Statistical Benchmarking of Automotive Closures

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Refer to SAE 2015-01-0574 for more detail
Role of Benchmarking in product design

Process of comparing systems across an industry. Provides a snapshot of industry performance
• range of performance for systems in the market
• the current best performance
• lightweighting design practices & technologies

Reference SAE 2015-01-0574
These questions can be addressed by benchmark analysis.

Direct comparison benchmark approach:
Reference vehicle is disassembled and mass is measured.
The reference vehicle –
• should have roughly the same dimensions as vehicle under design
• should be a mass efficient design
• should have representative materials for comparison
Difficulties with the direct comparison approach

Direct comparison benchmark approach:
Select a competitive product and compare mass.

• should have roughly the same dimensions as vehicle under design
  
  Usually very difficult to find a competitive vehicle with just the right characteristics for comparison.

• should be a mass efficient design

  How do we know the benchmark vehicle is mass efficient?

• should have representative materials for comparison

  How do we know the selected vehicle applies the materials efficiently?

In this work, we develop a statistical approach which addresses these issues by using all information in a large database.
Statistical analysis of benchmark database

Which door is a good example of mass efficiency for steel; for aluminum?

Variation from typical door mass for a particular door

mass of average or typical door frame

Reference SAE 2015-01-0574
Sources of variation in subsystem mass

- Errors in measuring
- Design efficiency
- Documented subsystem mass
- Variation from typical door mass
- Normalize door mass for mass drivers

So we can identify design efficiency

Mass drivers

Reference SAE 2015-01-0574

Attributes of the subsystem under study
Attributes of the interacting subsystems
Attributes of the vehicle
Defining the subsystem

Which parts are to be included?

Definition based on a functional description of the subsystem to insure that like systems will be compared across vehicles.
Propose mass drivers

Vehicle Attributes

<table>
<thead>
<tr>
<th>Vehicle type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger, Utility</td>
</tr>
</tbody>
</table>

Door Subsystem Attributes

<table>
<thead>
<tr>
<th>Side view area</th>
<th>Hinge span, Door length</th>
<th>Tumblehome</th>
<th>Height to belt, Height overall</th>
<th>Door frame material</th>
</tr>
</thead>
</table>
| ![Side view area](image) | ![Hinge span, Door length](image) | ![Tumblehome](image) | ![Height to belt, Height overall](image) | • aluminum  
• steel  
• other |

Interacting Subsystem Attributes

<table>
<thead>
<tr>
<th>Window regulator</th>
<th>Door beam type</th>
<th>Door-to-pillar construction</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Window regulator" /></td>
<td><img src="image" alt="Door beam type" /></td>
<td><img src="image" alt="Door-to-pillar construction" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cable</th>
<th>Linkage</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Cable" /></td>
<td><img src="image" alt="Linkage" /></td>
<td><img src="image" alt="Post" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rolled</th>
<th>Tube multiple stamped</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Rolled" /></td>
<td><img src="image" alt="Tube multiple stamped" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frame rear of A pillar</th>
<th>Frame over A pillar</th>
<th>Frame-less</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Frame rear of A pillar" /></td>
<td><img src="image" alt="Frame over A pillar" /></td>
<td><img src="image" alt="Frame-less" /></td>
</tr>
</tbody>
</table>
## Download information from database

### Table: Vehicle and Subsystem Attributes

<table>
<thead>
<tr>
<th>OEM</th>
<th>Front Door Frame Mass (kg)</th>
<th>Vehicle Type</th>
<th>Door Frame Material</th>
<th>Door Area (m²)</th>
<th>Hinge Span (mm)</th>
<th>Window Regulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hudson</td>
<td>9.2</td>
<td>2</td>
<td>1</td>
<td>1.2</td>
<td>400</td>
<td>2</td>
</tr>
<tr>
<td>Datsun</td>
<td>9.5</td>
<td>2</td>
<td>1</td>
<td>0.9</td>
<td>370</td>
<td>1</td>
</tr>
<tr>
<td>Rambler</td>
<td>9.5</td>
<td>2</td>
<td>2</td>
<td>1.2</td>
<td>395</td>
<td>2</td>
</tr>
</tbody>
</table>

*Data format for statistical analysis*

Reference SAE 2015-01-0574

Great Designs in Steel Seminar

Steel Matters Demand Nothing Less www.autosteel.org
**Visual analysis of data**

<table>
<thead>
<tr>
<th>Window regulator type</th>
<th>Door frame mass with regulator type shown (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post</td>
<td><img src="image" alt="Post Diagram" /></td>
</tr>
<tr>
<td>Linkage</td>
<td><img src="image" alt="Linkage Diagram" /></td>
</tr>
<tr>
<td>Cable</td>
<td><img src="image" alt="Cable Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Door Area</th>
<th>Length</th>
<th>Tumble-home</th>
<th>Hinge Span</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door Frame Mass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Door Area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tumble-home</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hinge Span</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Steel** (red circles)
- **Aluminum** (blue squares)
\[ \hat{m}(\text{kg}) = 10.14(Area \, m^2)^{0.884} \]

\[
\begin{bmatrix}
1.43\text{Steel} \\
1.00\text{Alum}
\end{bmatrix}
\begin{bmatrix}
1.06 \text{ Linkage Reg} \\
1.03 \text{ Cable Reg} \\
1.00 \text{ Post Reg}
\end{bmatrix}
\]

Reference SAE 2015-01-0574
Identifying the mass efficient designs

Estimated Door Frame Mass (kg)

Actual Door Frame Mass (kg) $m$

Mass of typical door frame adjusted for mass drivers

$\hat{m} = 10.14(Area \ m^2)^{0.884} - 1.06\ Linkage\ Reg - 1.00\ Post\ Reg$

$\hat{m} = 10.14(Area \ m^2)^{0.884} - 1.43\ Steel - 1.03\ Cable\ Reg - 1.00\ Alum$

Note: this door is mass efficient but is not the lightest door.
Identifying the mass efficient designs

Mass-efficient designs were approximately one standard error, $r$, below the nominal.

The criterion for choosing the number of standard errors below nominal, $n$, was at least three data samples were observed with mass equal to or less than that value.
Mass-efficient designs were approximately one standard error below the nominal.

The criterion for choosing the number of standard errors below nominal, $n$, was at least three data samples were observed with mass equal to or less than that value.
Using statistical benchmark data in product design

1. Investigating material substitution influences in practice

2. Investigating lightweighting at a system level

Mass comparisons can be adjusted for mass drivers allowing the population of benchmark data to be used.

The mass-efficient designs can be objectively identified.

\[ m(kg) = 10.14 \left( \text{Area } m^2 \right)^{0.884} \]

\[ \begin{array}{c|c|c}
\text{Steel} & 1.43 & 1.06 \\
\text{Cable} & 1.03 & \\
\text{Alum} & 1.00 & 1.00 \\
\end{array} \]

1. Investigating material substitution influences in practice

2. Investigating lightweighting at a system level
1. Investigating material substitution influences

Steel efficient designs

\[ \hat{m}_{\text{EFF}} (\text{kg}) = \frac{10.14 (\text{Area } m^2)^{0.884}}{(1.12)(1.123)} \]

\[ \begin{aligned} &\uparrow \quad n_{\text{STEEL}} \quad r \\ &1.43 \text{Steel} \\ &1.06 \text{ Linkage Reg} \\ &1.03 \text{ Cable Reg} \\ &1.00 \text{ Post Reg} \end{aligned} \]

Aluminum efficient designs

\[ \hat{m}_{\text{EFF}} (\text{kg}) = \frac{10.14 (\text{Area } m^2)^{0.884}}{(1.00)(1.123)} \]

\[ \begin{aligned} &\uparrow \quad n_{\text{ALUM}} \quad r \\ &1.00 \text{Alum} \\ &1.06 \text{ Linkage Reg} \\ &1.03 \text{ Cable Reg} \\ &1.00 \text{ Post Reg} \end{aligned} \]

For nominal door frame designs, \( n \cdot r = 1 \)

\[ \frac{\hat{m}_{\text{ALUM}}}{\hat{m}_{\text{STEEL}}} = \frac{1}{1.43} = 0.70 \]

For efficient door frame designs,

\[ \frac{\hat{m}_{\text{ALUM}}}{\hat{m}_{\text{STEEL}}} = \frac{\text{MatFactor}_{\text{ALUM}} / n_{\text{ALUM}}}{\text{MatFactor}_{\text{STEEL}} / n_{\text{STEEL}}} = \frac{1.00 / 1.00}{1.43 / 1.12} = 0.78 \]
1. Investigating material substitution influences

The graph shows the ratio $m_{\text{AL}}/m_{\text{ST}}$ for different vehicle closures: Side Door, Hood, Decklid, and Hatchback. The y-axis represents this ratio ranging from 0.0 to 1.0. The bars indicate the mass-efficient designs, nominal designs, and the range for closures reported in literature (theoretical range based on material modulus and density).
2. Investigating lightweighting at a system level

Door system mass normalized by area (kg/m²)

Non-significant mass reduction in door system

Significant mass reduction in door structure for aluminum vs. steel

All cars in database

- Steel N=201
- Aluminum N=16

Reference SAE 2015-01-0574

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2. Investigating lightweighting at a system level

Door system mass normalized by area (kg/m²)

Non-significant mass reduction in door system

Significant mass reduction in door structure for aluminum vs. steel

Premium cars in database

Steel N=35
Aluminum N=11

Door frame mass per unit area (kg/m²)

Premium cars in database

Reference SAE 2015-01-0574
## 2. Investigating lightweighting at a system level

<table>
<thead>
<tr>
<th></th>
<th>Side Door-Premium</th>
<th>Hood</th>
<th>Decklid</th>
<th>Hatchback</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frame</td>
<td>System</td>
<td>Frame</td>
<td>System</td>
</tr>
<tr>
<td>Alum</td>
<td>10.18</td>
<td>29.80</td>
<td>5.00</td>
<td>7.33</td>
</tr>
<tr>
<td>Steel</td>
<td>14.45</td>
<td>28.80</td>
<td>8.22</td>
<td>10.25</td>
</tr>
</tbody>
</table>

Mean normalized mass kg/m²

![Graphs showing comparison between Alum and Steel for different systems: Side Door-Premium, Hood, Decklid, and Hatchback.](chart.png)

Reference SAE 2015-01-0574
Summary for other closures

Hood

\[ \text{Area (m}^2\text{)}^{1.23} \begin{bmatrix} 1.66 \text{Steel} \\ 1.00 \text{Alum} \end{bmatrix} \]

\[ R^2 = 0.80, \text{ Standard error}=1.18 \]

Decklid

\[ \text{6.9(Area)}^{0.56} \begin{bmatrix} 1.32 \text{St} \\ 1.00 \text{Al} \\ 1.00 \text{ Lic Poc} \\ 0.89 \text{TorSpg} \\ 1.00 \text{ No LP} \\ 1.00 \text{ Others} \end{bmatrix} \]

\[ R^2 = 0.50, \text{ Standard error}=1.15 \]

Hatchback

\[ \text{3.02(Area m}^2\text{)}^{0.55} (\text{Depth m})^{0.144} \begin{bmatrix} 1.40 \text{Steel} \\ 1.00 \text{Alum} \end{bmatrix} \]

\[ R^2 = 0.39, \text{ Standard error}=1.20 \]
Conclusions

Statistical benchmarking gives an important perspective to mass budgeting and target setting beyond the direct comparison approach.

1. Mass comparisons can be adjusted for mass drivers allowing the population of benchmark data to be used.

2. The mass-efficient designs can be objectively identified.

3. Those mass-efficient designs can then be studied for best practices.

4. For mass reduction via material substitution, mass savings in the structure is not always realized in the system.
Presentations will be available May 18 at www.autosteel.org

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