Vehicle Lightweighting:

A Review of the Safety of Reduced Weight Passenger Cars and Light Duty Trucks

Final Report

Prepared for Consumers Union

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Author

Gregory Peterson

MICHIGAN MANUFACTURING TECHNOLOGY CENTER

45501 Helm St.
Plymouth, MI 48170
www.the-center.org

About the Michigan Manufacturing Technology Center

The Michigan Manufacturing Technology Center is an organization dedicated to supporting Michigan manufacturers to work smarter, to compete and to prosper. The Center offers personalized consulting services to meet the needs of clients in virtually every aspect of their businesses. The Center is affiliated with the National Institute of Standards and Technology (NIST) and is part of the Hollings Manufacturing Extension Partnership (MEP Program). The Center also is closely affiliated with the Michigan Economic Development Corporation (MEDC) with the shared goal of making Michigan businesses vibrant, driving GDP growth and creating new and lasting jobs. For more information, visit http://www.the-center.org.

About the Author

Gregg is the Michigan Manufacturing Technology Center Principal Materials Engineer assigned to the Lightweight Innovations For Tomorrow (LIFT) Institute located in Detroit. LIFT is one of 14 nationwide federal institutes and is dedicated to advancing lightweight metal technologies. He is contracted by NIST (National Institute for Standards and Technology) as part of a national program to accelerate emerging mass reducing technologies into commercially viable products that can be produced by U.S. manufacturers.

Gregg's background includes OEM (Pontiac Product Engineering, CPC Advanced Vehicle Engineering, Daimler Chrysler SRT, Lotus), Tier 1 and start-up experience in lightweight ferrous and non-ferrous body and structure design, aerodynamics, thermal systems, interiors/seating, electronic control systems and software development, advanced plastics technologies, chassis design and development, powertrain, manufacturing/processing, cost analysis and electrical power generation. He has engineered lightweight products for numerous industries including sustainable energy, military, aerospace, agriculture, truck/bus, as well as automotive. He led several government funded, lightweighting studies used by the EPA and NHTSA to assist in developing the 2025 fuel economy standards while at Lotus. These peer reviewed publications demonstrated cost effective approaches for engineering lightweight, multi-material body structures and total vehicle systems. He is also introducing successful lightweighting approaches applied to numerous other industries including to the Oil and Gas community.

He holds numerous patents in a wide variety of fields and is an SAE volunteer speaker for U.S. universities. He is a regular presenter on lightweight topics at national and international engineering conferences and has been published by a variety of professional organizations and universities, including "Principles of Lightweight Design" an online course offered by Ohio State University.

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Executive Summary

This report reviews the crash performance of two lightweight production vehicles and includes peer-reviewed government funded studies that document the safety of reduced weight vehicles. It also reviews the fundamental engineering principles used to create safe vehicles and the materials used to meet safety requirements in production vehicles. It concludes that lightweight materials can be deployed in such a way that they can achieve significant weight reduction with comparable or even improved vehicle safety performance, and minimal increases in vehicle production costs.

The higher cost of lighter weight materials has been found to be partially offset by other savings enabled by the lower vehicle weight such as smaller engines, smaller brakes, and a lighter suspension, and manufacturing efficiencies including reducing the number of parts which can reduce tooling and assembly costs. The total incremental costs of lightweighting has been shown in real world production and modeling studies to only increase the total vehicle costs on the order of 1 to 3%. This allows lightweight vehicles to remain highly competitive in the marketplace as evidenced by the lightweight Ford F-150, which is the bestselling vehicle in the US while shedding over 700 lbs. and achieving the highest possible safety ratings.

Key Physical Principles Support Vehicle Safety

Material independence. The physics of a vehicle crash are material agnostic; a properly designed structure minimizes the vehicle acceleration levels independent of the type of material. The crash safety of contemporary automobiles is the result of high performance materials, energy absorbing vehicle structures, and active and passive occupant protection systems. These elements, properly applied, are weight independent; a lightweight vehicle can protect occupants as well as a heavier vehicle.

Less severe crashes. A lighter weight total vehicle population, i.e., trucks, SUVs as well as passenger cars, can improve occupant safety because of reduced kinetic energy that must be managed in a two-vehicle collusion; a direct consequence of first principle physics: energy is proportional to mass.

Improved dynamic response. *Lighter weight vehicles improve dynamic response, including handling, braking and steering, compared to their equivalent sized, heavier counterparts. Improved vehicle control can contribute to avoiding an accident or minimizing the damage in a crash.*

Key Pillars of Safety can be Maintained or Improved

***Crush distance maintained*.** For front and rear crashes, the key design parameter is to maximize crush distance. Crush distances are a function of vehicle styling, geometry and powertrain layout. With proper design, acceleration forces on the occupants are directly proportional to the crush distance, with the effective spring rate of the crushable materials tuned to match the crush distance. The footprint-based fuel economy standards adopted by NHTSA in 2005 were specifically designed to eliminate any incentive to design smaller vehicles which could have less crush distance. Instead, the footprint standards incentivize lighter vehicles with the same size and crush distance, eliminating any effects of lightweighting on crush distance and crash protection in a properly designed vehicle.

Material strength. For side crashes, the crush distance is very small and very high effective spring rates can reduce intrusion into the vehicle. Advanced high-strength steels (AHSS) are typically used for the intrusion beams that protect the occupants and have higher effective spring rates than conventional steel, improving crash results and safety during side impacts.

Compatibility with ancillary safety equipment. The crash characteristics of a lightweight vehicle are compatible with existing ancillary safety equipment. For example, supplemental restraint systems and sensors are tunable to match the crash pulse of lighter weight vehicles. The 2009-10 Lotus lightweight Phase 2 CUV study predicted this and current production, fully safety compliant, lighter weight vehicles have verified that prediction. These systems continue to improve and will further enhance the safety of future, lighter weight vehicles.

Crash performance maintained. A well-engineered crush structure can incorporate a wide variety of materials and meet or exceed all safety parameters. The ability of lightweight materials to maintain crash performance has been widely demonstrated by both peer reviewed simulation studies and production vehicles with aluminum and high-strength steel intensive bodies. Multiple simulation studies demonstrate that lighter vehicles using high performance aluminum and steel perform as well in impacts as their similar size, heavier counterparts. These simulations predicted weight savings of approximately 700 lbs. to over 1,100 lbs. with safety performance comparable to their heavier baseline counterparts.

Highest safety ratings. Reduced weight production vehicles using current high strength materials, including aluminum and AHSS, have achieved the highest safety ratings from both NHTSA and IIHS and, in some cases perform better than vehicles that weigh as much as seven hundred pounds more in low speed and high speed crashes. Production vehicles such as the 2015-2018 Ford F150, the 2017 F-250 Super Duty, Jaguar and Audi sedans and Range Rover SUVs incorporate aluminum intensive body structures that meet or exceed U.S. safety regulations. The production F150 pickup is over 700 lbs. lighter than the previous generation and achieved the highest possible safety ratings from both NHTSA and IIHS.

I. Introduction

The objective of this study is to assess the impact of reduced mass on vehicle safety using public domain information. There have been numerous, peer reviewed studies published that have addressed the impact of lightweight materials on vehicle safety including passenger cars, crossover utility vehicles and light duty trucks. This study will use these government-funded studies as well as lightweight production vehicles to form the basis of the results and conclusions reported in this study.

Additionally, the fundamental physics of a collision are included to give the reader an understanding of the engineering principles guiding the design of safety related structural elements in an automobile.

This paper excludes powertrain lightweighting considerations. The continuing proliferation of hybrid electric/ICE (Internal Combustion Engine) and electric drive systems, in addition to the ongoing downsizing of ICE engines, is beyond the scope of this report. An underlying assumption is that powertrains are sized to maintain comparable weight/HP ratios, i.e., vehicle lightweighting drives reduced mass powertrains as part of the mass de-compounding process. For example, a six-cylinder engine can be replaced with a four-cylinder engine on a lighter, same physical size vehicle and have similar acceleration to the heavier six-cylinder model.

II. Material Properties and Selection

Automotive engineers select materials based on performance, cost, weight and durability relative to safety, fuel economy and dynamic targets. A key factor in selecting the materials that go into an automobile is the target price point for the vehicle. The most popular automotive materials used today include: 1. Steel (density: 490 lb./ft^3); 2. Aluminum (169 lb./ft^3); 3. Magnesium (109 lb./ft^3); and 4. Plastics and composites (carbon fiber density: 86 lb./ft^3)[1]. Titanium, a lightweight metal which is less than half the density of steel, but just as strong, has limited applications in high volume production vehicles primarily due to cost.

Figure 1. below shows the wide variety of steel types used by the automotive industry. The tensile strengths range from 200 MPa for mild steels to > 1400 MPa for the latest AHSS (Advanced High Strength Steel) steels. The targets for future generation steels will provide even greater tensile strengths while maintaining the elongation of current AHSS. This increase in tensile strength allows thinner, lighter steels to replace weaker, thicker wall, steels.

[1] These densities are for un-alloyed materials.

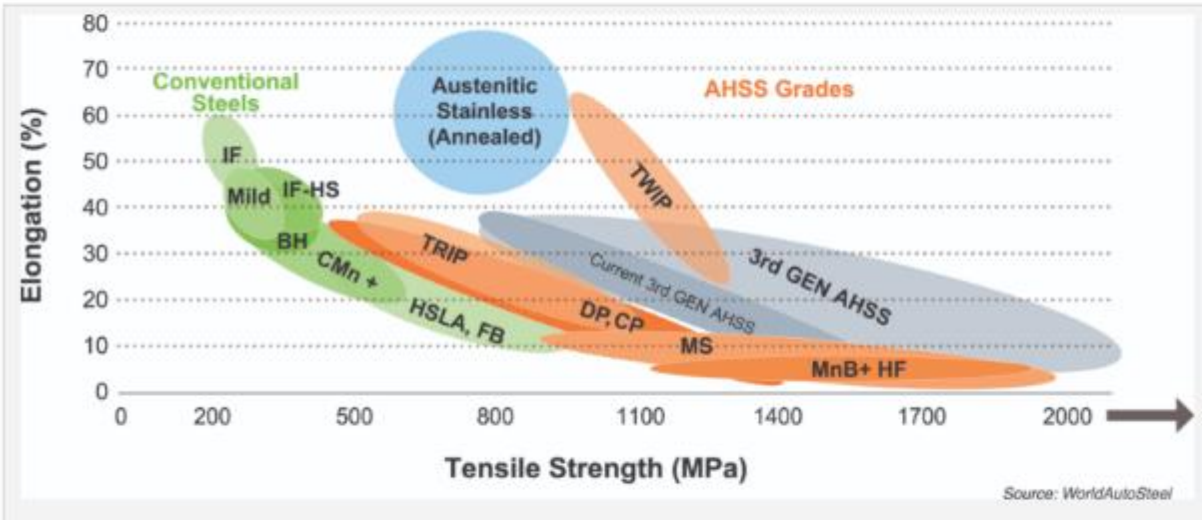

Figure 1. Tensile Strength vs. Elongation for Various Steel Types

Magnesium is used primarily for automotive castings; AZ91D is the most widely used diecasting alloy. It is alloyed with aluminum and zinc. Common uses include suspension components, transmission cases, pedals, subframes and liftgate support structures. Other magnesium grades include AMxx which are higher ductility alloys. AMxx alloys have been used for seat frames, wheels and instrument panels. The AExx and ASxx magnesiums are higher temperature alloys; they are not widely used due to lower strength and poor castibility. Typical magnesium alloy properties are shown in Figure 2. below. Additional details and the link are shown in Appendix A.

PROPERTIES OF MAGNESIUM ALLOYS

MECHANICAL PROPERTIES AND CORROSION PERFORMANCE

ALLOY	T.S. (MPa)	Y.S. (MPa)	E (%)	CREEP (%) (150ºC, 35MPa, 200hr)	CORROSION ($mg/cm^2/day$)
A380	325	160	3	0.19	–
AZ91D	240	165	3	2.54	0.11
AM60	220	130	6	2.15	0.13
AM50	200	125	6-10	2.15	0.22
AM20	135	105	10	–	–
AS41	225	135	4.5	–	0.25
AS21	170	110	4	–	–
AE42	225	140	8-10	0.33	0.21
ZC63*	240	145	5	–	–
ZE41*	180	135	2	–	–

Figure 2. Tensile Strength vs. Elongation for Magnesium Alloys

A wide variety of aluminum strengths and elongations are available. There are five (5xxx – principal alloying element: magnesium), six (6xxx – principal alloying element: magnesium and silicon) and seven (7xxx) series aluminum wrought families that are generally incorporated into automobiles and trucks. 6xxx series wrought aluminum is commonly used for sheet and extrusions. Cast aluminum alloys are used for components such as corner nodes on chassis and BIW structures. The three series (3xx.x) aluminum alloy is generally used for castings. Three series casting aluminum uses silicon as the principal alloying element; copper and magnesium are also used as alloying materials. Aluminums are typically heat treated; this is designated by Tx. 6061-T6 indicates that the 6061 aluminum material was solution heat treated at an elevated temperature, typically around 980 F, held there for about 1 hour (called aging) and then quenched. Figure 3. shows the relative strengths and elongations for steel, magnesium and aluminum alloys.

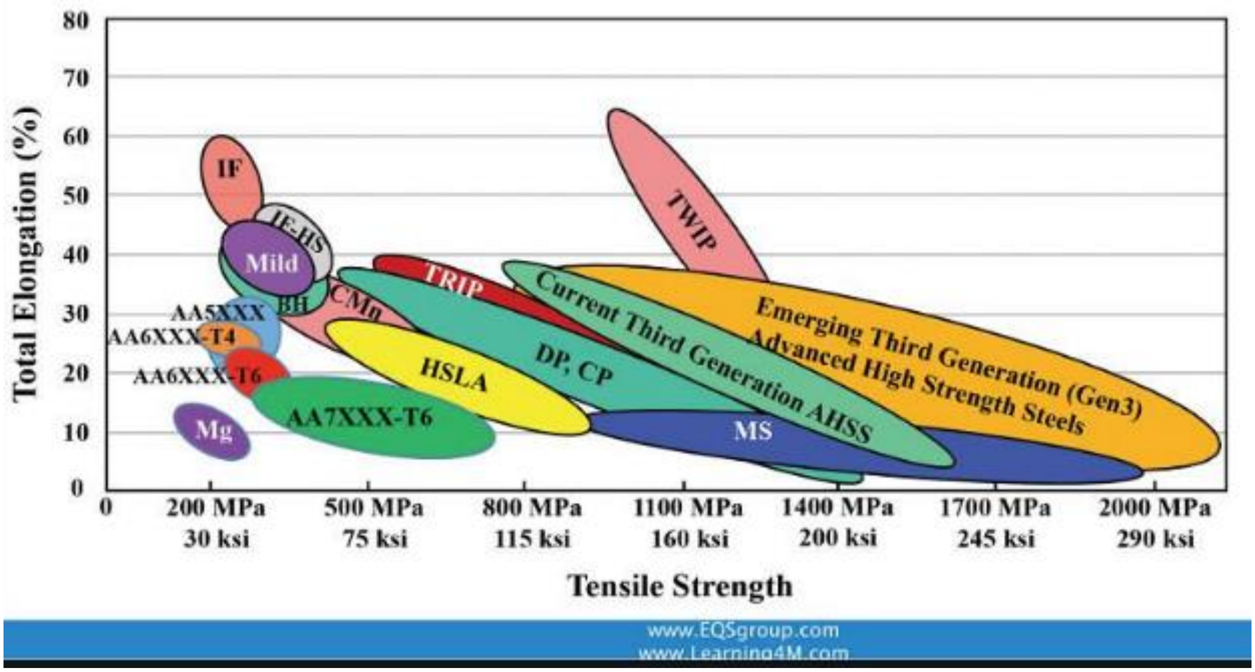

Figure 3. Tensile Strength vs. Elongation Steel, Magnesium and Aluminum Alloys

The use of these lightweight metals in the bodies of automobiles, including composites, is proliferating. Figure 4. shows this trend. The red line in Figure 4. shows the decreasing mass of the body in white (BIW) which is the primary vehicle structure that absorbs impact energy and which all vehicle components attach to.

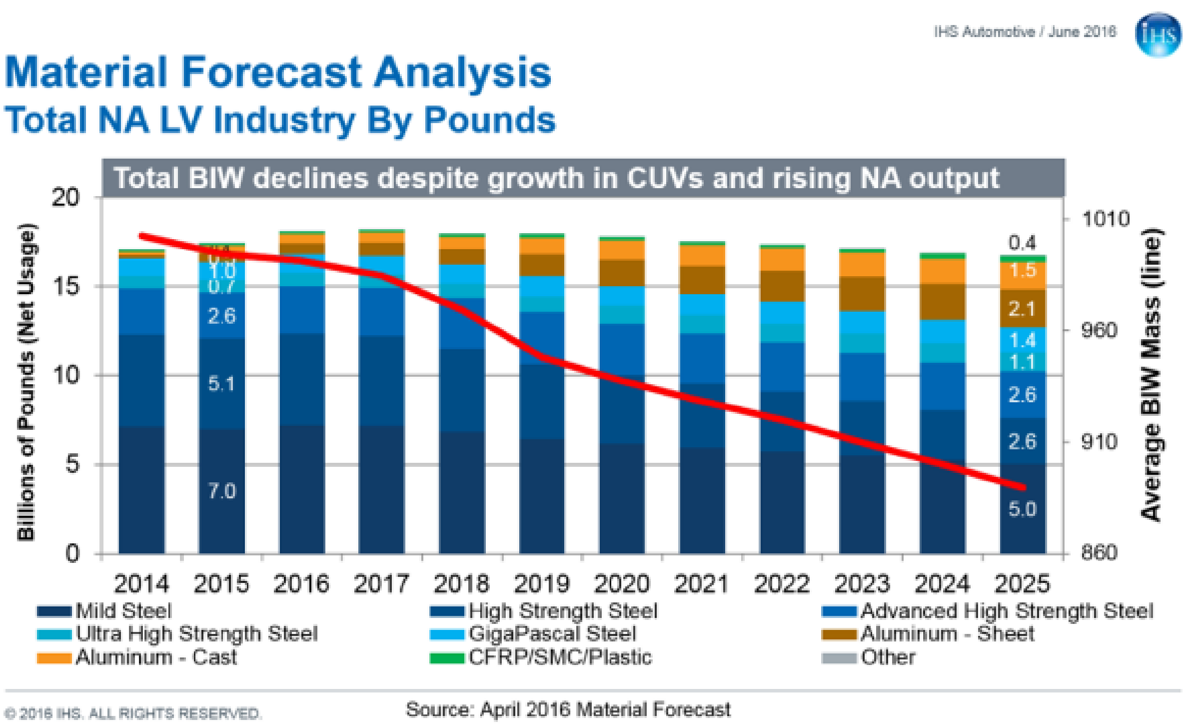

Figure 4. Lightweight Materials Utilization Forecast and Body in White Weight (Red Line)

Lightweight materials are typically used in the vehicle systems which have the greatest opportunity for mass reduction, i.e., the heaviest systems. Exclusive of powertrain, the BIW, closures, chassis/suspension including brakes and wheels and interiors typically comprise approximately 80% to 90% of vehicle mass. Figure 5. shows a typical mass breakdown for a mid-sized ICE powered CUV (crossover utility vehicle), less powertrain. Figure 6. shows a typical mass breakdown for a mid-sized EV (electric vehicle) passenger car less powertrain and battery mass. In both cases, the above four systems represent more than 80% of the non-powertrain mass and are the typical systems targeted for utilizing lightweight materials to reduce mass in volume production vehicles.

Weight Breakdown By System - Typical ICE Vehicle				
	Weight - lbs.	% Total	Heaviest Systems - Less P/T - lbs.	% Total - Less P/T
Powertrain	904	24.5%		
Body	845	22.9%	845	30.4%
Suspension/Chassis	836	22.7%	836	30.1%
Interior	553	15.0%	553	19.9%
Closures/Fenders	315	8.6%	315	11.3%
Glazing	97	2.6%		
Bumpers	40	1.1%		
Lighting	22	0.6%		
Thermal	20	0.5%		
Electrical	53	1.4%		
Totals	3685	100.0%	2549	91.7%

Figure 5. ICE (Internal Combustion Engine) CUV System Mass Contribution (Less Powertrain)

Typical Electric Vehicle System Weight Contribution				
System	**Weight - lbs.**	**% Of Total**	**Heaviest Systems - Less P/T - lbs.**	**% Total - Less P/T**
Powertrain (Includes batteries)	**1586.88**	**39.7%**		
Electrical	**121.12**	**3.0%**		
Chassis	**819**	**20.5%**	**819**	**33.9%**
Thermal	**60**	**1.5%**		
Interior	**385**	**9.6%**	**385**	**16.0%**
Body	**558**	**14.0%**	**558**	**23.1%**
Closures	**272**	**6.8%**	**272**	**11.3%**
Exterior	**198**	**5.0%**		
Total	**4000**	**100.0%**	**2034**	**84.3%**

Figure 6. Electric Vehicle (mid-size sedan) System Mass Contribution (Less Powertrain)

Multi-material body structures combining ferrous and non-ferrous materials can reduce weight while meeting safety and performance objectives. The Cadillac CT6, introduced in March 2016, uses 13 aluminum castings, aluminum extrusions and HSS stamped panels. Two aluminum castings replaced 35 stamped steel parts on this vehicle[1]; this saved the cost of stamping tools, fixtures, shipping, plant transfer equipment and the welding energy and time required to join 35 steel parts. The CT6 multi-material construction reduced the weight by 198 lbs. vs. an all steel body structure.[1] Illustration 1. shows the CT6 aluminum and steel body structure.

Illustration 1. Cadillac CT6 Multi-Material Body Structure[2]

III. Vehicle Safety

a. Applicable Safety Standards

NHTSA, the U.S. National Highway Traffic Safety Administration, is the federal agency assigned to create Federal Motor Vehicle Safety Standards (FMVSS) for North American passenger cars and light duty trucks sold in the U.S. This investigation will cover the dynamic standards, i.e., the front, rear, side and rollover tests, for vehicle impacts which are the most critical factor when introducing lighter weight materials into a vehicle.

FMVSS 208 is the front barrier impact test; a vehicle travelling at 35 MPH hits a fixed barrier head on as well as 25 MPH impacts into angled fixed barriers. The primary objective of this standard is to utilize the vehicle structure to crush in a controlled and repeatable manner such that the acceleration levels are minimized and that there is minimal intrusion of the vehicle structure into the passenger compartment. Vehicle safety systems, i.e., airbags, are tuned to act in concert with vehicle crush characteristics. FMVSS 208 defines the maximum allowable deceleration levels the driver and passengers can experience during a head on collision.

FMVSS 214 is the side impact test. The test vehicle strikes a fixed 10” diameter pole at speeds up to 20 MPH along the front door. The pole impact positions represent a wide range of driver types/seat locations. A movable deformable side barrier travelling at 33.5 MPH is also used for this test. MVSS 214 MDB is the Oblique Moving Deformable Barrier (OMDB) test where an MDB platform strikes a stationary vehicle at a 15 degree angle with a 35% overlap[3].

FMVSS 216 is the roof crush test. A large rectangular rigid platen applies a force three times the vehicle curb weight to the upper A pillar joint. The roof must withstand this force so that the maximum force acting on a 50th percentile male occupant is 50 lbs. or less.

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[2] http://www.popularmechanics.com/cars/a15428/2016-cadillac-ct6-aluminum-castings/
[3] https://www-esv.nhtsa.dot.gov/proceedings/24/files/24ESV-000108.PDF

FMVSS 301 is the rear impact test. A platform travelling at 50 MPH strikes a portion of the rear bumper. This is a fuel tank and battery integrity test; there can be no fluid leakage following the impact.

These tests represent the most severe dynamic conditions for evaluating vehicle safety in front, side, and rear impacts and in a rollover event.

b. Trends in Vehicle Weight and Safety

The federal safety standards have contributed to reducing traffic fatalities. Figure 7. below, compiled by the Insurance Institute for Highway Safety[4], shows that US traffic fatalities have steadily declined since 1975 and that deaths declined at a faster rate starting in the 2003 time frame, from 22,000 in 2003 to 14,000 in 2015, a 36% decrease. At the same time, per Figure 8., the fuel economy of US passenger cars increased from 28 MPG to 38 MPG, a 36% increase, to meet the more stringent fuel economy regulations. Figure 9. shows light truck fuel economy increasing from approximately 22 MPG to 27 MPG (NHTSA rating) over that time span[5]. Note: the 54.5 MPG figure is the NHTSA rating; it corresponds to an EPA (Environmental Protection Agency) rating of approximately 40 MPG.

Figure 10. shows a gradual increase in the number of vehicles on the road between 2003 and 2015[6]. VMT (Vehicle Miles Traveled) more than doubled, from 1.5 x 10^{12} miles in 1980 to 3.1 x 10^{12} miles in 2015.[6,7]. Decreasing deaths with increasing registrations and increased VMT is an indicator that vehicle safety was continuously improving.

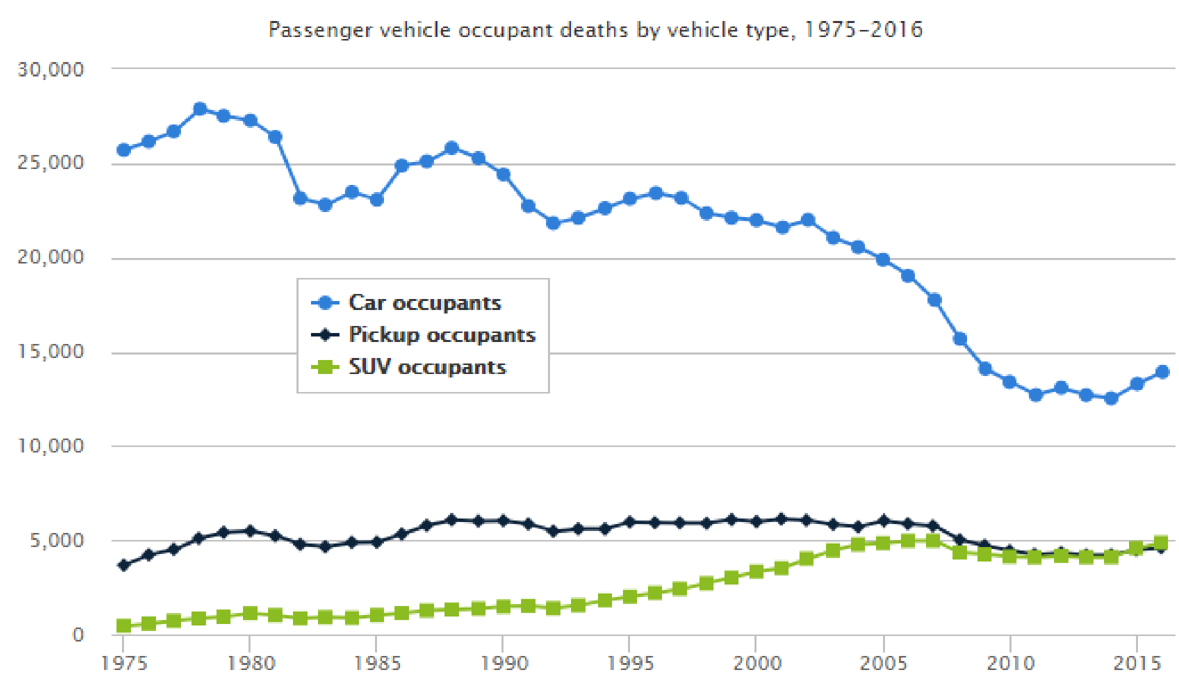

Figure 7. US Vehicle Occupant Deaths by Vehicle Category[4]

[4] http://www.iihs.org/iihs/topics/t/vehicle-size-and-weight/fatalityfacts/passenger-vehicles
[5] https://www.theicct.org/sites/default/files/CAFE_mpg_LT_Apr2018.pdf
[6] https://www.statista.com/statistics/183505/number-of-vehicles-in-the-united-states-since-1990/
[7] http://www.princeton.edu/~alaink/Orf467F17/NTS_Entire_2017Q2.pdf (Table 1-36)

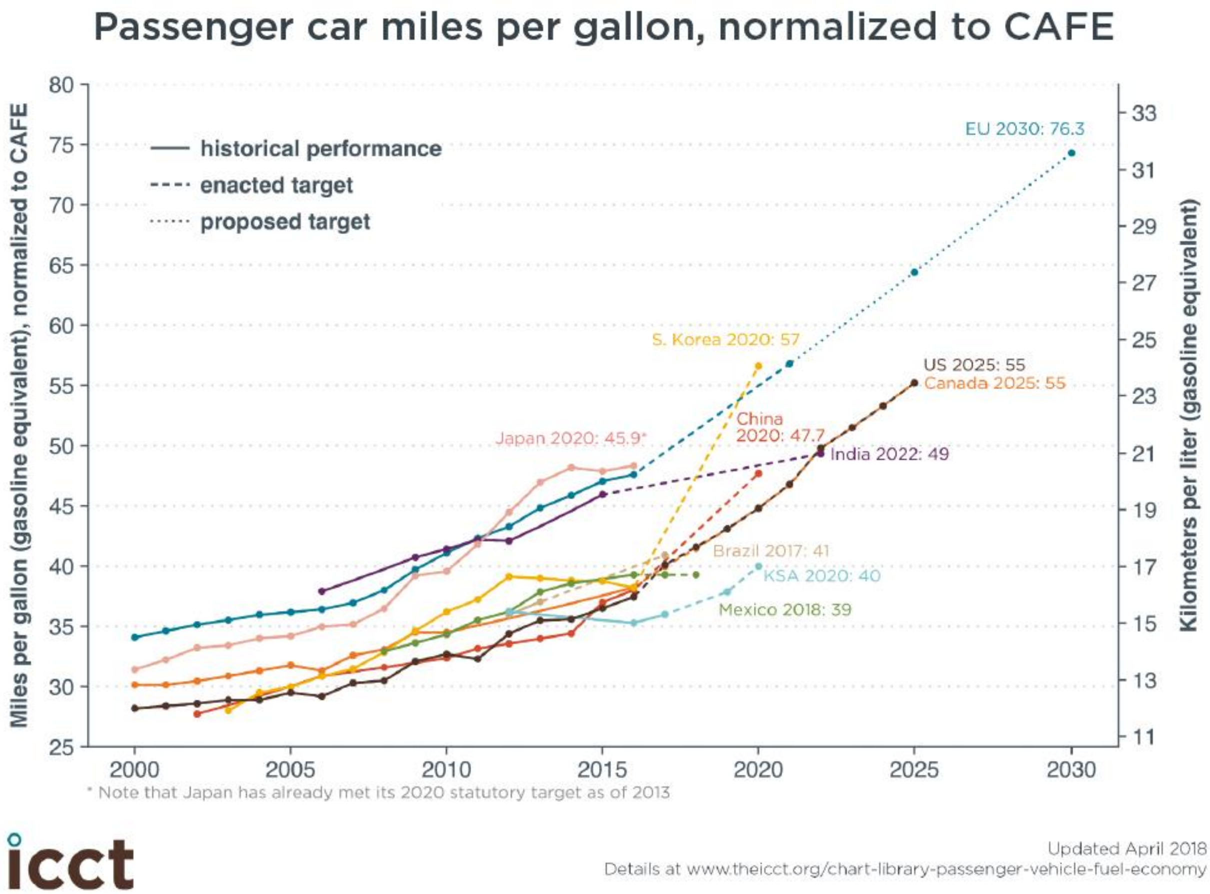

Figure 8. United States NHTSA Passenger Car Fuel Economy Averages[5]

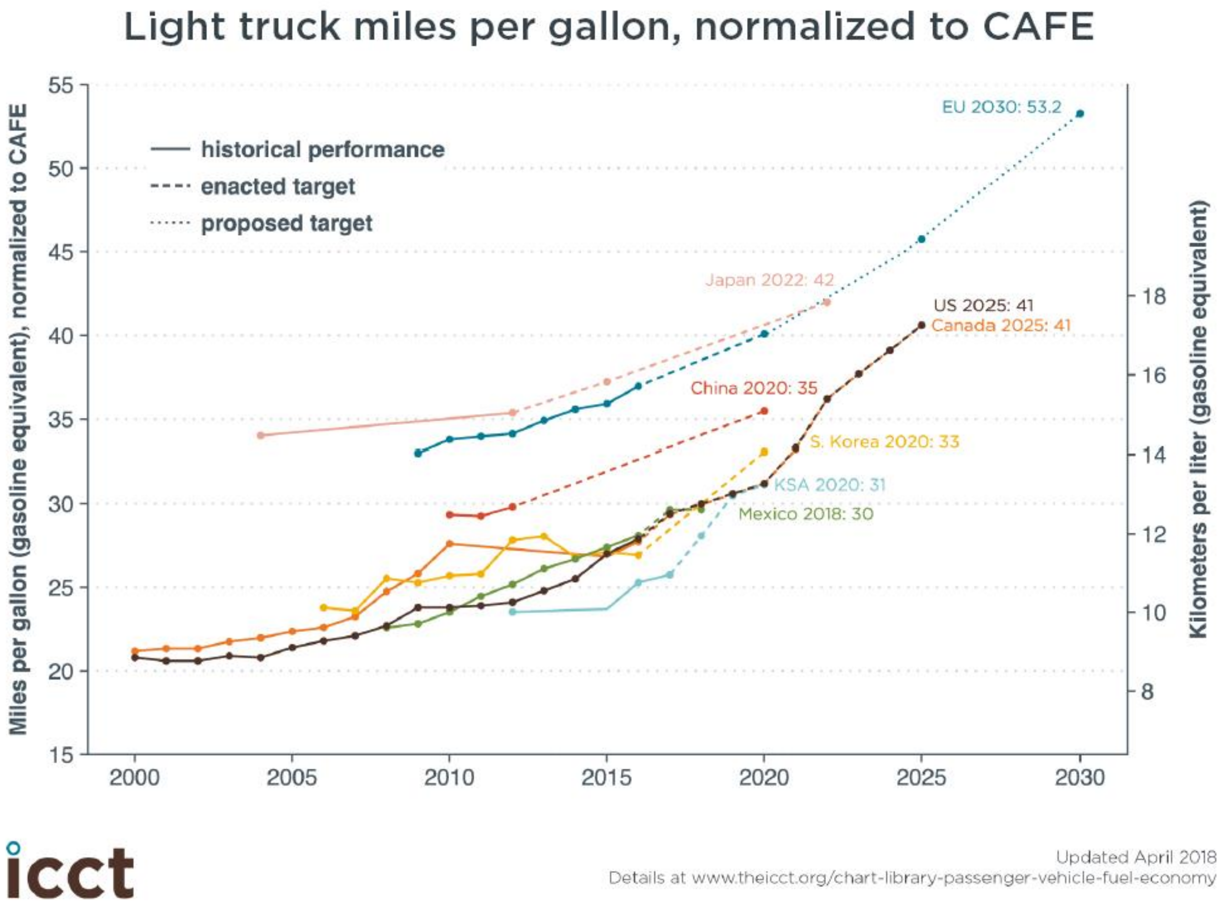

Figure 9. United States NHTSA Light Truck Fuel Economy Averages[5]

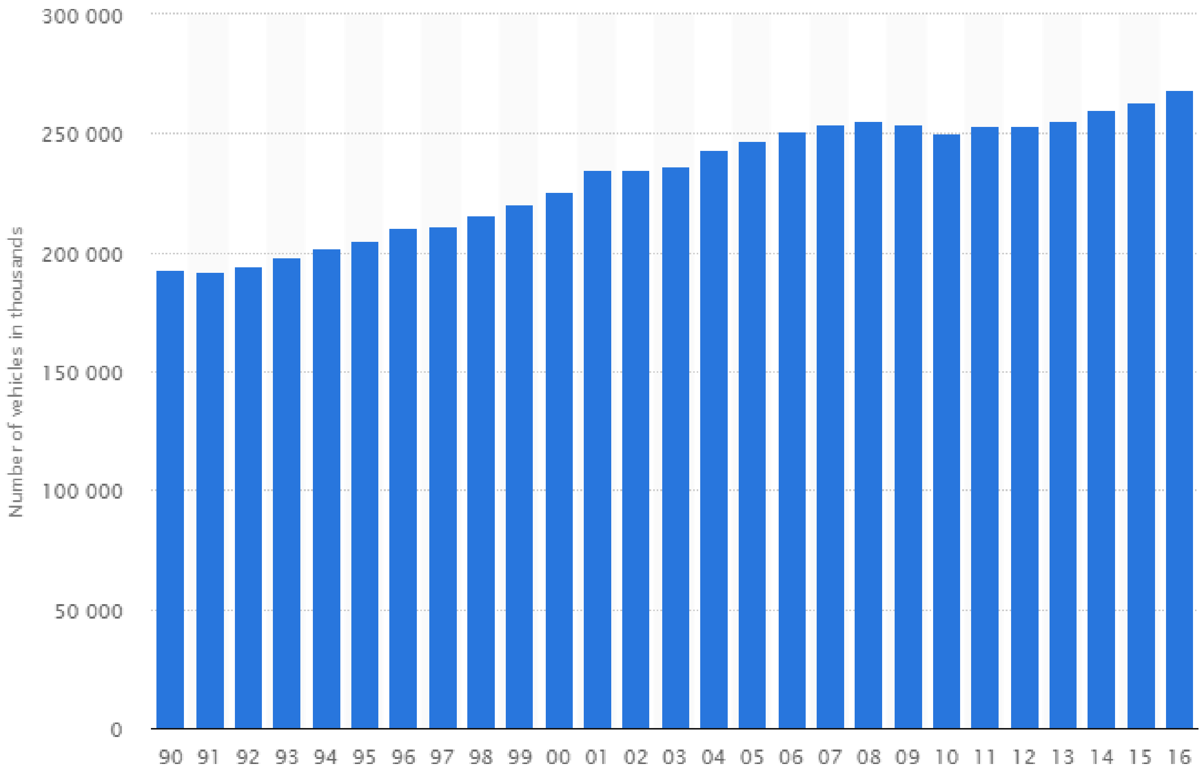

Figure 10. Number of motor vehicles registered in the United States: 1990 to 2016 (in 1,000s)[6, 7]

Although European cars, on average, are lighter than US vehicles[8], they have been rated safer than US vehicles by NHTSA[6]. Figures 11. and 12. depict this relationship and are from a 2014 Time magazine study.

NHTSA Overall Safety Rating

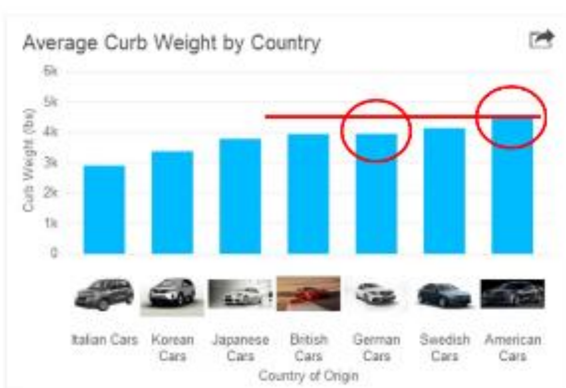

Figure 11. German Car Curb Weight vs. US[8]

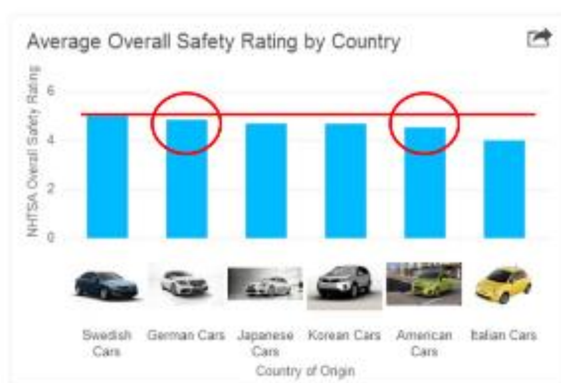

Figure 12. German Car NHTSA Safety Rating vs. US[8]

[8] http://time.com/3026672/best-cars-by-country/

Figure 13. compiled by the US EPA, shows the weight of vehicles sold in the U.S. has been relatively constant since 2005 despite the increasing use of lightweight materials[9]. One possible explanation for this is that larger, heavier vehicles such as trucks, SUVs and minivans have replaced traditional passenger cars.

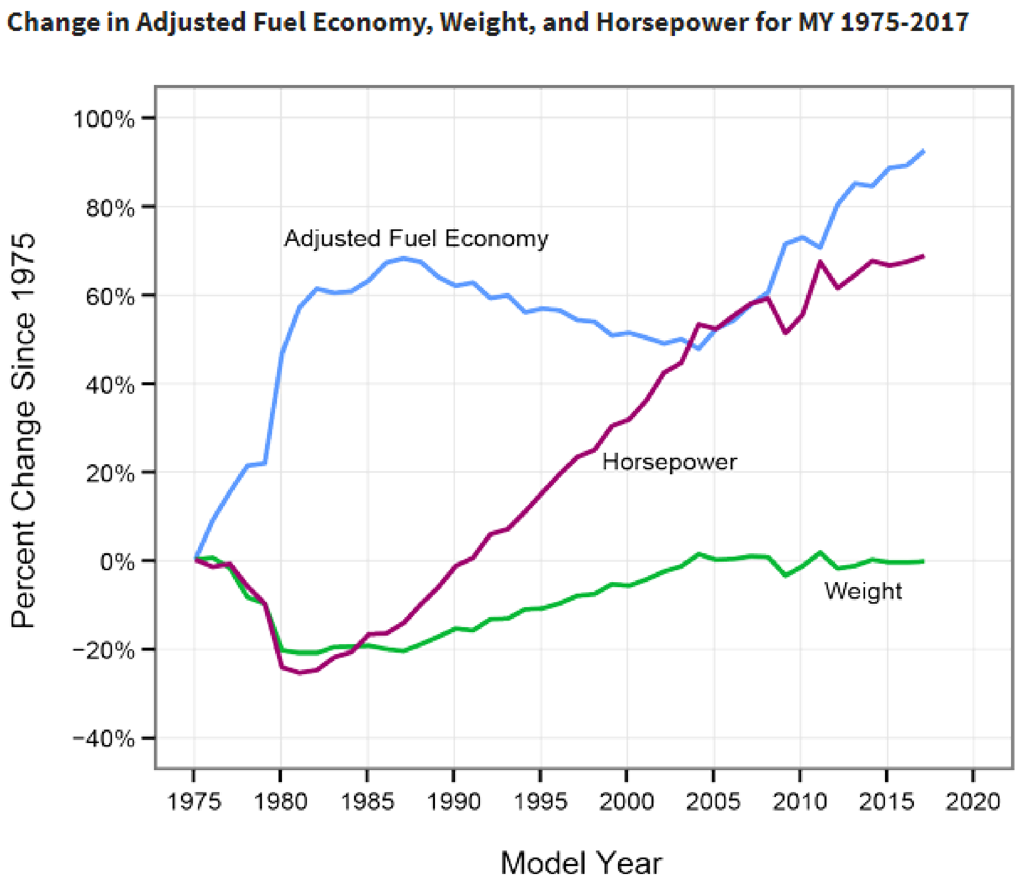

Figure 13. Weight, Fuel Economy and HP For US Vehicles: 1975 To 2017[9]

The 2017 EPA FE Trends report[10] shows increasing truck production beginning in 1980. Per this report, "The most important change was re-classification of many small and mid-sized, 2-wheel drive sport utility vehicles (SUVs) from the truck category to the car category. As with other such changes in this report, this change has been propagated back throughout the entire historical database. This reclassification reduced the absolute truck share by approximately 10% for recent years."[10] Figure 14. depicts this trend. Per this document, trucks comprised 46% of the 2016 U.S. vehicle production (page 15).

[9] https://www.epa.gov/fuel-economy-trends/highlights-co2-and-fuel-economy-trends
[10] https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100TGDW.pdf

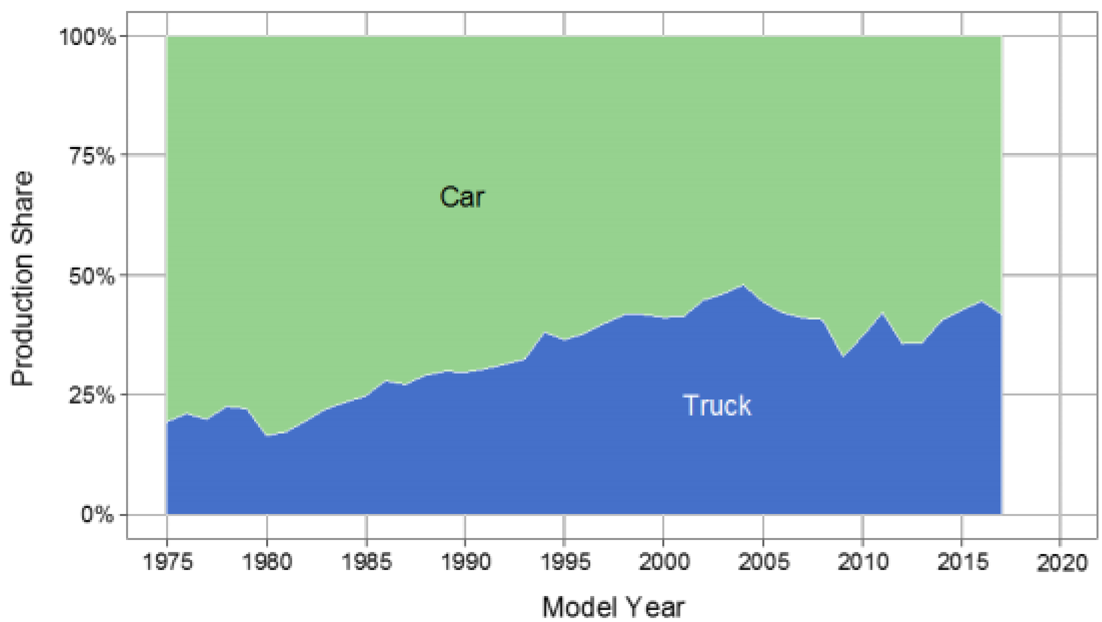

Figure 14. U.S. Passenger Car and Truck Production[10]

c. Accident Avoidance Considerations

An important aspect of safety is accident avoidance or minimizing the severity of a collision by steering and braking the vehicle. Lightweight vehicles typically provide noticeably improved maneuverability compared to heavier vehicles. An extreme example is comparing the evasive capability of a small sports car to a large SUV. The sports car has a lower center of gravity, less weight per tire contact patch area, a suspension tuned for handling and more braking capability per pound of vehicle weight. These attributes, a typical result of reducing vehicle weight, contribute to quicker turning response, better handling and shorter braking distances and can allow an average driver to control the vehicle more effectively in an impending accident. There are numerous examples of reduced weight vehicles having better chassis dynamics reported in automotive magazine road tests. The below excerpts highlight the improved response of reduced weight vehicles including a small car, a mid-size car and a large car.

Chevrolet Cruze:

"The new Cruze benefits from a weight-reduction program that reduced weight up to 250 pounds from the previous car, even though the new car's wheelbase is 0.6-inch longer. The Cruze's light weight and stiff chassis contribute to smooth, composed handling"[11].

Cadillac CTS:

"Since its launch in 2003, the CTS sedan has been Cadillac's stylish, fun, and agile sports sedan. This model shed a couple of hundred pounds, grew four inches longer, and acquired a plusher, posher interior. In short, it emerged from GM's finishing school as one of the most driver-focused midsized

[11] https://www.freep.com/story/money/cars/mark-phelan/2016/04/21/first-drive-2016-chevrolet-cruze-premier-compact-car/83321892/

luxury sedans you can buy. The CTS delivers an inviting blend of comfort, quietness, and sporty driving performance"[12].

BMW 7 Series:

"The 206 BMW 7 Series is a better dancer than the S-Class largely because it's lighter on its feet. Much of the new unibody, including the center tunnel, is made of carbon fiber — a payoff of BMW's huge investment in the stuff for Project i. That helps melt away up to 190 pounds compared with the last 7 Series and represents a 100-pound advantage over a similarly equipped S-Class. The 7 Series is thus quicker than before, even though its engines — a revised 4.4-liter turbo V-8 and an all-new 3.0-liter turbo inline-six — make similar power to their counterparts in the outgoing car"[13].

IV. FMVSS Vehicle Simulations and Lightweight Vehicle Designs

Modeling tools play an important role in assessing vehicle crash performance for low speed and high speed events. The ability to accurately predict the behavior of a vehicle can reduce development time and lower costs by minimizing the need to build and test prototype vehicles. Simulation tools, when properly applied, can assist engineers in creating safer structures by allowing them to evaluate hundreds of design iterations in a relatively short time. The previous process required: 1. designing and building prototypes; 2. crashing prototypes; 3. evaluating the areas needing improvement; 4. redesigning the parts; 5. building new tools and making new parts; 6. assembling new prototypes; 7. crashing the new prototypes; and 8. repeating the process until the targets were met or until the manufacturer ran out of time.

OEMs do not publish their internal studies used to create the vehicles that go into production; the development of new vehicle models is highly confidential. The simulation models used for new vehicles are generally not released to the public.

However, there have been numerous government funded, public domain, peer reviewed lightweighting studies published since 2012. They were funded to provide information for NHTSA and the EPA as part of the 2025 fuel economy and emissions regulation development.

A key element of the government funded lightweighting studies was maintaining the basic vehicle dimensions including wheelbase, length and width. This approach was consistent with NHTSA's change from a mass (weight) based standard for fuel economy to a "footprint" based standard; footprint is the wheelbase x average front and rear track (track is the cross-car distance between the centerline of the tires). Per the Executive Summary in NHTSA's June 2016 preliminary report[14] (Docket No. NHTSA-2016-0068 "Relationships between Fatality Risk, Mass, and Footprint in Model Year 2003-2010 Passenger Cars and LTVs):

[12] https://www.consumerreports.org/cars/cadillac/cts/2015/overview
[13] http://www.automobilemag.com/news/2016-bmw-7-series-review/
[14] https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/2016-prelim-relationship-fatalityrisk-mass-footprint-2003-10.pdf

"The standards for MY 2017-2021 are "footprint-based," with footprint being defined as a measure of a vehicle's size, roughly equal to the wheelbase times the average of the front and rear track widths. Basing standards on vehicle footprint ideally helps to discourage vehicle manufacturers from downsizing their vehicles, because the agencies set higher (more stringent) mpg targets for smaller-footprint vehicles, but would not similarly discourage mass reduction that maintains footprint while potentially improving fuel economy. Several technologies, such as substitution of light, high-strength materials for conventional materials during vehicle redesigns, have the potential to reduce weight and conserve fuel while maintaining a vehicle's footprint and maintaining or possibly improving the vehicle's structural strength and handling."

Three major modeling studies were selected to for detailed analysis in Section V. below. The Lotus Phase 2 CUV (Crossover Utility Vehicle) study incorporated a wide variety of structural body materials (aluminum, steel, magnesium and composites), used bonded construction, achieved a 37% BIW weight reduction, a 31% total vehicle weight savings and met key FMVSS crash requirements at near cost parity.[15] The EDAG/GWU mid-sized passenger car (Honda Accord) study showed a 22.4% weight reduction with a 2.13% cost increase[16]. Keys areas of the federally funded LDT (light duty truck) study, the FEV/EPA 2011 Silverado 1500 study, which was targeted for 2020 production, are also discussed in detail[17].

Additionally, production vehicles utilizing a significant quantity of lightweight materials are discussed in detail in Section VI. The light duty 2015 Ford F-150 truck incorporated a high percentage of aluminum and reduced the truck weight by as much as 700+ lbs., depending on the model[18]. An important new industry segment is the Battery Electric Vehicle (BEV). A production Tesla Model S, a fully certified BEV on sale in the U.S. since 2012 is included to represent this category.

a. Modeling Fidelity

A high degree of modeling fidelity for linear and non-linear events is essential for these studies to be meaningful. The accuracy is typically >85% and as high as 95% per Altair Engineering and Detroit Engineered Products (DEP), two Tier 1 automotive suppliers with internally developed state of the art software. Per Detroit Engineered Products Director of Engineering, Mudha Jampala:

Correlation of high speed crash analysis depends on the accurate modeling of the FE models. Structural performance correlation will be achieved by proper consideration of the weld and material failure definitions. If we are able to capture the engine mount failures and suspension joint failures, then part of the problem will be solved. But in order to achieve robust performance results, crash engineers must work on the crush mode and you need to have a good stable crush, then the robustness and correlation can be achieved. If the crush mode is not good and instead of absorbing energy, the load path is buckling, then correlation will be very difficult. So achieving a load path with the necessary optimization and a good FE model will provide an approximate 90% correlation/reliability. DEP has a history of success in achieving both structural and occupant correlation where we can rely confidently on simulations.

[15] https://www.arb.ca.gov/msprog/levprog/leviii/final_arb_phase2_report-compressed.pdf
[16] https//www.nhtsa.gov/sites/nhtsa.dot.gov/files/3-singh-edag-nhtsa_2013.pdf
[17] https://nepis.epa.gov/Exe/ZyPDF.cgi/P100MS0E.PDF?Dockey=P100MS0E.PDF
[18] https://jalopnik.com/the-732-lbs-lighter-2015-ford-f-150-v6-was-weighed-agai-1610205046

b. Fundamental Physics of an Impact

A key vehicular safety objective is to control acceleration levels in an impact to levels that the human body can withstand with minimal or no injury.

Industry protocol defines crash acceleration as positive, i.e., the crash pulse is displayed as a positive acceleration rather than a negative acceleration (deceleration) which the vehicle is undergoing. Deceleration occurs when a vehicle is undergoing a change in velocity from some initial speed V_i, which is greater than zero, to a final speed, V_f, of zero over a specified time period. This positive acceleration pulse is what the occupant experiences as the vehicle decelerates in an impact as a reaction to the actual deceleration rate of the vehicle. The occupant accelerates as the vehicle decelerates. This follows Newton's third law: for every action, there is an equal and opposite reaction.

During a collision, the occupant's effective weight increases directly proportional to the acceleration they experience. A 40 'g' vehicle impact increases the effective weight (force) of a 150-pound passenger to 6,000 lbs. (40 g's x 150 lbs.). Additionally, human organs, such as the brain, accelerate at similar levels. A brain contacting the skull at high 'g' levels can cause traumatic injuries such as concussions.

Acceleration is the change of velocity with respect to time, a = dV/dt where dV is the change in velocity and dt is the time period the velocity change occurs in. A vehicle travelling at 44 ft/sec (30 MPH) that hits a solid wall and stops in 0.05 seconds has an acceleration of 880 ft/sec^2 or a "g" level (1 "g" = an acceleration of 32.2 ft/sec^2) of 27.4 (880 ft/sec^2/32.2 ft/sec^2/g). Acceleration is inversely proportional to the time duration for an impact; the shorter the time period, the higher the acceleration.

An automobile acts a deformable element in a collision, i.e., a vehicle energy absorbing structure has a stiffness, or spring rate, that determines the time to zero (TTZ) in a rigid body collision. There is essentially zero spring back in a high speed collision. The vehicle structure is engineered to absorb energy by permanently deforming the material in the crush zone. The formula is F = kx where k is the average spring rate (lbs./inch) and x is the displacement or crush distance in inches. The instantaneous spring rate k for a vehicle hitting a solid barrier at 35 MPH is generally non-linear. The crash pulses for the Lotus CUV study and the EDAG mid-size passenger car study (shown later in this report) are examples showing these non-linear energy absorbing characteristics. These non-linear curves are typically averaged over various portions of the crash time period. An average spring rate can be calculated based on the applied force and the crush distance. The crush distance is a function of front end structure, materials, engine type and location, engine mount design as well as other design factors. Increased crush space, for a given average spring rate, reduces the acceleration levels acting on an occupant. Lower occupant acceleration levels generally reduce potential injury levels.

Lightweight designs can utilize the same crush space as a heavier, identical size platform. A lightweight design does not require a change in the crush distance compared to a heavier vehicle that is the same size. The Lotus and EDAG lightweight studies included below had comparable or lower acceleration levels relative to their significantly heavier baseline vehicles while retaining the baseline vehicle crush distances. Engineers balance the energy absorbing characteristics of the vehicle structure with the available crush distance to limit acceleration levels. A lighter vehicle has less kinetic energy, so its effective spring rate will be less than a heavier vehicle traveling at the identical velocity impacting a fixed barrier and stopping in the same time. A lower effective spring rate allows lower density, lower strength lightweight materials to be used to absorb energy or it can reduce the amount of steel required for the energy absorbing structure. Regardless of the material type, less material is needed to absorb the reduced impact energy of a lighter weight vehicle vs. a heavier vehicle.

The fundamental physics showing these relationships are:

1. Kinetic energy equation: KE = ½ M x V^2 where M = vehicle mass (slugs) and V = velocity (ft./second); Units: ft.-lbs.
2. Work = F x D where F = force (lbs.) and D = crush distance (ft.); Units: lb.-ft.
3. Acceleration (average) = F/M where F = force (lbs.) and M = mass (slugs); Units: ft./sec^2; 1 g = 32.174 ft./sec^2
4. Impulse = F x $t_ð$ where F = force (lbs.) and $t_ð$ = change in time (seconds); Units = lb.-seconds
5. Effective Spring Rate = K x X where K = spring rate (lb./ft.) and X = distance the effective spring is compressed.

The average acceleration, effective spring rate and crash time are calculated using the above formulas. The steps are as follows:

A. Solve for total impact force: Let KE = Work. ½ M x V^2 = F x D; F = ½ M x V^2/D; define D, the crush distance, and solve for the total impact force. To illustrate the above relationships, a 100% inelastic collision with a solid barrier is assumed.
B. Solve for effective spring rate: K = F/X; define D and solve for K.
C. Solve for average acceleration; A = F/M and solve for A using the previously calculated impact force and vehicle mass;
D. Solve for the impact TTZ (time to zero): Impulse = F x $t_ð$; substitute M x A for F and re-arrange to create the equation: $t_ð$ = M x delta V/F where M is defined, delta V is the initial impact velocity minus the final velocity (0 ft./second) and F is the impact force previously calculated.

The average acceleration for a 35 MPH fixed barrier collision for a 1,000 lb. vehicle and a 6,000 lb. with identical crush distances is the same. However, because of the reduced weight, the effective spring rate is much lower for the lighter weight vehicle. The spring rate difference is directly proportional to the vehicle weight ratio, i.e., a 1,000 lb. vehicle effective crush spring rate is 6x less that the effective spring rate for a 6,000 lb. vehicle (1,000/6000 = 1/6). The TTZ and acceleration levels are linearly dependent on the impact force and vehicle weight. For identical impact speeds and crush distances, the 6,000 lb. vehicle has 6x the impact force but 6x the mass of the lighter vehicle. Given that the speed and crush distances are the same, the mass and force value ratios are identical for the 1,000 lb. vehicle and the 6,000 lb. vehicle in the acceleration and TTZ formulas: A = F/M and tð = M x delta V/F.

The significance of these formulas is that impact acceleration levels are independent of vehicle weight. A lightweight vehicle will have the same acceleration level as a heavier vehicle for an identical crush distance and impact velocity.

These first principal calculations verify that a 1,000 lb. vehicle with a 30" (2.5 ft.) crush distance will have a significantly lower acceleration level than a 6,000 lb. vehicle with an 18" (1.5 ft.) crush distance or a 6,000 lb. vehicle with a 24" (2.0 ft.) crush distance for the same impact speed. Lower vehicle acceleration in a crash is a key factor for occupant safety. Table 1 below shows the calculated accelerations, effective spring rates and TTZ values for a 1,000 lb. vehicle and a 6,000 lb. vehicle for a 35 MPH front barrier inelastic impact for varying crush distances.

35 MPH Fixed Barrier Impact - Inelastic Model	Crush Distance - ft.	Impact Velocity - ft./sec.	Average Acceleration - g's	Effective Spring Rate (lb./ft.)	Time - seconds
1,000 lb. Vehicle	1.5	51.3	27.3	18200	0.058
6,000 lb. Vehicle	1.5	51.3	27.3	109203	0.058
1,000 lb. Vehicle	2.0	51.3	20.5	10238	0.078
6,000 lb. Vehicle	2.0	51.3	20.5	61426	0.078
1,000 lb. Vehicle	2.5	51.3	16.4	6552	0.097
6,000 lb. Vehicle	2.5	51.3	16.4	98282	0.097

Table 1. Light and Heavy Vehicle Impact Parameters vs. Crush Distance

An important safety consideration is the kinetic energy of a vehicle in motion. This energy is calculated using the formula KE = $(m \times v^2)/2$ where: KE = kinetic energy, m = vehicle mass and v = velocity. A heavier vehicle travelling at the same speed as a lighter vehicle will have more kinetic energy. Because of this higher energy, a heavier vehicle will cause more damage to a lighter weight vehicle in a collision than a lighter weight vehicle will cause to a heavier vehicle. Reducing the weight of the total vehicle population will reduce the severity of both vehicle-to-vehicle crashes and almost all single car impacts.

V. FMVSS Modeling Studies: Analysis and Results

This section includes three detailed government funded lightweighting studies, a CUV, a mid-sized passenger car and a full size pick-up truck. These investigations used OEM engineering approaches and comparable modeling software to reduce weight and meet MVSS requirements. These studies were led by experienced automotive engineers with backgrounds in lightweight materials and processes. The theoretical government models, because of cost and time constraints, were not built and crash tested.

a. CUV Analysis Results

i. Weight Comparison

The Lotus lightweight CUV Phase 2 BIW was 37% lighter than the baseline steel vehicle BIW. The total vehicle weight was 31% lighter overall than the baseline Toyota Venza. The baseline 2012 Toyota Venza curb weight is 3,749 lbs. (1700 kg.); the Phase 2 CUV curb weight is 2,587 lbs. The Phase 2 CUV is 1,162 lbs. lighter than the baseline vehicle, a 31% weight reduction[19]. Figure 15. shows the breakdown of the masses including the Phase 2 HD CUV used for this analysis.

[19] https://www.arb.ca.gov/msprog/levprog/leviii/final_arb_phase2_report-compressed.pdf

Table 4.5.5.d: ***Venza, Phase 1, and Phase 2 system masses***

Area/System	Venza Baseline Mass (kg)	Phase 1 Low Development Mass (kg)	Phase 1 High Development Mass (kg)	Phase 2 High Development Mass (kg)
Body-in-white	382.5	357.4	221.1	241.8
Closures/Fenders	143.02	107.6	83.98	83.98
Bumpers	17.95	15.95	15.95	20.17
Thermal	9.25	9.25	9.25	9.25
Electrical	23.6	16.68	15.01	15.01
Interior	250.6	182.0	153	153
Lighting	9.9	9.9	9.9	9.9
Suspension/Chassis	378.9	275.5	217.0	217.0
Glazing	43.71	43.7	43.71	43.71
Misc.	30.1	22.9	22.9	22.9
Powertrain	410.16	356.2	356.2	356.2
Total excluding powertrain	1290	1041	795	817
Reduction from baseline	-	19%	39%	38%
Total including powertrain	1700	1397	1151	1173
Reduction from baseline	-	18%	32%	31%

Figure 15. Phase 1 and Phase 2 Mass Breakdown by System vs. Toyota Venza

Figure 16. shows the cost factors for all vehicle systems. The body cost increase was 35%. The cost of the heaviest non-body systems, which used equivalent materials for the most part, went down as a result of using less material overall. The total vehicle weighted cost increase was estimated at 3.0%.

Mass and Cost Summary	Baseline CUV	Low Mass	Low Mass
		Mass	Cost Factor
Body	382.50	221.06	1.35
Closures/Fenders	143.02	83.98	0.76
Bumpers	17.95	17.95	1.03
Thermal	9.25	9.25	1.00
Electrical	23.60	15.01	0.96
Interior	250.60	153.00	0.96
Lighting	9.90	9.90	1.00
Suspension/Chassis	378.90	217.00	0.95
Glazing	43.71	43.71	1.00
Misc.	30.10	22.90	0.99
Totals:	1289.53	793.76	
Base CUV Powertrain Mass	410.16	Mass	Wtd. Cost
Base CUV Total Mass	1699.69	61.6%	103.0%

Figure 16. Lotus Phase 2 System Cost Factors

The Phase 2 HD BIW cost was $723 more than the baseline Venza BIW. However, there were significant cost offsets as a result of the selected manufacturing, assembly and joining technologies. Key contributors were a 35% reduction in parts count achieved by utilizing castings and extrusions, integrating multiple stamped parts into single assemblies to reduce tooling costs and replacing welded joints with structural adhesives, rivets and friction spot joining. These choices resulted in savings that were 2/3rds of the BIW cost increase. Figure 17. summarizes these offsets.

Lotus Phase 2 HD BIW Cost Increase		$723
Cost Offsets		
Part Tooling (Decrease)		($233)
Assembly (Decrease)		($251)
Total Cost Offset		($484)
% Of BIW Cost Offset		67%
Net BIW Cost Increase		$239

Figure 17. Lotus Phase 2 HD BIW Net Cost Calculations

The estimated cost differential, after tooling amortization, was estimated to be 1.44% higher. Figure 18. shows this breakdown. This is approaching cost parity and is an indication that a lightweight vehicle can be produced economically by using a holistic, total vehicle approach.

	Cost Factor	Cost Weighting Factor	Weighted Cost Factor
Complete body	118.00%	18.00%	21.24%
Non-body	100.00%	82.00%	82.00%
Totals		**100.00%**	**103.24%**
Cost Differential			**3.24%**

Includes BIW Assembly Plant Cost Amortization (3 years)

	Cost Factor	Cost Weighting Factor	Weighted Cost Factor
Complete body	108.00%	18.00%	19.44%
Non-body	100.00%	82.00%	82.00%
Totals		**100.00%**	**101.44%**
Cost Differential			**1.44%**

BIW Assembly Plant Cost Fully Amortized

Figure 18. Lotus Phase 2 Amortization Impact On Vehicle Cost Factors

The material utilization for the Lotus Phase 2 HD BIW is shown in illustration 2. It is comprised of 75% aluminum, 12% magnesium, 8% AHSS and 5% composites.

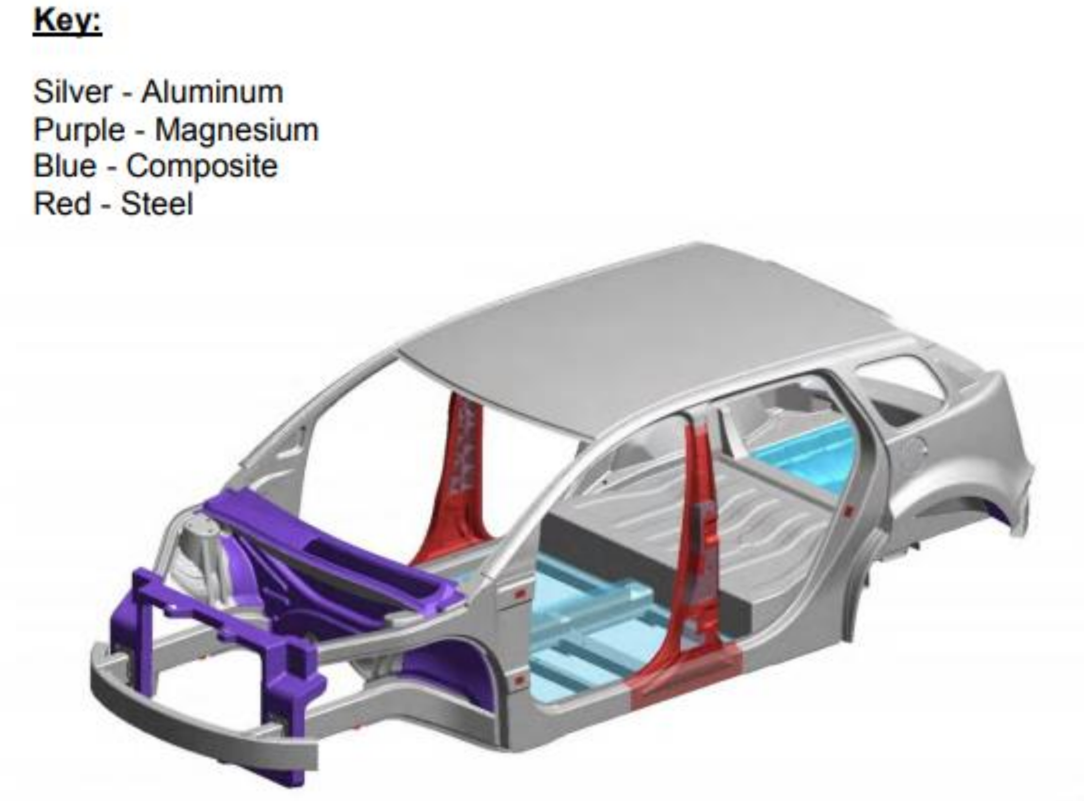

Illustration 2. Phase 2 CUV Multi-Material Lightweight Body in White Structure

ii. Safety Results Comparison

The baseline 2012 Toyota Venza was rated four stars in overall safety[20]. The individual crash ratings were: frontal - three stars; side crash – five stars; and rollover - four stars.

In the MVSS 208 test, the 2012 Toyota Venza crush distance was 573mm vs. 555 mm for the lightweight vehicle. The average acceleration level of the lightweight vehicle, 26.7 g, was judged comparable to a typical steel vehicle and could utilize existing safety systems per TRW, an automotive safety system supplier per the Lotus report. The driver footwell intrusion results, an indicator that the vehicle structure is absorbing the impact energy, were -15 mm for the Venza and -10mm for the lightweight vehicle. The post-crash pictures below show comparable crush performance between the 2012 Venza and the lightweight vehicle.

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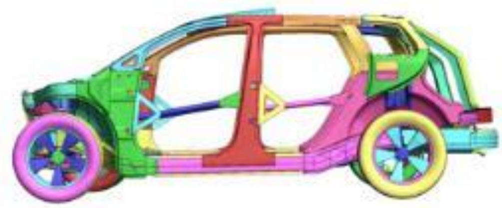
[20] https://www.nhtsa.gov/vehicle/2010/TOYOTA/VENZA/4%252520DR/FWD%25252FAWD



NHTSA MVSS 208 Toyota Venza (After Crash) Phase 2 CUV MVSS 208 (After Crash)

The Phase 2 HD crash pulse, identified as CA-ARB v26, was compared to the Venza (Three Star Rating[21]) and other production vehicles with NHTSA ratings of Four Stars or above in the MVSS 208 test. Figure 19. shows the crash pulses for a variety of similar sized production vehicles. Figure 20. shows the upper and lower limits of the crash pulses superimposed on the lightweight CUV crash pulse. "Based on this data and Lotus' engineering judgment, the Phase 2 HD vehicle is predicted to perform as well as or better than comparable vehicles on the market"[22].

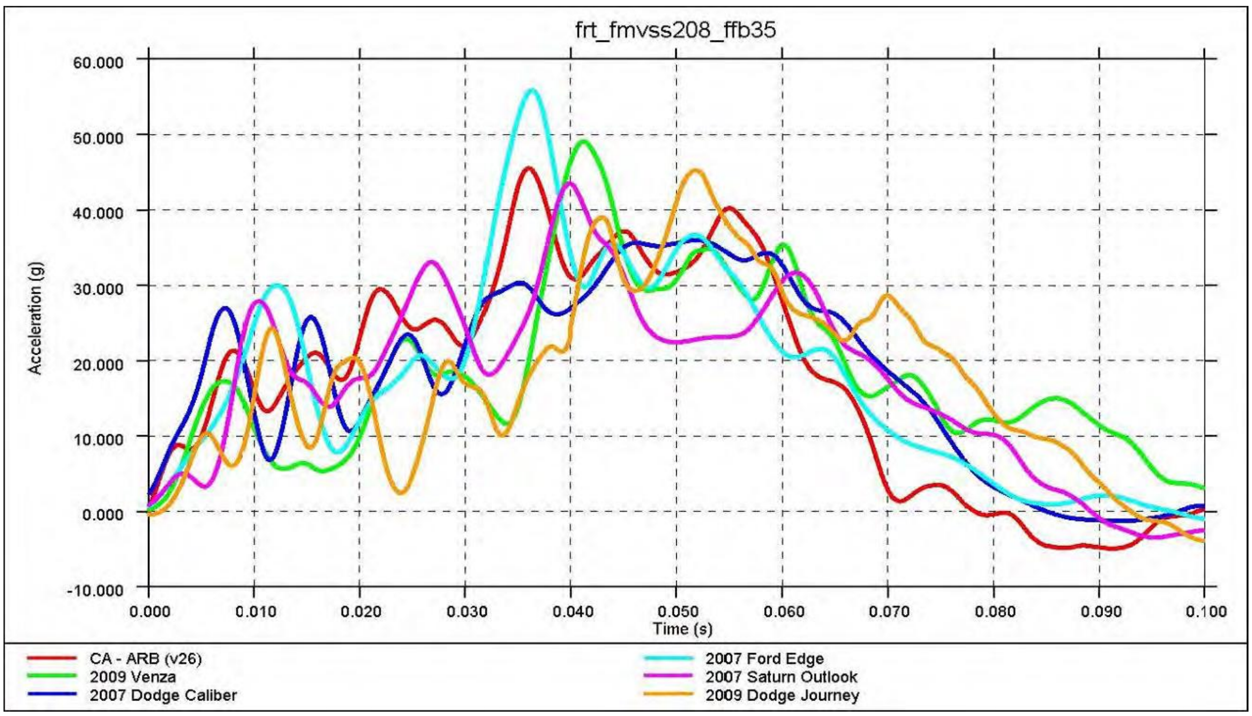


Figure 19. Lightweight CUV Crash Pulse vs. Comparable Vehicles

[21] https://www.nhtsa.gov/vehicle/2012/TOYOTA/VENZA/SUV/FWD#safety-ratings-frontal

[22] https://www.arb.ca.gov/msprog/levprog/leviii/final_arb_phase2_report-compressed.pdf

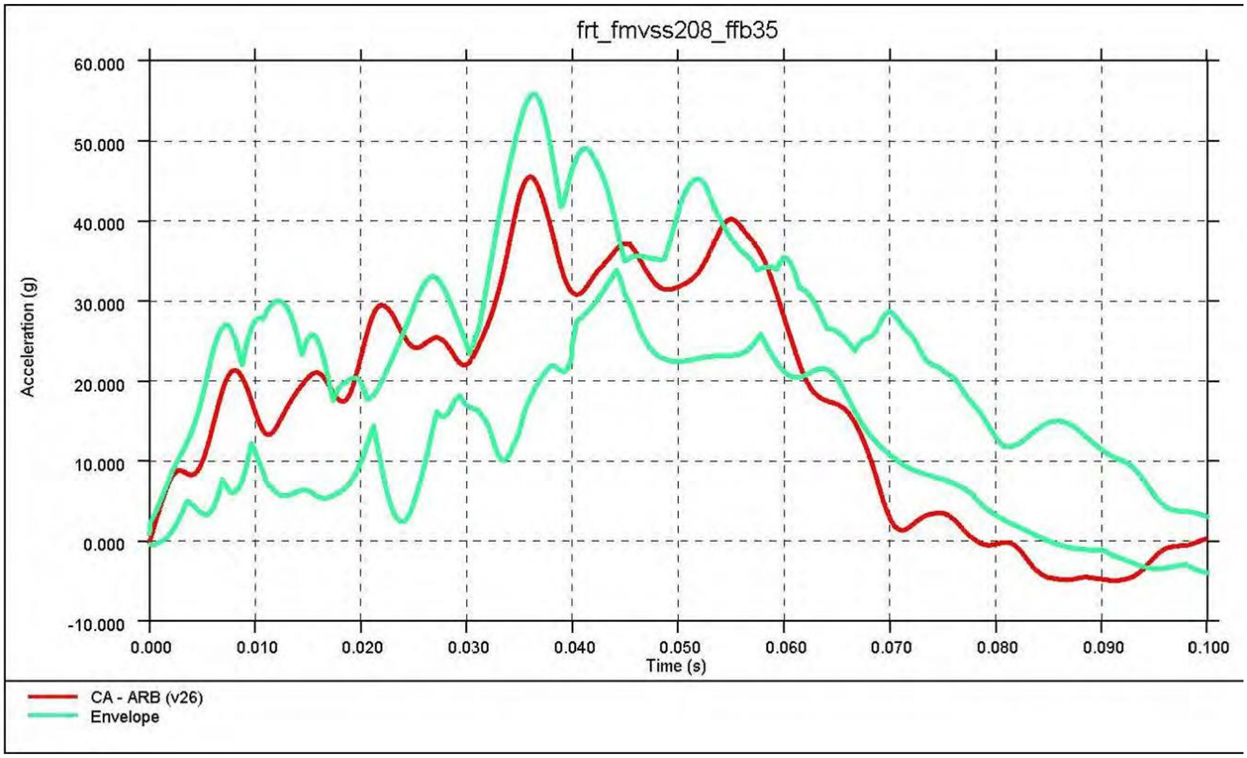


Figure 20. Lightweight CUV Crash Pulse vs. Upper and Lower Limits for Comparable Vehicles

The Phase 2 report identifies that the MVSS 208 crash performance could have been improved further given some flexibility on the packaging constraints imposed by using the Toyota Venza's geometry and architecture[23]. The front crush distance could have been adjusted to better meet the lightweight design energy absorbing characteristics.

The intrusion levels for MVSS 214, the side impact moving barrier and pole strikes, were all less than 300 mm, the maximum allowable displacement. 300 mm is a standard distance used between the outer door panel and the edge of the front seat, i.e., the impacting hardware could not touch the seat.

A primary contributor to this performance was the utilization of high strength steel for the side intrusion beam. The side door beams interact with the rigid A and B pillar areas to distribute the load. The geometry and length of these steel beams are shown in the figures below.

Figure 21. below shows the FMVSS 214 33.5 MPH crabbed barrier side impact configuration. Figure 22. shows the post-crash results for the crabbed barrier side impact. Figure 23. shows the FMVSS 214 20 MPH 75° 5th percentile female side pole impact results.

[23] pages 80, 81 in the Lotus report

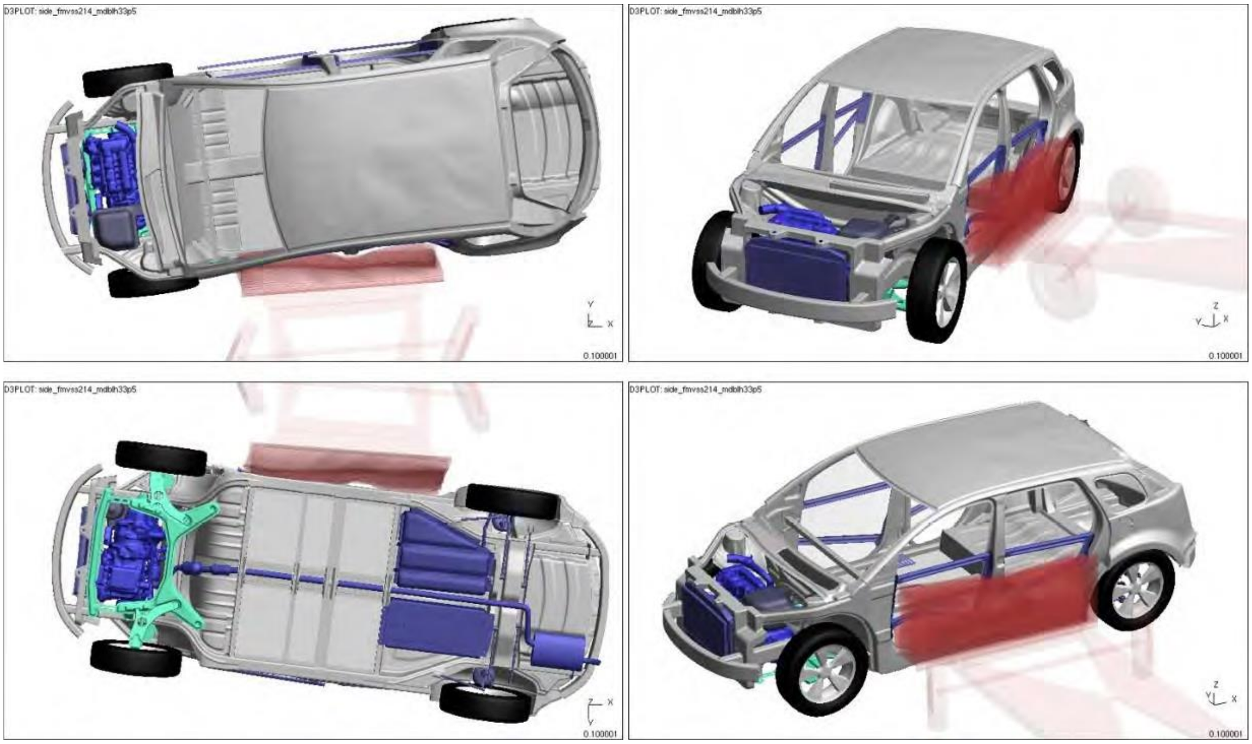


Figure 21. MVSS 214: Lotus Lightweight CUV Crabbed Barrier Side Impact

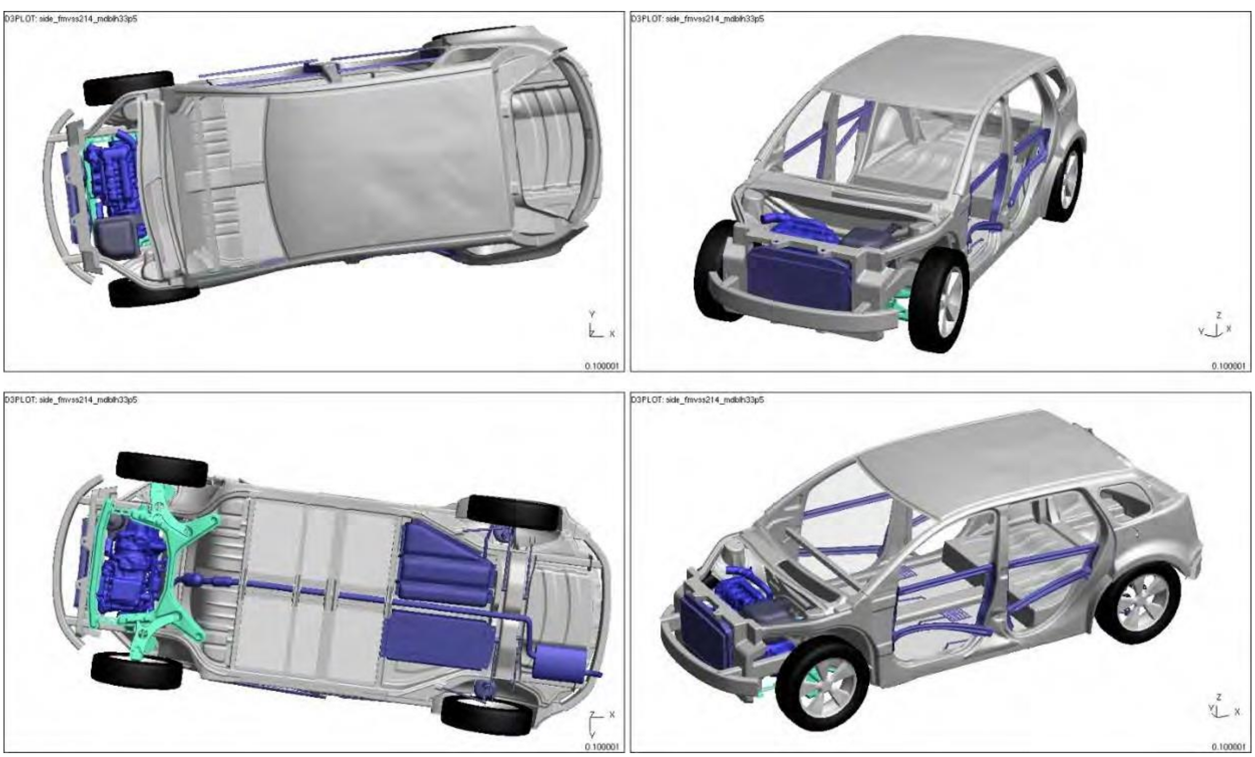


Figure 22. MVSS 214: Lotus Lightweight CUV Crabbed Barrier Side Impact Post Crash Deformation

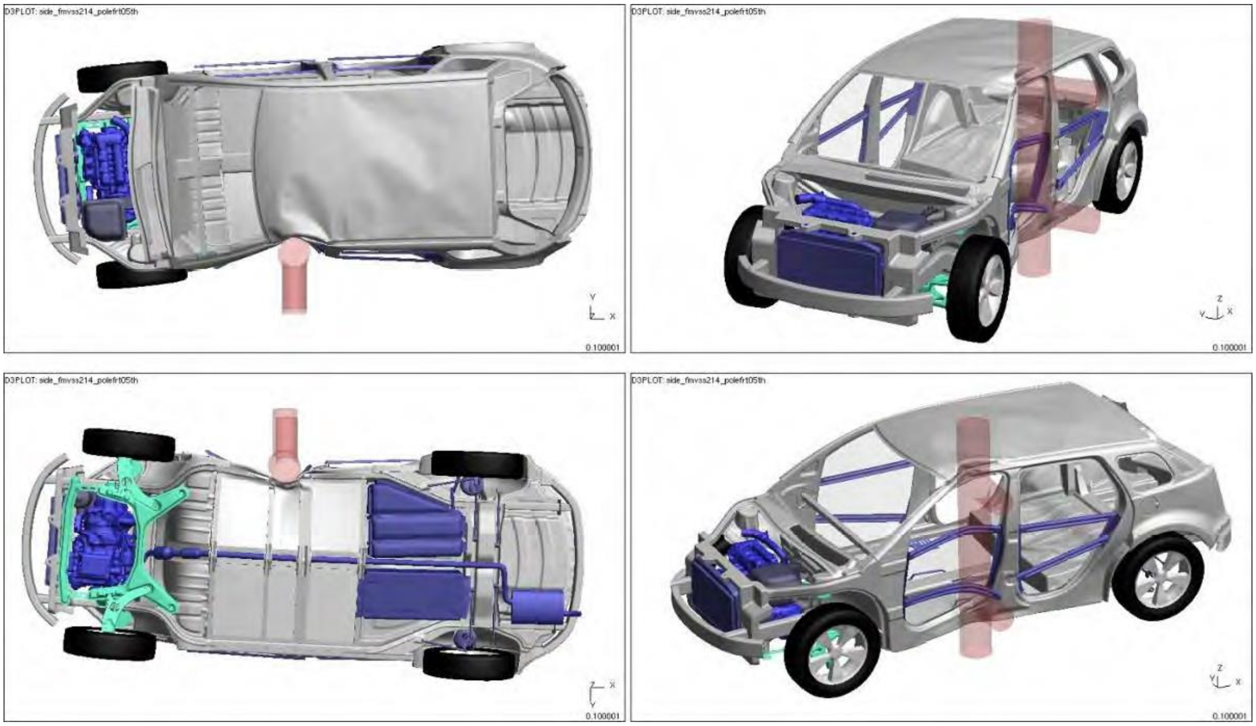


Figure 23. MVSS 214: Lotus Lightweight CUV Pole Side Impact (5th Percentile Female) Deformation

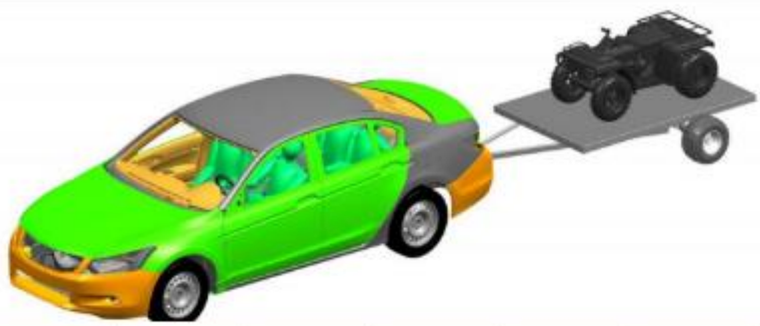
The moving barrier intrusion distance was 115mm (185mm from the outboard seat edge). The pole strike intrusion displacements were 250mm (5th percentile female where the pole strikes the door forward of the “B” pillar) and 225mm (50th percentile male where the pole strikes the “B” pillar). The Phase 2 CUV vehicle structure prevented any contact with the outboard edge of the seat in every test.

The MVSS 216 rollover test uses a platen that is loaded to 3x vehicle curb weight for and cannot displace more than 127 mm and must not load a 95th percentile male’s head to more than 222 N (50 lbs.). The analysis showed that the Phase 2 HD BIW exceeds this standard as only 20 mm of displacement is predicted at three times the vehicle curb weight. The structure displacement is 1/5 of the allowable target and does not touch the occupant’s head. The Phase 2 CUV also met the standard at 3x the Venza curb weight (p. 127), a load factor of 3.9x the Phase 2 CUV weight. The lightweight, high strength steel “B’ pillar, reinforced with a composite inner reinforcement, contributed substantially to this performance. This is an example of a multi-material solution. The lightest, highest performing part was achieved with a ferrous/composite part vs. utilizing an all steel solution or an all-aluminum design. The MVSS 301 rear impact test run at 50 MPH requires that no liquid escape from a fuel tank or battery pack. The Phase 2 HD vehicle met this requirement.

b. Mid-size Passenger Car Results

The EDAG Honda Accord LWV study (link shown in the FMVSS Simulation section) achieved a 22.4% weight reduction. The cost was projected to increase 2.13% compared to the baseline 2011 Honda Accord. Page 30 (below) in the EDAG report shows the system masses for the baseline Honda Accord and for the EDAG LWV (Light Weight Vehicle)[24].

Summary of Mass Reduction



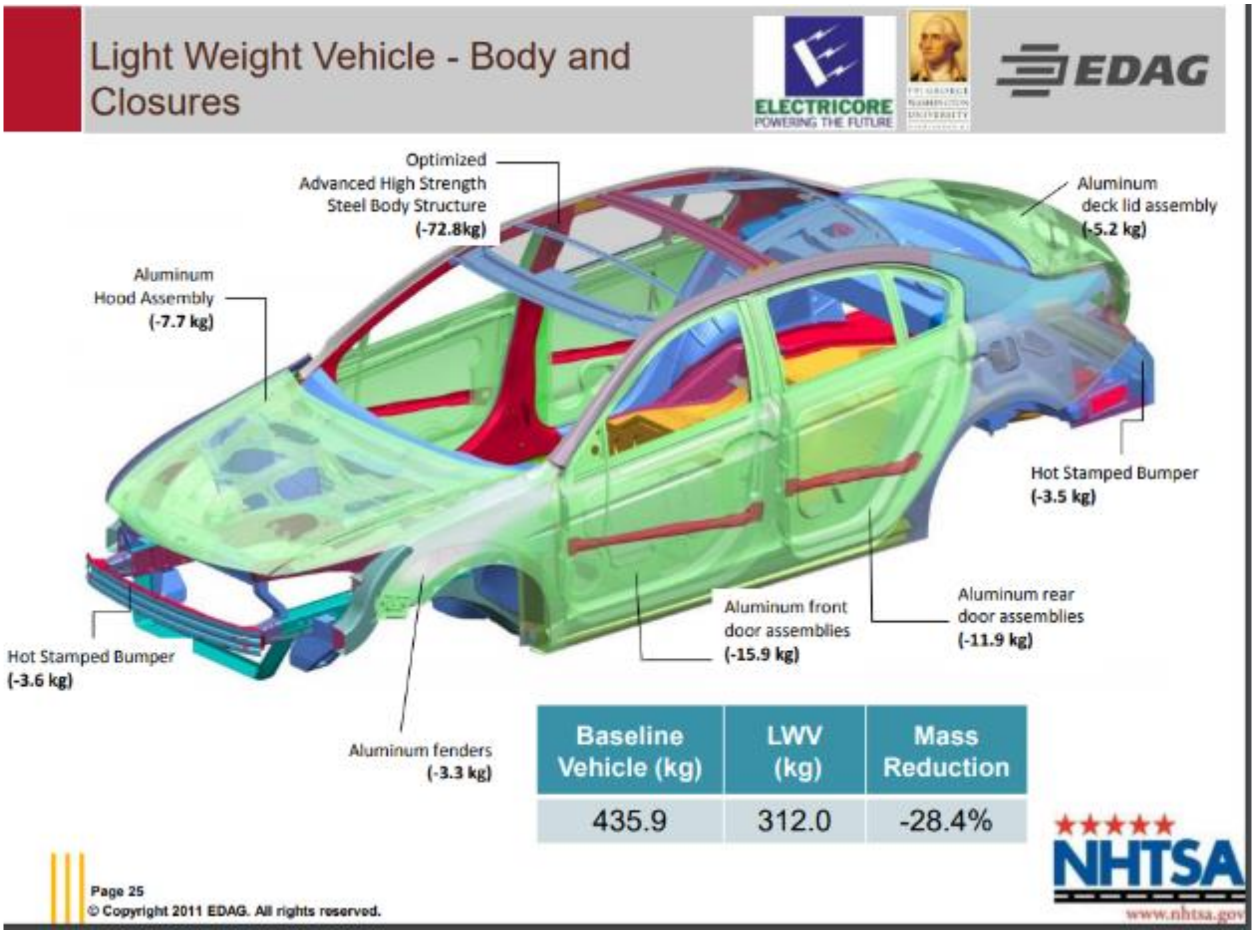
Mass (kg)	Payload	Non-Structure	Body Structure	Chassis	Powertrain	GVWR	CVW	MSRP ($)
Baseline Vehicle	470	465.1	343.8	287.8	383.3	1950	1480	21,980
EDAG-LWV	470	366.5	261.1	206.1	311.7	1615	1148	22,449
Reduction (%)		-21%	-24%	-28%	-19%	-17%	-22.4%	2.13%

Page 30

EDAG Honda Accord Lightweighting Study: Page 30

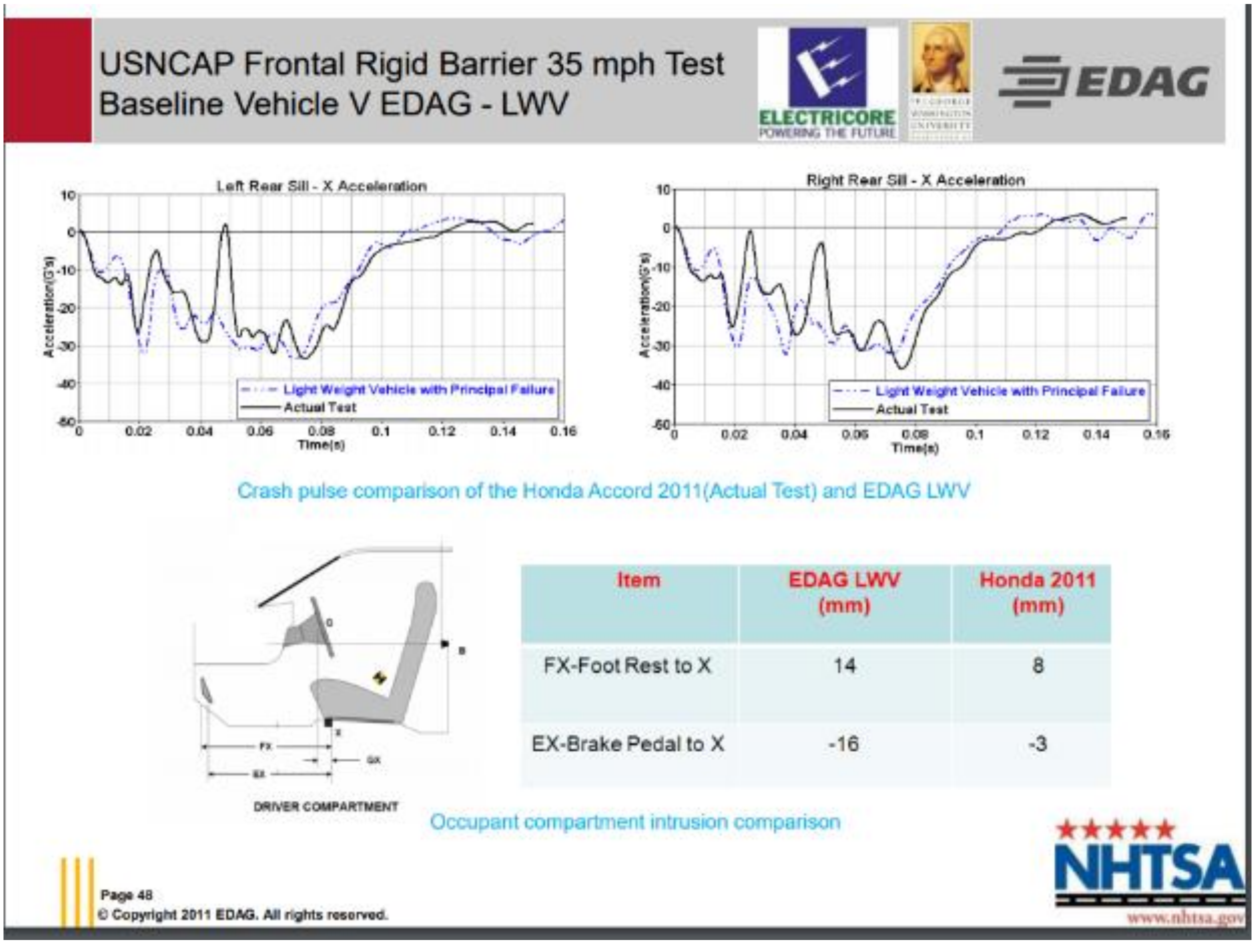
[24] https//www.nhtsa.gov/sites/nhtsa.dot.gov/files/3-singh-edag-nhtsa_2013.pdf

Page 25 from the EDAG study shows the advanced high strength steel body structure and aluminum closures that were used for all crash test simulations.

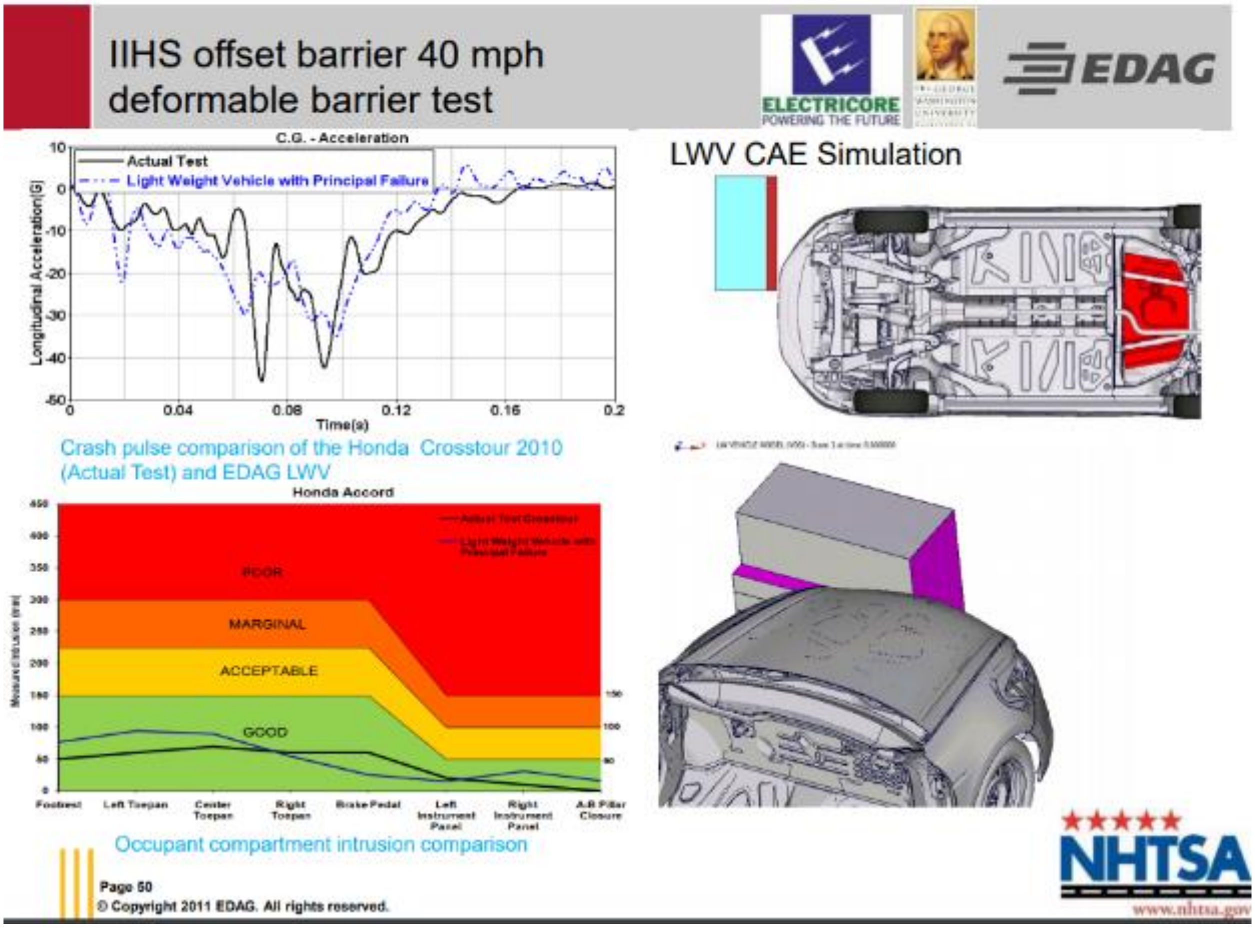


EDAG Honda Accord Lightweighting Study: Page 25

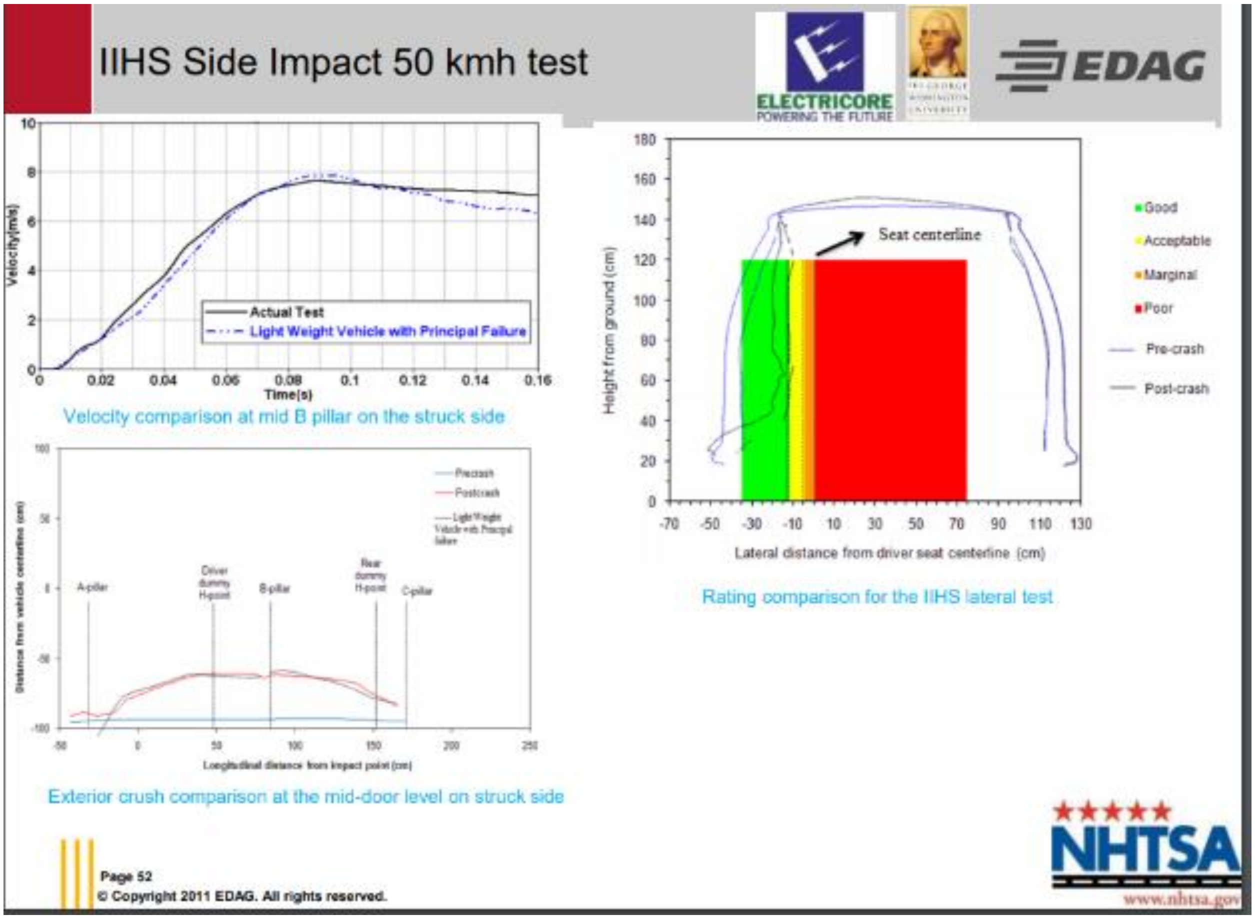
The EDAG LWV crash performance, in general, was comparable to the baseline model. The illustrations below, pages 48, 50 and 52, from the EDAG report, show the relative performance of the 22% lighter vehicle vs. the baseline vehicle. The baseline vehicle weighed 3,263 lbs.; the 22% lighter design weighed 2,531 lbs., a difference of 732 lbs.



EDAG Honda Accord Lightweighting Study: Page 48



EDAG Honda Accord Lightweighting Study: Page 50


IIHS Side Impact 50 kmh test
ELECTRICORE
POWERING THE FUTURE
EDAG
Velocity(m/s)
Time(s)
Actual Test
Light Weight Vehicle with Principal Failure
Velocity comparison at mid B pillar on the struck side
A-pillar
B-pillar
C-pillar
Exterior crush comparison at the mid-door level on struck side
Height from ground (cm)
Seat centerline
Good
Acceptable
Marginal
Poor
Pre-crash
Post-crash
Lateral distance from driver seat centerline (cm)
Rating comparison for the IIHS lateral test
Page 52
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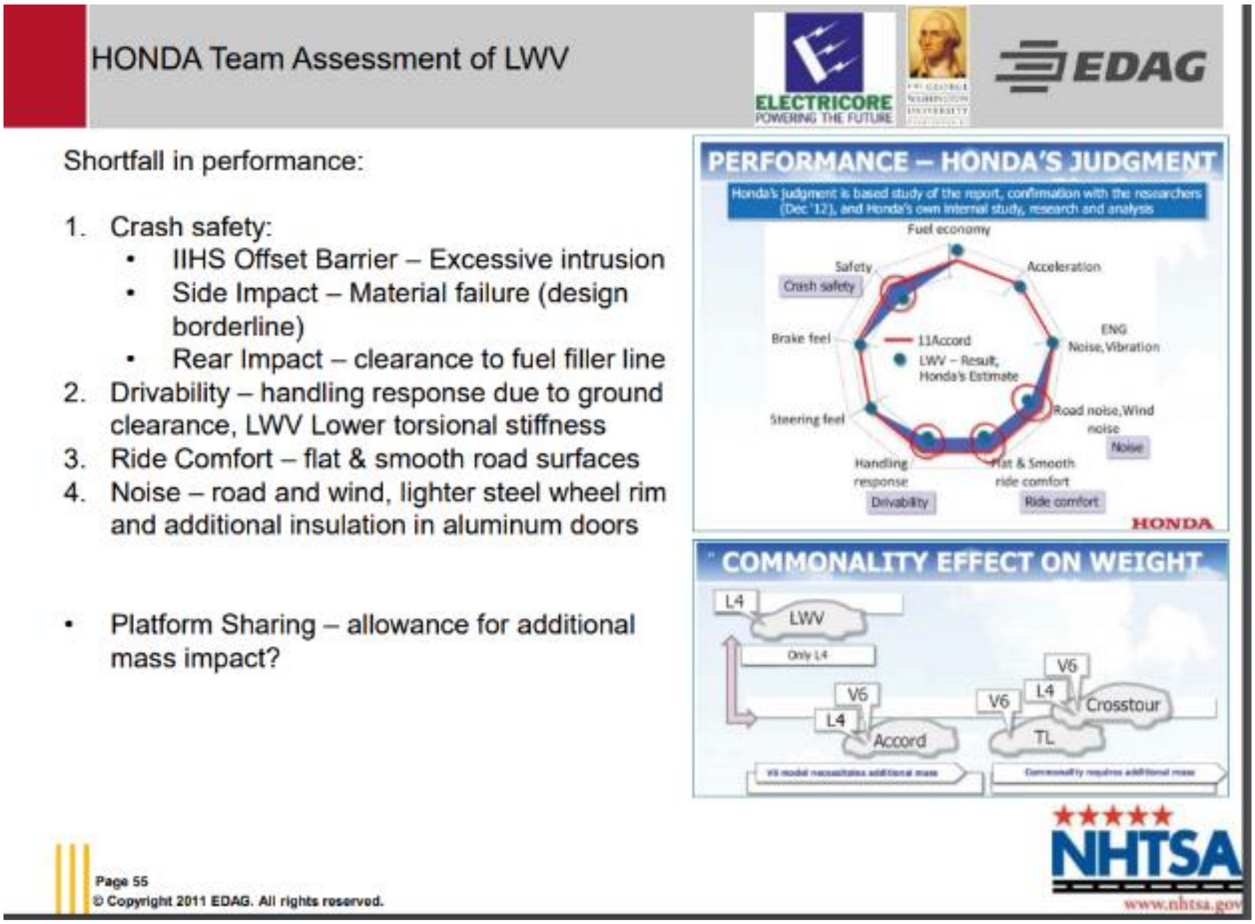
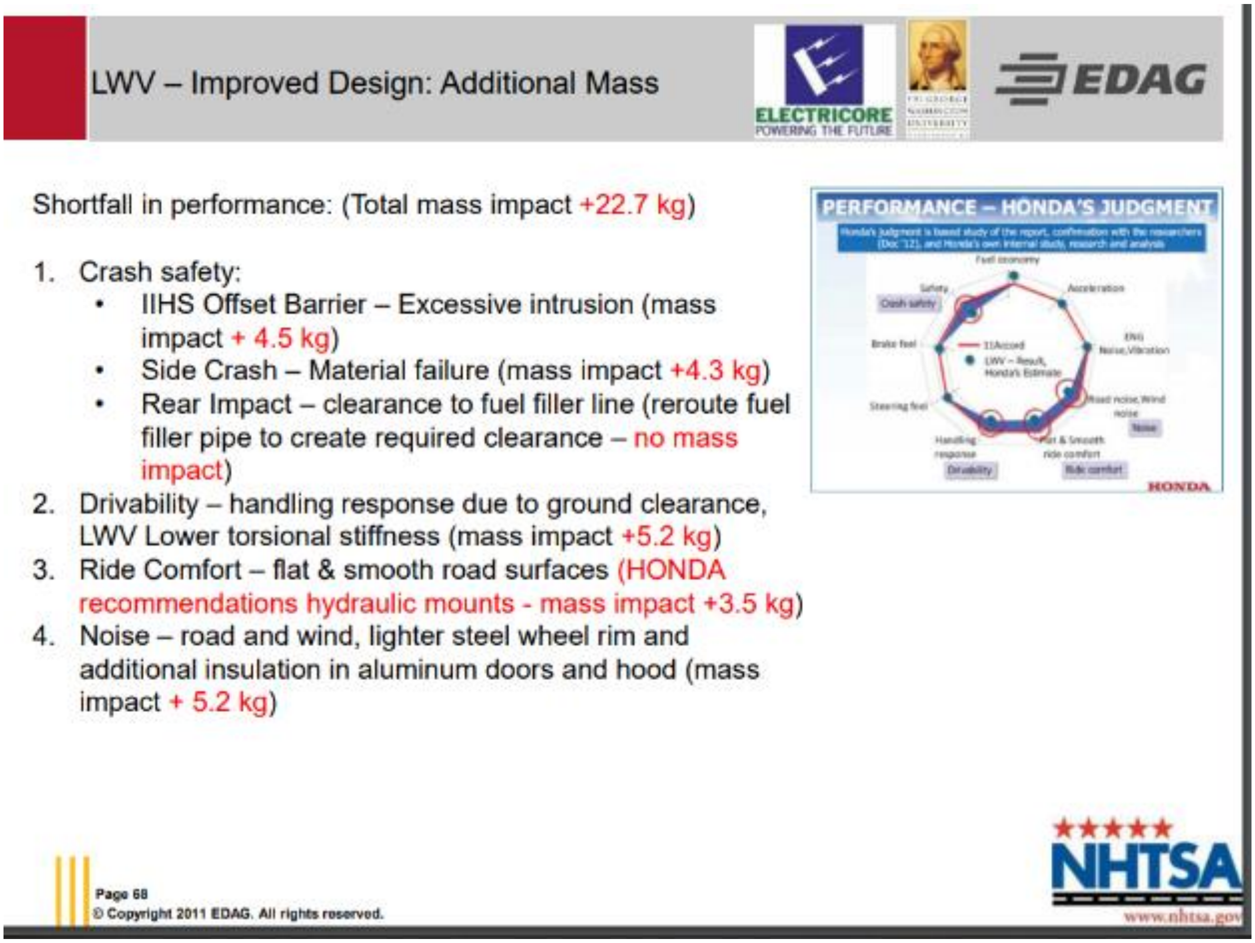
NHTSA
www.nhtsa.gov

Honda reviewed the performance of the EDAG lightweight Accord model for crash, drivability, stiffness, ride comfort and noise and made recommendations to better meet their requirements and customer expectations. Honda specified that the vehicle structure be improved for IIHS offset barrier, side crash and FMVSS 301 rear impact performance. Page 55 of the report (below) documents the performance shortfalls identified by Honda, including ride comfort and noise considerations.



EDAG Honda Accord Lightweighting Study: Page 55

EDAG corrected these shortfalls by improving the vehicle structure; this added a total of 50.1 lbs. (22.7 kg). The fuel filler pipe was moved to improve the rear crash performance; no weight was added. Page 68 of the EDAG report (below) identifies the specific weight additions.



EDAG Honda Accord Lightweighting Study: Page 68

The weight savings, after adding weight to improve the structure to address Honda's concerns, was 20.9% or 682 lbs.

c. Lightweight 2011 Silverado Study

The 2011 Lightweight Silverado Study predicted a 20.8% mass reduction (with NVH provisions included) at a cost increase of $2,222.65[25]. This summary is shown in Appendix B. The >20% weight reduction for the Lightweight 2011 Silverado is due to a substantial increase in lightweight materials including HSS (high strength steel), aluminum and magnesium. Figure 24. shows the baseline 2011 Silverado material utilization.

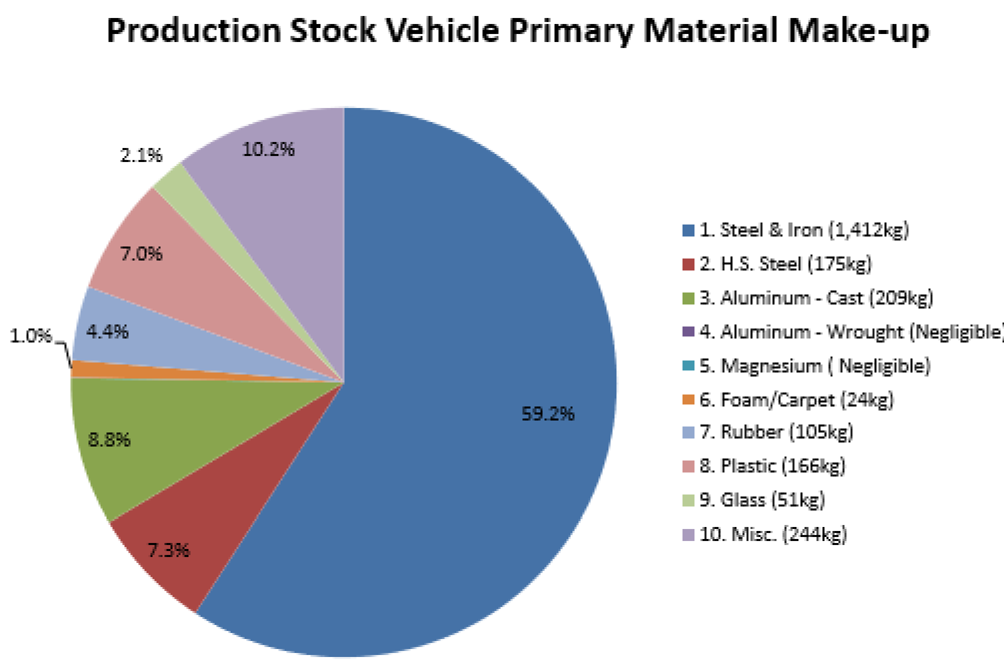


Figure 24. Baseline Materials for 2011 Lightweight Silverado Study

The material utilization for the lightweight 2011 Silverado included 330 kg. of wrought aluminum and 70 kg. of magnesium; this represented 22.2% of the total material for the lightweight Silverado model. There was negligible use of these materials on the baseline vehicle, i.e., essentially 0% of these materials were used in the baseline vehicle. Additionally, the use of steel, iron and high strength steel (H.S. Steel) dropped from 66.5% to 36.1%. Figure 25. shows this revised material usage.

[25] https://nepis.epa.gov/Exe/ZyPDF.cgi/P100MS0E.PDF?Dockey=P100MS0E.PDF

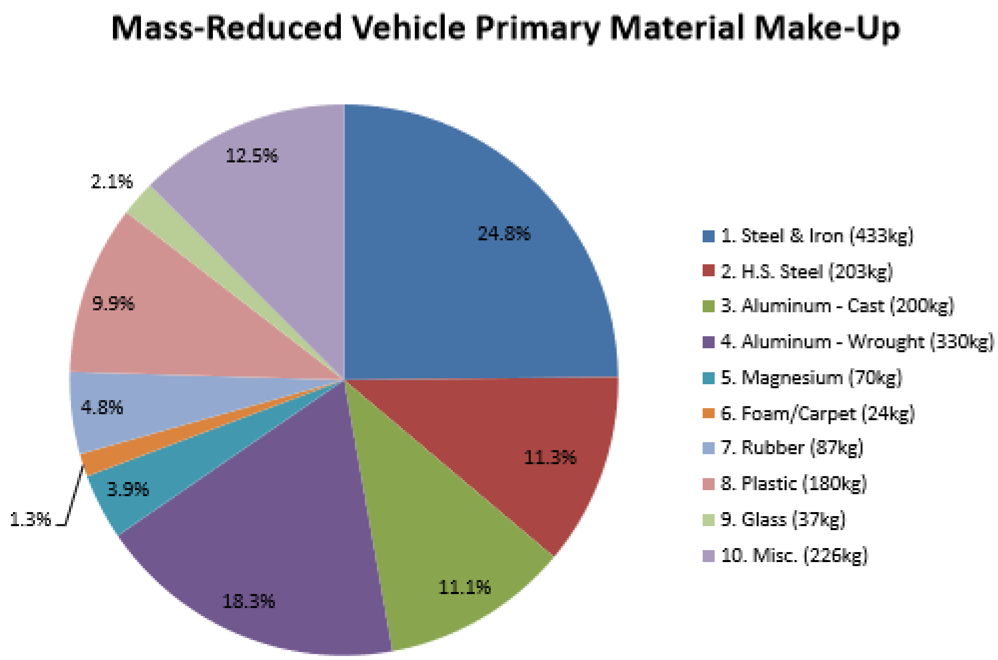


Figure 25. Materials Used for 2011 Lightweight Silverado Study

The lightweight materials were used in the body, cargo box, frame and closures. This makeup is shown in the excerpt below published in the lightweight study.

4.18.5.1 Optimized Body and Frame Mass reduction Overview

The outcome of the lightweight design optimization included the optimized frame, cabin, cargo box, bumpers, and closures and incorporated the following:

- Optimized gauge and material grades.
- Frame - Utilizing HSS/AHSS and aluminum materials
- Cabin - Utilizing HSS/AHSS and aluminum materials
- Cargo box - Utilizing aluminum materials
- TRBs on frame rails - mid and rear rails (inner and outer)
- Aluminum fender, radiator structure and IP cross-member assemblies
- Aluminum front and rear bumpers
- Doors - Utilizing HSS/AHSS and aluminum materials
- Aluminum hood
- Tailgate - Utilizing HSS/AHSS and aluminum materials

o

Figure 26. lists the tests run to verify the vehicle crash test performance. The numbers on the right reference the report sections.

Crash/Safety	Full Vehicle	FMVSS 208 - 35 MPH Flat Frontal Crash (UN NCAP)	Pulse Crush Time-To-Zero Velocity Dash Intrusion	9
		IIHS - 40 mph ODB Frontal Crash	Pulse Crush Time-To-Zero Velocity Dash Intrusion	10
		FMVSS 214 - 38.5 MPH MDB Side Impact (US SINCAP)	B-Pillar Velocity Side Structures Intrusion	11
		IIHS - 31 MPH MDB Side Impact	B-Pillar Velocity B-Pillar Intrusions Survival Space Exterior Crush	12
		FMVSS 214 - 20 MPH, 5th Percentile Pole Side Impact	B-Pillar Velocity B-Pillar Intrusions Structures Intrusions	13
		FMVSS 301 - 50 MPH MDB Rear Impact	Under Structural Zone Deformation Door Operability Fuel Tank Damage	14
		FMVSS 261a - Roof Crush	Roof Strength to Weight Ratio	15
		FMVSS 581 - Bumper Impact	Front End Deformation	16

Figure 26. Crash Tests Modeled in the Lightweight Silverado Study

Section 4.18.3 of this report, Baseline Crash Results, reviews the correlation process used to establish the baseline performance results for the 2011 Silverado. This study correlated baseline crash results using FMVSS 208 flat frontal, FMVSS 214 MDB side impact and FMVSS Pole side impact load cases. This model was then used to establish the baseline crash results for MVSS 301 and IIHS front ODB, side MDB and Roof-Crush evaluations. Pages 823 to 847 detail this development.

The lightweight aluminum intensive model performance was evaluated vs. the steel baseline model; the results are listed below:

- MVSS 208 – 35 MPH Frontal Fixed Barrier: "Similar characteristics in structural deformation" (p. 878);
- IIHS – 40 MPH ODB Frontal Crash: "Similar characteristics in structural deformation" (p. 883);
- FMVSS 214 – 38.5 MPH MDB side impact: "Similar deformation" (p. 888);
- IIHS – 31 mph MDB Side Impact: "Similar deformation shapes but different magnitude levels for intrusions" (p. 892);
- FMVSS 214 – 20 MPH 5th Percentile Pole Side Impact: "Similar deformation" (p. 897);
- FMVSS 301 – 50 MPH MDB Rear Impact: "Rear structure protect(ed) the fuel system well" (p. 902);
- Roof Crush Resistance: "… has the same level of roof crush resistance performance as the baseline model" (p. 907).

Based on these peer reviewed results, the crash performance of the lightweight Silverado was considered comparable to the significantly heavier baseline steel model.

To put these weight and cost estimates in perspective, the new lighter weight 2019 Silverado 1500, which retains steel as its primary material, is over 200 lbs. lighter than the 2018 base Silverado 1500 and almost 500 lbs. lighter than a premium 2018 model. Figure 27. shows the weight reductions achieved by the 2019 Silverado models vs. their 2018 equivalents. The 2019 Silverado weight savings is roughly half that of the aluminum intensive 2011 Lightweight Silverado but is much more cost effective with lower prices on some 2019 variants vs. the same 2018 models. Appendix C contains the specifications and cost information for the individual Silverado models and years.

Year	Model		Base MSRP	Curb Weight - lbs.	Weight Delta	Overall Length - inches	Specific Density (lbs./length)	% Weight Change	$/lb.	% Change In $/lb.
	Green = Major Redesign							2019 vs. 2018		
2018	Silverado 4x2 Work Truck 2dr Regular Cab 6.5 ft. SB	Base	$28,700	4696		224.4	20.93		$6.11	
2018	Silverado 4x4 LT 4dr Crew Cab 5.8 ft. SB	2011 Study	$43,300	5300		230.0	23.04		$8.17	
2018	Silverado 4x4 LTZ 4dr Crew Cab 6.5 ft. SB	Premium	$48,200	5461		239.6	22.79		$8.83	
2019	Silverado 4x2 Work Truck 2dr Regular Cab 8 ft. SB	Base	$28,300	4474	-222	229.5	19.49	-4.7%	$6.33	3.5%
2019	Silverado 4x4 LT 4dr Crew Cab 5.8 ft. SB	2011 Study	$42,600	4915	-414	231.7	21.21	-7.8%	$8.67	6.1%
2019	Silverado 4x4 LTZ High Country 4dr Crew Cab 6.6 ft. SB	Premium	$56,600	4965	-496	229.5	21.63	-9.1%	$11.40	29.2%
Data Source:	vehiclehistory.com									

Figure 27. Reduced Weight Production 2019 Silverado 1500 Models vs. 2018 Silverado 1500 Equivalents

VI. Lightweight Vehicles: Analysis and Results

This section includes two lightweight production vehicles, a full size pick-up truck and a battery electric vehicle. These vehicles underwent modeling processes similar to the government funded studies to validate their compliance with MVSS requirements prior to being released into production. As an additional step, the production models were built and crash tested to verify the safety of the actual vehicle and the accuracy of the CAD models.

a. Battery Electric Vehicle (BEV) Review

BEVs use lightweight construction to reduce weight to increase range and/or to reduce the battery pack capacity, size and cost. This is an important market segment that is growing exponentially; many industry forecasters, including Forbes[26] and Morgan Stanley[27], are forecasting worldwide BEV sales of 125 to 130 million vehicles by 2030.

A 10% weight reduction reduces the energy requirement by 6% to 7% which reduces the battery pack size, weight and cost. This number has been widely verified by the automotive industry and is the key reason that lightweighting is used to improve fuel economy and reduce CO_2 emissions.

A 30% weight reduction can reduce the battery pack size by approximately 20% or 20 KWh for a 100 KWh battery pack. Conversely, reducing vehicle weight by 30% can increase range by about 20% with

[26] https://www.forbes.com/sites/neilwinton/2017/05/22/electric-car-price-parity-expected-next-year-report/#617759367922

[27] https://insideevs.com/morgan-stanley-evs-price-parity-ice-2025

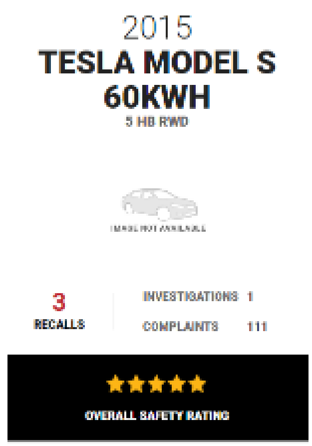
the same battery capacity, e.g., a 30% mass reduced BEV that originally had a 400-mile range could travel about 480 miles without increasing the battery pack size.

The Tesla Model S utilizes an aluminum body and chassis, a titanium underbody and boron steel reinforcements to reduce weight[28]. NHTSA evaluated a 2015 Tesla Model S with a 60 KWh battery pack. The NHTSA overall safety rating for this vehicle is five stars, the highest NHTSA rating. The Frontal Crash, Side Crash and Rollover ratings are all five stars.[29]

Model S Frontal Crash

Model S Side Barrier

Model S Side Pole



NHTSA Model S Safety Rating

b. 2015 Ford Aluminum Intensive F-150

The lightweight F-150, introduced in late 2014, incorporates a high percentage of aluminum in the cab and bed and reduced the F-150 weight by as much as 700+ lbs.[30], depending on the model, compared to Ford's 2014 steel intensive F-150. The lightest 2014 F-150 weighed 4,685 lbs.[31]; the lightest 2015 F-150 weighed 4,050 lbs., a savings of 635 lbs., a 13% reduction. It achieved the highest possible safety ratings

[28] http://www.visualcapitalist.com/extraordinary-raw-materials-in-a-tesla-model-s/
[29] https://www.nhtsa.gov/vehicle/2015/TESLA/MODEL%252520S%25252060KWH/5%252520HB/RWD#safety-ratings-frontal
[30] https://media.ford.com/content/dam/fordmedia/North%20America/US/2014_Specs/2014_F150_Specs.pdf
[31] https://www.nhtsa.gov/vehicle/2015/FORD/F150%20PICKUP

from both NHTSA (5 Star) and the IIHS (Good)[32]. The 2014 F-150 truck was rated at four stars by NHTSA and received a “Good” rating from IIHS[33].

The 2015 Ford F-150 is 471 lbs. lighter than the lightest 2015 Chevrolet Silverado model, the 2WD LS Regular Cab 6.5 Short Bed, which weighs 4,521 lbs. This is a 10% weight reduction vs. a model which was new for the 2014 model year[34].

The aluminum 2015 F-150 was rated higher than all steel bodied competitors by the IIHS: “(the) aluminum F-150 is the only pickup truck to earn a Top Safety Pick rating from the Insurance Institute for Highway Safety, outperforming trucks from Chevrolet , GMC, Toyota and Ram on an important new crash test.”[34]

Figure 28. below shows the FMVSS 208 performance for the 2015 Ford F-150 as tested by NHTSA. The F-150 occupant measurements were typically about 1/3 of the allowable threshold values. The crush distance is 24.7” (628 mm).

The impact velocity of the vehicle was 56.4 km/h and the ambient temperature at the barrier face at the time of impact was 20.8°C. The target vehicle post-test maximum crush was 628 located at the vehicle’s centerline. The test vehicle’s performance was as follows:

Measurement Description	Units	Driver ATD		Passenger ATD	
		Threshold	Result	Threshold	Result
Head Injury Criteria (HIC_{15})	N/A	700	189	700	121
Maximum Chest	mm	63	18	52	10
Nij	N/A	1	0.30	1	0.38
Neck Tension	N	4170	1339	2620	667
Neck Compression	N	4000	84	2520	17
Left Femur Force	N	10000	531	6800	2088
Right Femur Force	N	10000	537	6800	1037

Figure 28. 2015 Ford F-150 NHTSA FMVSS 208 Test Measurements

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[32] https://www.forbes.com/sites/joannmuller/2016/04/12/in-crash-tests-fords-aluminum-f-150-is-the-safest-pickup/#160b60222367
[33] https://cars.usnews.com/cars-trucks/ford/f-150/2014/safety
[34]https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2015&style_id=400888778

2015 Ford F-150 Front Fixed Barrier Crash Testing

An additional factor is fatigue/durability. The aluminum F-150 underwent > “10,000,000 miles of pounding” and was tested “longer and further” than Ford had ever done before[35].

Aluminum is significantly more expensive than steel; it is essential that it is economically integrated so that lighter weight vehicles remain cost competitive. Several approaches to analyzing the economic viability of the F-150 are included below.

The new aluminum 2015 F-150 base truck (4x2, XL, Regular Cab, 6.5’ Short Bed, the lowest cost model) was $305 less expensive than the carryover steel comparable base 2015 Silverado model, the 4x2 Work Truck, Regular Cab, 6.5’ Short Bed, the lowest cost Silverado 1500.[36,37] These prices, and additional information including curb weights, are shown in Appendix D. where the 2014 and 2015 F-150 and Silverado model pricing is listed for the above base models. The base F-150 price increase from 2014 to 2015 was $245 more than the price increase for the 2015 base Silverado[38,39] which was essentially a carryover design. This increase in MSRP (Manufacturer’s Suggested Retail Price) for an all new truck design is typically distributed over the new systems which typically include, but are not limited to, the body, powertrain, frame, suspension and interior.

Forbes estimates the cost for the aluminum body at $725 and the aluminum scrap value at $280 for a net cost of $445/body[28]. This weight savings created savings in other areas. Per Forbes: “Replacing the truck’s steel body panels with aluminum accounts for a little more than half the F-150’s 700-pound weight loss. Aluminum extrusions save an additional 50 pounds and a new high-strength steel frame saves 70 pounds. The rest comes from smaller engines and other lightweight components.” And “ …the switch to an aluminum body created a domino effect that freed Ford to make other once-unthinkable changes to the F-150, like a tiny-but-surprisingly powerful 2.7-liter Ecoboost engine option, smaller

[35] http://www.assemblymag.com/articles/92728-assembling-fords-aluminum-wonder-truck

[36] https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=ford&model=f-150&year=2015&style_id=400888276

[37] https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2015&style_id=400888774

[38] https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=ford&model=f-150&year=2014&style_id=400885035

[39] https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2015&style_id=400888774

brakes and a lighter suspension, all of which were cheaper than previous versions and provided secondary weight benefits that further enhanced fuel economy."[40] This mass decompounding results in cost savings in other systems that can partially offset the cost of the more expensive aluminum body. The cost increase for the 2015 F-150 base model 4x2 XL Regular Cab 6.5' Short Bed F-150 was 3%; this figure is identical to the price increase for the 2015 base Silverado 1500 4x2 Work Truck Regular Cab 6.5' Short Bed. This is an indication that the more expensive materials used in the aluminum intensive F-150 were substantially offset by savings in other areas.

The Lotus ARB study showed key areas where cost offsets were possible (Figures 10. And 11.). The Lotus study also predicted a 3.4% price increase that decreased to 1.44% after amortizing the new body assembly plant (Figure 12.).

Figure 29. (based on the above vehiclehistory.com references used for both Ford and Chevrolet truck specifications and prices) below compares the 2015 F-150 MSRP vs. the 2014 (steel) F-150 and the 2015 Chevrolet Silverado prices. This data shows the price increase for the F-150 was $245 for the significantly lighter aluminum intensive F-150, a relatively small difference. Despite this slightly higher increase for the F-150, the MSRP of the base model 2015 aluminum F-150 was $305 less expensive than the comparable base 2015 Silverado model.

Year	Model		Base MSRP	Cost Delta - $	2015 vs. 2014 $ Increase
2014	Ford F150 4x2, XL, Regular Cab Styleside, 6.5' Short Bed		$25,025		
2014	Chevrolet Silverado 1500 4x2 Work Truck, Regular Cab, 6.5' Short Bed		$25,575	$550	
2015	Ford F150 Regular Cab 6.5' Short Bed		$25,800		$775
2015	Chevrolet Silverado 1500 4x2 Work Truck, Regular Cab, 6.5' Short Bed		$26,105	$305	$530
2015	F150 vs. Silverado Net Cost Increase Delta				$245
Data Source:	vehiclehistory.com				

Figure 29. 2014/2015 Base Ford F150 and Base Chevrolet Silverado 1500 Annual Price Increases

Another method of analyzing cost is to calculate the cost per pound based on the vehicle MSRP and curb weight. Figure 30. shows the $/lb. for the 2015 F-150 is 10% more than the Silverado and 19% higher than the 2014 base F-150 (steel) model. These $/lb. premiums are an indication that the added cost for more expensive lightweight materials can be recovered without increasing the MSRP of the lighter vehicle to an uncompetitive level.

[40] https://www.forbes.com/sites/joannmuller/2014/11/10/inside-the-numbers-how-ford-wont-lose-its-shirt-building-the-pricey-new-aluminum-f-150-pickup/#3ec69d43f122

Year	Model		Base MSRP	Curb Weight	$/lb.
2014	Ford F150 4x2, XL, Regular Cab Styleside, 6.5' Short Bed		$25,025	4685	$5.34
2014	Chevrolet Silverado 1500 4x2 Work Truck, Regular Cab, 6.5' Short Bed		$25,575	4387	$5.83
2015	Ford F150 Regular Cab 6.5' Short Bed		$25,800	4050	$6.37
2015	Chevrolet Silverado 1500 4x2 Work Truck, Regular Cab, 6.5' Short Bed		$26,105	4521	$5.77
2015	F150 vs. Silverado $/lb.% Delta				110%
	2015 vs. 2014 F150 $/lb. % Increase				119%
Data Source:	vehiclehistory.com				

Figure 30. 2014/2015 Base Ford F150 and Base Chevrolet Silverado 1500 Cost Per Pound Analysis

The F-150 uses steel to provide increased strength in the front bulkhead: "The use of high-strength, military-grade aluminum alloy cut as much as 500 pounds from the cab and bed of the new truck. The only steel that remains is the laminated firewall"[41].

The F-150 frame remained steel but high strength steel utilization increased from 23% to 77% of the frame material.[42]

Towing capability is an important consideration for pick-up trucks. The maximum towing capacity of the lightweight 2015 F-150 is 12,100 lbs.[43] This is an 800 lb. increase over the steel intensive 2014 F-150 which is rated at 11,300 lbs.[44]

VII. Vehicle Size Impact On Weight Reduction and Cost

It is generally more difficult to reduce mass on a smaller vehicle than on a larger vehicle. The Lotus Phase 2 report Table 4.5.8.10.a (below) showed a significant difference between reducing weight on a small car vs. a large car. The report projects a 30% higher weight reduction potential for a large luxury car vs. a micro car.

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41 http://www.hendonpub.com/resources/article_archive/results/details?id=5791
42 https://media.ford.com/content/fordmedia/fna/us/en/news/2014/01/13/ford-uses-high-strength-steel-plus-high-strength--aluminum-alloy.html
43 https://www.ford.com/resources/ford/general/pdf/towingguides/15RV&TT_Ford_F150_r1_Jan12.pdf
44 https://www.ford.com/resources/ford/general/pdf/towingguides/14FLRV&TT_F150_Sep11.pdf

Table 4.5.8.10.a: ***Projected total vehicle weight savings by vehicle class***

Averages:						
Density (lbs./ft3):		±	Specific Density (unitless):		±	Projected Weight Savings
Micro cars:	7.91	0.00	Micro cars:	1.40	0.00	28.01%
Mini Cars:	8.23	0.43	Mini Cars:	1.46	0.08	29.13%
Small Cars:	8.61	0.53	Small Cars:	1.52	0.09	30.48%
Midsize Cars:	9.19	0.24	Midsize Cars:	1.63	0.04	32.54%
Midsize Luxury Cars:	10.17	0.28	Midsize Luxury Cars:	1.80	0.05	36.02%
Large Cars:	9.75	0.38	Large Cars:	1.73	0.07	34.51%
Large Luxury Cars	10.25	0.46	Large Luxury Cars	1.81	0.08	36.29%
Small SUVs:	8.56	0.37	Small SUVs:	1.52	0.07	30.30%
Midsize SUVs:	9.10	0.42	Midsize SUVs:	1.61	0.07	32.23%
Midsize Luxury SUVs:	9.56	0.21	Midsize Luxury SUVs:	1.69	0.04	33.86%
Large BoF SUVs:	9.46	0.18	Large BoF SUVs:	1.67	0.03	33.49%
Large Unibody SUVs:	8.78	0.08	Large Unibody SUVs:	1.56	0.01	31.10%
Small BoF Pickups:	10.03	0.49	Small BoF Pickups:	1.78	0.08	35.53%
Small Uni Pickups:	10.37	0.00	Small Uni Pickups:	1.84	0.00	36.71%
Large Pickups:	9.29	0.35	Large Pickups:	1.64	0.06	32.88%
Minivans:	8.17	0.17	Minivans:	1.45	0.03	28.93%

It is also more difficult to incorporate traditionally higher priced, lightweight materials into inexpensive vehicles, e.g., sub-compact and compact cars which typically cost less than $20,000. For example, a 2018 Chevrolet Malibu L, a mid-size car, has an MSRP (Manufacturers Suggested Retail Price) of $21,680 and weighs 3,086 pounds; the cost per pound is $7.03. A 2018 Chevrolet Spark LS hatchback has an MSRP of $13,050 and weighs 2,246 pounds; the cost per pound is $5.81. The Malibu L material cost/pound is >1.2x the Spark LS cost per pound. A 2019 base Chevrolet Silverado 4x2 Work Truck 2 Dr. Regular Cab 8' Long Bed has an MSRP of $28,300 and weighs 4,474 pounds; the cost per pound is $6.33. At the other end of the Silverado price spectrum, the LTZ High Country 4x4 Crew Cab 6.6' Box 157" WB, has an MSRP of $56,600 and weighs 4,965 lbs.; the cost per pound is $11.40. This is 80% higher than the base Silverado model and nearly double the cost per pound of the Chevrolet Spark LS. These cost differentials allow higher priced vehicles to use more expensive materials such as UHSS, aluminum and magnesium and still maintain a competitive MSRP.

The following calculations illustrate this point:

Low Cost Vehicle: Chevrolet Spark LS

Cost of weight reduction per lb.: $2.00 (See Appendix E for background for this number); remove 200 lbs. from a Spark LS: 200 lbs. x $2.00 lb. = $400. % of MSRP: 3.1% ($400/$13,050).

Premium Priced Vehicle: Chevrolet Silverado LTZ High Country 4x4 Crew Cab 6.6' Box

Cost of weight reduction per lb.: $2.00; remove 200 lbs. from a Silverado LTZ: 200 lbs. x $2.00 lb. = $400. % of MSRP: 0.7% ($400/$56,600).

The cost to reduce weight on the low-priced vehicle is 4.4 times more expensive, at an MSRP level, than it is to remove the same weight from the premium priced vehicle.

The Aluminum Association tabulated recent lightweighting efforts by the automotive industry and found that there were no weight reductions in small cars, defined as vehicles with a footprint less than 41 ft^2. Figure 31. shows the results of this study. This lack of lightweighting is a possible indication that reducing weight on small vehicles, roughly 3% of the U.S. passenger car market, may not be economically feasible.

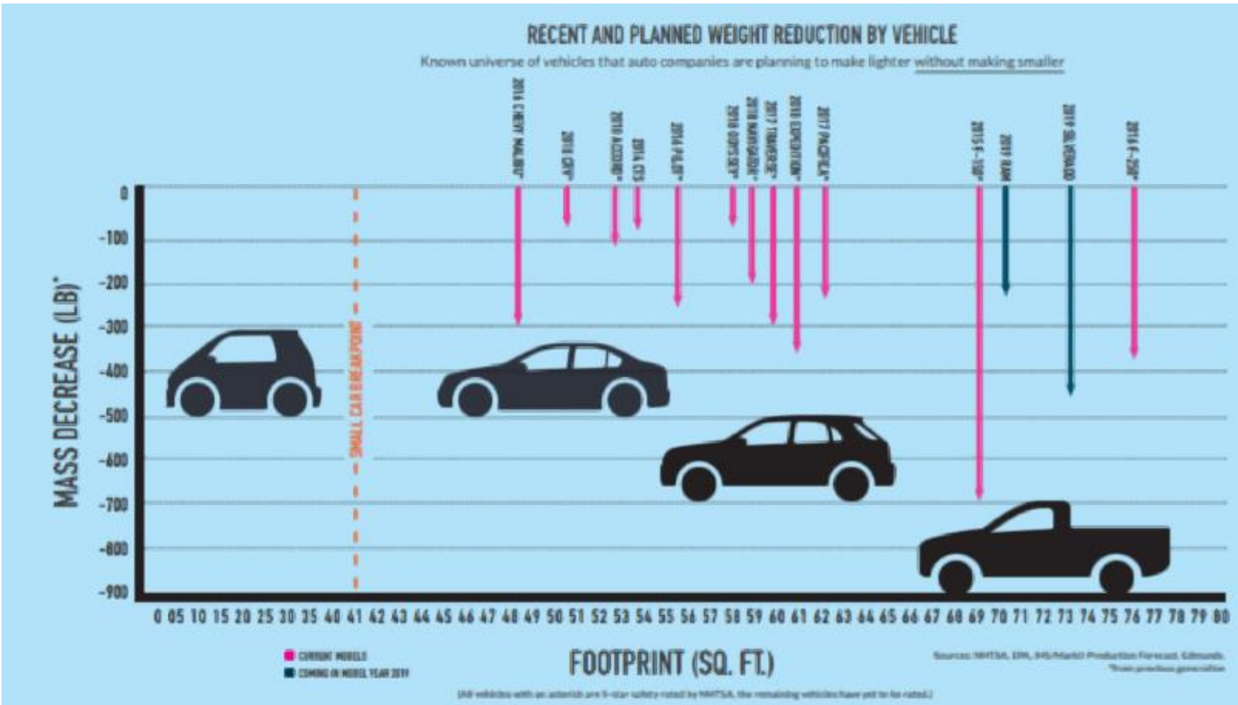

Figure 31. Vehicle Size vs. Weight Reduction[45]

VIII. Conclusions

The physics of a vehicle crash are material agnostic; a properly designed structure minimizes the vehicle acceleration levels independent of the type of material. The key design parameters are: 1. Maximize crush distance; and 2. Minimize the effective spring rate of the crushable elements. Crush distances are a function of vehicle styling, geometry and powertrain layout. The effective spring rate is tunable for both ferrous and non-ferrous materials. A well-engineered crush structure can incorporate a wide variety of materials, including ferrous and non-ferrous metals, and meet or exceed all safety parameters, including high speed front and rear impact requirements.

Additionally, the crash characteristics of a lightweight vehicle are compatible with existing ancillary safety equipment. Supplemental restraint systems and sensors are tunable to match the crash pulse of lighter weight vehicles. The 2009-10 Lotus lightweight Phase 2 CUV study predicted this and current production, fully safety compliant, lighter weight vehicles have verified that prediction. These systems continue to improve and will further enhance the safety of future, lighter weight vehicles.

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[45] https://www.drivealuminum.org/news-releases/automotive-aluminum-industry-statement-on-todays-epa-determination-on-emissions-regs/

Lightweight production vehicles such as the 2015-2018 Ford F150, the 2017 F-250 Super Duty, Jaguar and Audi sedans and Range Rover SUVs incorporate aluminum intensive body structures that meet or exceed U.S. safety regulations and are significantly lighter than their steel intensive predecessor's. These lessons learned can be applied to electrified vehicles to improve their range and to reduce battery size and cost.

The cost impact of typically more expensive, lighter weight materials, including high performance steels, is an essential consideration. The Lotus CUV study and the EDAG mid-size passenger car study both predicted near cost parity as a result of using less material, part consolidation, reduced tooling costs, lower joining costs and reduced assembly time. The F-150 aluminum intensive truck is cost competitive with GM and FCA models and is the best-selling vehicle in the U.S.[46] and is the highest volume aluminum intensive vehicle produced today at an estimated > 500,000 units in 2017. Additionally, the 2017 aluminum intensive F-150 sold approximately 100,000 units more than the last steel body F-150, the 2014 model.[47]

Reduced weight production vehicles using current high strength materials, including aluminum and AHSS, have achieved the highest safety ratings from both NHTSA and IIHS. These lighter weight vehicles perform as well as heavier vehicles, and in some cases, better than vehicles that weigh as much as seven hundred pounds more, in low speed and high speed crashes.

The wide variety of vehicle classes investigated in this paper and their superior performance in NHTSA and IIHS tests demonstrate that a lighter weight vehicle, given the same overall length, can be engineered to be just as safe in FMVSS impact tests as a significantly heavier vehicle. Peer reviewed simulation studies demonstrate that lighter vehicles using high performance ferrous and non-ferrous materials perform as well in impacts as their similar size, heavier counterparts. These simulations predicted weight savings of approximately 700 lbs. to over 1,100 lbs. with safety performance comparable to their heavier baseline counterparts. A production truck that is over 700 lbs. lighter than the previous generation achieved the highest possible safety ratings from both NHTSA and IIHS.

This overview clearly indicates that properly engineered light weight vehicles can be as safe as their heavier counterparts in crash situations. Additionally, this report documents that a lighter weight total vehicle population can contribute to less severe vehicle crashes.

Lighter weight vehicles provide improved operational efficiency and, typically, better dynamic response including handling, braking and steering when compared to their equivalent sized, heavier counterparts. Improved vehicle control can contribute to avoiding an accident or minimizing the damage in a crash. These characteristics are a desirable result of reducing vehicle weight and are useful to every driver.

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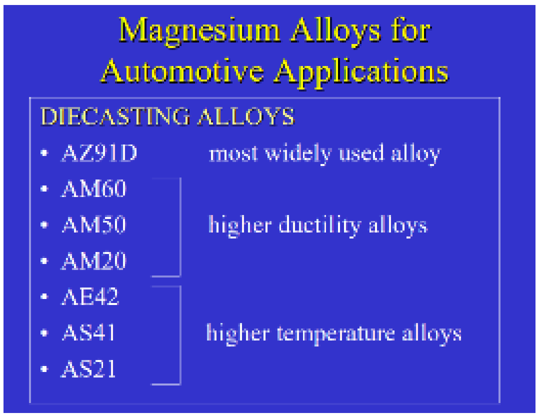
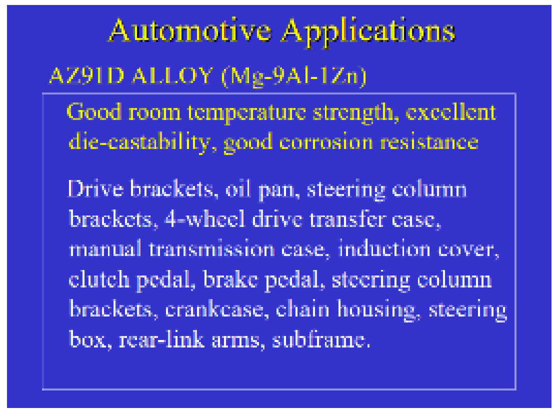
[46] https://www.businessinsider.com/best-selling-cars-and-trucks-in-america-in-2018-2018-8
[47] https://www.torquenews.com/106/aluminum-ford-f150-outselling-steel-trucks-massive-margin

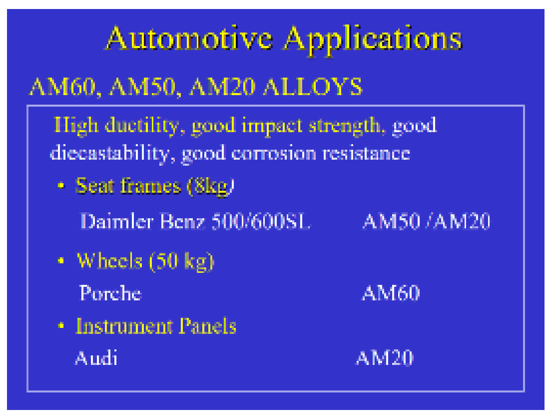
Appendix

Appendix A.

Magnesium Alloys and Automotive Applications[48]







48 https://www.tms.org/Communities/FTAttachments/Mg%20Alloys%20for%20Automotive.pdf

Appendix B

2011 Lightweight Silverado Mass Reduction Summary

Executive Table 2: Mass Reduction and Net Incremental Direct Manufacturing Cost (NIDMC) Impact for Each Vehicle System Evaluated

			Mass Reduction Impact by Vehicle System (Includes Secondary Mass Savings)						
Item	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 "%"
1500 Series Chevrolet Silverado Pick-Up Truck									
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	-1194.86	-5.77	-5.77	36.0%	8.4%
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%	4.3%
8	05	Driveline System	183.8	20.4	38.01	1.86	1.89	11.1%	0.8%
9	06	Brake System	101.0	45.8	-148.92	-3.25	-3.35	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	-147.48	-17.44	-17.45	26.0%	0.3%
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%	0.3%
20	00	Fluids and Miscellaneous Coating Materials	116.8	0.0	0.00	0.00	0.00	0.0%	0.0%
		a. Analysis Totals Without NVH Counter Measures →	**2454.4**	**560.9**	**-2073.82**	**-3.70**	**-3.69**	**n/a**	**22.9%**
		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 →	**2454.4**	**510.9** (Decrease)	**-2223.82** (Increase)	**-4.35** (Increase)	**-4.35** (Increase)	**n/a**	**20.8%**

(1) Negative value (i.e., -X.XX) represents an increase in mass
(2) Negative value (i.e., -$X.XX) represents an increase in cost

Appendix C

Base Prices, Dimensions and Curb Weights for Chevrolet Silverado and Ford F-150 Trucks

1. **Chevrolet Silverado Trucks**

2011 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x2 LT 2dr Regular Cab 6.5 ft. SB

Original MSRP:

$26,810

Exterior Dimensions

WHEELBASE	119
OVERALL LENGTH	205.6
OVERALL HEIGHT	73.6
TRACK WIDTH, FRONT	68.1
TRACK WIDTH, REAR	67
MIN GROUND CLEARANCE	7.7
BASE CURB WEIGHT	4463
MAX TOWING CAPACITY	9100

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2011&style_id=400874475

2011 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x4 LS 4dr Crew Cab 5.8 ft. SB

Original MSRP:

$33,895

Exterior Dimensions

WHEELBASE	143.5
OVERALL LENGTH	230.2
OVERALL HEIGHT	73.7
TRACK WIDTH, FRONT	68.1
TRACK WIDTH, REAR	67
MIN GROUND CLEARANCE	9
BASE CURB WEIGHT	5329
MAX TOWING CAPACITY	5500

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2011&style_id=400874512

The base 2011 Silverado 1500 4x4 LS Crew Cab 5.8 ft. Short Bed was equipped with a 4.8L V-8 as indicated below. The Lightweight 2011 Silverado baseline vehicle was equipped with a 5.3L V8 which could have contributed to an increase in vehicle weight depending on the transmission and axles specified.

2011 Chevrolet Silverado 1500 Features: Mechanical Performance

2019 2017 2016 2015 2014

Select Trim

4x4 LS 4dr Crew Cab 5.8 ft. SB

Original MSRP:

$33,895

Mechanical

ENGINE	Vortec 4.8L Flex Fuel V8 302hp 305ft. lbs.
TRANSMISSION	4-Speed Automatic
DIFFERENTIAL	3.42
FRONT SUSPENSION	upper and lower control arms
REAR SUSPENSION	multi-leaf
FUEL CAPACITY	26

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-mechanical.php?make=chevrolet&model=silverado+1500&year=2011

2014 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x2 Work Truck 2dr Regular Cab

Original MSRP:

$25,575

Exterior Dimensions

WHEELBASE	119
OVERALL LENGTH	205.6
OVERALL HEIGHT	74
TRACK WIDTH, FRONT	68.8
TRACK WIDTH, REAR	67.6
MIN GROUND CLEARANCE	8.2
BASE CURB WEIGHT	4387
MAX TOWING CAPACITY	9300

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2014&style_id=400884519

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2014&style_id=400882614

2015 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x2 Work Truck 2dr Regular Cab

Original MSRP:

$26,105

Exterior Dimensions

WHEELBASE	119
OVERALL LENGTH	205.6
OVERALL HEIGHT	74
TRACK WIDTH, FRONT	68.8
TRACK WIDTH, REAR	67.6
MIN GROUND CLEARANCE	8.2
BASE CURB WEIGHT	4521
MAX TOWING CAPACITY	9000

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2015&style_id=400888774

2018 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x2 Work Truck 2dr Regular Cab

Original MSRP:

$28,700

Exterior Dimensions

WHEELBASE	133
OVERALL LENGTH	224.4
WIDTH, MAX W/O MIRRORS	80
OVERALL HEIGHT	73.5
TRACK WIDTH, FRONT	68.8
TRACK WIDTH, REAR	67.6
MIN GROUND CLEARANCE	8.3
BASE CURB WEIGHT	4696

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2018&style_id=400899232

2018 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x4 LT 4dr Crew Cab 5.8 ft. SB

Original MSRP:

$43,300

Exterior Dimensions

WHEELBASE	143.5
OVERALL LENGTH	230
WIDTH, MAX W/O MIRRORS	80
OVERALL HEIGHT	74
TRACK WIDTH, FRONT	68.7
TRACK WIDTH, REAR	67.6
MIN GROUND CLEARANCE	8.9
BASE CURB WEIGHT	5300

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2018&style_id=400899218

2018 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x4 LTZ 4dr Crew Cab 6.5 ft. SB

Original MSRP:

$48,200

Exterior Dimensions

WHEELBASE	153
OVERALL LENGTH	239.6
WIDTH, MAX W/O MIRRORS	80
OVERALL HEIGHT	73.8
TRACK WIDTH, FRONT	68.7
TRACK WIDTH, REAR	67.6
MIN GROUND CLEARANCE	8.9
BASE CURB WEIGHT	5461

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2018&style_id=400899228

2019 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x2 Work Truck 2dr Regular Cab

Original MSRP:

$28,300

Exterior Dimensions

WHEELBASE	139.5
OVERALL LENGTH	229.5
WIDTH, MAX W/O MIRRORS	81.2
OVERALL HEIGHT	75.6
MIN GROUND CLEARANCE	8.3
BASE CURB WEIGHT	4474
MAX TOWING CAPACITY	10100

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2019&style_id=400904227

2019 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x4 LT 4dr Crew Cab 5.8 ft. SB

Original MSRP:

$42,600

Exterior Dimensions

WHEELBASE	147.4
OVERALL LENGTH	231.7
WIDTH, MAX W/O MIRRORS	81.2
OVERALL HEIGHT	75.51
MIN GROUND CLEARANCE	8.1
BASE CURB WEIGHT	4915
MAX TOWING CAPACITY	11400

Equivalent vehicle to 2011 Silverado vehicle content study (study published a weight of 5410 lbs.)

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2019&style_id=400903523

2019 Chevrolet Silverado 1500 Specifications: Exterior

Select Trim

4x4 High Country 4dr Crew Cab (

Original MSRP:

$56,600

Exterior Dimensions

WHEELBASE	157
OVERALL LENGTH	241.21
WIDTH, MAX W/O MIRRORS	81.2
OVERALL HEIGHT	75.4
MIN GROUND CLEARANCE	8
BASE CURB WEIGHT	4965
MAX TOWING CAPACITY	12000

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=chevrolet&model=silverado-1500&year=2019&style_id=400904260

Appendix D

2. Ford F-150

2014 Ford F 150
Specifications: Exterior

2019 2017 2016 2015 2014

Select Trim

4x2 XL 2dr Regular Cab Styleside

Original MSRP:

$25,025

Exterior Dimensions

WHEELBASE	125.9
OVERALL LENGTH	213.2
WIDTH, MAX W/O MIRRORS	79.2
OVERALL HEIGHT	74.8
TRACK WIDTH, FRONT	67
TRACK WIDTH, REAR	67
MIN GROUND CLEARANCE	8.2
BASE CURB WEIGHT	4685
MAX TOWING CAPACITY	8300

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=ford&model=f-150&year=2014&style_id=400885035

2015 Ford F 150
Specifications: Exterior

2019 2017 2016 2015 2014

Select Trim

4x2 XL 2dr Regular Cab 6.5 ft. SI

Original MSRP:

$25,800

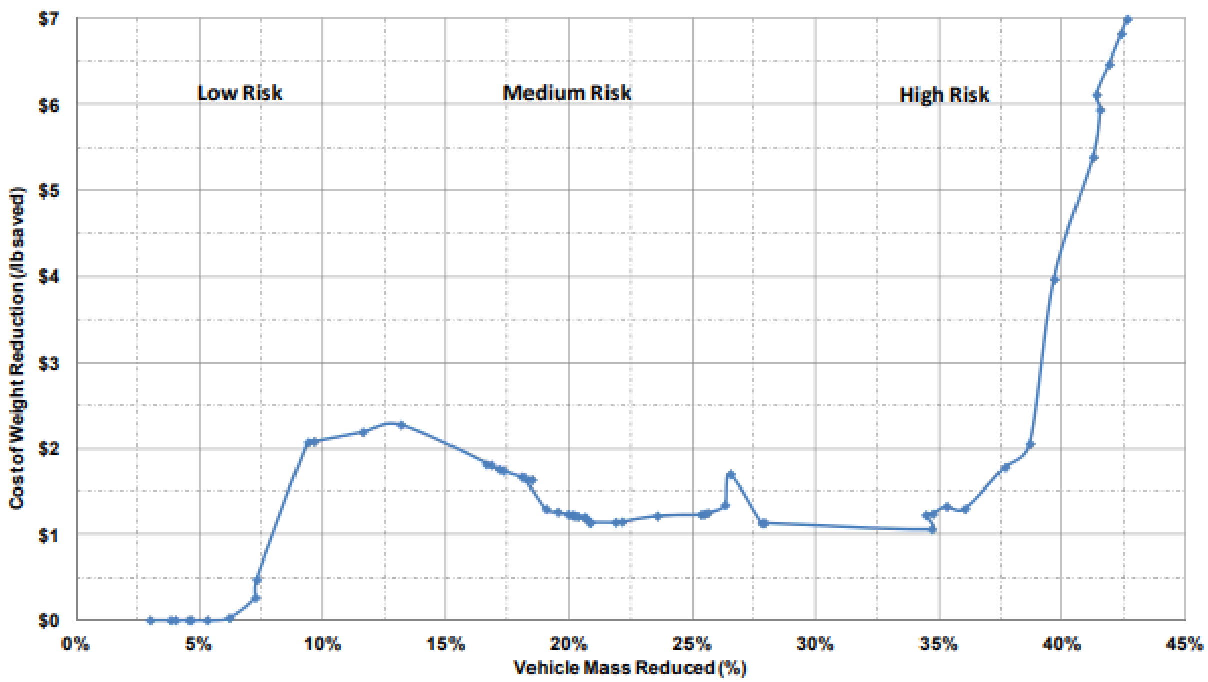
Exterior Dimensions

WHEELBASE	122.4
OVERALL LENGTH	209.3
WIDTH, MAX W/O MIRRORS	79.9
OVERALL HEIGHT	75.2
TRACK WIDTH, FRONT	67.6
TRACK WIDTH, REAR	67.6
MIN GROUND CLEARANCE	8.8
BASE CURB WEIGHT	4050
MAX TOWING CAPACITY	9200

https://www.vehiclehistory.com/reports/free-reviews-complaints-report/features-exterior.php?make=ford&model=f-150&year=2015&style_id=400888276

Appendix E

Source of the $2/lb. number used for the cost of reducing weight on a per pound basis[49].



[49] https://www.osti.gov/servlets/purl/1363637