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
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)
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 Average

Conversion factor between fuel economy and CO₂ emissions:
- 8887 g CO₂ per gallon of gasoline
- 10180 g CO₂ 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

Truck CAFE targets

Footprint (sq ft)
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.
Low Friction Lubricants

Engine Friction Reduction

VVT - Dual Cam Phasing (DCP)

Discrete Variable Valve Lift (DVVL) on OHV

Stoichiometric Gasoline Direct Injection (GDI)

Combustion Restart

Turbocharging and Downsizing

Exhaust Gas Recirculation (EGR) Boost

6/7/8-Speed Auto. Trans with Improved Internals

Dual Clutch or Automated Manual Transmission

Electric Power Steering

Improved Accessories

Belt mounted Integrated Starter Generator

Mass Reduction (3.5 to 8.5% of Curb Weight)

Mass Reduction (1.5% of Curb Weight)

Low Rolling Resistance Tires

Low Drag Brakes

Aero Drag Reduction

% Improvement in Fuel Economy

Drivetrain Alone Cannot Provide the Fuel Savings Required by 2020

# Material Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Steels</th>
<th>Aluminum alloys</th>
<th>Magnesium alloys</th>
<th>Polymers</th>
<th>Polymer Composites</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Available product forms</strong></td>
<td>Sheet, bar, single hollow tube, casting, forging</td>
<td>Sheet, bar, extrusions, casting, forging</td>
<td>casting</td>
<td>Sheet, molding, extruded shapes</td>
<td>Sheet, molding, pultruded shapes</td>
</tr>
<tr>
<td><strong>Density (g/mm(^3)) x10(^{-2})</strong></td>
<td>0.72 to 0.80</td>
<td>0.26 to 0.27</td>
<td>0.19</td>
<td>0.11 to 0.22</td>
<td>0.17 to 0.19</td>
</tr>
<tr>
<td><strong>Modulus (GPa)</strong></td>
<td>207</td>
<td>69 to 73</td>
<td>45</td>
<td>0.89 to 3.3</td>
<td>3.4 to 34</td>
</tr>
<tr>
<td><strong>Yield Strength (MPa)</strong></td>
<td>172 to 900</td>
<td>68 to 590</td>
<td>206</td>
<td>41 to 90</td>
<td>97 to 145</td>
</tr>
<tr>
<td><strong>Tensile Strength (MPa)</strong></td>
<td>365 to 1200</td>
<td>310 to 620</td>
<td>310</td>
<td>55 to 1124</td>
<td>110 to 172</td>
</tr>
<tr>
<td><strong>Elongation (mm/mm)%</strong></td>
<td>10 to 33</td>
<td>6 to 20</td>
<td>15</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Poisson's Ratio</strong></td>
<td>0.3</td>
<td>0.33</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Thermal expansion (mm/mm/°C)</strong></td>
<td>10.8 to 19.4</td>
<td>19.4 to 24.5</td>
<td>25</td>
<td>81 to 216</td>
<td>16.7 to 90</td>
</tr>
<tr>
<td><strong>Thermal conductivity (W/(m.°K))</strong></td>
<td>36 to 52</td>
<td>159 to 216</td>
<td>100</td>
<td>0.2 to 0.5</td>
<td>0.2 to 0.8</td>
</tr>
<tr>
<td><strong>Corrosion resistance</strong></td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Useable temp. range (°C)</strong></td>
<td>315</td>
<td>150</td>
<td>120</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td><strong>Joining methods</strong></td>
<td>Arc &amp; spot welding, bonding, mechanical</td>
<td>Arc &amp; spot welding, bonding, mechanical</td>
<td>Bonding, mechanical</td>
<td>Bonding, mechanical</td>
<td>Bonding, mechanical</td>
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<tr>
<td><strong>Formability</strong></td>
<td>Good</td>
<td>Fair to Good</td>
<td>-</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td><strong>Relative cost</strong></td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>

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The table above compares the properties of different materials, including steels, aluminum alloys, magnesium alloys, polymers, and polymer composites. Each property is listed with a range of values, allowing for a comprehensive comparison of their characteristics.
# Potential Weight Savings with Aluminum D-Class Vehicle

<table>
<thead>
<tr>
<th>Component</th>
<th>Steel (lb)</th>
<th>Aluminum (lb)</th>
<th>Wt. Saving (lb)</th>
<th>% saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hood</td>
<td>56</td>
<td>28</td>
<td>28</td>
<td>50</td>
</tr>
<tr>
<td>Fenders</td>
<td>16</td>
<td>8</td>
<td>8</td>
<td>50</td>
</tr>
<tr>
<td>Decklid</td>
<td>38</td>
<td>19</td>
<td>19</td>
<td>50</td>
</tr>
<tr>
<td>Doors</td>
<td>160</td>
<td>95</td>
<td>65</td>
<td>40</td>
</tr>
<tr>
<td>BIW</td>
<td>720</td>
<td>430</td>
<td>290</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>990</td>
<td>580</td>
<td>410</td>
<td>41</td>
</tr>
</tbody>
</table>
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.
- 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:

\[ E_{\text{alum}} I_{\text{alum}} = E_{\text{steel}} I_{\text{steel}} \]

Since Modulus of aluminum is 1/3 of steel

\[ I_{\text{alum}} = 3 I_{\text{steel}} \]

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

To Match Bending Strength:

\[ S_{\text{alum}} \sigma_{\text{alum}} = S_{\text{steel}} \sigma_{\text{steel}} \]

\[ S_{\text{alum}} = S_{\text{steel}} \left( \frac{\sigma_{\text{steel}}}{\sigma_{\text{alum}}} \right) \]
Simple Example: Steel Box Beam Simply Supported

Mild Steel with 250 MPa yield

\[ P = 1000 \text{ N} \]

\[ I = 2 \text{ m} \]

Max Moment: \[ M = \frac{Pl}{4} \]
Max bending Stress: \[ \sigma = \frac{M}{S} \]
Max Deflection: \[ \delta = \frac{Pl^3}{48EI} \]

100 mm square

4 mm thickness

\[ I = 2363392 \text{ mm}^4 \]
\[ S = 47268 \text{ mm}^3 \]
\[ A = 1537 \text{ mm}^2 \]
\[ Wt = 12.5 \text{ kg/m} \]
Simple Example: Aluminum Box Beam Simply Supported

Aluminum with 250 MPa yield

**OPTION 1**

\[
I_a = 1.91 \, I_s \\
S_a = 1.73 \, S_s \\
\text{Weight}_a = 0.54
\]

\[
I = 4514432 \, \text{mm}^4 \\
S = 82080 \, \text{mm}^3 \\
A = 2496 \, \text{mm}^2 \\
Wt = 6.78 \, \text{kg/m}
\]

**OPTION 2**

\[
I_a = 2.5 \, I_s \\
S_a = 2.1 \, S_s \\
\text{Weight}_a = 0.59
\]

\[
I = 5942592 \, \text{mm}^4 \\
S = 99043 \, \text{mm}^3 \\
A = 2736 \, \text{mm}^2 \\
Wt = 7.44 \, \text{kg/m}
\]

**OPTION 3**

\[
I_a = I_s \\
S_a = S_s \\
\text{Weight}_a = 0.33
\]

\[
I = 2363392 \, \text{mm}^4 \\
S = 47268 \, \text{mm}^3 \\
A = 1537 \, \text{mm}^2 \\
Wt = 4.17 \, \text{kg/m}
\]
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.

- \(\sigma_u\) = Ultimate strength
- \(\sigma_y\) = 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
- \(\delta\) = Crush distance
III. Typical areas of the structure

Typical areas...(cont.): Load cases

Stiffness: Bending

- Fixed here
- Loaded here
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

Fig. 2-2: Subdivision of body-in-white into 22 components
Results Stiffness vs. Strength Relevance

For 38% of the components 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)
56% Mass Savings (Rel. Mild Steel)
38% Mass Savings (Rel. 800 MPa HSS)
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

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

where \( K \) = strain rate effect function

\( = 1.16 \) for 48 km/h crash (steel to aluminum ratio)
Aluminum Alloys
<table>
<thead>
<tr>
<th>Alloy Series</th>
<th>Major Element</th>
<th>Thermal Treatment</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1XXX</td>
<td>99% Pure Aluminum</td>
<td>Non-heat treatable</td>
<td>Non-structural-heat exchangers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>electrical conductors</td>
</tr>
<tr>
<td>2XXX</td>
<td>Copper</td>
<td>Heat treatable</td>
<td>Structural - aerospace</td>
</tr>
<tr>
<td>3XXX</td>
<td>Manganese</td>
<td>Non-heat treatable</td>
<td>Non-structural, beverage cans</td>
</tr>
<tr>
<td>4XXX</td>
<td>Silicon</td>
<td>Heat treatable</td>
<td>Non-structural - filler wire</td>
</tr>
<tr>
<td>5XXX</td>
<td>Magnesium</td>
<td>Non-heat treatable</td>
<td>Structural-auto/marine/tanks</td>
</tr>
<tr>
<td>6XXX</td>
<td>Mg + Si</td>
<td>Heat treatable</td>
<td>Structural-auto/general purpose</td>
</tr>
<tr>
<td>7XXX</td>
<td>Zinc</td>
<td>Heat treatable</td>
<td>Structural - aerospace</td>
</tr>
<tr>
<td>8XXX</td>
<td>Other Elements</td>
<td>-</td>
<td>Electrical conductors</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>ALLOYS</th>
<th>OUTERS</th>
<th>SURFACE</th>
<th>MECH PROPS</th>
<th>PB STRENGTH</th>
<th>FORMABILITY</th>
<th>Gauges /Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>6022-T43</td>
<td>6022-T4E32</td>
<td>6111-T43</td>
<td>Class A</td>
<td>OEM SPEC for 3 Directional TYE N&amp;R</td>
<td>OEM SPEC For YIELD STRENGTH MIN</td>
<td>FLAT HEM &amp; STRETCHABILITY</td>
</tr>
<tr>
<td>6022-T4</td>
<td>5182-O</td>
<td>5754-O</td>
<td>Class A/B (RSS for 5182-O)</td>
<td>OEM SPEC Driven 3 Directional TYE N&amp;R</td>
<td>Typically No YIELD STRENGTH MIN</td>
<td>DEEP DRAWABILITY</td>
</tr>
<tr>
<td>6022-T4</td>
<td>6111-T4</td>
<td>6013-T4</td>
<td>Class C</td>
<td>OEM SPEC Driven 3 Directional TYE N&amp;R</td>
<td>YIELD STRENGTH MIN</td>
<td>MINIMAL FORMING – PART SPECIFIC</td>
</tr>
</tbody>
</table>

#### 6xxx | 5xxx
### Compositions of Automotive Sheet Alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Ti</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>6022</td>
<td>0.8 - 1.5</td>
<td>0.05 - 0.20</td>
<td>0.01 - 0.11</td>
<td>0.02 - 0.10</td>
<td>0.45 - 0.70</td>
<td>0.10</td>
<td>0.15</td>
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<tr>
<td>6016</td>
<td>1.0 - 1.5</td>
<td>0.50</td>
<td>0.20</td>
<td>0.20</td>
<td>0.25 - 0.6</td>
<td>0.10</td>
<td>0.15</td>
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<tr>
<td>6181A</td>
<td>0.7 – 1.1</td>
<td>0.15– 0.50</td>
<td>0.25</td>
<td>0.40</td>
<td>0.6 - 1.0</td>
<td>0.15</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>6014</td>
<td>0.3 - 0.6</td>
<td>0.35</td>
<td>0.25</td>
<td>0.05 – 0.2</td>
<td>0.4 - 0.8</td>
<td>0.20</td>
<td>0.10</td>
<td>0.05-0.2</td>
</tr>
<tr>
<td>6451</td>
<td>0.6 - 0.1</td>
<td>0.40</td>
<td>0.40</td>
<td>0.05 – 0.4</td>
<td>0.4 - 0.8</td>
<td>0.10</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td>6111</td>
<td>0.6 - 1.1</td>
<td>0.40</td>
<td>0.50 - 0.9</td>
<td>0.10 - 0.45</td>
<td>0.50 - 1.0</td>
<td>0.10</td>
<td>0.10</td>
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<tr>
<td>6013</td>
<td>0.6 - 1.0</td>
<td>0.50</td>
<td>0.6 – 1.1</td>
<td>0.20 – 0.8</td>
<td>0.8 - 1.2</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>5182</td>
<td>0.20</td>
<td>0.35</td>
<td>0.15</td>
<td>0.20 - 0.50</td>
<td>4.0 - 5.0</td>
<td>0.10</td>
<td>0.10</td>
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<tr>
<td>5754</td>
<td>0.40</td>
<td>0.40</td>
<td>0.10</td>
<td>0.50</td>
<td>2.6-3.6</td>
<td>0.30</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Single numbers refer to the maximum values.
Aluminum Auto Applications
BIW Weight Versus Wheel Base - Steel Vs Aluminum

Wheel Base (in) vs Pounds for BIW-Steel and BIW-Alloy.
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 CO₂ per ton mile.