# Cost-Effectiveness of a Lightweight Design for 2020-2025: An Assessment of a Light-Duty Pickup Truck

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## Abstract

The United States Environmental Protection Agency contracted with FEV North America, Inc. to conduct a whole vehicle analysis of the potential for mass reduction and related cost impacts for a future light-duty pickup truck. The goal was to evaluate the incremental costs of reducing vehicle mass on a body on frame vehicle at levels that are feasible in the 2020 to 2025 model year (MY) timeframe given the design, material, and manufacturing processes likely to be available, without sacrificing utility, performance, or safety.

The holistic, vehicle-level approach and body-structure CAE modeling that were demonstrated in a previous study of a mid-sized crossover utility vehicle were used for this study. In addition, evaluations of closures performance, durability, and vehicle dynamics that are unique to pickup trucks are included. Secondary mass reduction was also analyzed on a part by part basis with consideration of vehicle performance requirements.

This paper presents an overview of the study "Vehicle Mass Reduction and Cost Analysis-Light-duty Pickup Truck Model Years 2020-2025", by FEV North America, Inc. This study indicates that when mass reduction strategies are considered using a full-vehicle approach, significant mass reduction can be achieved relative to a 2011 light-duty pickup while maintaining vehicle functional objectives. The incremental results are assembled into a curve for mass reduction costs (in \$/kg), as a function of the vehicle mass reduction level. Results from the study show that relative to the baseline vehicle (2011MY), mass reduction levels below 9% can result in a cost savings (cumulative net incremental direct manufacturing costs) with cumulative costs increasing to \$4.36/kg, or \$2,228 per vehicle, at 21.4% (510.9 kg) mass reduction.

## Introduction

Light-duty pickup trucks, Figure 1, have a number of characteristics that are unique from other passenger vehicles, and which influence the potential solutions for achieving vehicle mass reduction in order to improve fuel economy and reduce greenhouse gas emissions. One primary difference is the use of a body-on-frame design in which the bed and cab are separately mounted to a frame that provides the main load bearing structure for towing, hauling, and crash performance. Furthermore, the intended market usage for these vehicles imposes a unique loading on the suspension, chassis, and bed, so it is especially important to consider strength and durability performance of alternative designs.

Figure 1. 2011 Light-duty Truck

The two major strategies for primary mass reduction utilized in this study include 1) Material choice: substitute materials for those with lower density and adjust material volume as necessary for given performance requirements, and 2) Design approaches, to minimize material use through part reduction/integration, new manufacturing processes, and design optimization (gauge, grade).

When significant levels of mass reduction are required, the most cost-efficient lightweight design solution will likely require contributions from multiple systems on the vehicle. In addition to the components that are targeted for primary mass reduction, a design that has been lightened sufficiently will benefit from compounding (synergistic) effects as secondary mass reduction options become available. For example, if the mass of a vehicle body is reduced through the use of a lower-density material, a smaller, lighter, and potentially more efficient powertrain may be used while maintaining acceleration performance. For this reason, a comprehensive evaluation of mass reduction requires a full-vehicle holistic approach.

The study described herein applies the same holistic, vehicle-level approach and body structure CAE modeling methodology applied previously to an EPA mass reduction study of a mid-sized crossover utility vehicle [1]. In addition to the techniques that were demonstrated in that earlier work, this project also addresses the unique characteristics and requirements of full-size pickups, including frame durability, vehicle dynamics, and static structural performance of doors, hood and tailgate. The goal of this study was to estimate the change in manufacturing cost (referred to as Net Incremental Direct Manufacturing Cost, or NIDMC) at levels of mass reduction from zero up to or beyond 20 percent using technologies available in the 2020 to 2025 MY timeframe without compromising safety or other attributes. This includes maintaining the size, function, and performance of the original truck design, including payload and towing capability. Additional boundary conditions specified a production volume of 450,000 units per year, a maximum ten percent increase in total direct manufacturing costs, and no change in the type or architecture of the powertrain or any other vehicle system to gain additional mass-savings.

The following sections summarize the approach, some of the main findings and overall result described in the report "Vehicle Mass Reduction and Cost Analysis - Light-duty Pickup Truck Model Years 2020-2025" performed by FEV North America, Inc. with subcontractors EDAG, Inc.. and Munro and Associates Inc.[2]. The Methodology section contains background information on the selection of the baseline vehicle, modeling approaches, selection of performance and cost criteria, and a description of how lightweighting ideas where developed and selected for the Powertrain, Chassis and Trim systems and the Body and Frame systems. The Results and Discussion section includes some of the lightweighting ideas considered, and an overall summary of the cost of mass reduction. The eight systems with the most mass reduction are identified along with the respective technology that provided a significant mass reduction within each system. For the Body and Frame systems, an overview of the structural analysis is also provided. This includes a sample of the hood torsional rigidity for baseline and lightweight designs, a description of the vehicle dynamics study to obtain inputs for the frame durability evaluation and crash safety overview. The Results and Discussion section wraps up with a discussion of the secondary mass savings and a cost curve of primary and compounded $/kg over a range of % mass reduction.

## Methodology

The underlying approach for this work is based on the methodology used in the EPA's mass reduction study of a mid-sized crossover utility vehicle[1] A summary is provided here, with an emphasis on the unique aspects of this work. A more comprehensive discussion of the full methodology for this work can be found in the main report [2].

### *Baseline Vehicle Selection and Modeling*

The baseline vehicle for this project was specified as a high volume full-sized pickup truck, available in the 2011 calendar year, with significant market share in North America. Trucks for consideration included the Ford F150, Dodge Ram 1500, Chevrolet Silverado 1500, and Nissan Titan.

The Chevrolet Silverado 1500 was selected as being highly representative of the technologies and performance characteristics in this market segment. A 2011 Silverado 1500 crew cab 4×4 was purchased, measured, torn down and the vehicle components were grouped into 19 vehicle systems, see Table 1. These systems were analyzed in two groups: a Powertrain Chassis and Trim group, and a Body and Frame group.

Table 1. Vehicle Systems

| SYSTEM | SYSTEM |
|---|---|
| **Powertrain/Chassis/Trim** | |
| Engine | Fuel |
| Transmission | Steering |
| Body Group B (Body Interior) | Climate Control |
| Body Group C (Body Exterior Trim) | Information, Gage and Warning Device |
| Body Group D (Glazing and Body Mechatronics) | Electric Power Supply |
| Suspension | In-Vehicle Entertainment |
| Driveline | Lighting System |
| Brake | Electrical Distribution and Electronic Control |
| Exhaust | |
| **Body and Frame** | |
| Body Group A (Body Sheetmetal) | Frame and Mounting |

The body and frame CAE model for a 2007 Silverado Crew Cab developed for NHTSA[3] was used as the starting point for the simulation of structural performance. Due to the fact that the 2007 and 2011 model year vehicles were within the same design cycle, minor differences between the years were accounted for by updating the 2007 model year CAE model. Items updated included incorporating the 2011 frame, modifying some weld placement information in the cabin structure and adding in 4×4 components (transfer case, front driveshaft, front differential and drive axles). Powertrain, chassis and trim components were represented as lump masses.

The resultant CAE baseline model was compared to actual vehicle test data for static torsional and bending stiffnesses of the cabin, box, and frame. Crash performance was compared with available NHTSA (FMVSS) test data for actual 2007 and 2011 model year Silverado

1500 vehicles. The baseline model was also run in a number of additional CAE crash tests to create a complete set of baseline results for evaluation of the lightweighted vehicle.

Analyses for all of the CAE crash test simulations were limited to visual inspection of vehicle crash results and comparison of outputs for acceleration (g's) vs time, intrusion (mm), etc. of specific areas on the Body and Frame. Modeling of the interior, restraint systems and dummies were beyond the scope of the study and as a result, dummy injury criteria were not analyzed. Results, therefore, are indicative of expected crash performance, however, further development would be required to guarantee compliance with safety standards.

### *Performance and Cost Criteria*

For any mass reduction to be judged acceptable for this project, the function and performance of the baseline vehicle systems was to be maintained in terms of safety, fuel economy, vehicle utility, comfort and ride quality, durability, ergonomics, aesthetics, manufacturability, and serviceability. Any ideas that involved the removal of content or a reduction in vehicle size were not considered. In addition, changes to powertrain architecture were not permitted in the analysis. For example, while engine materials modification, and reduction in engine size enabled by overall vehicle mass reduction were allowed, the adoption of a turbocharger and any associated engine downsizing was considered outside of the scope of this project.

Net incremental direct manufacturing cost is defined as the difference to the OEM for component and assembly costs between the mass reduced and baseline technology configurations. Both external costs for purchased components and assemblies from suppliers, as well as internal costs for manufacturing operations performed by the OEM are included. As Table 2 shows, NIDMC includes the 1) OEM and supplier direct manufacturing costs made up of material, labor, and manufacturing overhead, and 2) supplier markup (i.e. end item scrap, SG&A (selling, general, and administrative expenses), profit and ED&T (engineering, design, and testing)). OEM markup is not included as part of this analysis. The incremental tooling was calculated separately; amortized into the piece cost at 450k units per year over 5 years. Calculations with and without tooling are provided in the analysis. A ten percent maximum cost limit was set to constrain the ideas to those that could be applied most easily to mainstream vehicles, while not predetermining the maximum level of mass reduction included in the findings. All cost estimates were based on requirements for production at a volume of 450,000 units per year, with mass reduction concepts and manufacturing techniques that were judged to be feasible at this volume in the 2020 to 2025 model year time frame.

Table 2. Net Incremental Direct Manufacturing Cost Elements

| Net Incremental Direct Manufacturing Cost | | | | |
|---|---|---|---|---|
| | Total Manufacturing Cost | | | Packaging |
| | Material | Labor | Manufacturing Overhead | |
| Supplier | X | X | X | X |
| OEM | X | X | X | X |
| | Markup | | | |
| | End Item Scrap | SG&A | Profit | ED&T |
| Supplier | X | X | X | X |
| OEM | - | - | - | - |

Tooling cost was defined as the cost to buy or build new tools to make a specific product, such as stamping dies, extrusion dies, holding fixtures, cutting tools etc. Over the course of normal vehicle redesign cycles, any design changes made to a component normally necessitates a manufacturing tooling change. Non-perishable tooling (e.g., stamping dies, extrusion dies, weld fixtures, gauges, etc.) were also evaluated. Perishable tooling used in welding, riveting and adhesive application is amortized into the piece cost. The costing methodology is described in greater detail in the full report [2] and in an earlier report [4].

Cost modeling for the Powertrain, Chassis and Trim systems were done using cost modeling analysis templates (CMAT's) at the sub-subsystem, subsystem and system levels. First, the cost analysis boundary conditions were determined, then an update to the database and process parameter models (based on initial assessment) was performed. The third step is to determine if commodity costing (such as for nuts and bolts) or detail costing is required (vehicle specific components).

The incremental costs for the Body and Frame components were estimated by EDAG using the Technical Cost Modeling (TCM) approach developed by the Massachusetts Institute of Technology Materials Systems Laboratory's researchers [5]. In this method each of the elements that contribute to the total cost is individually estimated. For example, for a stamped sheet metal part, the cost model estimates the costs for each of the operations involved in the manufacturing process, starting from blanking the steel coil through the final stamping operation to fabricate the component. The final estimated total manufacturing cost and assembly cost are a sum total of all the respective cost elements including the costs for material, tooling, equipment, direct labor, energy, building and maintenance.

All of the mass reduction and cost information was utilized to develop a cost curve. The primary mass reduction ideas and their respective costs were used to calculate individual $/kg and these were ranked from best to least value. The individual cost and mass reduction values were then cumulatively added to create a primary mass reduction cost curve ($/kg vs %MR). Secondary mass reduction estimates made on a part by part basis were then utilized to create a curve that expresses the compounded cost per kilogram of mass reduction at every level of vehicle mass reduction.

### *Powertrain, Chassis and Trim Systems Lightweight Solution*

The process for generating ideas for the powertrain, chassis and trim vehicle systems involved looking at applying the same system technologies used in the mid-sized crossover utility vehicle project [1] in addition to researching the latest technologies. The experience of FEV, EDAG, and Munro engineers was utilized, as well as, automotive parts supplier ideas, mass production vehicle benchmark data, published OEM literature, and other sources. The final list of technologies were ranked in terms of product function and performance risk, manufacturing implementation readiness and risk, and overall value of mass-reduction in term of weight savings versus net incremental direct manufacturing cost. Viable options included both direct mass reduction of components by material change, part integration and/or new manufacturing processes or technologies.

Secondary mass reduction, enabled by lowered component load requirements (as component masses and overall vehicle mass are reduced), was also evaluated on the component level.

For the initial screening process, the comprehensive list of mass reduction ideas at a component level were assembled in different combinations at the assembly, subsystem, and system levels to create different value propositions based on the preliminary estimated cost per kilogram for the forecasted mass reduction. Mass-reduction ideas were sorted and grouped at the component level by value in terms of cost per kg saved with the goal of achieving the greatest possible mass reduction at any given cost.

Ideas that were identified as potentially high value by the initial screening process were then evaluated in more detail for cost impact and additional analyses to make sure the estimated amount of mass reduction was dependable, and achievable without any degradation of function or performance. This included in some cases performing detailed analytical calculations, and in other cases normalizing existing reference vehicle components for differences in size and loading. For example, if a technology were found on a smaller vehicle then it would be scaled up for use on the lightweighted truck.

Once the final technology selection were made, an individual scaling factor for each idea's contribution to secondary mass savings was also determined based on a 20 percent mass reduction reference point.

### *Body and Frame Systems Lightweight Solution*

For development of the lightweighted solution of the Body and Frame systems, the baseline CAE model underwent a design optimization process using the HEEDS MDO (Multi-Disciplinary Optimization) model to create potential solutions for lightweight design within specific constraints. The structural parameters of material type, grade, gauge and cost were iterated without compromising structural and crash/safety performance requirements. The body and frame geometry and packaging space were kept unchanged.

Once solutions from the mathematically predicted results from the HEEDS MDO model were identified, the solutions were evaluated external to the model based on the criteria listed in Table 3 with targets defined by an acceptable tolerance around the baseline vehicle's performance. The CAE models were rerun with the final powertrain, chassis and trim mass reduction values and final CAE updates to body structure and frame to assure comparison to the baseline model. As with the baseline model, simulated crash results were obtained from CAE modeling of the Body and Frame and lump mass representation of remaining vehicle components. Evaluation of the lightweighted vehicle crash simulation results was based on comparing the baseline and lightweighted vehicle crash results for acceleration (g's) vs time, intrusion (mm), and visual inspection of deformation.

Durability and Vehicle Dynamics analyses were also performed. A vehicle was instrumented to collect data to be utilized in the frame and other analyses. For some components where actual vehicle test data was not available, comparisons were limited to the baseline and lightweighted simulation results. Items include static structural performance of doors, hood, and tailgate as listed in Table 3.

Table 3. CAE Model Evaluation Criteria

| System | | Load Case | Measure |
|---|---|---|---|
| NVH | Frame | Static Bending | Global Bending Stiffness |
| | | Static Torsion | Global Bending Stiffness |
| | Cabin | Static Bending | Global Bending Stiffness |
| | | Static Torsion | Global Bending Stiffness |
| | Cargo Box | Static Bending | Global Bending Stiffness |
| | | Static Torsion | Global Bending Stiffness |
| | Body-on-Frame | Static Bending | Global Bending Stiffness |
| | | Static Torsion | Global Bending Stiffness |
| Crash/Safety | Full Vehicle | FMVSS 208-35 MPH Flat Frontal Crash (UN NCAP) | Pulse<br>Crush<br>Time-to-Zero Velocity<br>Dash Intrusion |
| | | IIHS – 40 mph ODB Frontal Crash | Pulse<br>Crush<br>Time-to-Zero Velocity<br>Dash Intrusion |
| | | FMVSS 214 – 38.5 MPH MDB Side Impact (US SNCAP) | B-pillar Velocity<br>Side Structures Intrusion |
| | | IIHS – 31 MPH MDB Side Impact | B-Pillar Velocity<br>B-pillar Intrusions<br>Survival Space<br>Exterior Crush |
| | | FMVSS 214- 20 MPH 5th Percentile Pole Side Impact | B-Pillar Velocity<br>B-Pillar Intrusions<br>Structure Intrusions |
| | | FMVSS 301- 50 MPH MBD Rear Impact | Under Structural Zone Deformation<br>Door Operability<br>Fuel Tank Damage |
| | | FMVSS 261a- Roof Crush | Roof Strength to Weight Ratio |
| | | FMVSS 581 Bumper Impact | Front End Deformation |
| Durability | Frame | Fatigue | Component Life Cycle |
| | Doors | Frame Rigidity | Stiffness |
| | | Beltline Compression | Stiffness |
| | | Beltline Expansion | Stiffness |
| | | Torsion | Twist Stiffness |
| | | Sag | Vertical Deformation |
| | | Oil Canning | Outer Panel Deformation |
| | Hood | Bending | Stiffness |
| | | Torsion | Twist Stiffness |
| | | Oil Canning | Outer Panel Deformation |
| | Tailgate | Torsion | Twist Stiffness |
| | | Oil Canning | Outer Panel Deformation |
| Vehicle Dynamics | Full Vehicle | Static Bending | Understeer Gradient<br>Cornering Compliance<br>Roll Gradient |
| | | Static Torsion | Tire Load |
| | | Static Bending | Steering Response Phase Lag |
| | | | Steering Response Gain |
| | | Static Torsion | Track Width (2xCG Height) |

## Results and Discussion

Figure 2 illustrates the change in material makeup between the Production Stock Vehicle (based on a 2011 Silverado 1500) and the Lightweighted Vehicle. The overall lightweighted vehicle reduces the amount of steel and iron and increases the materials of plastic, rubber, high strength steel and cast aluminum while adding in materials of wrought aluminum and magnesium.

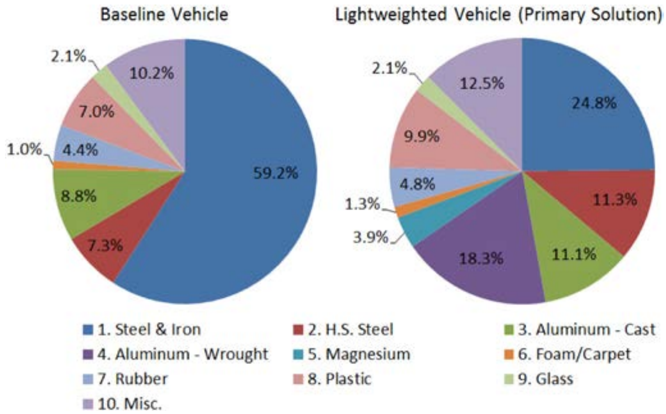


Figure 2. General Material Make-up of 2011 Silverado 1500 Production Vehicle and Lightweighted Vehicle

Table A in the Appendix contains a summary for each of the 19 systems. The table contains the base mass for each system, the mass reduction achieved in the system (both primary and secondary), the cost impact for net incremental direct manufacturing cost with and without tooling, system mass reduction % and overall vehicle mass reduction %.

The systems are categorized into two distinct groups in this paper and in the full report. Powertrain, Chassis and Trim contain all systems with the exception of the Body and Frame group which is made up of the Body System Group -A- (Body Sheetmetal) and the Frame and Mounting System. The top eight contributing systems are listed in Table 4. A sample of the detail and information included in the full report are provided in the following descriptions of one high mass reduction technology per system. The description begins with the cost and primary mass reduction of technologies in the Powertrain, Chassis and Trim systems followed by the Body and Frame systems. Secondary mass determination for the applicable systems and the resultant cost curve follow. Refer to the full report for complete information [2]. It is to be noted that while most of these technologies are not new, the novelty of this work is that they are all being placed all on one vehicle.

Table 4. Systems with Highest Mass Reduction and Sample Technology per System

| | System | System Mass Reduction (kg) | Vehicle Mass Reduction % | High Mass Reduction Technology Per System |
|---|---|---|---|---|
| Powertrain/Chassis/Trim | | | | |
| 1 | Suspension | 105.4 | 4.4 | Composite Fiber Leaf Springs (rear susp) |
| 2 | Brake | 45.8 | 1.9 | Front Rotor |
| 3 | Transmission | 39.4 | 1.6 | Transmission Case |
| 4 | Body Group B (Interior) | 34.0 | 1.4 | Seating Sub-system |
| 5 | Engine | 31.3 | 1.3 | Plasma Transfer Wire Arc |
| 6 | Driveline | 20.4 | 0.9 | Beam Rear Axle Assembly |
| Body and Frame | | | | |
| 7 | Body Group A (Body) | 207.0 | 8.7 | Aluminum |
| 8 | Frame and Mounting | 23.7 | 1.0 | HSS and 2 Aluminum Cross Sections |

## *Powertrain, Chassis and Trim*

The Powertrain, Chassis and Trim section of the main report contains a great number of lightweighted items. The following are examples of the higher mass reduction technologies per system presented in the report. This section outlines the primary mass reduction and related costs for these technologies. Secondary mass savings and cost changes are described later in this section. It should also be noted that the amount of mass reduction for some technologies were limited by the vehicle's hauling and towing specifications.

### Suspension System: Composite Fiber Leaf Springs

The Suspension system, subsystems and sub-subsystems are listed in Table 5. The technology highlighted in this section is the composite fiber leaf spring in the Rear Suspension Subsystem.

Table 5. Primary Mass Reduction and Cost Impact for the Suspension System

| System/Subsystem/ Sub-subsystem | Net Value of Mass Reduction | | | | |
|---|---|---|---|---|---|
| | Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC ($) (2) | Avg $/kg (2) | Vehicle Mass Reduction "%" |
| **SUSPENSION SYSTEM** | | | | | |
| Front Suspension Subsystem | 54.76 | 21.3 | -23.71 | -1.11 | 0.89% |
| **Rear Suspension Subsystem** | **63.52** | **35.75** | **-113.47** | **-3.17** | **1.5%** |
| ***- Rear Road Springs (composite)*** | ***63.52*** | ***35.75*** | ***-113.47*** | ***-3.17*** | ***1.5%*** |
| Shock Absorber Subsystem | 24.36 | 6.44 | -3.77 | -0.58 | 0.27% |
| Wheels and Tires Subsystem | 158.61 | 19.56 | -119.89 | 6.13 | 1.82% |
| TOTAL | 301.24 | 83.1 (decrease) | -260.84 (increase) | -3.14 | 3.48% |

(1) "+"=mass decrease, "-" = mass increase
(2) "+"=cost decrease, "-"=cost increase

The baseline OEM Chevrolet Silverado Rear Leaf Spring Assembly is a multi-piece assembly, with the major portions being made from steel bar stock as shown in Figure 3.

Figure 3. Rear Suspension Subsystem(Source: A2MAC1)

The Rear Suspension Subsystem, shown in Figure 4, consists of the major components of the leaf spring assembly: leaf springs, leaf spring bushings, shackle bracket, shackle bracket bushings, saddle bracket, spacer blocks, U-bolts, and miscellaneous attaching components.

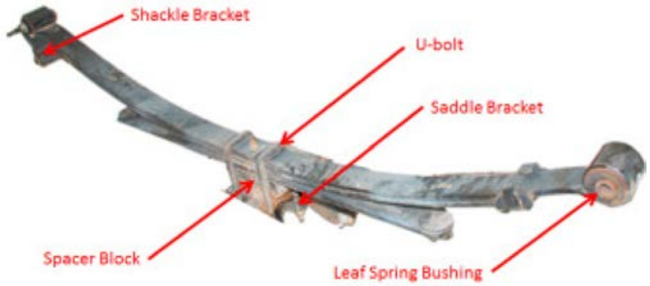


Figure 4. Rear Suspension Subsystem Current Assembly(Source: A2MAC1)

A significant mass reduction opportunity exists in the Rear Suspension System - namely the leaf spring assembly. Traditional steel leaf springs are rectangular shape and can be multi-stacked in order to obtain the desired spring load. Although there have been advances in steel leaf spring design that have reduced the mass, they pale in comparison to the mass savings opportunity that composites offer.

Glass fiber reinforced plastic (GFRP) leaf springs, as shown in Figure 5, are used extensively in Europe and in the U.S. on heavy-duty trucks and trailers. They are typically made from a glass fiber fabric that is laminated and bonded by a polyester resin. The fiber strands are soaked with resin and then wrapped together using a filament winding process and then squeezed together under pressure to obtain the final shape.

A manufacturer of OEM composite leaf springs, whom has supplied composite leaf springs since 1998 to support production requirements on the Sprinter commercial vehicles, namely the NCV3 Sprinter. Other customers using composite leafs springs are the GM Corvette and Land Rover. Composite leaf springs are also used in heavy duty truck applications for Kenworth, Peterbilt, Freightliner, and International.

Figure 5. Rear Leaf Spring Mass Reduced Assembly(Source:http://www.bing.com/images/search?q=Fiberglass+Leaf+Spring+Lightweight&FORM)

## Brake System: Grouped Rotor Mass Reduction Ideas

The Brake system, subsystem and sub-subsystem results are listed in Table 6. The technology highlighted in this section is the front rotor in the Front Rotor and Shield Sub-Subsystem.

Table 6. Primary Mass Reduction and Cost for Brake System

| System/Subsystem/Sub-subsystem | Net Value of Mass Reduction | | | | |
|---|---|---|---|---|---|
| | Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC ($) (2) | Avg $/kg (2) | Vehicle Mass Reduction "%" |
| **BRAKE SYSTEM** | | | | | |
| **Front Rotor/Drum and Shield Subsystem** | **42.98** | **22.00** | **-56.2** | **-2.55** | **0.92%** |
| ***- Front Rotor and Shield*** | ***24.29*** | ***12.61*** | ***-65.4*** | ***-5.19*** | ***0.53%*** |
| ***- Front Caliper, Anchor and Attaching Components*** | ***18.69*** | ***9.39*** | ***9.20*** | ***0.98*** | ***0.39%*** |
| Rear Rotor/Drum and Shield Subsystem | 34.26 | 16.31 | -71.02 | -4.35 | 0.68% |
| Parking Brake and Actuation Subsystem | 4.70 | 1.45 | -19.58 | -13.49 | 0.06% |
| Brake Actuation Subsystem | 10.66 | 2.53 | -0.46 | -0.18 | 0.11% |
| Power Brake Subsystem | 4.24 | 1.58 | -24.64 | -15.57 | 0.07% |
| Brake Controls Subsystem | 4.17 | 0.00 | 0.00 | 0.00 | 0.00% |
| TOTAL | 101.01 | 43.9 (dec) | -171.89 (inc) | -3.92 (inc) | 1.84% |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

The baseline OEM Chevrolet Silverado front rotor, [Figure 6] is a single-piece, vented design cast from grey iron and has a mass of 11.66 kg. Many high performance and luxury vehicle models have begun utilizing alternate rotor designs in order to improve both performance and economy.

Figure 6. Front Rotor Current Component(Source: FEV North America, Inc.)

Two-piece rotor assemblies are now found in many Mercedes, BMW, Audi, Porsche, and Chevrolet Corvettes across multiple platforms and models. Aftermarket suppliers that use this design in various production applications include Brembo and Wilwood. This two-piece design usually utilizes an aluminum center hub (or "hat") along with a disc braking surface (typically cast iron or steel).

The rotor center (hat) can be made from several material choices including aluminum, titanium, magnesium, grey iron or steel and manufactured from cast forms or billet machined from solid.

The rotor disc surfaces are also able to be made from various materials and processing methods. These include aluminum metal matrix composites (Al/MMC), metal matrix composites, titanium, and iron. Even carbon/ceramic matrices have been used to produce rotors of less mass. Processing includes casting vented or solid disc plates and the machining cross-drilled plates, slotted plates and scalloped disc diameters (both ID and OD) profiles.

The solutions chosen to be implemented on the final front rotor assembly was the combination of multiple individual brainstorming ideas. These ideas included the modifications to component design, material utilized and processing methods required as listed in Table 7.

Table 7. Mass Reduction Ideas Selected - Front Rotor in Front Rotor/Drum and Shield Subsystem

| Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|
| **Front Rotor/Drum and Shield Subsystem** | |
| Front Rotor | Downsize based on 2006 Dodge Ram |
| | Two Piece Rotor – Aluminum Center (Hat) |
| | Change disc material to Al/MMC |
| | Change vanes from straight to directional |
| | Cross-drill disc surface |

In addition, the final front rotor [in Figure 7] is the approximate design configuration based on many in production ideas. This redesigned front rotor solution has a calculated mass of 5.604 kg. Although nearly all of these individual mass reduction ideas have been implemented by plenty of manufactures and OEMs individually, none have been utilized all at once in a single vehicle application. Therefore, the appropriate amount of industry testing and validation must be performed by any vehicle manufacturer in order to fit this design to a particular vehicle application. Concerns to be addressed would include the normal list of topics that are determined with any braking system and include brake pad wear, cracking a deformation resistance, NVH testing versus functional performance, etc.

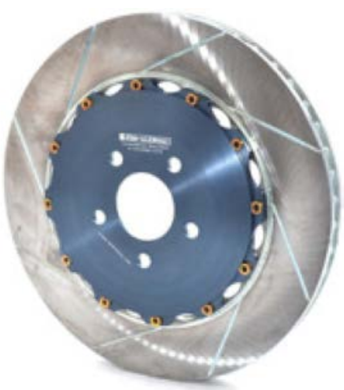

Figure 7. Front Rotor Mass Reduced Component Example(Source: http://www.girodisc.com/Girodisc-Front-2-piece-rotors-for-Mazda-RX8_p_6346.html)

## Transmission System: Transmission Case

The Transmission system, subsystem and sub-subsystem results are listed in Table 8. The technology highlighted in this section is the material for the transmission case in the Case Subsystem.

Table 8. Primary Mass Reduction and Cost for Transmission System

| System/Subsystem/ Sub-subsystem | Net Value of Mass Reduction | | | | |
|---|---|---|---|---|---|
| | Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC ($) (2) | Avg $/kg (2) | Vehicle Mass Reduction "%" |
| **Transmission System** | | | | | |
| External Components | 0.023 | 0.00 | 0.00 | -- | 0.00% |
| **Case Subsystem** | **30.72** | **10.66** | **-30.60** | **-2.87** | **0.45%** |
| ***-Transmission Case*** | ***18.78*** | ***6.93*** | ***-21.38*** | ***-3.08*** | ***0.29%*** |
| ***-Transfer Housing*** | ***10.09*** | ***3.41*** | ***-4.50*** | ***-1.32*** | ***0.14%*** |
| ***-Covers*** | ***0.037*** | ***0.01*** | ***-0.13*** | ***-9.51*** | ***0.00%*** |
| ***-Transmission Fluid Meas.*** | ***0.36*** | ***0.303*** | ***-1.07*** | ***-3.52*** | ***0.01%*** |
| ***-Bolts*** | ***1.30*** | ***0.00*** | ***-3.53*** | ***--*** | ***0.00%*** |
| ***-Misc*** | ***0.15*** | ***0.00*** | ***0.00*** | ***--*** | ***0.00%*** |
| Gear Train Subsystem | 12.39 | 2.05 | 24.18 | 11.79 | 0.09% |
| Internal Clutch Subsystem | 30.47 | 4.23 | -39.94 | -9.44 | 0.18% |
| Launch Clutch Subsystem | 20.29 | 8.62 | -21.73 | -2.52 | 0.36% |
| Oil Pump and Filter Subsystem | 7.5 | 2.42 | -11.52 | -4.76 | 0.10% |
| Mechanical Controls Subsystem | 7.14 | 0.87 | -5.03 | -5.76 | 0.04% |
| Electrical Controls Subsystem | 4.30 | 0.00 | 0.00 | -- | 0.00% |
| Parking Mechanism Subsystem | 0.88 | 0.06 | 5.24 | 87.45 | 0.00% |
| Misc. Subsystem | 0.00 | 0.00 | 0.00 | -- | 0.00% |
| Electric Motor and Controls Subsystem | 0.00 | 0.00 | 0.00 | -- | 0.00% |
| Transfer Case Subsystem | 28.44 | 5.27 | -48.81 | -9.26 | 0.22% |
| Driver Operated External Controls Subsystem | 3.13 | 0.00 | 0.00 | -- | 0.00% |
| TOTAL | 145.28 | 34.19 | -128.20 | -3.75 | 1.43% |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

The Case Subsystem is made up of three sections: the bell housing, transmission, and transfer case. These sections are currently made of aluminum SAE 380 alloy, as shown in Figure 8.

Figure 8. Case Subsystem Housings in the 2011 Silverado 1500(Source: FEV North, America, Inc.)

The use of alternate materials such as magnesium alloy has been used by a number of OEM's in order to reduce transmission weight and still maintain case integrity. Manufacturers that produce magnesium transmission cases include Mercedes-Benz with its seven-speed transmission, the 7G-TRONIC. Volkswagen produces magnesium alloy manual transmission cases for its Passat and the Audi A4/A6. The 2015 Audi TT and Audi TTS are also manufactured with a six speed manual gearbox that features a lightweight magnesium housing.

Other technologies were considered including carbon fiber transmission cases seen in Formula 1 race cars. Even though this technology held promise, it is currently seen as limited due to the ability to produce the transmission cases in the time required for mass production. Also, analysis of the thin wall on each of the components of the subassembly did not yield an outcome that would have proven to be an advantage to the end product. Hence, the greatest mass reduction was gained by the material selection of magnesium alloy in the transmission case.

### Body Group B (Interior): Magnesium Seat Frames and Plastic Seat Frames

The Body Group B (Interior) system, subsystem and sub-subsystem results are listed in Table 9. The technology highlighted in this section is the Seating Subsystem. This analysis takes the current seat technologies and describes the potential technologies of the cast magnesium frame design as well as the BMWi3 seat design and Opal Aspen composite seat base.

Table 9. Primary Mass Reduction and Cost for the Body Group B

| System/Subsystem/ Sub-subsystem | Net Value of Mass Reduction | | | | |
|---|---|---|---|---|---|
| | Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC ($) (2) | Avg $/kg (2) | Vehicle Mass Reduction "%" |
| **Body Group B (Interior)** | | | | | |
| Interior Trim and Ornamentation Subsystem | 56.55 | 2.06 | 6.84 | 3.32 | 0.09% |
| Sound and heat Control Subsystem (Body) | 4.78 | 0.00 | 0.00 | 0.00 | 0.00% |
| Sealing Subsystem | 14.52 | 4.72 | 32.23 | 6.84 | 0.20% |
| **Seating Subsystem** | **120.69** | **19.16** | **-127.89** | **-6.68** | **0.80%** |
| ***-Seat Drivers Front*** | ***31.76*** | ***3.11*** | ***-15.00*** | ***-4.83*** | ***0.13%*** |
| ***-Seat passenger Front*** | ***26.77*** | ***3.10*** | ***-15.36*** | ***-4.96*** | ***0.13%*** |
| ***-Rear 60% Seat*** | ***25.86*** | ***5.55*** | ***-43.73*** | ***-7.88*** | ***0.23%*** |
| ***-Rear 40% Seat*** | ***17.24*** | ***3.35*** | ***-23.87*** | ***-7.13*** | ***0.14%*** |
| ***-Front Center Seat and Console*** | ***19.06*** | ***4.05*** | ***-29.93*** | ***-7.38*** | ***0.17%*** |
| Instrument Panel and Console Subsystem | 30.84 | 6.82 | -35.29 | -5.17 | 0.29% |
| Occupant Restraining Device Subsystem | 19.64 | 1.26 | -3.12 | -2.47 | 0.05% |
| TOTAL | 247.02 | 34.02 (dec) | -127.23 (inc) | -3.74 (inc) | 1.43% |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

Figure 9 shows the current seating technology for the Rear 40% seat back frame. The seating technology in the 2011 Silverado includes an array of stamped and welded parts to construct the back and bottom frames for all four seat groups. Steel springs are added and then foam is placed on top with a covering over the foam.

Figure 9. Rear 40% Seat Back Frame(Source: FEV North America, Inc.)

Figure 10 shows an example of the cast magnesium back frame used in the 2011 Ford Explorer's third row seats. Magnesium back frames can also be found in the 2013 GM Corvette. Magnesium has about 25% the density of steel although additional material is needed in the frame and as a result the mass save is not a straight material substitution.

Figure 10. Magnesium Seat Cushion Frame for the 2011 Ford Explorer(Source: A2Mac1.com)

While magnesium is one of the major players in weight reduction, plastics have also improved to provide strength as well as weight loss. One company has been developing different plastic alternatives to achieve different degrees of weight loss.

The company has used the laminate for parts with areas of highest local anisotropic load distribution (e.g., front seat back rests and the laminates are used for predominantly closed areas, mechanical load rather evenly distributed e.g. seat pans, rear seat backrests, vehicle floors). The advanced tapes and laminates can also be used for structural automotive parts such as roof cross member, cross car beam, crash extensions, fire wall, front end, structural floor, battery integration, and structural inserts in the pillars and roof frame. The company has used a plastic laminate in the production front seat pan in the Opal Aspen, see Figure 11.

Figure 11. Opal Astra Seat Bottom Frame Using the Laminate

The hardest part in using plastics in the seat areas for weight reduction is in the recliner area. It is much harder to achieve the required strength to pass OEM testing on the front seat back using a recliner mechanism. The technology company has used two distinctive methods to try and overcome this issue with different weight loss reduction outcomes. One is to use an all plastic injection molded seat back frame suing PA6 or Pa66 with a long glass fiber. This is currently being used in the new BMWi3, see Figure 12. Although this frame only weighs 2.3kg it requires added steel reinforcements from the recliner up the back sides of the plastic seat back that adds another approximately 2kg. This seems to be an intermediate high breed step from steel to full plastic.

Figure 12. BMWi3 Seat(Source: BASF) http://www.plasticsportal.net/wa/plasticsEU~en_GB/portal/show/common/plasticsportal_news/2014/14_176

The other method that shows promise for the future is to remove the steel reinforcements used in the BMWi3 and use the layer laminate tape in focused areas to gain strength were its needed. Although this method may have added cost for processing, the weight loss potential is up to 50%.

Figure 13 shows an example of a prototype seat backrest with over molded tape reinforcement. The seat back frame is not in production at this time, but is in the testing phase.

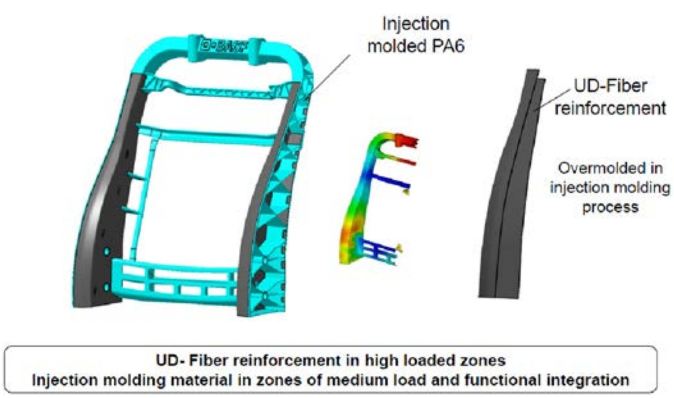


Figure 13. Prototype-Seat Backrest with Over-Molded Tape Reinforcement(Source: BASF)

Table 10 lists the selection of frame materials for the front and back seats. The selections include plastic and cast magnesium.

With the injection molding process and added integrated parts into the frame over conventional seat processing of multiple stampings and weldings, it can be a cost wash or savings. And continues to state a number of considerations on the composites. The items listed include:

- Indications are a 33% or more weight save in the case of a whole front seat assembly
- Thermoplastic composites have potential to be produced via volume processes
- Costs are between Carbon Fiber and Steel, less with part integration

Table 10. Mass Reduction Concepts Selected for Seating Subsystem

| Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|
| **Body Group B** | |
| **Seating Subsystem** | |
| **Seat Drivers Front** | |
| Driver seat back frame | Plastic |
| Driver seat bottom frame | Plastic |
| Drivers seat trim | Foaming agent |
| **Seat Passenger Front** | |
| Passenger seat back frame | Plastic |
| Passenger seat back frame | Plastic |
| Passenger seat trim | Foaming agent |
| **Rear 60% seat arm rest** | |
| 60% Seat back frame | Cast Magnesium |
| 60% Seat bottom frame | Cast Magnesium |
| 60% Arm rest frame | Cast Magnesium |
| 60% Arm rest frame hinge RH & LH | Aluminum |
| 60% Seat trim | Foaming Agent |
| **Rear 40% Seat Back** | |
| 40% Seat back frame | Cast Magnesium |
| 40% Seat bottom frame | Cast Magnesium |
| 40% Seat trim | Foaming Agent |
| **Front Center Console** | |
| Bottom Frame | Cast Magnesium |
| Mid frame | Cast Magnesium |
| Seat frame | Cast Magnesium |
| Front center console trim | Foaming Agent |

## Engine System: Plasma Cylinder Liner

The Engine system, subsystem and sub-subsystem results are listed in Table 11. The technology highlighted in this section is the plasma transfer wire arc cylinder liner.

The engine in the 2011Silverado 1500 is a 5.3L V-8. The cylinders in the 2011 Silverado 1500 torn down for this work includes cast iron cylinder liners, as shown in Figure 14. Prior to filling, the liners are inserted into the casting cavity. The liners are machined to finish the cylinder bore following casting.


Figure 14. Cast Iron Cylinder Lines(Source:http://www.anandenterprise.com/innovation.html)

Table 11. Primary Mass Reduction and Cost for Engine System

| System/Subsystem/Sub-subsystem | Net Value of Mass Reduction | | | | |
|---|---|---|---|---|---|
| | Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC ($) (2) | Avg $/kg (2) | Vehicle Mass Reduction "%" |
| **ENGINE SYSTEM** | | | | | |
| Engine Frames, Mounting and Brackets Subsystem | 6.07 | 1.10 | -0.01 | -0.01 | 0.05% |
| Crank Drive Subsystem | 37.00 | 2.376 | 2.95 | 1.24 | 0.10% |
| **Cylinder Block Subsystem** | **59.86** | **3.30** | **0.80** | **0.24** | **0.14%** |
| **-PTWA for cylinder liners** | 4.208 | **2.636** | **3.31** | **1.256** | **0.11** |
| **-Rear Seal Retainer Al to PL** | 0.790 | **0.298** | **-0.53** | **-1.78** | **0.01** |
| **-Misc (Plate Al to Mg)** | 2.596 | **0.364** | **-1.98** | **5.45** | **0.02** |
| Cylinder Head Subsystem | 24.90 | 1.16 | 6.06 | 5.22 | 0.05% |
| Valvetrain Subsystem | 16.26 | 0.19 | 0.05 | 0.26 | 0.01% |
| Timing Drive Subsystem | 1.75 | 0.42 | -2.44 | -5.88 | 0.02% |
| Accessory Drive Subsystem | 8.27 | 1.73 | 0.73 | 0.42 | 0.07% |
| Air Intake Subsystem | 11.95 | 0.94 | -0.54 | -0.58 | 0.04% |
| Fuel Induction Subsystem | 1.12 | 0.00 | 0.00 | 0.00 | 0.00% |
| Exhaust Subsystem | 12.17 | 3.15 | -20.00 | -6.35 | 0.13% |
| Lubrication Subsystem | 10.55 | 3.01 | -11.24 | -3.74 | 0.13% |
| Cooling Subsystem | 24.32 | 3.31 | -92.06 | -21.67 | 0.17% |
| Exhaust Gas Re-curculation Subsystem | 0.05 | 0.00 | 0.00 | 0.00 | 0.00% |
| Breather Subsystem | 0.11 | 0.00 | 0.00 | 0.00 | 0.00% |
| Engine Management, Engine Electronic, etc. | 5.67 | 0.89 | 1.97 | 2.23 | 0.04% |
| Accessory Subsystems | 19.89 | 2.23 | -0.89 | -0.40 | 0.09% |
| TOTAL | 239.95 | 23.81 (decrease) | -114.63 (increase) | -4.82 (inc) | 1.00% |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

Lightweighting options considered for the cylinder liners were changing to plasma transfer wire arc (PTWA), as shown in Figure 15.

Figure 15. Plasma Transfer Wire Arc (PTWA)(Source:http://www.geencarcongress.com/2009/05/ptwa-20090529.html)

The new process began development by Ford in the early 1990s and forms an iron surface for the cylinder wall by plasma transfer wire arc. The process was first implemented on the 2008 Nissan GT-R and the 2011 Shelby Mustang GT500. The ultra thin lining, 10% of cast liner thickness found on Silverado's 5.3L, is done by casting the block without liners and premachining the bores to near net size. A bonding coat is put onto the bore surface after the bore is cleaned and fluxed. The coating is put onto the cylinder wall by continuously feeding a low carbon steel wire into the nozzle apparatus. The plasma coating is 0.070-0.170 mm thick. Although Ford has a variety of patents on this process from the 1990s and later, this technology has been used on BMW's new N20 engine block (two iron wires in similar process), and Volkswagen's Touareg, Lupo and Van T5 (steel and molybdenum powder applied by plasma jet).

Table 11 shows the mass and cost impact for the Cylinder Block Subsystem. Utilizing the process of plasma transfer wire arc reduces 2.636 kg and saves $3.31 cost.

Cost considerations included tooling which accounts for any item that touches the part (part specific fixtures, gauging and perishable tooling), piece price includes perishables (tooling tips, material, etc), overhead rate includes equipment (amortized), facilties and utilities.

## Driveline System: Hollow Half Shafts

The Driveline system, subsystem and sub-subsystem results are listed in Table 12. The technology highlighted in this section includes the Rear Drive Housed Axle Subsystem and specifically the axle half shaft.

Table 12. Primary Mass Reduction and Cost of Driveline System

| System/Subsystem/Sub-subsystem | Net Value of Mass Reduction | | | | |
|---|---|---|---|---|---|
| | Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC ($) (2) | Avg $/kg (2) | Vehicle Mass Reduction "%" |
| DRIVELINE SYSTEM | | | | | |
| Driveshaft Subsystem | 14.31 | 2.10 | 3.38 | 1.61 | 0.09% |
| **Rear Drive Housed Axle Subsystem** | **89.07** | **10.47** | **25.78** | **2.46** | **0.44%** |
| ***-Beam Rear Axle Assembly*** | ***66.60*** | ***7.56*** | ***13.82*** | ***1.83*** | ***0.32%*** |
| ***-Rear Drive Unit*** | ***7.56*** | ***2.91*** | ***11.96*** | ***4.11*** | ***0.12%*** |
| ***-Rear Axle Differential Carrier Assy*** | ***14.91*** | ***0.00*** | ***0.00*** | ***0.00*** | ***0.00%*** |
| Front Drive Housed Axle Subsystem | 52.53 | 6.49 | 6.27 | 0.97 | 0.27% |
| Front Drive Half Shafts Subsystem | 27.62 | 1.36 | 2.58 | 1.90 | 0.06% |
| 4WD Driveline Control Subsystem | 0.29 | 0.00 | 0.00 | 0.00 | 0.00% |
| TOTAL | 183.82 | 20.42 (decrease) | 38.01 (decrease) | 1.86 (decrease) | 0.86% |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

The Beam Rear Axle Assembly Sub-subsystem provided an opportunity to strategically thin the walls of the axle tubing without losing any structural integrity. This is achieved through a proprietary extrusion process used to manufacture the tube sleeves. This process is known as the Vari-lite® tube process….. [see Figure 16]. The process is an extrusion process which begins with steel tube stock and through a series of different machining process creates a unique profile inside of the tube. This extrusion process maintains the same structural properties as the parent tube material, yet reduces the mass by approximately 20% per axle housing.

The same conceptual process is used for the extrusion of the axle shafts. These components yield a little more mass savings, around 25% per axle assembly. These are produced by the same manufacturer as the rear axle housing tubing. Coupled with the axle shaft, the wheel hub was also mass-reduced by drilling six additional holes in the forging.

Another opportunity was to change the rear axle differential housing cover from sheet steel to sheet aluminum. This provided an additional 1.101 kg mass-reduction. To compliment the differential change, the ring gear can also be downsized due to application.

Figure 16. Silverado Vari-Lite® Tube - Axle Half-Shaft(Source: U.S. Manufacturing, Warren, Michigan)

## Body Group A, and Frame and Mounting Subsystems

The Body Group A, and Frame Mounting systems, subsystems and sub-subsystems results are listed in Table 13. The technologies highlighted in this section include aluminum cabin structure, aluminum closures, aluminum cargo box and high strength steel frame with two aluminum cross members. Note that the mass savings and cost changes from the Bumpers Subsystem and the Frame and Mounting System were found to have more of a leaning in the secondary mass accounting and hence are removed from the primary table below. Detailed analysis was not performed to determine the distribution between primary and secondary mass reduction for these components.

The report contains pie charts showing the baseline material makeup of the baseline and hybrid aluminum Body Group A are shown in Figure 17. As can be seen, the amount of mild steel is reduced from 79% to 8% while aluminum increases to 58%.

The Body and Frame is divided into systems and subsystems as shown in Table 14, along with mass values for the baseline vehicle.

The baseline Body and Frame (frame, cabin, cargo box) CAE model began with the FEM model of the 2007 Silverado 1500 by the National Crash Analysis Center at George Washington University for the NHTSA report "Investigation of Opportunities for Lightweight Vehicles Using Advanced Plastics and Composites"[3]. Figures 18, 19, 20 illustrate the components that make up each of the frame, cabin and cargo box. The baseline model frame components were made of 370-420 MPa steel and closures were made of mild steel from 140 to 300MPa with. A 2011 Silverado 1500 was purchased and torn down and components compared. Updates included the frame in the 2011 Silverado 1500, several modified weld locations in the cabin structure and the addition of 4×4 components (transfer case, front driveshaft, front differential and drive axles).

Table 13. Primary Mass Reduction and Cost Impact for the Body Group A and Frame and Mounting Systems

| System/Subsystem/ Sub-subsystem | Net Value of Mass Reduction | | | | |
|---|---|---|---|---|---|
| | Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC ($) (2) | Avg $/kg (2) | Vehicle Mass Reduction "%" |
| **BODY SYSTEM GROUP 'A'** | **574.7** | **190.7** | **-1125.15** | **-6.0** | **8.0%** |
| **Body Structure Subsystem** | **207.2** | **75.40** | **-506.61** | **-6.72** | **3.16%** |
| Cabin | 207.2 | 75.40 | -506.61 | -6.72 | 3.16% |
| **Front End Subsystem** | **25.00** | **11.60** | **-62.92** | **-5.42** | **0.49%** |
| Radiator Asm | 12.90 | 5.70 | -10.36 | -1.82 | 0.24% |
| Radiator Support | 12.10 | 5.90 | -52.56 | -8.91 | 0.25% |
| Tow Hook | 2.25 | 0.00 | 0.00 | 0.00 | 0.00% |
| Hood Hinges | 3.25 | 0.00 | 0.00 | 0.00 | 0.00% |
| **Body Closure Subsystem** | **153.70** | **60.00** | **-288.90** | **-4.82** | **2.51%** |
| Panel Fender outer LH | 14.90 | 7.50 | -19.34 | -2.58 | 0.31% |
| Panel Fender Outer RH | 14.00 | 7.00 | -18.21 | -2.60 | 0.29% |
| Hood | 22.70 | 11.00 | -35.19 | -3.2 | 0.46% |
| Door Asm, front LH | 29.00 | 10.20 | -58.99 | -5.78 | 0.43% |
| Door Asm, front RH | 28.90 | 10.10 | -58.73 | -5.81 | 0.42% |
| Door Asm, Rear LH | 22.00 | 7.00 | -49.31 | -7.04 | 0.29% |
| Door Asm Rear RH | 22.20 | 7.20 | -49.14 | -6.83 | 0.30% |
| **Bumpers Subsystem** | **48.40** | **Moved to Secondary Mass Reduction Section** | | | |
| **Cargo Box Subsystem** | **127.10** | **43.00** | **-267.57** | **-6.22** | **1.80%** |
| Cargo Box | 108.30 | 34.40 | -241.47 | -7.02 | 1.44% |
| Tailgate | 18.80 | 8.60 | -26.10 | -3.03 | 0.36% |
| **Misc. Subsystem** | **13.32** | **0.7** | **0.85** | **1.21** | **0.03%** |
| **FRAME AND MOUNTING SYSTEM** | **267.6** | **Moved to Secondary Mass Reduction Section** | | | |
| **TOTAL** | **842.4** | **190.7 (decrease)** | **-1125.15 (decrease)** | **-6.0 (dec)** | **8.0%** |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

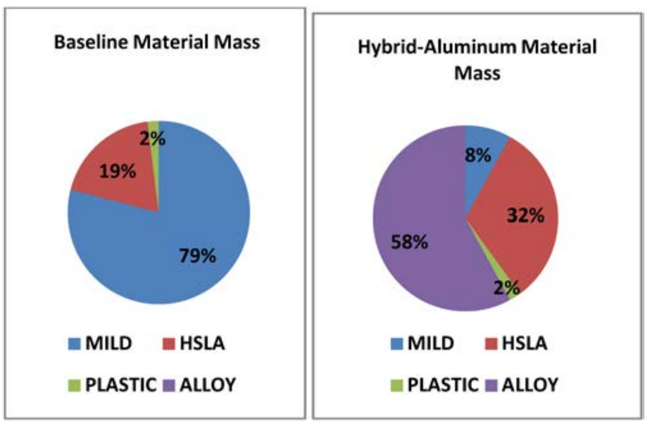


Figure 17. Pie Chart Overview of Baseline and Hybrid-Al Body and Frame Systems

Table 14. Body and Frame Components: Baseline Material and Mass for the 2011 Silverado

| System | Subsystem | Steel Material Strength |
|---|---|---|
| Closures | Door Front | 270 MPa |
| | Door Rear | 270 MPa |
| | Hood | 270 MPa |
| | Tailgate | 300 MPa |
| | **Sub-Total** | |
| BIW | Frame Assembly | 240MPa-420MPa |
| | Cabin | 140-270 MPa |
| | Box Ass'y | 240-270MPa |
| | Fenders | 140MPa |
| | **Sub-Total** | |
| BIW Extra | Radiator Structure | 370 MPa |
| | Extra Cabin –radiator support | 420 MPa |
| | **Sub-Total** | |
| Bumper | Bumper Front | 370-420MPa |
| | Bumper Rear | 300 MPa |
| | **Sub-Total** | |

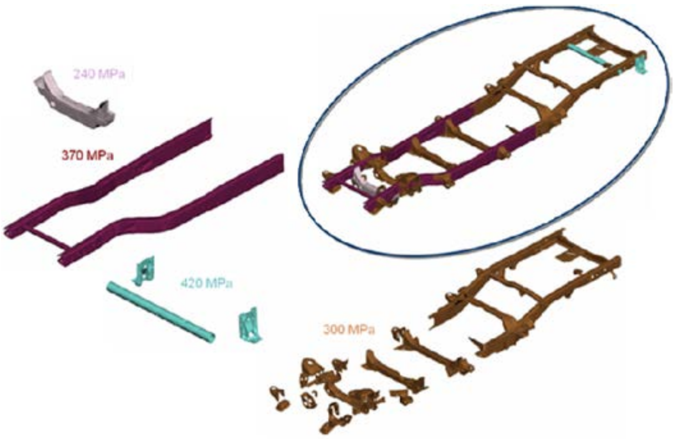


Figure 18. Material Map of Baseline Frame

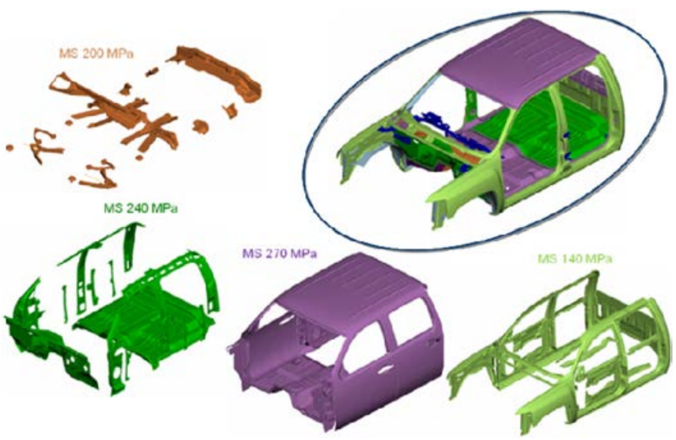


Figure 19. Material Map of Baseline Cabin Model

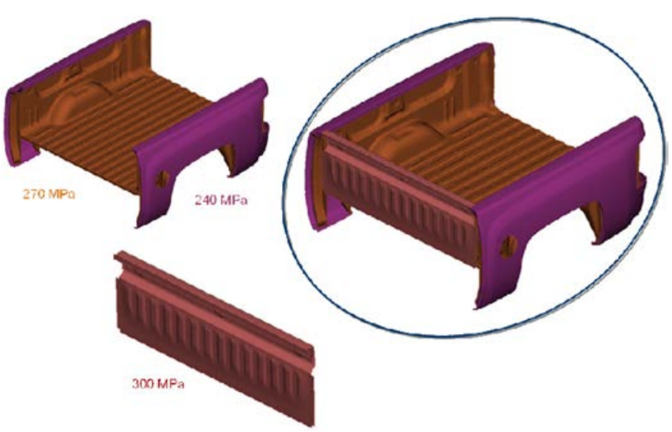


Figure 20. Material Map of Baseline Cargo Box Model

The CAE models of the different components of the light-duty truck including the frame, cabin, cargo box and the complete model (body-on-frame) underwent static torsion and bending stiffness (i.e. NVH) comparison to lab test data on the actual light-duty truck (2011 Silverado 1500). The cabin was rubber mounted (with four bushings on each side) and the cargo box was hard mounted (bolted) on to the frame.

The CAE modeling of the baseline frame, cabin, and body-on-frame structure yielded less than 5 percent difference for each of the static torsion stiffness, and bending stiffness compared to the actual measurements. No test data was available for comparing the cargo box.

The baseline vehicle CAE model was also run under three NHTSA crash tests and compared to the data from the actual NHTSA crash test through for vehicle acceleration pulse, dynamic crush and intrusion and visual appearance of deformation, The results were analyzed and judged to be acceptable. The tests were:.

- FMVSS 208-35 MPH flat frontal crash with rigid wall barrier (same as US NCAP)
- FMVSS 214-38.5 MPH side impact with moving deformable barrier (MDB)
- FMVSS 214-20mph, 5$^{th}$ Percentile Pole Side Impact

The lightweight BIW structure and frame were determined from a Multi-Disciplinary Optimization (MDO) program which took into account items including cost, load cases of regulatory safety requirements, and structural performance standards, etc. and their results chosen were the solutions for the frame, cabin structure and cargo box and closures listed in Table 15 and shown in Figures 21, 22, 23. The lightweight design optimization included the following for the frame, cabin, cargo box, bumpers, and closures. Design changes were based on changes in material, optimized gauge, and material grades. The material gauges were considered conservative for this work.

Table 15. Body and Frame Lightweight Component CAE Model Material Specifics

| Component | Material | Material Specifics |
|---|---|---|
| Frame | HSS/AHSS/ Aluminum | DP 300<br>BH 280<br>HSLA 350<br>CP 1000<br>HSLA 420<br>SF 570<br>DP 300<br>TRIP 600<br>AL 6082 |
| | TRB's on frame rails (mid and rear rails (inner and outer) | |
| Cabin | Aluminum, HSS/AHSS | 5 Series Al<br>DP 300/500<br>Cast Al 169 |
| Rocker | HSS/AHSS | HSLA 420 |
| Cargo Box | Aluminum | 5 series Al |
| Fender, Radiator Structure | Aluminum | Al 6082, AL 6111, Plastic |
| Bumpers | Aluminum | AL 6022 T6 (front)<br>Al 6013 T6 (rear) |
| Doors | Aluminum HSS/AHSS | AL6022 |
| Hood | Aluminum | AL6111 |
| Tailgate | Aluminum, HSS/AHSS | 6 series Al<br>DP 300/500 |

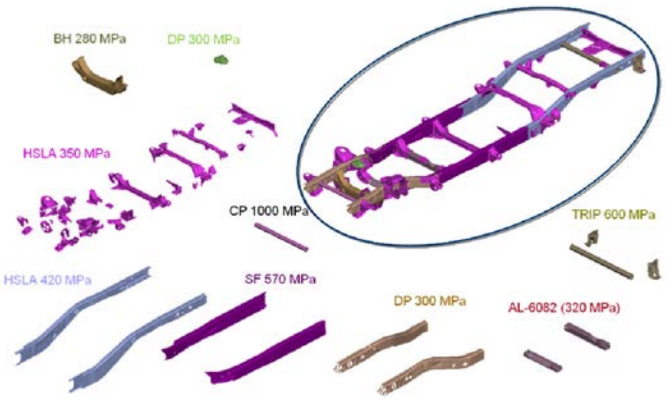


Figure 21. Material Map of Lightweighted Frame

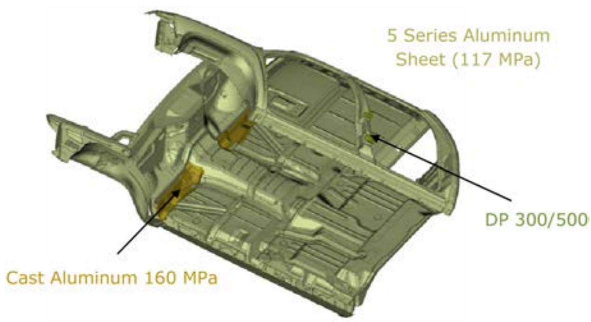


Figure 22. Material Map of Lightweighted Cabin


Figure 23. Material Map of Lightweighted Cargo Box

### *Body and Frame Costing*

Table 16 contains the manufacturing and assembly costs for the lightweight model compared to the baseline model. The manufacturing cost includes: material, labor, energy, equipment, tooling, building, maintenance, scrap recycle and packaging.

Tooling cost in the manufacturing price includes perishable tooling used in welding, riveting and adhesive application is amortized into the piece cost. Tooling cost outside of these items were found to be cost neutral when assuming a ground up assembly plant.

The scrap is included in the material cost: Material cost = Blank Size × Material Cost - Scrap Percentage × Blank Size × Scrap Value. The scrap value for the aluminum was $2/kg which assumes the scrap is separated for maximum price by the companies that recycle aluminum.

For the purpose of this mass reduction analysis, component/assembly packaging costs were considered to be neutral due to the relative size envelope of these parts not changing significantly between the production stock and mass-reduced parts.

Assembly changes were also observed in number of assemblies. The assembly cost of replacing steel grades with aluminum were calculated based on the number of parts and connections in the assembly, type of connections, assembly equipment and tooling. The baseline vehicle assemblies were made up of resistance spot welding (RSW) whereas the optimized vehicle assemblies of aluminum parts were made up of self-piercing rivets (SPR), adhesives and bolted fasteners. Costs for adhesive bonding were included. Additionally, in the optimized model the assembly of the aluminum parts included adhesive bonding at all SPR areas, resulting in an estimated adhesive length of 180 meters. The cost of adhesive was assumed to be $20/kg.

Table 16. Manufacturing and Additional Assembly Costs for the Lightweighted Vehicle

| System | Component | Manufacturing Cost | Add'l Assy Cost |
|---|---|---|---|
| Closure | 2 Doors Front | -117.72 | - |
| | 2 Doors Rear | -98.45 | - |
| | Hood (no hinges) | -35.19 | - |
| | Tailgate | -22.77 | -2.38 |
| | **Sub-Total** | **-274.13** | **-2.38** |
| BIW | Frame Assembly | -54.42 | - |
| | Cabin | -381.31 | -89.52 |
| | Box Ass'y Pickup | -216.44 | -17.88 |
| | Fenders | -27.08 | -7.48 |
| | **Sub-Total** | **-679.25** | **-114.88** |
| BIW Extra | Radiator Structure | -4.83 | -3.95 |
| | Extra Cabin – Rad Support | -38.3 | -10.19 |
| | **Sub-Total** | **-43.13** | **-21.61** |
| Bumper | Bumper Front | -19.72 | -2.83 |
| | Bumper Rear | -42.64 | -2.42 |
| | **Sub-Total** | **-62.36** | **-5.25** |
| **Adhesives** | | | **-57.60** |
| **TOTAL** | | **-1,066.42** | **-201.72** |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

Within these numbers were accountings for Aluminum Castings, as listed in Table 17.

Table 17. Aluminum Castings

| Silverado Part Name | Part Weight (kg) | Part Cost |
|---|---|---|
| **CABIN** | **4.63** | **-$56.26** |
| 23-bw-toepanleft | 1.90 | -$23.13 |
| 17-bw-toepan-left | 1.80 | -$21.92 |
| 78-bw-cabxmemberrearbrkt | 0.46 | -$5.60 |
| 78-bw-cabxmemberrearbrktR | 0.46 | -$5.61 |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

***Analyses***

A number of analyses were done throughout this project. This report includes an evaluation of the unique characteristics and requirements of full-size pickups, including and static structural performance of doors, hood and tailgate, frame durability, and vehicle dynamics,. In addition, the front/back weight balance was maintained. The baseline truck was a balance of front axle/rear axle 58.1%/41.9% and the hybrid aluminum light weight model was 58%/42% GVW. A broad spectrum of CAE NVH and crash analyses were performed.

## Durability

A number of baseline and lightweighted components were analyzed for durability in CAE. The FEA models were developed in ABAQUS non-linear solver format. The acceptance criteria along with the loads and load locations were based on generic targets and information used in / from other programs known to EDAG.

The hood baseline material contained BH 280/400 and 260/370 and was 0.78mm on the hood and 3.2mm on the hinge. The lightweighted hood, as illustrated in Figure 24, contained 6022 aluminum of 290MPa and 1.17mm thick and DP350/600 hinges of 3.2mm.


Figure 24. Gauge Map of Optimized Hood

A) Hood was analyzed for 1) Cantilever Bending, 2) Torsional Rigidity and 3) Oil Canning Load Deflection. The results in Table 18 show that the lightweighted hood is comparable to the baseline hood with respect to cantilever bending, torsional rigidity and oil canning load deflection.

Table 18. Hood Performance Results Optimized

| No. | Loadcase | Baseline (mm) | Optimized (mm) |
|---|---|---|---|
| 1 | Cantilever Bending | 3.3E-03 | No Set |
| 2 | Torsional Rigidity | 8.83 | 13.4 |
| 3 | Oil Canning Load Deflection | No Set | No Set |

Other components were also analyzed. The doors were analyzed for 1) Frame Lateral Rigidity (front), 2) Frame Lateral Rigidity (rear), 3) Beltline Strength -Compression, 4) Beltline Strength - Expansive, 5) Torsional Rigidity, 6) Door Sag, and 7) Oil Canning Load Deflection. The tailgate was analyzed for 1) Torsional Rigidity and 2) Oil Canning Load Deflection.

## Vehicle Dynamics

The vehicle dynamics model is a ride and handling model of the vehicle. The purpose of it is to assess what effect the mass center of gravity and inertia changes and related spring /damper changes will have on the overall handling of the vehicle.

Overall weight reduction has beneficial effects for Vehicle Dynamics in the following areas:

- Sprung and unsprung masses are easier to control resulting in improved roll damping and ride characteristics
- Lower weight and roll/pitch/yaw inertias allow more opportunity for trade-off between steering performance and roll/yaw stability
- Reduced loads into suspension and body components allowing a better trade-off between Ride/Handling/Steering and Durability requirements

A Silverado was instrumented and operated at the MGA Proving Ground and was run on a number of terrain types including 35$^{th}$ street railroad crossing, 550mm Tramp 20 mph, 760mm Pothole 10 mph, Barrel Hoops 20 mph, Body Twist 12mph, Cobblestone20mph, Decel65mph, Pothole Lane15 mph, sweeping turn 25 mph and washboard 30mph. Data was collected on a number of items including CMM data, wheel spindle accelerations and analytical load cases were validated. Only the frame was validated for fatigue loads and included the following steps: 1) Develop a Multi-Body Dynamics Model, 2) Develop analytical load cases, and 3) Perform stress and fatigue analysis.

The vehicle dynamics model was created and analysed in MSC ADAMS. The Durability MBD model was created using Altair MotionView. This was used along with some standard durability loadcases to translate wheel spindle loads to loads at the chassis frame for the durability analysis.

Results of the baseline and optimized frame durability revealed that there was a very small reduction in fatigue life in the optimized frame at the right and left hand body mount brackets as well as the left hand side cargo box mount. This could be resolved with minor trim and weld changes and physical testing for confirmation.

## CAE Analyses - NVH and Crash Safety

For NVH, bending and torsional stiffness comparisons of the baseline and light weighting vehicles were analyzed. The baseline CAE model was evaluated to actual vehicle tests. The three main parts of the vehicle, cabin, cargo box and frame were each modeled separately and then all together. The baseline model correlated within 5% of the actual test data. The lightweight model Bending and Torsion Stiffness results were very similar to the baseline model in terms of meeting the <5% comparison error requirement.

For Safety, the baseline model was compared to actual NHTSA crash test information for the following crash tests for the 2007 and/or 2011 Silverado 1500. This was used to confirm that the baseline CAE model was reasonable.

FMVSS 208 - 35 mph flat frontal crash (US NCAP)

FMVSS 214 - 38.5mph MDB side impact (US SINCAP)

FMVSS 214 - 20mph 5$^{th}$ Percentile pole side impact

Additional simulations were done on the baseline model without comparison to actual crash data. These included:

IIHS - 40mph ODB frontal crash

IIHS - 31 mph MDB side impact

FMVSS 301 - 50 mph MDB rear impact

FMVSS 581 - bumper impact

Following this step, the lightweighted model was run and compared to the baseline model in all crash tests. Results were acceptable for the lightweight design and the detailed results can be found in the full report[2].

## Secondary Mass

Identification of Secondary Mass Savings (SMS) was performed for the Powertrain, Chassis and Trim systems on a part by part basis. The SMS for the Body and Frame systems, were done through consideration of the light-duty pickup truck performance specifications as well as CAE analysis for specific technologies, specifically the cabin structure and frame. The bumpers were also included in the secondary mass calculations. Table 20 summarizes the information of the total mass reduction and cost for the systems in which SMS was found. The table also lists the secondary mass savings and cost savings contribution for each system. Lastly, the percentage SMS per system is calculated as well as the percentage SMS for the whole light-duty pickup truck mass. The full table is in Table B in the Appendix.

Table 20. Vehicle Secondary Mass and Cost Summary

| Description | Total Mass Reduction with SMS "kg" | Total Cost with SMS "$" | Incremental Mass Reduction from SMS "kg" | Incremental Cost Impact from SMS "$" | SMS(kg)/ Total(kg) "%" |
|---|---|---|---|---|---|
| Engine System | 31.8 | -92.83 | 8.0 | 21.81 | 25.2% |
| Transmission System | 39.4 | -96.57 | 5.2 | 31.64 | 13.2% |
| Suspension System | 105.4 | -154.90 | 22.4 | 105.94 | 21.3% |
| Brake System | 45.8 | -152.94 | 2.0 | 18.95 | 4.3% |
| Exhaust System | 6.9 | -13.69 | 0.6 | 5.85 | 8.7% |
| Fuel System | 7.3 | 11.92 | 5.7 | 8.67 | 78.1% |
| Body Group A (bumpers) | 207.1 | -1194.79 | 16.4 | -69.71 | 7.9% |
| Frame and Mounting System (frame) | 23.7 | -54.42 | 23.7 | -54.42 | 100% |
| Analysis Totals Without NVH Counter Measures | 467.4 (Dec) | -1748.29 (Increase) | 83.9 (Decrease) | 68.74 (Dec) | 3.8% over total vehicle (kg) |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

For the Powertrain, Chassis and Trim systems, the primary mass savings and costs were identified through the research for lightweighting technologies and included the techniques of material substitution or design/technology changes. The technologies were then reviewed for secondary mass savings with the assumption that the vehicle was 20% lighter than the base vehicle. Secondary mass reduction is achieved through downsizing of components while keeping in mind the functionality requirements of a light-duty pickup truck.

For the Body and Frame systems, a multi disciplinary optimization (MDO) process approach was used to determine the lightweight solutions. This process used an assumption of a 20% lighter vehicle to develop the mass reduction design. Hence the primary and secondary mass savings were not evaluated separately but simultaneously. As a result, each component of the Body and Frame systems were considered separately for primary or secondary mass reduction.

Table 21 summarizes the assignments of primary and secondary mass savings for the major Body and Frame subsystems. Primary is interpreted as the ability to adopt a mass reduction technology in the baseline vehicle design without performance degradation. Secondary is interpreted as the inability to adopt the mass reduction technology in the baseline vehicle design without performance degradation. No additional analyses were done to determine splits in primary/ secondary percentages for the system components.

Table 21. Vehicle Secondary Mass Summary - Body and Frame Systems

| Body and Frame Sub-Subsystems | Primary | Secondary |
|---|---|---|
| Cabin - Closures | Y | N |
| Cargo Box – Closures | Y | N |
| Cargo Box - Structure | Y | N |
| Cabin - Structure | Y | N |
| Frame | N | Y |
| Bumpers | N | Y |

The Body Closure Subsystem includes the doors, fenders, and hood. The mass reductions accomplished on the Body Closures are mostly driven by primary reasons because gross vehicle mass does not play a significant role in these sub-systems performance targets. This is the same for the Cargo Box Subsystem - closures and structure. In addition, the cargo box structure is expected to meet hauling criteria as in the baseline design. The hauling performance far outweighs any mass reduction from the cargo box closures. The assignments for the Body Structure Subsystem and the Frame Subsystem were not as clear and as a result additional CAE analyses were performed. The mass reduced Body Structure design was installed into the baseline model and several crash tests were run. It was found that the results were equal to or better than the baseline vehicle and so the mass reductions in the Body Structure were assigned to be primary. The redesigned Frame Subsystem design was installed in the baseline vehicle and it was observed that the frame did not maintain the baseline specifications acceptably and so the mass reductions in this system were assigned as secondary. The bumpers were included as secondary as well for they function with the frame in a crash. Further analyses may reveal a portion of primary and secondary for some of these components, although this analysis was not pursued.

## Part by Part System Secondary Mass Calculations Compared to Previous Regression Estimates

This report determines the benefit of secondary mass reduction on a part by part basis for the vehicle systems[6]. Of the total mass reduction, 511 kg, 84 kg of this was determined to be secondary mass reduction, as shown in Table 20, and hence 427 kg was primary. The results of breaking this down into subsystems, of, powertrain, chassis and body are shown in Table 22.

Table 22. Secondary Mass Reduction (kg) per kg Primary, Per System for a Light-Duty Pickup Truck

| | System | Secondary (kg) | kg Secondary per kg Primary |
|---|---|---|---|
| Powertrain | | | |
| | Engine | 8.0 | 0.019 |
| | Transmission | 5.2 | 0.012 |
| | Exhaust | 0.6 | 0.001 |
| | Fuel | 5.7 | 0.013 |
| Chassis | | | |
| | Suspension | 22.4 | 0.052 |
| | Brakes | 2.0 | 0.005 |
| Body | | | |
| | Bumper | 16.4 | 0.038 |
| | Frame | 23.7 | 0.056 |
| Primary=510.9-83.9=427kg | | | |

For this study, some of the potential secondary mass savings were influenced by the performance metrics of a light-duty pickup truck. These results were different from other literature documents on secondary mass reduction which are based on regression or analytical analyses [7][8].

### *Cost Curve*

Figure A in the Appendix contains the two cost curves developed for the light-duty truck. The curves were baselined on the technologies in the 2011 Silverado 1500 and shows the resultant incremental $/kg per mass reduction % for the net incremental direct manufacturing costs. The top curve is the non-compounded (primary) mass reduction curve and the curve on the bottom represents the compounded (primary and secondary) mass reduction curve.

To create the primary curve, all of the technologies identified in this work were ranked according to their $/kg, from least to greatest, and then the cost change and mass savings per technology were incrementally added and a resultant $/kg and % mass reduction calculated.

The creation of the secondary curve begins with the point on the right side of the curve at 21.4% MR (solution for this project), For this point, secondary mass reduction was determined for the major components in each system assuming a 20% mass reduction for the whole vehicle. The compounded curve is then created by ratioing the points between the primary solution point (at 21.4%) and zero along the primary curve. This represents our expectation that secondary mass reduction will be feasible at all mass reduction percentages. Secondary mass reduction is the result of decreasing component and system mass which in turn allows for reduced power and load requirements while maintaining overall vehicle performance, including payload and towing.

The long-term cost impact of the innovative mass-reduction solution, as shown by the red point of the Aluminum Intensive Body and HSS Intensive Frame, resulted in an overall vehicle cost of $2228 per-vehicle-unit cost. Based on the associated vehicle mass-reduction (510.9 kg, or 21.4 percent), this resulted in an average $4.36/kilogram cost. With all vehicle systems included in the analysis, the NIDMC cost was approximately 9.2% of the 10% boundary condition alloted for this study. When the tooling impact was considered the cost/kilogram decreased by approximately $0.024/kg, resulting in a net cost of $4.34/kg.

## Conclusions

This paper summarizes the detail and results contained within the report “Mass Reduction and Cost Analysis - Light-duty Pickup Truck Model Years 2020-2025” led by FEV North America, Inc. The goal to evaluate the incremental costs of mass reduction at levels that are feasible in the 2020 to 2025 timeframe given the design, material, and manufacturing processes likely to be available, without sacrificing utility, performance, or safety was achieved. This work is based on the design of a 2011 Silverado 1500, body-on-frame light-duty truck. The methodology utilized in this work was similar to that from the Midsize CUV study [1]. Sources of information for mass reduction technologies came from those in the Midsize CUV study, research on the most recent technical information as of 2012-2013, FEV North America, Inc. and subcontractor Munro's extensive knowledge of vehicle teardowns of both North American and European vehicles and EDAG's knowledge of body structure. EDAG performed the CAE model development, comparison and analyses on the baseline and mass reduced models. CAE analysis of static bending and torsional stiffness (ie: NVH), crash safety performance, frame durability, static structural performance of doors, hood and tailgate, full vehicle dynamic analysis were performed. Detailed cost modeling was conducted to calculate NIDMC and incremental tooling cost. CAE models and detailed cost spreadsheets are available[2].

The results indicate that when mass reduction strategies are considered using a full-vehicle approach, significant mass reduction can be achieved while maintaining vehicle functional objectives. For the light-duty truck (based on a 2011Silverado 1500), a 511 kg mass reduction (21.4% of kg) was found to result in a net incremental direct manufacturing cost of $2228 per vehicle, or $4.36 per kilogram. When the decreased tooling costs of $0.24/kg are included, the net costs are $4.34 per kilogram.

The efforts made to conduct a methodologically rigorous study were intended to provide additional confidence in the feasibility and the cost associated with reducing the mass of a 2011 light-duty truck. This report provides a set of feasible mass reduction solutions that could potentially be applied, however, there is a high likelihood that each manufacturer will implement a different set of solutions. The realized mass reduction for MY2022-2025 vehicles may be different than that outlined herein due to a number of factors. Manufacturer specific requirements for vehicle functionality, supplier base, platform sharing, and experience (or lack thereof) with certain mass reduction solutions could increase or decrease the amount of mass reduction and the cost realized by a given manufacturer.

Future incremental mass reductions and costs could be different based on the amount of mass reduction potential of each vehicle design. Manufacturers and suppliers continue to develop new mass reduction technologies which have not been accounted for in this study. In addition, some technologies included in this report have been and continue to be adopted in vehicle designs between 2011 and 2021, such as in the 2014 Silverado 1500 or 2015 F150 and in the next generations thereof.

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## Definitions/Abbreviations

**NIDMC** - Net Incremental Direct Manufacturing Cost

**MDO** - Multi-Disciplinary Optimization - referring to the method in which the Body and Frame solutions were mathematically determined

**SMS** - Secondary Mass Savings

# APPENDIX

Table A. Vehicle Mass Reductions and Cost Impact for a Light-Duty Pickup Truck (Primary and Secondary Mass Savings)

| | System ID | Description | Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC "$" (2) | Cost/ Kilogram NIDMC "$/kg" (2) | Cost/ Kilogram NIDMC + Tooling "$/kg" (2) | System Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 01 | Engine System | 239.9 | 31.8 | -92.83 | -2.92 | -2.63 | 13.3% | 1.3% |
| 2 | 02 | Transmission System | 145.3 | 39.4 | -96.57 | -2.45 | -2.47 | 27.1% | 1.6% |
| 3 | 03A | Body System Group -A- ( Body Sheetmetal) | 574.7 | 207.1 | -1194.79 | -5.77 | -5.77 | 36.0% | 8.7% |
| 4 | 03B | Body System Group -B- (Body Interior) | 247.0 | 34.0 | -127.23 | -3.74 | -3.78 | 13.8% | 1.4% |
| 5 | 03C | Body System Group -C- (Body Exterior Trim) | 40.5 | 2.1 | 2.73 | 1.28 | 1.28 | 5.3% | 0.1% |
| 6 | 03D | Body System Group -D- (Glazing & Body Mechatronics) | 50.9 | 4.5 | 2.30 | 0.51 | 0.51 | 8.9% | 0.2% |
| 7 | 04 | Suspension System | 301.2 | 105.4 | -154.90 | -1.47 | -1.48 | 35.0% | 4.4% |
| 8 | 05 | Driveline System | 183.8 | 20.4 | 38.01 | 1.86 | 1.89 | 11.1% | 0.9% |
| 9 | 06 | Brake System | 101.0 | 45.8 | -152.94 | -3.34 | -3.23 | 45.4% | 1.9% |
| 10 | 07 | Frame and Mounting System | 267.6 | 23.7 | -54.42 | -2.30 | -2.30 | 8.9% | 1.0% |
| 11 | 09 | Exhaust System | 38.4 | 6.9 | -13.69 | -1.97 | -1.97 | 18.1% | 0.3% |
| 12 | 10 | Fuel System | 26.3 | 7.3 | 11.92 | 1.62 | 1.77 | 27.9% | 0.3% |
| 13 | 11 | Steering System | 32.5 | 8.5 | -147.46 | -17.44 | -17.45 | 26.0% | 0.4% |
| 14 | 12 | Climate Control System | 20.3 | 1.9 | 14.71 | 7.59 | 7.59 | 9.5% | 0.1% |
| 15 | 13 | Information, Gage and Warning Device System | 1.6 | 0.2 | 0.66 | 2.66 | 2.97 | 15.7% | 0.0% |
| 16 | 14 | Electrical Power Supply System | 21.1 | 12.8 | -172.73 | -13.49 | -13.44 | 60.6% | 0.5% |
| 17 | 15 | In-Vehicle Entertainment System | 2.2 | 0.0 | 0.00 | 0.00 | 0.00 | 0.0% | 0.0% |
| 18 | 17 | Lighting System | 9.6 | 0.4 | -2.00 | -5.18 | -5.18 | 4.0% | 0.0% |
| 19 | 18 | Electrical Distribution and Electronic Control System | 33.6 | 8.5 | 61.44 | 7.26 | 7.27 | 25.2% | 0.4% |
| 20 | 00 | Fluids and Miscellaneous Coating Materials | 49.6 | 0.0 | 0.00 | 0.00 | 0.00 | 0.0% | 0.0% |
| a. Analysis Totals Without NVH Counter Measures → | | | 2386.0 | 560.9 | -2077.84 | -3.70 | -3.68 | n/a | 23.5% |
| b. Vehicle NVH Counter Measures (Mass & Cost ) → | | | 0.0 | -50.0 | -150.00 | n/a | n/a | n/a | n/a |
| c. Analysis Totals With NVH Counter Measures → | | | 2386.0 | 510.9 (Decrease) | -2227.84 (Increase) | -4.36 (Increase) | -4.34 (Increase) | n/a | 21.4% |

(1) Negative value (i.e.-x.xx) represents an increase in mass,
(2) Negative value (i.e.-x.xx) represents an increase in cost

Table B. Vehicle Secondary Mass Summary-Powertrain, Chassis and Trim Only

| Secondary Mass Savings (SMS) Impact by Vehicle System | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Description | Base Mass "kg" | Mass Reduction with SMS "kg" | Mass Reduction w/o SMS "kg" | Incremental Mass Red from SMS "kg" | % SMS of the total sys | Cost Impact NIDMC with SMS "$" | Cost Impact NIDMC w/o SMS "$" | Incremental Cost Imapct from SMS "$" | Cost/Kg NIDMC w/ SMS "$/kg" | Cost/Kg NIDMC w/o SMS "$/kg" | Incremental Cost/Kg NIDMC from SMS "$/kg" |
| 1500 Series Chevrolet Silverado Pickup Truck (Powertrain, Chassis and Trim Systems Only) | | | | | | | | | | | |
| Engine System | 239.9 | 31.8 | 23.8 | 8.0 | 25% | -92.83 | -114.63 | 21.81 | -2.92 | -4.82 | 1.90 |
| Transmission System | 145.3 | 39.4 | 34.2 | 5.2 | 13% | -96.57 | -128.20 | 31.64 | -2.45 | -3.75 | 1.30 |
| Suspension System | 301.2 | 105.4 | 83.1 | 22.4 | 21% | -154.90 | -260.84 | 105.94 | -1.47 | -3.14 | 1.67 |
| Brake System | 101.0 | 45.8 | 43.9 | 2.0 | 4% | -152.94 | -171.89 | 18.95 | -3.34 | -3.92 | 0.58 |
| Exhaust System | 38.4 | 6.9 | 6.3 | 0.6 | 9% | -13.69 | -19.54 | 5.85 | -1.97 | -3.08 | 1.11 |
| Fuel System | 26.3 | 7.3 | 1.6 | 5.7 | 78% | 11.92 | 3.25 | 8.67 | 1.62 | 2.02 | 0.40 |
| Body Sys Grp A(Body Sheetmetal) | 574.7 | 207.1 | 190.7 | 16.4 | 8% | -1194.86 | -1125.15 | -69.71 | -5.77 | -5.90 | 0.13 |
| Frame and Mounting | 267.6 | 23.7 | 0.0 | 23.7 | 100% | -54.42 | 0 | -54.42 | -2.30 | 0 | -2.30 |
| Analysis Totals W/o NVH Counter Measures | 1694.5 | 467.5 (Dec) | 383.6 (Dec) | 83.9 (Decrease) | | -1772.06 (Increase) | -1817.01 (Increase) | 68.74 (Decrease) | -3.74 (Increase) | -4.74 (Increase) | 0.82 (Decrease) |

"+"=mass decrease, "-" = mass increase
"+"=cost decrease, "-"=cost increase

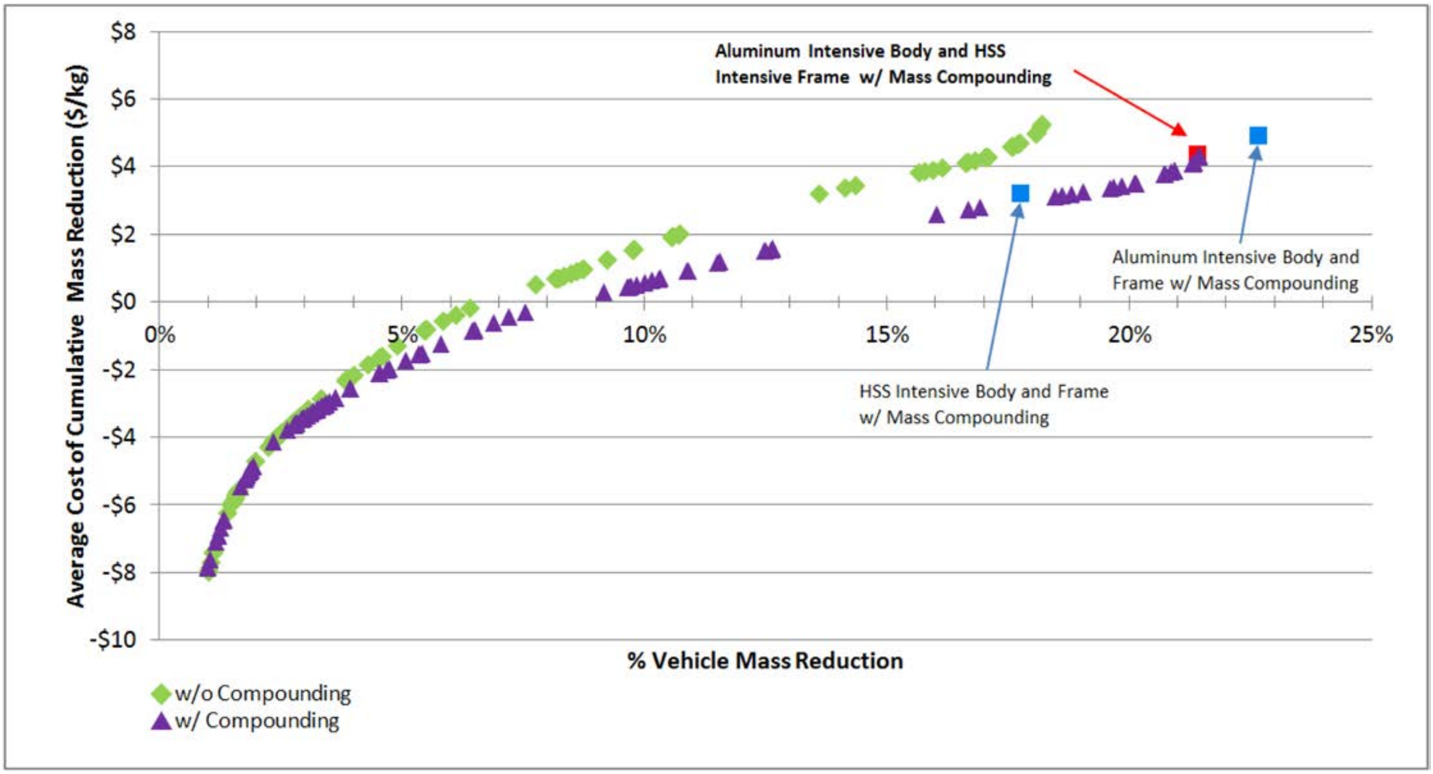


Figure A. Mass Reduction Cost Curve for a 2011 Light-Duty Pickup Truck in 2020-2025 Timeframe



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