Composite / Steel Cost Comparison: Utility

Composites offer the following:

- Advantages
  - Parts Consolidation Opportunities
  - Primary / Secondary Weight Savings
  - Low Investment Costs
  - Increased Design Flexibility

- Disadvantages
  - Materials and Labor Intensive Process
  - Long Cycle Times
  - Non-traditional Manufacturing Technology

What is the competitive position of composite parts compared to its steel comparator?

Cost Analysis: Methodology

- Composites Vehicle Design
  - Ford Composite Intensive Vehicle (CIV)
  - Complete Body in White : 8 pieces
  - BIW Weight : approx. 300 kg

- Steel Comparator
  - Honda Odyssey minivan
  - Based on Accord chassis, so comparable size
  - BIW Weight : approx. 400 kg

- Use steel stamping and assembly models to estimate Odyssey's BIW cost
- Use RTM and composites assembly models to estimate CIV's BIW cost
- Identify key process variables, cost drivers, necessary technical improvements
Conceptual Resin Transfer Molding Process Flow

Preforming
- Cut Reinforcement Material
- Thermoform
- Trim
- Foam Core / Preform Subassembly
- Resin Transfer Molding
- Trim/Inspect

Foam Core Molding
- Reaction Injection Mold
- Cure
- Trim
- Resin Transfer Molding

General RTM Cost Model Structure

Inputs:
- Material Composition
- Part Geometry
- Preform, Foam Core Geometry
- Exogenous Cost Factors
- Process Conditions
- Parameter Estimation Data

Secondary Calculations:
- Cycle Time Estimation
- Machine Cost Estimation
- Number of Machines
- Tooling Cost Estimation
- Number of Tools

Cost Estimation per Operation and Cost Summary
Resin Transfer Molding Cycle Time Estimation

- Cycle Time = Preparation Time + Fill Time + Cure Time

  - Preparation Time:
    - Mold Cleaning + Release Agent Coating + Gel Coating + Subassembly Placement + Mold Open/Close + Demold

  - Fill Time:
    - Based on D’Arcy’s Law of Flow through Porous Media
    - Six Mold Design Options
    - f(Fiber and Resin Material Properties, Injection Pressure, Mold Geometry)

  - Cure Time:
    - f(Arrhenius constants, Mold Temperature, Percent Conversion)
    - Rate Constants from typical values found in literature

RTM Fill and Cure Equations

- Fill Time
  - Based on application of D’Arcy’s Law: \( Q = -\frac{KA}{m} \frac{dp}{dx} \), where \( Q \) = volumetric flow rate, \( K \) = permeability, \( A \) = cross-sectional area, \( m \) = viscosity and \( \frac{dp}{dx} \) = pressure gradient
  - Assumptions:
    - Isothermal flow
    - Incompressible, constant viscosity fluid
    - Homogeneous reinforcement

- Cure Time
  - \( \frac{dc}{dt} = (k_1 + k_2 c^m) (1-c)^n \), where \( c \) = degree of conversion, \( k_1 \) and \( k_2 \) are Arrhenius constants, and \( m, n \) are empirical constants
  - Assume \( m = 0, n = 2 \),
    - \( \text{Cure Time} = \frac{(1/A)\exp(E/RT)}{c(1-c)} \), where \( A \) = pre-exponential factor, \( E \) = activation energy, \( R \) = gas constant, \( T \) = mold temperature, \( c \) = degree of conversion
**RTM Fill Time Process Flow**

- **Constant Flow or Pressure?**
  - Rectilinear or Radial Flow?
  - Line Source or Sink?
  - Rectilinear Calculation
  - Radial Calculation
  - Line Source Calculation

**RTM Machine and Tooling Cost Equations**

- Machine Cost = C1 + C2 x (Clamping Force Requirement) + C3 x (Platen Area)
  - C1, C2, C3: regression constants
  - Clamping Force = f(maximum injection pressure, mold geometry and mold design)

- Tooling Cost = C1 + C2 x (Part Weight)^C3 + C4 x (Part Surface Area)
  - C1, C2, C3, C4: regression constants, dependent on tool material
  - Tool Material Options
    - Steel
    - Aluminum
    - Epoxy
**Effect of Mold Design on Fill Time and Machine Cost**

<table>
<thead>
<tr>
<th></th>
<th>Fill Time (sec)</th>
<th>Mold Force (N)</th>
<th>Press Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectilinear, Constant Flow</td>
<td>12.15</td>
<td>$5.4 \times 10^6$</td>
<td>$3,012,346$</td>
</tr>
<tr>
<td>Rectilinear, Constant Pressure</td>
<td>249.11</td>
<td>$4.03 \times 10^5$</td>
<td>$355,782$</td>
</tr>
<tr>
<td>Radial Source, Constant Pressure</td>
<td>233.45</td>
<td>$9.04 \times 10^4$</td>
<td>$176,850$</td>
</tr>
<tr>
<td>Radial Sink, Constant Pressure</td>
<td>15.54</td>
<td>$1.36 \times 10^6$</td>
<td>$903,743$</td>
</tr>
</tbody>
</table>

Flow Length = 1.4m (Rectilinear), 0.7m (Radial)
Initial Injection Pressure = $5 \times 10^5$ N

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**RTM Cost Modeling Assumptions**

- **Materials Prices:**
  - Resin (Vinyl Ester) $2.60 / kg
  - Filler (Calcium Carbonate) $0.13 / kg
  - Reinforcement:
    - Glass Fiber CSM $2.00 / kg
    - Carbon Fiber $11.00 / kg
    - Carbon / Glass Blend $6.50 / kg
  - Catalyst $3.24 / kg
  - Foam Core (Polyurethane) $2.54 / kg

- Foam Core Molding, Thermoforming and RTM Tool Material: Steel
- RTM Flow: Rectilinear, Constant Pressure
- 32 Steel Inserts
**Key Carbon Fiber Design Assumptions for CIV**

- Use simple beam loading equations to estimate the equivalent thickness of carbon fiber part compared to its glass fiber equivalent.
- Ratio of moduli determines the thickness of the carbon fiber part.
  - Elastic Modulus (Msi):
    - $E_{\text{glass fiber}} : 10.5$
    - $E_{\text{carbon fiber}} : 34$
    - $E_{\text{carbon/glass}} : 22.25$
- Part thickness for glass fiber component: 3 mm

**Results**

- Part thickness:
  - Carbon fiber: 2.03 mm
  - Carbon/Glass: 2.3 mm
- Relative Weight assuming calculated thicknesses (Glass fiber = 1.0)
  - Carbon fiber: 46%
  - Carbon/Glass: 65%

**Key SMC Design Assumptions for CIV**

- SMC part thickness: 4 mm
- Reinforcing rib structure placed every 150 mm
- Reinforcing rib dimensions
  - Length = 150 mm
  - Height and Width are dependent on part geometry
- Foam cores assumed in parts where crush resistance is necessary
  - Front End rails
  - Floorpan
- SMC part is composed of two halves forming a closed section

![Rib Pattern](image)
Comparison of Part Weights (including CiV inserts)

<table>
<thead>
<tr>
<th>Material</th>
<th>Bodyside</th>
<th>Cross Member</th>
<th>Roof</th>
<th>Front End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>193.6</td>
<td>367.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMC</td>
<td>241.3</td>
<td>286.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass Fiber</td>
<td>193.6</td>
<td>241.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon/Glass</td>
<td>172</td>
<td>241.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>172</td>
<td>241.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Weight (Kg)

Results: Total Manufacturing and Assembly Cost

Magnitude of Cost:

<table>
<thead>
<tr>
<th>Material</th>
<th>$1,000</th>
<th>$1,500</th>
<th>$2,000</th>
<th>$2,500</th>
<th>$3,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td></td>
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<tr>
<td>RTM Glass</td>
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<tr>
<td>RTM Carb</td>
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<tr>
<td>RTM Ca/Gl</td>
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<tr>
<td>SMC</td>
<td></td>
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SMC-Steel Break-even Point: ~30,000 vehicles/yr

RTM Glass-Steel Break-even Point: ~35,000 vehicles/yr

(Composites Wage: $25/hr)
Manufacturing Cost Breakdown: Glass vs Carbon Fiber

<table>
<thead>
<tr>
<th>Volume (35,000)</th>
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<tbody>
<tr>
<td>$0</td>
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<tr>
<td>$500</td>
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<tr>
<td>$1,000</td>
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<tr>
<td>$1,500</td>
</tr>
<tr>
<td>$2,000</td>
</tr>
</tbody>
</table>

Other Fixed
Tooling
Equipment
Energy
Labor
Materials

Cost per Kilogram Saved (Relative to Steel Base Case)

<table>
<thead>
<tr>
<th>Annual Production Volume (x 1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>15</td>
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<tr>
<td>20</td>
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<td>130</td>
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<td>135</td>
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<tr>
<td>140</td>
</tr>
</tbody>
</table>

RTM Glass
RTM Ca/Gl
SMC

Massachusetts Institute of Technology
Cambridge, Massachusetts
Materials Systems Laboratory
Individual Sub-Systems: Roof

- Steel: 9 parts
- RTM: 2 Parts
- SMC: 1 Part

Annual Production Volume (x 1000)

Individual Subsystems: Floorpan/Cross Member

- Steel: 57 parts
- RTM: 2 parts + 20 inserts
- SMC: 9 parts + 20 inserts

Annual Production Volume (x 1000)
Hybrid Vehicle Scenarios

Hybrid Vehicle
Bodyside: SMC (5-30% Scrap)
Floorpan/Cross Member: RTM
Front End: RTM
Roof: Steel

Hybrid Vehicle Scenarios

Hybrid Vehicle
Bodyside: SMC (5-30% Scrap)
Floorpan/Cross Member: RTM
Front End: RTM
Roof: Steel
**Conclusions**

- Total cost of composites BIW is competitive with steel at low production volumes (< 40,000 per year)
- Carbon Fiber
  - Use of carbon fiber significantly reduces BIW weight
  - Material price for carbon fiber is too high to justify use in BIW applications
- SMC
  - SMC design requires reinforcing ribs and box sections, which increase weight, tooling costs and assembly costs
  - SMC can be competitive with RTM BIW, given design assumptions
- Subsystems
  - Parts consolidation is a significant advantage for composites
    - Roof: low parts consolidation, no crossover with steel
    - Floorpan/Cross Member: high parts consolidation, > 50,000 crossover
  - Designs must minimize material waste
    - Bodyside: significant consolidation, high material costs => low crossover
- Hybrid vehicles can potentially become competitive with steel at high production volumes