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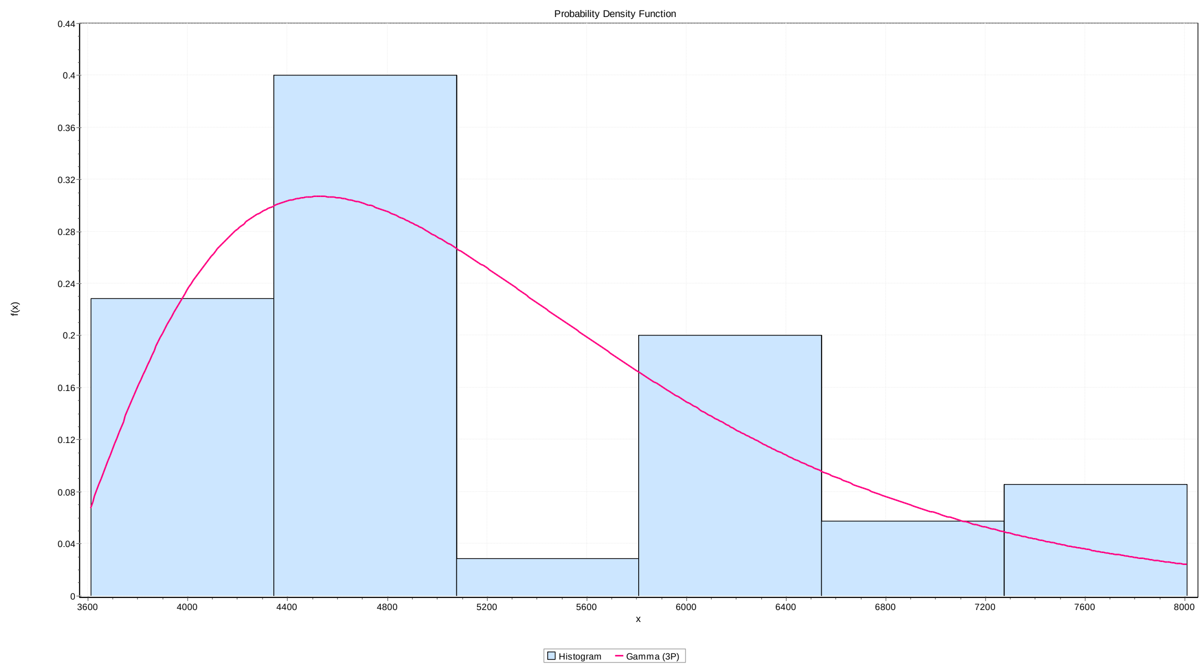
Figure 10: Statistical Distribution Fit of the Vehicle Scores (Cars & CUV Only)



In Figure 11 a chart is shown for the body-on-frame (BoF) vehicles that include light-duty pickup trucks and SUVs with frames. It shows the lightweight technology scores in contrast with the 2011 Silverado truck studied by FEV.[15] As in the case with the 2011 Honda Accord, the 2011 Silverado was not in the CAR survey and its score was derived by reviewing the materials from the teardown study conducted by FEV.

Observations of the body-on-frame scores:

- The range in lightweighting technology scores of the surveyed BoF vehicles is four times the score of the lowest vehicle. The low score of 1500 and the high score of 7500 giving a range of 6000. As expected, the level of lightweighting technology varies greatly among the surveyed vehicles.
- The range in technology from the lowest to the highest is much greater than the range for cars. This is likely because of the longer product life of the BoF vehicles than cars' product life.
- Every 2015/2016 model light-duty BoF vehicle in the survey has a higher lightweighting technology score than the 2011MY BoF vehicle. Opportunities for mass reduction have already been taken on these vehicles, leaving those opportunities unavailable for yet more mass reduction in the future.

[15] Mass Reduction and Cost Analysis - Light-Duty Pickup Truck Model Years 2020-2025, Techncial report, EPA-420-R-15-006, June 2015

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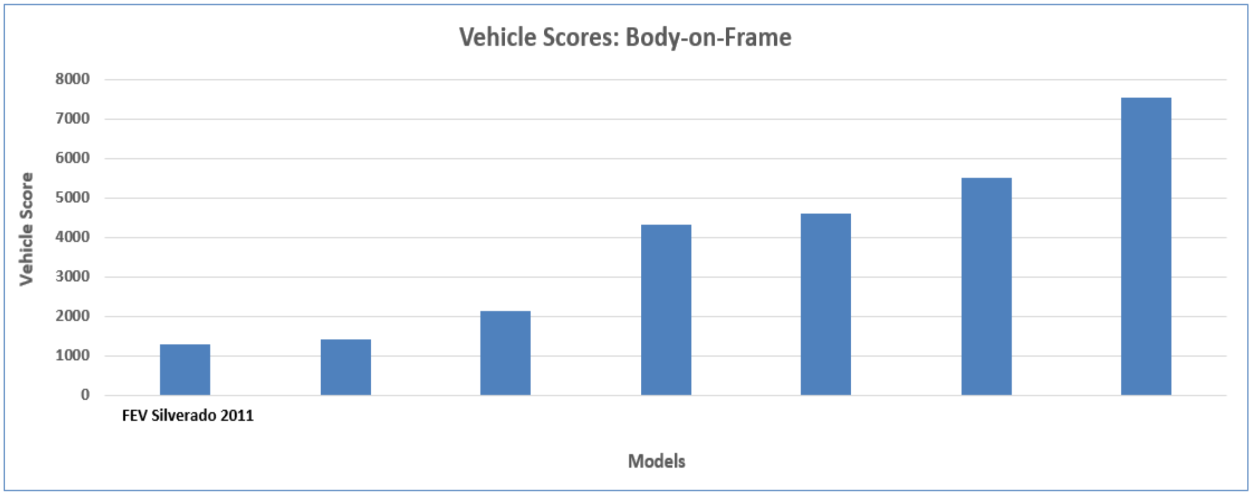
Figure 11: Lightweighting Technology Scores for 2015 Body-on-Frame Vehicle Models with Comparison to the 2011 Silverado that was a Tear-Down Study by FEV



Although the survey only collected data on 2015/2016 model year vehicles, many of these vehicles were initially launched in previous years. The launch year is important because other than minor upgrades made since the launch, much of the vehicle's architecture is established in the year of the initial platform launch, reflecting the lightweighting technology at the time. Launch year was provided in the survey, and Figure 12 and Figure 13 shows the average lightweight technology score for the vehicles in each year beginning with 2007. As expected, the lightweighting score trend increase each year, reflecting the addition of lightweighting technology both in unibody and body-on-frame vehicles. Body-on-frame vehicles, which include light duty pickups and SUVs, shows a faster rate of material technology deployment, most of which is to achieve better fuel efficiency while improving safety, NVH, and drivability, and thereby providing a better customer experience. The use of advanced materials in the industry has been increasing in recent years and is expected to continue at an accelerated pace.

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Figure 12: Average Level of Lightweighting Technology Score by Year of Vehicle Launch for Cars. The Regression Shows a Strong Positive Correlation Between Launch Year with Vehicle Scores[16]

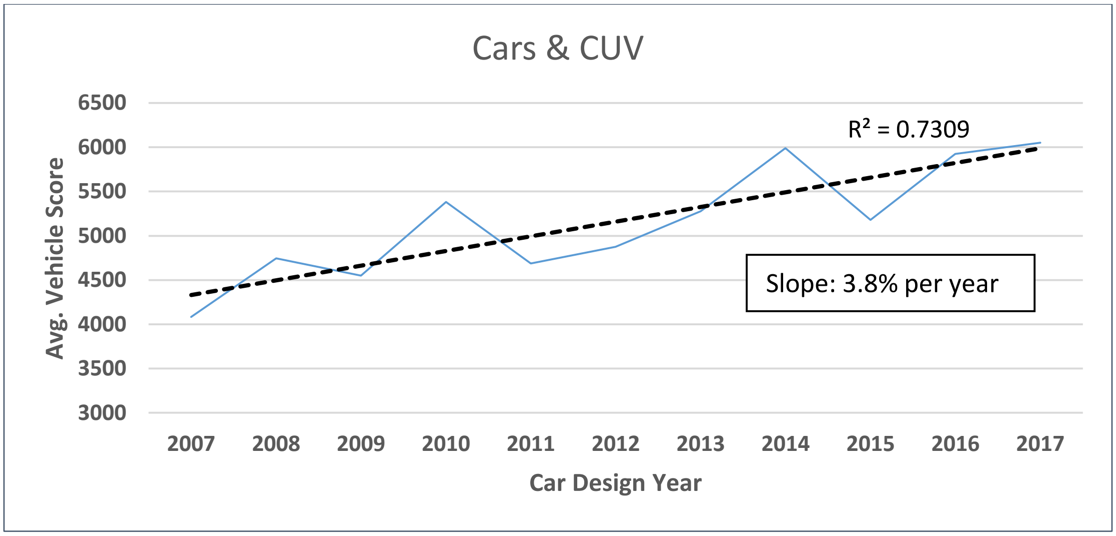

Figure 13: Average Level of Lightweighting Technology Score by Year of Vehicle Launch for Body-on Frame. The Regression Shows a Strong Positive Correlation Between Launch Year with Vehicle Scores.

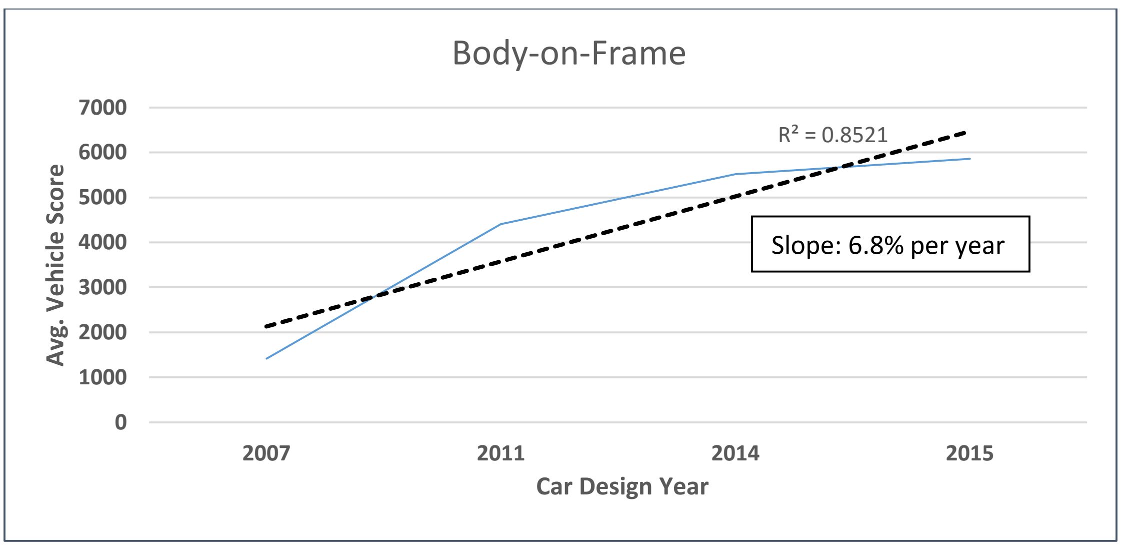

Figure 14 shows the sales-weighted vehicle technology scores for cars and CUVs of the surveyed models with the 2011MY Honda vehicle used in the tear-down lightweighting cost study by EDAG[17] and the

[16] Although the CAR survey asked data for 2015 model year vehicles, some manufacturers submitted data for 2016 or 2017 because the new model of the vehicle had been launched.

[17] Singh, Harry. (2012, August). Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025. (Report No. DOT HS 811 666)

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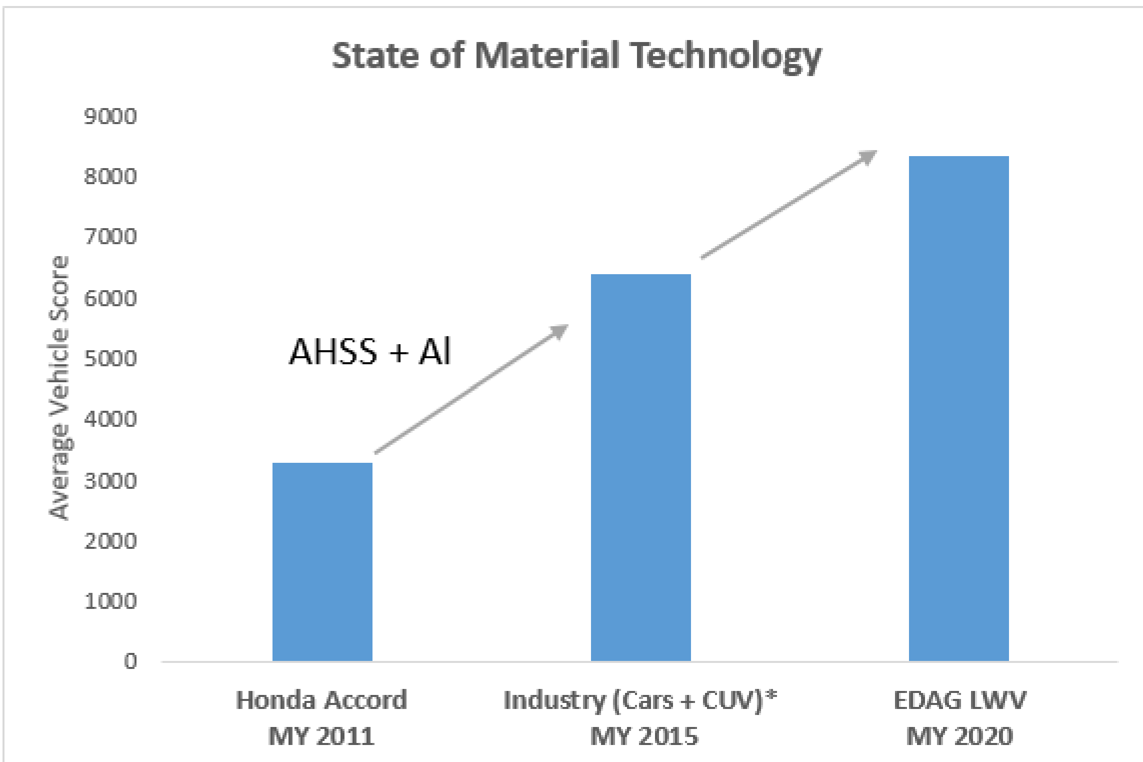
2020MY lightweight vehicle (LWV) solution proposed in the same study. The analysis illustrates that the industry has been applying advanced material technologies at the anticipated rate over the past several years and is about half-way to the proposed MY2020 lightweight vehicle solution proposed by EDAG. The lightweight EDAG vehicle has an advanced high strength steel body, aluminum closures and fenders, and magnesium instrument panel beam and front seat frame.

Figure 14: State of Material Technology
(Based on CAR's Technology Scores, Sales Weighted, CAR Survey)



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The lightweighting scores were categorized into three technology vintages, new, middle, and old, representing vintages of approximately: less than 5 years, 5 to 10 years, and greater than 10 years respectively. Combining the frequency of technology applications by vintage resulted in two-thirds[18] of the lightweighting technologies falling within the middle to state-of-the-art vintage, or under 10 years (see Figure 15).

Figure 15: Distribution of the Age of Lightweighting Technologies in Today's Cars.
Two-Thirds of the Technologies have been Deployed within the Past 10 Years.

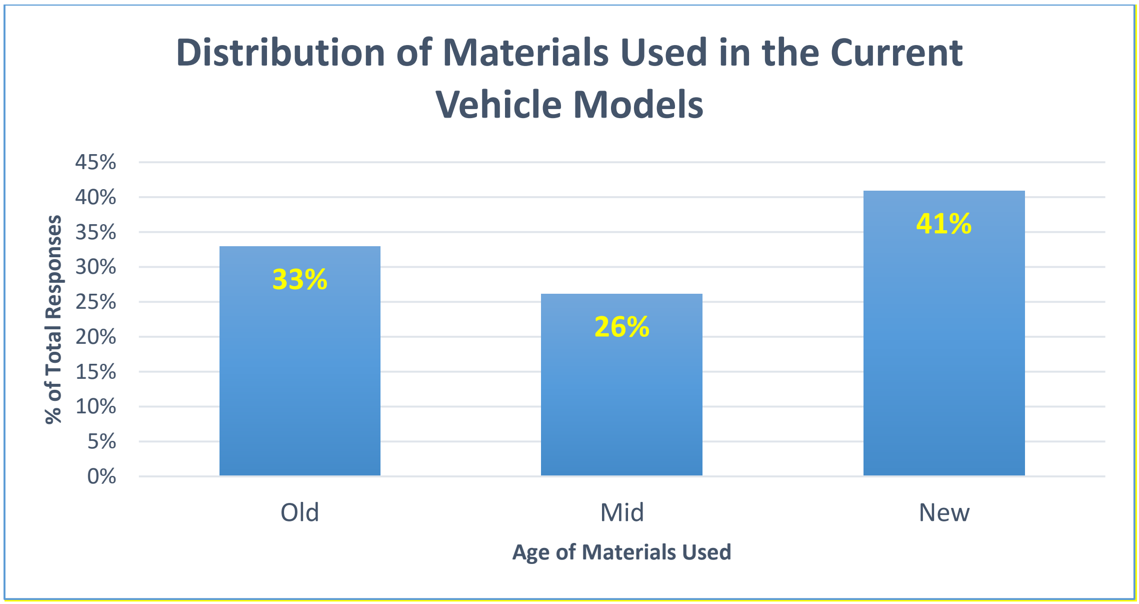

Table 10 shows level of technology in some specific components. The components with 40% or more old technology (percentage of responses) offers future lightweighting potential. However, material strength is restricted in some components (such as the roof panel due to formability, dent resistance etc.). A likely option to lightweight such components is to substitute steel with aluminum or composites, which is not always cost effective or may have supply chain issues because of global platforms.

[18] Two-thirds of the 20 components surveyed for 42 vehicles

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Table 10: Level of Technology in Components

40% or More New Technology (% of Responses)	**40% or More Old Technology (% of Responses)**
Steering Shaft	Roof Panel
B Pillar	Decklid
A Pillar	Fender
Front Bumper Structure	Steering Knuckle
Engine Cradle	Floor
Instrument Panel Cross-Beam	Wiring Harness
Hood	
Fuel Tank	

VI. COSTS

The industry broadly accepts that there are many options to lightweight mainstream vehicles in today's fleet. While there are many barriers that limit the pace of cost-effective implementation, given enough funding and time, most barriers can be overcome. Out to 2025, the lightweighting pathways, summarized in this report, focus on applying mixed materials with: higher strength steel, aluminum, and reinforced composites. Other materials, such as plastic and magnesium have an important but smaller role.

Cost estimates to lightweight ($/pound) were not requested in the technology survey. The cost to apply technologies across different companies can be very different because of differences in an organization's knowledge base, infrastructure, and accounting methods that make comparisons of cost problematic. For the purpose of a qualitative cost analysis this study uses the cost analysis in the updated EDAG study [19] on the 2011MY Honda Accord (baseline) which was updated after Honda's comments (see Figure 16). The original solution (LWV 1.0) was disputed by Honda because the proposed modifications compromised safety and performance. The point labeled LWV 1.2, AHSS BIW & Aluminum Closures & Chassis Frames at the cost of $1.2/kg, is the final proposed solution in the updated study. Honda did not comment on the

[19] Singh, H., Kan, C-D., Marzougui, D., & Quong, S. (2016, February). *Update to future midsize lightweight vehicle findings in response to manufacturer review and IIHS small-overlap testing* (Report No. DOT HS 812 237). Washington, DC: National Highway Traffic Safety Administration.

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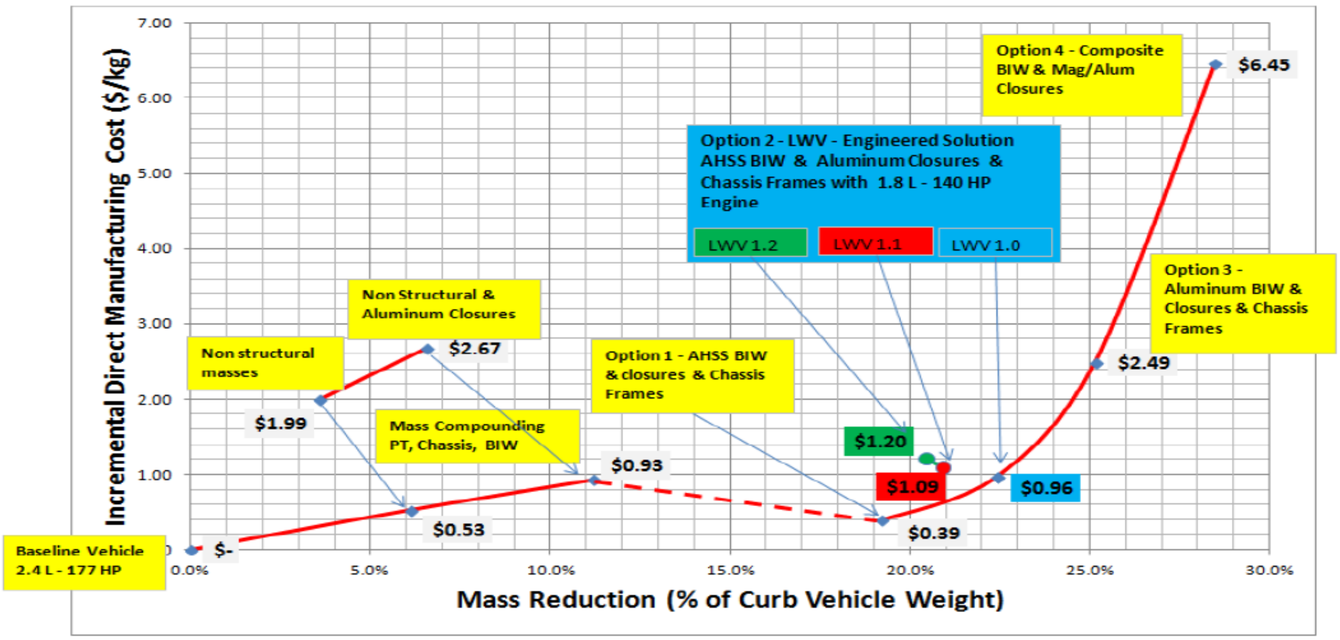
costs. Based on the learnings from the CAR survey, several adjustments should be further made to the cost curve:

- The fleet baseline technology has continued to evolve since 2011. An estimated fleet baseline will be suggested.
- Barriers to implementation have not been captured by the EDAG study.
- Mass decompounding does not reflect industry estimates by 50%.
- Mass add-back is not recognized by the EDAG study.

Figure 16: Cost Curve Produced by EDAG for Lightweighting the 2011 Honda Accord



Source: EDAG Honda Accord MY2011 study, Singh, Harry. (2012, August)

Baseline

Option 1 shown in Figure 16 maximizes use of AHSS in the body structure and closures to achieve a 19% lighter vehicle for 0.39 $/kg. (0.17 $/lb.). The AHSS mix includes very high tensile steel (up to 1500MPa), TRIP, CP, martensite, boron, dual phase and HSLA, etc. (see Figure 17). The closure panels are also steel. Option 1 is suggested by the EDAG study as a cost-effective initial solution to advance vehicle structures with high strength steels. CAR's survey indicates that the majority of the 2015 survey vehicles use these steels today throughout their structure. Survey responses show this in the A & B pillars, instrument panel crossbeam, and hood (see Appendix 3 for steel grade distribution and frequency, and Figure 18). Not all surveyed vehicles have fully exploited this level of technology, but the 2015 survey vehicles are well ahead of the 2011 baseline vehicle studied by EDAG, and some have already achieved the level of AHSS steel technology described as Option 1.

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Figure 17: Comparison of 2011 Materials for BIW Structure for Honda Accord Baseline Vehicle Versus Materials for the Lightweight Vehicle Design (Source: EDAG study).

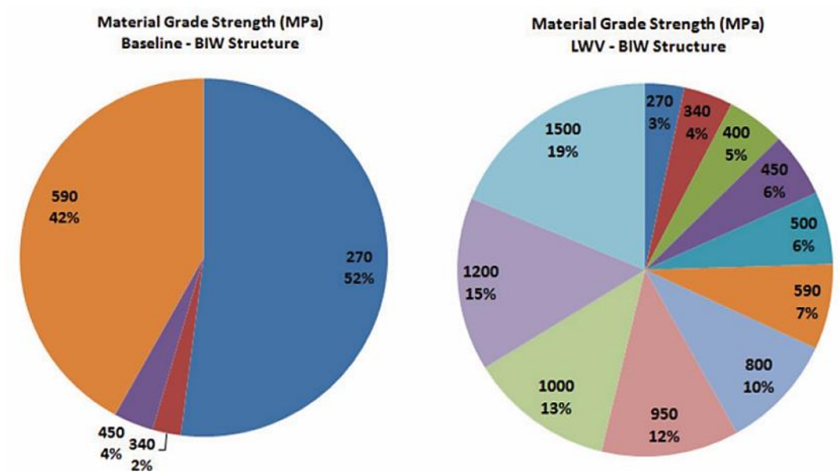
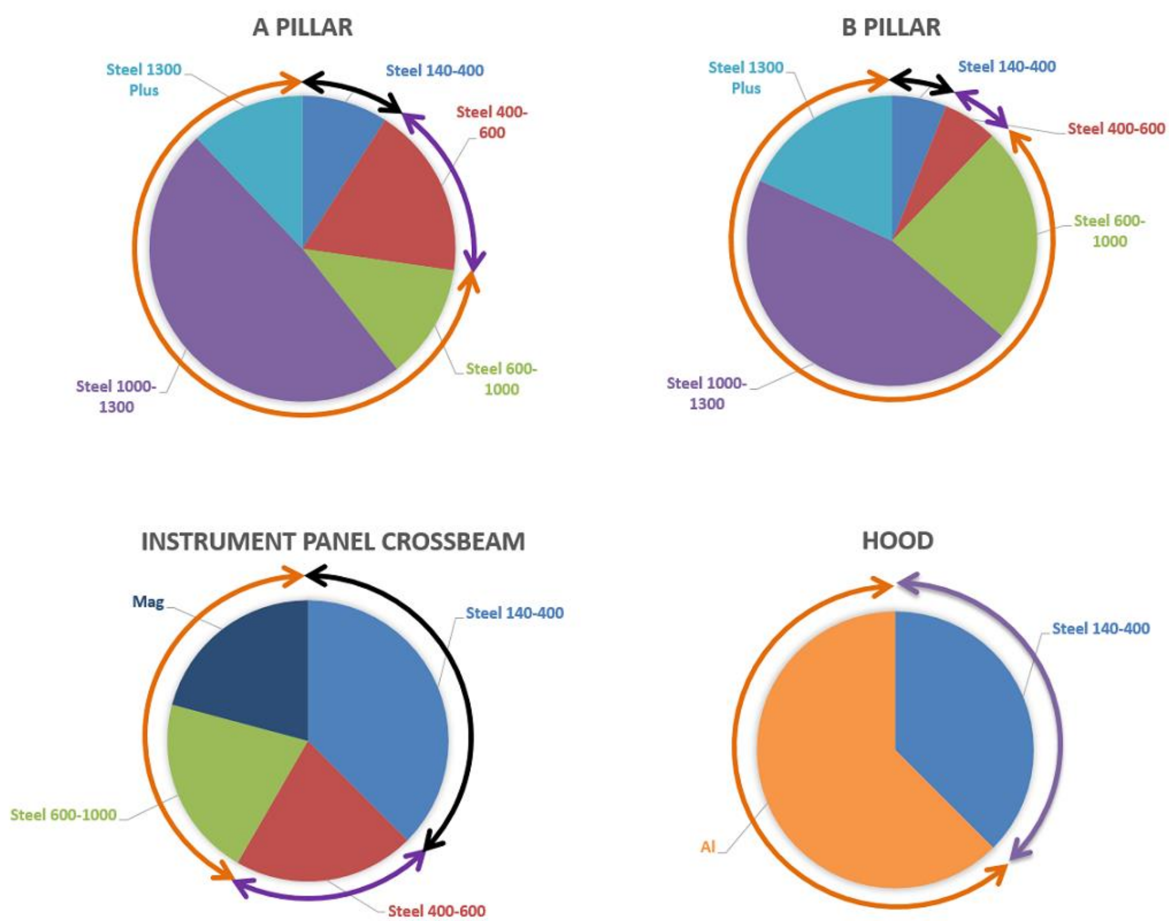


Figure 18: Material Use in Four Key Vehicle Components Shows Broad Use of Advanced Metals in the Surveyed Vehicles, CAR Survey



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Barriers to Implementation

Recommendations for AHSS materials in the EDAG study focused on materials that would be expected to be available in 2020. ***Material availability*** is an incomplete threshold of acceptability for automotive mass production, and a number of barriers that delay implementation for large-scale use are cited in the Barriers to Lightweight paper (CAR, 2016[20]). Major issues include: global availability, material qualification, digital modeling software, supply chain development (prototype, tooling, and a robust material supply), etc. The CAR Barriers study mentions how the qualification process for some materials often exceeded 10 years for some metals that are in today's vehicles. While it is difficult to quantify the impact of these barriers on cost, the major impact is on timing. **Advanced materials available in 2020 will not be ready for adoption into the car for several years after they initially become available.**

Mass Decompounding

Under optimal conditions on paper studies, levels of mass decompounding have been shown to approach 40%. Decompounding comes from down-sizing components as the weight elsewhere in the vehicle is reduced. Components that are recognized for decompounding have typically included: engine, transmission, fuel tank and brakes. The survey responses suggested that these conditions seldom exist where 40% decompounding can be realized. The ideal conditions are constrained because of vehicle model variations, non-continuous choices of off-the-shelf technology (engines, transmissions, etc.) cannot be optimized for a vehicle, and aggressive program timing all inhibit the ability to design optimal, mass-decompounding vehicles. In most cases, without significant weight reductions, the cost and time required to apply decompounding is not practical. Survey estimates suggested that the opportunity is in the order of 20% for decompounding, but only for major vehicle weight reductions. "Major weight reductions" was not defined by the survey responses, but a net weight reduction of 10% or more is supported by the NAS report[21].

Mass Add-Back

In estimating the cost to lightweight, no provision is made to allow for advancing the performance of existing vehicles in the tear-down studies. Competitive and customer requirements demand performance improvements for ride and handling, crashworthiness, drivability etc. The summary of the survey assessment was that between 2015 and 2025, 5% (rounded up from 4.86%) weight (see Table 7) would be required for mass add-back. If a net improvement of 10% weight reduction is needed, then 15% weight reduction technology would need to be applied.

Much of the lightweighting technology for the surveyed vehicles is approximately at the AHSS level in Option 1 of the EDAG study (see Figure 16). The lightweighting pathway past this level will be the application of additional AHSS/UHSS as it becomes available, and additional aluminum and reinforced

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[20] Baron J., Identifying Real World Barriers to Implementing Lightweighting Technologies and Challenges in Estimating the Increase in Costs, January 2016

[21] National Research Council. *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. Washington, DC: The National Academies Press, 2015. doi:10.17226/21744

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plastics. Both the industry response and the EDAG lightweighting pathway are consistent with the mixed material approach. Attributes of Option 2 in the EDAG study are:

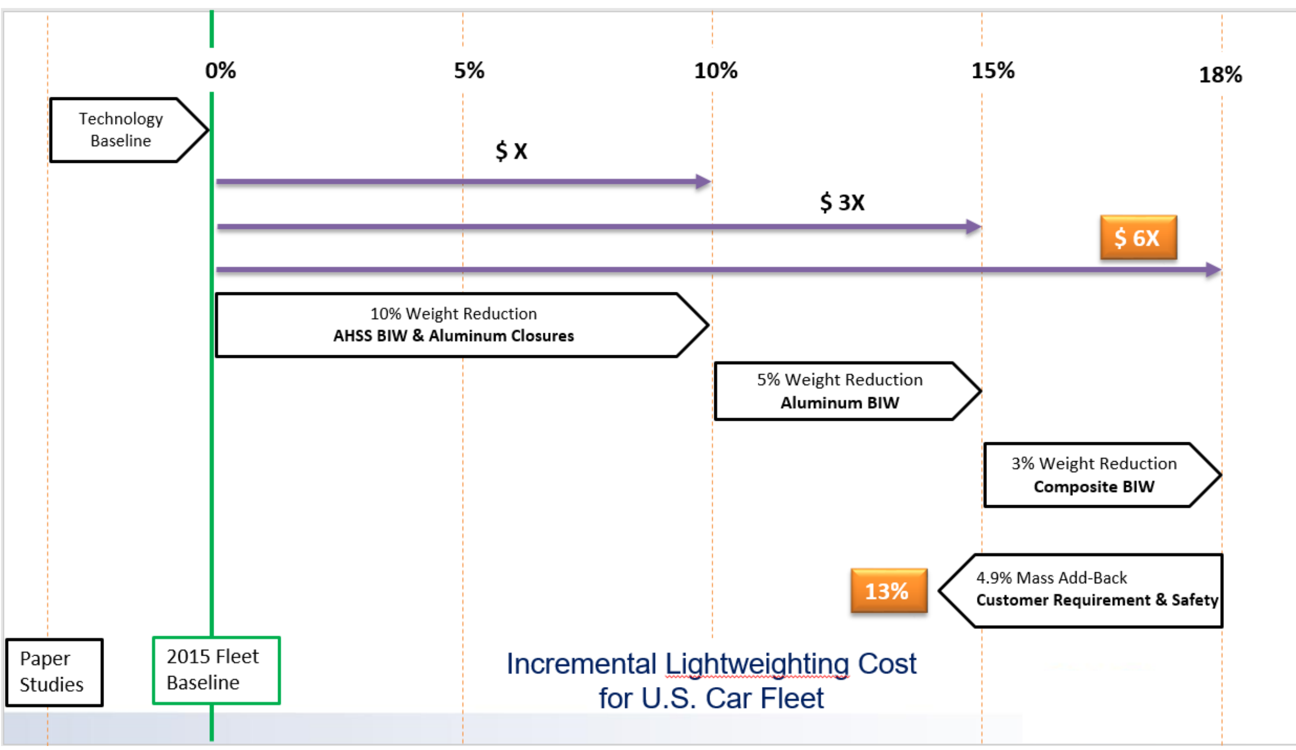
- Continue introducing AHSS/UHSS
- Addition of aluminum in the doors, fenders, decklid, and engine cradle
- Use of magnesium for instrument panel beam and front seat frame
- Addition of reinforced composites, such as into the rear floor panel

Figure 4 shows that aluminum doors are broadly being introduced across most vehicles, even with minimal (5%) lightweighting objectives. A review of Table 9 component pathways shows similar trends introducing aluminum and composites in the floor, roof, and other components.

Generic Lightweighting Cost Analysis

Having established the technology baseline for the current fleet and the overall vehicle technology pathway, a generic lightweighting cost analysis can be done based on the incremental cost observed in the teardown studies after adjusting for the real world constraints mentioned previously. Since the CAR survey did not ask for the cost numbers, the results will be limited to the differences for incremental mass reduction percentages. Absolute cost numbers are highly dependent on the manufacturer and is out of scope for this study.

Figure 19: Incremental Cost to Lightweight



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General cost estimates can be gleaned from the EDAG study by making adjustments for real-world conditions. For this analysis, it is assumed that a 10% weight reduction (5% net accounting for mass-add back), starting at the 2015MY fleet technology baseline, would incur a cost of "X" dollars per kilogram (see Figure 19). At this stage, the fleet would likely have advanced AHSS BIW and aluminum closures. For an additional 5% in lightweighting, the BIW needs to be more aluminum intensive, and the cost would be 3X $/kg. (2X delta). Another 3% weight reduction could be achieved by introducing a composite BIW structure. Accounting for 5% mass add-back for safety and customer requirements, a net 13% weight reduction from the 2015MY baseline could be achieved; a manufacturer would pay six times X for making this move. Thus, a 13% net mass reduction can be realistically attained for 6X $/kg.

Based on manufacturers' opinion on model year 2025 vehicle technologies, it can be surmised that the majority of the vehicles will have an AHSS BIW, aluminum closures, and magnesium in a few components like the instrument panel beam. Thus, from 2015 to 2025 the fleet is expected to achieve an estimated net mass reduction of 5%.

VII. SUMMARY

1. The cost-effective (business case) technology pathway to lightweighting vehicles is generally consistent within vehicle segments across auto companies. The teardown studies funded by the regulating agencies outline pathways that are consistent with industry strategies. Briefly, the pathways encompass the following progressions, most often with several of these steps being pursued for a specific vehicle:
    a. Movements from milder steel to higher strength steels (that are down-gauged)
    b. Increasing amounts of aluminum, particularly in closure panels (hood and decklid)
    c. Aluminum doors and additional aluminum throughout the vehicle
    d. Increasing use of composites and magnesium throughout the vehicle
    e. Aluminum intensive structures (body-in-white)
    f. Additional use of composites in structural areas

    The incremental cost to reduce weight increases through this pathway, which is one of the limiting factors to weight reduction. The technologies in each of these steps can improve over time and the associated costs can vary either higher or lower, thus affecting the business case to use the technology. Current lightweighting priorities focus largely on introducing aluminum for the hoods and in some cases fenders, and this priority is followed by adding aluminum doors and decklid. There is also a focus on increasing the steel strength, often using hot-formed steels, such as for the A and B pillars and in the engine cradle. Additional composites are also anticipated.

2. Vehicle performance and safety (e.g., crashworthiness) have improved greatly over time as a result of improving design and adding new material technologies. Performance attributes include, for example, ride quality such as quietness of ride, structural stiffness, and smoothness of ride (absence of vibrations). Reducing vehicle weight can help these attributes, but other factors also important include mass distribution (e.g., center of gravity), sprung versus un-sprung mass, and noise mitigation strategies such as sound dampers, etc. Additional vehicle content is also

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demanded by consumers for electronics and infotainment. To respond to the market, automakers project incremental mass requirements for performance and safety through 2025 to add 4.9% and 4.6% for cars and trucks, respectively. Consequently, vehicle design technology to reduce weight by, for example 5% net, requires lightweighting technology objectives to achieve 9.9% and 9.6% for cars and trucks, respectively after performance and safety requirements are met.

3. New, lightweighting technologies are added to vehicles over time complicating the comparison of technologies on randomly chosen vehicles. The opportunity to add the most cost-effective technology occurs when a new model architecture (platform) is designed. Vehicle platforms can exist for as little as a few years, or can be extended for twenty years or more. Once designed, smaller incremental improvements in technology are practical. Most vehicles are designed with a combination of existing (carryover) and new designs because of resource constraints. Very few vehicles are designed completely with all new technologies and have the opportunity to "optimize" the design. When evaluating lightweighting opportunities with one vehicle (e.g., a teardown) and extrapolating its cost curve to another vehicle requires consideration for where the vehicles are in their product life cycle as well as the design strategy used for that vehicle. Benchmarking an old design that used carryover technology (i.e., sub-optimized) and applying that cost curve to a newer vehicle that may be a better optimized design, will under-state the cost to achieve lightweighting on the new vehicle.

4. Lightweighting technologies are advancing every year and the industry "learns" with each technology, resulting in cost reductions over time. But one learning factor cannot be applied uniformly to all lightweighting technologies since each start with different histories of experience, and different future rates of deployment from which to learn from. The traditional steel-based infrastructure has been the foundation for the industry for 100 years, but with progress in use of advanced and ultra-high strength steels, learning continues in tool making, fabrication, and joining of these metals. Aluminum has less learning associated with it because the material properties, unlike steel, have not changed as much with multiple grades or forming technologies. Magnesium is advancing as its applications grow from die-cast to possible sheet forms, which are not widely used today but could be used if developed. Composites have the largest learning curves of all the materials. The appropriate learning curve to use for lightweighting depends where the vehicle is on the technology pathway. There is not a single learning curve that is applicable to all lightweighting. Since the current lightweighting pathway is emphasizing AHSS/UHSS and aluminum, the learning curves should emphasize learning from these materials and less so on the others.

	Time Period	**AHSS/UHSS**	**Aluminum**	**Magnesium**	**Composites**
AVERAGE % cost reduction/year	2012-2021	1.21%	0.79%	1.08%	1.50%
	2022-2027	0.69%	0.69%	0.42%	1.47%

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5. Estimates to implement new lightweighting technologies have typically focused on identifying pathways and estimating direct manufacturing cost. There are additional "real world" constraints that impact a company's decision to implement a new technology. A discussion of constraints is provided in the CAR report, "Identifying Real World Barriers to Implementing Lightweighting Technologies and Challenges in Estimating the Increase in Costs," January 2016.

   Capital investment was identified as the leading barrier to adding new lightweighting technology. The investment for equipment needed to form parts (e.g., form tools, stamping or molding), assemble parts (e.g., fixtures, robots, joining, automation), and paint parts (i.e., the paint shop) can all be affected by the material choice. Traditionally, these processes have been designed to accommodate mild steel. Other challenges involve capacity (matching production rates with different material processes), design (modeling and integration into the structure), and qualification of new materials are additional challenges. While many of these challenges can be overcome, they require capital resources and sometimes extensive development time.

   Survey responses support the concept of mass decompounding for major (greater than 10%) lightweighting initiatives. However, since very few vehicles, if any, are ever fully "optimized," the opportunity to decompound is less than 40% as suggested by some of the independent teardown studies. Optimizing all the components and systems in the vehicle to achieve 40% decompounding is not practical in most cases for the same reasons that vehicle optimization is not practical on all vehicles. The survey estimates that about 20% decompounding is feasible when the weight reduction is over 10%.

6. Vehicles are progressing rapidly with lightweighting technologies and there is a large range in technology levels for the forty-two vehicles in the survey. Each of the forty-two vehicles is a unique baseline with its own incremental cost to further reduce weight. It is likely that a large range in lightweighting cost ($/lb) is necessary to encompass the entire fleet. In order to generate a single fleet average cost, a weighted average using each vehicle's starting baseline and individual vehicle sales volume would be one approach.

7. According to the lightweighting technology scores, each of the 2015 survey vehicles has made progress implementing lightweight technology beyond the 2011 Honda Accord example studied by EDAG. None of the survey vehicles are at the baseline of the Accord and most are near the Option 1 level of technology on the EDAG chart (AHSS body-in-white and closures and chassis frames). 80% of the survey responses have indicated that they are proceeding toward Option 2 by adding additional aluminum (e.g., into the doors) and higher strength steels. Additional composites will be used, but not in structural areas. Much of the fleet is at the exponentially increasing portion of the cost curve, and vehicles are not expected to move much beyond this point by 2025. The estimated overall net weight reduction from 2015 to 2025 is approximately 5%.

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8. A more balanced analysis sensitive to industry constraints can be developed by combining industry data with Agency analysis. The industry data from this study establishes the technology baseline for one-half of the U.S. vehicle fleet. With adjustments to establish the baseline for the entire U.S. fleet, this data can be used to establish a distribution of lightweight technology to overlay with the idealistic lightweighting teardown studies. The 2011 Honda Accord and 2014 Silverado studies would be improved by using the fleet distribution for the starting baseline. Real-world estimates for the timing to overcome barriers, vehicle development programs, the ability to decompound, and the need to maintain competitive requirements for drivability can be incorporated to establish a distributional result that recognizes real-world constraints. A sensitivity analysis could also incorporate the effects of learning.

9. There is a significant range in vehicle performance across the fleet. Traditionally, different manufacturer philosophies have emphasized different performance attributes, such as: safety, drivability, luxury etc. Vehicles by different manufacturers may have greater or less opportunity to reduce mass while maintaining their current level of performance. Some vehicles may already be far up the technology curve, but are proportionately heavy, and to reduce weight requires significantly greater costs than a vehicle with less performance. Overall, the heterogeneity of the industry will result in some automakers affected to a much greater extent than others. Evaluating this impact may be important.

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VIII. APPENDICES

1. General Lightweighting Strategy Survey
2. Vehicle Model-Specific Survey
3. Frequency Histogram and Technology Scoring Charts

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Appendix 1 – General Lightweighting Strategy Survey

1. Please rank your current priorities or opportunities for mass reduction by vehicle system category, as provided below (1=highest, 6=lowest):

Rank	Systems
	Closures : e.g. hoods, front doors, rear door, decklid
	BIW : e.g. pillars, floor, fenders, shock towers, frame (if light-truck)
	Unsprung Mass : e.g. wheels, suspension, brakes
	Non-Structural : e.g. shock tower, exhaust system, glazing
	Interiors : e.g. seats, trim, instrument panel, switches, electronics
	Components : e.g. power-steering, HVAC, electronics, starter motor

2. Please rank your priorities or opportunities for mass reduction by component, using the above categories (1=highest), and list all other components that in your view should be also included based upon their impact on overall vehicle curb weight:

Rank	**Closures**	*Rank*	**BIW**	*Rank*	**Unsprung Mass**	*Rank*	**Non-Structural**	*Rank*	**Interiors**	*Rank*	**Components**
	Hood		A Pillar		Wheels		Radiator		Seats		Power-steering
	Fenders		B Pillar		Suspension system		Exhaust system		Trim		HVAC
	Front Doors		C Pillar		Brakes		Glazing		Instrument Panel		Electronics
	Rear Door		Floor		Tires		Other ________		Other _________		Starter motor
	Decklid		Engine Cradle		Other ________		Other ________		Other _________		
			Shock Tower		Other ________		Other ________		Other _________		
			Frame (Light-Truck)								

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3. The National Research Council report[22] on cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles assumes that no mass decompounding[23] will happen until 10% mass reduction level is achieved. Beyond 10% mass reduction level, 40% decompounding for cars and 25% for trucks is assumed. Do you agree with this assumption? If not, then please explain.

4. Please provide your expectations for 'learning curves' as they relate to mass reduction (NHTSA defines learning curves as 'cost reductions through manufacturing learning'):

Time Periods (Model Years)	**NHTSA: Learning Curve – Mass Reduction *(% per year)****	***Please estimate if different:***				***Please provide key assumptions related to the estimate:***
		AHSS/UHSS	*Aluminum*	*Magnesium*	*Composites*	
MY 2012-2021*	3% *(Note: Total = 34.4% over 10 yr period, assuming 3% compounded annually)*	*%/year*	*%/year*	*%/year*	*%/year*	
MY 2022-2027	2% *(Note: Total = 12.6% over 6 yr period, assuming 2% compounded annually)*	*%/year*	*%/year*	*%/year*	*%/year*	

** Source: NHTSA, VOLPE Model assumptions for mass reduction for all vehicle segments, including passenger cars and light trucks*
NHTSA estimates are provided for reference

Space provided for additional comments (optional):

[22] National Research Council. Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles. Washington, DC: The National Academies Press, 2015. doi:10.17226/21744 http://www.nap.edu/read/21744/chapter/1

[23] Decomponding = Secondary Mass Reduction / Primary Mass Reduction

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5. Please estimate the impact of incremental mass on overall vehicle mass for safety, comfort features, as well as improved vehicle performance attributes from MY-2015 (Baseline) to 2025 required to meet regulations and company objectives:

<table>
<tr><th rowspan="2">Add-Back Category</th><th rowspan="2">Description</th><th colspan="2">Mass MY2015 (Baseline) thru MY2025</th><th rowspan="2">Please provide key assumptions related to estimates:</th></tr>
<tr><th>Passenger Cars
(Avg. % of curb weight/Vehicle)

3,500 lb car</th><th>Light Trucks
(Avg. % of curb weight/Vehicle)

5,300 lb truck</th></tr>
<tr><td>Safety</td><td>-Crashworthiness required for safety standards thru 2025, e.g. subframe, dashboard/IP, side & rear
-Active Safety (electronics)</td><td>%</td><td>%</td><td></td></tr>
<tr><td>Performance & Comfort</td><td>- Stiffness

-NVH

-Ride and Handling etc.</td><td>%</td><td>%</td><td></td></tr>
</table>

(Typical answer is likely less than 1%)

Space provide for additional comments (optional)

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6. Please rank the most significant barriers as you see them to achieving threshold volume, as defined as 450,000 units/year, for the following lightweighting technologies by 2025:

Materials	**Mfg. Capacity Constraints**	**Qualification Process Requirements**	**Uncompetitive Supply Base**	**Design Constraints, i.e. Global Platform Requirements**	**Capital Investment Requirements**
	Please Rank: 1-5 (1= Greatest, 5=Lowest)				
Steel – AHSS & UHSS					
Aluminum					
Magnesium					
Carbon Fiber Reinforced Plastics (CFRP)					
Glass Fiber Reinforced Plastics (GFRP)					

Space provide for additional comments (optional)

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Appendix 2 – Vehicle Model-Specific Survey

Instructions Sheet

General Instructions

1. Please indicate the material and grade of the most used material in the component if it is mixed material.
2. The material description should be of the highest performance package offered for the vehicle, including largest engine (displacement) available and premium options package.
3. The closure panels (hood, deck lid, doors) mentioned here does not include hinges, or other attachments.
4. BIW weight should not include weight of closures.
5. Every mass reduction percentage is based on the current model year, not incremental.
6. Please refer to the acronyms listed on the next page.

Assumptions

1. No degradation in vehicle performance (stiffness, crash worthiness, NVH etc.).
2. Vehicle should meet the current safety standards.

Definition of Terms

1. **Direct Manufacturing Cost (DMC):** Cost excluding indirect and overhead expenses due to warranty; research and development; depreciation and amortization; repair and maintenance; general and administrative; retirement; healthcare; transportation; marketing; dealer selling; and profit.
2. **Body-In-White (BIW)**: Body-In-White refers to the stage in automotive manufacturing in which the vehicle's body sheet metal components have been welded together. BIW is without including closures.
3. **Closures** : deck lid, doors, and hood
4. **Torsional stiffness (N-m/deg.):** Torsional stiffness is determined when a static moment is applied to the body-in-white at the front shock towers when the rear shock towers are constrained.
5. **Mixed-Material Component**: Two or more parts made of different materials such as steel & aluminum etc.
6. **UTS (MPa):** Ultimate tensile strength (UTS) is the maximum stress that a material can withstand while being stretched or pulled before failing or breaking. Expressed in terms of Mega Pascals.
7. **Curb Weight :** The weight of an automobile without occupants or baggage

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Material Grades and Acronym

Steel

Category	Steel Type	Description	Yield Strength Range (Mpa)	Ultimate Tensile Strength (Mpa) Range
Baseline	Mild	Mild Steel	140	270
High Strength Steels	IF	Intersitial Free	260-300	410-420
	BH	Bake Hardenable	210-280	340-400
	HSLA	High-Strength Low Alloy	350-700	450-780
Advanced High Strength Steels	DP	Dual Phase	210-1150	440-1270
	FB	Ferritic-bainitic (SF - stretch flangeable)	330-450	450-600
	CP	Complex Phase	500-1050	800-1470
	MS	Martensitic	950-1250	1200-1500
Ultra High Strength Steels	TRIP	Transformation-induced plasticity	350-750	600-980
	HF	Hot-formed (boron)	340-1200	480-1900
	TWIP	Twinning-induced plasticity	500-950	900-1200

Aluminum

Category	Series	Acronym
Commercially Pure Aluminum	1xxx	Al
Heat-Treatable Alloys	2xxx , 6xxx , 7xxx	Al
Non Heat-Treatable Alloys	3xxx , 4xxx , 5xxx	Al

Magnesium

Category	Acronym
Magnesium Alloy (Any series)	Mag

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Composites

Composite	Acronym
Carbon fiber reinforced polymers	CFRP
Glass fiber reinforced polymers	GFRP
Sheet Molded Compounds	SMC
Fiberglass	FG
Plastic Thermoforming	PSF
Plastic Thermosetting	PSS

Processes

Examples of Forming Process	Examples of Joining Process
Cold stamping (CS), Cold Rolling (CR), Laser welded blanks (LWB), Tailor rolled blanks (TRB), Hot stamping (HS), Roll Forming (RF)	Resistance spot welding (RSW), MIG/TIG Welding, Flow Drill Screws (FDS), Adhesives (Adv), Laser/Friction welding (LW/FW), Rivets – solid or self-piercing (Riv)

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Mass Reduction Pathway

Manufacturer:	**Model:**	**Category:**

Trim Level: **Model:** **Platform:** **Curb Weight**: **Avg. Track Width**: **Crash Rating (NHTSA Overall):**	**Engine Specs**: **Transmission**: **Drive**: **Wheels**: **Wheelbase:**

Questions:

1. When did you launch the last significantly redesigned body architecture or platform for this vehicle ______ (Model Year)?

2. When do you expect to significantly redesign the body architecture, i.e. launch platform redesign/replace ______(Model Year)?

3. Body-in-white, mass (for vehicle as described above) ______ lbs?

4. Please use the following tables to describe the technology pathways at select mass reduction levels, as you see them.

Please indicate all that may apply for the mass reduction pathway that could be implemented to help reduce mass for the next model. (check all that apply)

Vehicle Mass Reduction %[1]	**Body in White Pathway – Material Substitution**					
	Design	**BIW Materials (without closures)**				
MR 5%	Design Optimization ☐	AHSS ☐	UHSS ☐	Al. ☐	Carbon Fiber ☐	Composites ☐
MR 10%	Design Optimization ☐	AHSS ☐	UHSS ☐	Al. ☐	Carbon Fiber ☐	Composites ☐
MR 15% plus	Design Optimization ☐	AHSS ☐	UHSS ☐	Al. ☐	Carbon Fiber ☐	Composites ☐

AHSS – Advanced high strength steels, Al. – Aluminum, Mag. – Magnesium

[1] Mass Reduction percentage (MR %) means percent of total vehicle curb weight. The timeframe for mass reduction is model year 2025.

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Vehicle Mass Reduction %[1]	Subsystem Pathway – Material Substitution									
	Closures			**Seats**				**Wheels**		
MR 5%	Al. ☐	Mag. ☐	Steel + Composite ☐	AHSS ☐	Al. ☐	Mag. ☐	Composite ☐	AHSS ☐	Al. ☐	Mag. ☐
MR 10%	Al. ☐	Mag. ☐	Steel + Composite ☐	AHSS ☐	Al. ☐	Mag. ☐	Composite ☐	AHSS ☐	Al. ☐	Mag. ☐
MR 15% plus	Al. ☐	Mag. ☐	Steel + Composite ☐	AHSS ☐	Al. ☐	Mag. ☐	Composite ☐	AHSS ☐	Al. ☐	Mag. ☐

AHSS – Advanced High Strength Steels, Al. – Aluminum, Mag. – Magnesium

The tables below intend to capture lightweighting strategy at the component level for the vehicle described above.

In the Forming, Joining and Comment fields provided below please input the type of manufacturing process you would expect to use in order to achieve the select mass reduction level.

Body Structure Pathway

Component Technology Pathways	**A Pillar**					**B Pillar**				
	Materials		**Process**			**Materials**		**Process**		
	Type	**Grade (MPa) or Fiber Structure****	**Forming**	**Joining**	**Comment**	**Type**	**Grade (MPa) or Fiber Structure****	**Forming**	**Joining**	**Comment**
Current Model *										
MR 5%										
MR 10%										
MR 15% plus										

* Please mention the technology used in the current production vehicle;
** Fiber Structure - Please include fiber orientation (random or unidirectional) for Carbon Fiber Reinforced Polymers and Glass Fiber Reinforced Polymers

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Body Structure Pathway

Component Technology Pathways	Floor					Front Bumper Structure				
	Materials		Process			Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *										
MR 5%										
MR 10%										
MR 15% plus										

Component Technology Pathways	Roof Panel				
	Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *					
MR 5%					
MR 10%					
MR 15% plus					

* Please mention the technology used in the current production vehicle;
** Fiber Structure - Please include fiber orientation (random or unidirectional) for Carbon Fiber Reinforced Polymers and Glass Fiber Reinforced Polymers

[1] Mass Reduction percentage (MR %) means percent of total vehicle curb weight.

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Closures and Fenders

Component Technology Pathways	Front Door Inner					Front Door Outer				
	Materials		Process			Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *										
MR 5%										
MR 10%										
MR 15% plus										

Component Technology Pathways	Hood					Decklid				
	Materials		Process			Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *										
MR 5%										
MR 10%										
MR 15% plus										

* Please mention the technology used in the current production vehicle;
** Fiber Structure - Please include fiber orientation (random or unidirectional) for Carbon Fiber Reinforced Polymers and Glass Fiber Reinforced Polymers

[1] Mass Reduction percentage (MR %) means percent of total vehicle curb weight.

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Closures and Fenders

Component Technology Pathways	Fender LH/RH				
	Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *					
MR 5%					
MR 10%					
MR 15% plus					

Chassis

Component Technology Pathways	Engine Cradle					Lower Control Arm				
	Materials		Process			Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *										
MR 5%										
MR 10%										
MR 15% plus										

* Please mention the technology used in the current production vehicle;
** Fiber Structure - Please include fiber orientation (random or unidirectional) for Carbon Fiber Reinforced Polymers and Glass Fiber Reinforced Polymers

[1] Mass Reduction percentage (MR %) means percent of total vehicle curb weight.

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Chassis

Component Technology Pathways	Rear Suspension – Leaf Spring (Light Truck)					Brake Disk/Rotor				
	Materials		Process			Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *										
MR 5%										
MR 10%										
MR 15% plus										

Component Technology Pathways	Steering Knuckle				
	Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *					
MR 5%					
MR 10%					
MR 15% plus					

* Please mention the technology used in the current production vehicle;
** Fiber Structure - Please include fiber orientation (random or unidirectional) for Carbon Fiber Reinforced Polymers and Glass Fiber Reinforced Polymers

[1] Mass Reduction percentage (MR %) means percent of total vehicle curb weight.

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Powertrain

Component Technology Pathways	Engine heads					Fuel Tank				
	Materials		Process			Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *										
MR 5%										
MR 10%										
MR 15% plus										

Interiors

Component Technology Pathways	Instrument Panel Cross Beam					Seats Frame				
	Materials		Process			Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *										
MR 5%										
MR 10%										
MR 15% plus										

* Please mention the technology used in the current production vehicle;
** Fiber Structure - Please include fiber orientation (random or unidirectional) for Carbon Fiber Reinforced Polymers and Glass Fiber Reinforced Polymers

[1] Mass Reduction percentage (MR %) means percent of total vehicle curb weight.

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Steering

Component Technology Pathways	Steering Shaft				
	Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *					
MR 5%					
MR 10%					
MR 15% plus					

Electrical

Component Technology Pathways	Wiring Harnesses				
	Materials		Process		
	Type	Grade (MPa) or Fiber Structure**	Forming	Joining	Comment
Current Model *					
MR 5%					
MR 10%					
MR 15% plus					

* Please mention the technology used in the current production vehicle;
** Fiber Structure - Please include fiber orientation (random or unidirectional) for Carbon Fiber Reinforced Polymers and Glass Fiber Reinforced Polymers

[1] Mass Reduction percentage (MR %) means percent of total vehicle curb weight.

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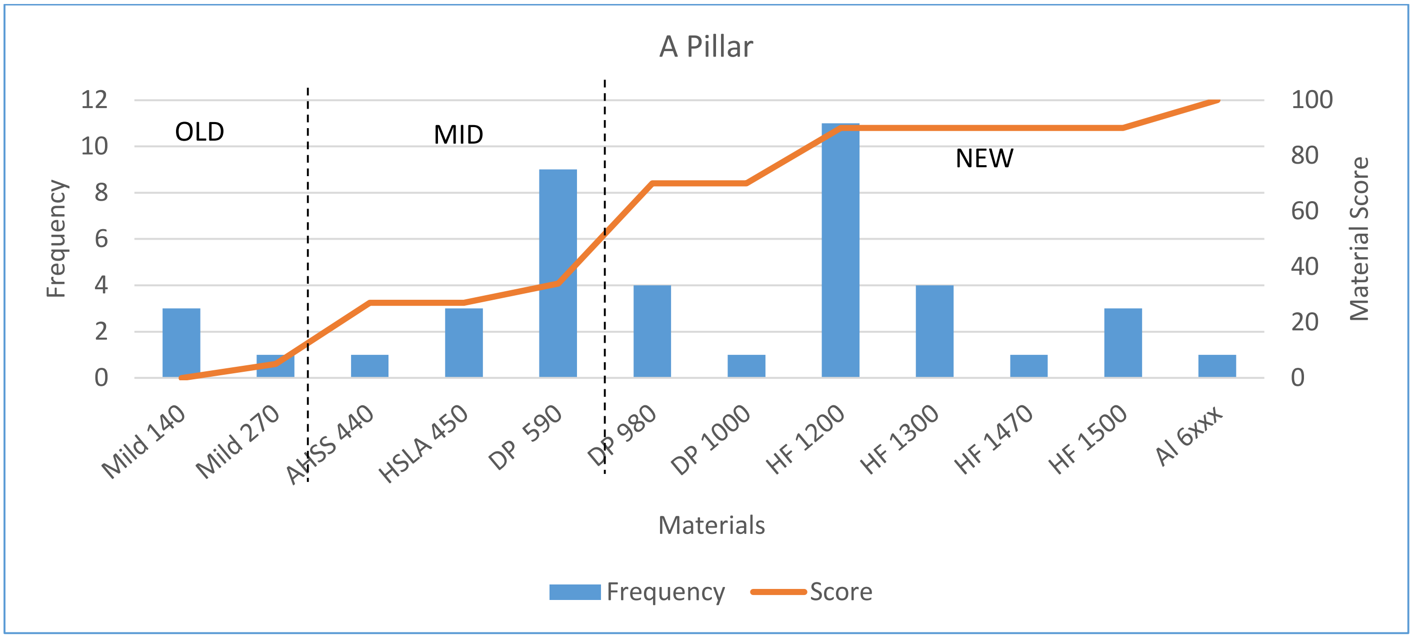
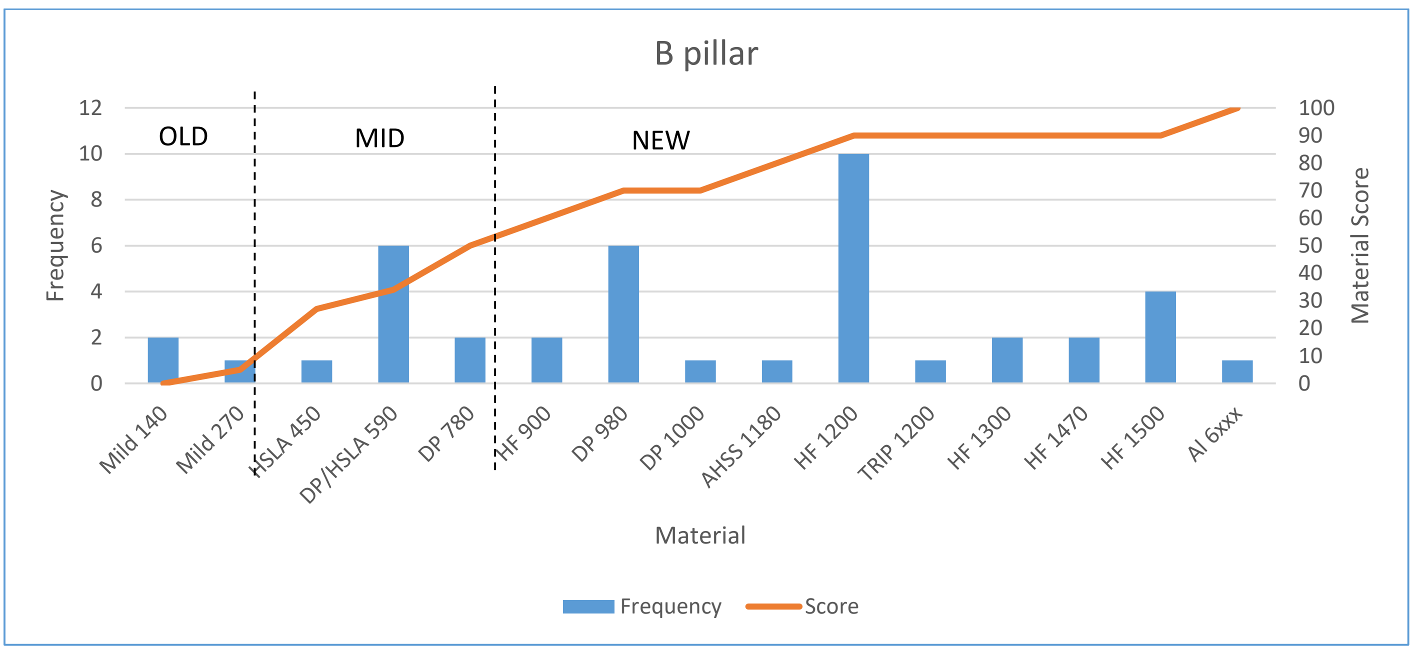
Appendix 3 – Technology Scores and Sample Frequency





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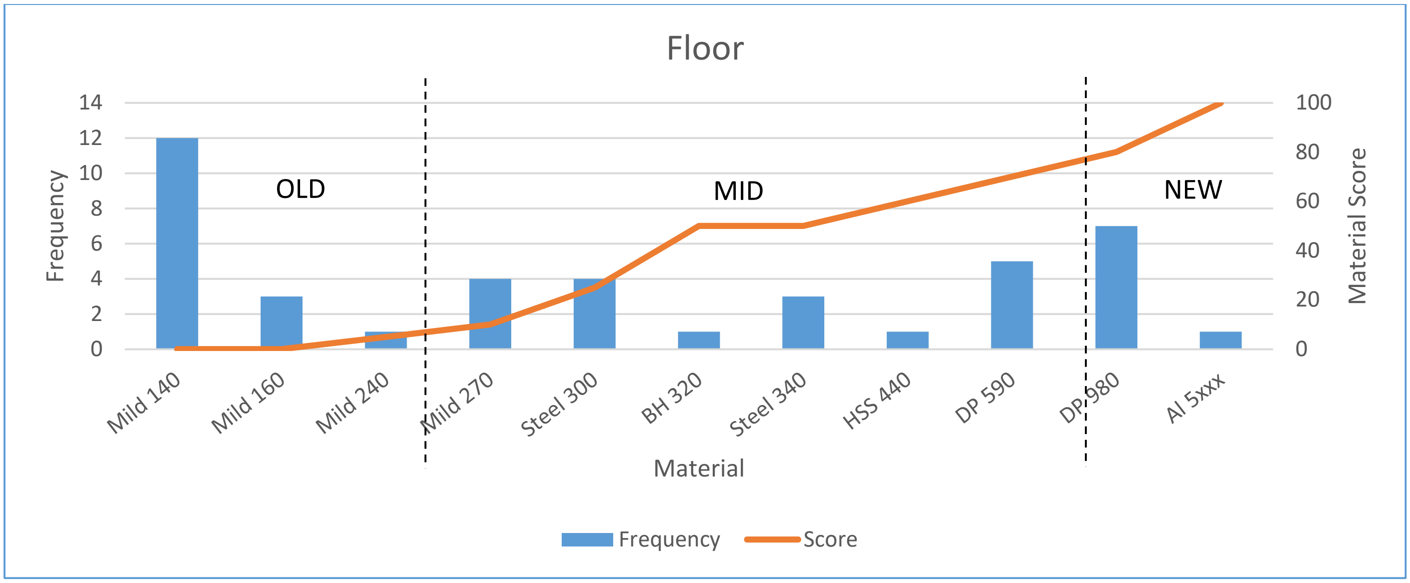

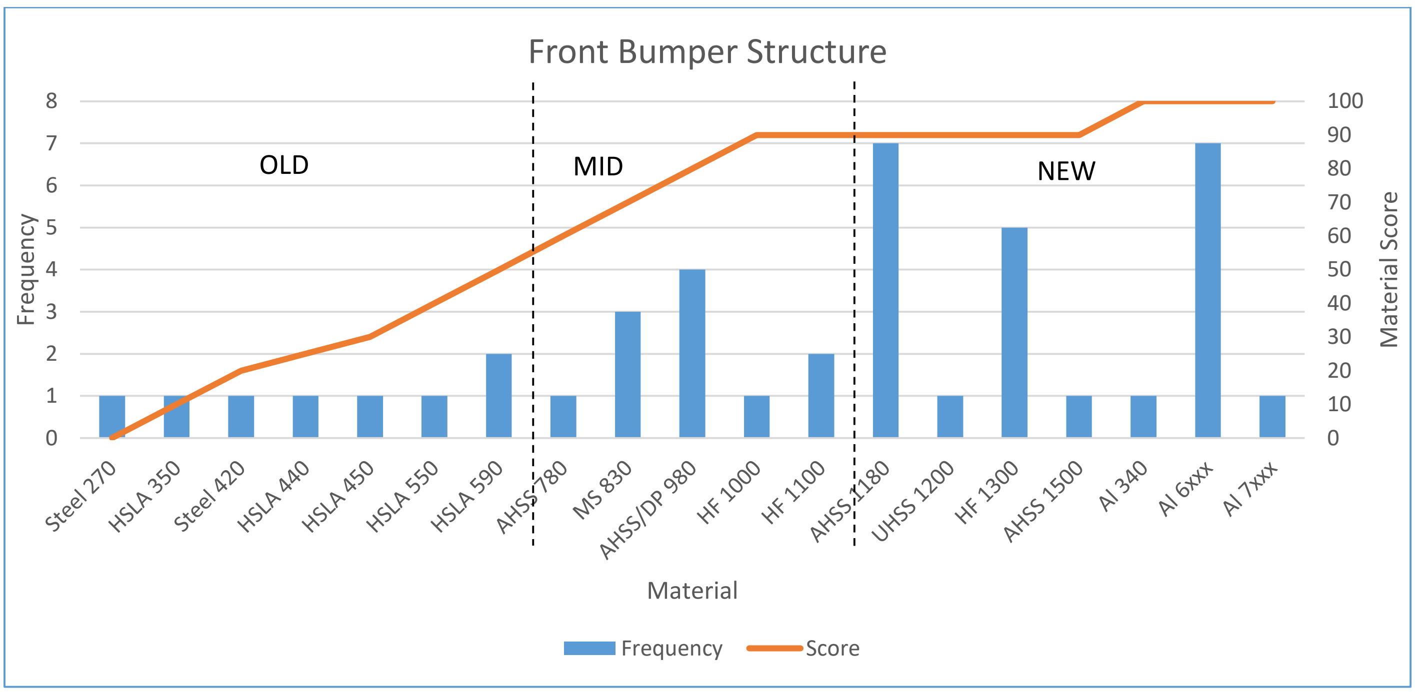

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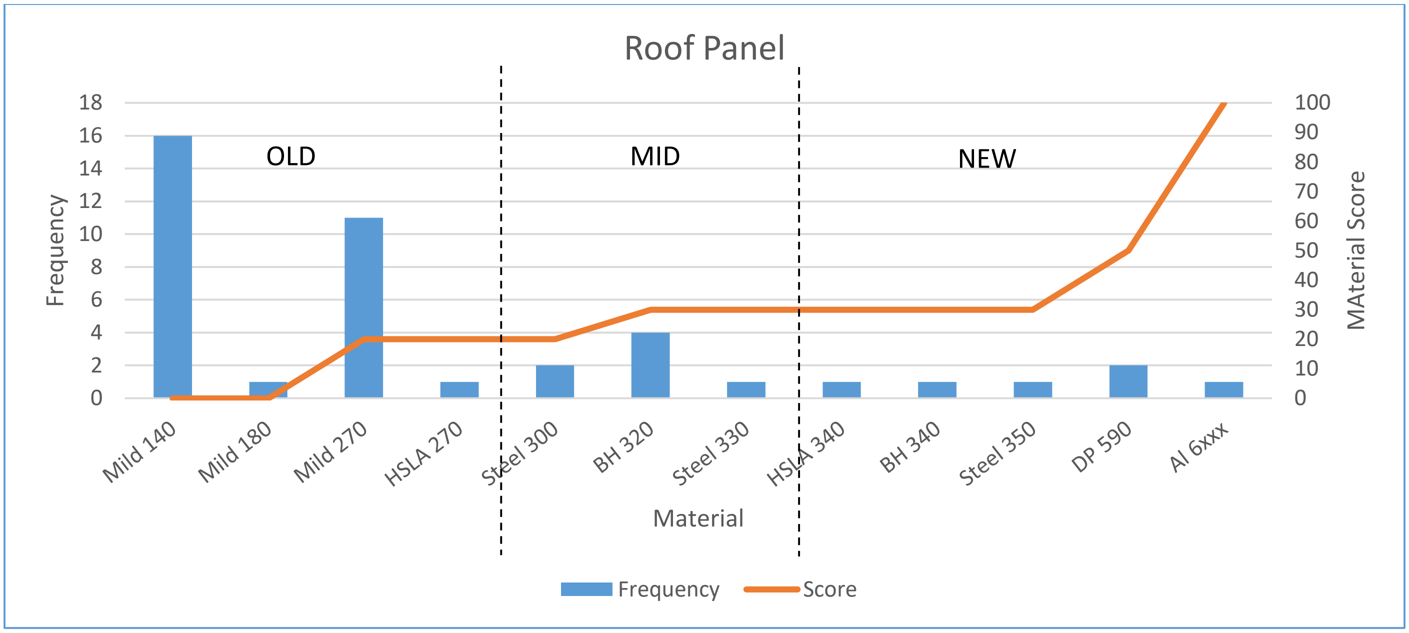

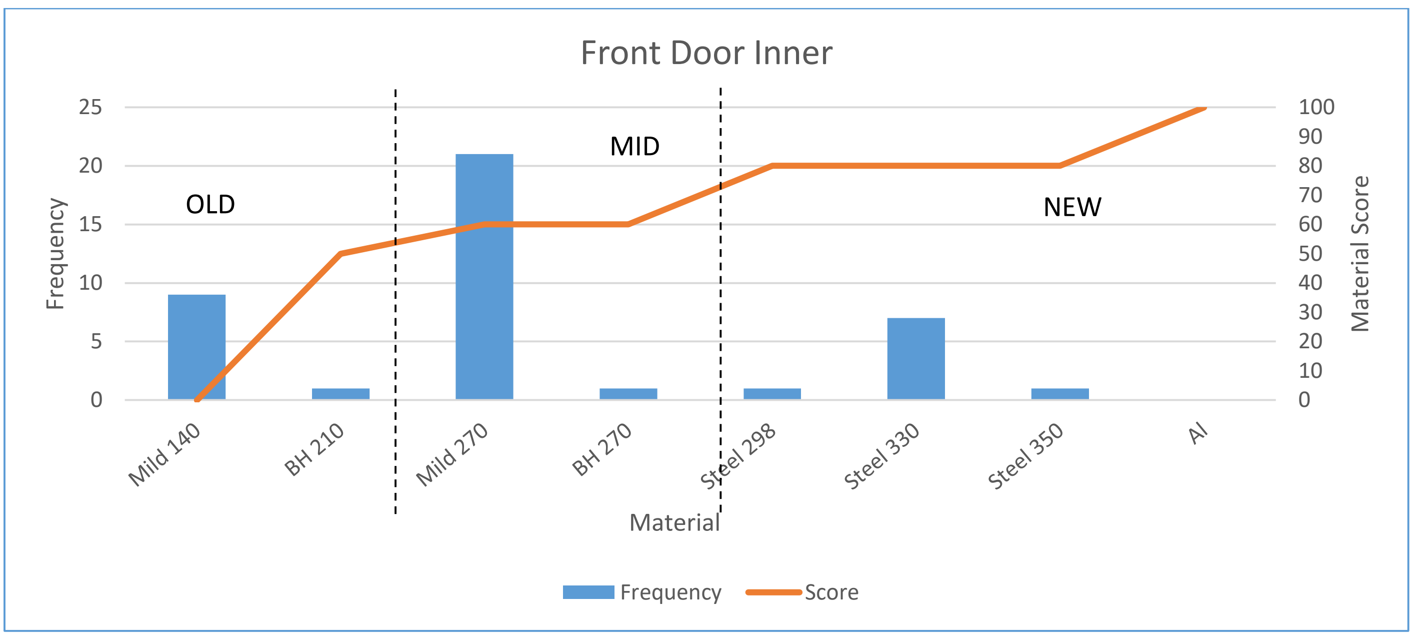

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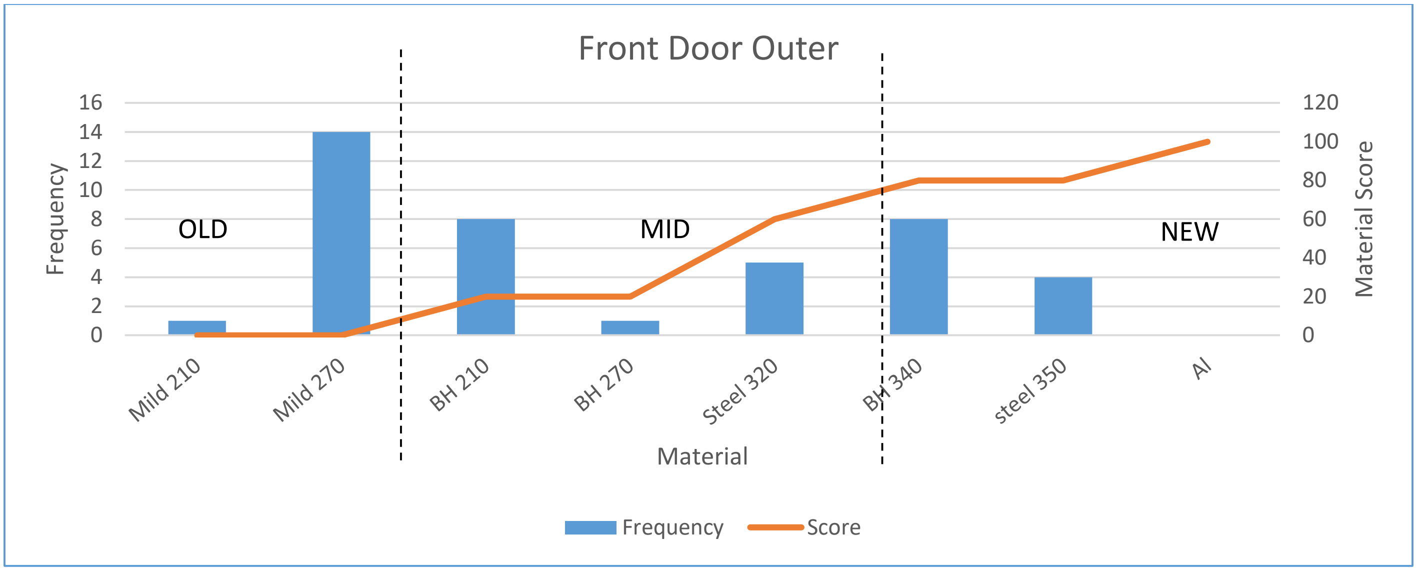

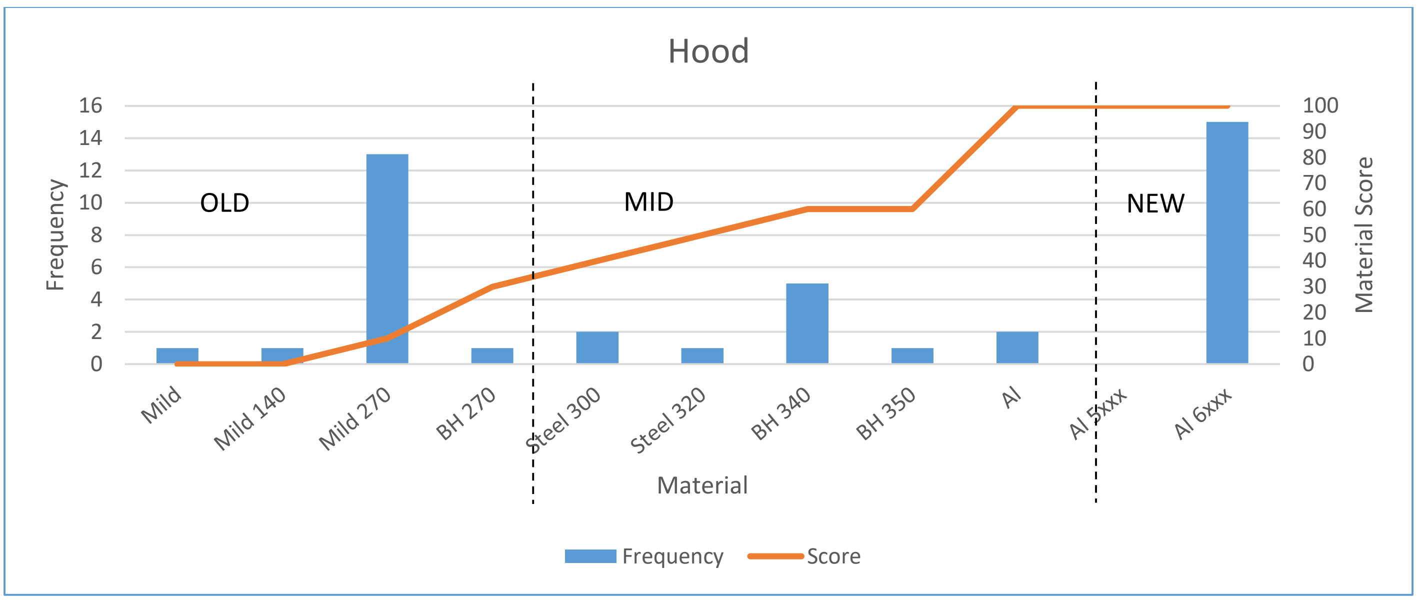

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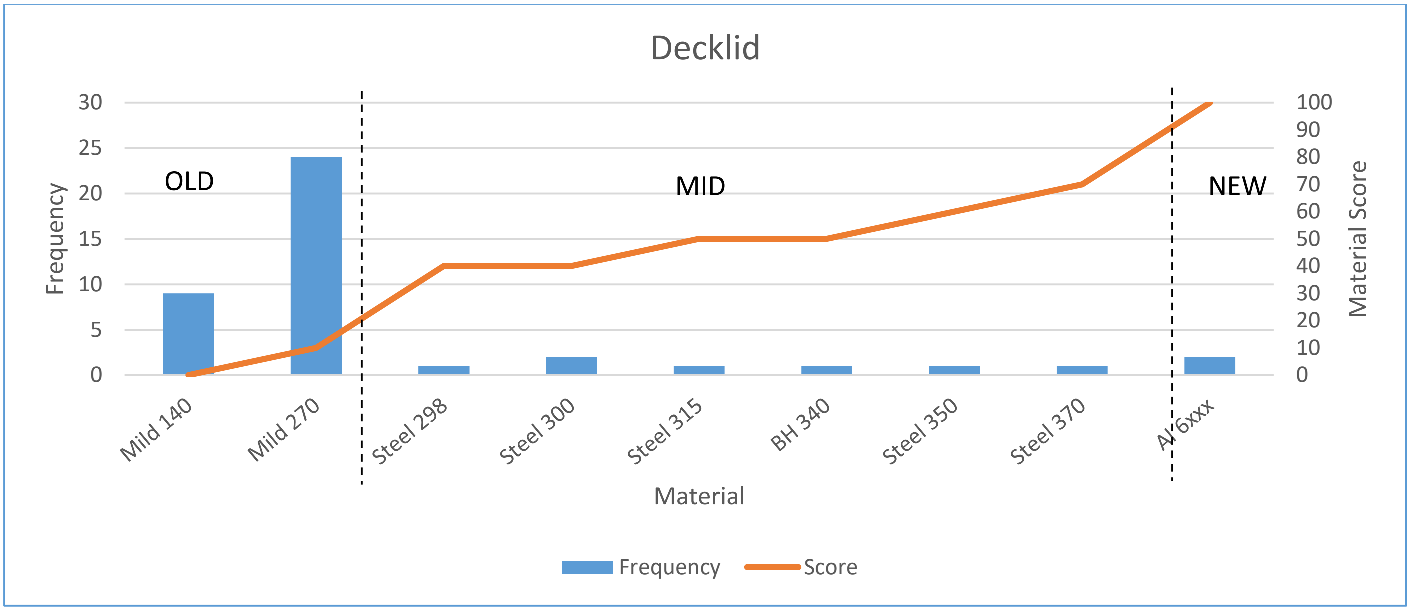

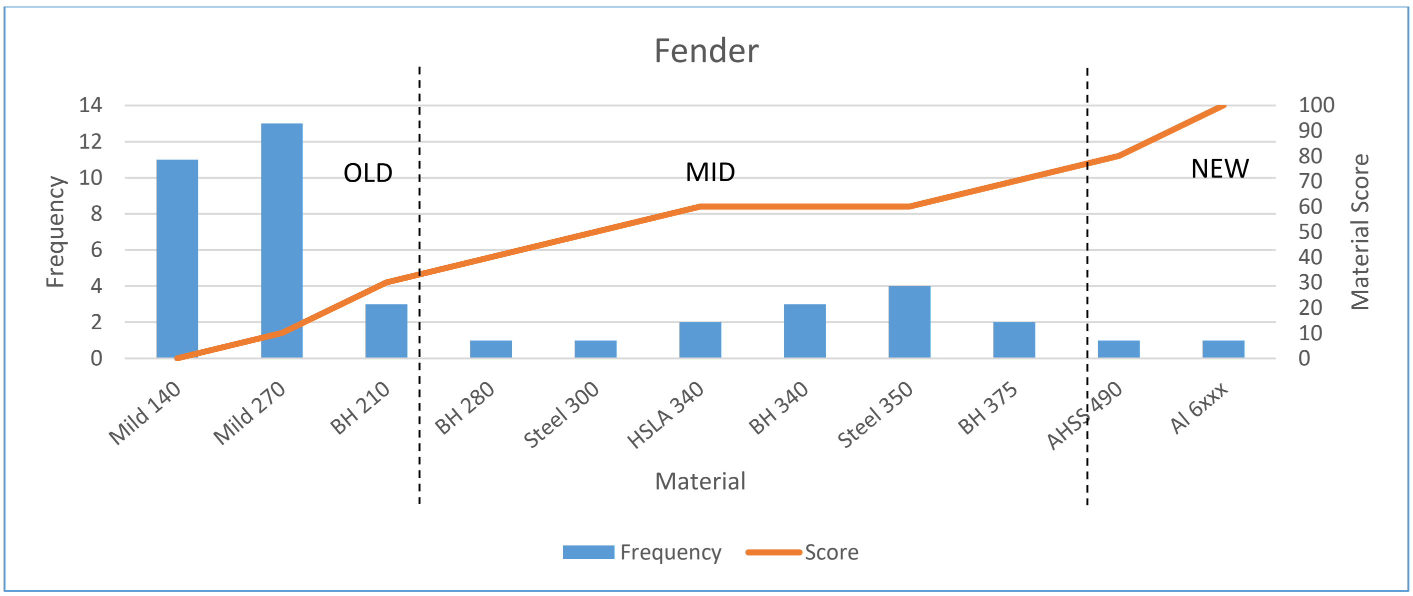

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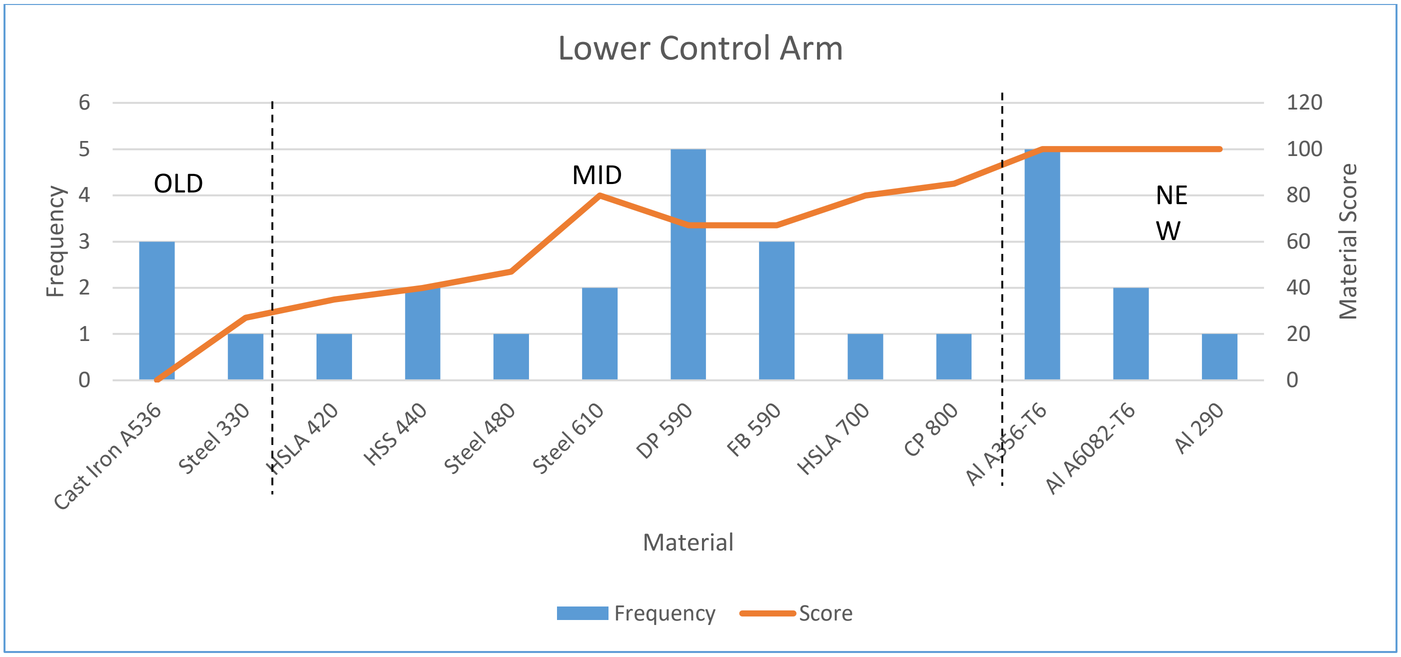

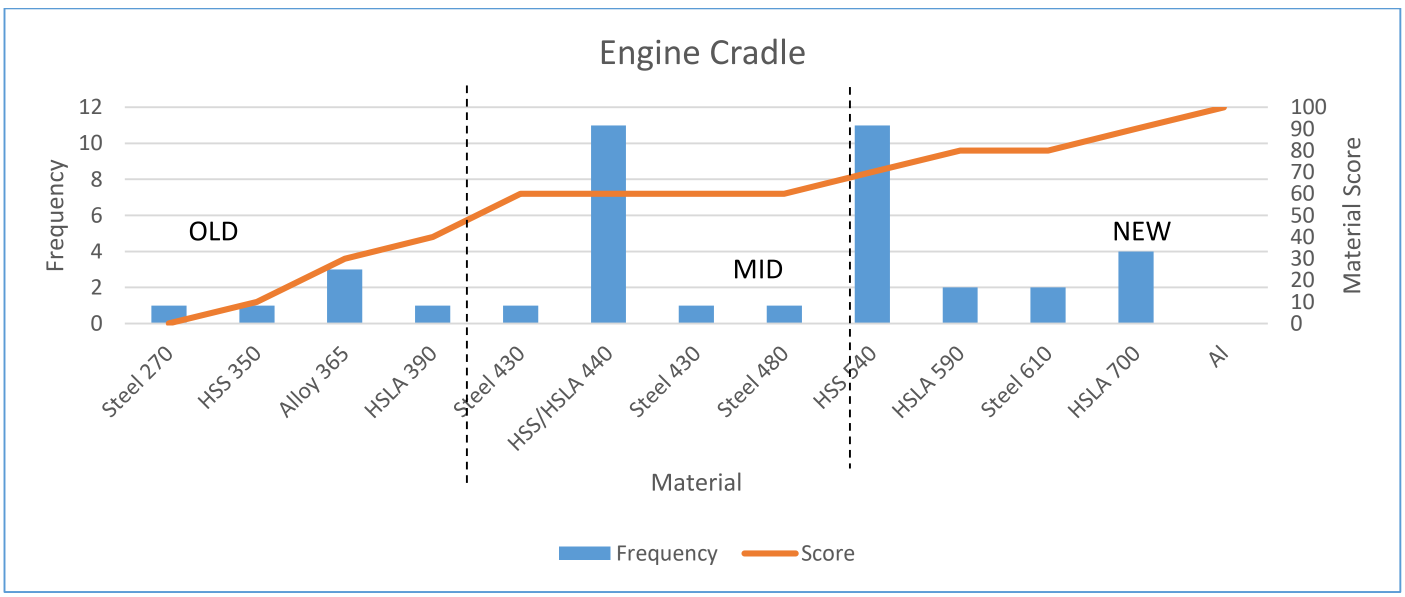

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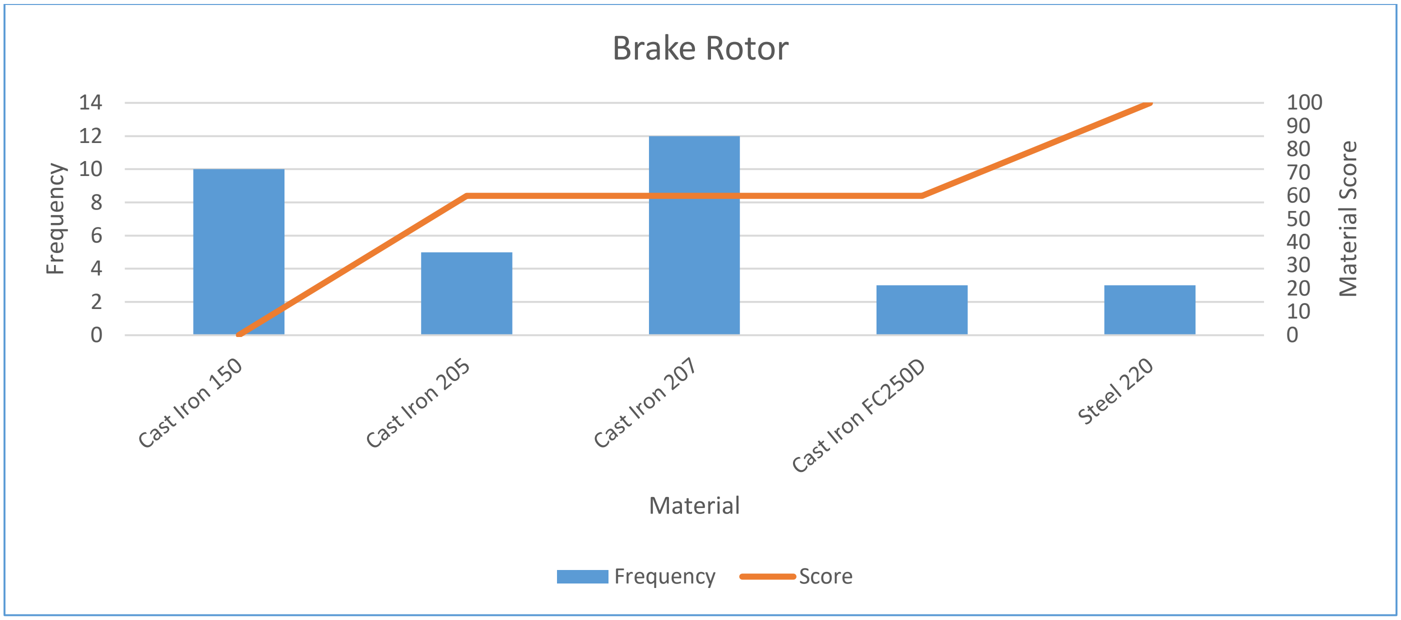
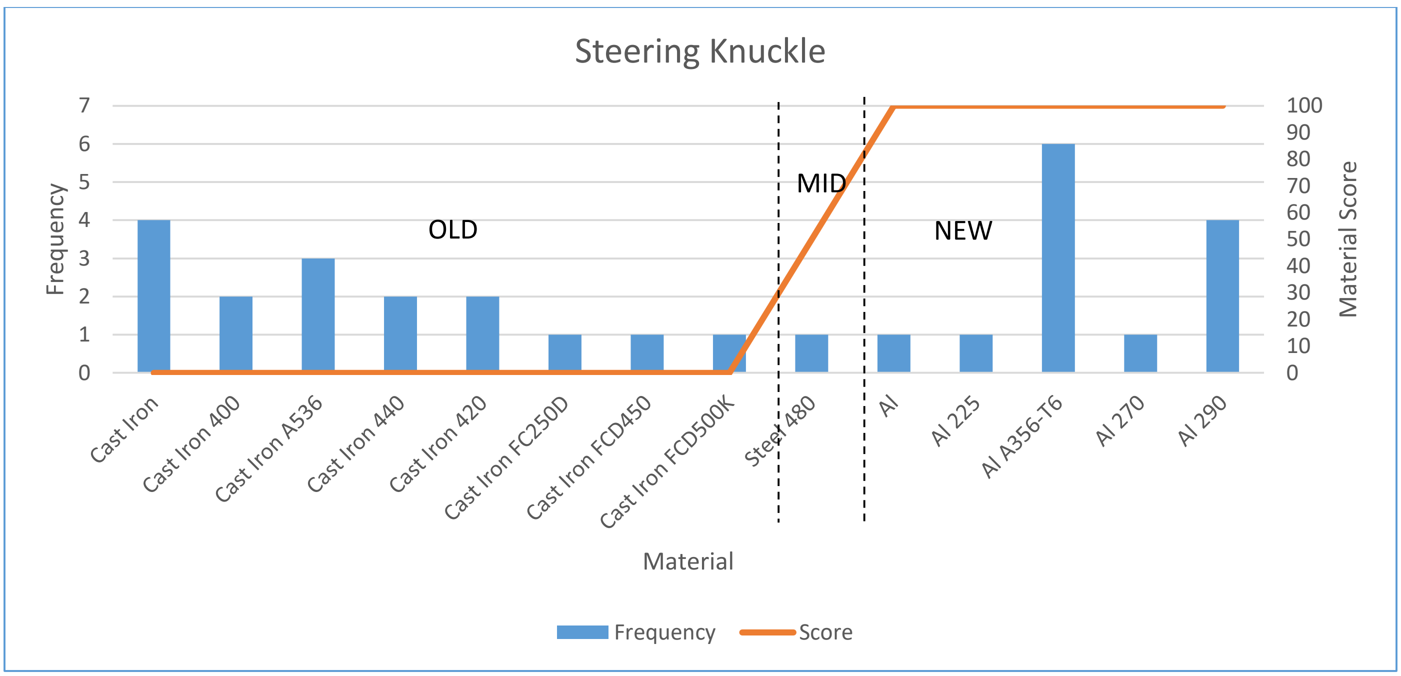
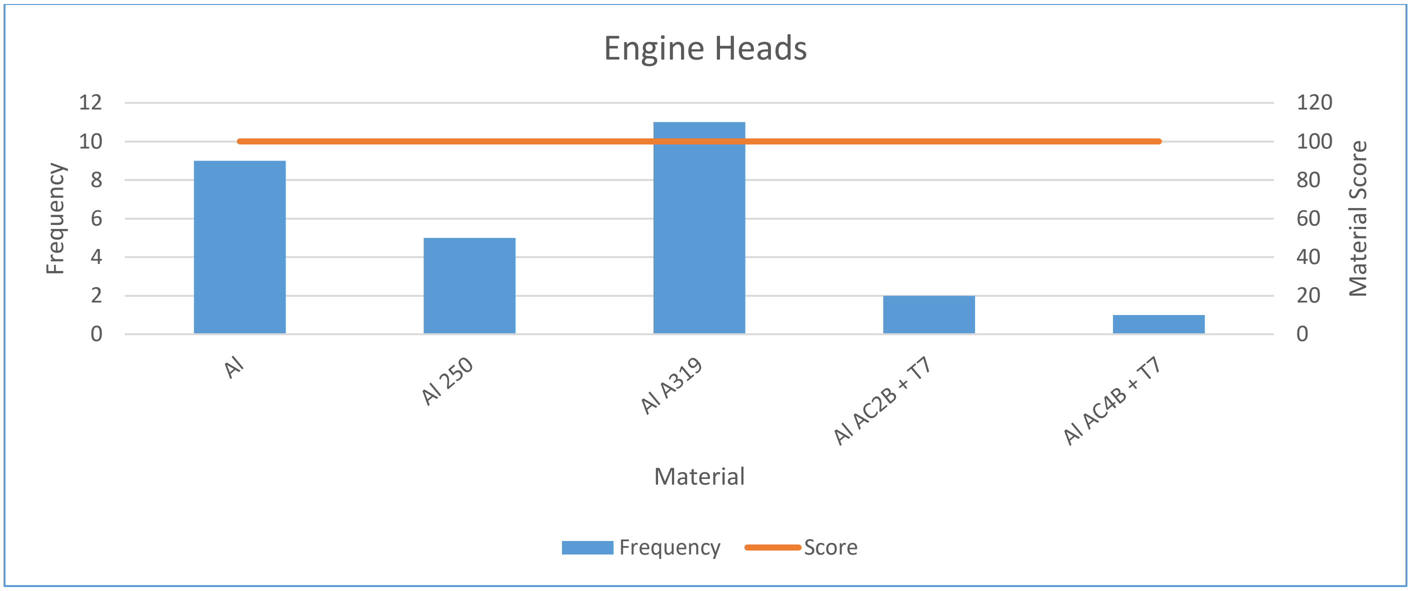
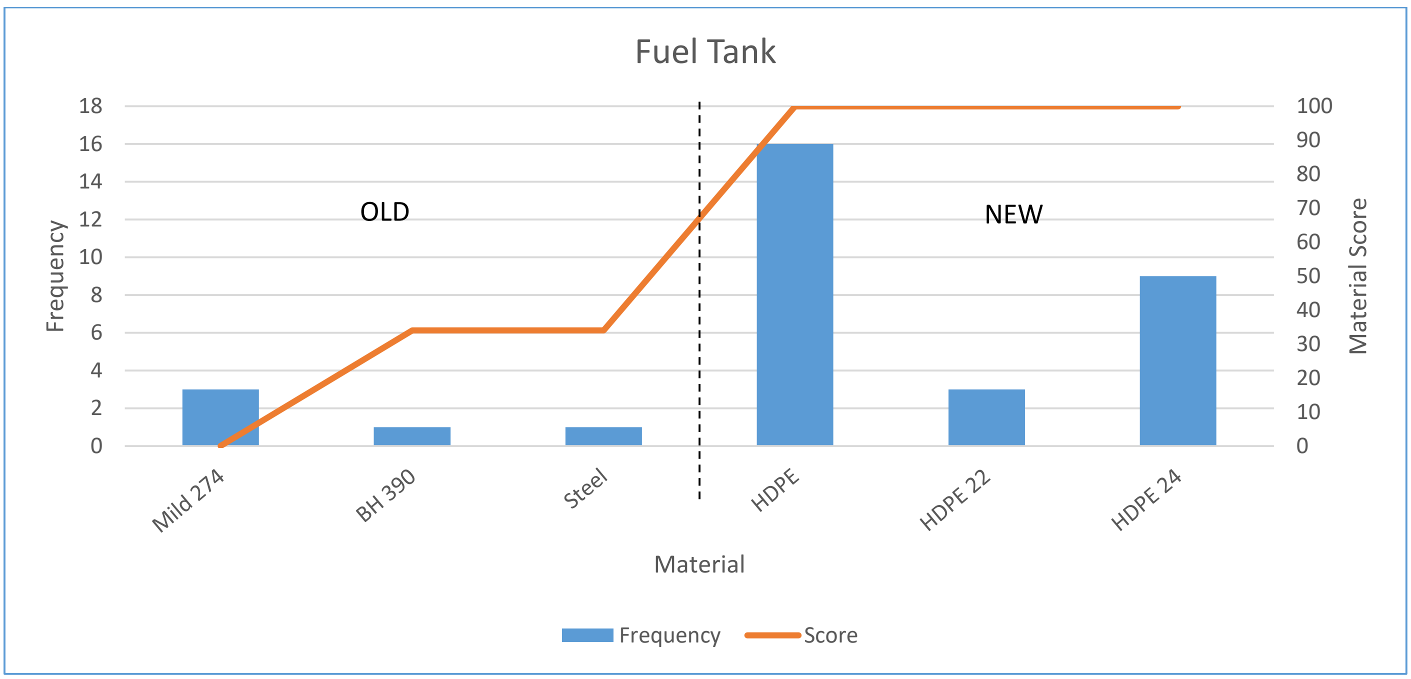


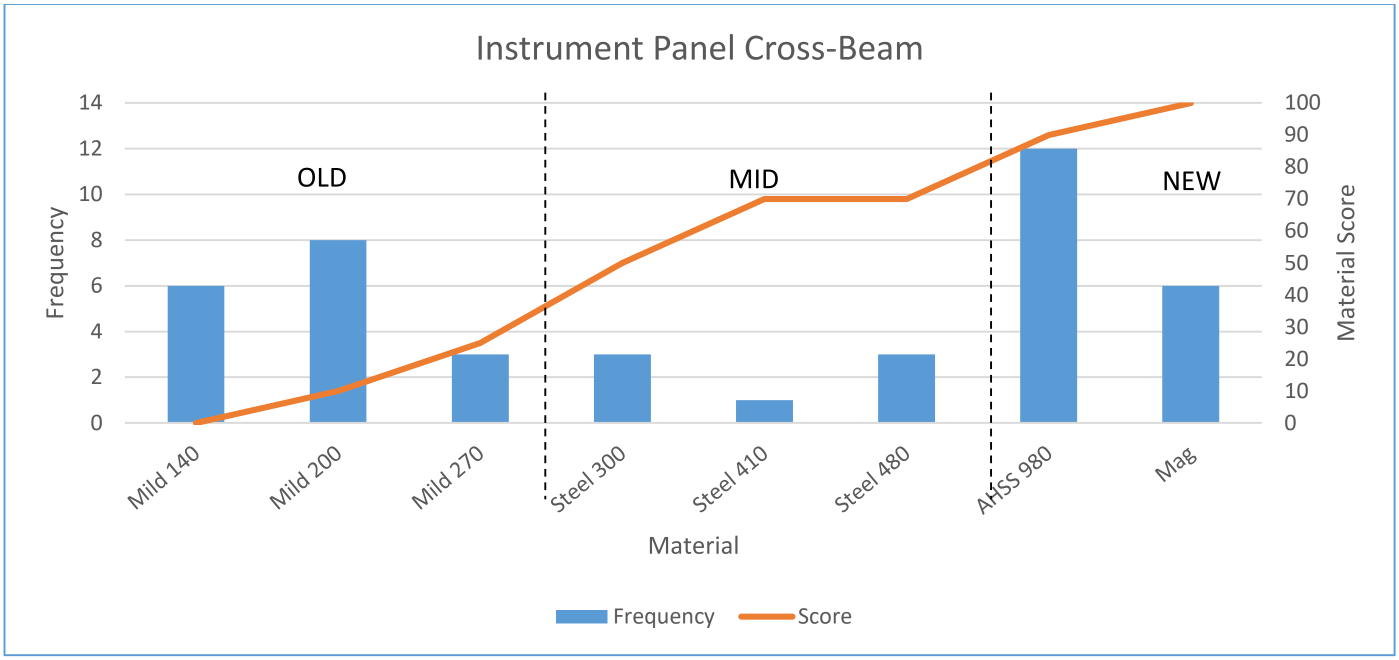
Brake Rotor
Frequency
Material Score
14
12
10
8
6
4
2
0
100
90
80
70
60
50
40
30
20
10
0
Cast Iron 150
Cast Iron 205
Cast Iron 207
Cast Iron FC250D
Steel 220
Material
Frequency
Score

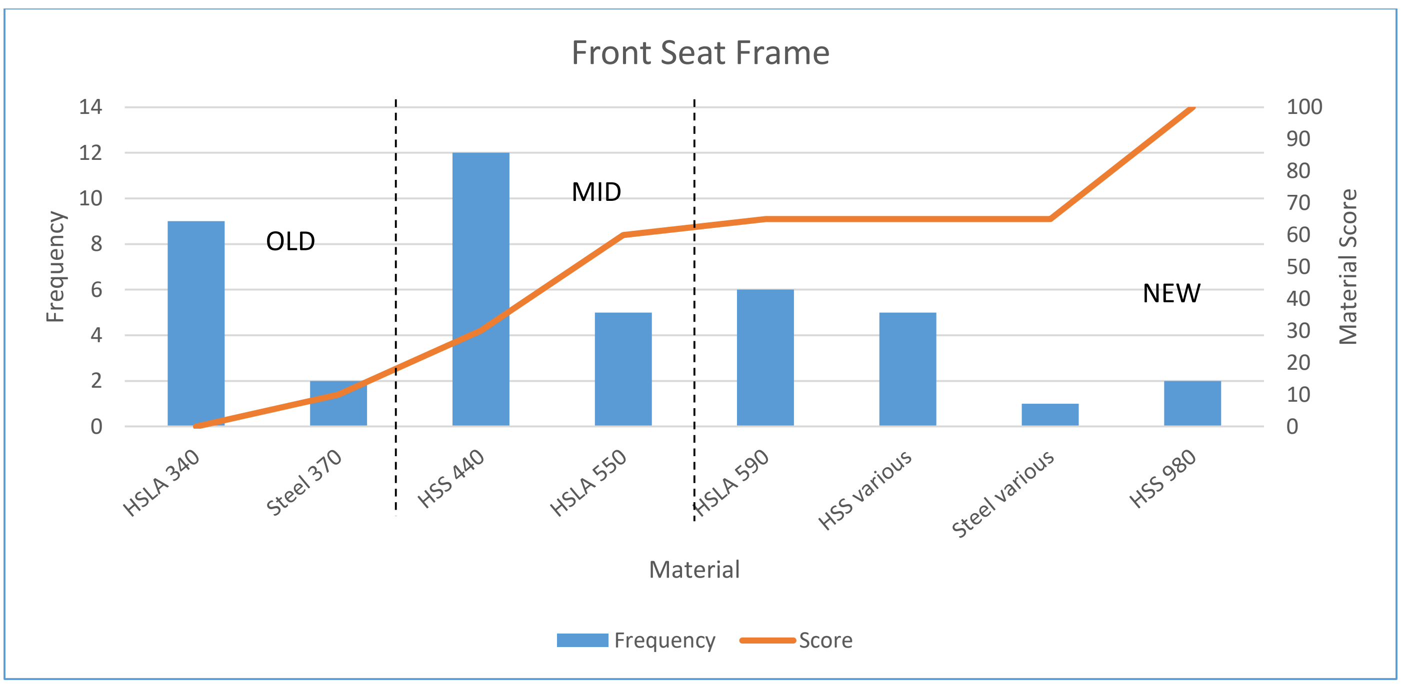


Steering Knuckle
Frequency
Material Score
7
6
5
4
3
2
1
0
100
90
80
70
60
50
40
30
20
10
0
OLD
MID
NEW
Cast Iron
Cast Iron 400
Cast Iron A536
Cast Iron 440
Cast Iron 420
Cast Iron FC250D
Cast Iron FCD450
Cast Iron FCD500K
Steel 480
Al
Al 225
Al A356-T6
Al 270
Al 290
Material
Frequency
Score


Engine Heads
Frequency
Material Score
12
10
8
6
4
2
0
120
100
80
60
40
20
0
Al
Al 250
Al A319
Al AC2B + T7
Al AC4B + T7
Material
Frequency
Score


Fuel Tank
Frequency
Material Score
18
16
14
12
10
8
6
4
2
0
100
90
80
70
60
50
40
30
20
10
0
OLD
NEW
Mild 274
BH 390
Steel
HDPE
HDPE 22
HDPE 24
Material
Frequency
Score





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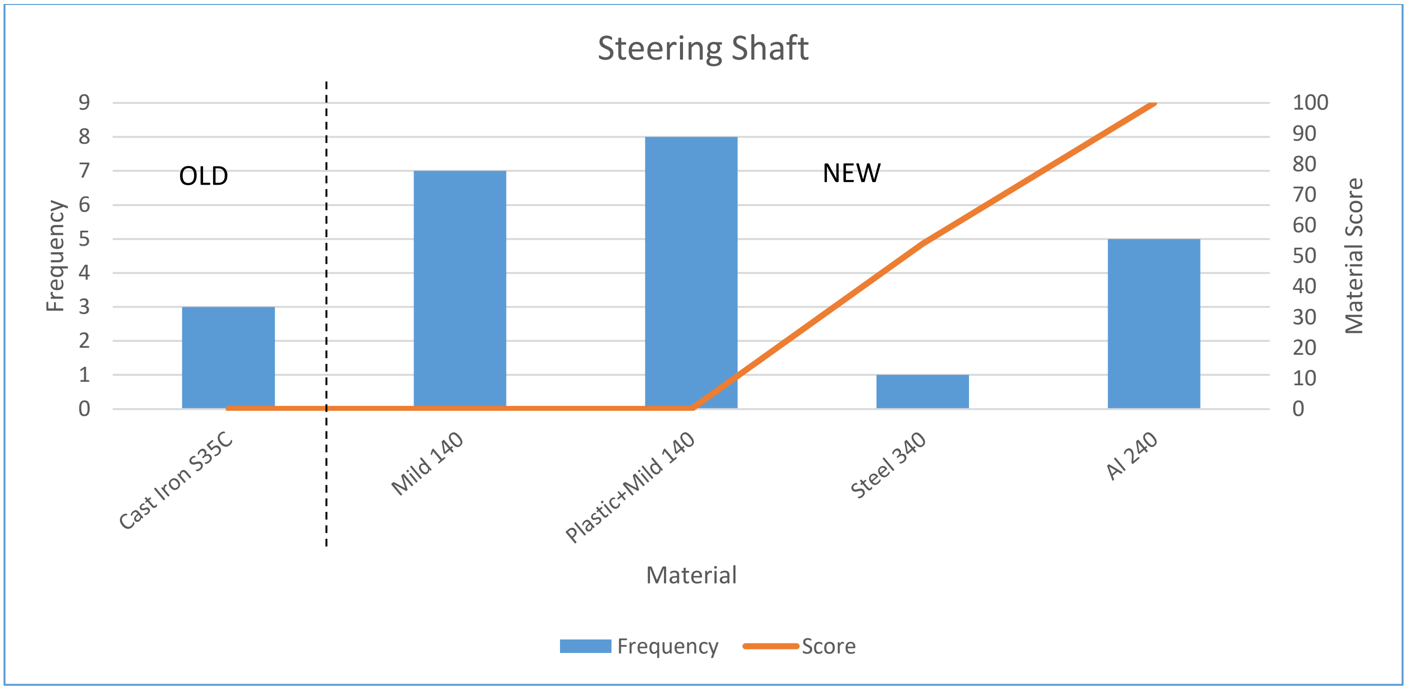

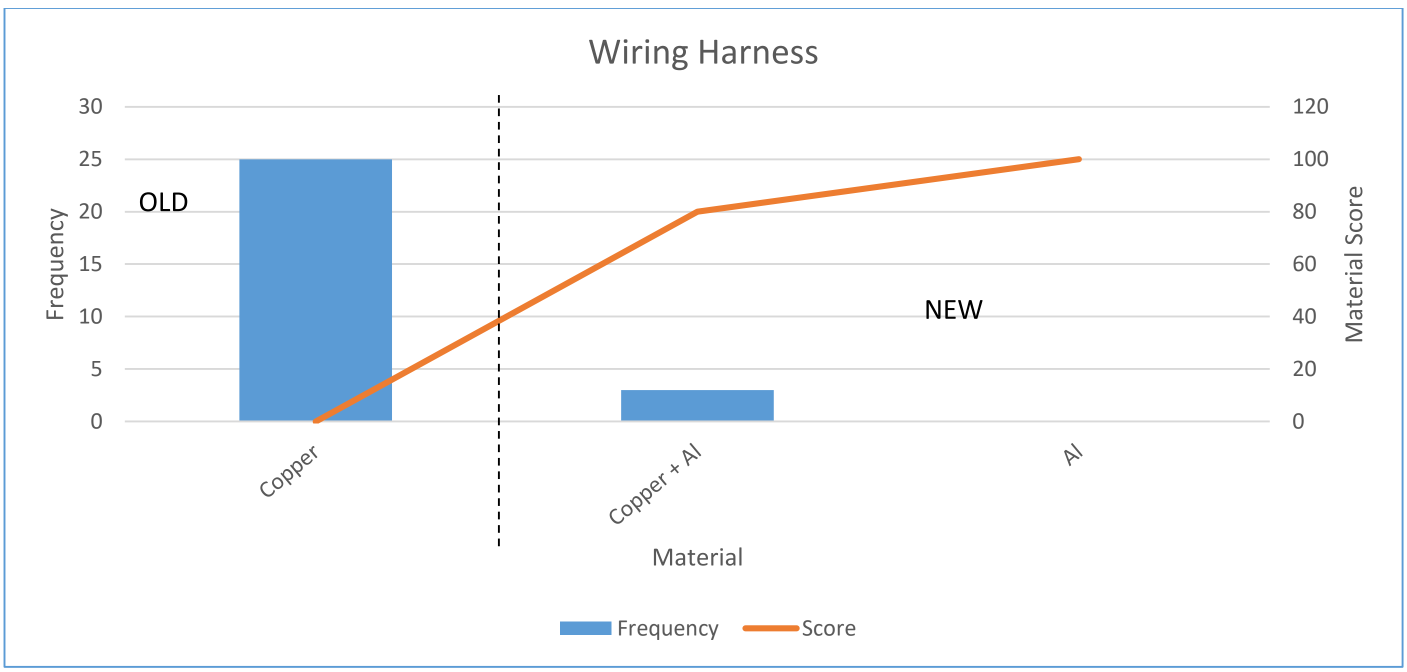

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