ALCOA

The Future of Aluminum Use in the Auto Industry

October 31, 2013

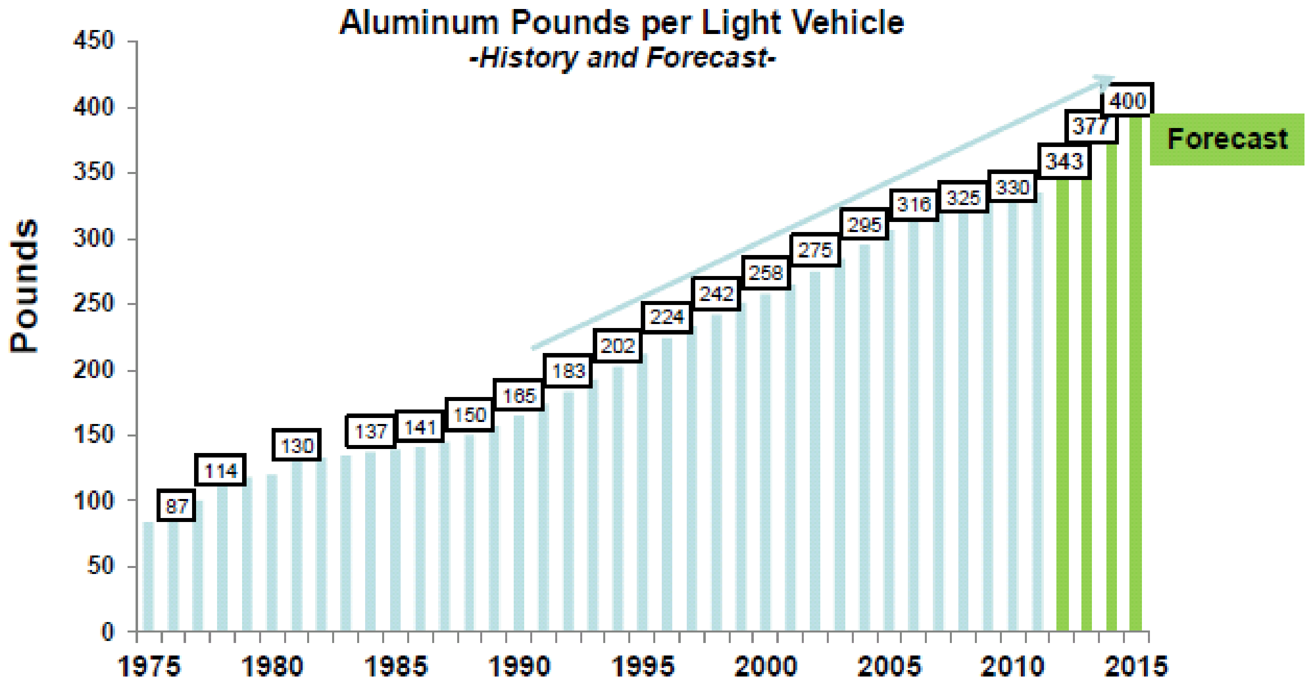
Agenda

- Aluminum is used in most cars and trucks (where and what extent)
- Fuel economy legislation (NA and Global)
- Technologies available to reach fuel economy improvements
- Design Changes from Steel to Aluminum
- Possible directions for aluminum implementation
- Impact of aluminum use
- Conclusions
- Questions

IMPACT OF MANDATES ON 2015/2016 ALUMINUM CONTENT

DUCKER WORLDWIDE
ducker.com

After a short period of slow growth, North American light vehicle aluminum content growth will take a large step back toward the long term trend line in 2012, and march to 400 pounds per vehicle by 2015/2016



Source: Ducker

Universal Aluminum Use (or at least very common)

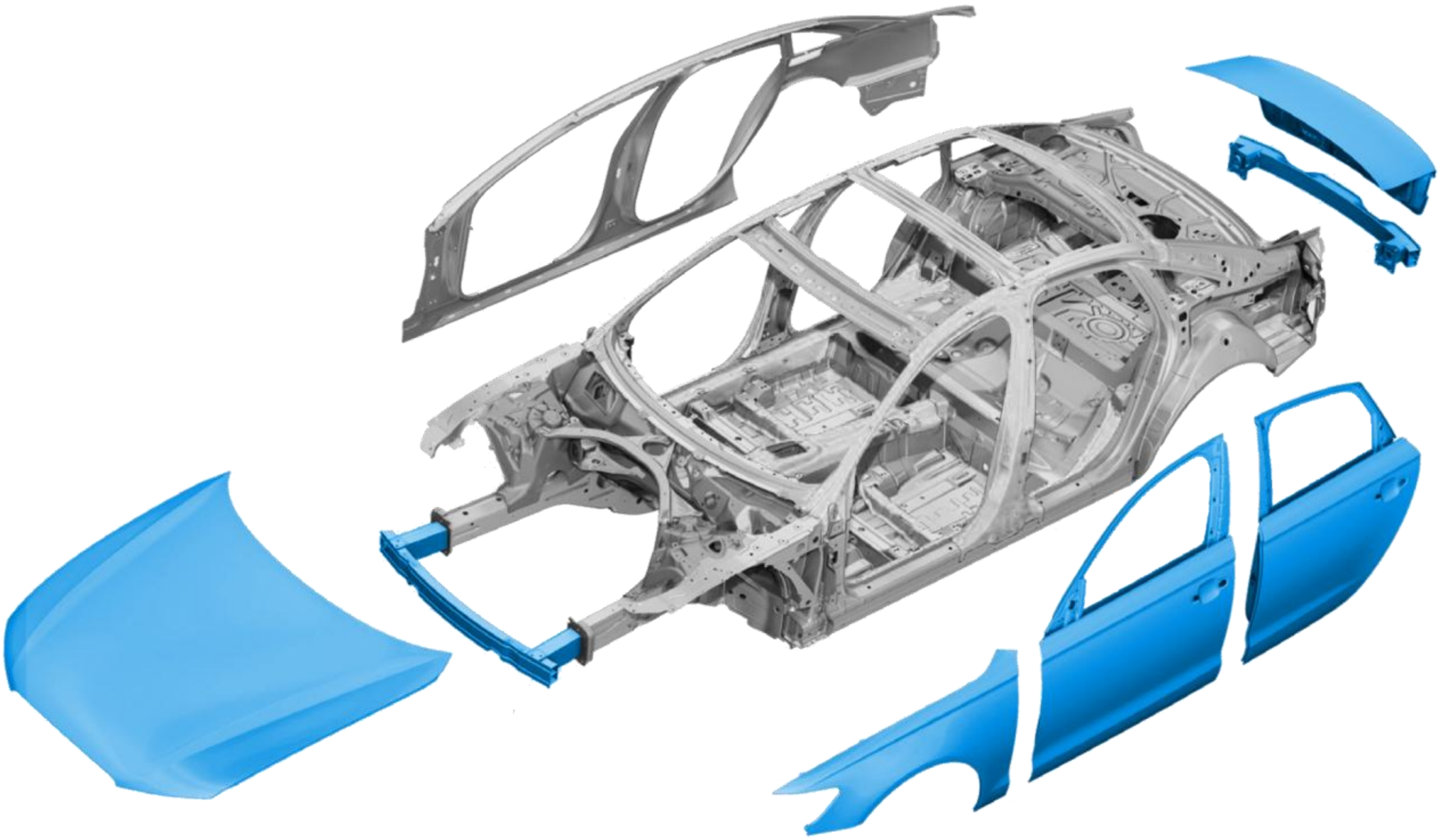
Heat Exchangers

Engines

Transmissions

Wheels

Closures and Body in White (BIW)

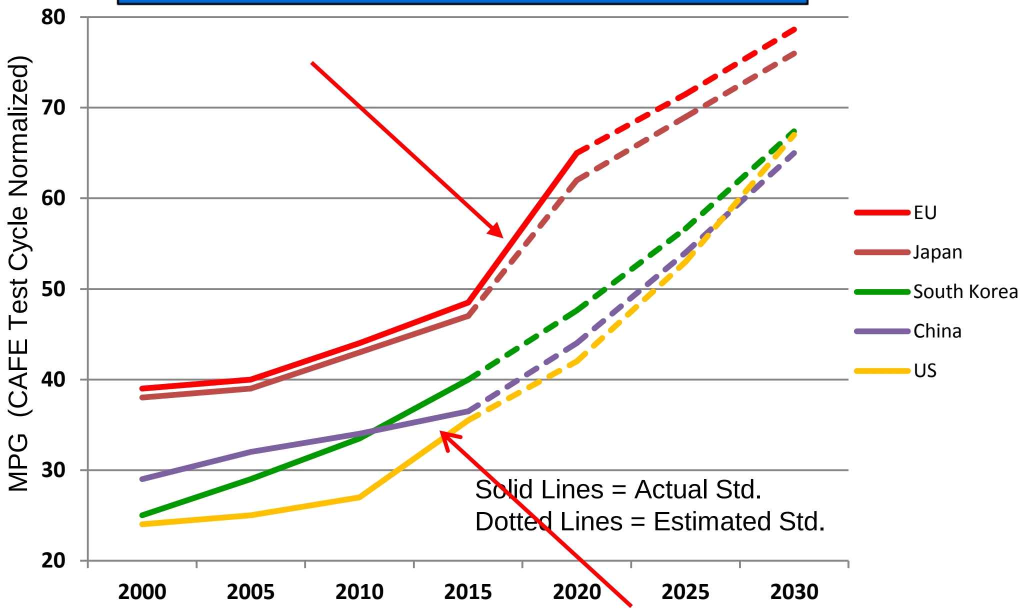


Fuel Economy Legislation

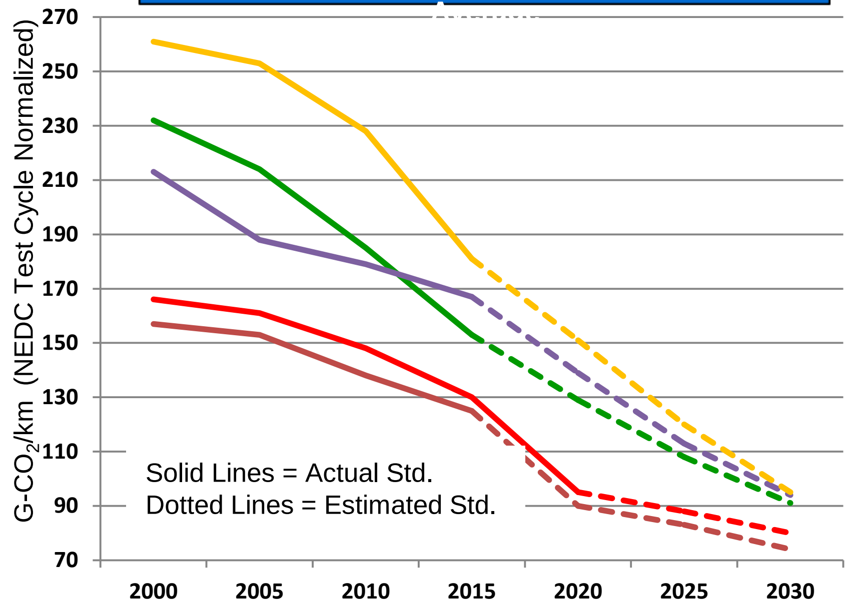
Fuel Economy Regulations

Regulations only get tougher moving forward

Passenger Vehicle Fuel Economy Fleet Average



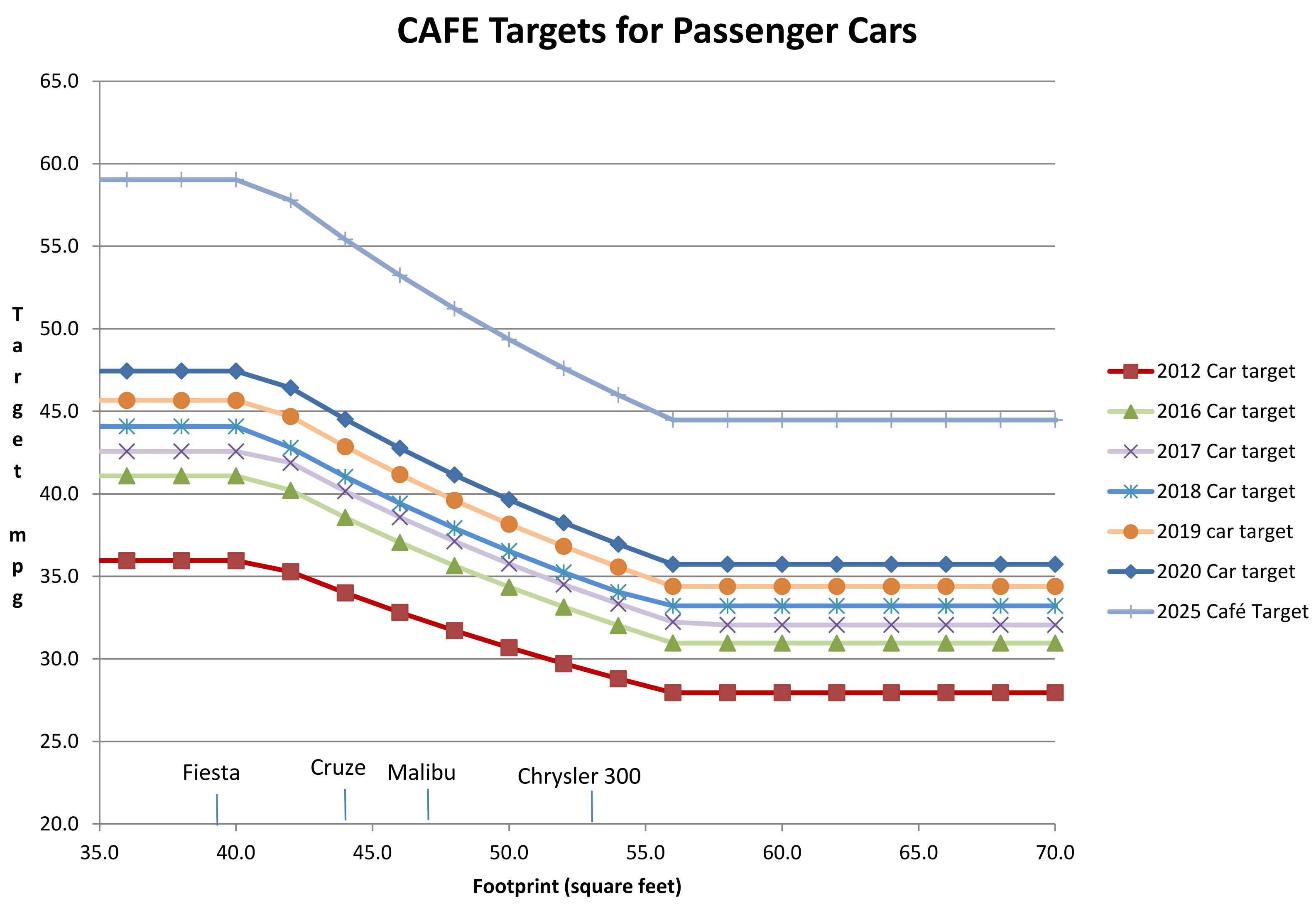
Passenger Vehicle GHG Emissions Fleet



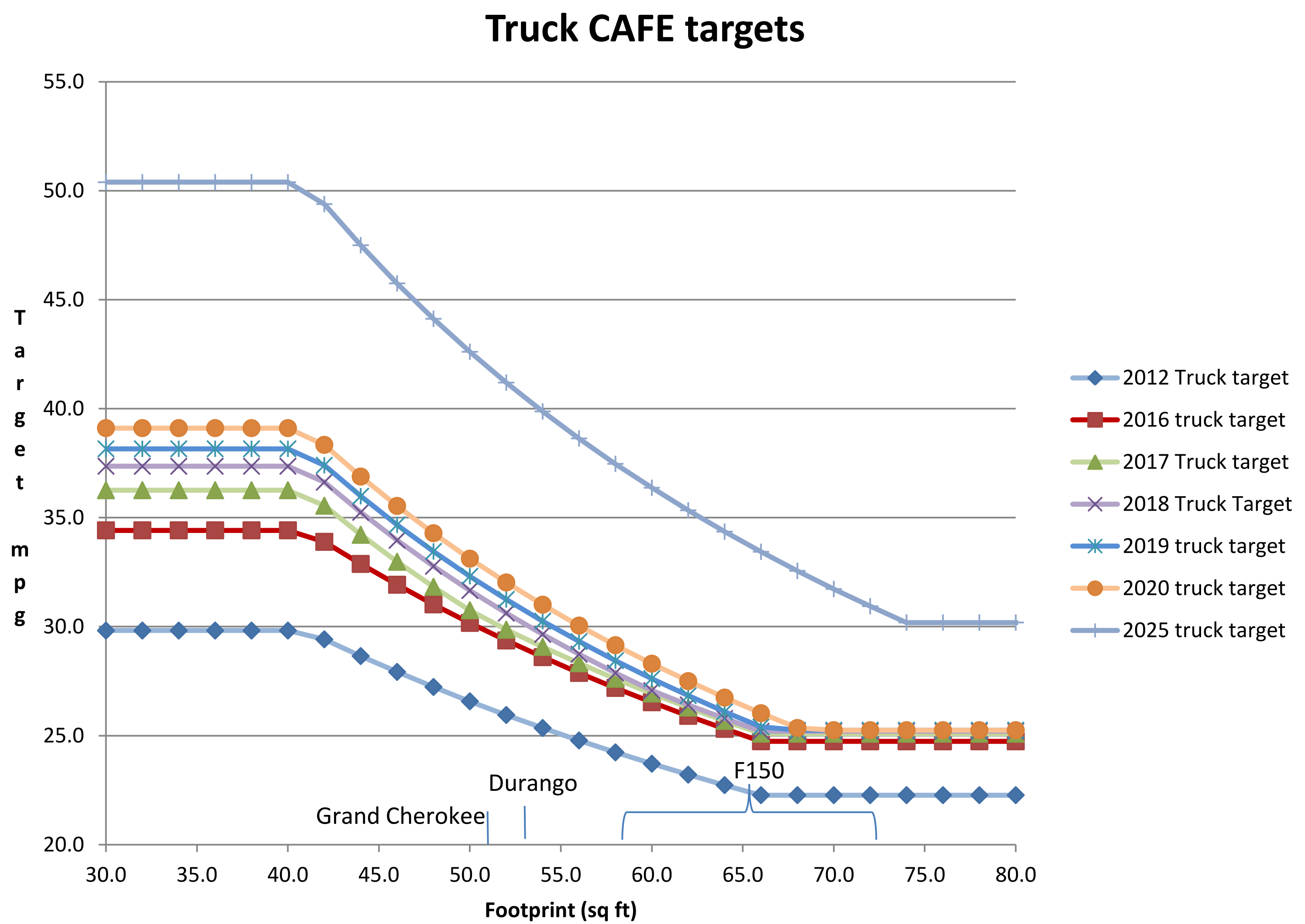
Conversion factor between fuel economy and CO_2 emissions:

- 8887 g CO_2 per gallon of gasoline
- 10180 g CO_2 per gallon of diesel

US Corporate Average Fuel Economy (CAFE) standards are size based, so each vehicle has a fuel economy target based upon its wheelbase and track



CAFE standards for Trucks – also size based



CAFE Calculation

- Fleet fuel economy is calculated using a harmonic mean, not a simple arithmetic average. For a fleet composed of four different kinds of vehicle A, B, C and D, produced in numbers n_A, n_B, n_C and n_D, with fuel economies f_A, f_B, f_C and f_D, the CAFE would be:

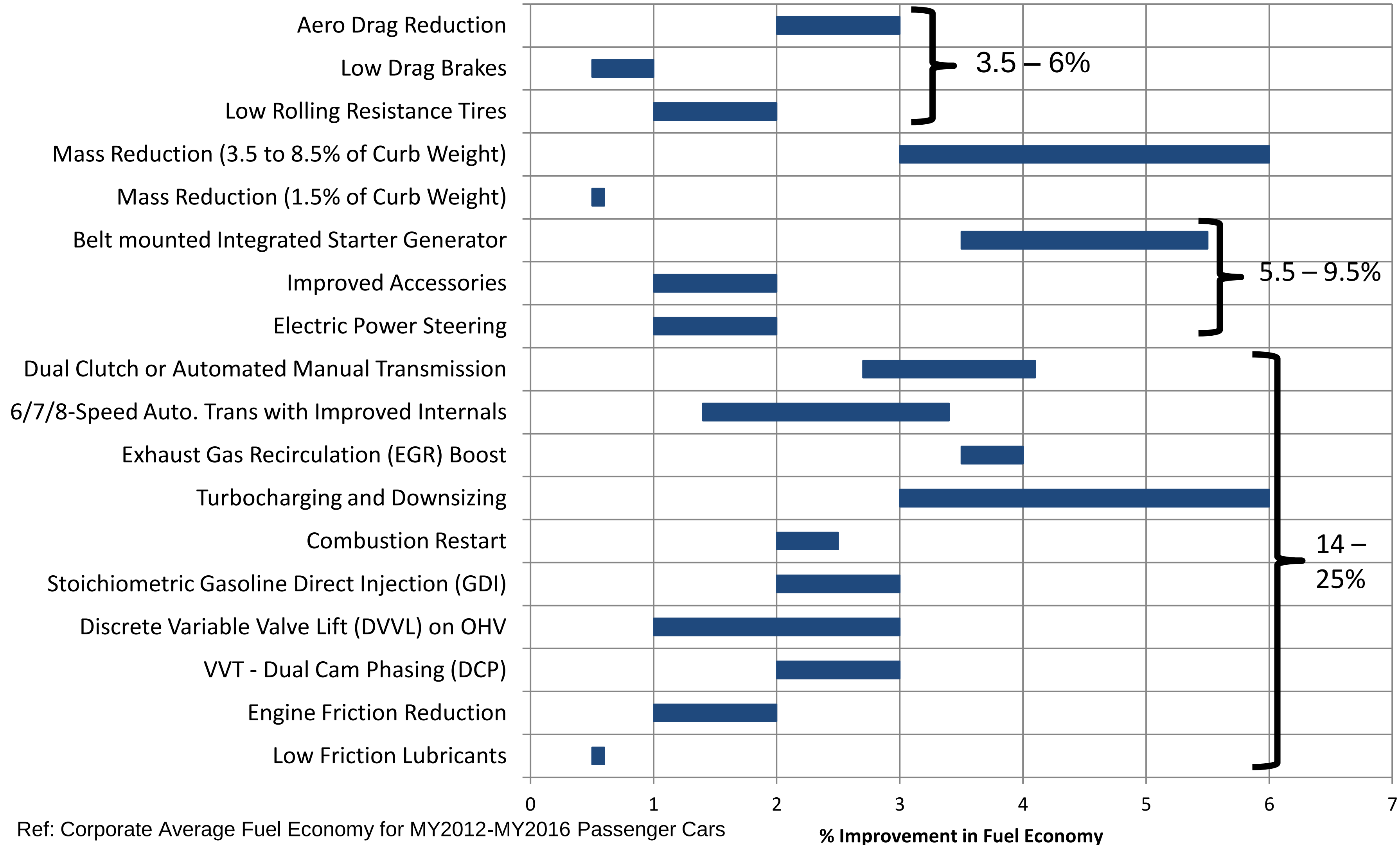
$$\frac{n_A + n_B + n_C + n_D}{\frac{n_A}{f_A} + \frac{n_B}{f_B} + \frac{n_C}{f_C} + \frac{n_D}{f_D}}$$

- For example, a fleet of 4 vehicles getting 15, 13, 17, and 100 mpg has a CAFE of slightly less than 19 mpg:

$$\frac{4}{\frac{1}{15} + \frac{1}{13} + \frac{1}{17} + \frac{1}{100}} = 18.83$$

- Penalty for missing CAFE requirement is $5.50 per each 1/10 of MPG missed.

Drivetrain Alone Cannot Provide the Fuel Savings Required by 2020

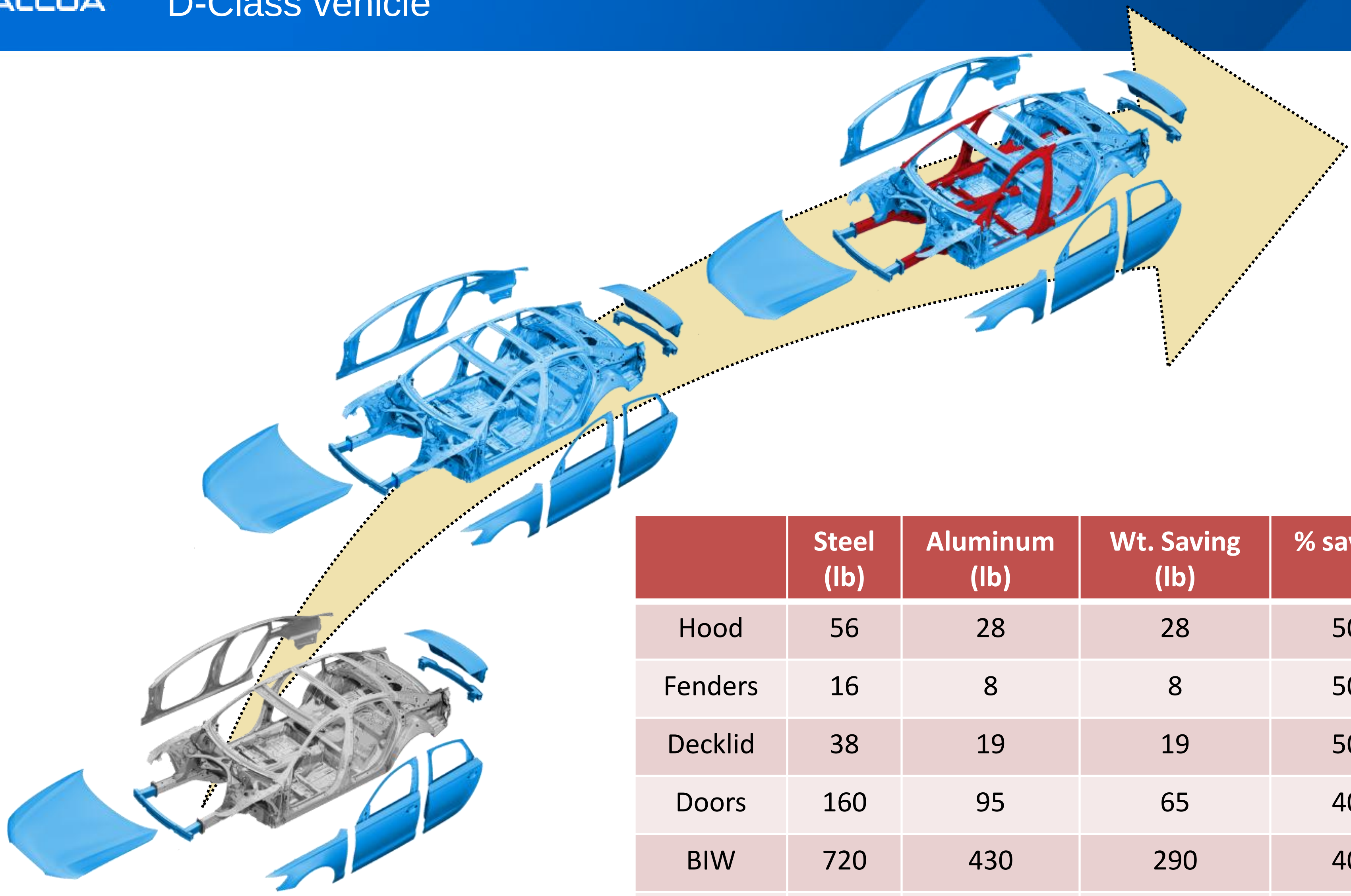


Ref: Corporate Average Fuel Economy for MY2012-MY2016 Passenger Cars and Light Trucks – Final Regulatory Impact Analysis, NHTSA, March 2010

Material Comparisons

	Steels	Aluminum alloys	Magnesium alloys	Polymers	Polymer Composites
Available product forms	Sheet, bar, single hollow tube, casting, forging	Sheet, bar, extrusions, casting, forging	casting	Sheet, molding, extruded shapes	Sheet, molding, pultruded shapes
Density (g/mm3) x10-2	0.72 to 0.80	0.26 to 0.27	0.19	0.11 to 0.22	0.17 to 0.19
Modulus (GPa)	207	69 to 73	45	0.89 to 3.3	3.4 to 34
Yield Strength (MPa)	172 to 900	68 to 590	206	41 to 90	97 to 145
Tensile Strength (MPa)	365 to 1200	310 to 620	310	55 to 1124	110 to 172
Elongation (mm/mm)%	10 to 33	6 to 20	15	NA	NA
Poisson's Ratio	0.3	0.33	NA	NA	NA
Thermal expansion (mm/mm/°C)	10.8 to 19.4	19.4 to 24.5	25	81 to 216	16.7 to 90
Thermal conductivity (W/(m.°K))	36 to 52	159 to 216	100	0.2 to 0.5	0.2 to 0.8
Corrosion resistance	Medium	High	Low	High	Low
Useable temp. range (°C)	315	150	120	120	150
Joining methods	Arc & spot welding, bonding, mechanical	Arc & spot welding, bonding, mechanical	Bonding, mechanical	Bonding, mechanical	Bonding, mechanical
Formability	Good	Fair to Good	-	Poor	Poor
Relative cost	Low	Medium	Medium	Low	Medium

Potential Weight Savings with Aluminum D-Class vehicle



	Steel (lb)	Aluminum (lb)	Wt. Saving (lb)	% saving
Hood	56	28	28	50
Fenders	16	8	8	50
Decklid	38	19	19	50
Doors	160	95	65	40
BIW	720	430	290	40
Total	990	580	410	41

Primary and Secondary Weight Savings

- Primary weight savings is the actual savings associated with changes to the Body and closures via material changes, design optimization and thickness reductions.
- In all cases, a primary weight savings leads to a secondary weight savings:
  - A lighter vehicle allows for smaller suspension components, brakes, engine, etc. with comparable performance of the base vehicle
  - Typically, 30% of the primary savings can be obtained as secondary savings in cars [1] .
  - In light trucks, 10-15% of the primary savings is achievable (because of towing and cargo requirements).
- At the specification stage, the weight target for the secondary systems must be reduced to reflect the primary weight savings.

- A 10% REDUCTION IN CURB WEIGHT RESULTS IN A 6 TO 7% FUEL ECONOMY IMPROVEMENT (INCLUDING ENGINE DOWNSIZING)

1. AZT reference

Design Changes from Steel to Aluminum

To Convert from Steel to Aluminum:

To Match Bending Stiffness:

$$E_{alum}\, I_{alum} = E_{steel}\, I_{steel}$$

Since Modulus of aluminum is 1/3 of steel

$$I_{alum} = 3\, I_{steel}$$

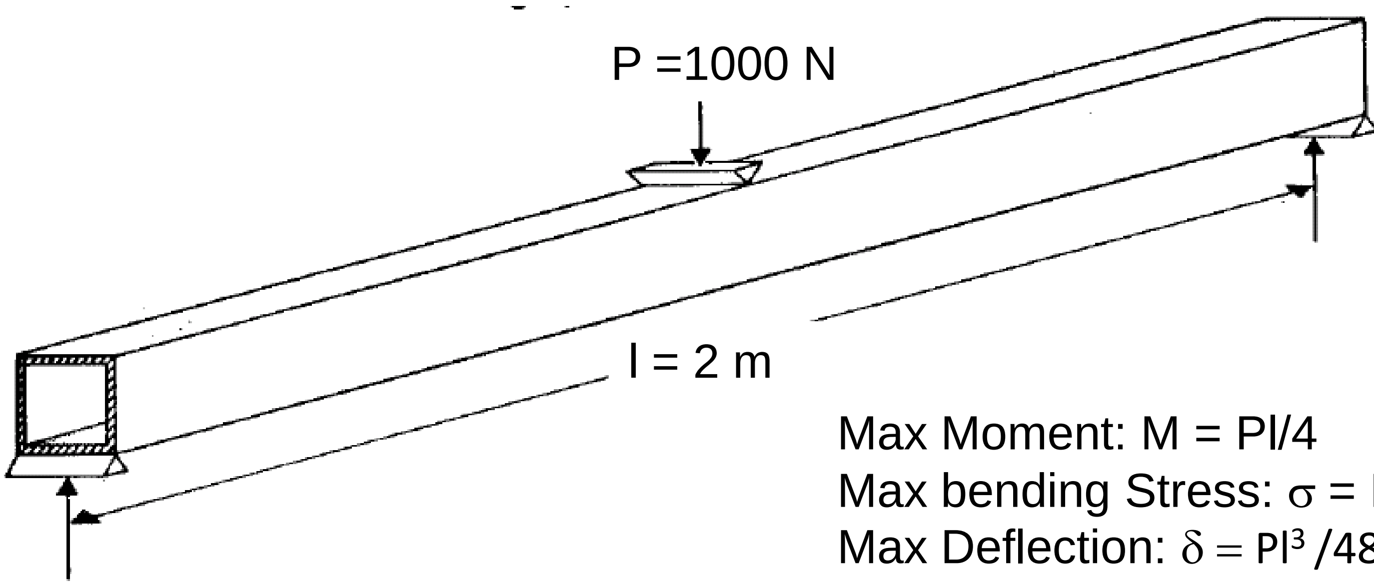
Normally, we target moment of inertia of aluminum parts at roughly 1.5 to 2 I_{steel}

To Match Bending Strength:

$$S_{alum}\, \sigma_{alum} = S_{steel}\, \sigma_{steel}$$

$$S_{alum} = S_{steel}\, (\sigma_{steel/}\, \sigma_{alum)}$$

Simple Example: Steel Box Beam Simply Supported

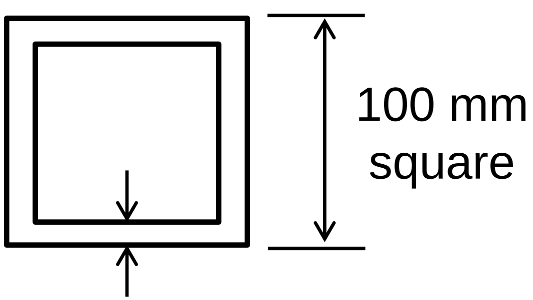


Max Moment: $M = Pl/4$

Max bending Stress: $\sigma = M/S$

Max Deflection: $\delta = Pl^3/48\,EI$

Mild Steel with 250 MPa yield



$I = 2363392\ mm^4$

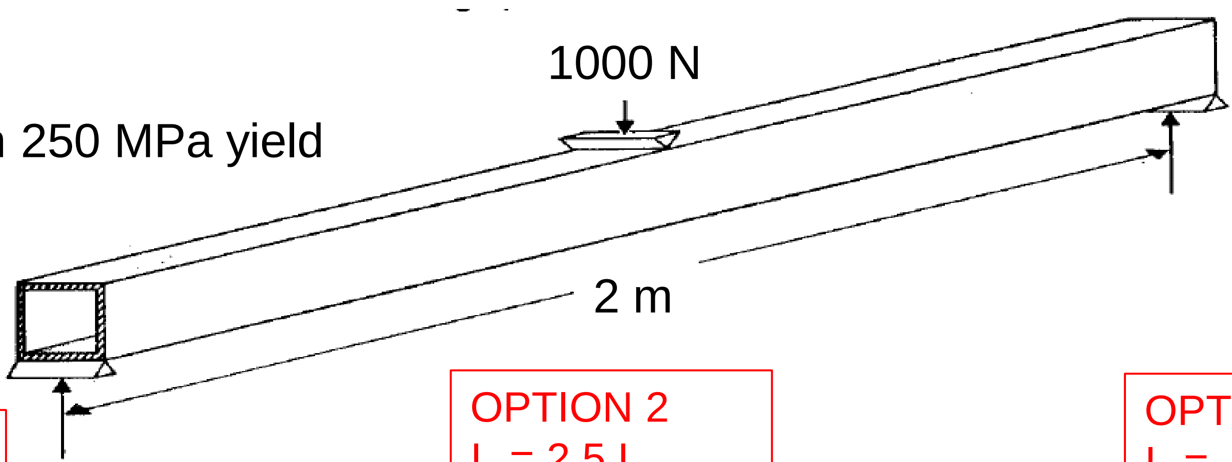
$S = 47268\ mm^3$

$A = 1537\ mm^2$

Wt = 12.5 kg/m

Simple Example: Aluminum Box Beam Simply Supported

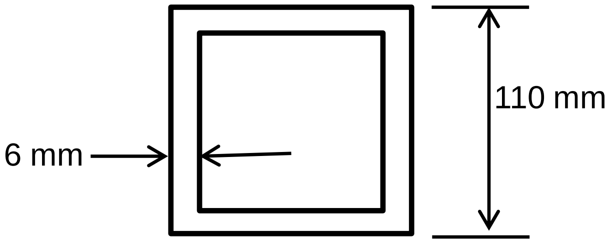
Aluminum with 250 MPa yield



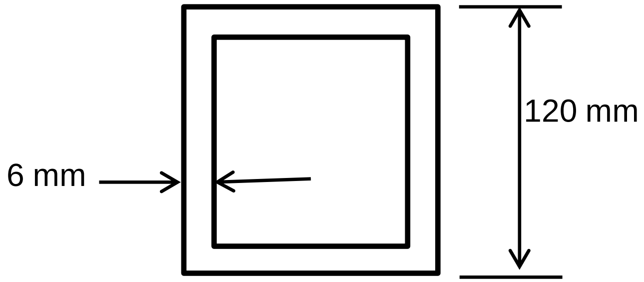
OPTION 1
$I_a = 1.91\ I_s$
$S_a = 1.73\ S_s$
$\text{Weight}_a = 0.54$

OPTION 2
$I_a = 2.5\ I_s$
$S_a = 2.1\ S_s$
$\text{Weight}_a = 0.59$

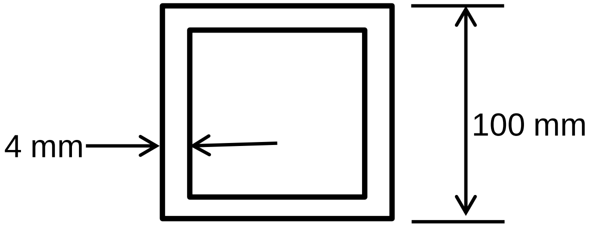
OPTION 3
$I_a = I_s$
$S_a = S_s$
$\text{Weight}_a = 0.33$



$I = 4514432\ mm^4$
$S = 82080\ mm^3$
$A = 2496\ mm^2$
Wt = 6.78 kg/m



$I = 5942592\ mm^4$
$S = 99043\ mm^3$
$A = 2736\ mm^2$
Wt = 7.44 kg/m



$I = 2363392\ mm^4$
$S = 47268\ mm^3$
$A = 1537\ mm^2$
Wt = 4.17 kg/m

Steel to Aluminum Conversion Formulas

For beam bending stiffness (Square cross section)

$$\frac{t_a}{t_s} = \left(\frac{b_s}{b_a}\right)^3 \left(\frac{E_s}{E_a}\right)$$

or

$$\frac{b_a}{b_s} = \left(\frac{E_s t_s}{E_a t_a}\right)^{\frac{1}{3}}$$

For beam bending stress (yield of extreme fiber in Square cross section)

$$\frac{t_a}{t_s} = \left(\frac{b_s}{b_a}\right)^2 \left(\frac{\sigma_{ys}}{\sigma_{ya}}\right)$$

or

$$\frac{b_a}{b_s} = \left(\frac{t_s \sigma_{ys}}{t_a \sigma_{ya}}\right)^{\frac{1}{2}}$$

A list of the symbols used in the equations is given below. Subscripts “a” and “s” have been used to identify properties for aluminum and steel, respectively.

σ_u = Ultimate strength

σ_y = Yield strength

E = Modulus of elasticity

I = Moment of inertia

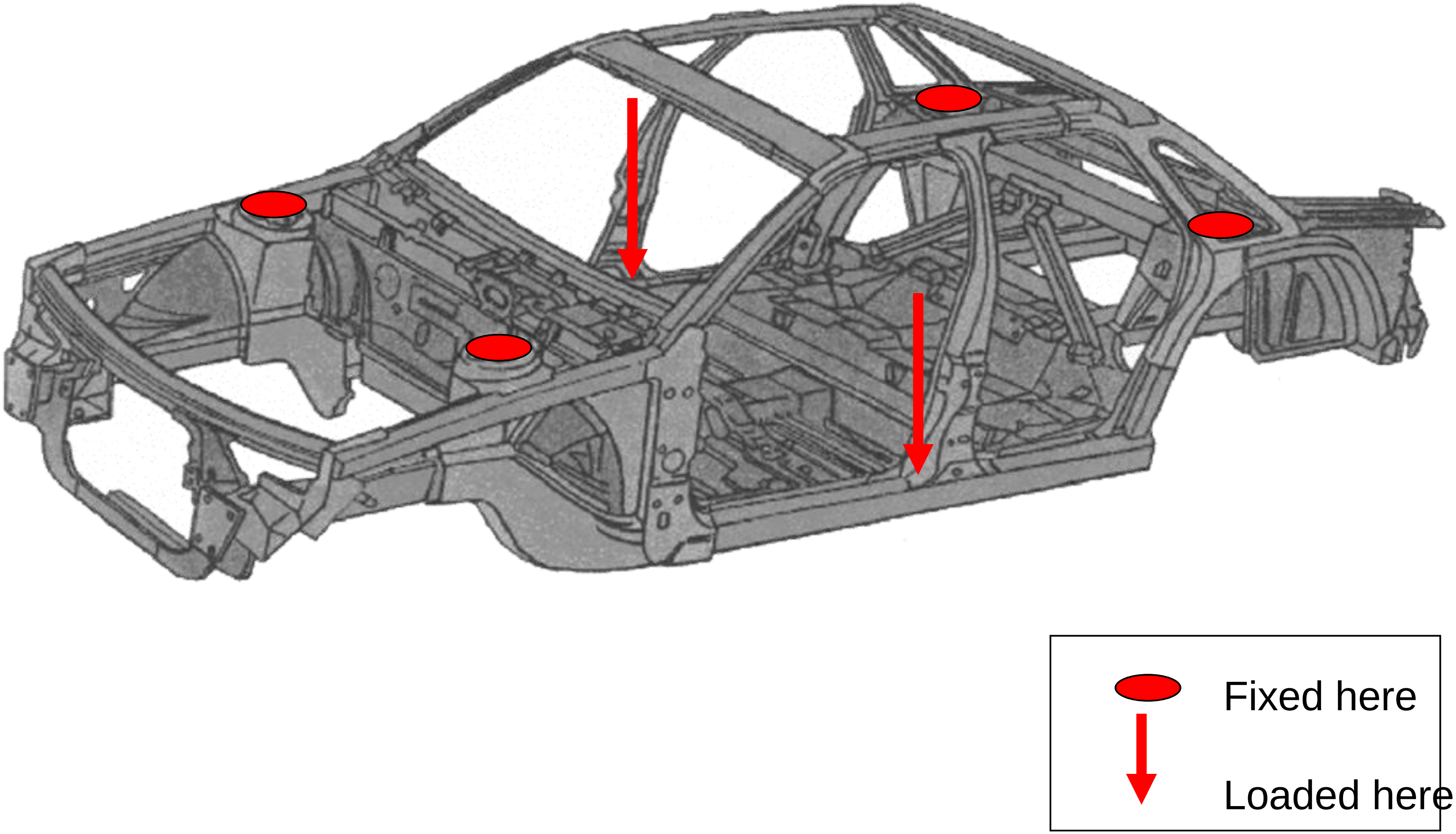
S = Section modulus

b = Side width of a hollow rectangular section

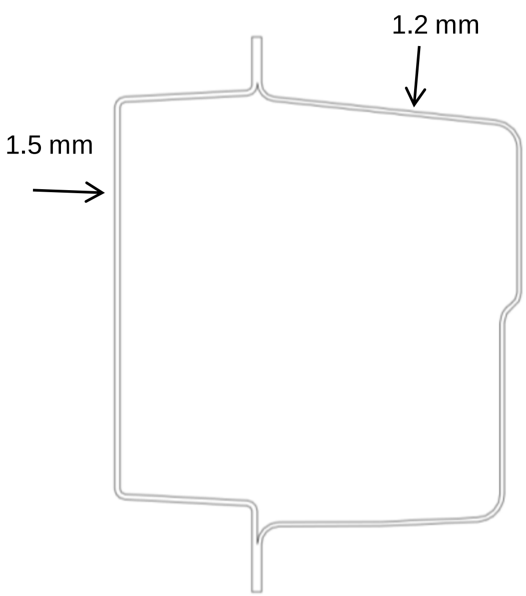
t = Thickness of a hollow rectangular section or thickness of sheet

δ = Crush distance

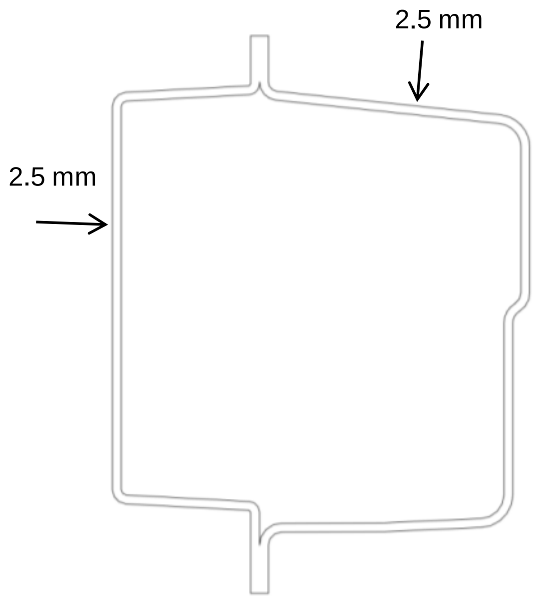
Stiffness: Bending



Rocker Comparison

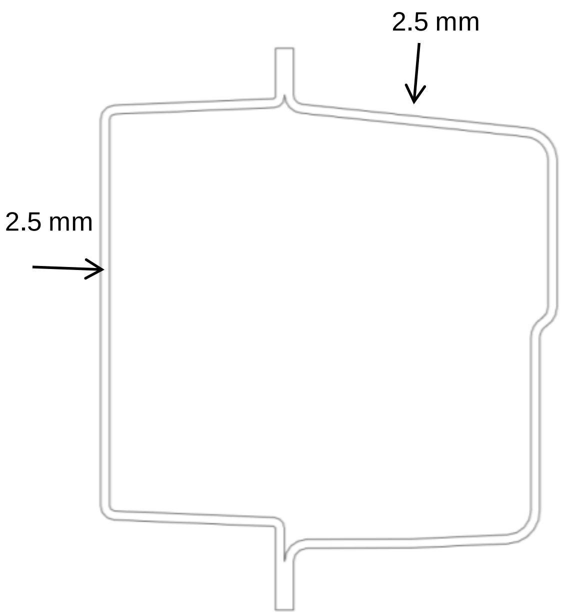


Steel Rocker
Moment of Inertia = Baseline
Wt = 3.8 lb/ft



Aluminum Rocker
(w Increased Thickness)
Moment of Inertia = 1.93X
Wt =2.33 lb/ft

38% Weight Savings



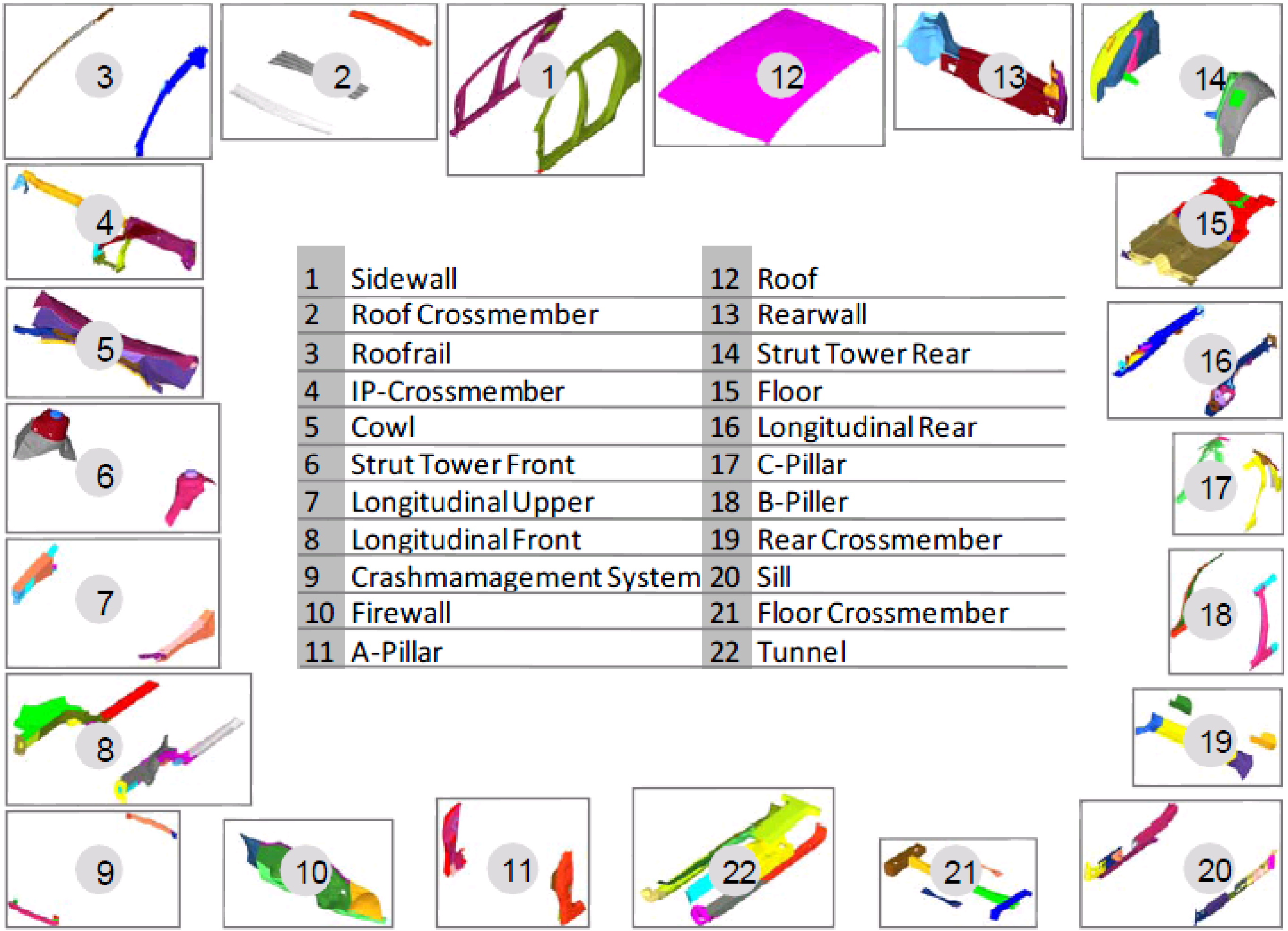
Aluminum Rocker
(w 10 mm section increase
And thickness increase)
Moment of Inertia = 2.33X
Wt =2.42 lb/ft

36% Weight Savings

University of Aachen Study

Stiffness Versus Strength Driven Components

Aachen Study

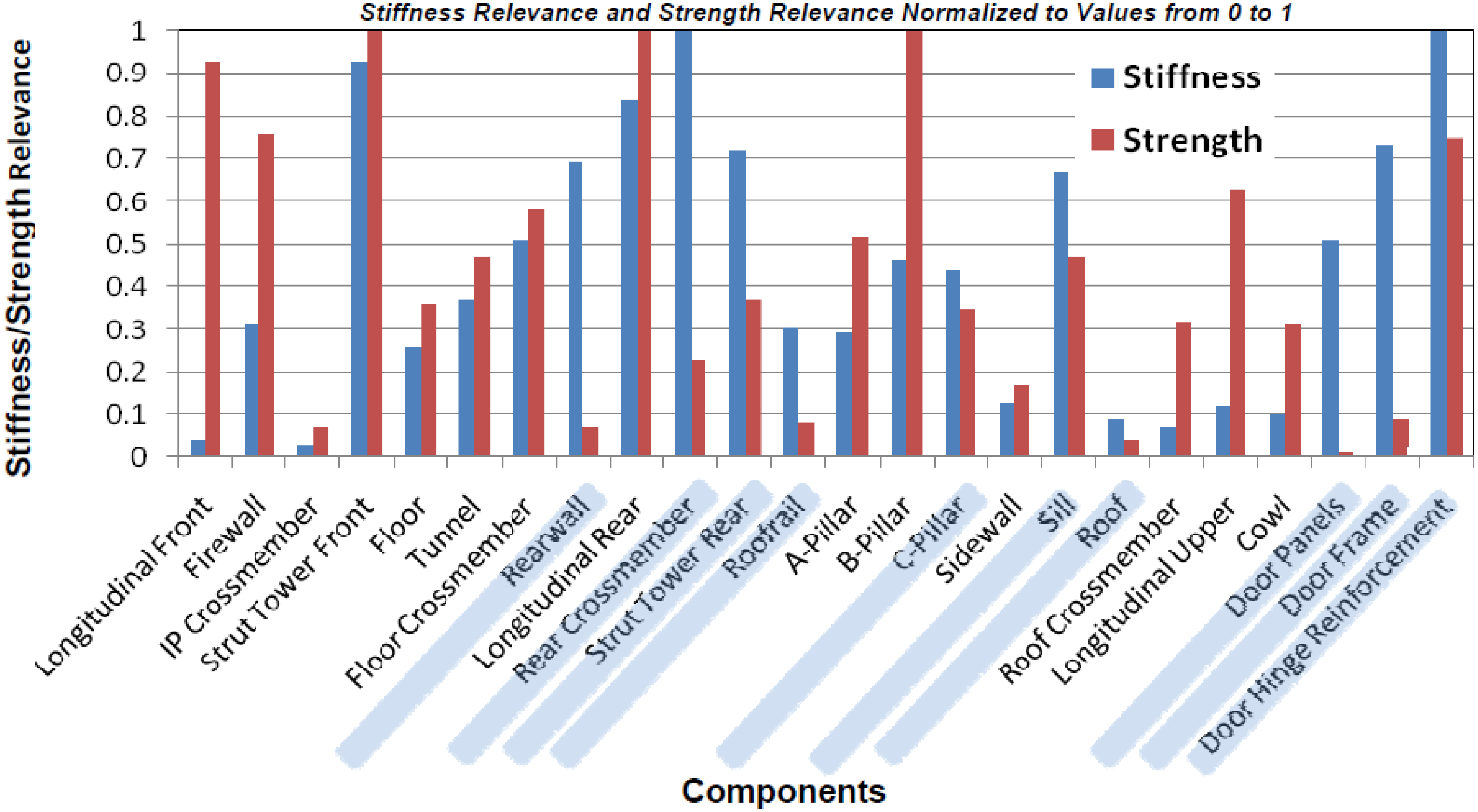


1	Sidewall	12	Roof
2	Roof Crossmember	13	Rearwall
3	Roofrail	14	Strut Tower Rear
4	IP-Crossmember	15	Floor
5	Cowl	16	Longitudinal Rear
6	Strut Tower Front	17	C-Pillar
7	Longitudinal Upper	18	B-Piller
8	Longitudinal Front	19	Rear Crossmember
9	Crashmamagement System	20	Sill
10	Firewall	21	Floor Crossmember
11	A-Pillar	22	Tunnel

Fig. 2-2: Subdivision of body-in-white into 22 components

Numerical Analysis – Results

Results Stiffness vs. Strength Relevance

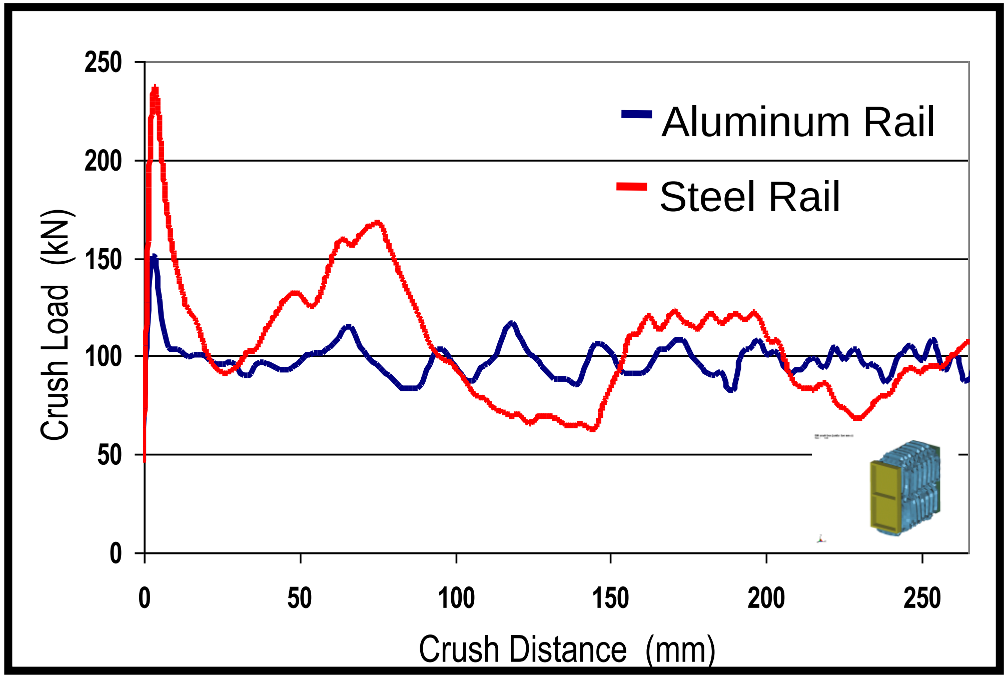


- For 38% of the componets investigated stiffness relevance is higher than strength relevance
- 80% of modeling results meet expectations of Car Body Experts of 4 European OEMs

Source: ika - University of Aachen and the European Aluminium Association (EAA)

Safety Solutions – Axial Crush

- 56% Mass Savings (Rel. Mild Steel)
- 38% Mass Savings (Rel. 800 MPa HSS)



Steel to Aluminum Conversion Formulas

For energy absorption in axial crush:

For the same mean load

$$\frac{t_a}{t_s} = K\left(\frac{b_s}{b_a}\right)^{\frac{1}{5}}\left(\frac{\sigma_{ys}}{\sigma_{ya}}\right)^{\frac{2}{5}}\left(\frac{E_s}{E_a}\right)^{\frac{1}{5}}$$

or

$$\frac{b_a}{b_s} = K^5\left(\frac{t_s}{t_a}\right)^5\left(\frac{\sigma_{ys}}{\sigma_{ya}}\right)^2\left(\frac{E_s}{E_a}\right)$$

where K = strain rate effect function
= 1.16 for 48 km/h crash (steel to aluminum ratio)

Aluminum Alloys

Aluminum Alloy Designation and Nomenclature

Alloy Series	Major Element	Thermal Treatment	Applications
1XXX	99% Pure Aluminum	Non-heat treatable	Non-structural-heat exchangers electrical conductors
2XXX	Copper	Heat treatable	Structural - aerospace
3XXX	Manganese	Non-heat treatable	Non-structural, beverage cans
4XXX	Silicon	Heat treatable	Non-structural - filler wire
5XXX	Magnesium	Non-heat treatable	Structural-auto/marine/tanks
6XXX	Mg + Si	Heat treatable	Structural-auto/general purpose
7XXX	Zinc	Heat treatable	Structural - aerospace
8XXX	Other Elements	-	Electrical conductors

Alloy Strengthening Mechanisms

Heat Treatable Alloys

- **Precipitation Hardening**
  - **Precipitate volume fraction (alloy and heat treatment)**
  - **Precipitate size (aging practice)**

TYPICAL ALLOY SYSTEMS

2000, 6000, 7000

Non-Heat Treatable Alloys

- **Solid Solution Strengthening**
  - **Amount of solute (alloy)**
  - **Type of atom**
- **Work Hardening**
  - **Solute atoms (alloy)**
  - **% cold work**
  - **Deformation temperature**

TYPICAL ALLOY SYSTEMS

3000, 5000

Basic Temper Designations

F **As-Fabricated – no property limits**

O **Annealed – fully softened**

H **Strain-Hardened (wrought products only)**

W **Solution Heat-Treated and Quenched**

T **Thermal Treatment (Excluding F, O, or H)**

Alcoa Automotive Alloy Options

	ALLOYS	SURFACE	MECH PROPS	PB STRENGTH	FORMABILITY	Gauges /Parts
OUTERS	6022-T43 6022-T4E32 6111-T43	Class A	OEM SPEC for 3 Directional TYE N&R	OEM SPEC For YIELD STRENGTH MIN	FLAT HEM & STRETCHABILITY	0.9 – 1.2 mm Hood/Deck-Lid/Door Outers
INNERS	6022-T4 5182-O 5754-O	Class A/B **(RSS for 5182-O)**	OEM SPEC Driven 3 Directional TYE N&R	Typically No YIELD STRENGTH MIN	DEEP DRAWABILITY	0.8 – 1.6 mm Hood/Deck-lid/Door Inners
REINFORCEMENT	6022-T4 6111-T4 6013-T4	Class C	OEM SPEC Driven 3 Directional TYE N&R	YIELD STRENGTH MIN	MINIMAL FORMING – PART SPECIFIC	1 – 3 mm Hinge/palm reinforcement

6xxx | 5xxx

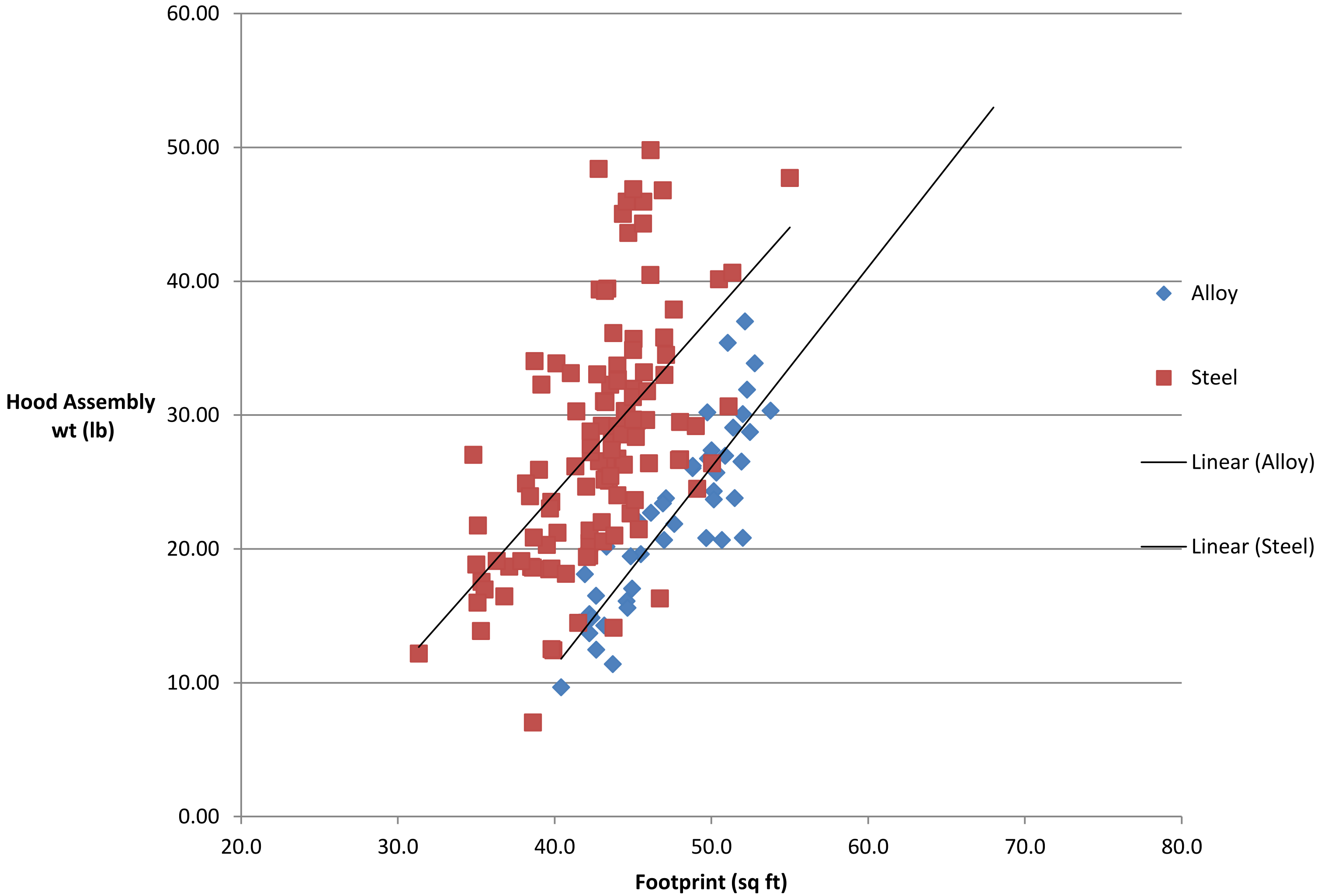
Compositions of Automotive Sheet Alloys

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ti	V
Aluminum Association Composition Ranges (in Wt. %)								
6022	**0.8 - 1.5**	**0.05- 0.20**	**0.01- 0.11**	**0.02- 0.10**	**0.45- 0.70**	**0.10**	**0.15**	
6016	1.0 - 1.5	0.50	0.20	0.20	0.25 -0.6	0.10	0.15	
6181A	0.7 – 1.1	0.15–0.50	0.25	0.40	0.6 - 1.0	0.15	0.25	
6014	0.3 - 0.6	0.35	0.25	0.05 – 0.2	0.4 -0.8	0.20	0.10	0.05-0.2
6451	0.6 - 0.1	0.40	0.40	0.05 – 0.4	0.4 -0.8	0.10	-	0.10
6111	0.6 - 1.1	0.40	0.50 - 0.9	0.10 -0.45	0.50 -1.0	0.10	0.10	
6013	0.6 - 1.0	0.50	0.6 – 1.1	0.20 – 0.8	0.8 - 1.2	0.10	0.10	
5182	0.20	0.35	0.15	0.20 -0.50	4.0-5.0	0.10	0.10	
5754	0.40	0.40	0.10	0.50	2.6-3.6	0.30	0.15	

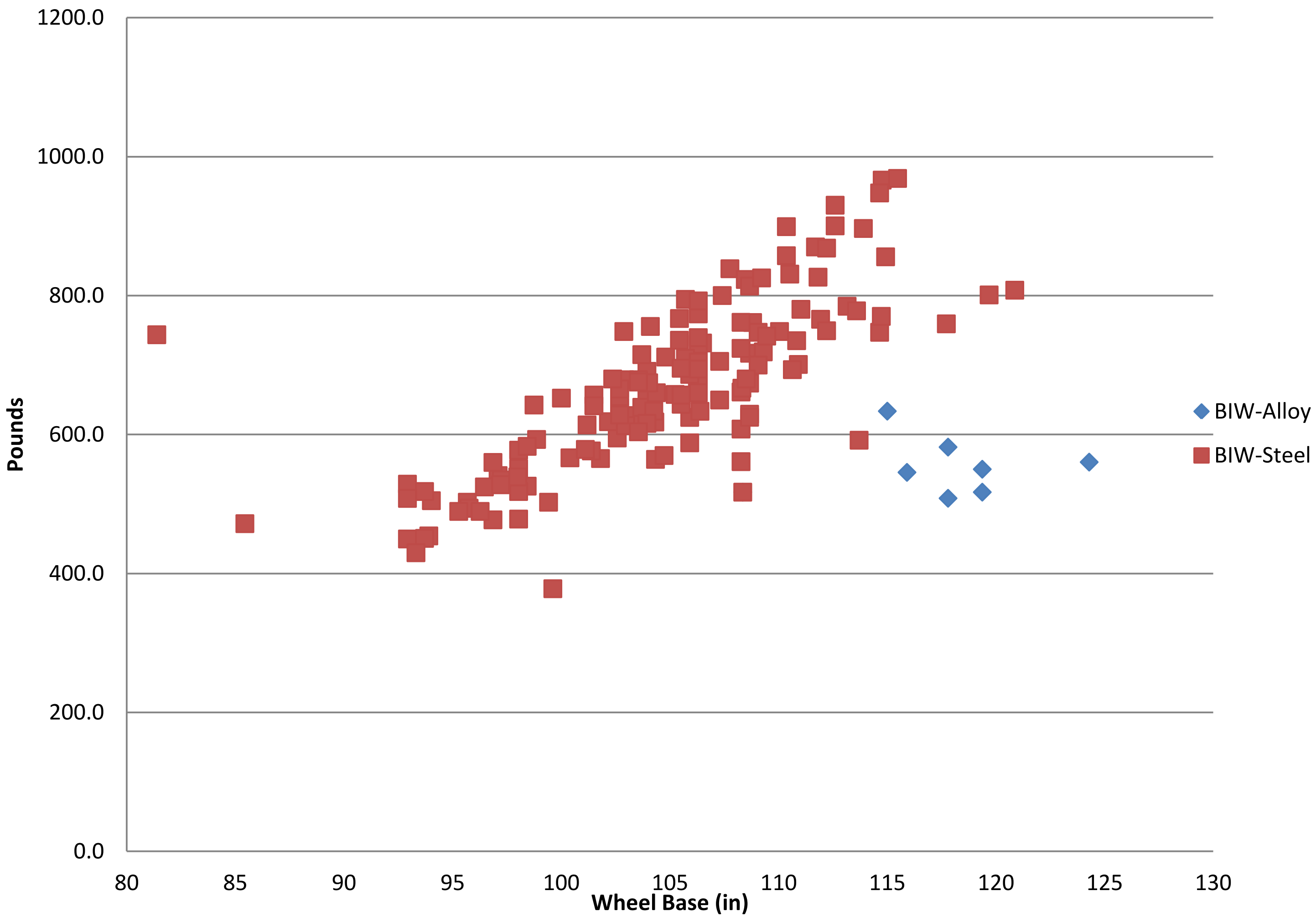
Note: Single numbers refer to the maximum values

Aluminum Auto Applications

Hood Weight Versus Footprint



BIW Weight Versus Wheel Base - Steel Vs Aluminum



Conclusions

- Some technologies are a given such as low friction lubes, aero improvements, electric power steering.
- Engine and transmission improvements are critical to reaching Café targets, but…
- Weight reduction without significant vehicle downsizing allows for additional engine downsizing (along with turbos) to improve fuel economy without reducing performance.
- Aluminum hoods are common place and are continuing to grow, more closures will become aluminum.
- Body applications are the next area for aluminum implementation after closures – typically only on the larger vehicles. Some OEMs will focus on all aluminum and others will use a hybrid material (steel/aluminum) approach.
- The larger trucks (GVW > 8500 lb) are not covered by CAFE but by the Truck emissions standard taking effect in 2014. This standard is expressed as CO_2 per ton mile.