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

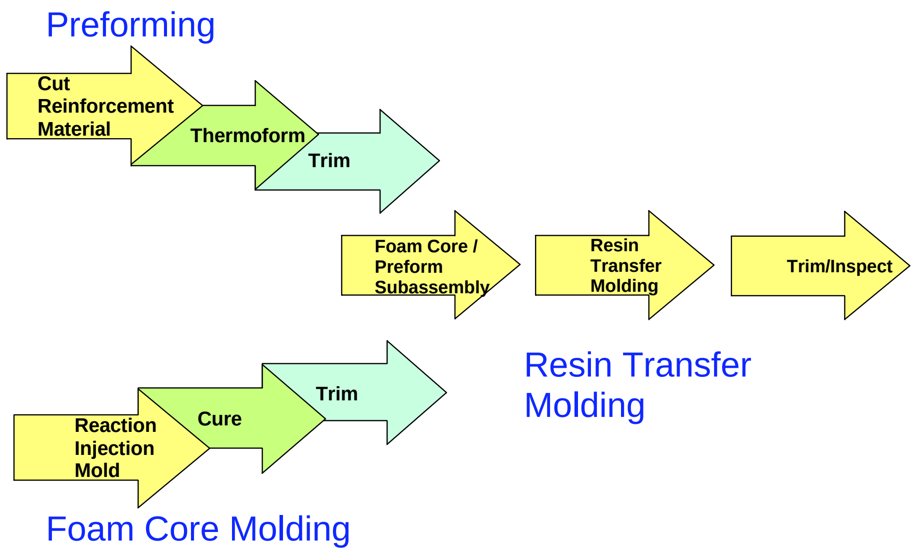
- Steel Comparator
  - Honda Odyssey minivan
  - Based on Accord chassis, so comparable size
  - BIW Weight : approx. 400 kg

- 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



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

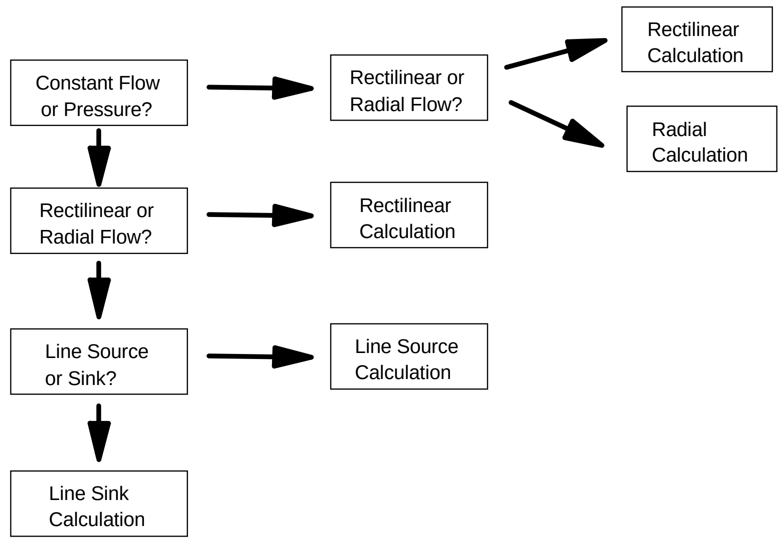
Resin Transfer Molding Cycle Time Estimation

- 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 = -(KA/m) dp/dx, where Q = volumetric flow rate, K=permeability, A=cross-sectional area, m=viscosity and dp/dx = pressure gradient
  - Assumptions:
    - *Isothermal flow*
    - *Incompressible, constant viscosity fluid*
    - *Homogeneous reinforcement*
- Cure Time
  - dc/dt = (k1 + k2 c^m) (1-c)^n, where c=degree of conversion, k1 and k2 are Arrhenius constants, and m,n are empirical constants
  - Assume m = 0, n = 2,
    - *Cure Time = (1/A)exp(E/RT) x 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



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

	Fill Time (sec)	Mold Force (N)	Press Cost ($)
Rectilinear, Constant Flow	12.15	5.4×10^6	$3,012,346
Rectilinear, Constant Pressure	249.11	4.03×10^5	$355,782
Radial Source, Constant Pressure	233.45	9.04×10^4	$176,850
Radial Sink, Constant Pressure	15.54	1.36×10^6	$903,743

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

RTM Cost Modeling Assumptions

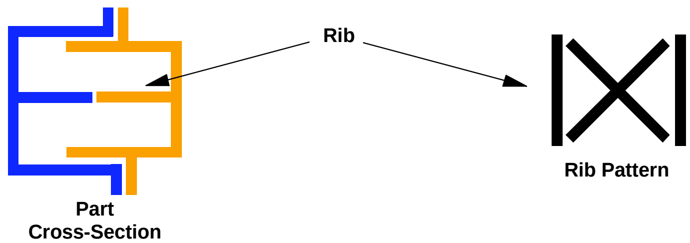
- Materials Prices:
  - Resin (Vinyl Ester) $2.60 / kg
  - Filler (Calcium Carbonate) $0.13 / kg
  - Reinforcement:
    - *Glass Fiber CSM* $2.00 / kg
    - *Carbon Fiber* $11.00 / kg
    - *Carbon / Glass Blend* $6.50 / kg
  - Catalyst $3.24 / kg
  - Foam Core (Polyurethane) $2.54 / kg
- Foam Core Molding, Thermoforming and RTM Tool Material: Steel
- RTM Flow: Rectilinear, Constant Pressure
- 32 Steel Inserts

Key Carbon Fiber Design Assumptions for CIV

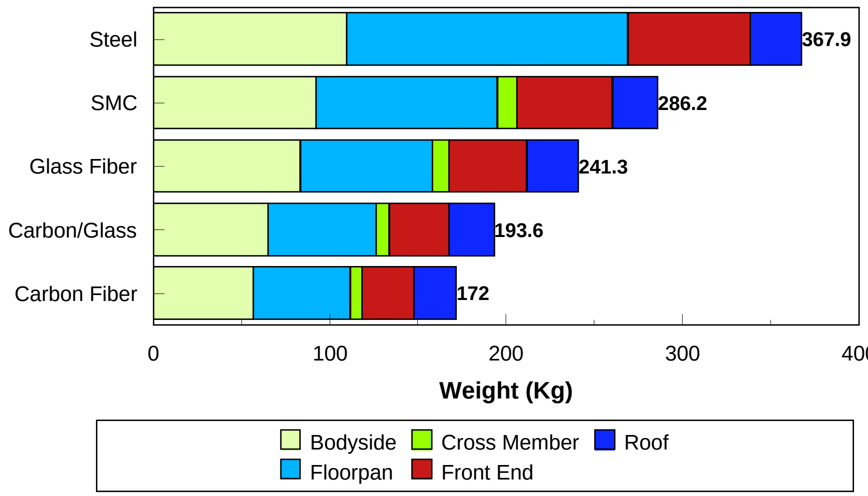
- Use simple beam loading equations to estimate the equivalent thickness of carbon fiber part compared its glass fiber equivalent
- Ratio of moduli determines the thickness of the carbon fiber part
  - Elastic Modulus (Msi):
    - *E glass fiber : 10.5*
    - *Carbon fiber : 34*
    - *Carbon / Glass : 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

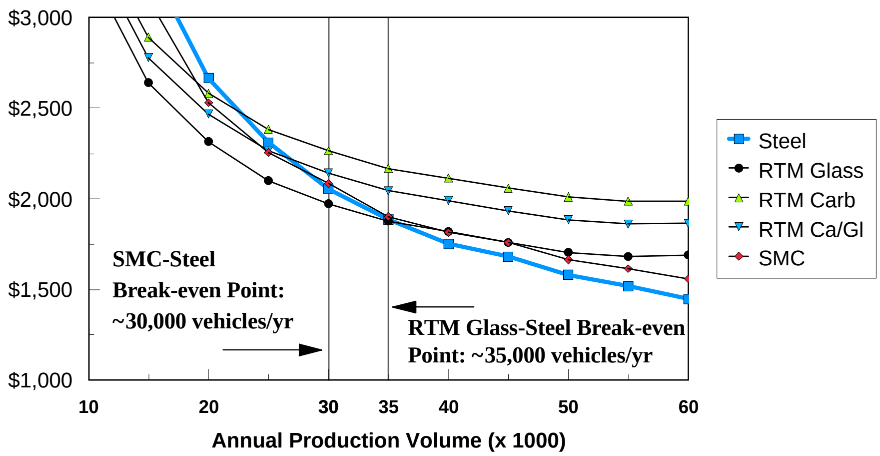
- SMC part thickness : 4 mm
- Reinforcing rib structure placed every 150 mm
- Reinforcing rib dimensions
  - Length = 150 mm
  - Height and Width are dependent on part geometry
- Foam cores assumed in parts where crush resistance is necessary
  - Front End rails
  - Floorpan
- SMC part is composed of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



Comparison of Part Weights (including CIV inserts)



Results: Total Manufacturing and Assembly Cost

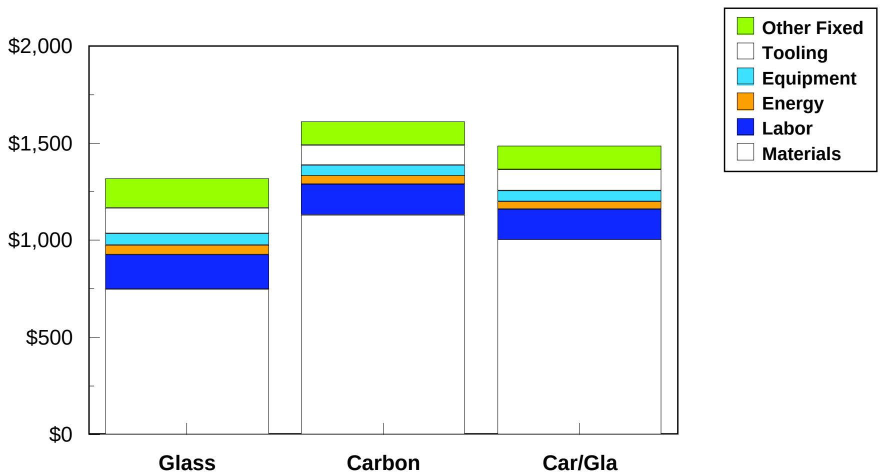


(Composites Wage: $25/hr)

Massachusetts Institute of Technology
Cambridge, Massachusetts

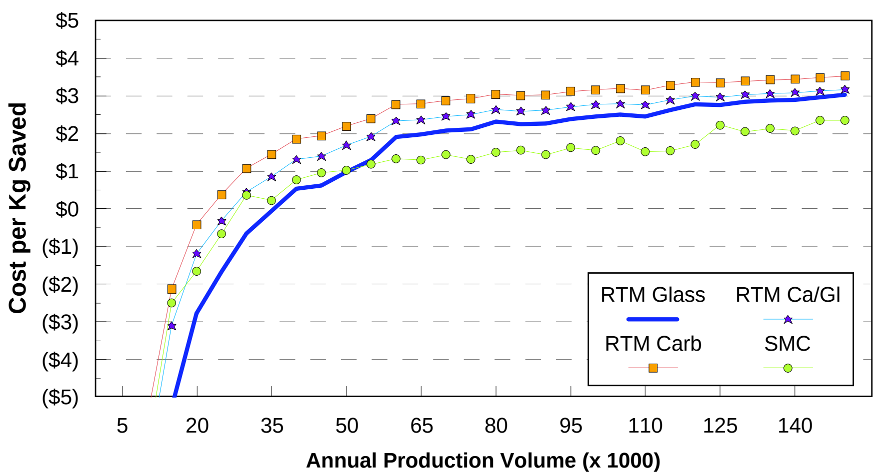
MSL
Materials Systems Laboratory

Manufacturing Cost Breakdown: Glass vs Carbon Fiber

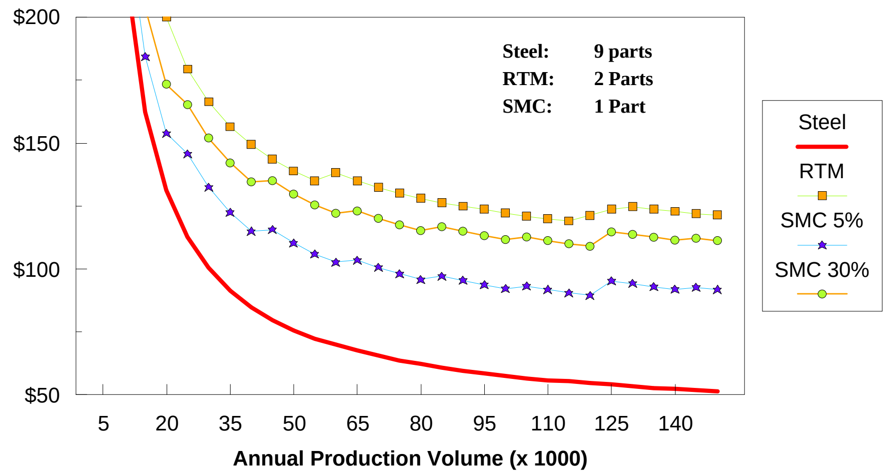


(Volume = 35,000)

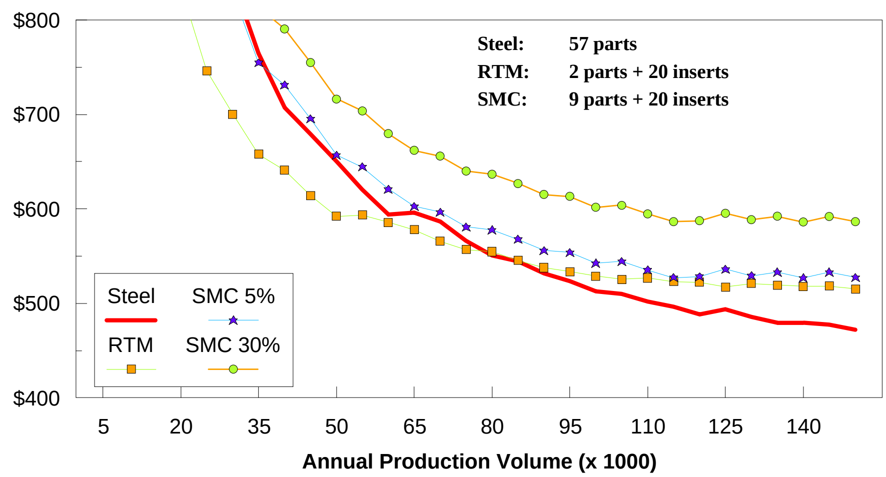
Cost per Kilogram Saved (Relative to Steel Base Case)



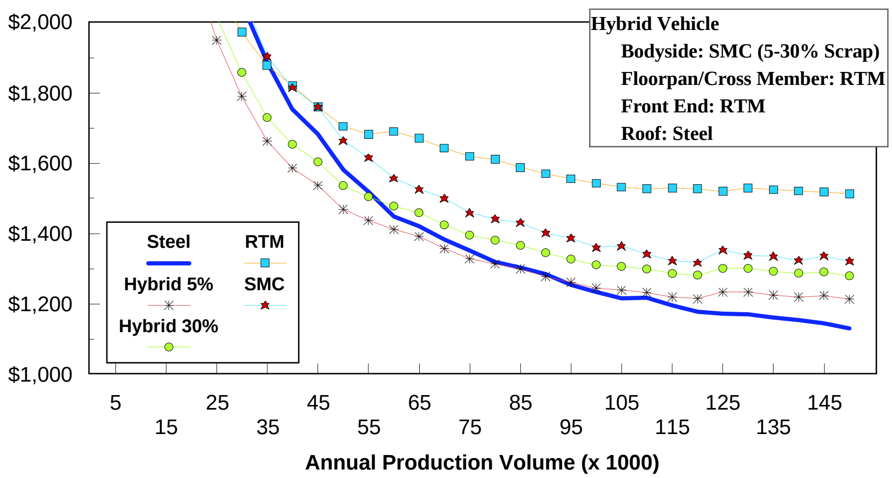
Individual Sub-Systems: Roof



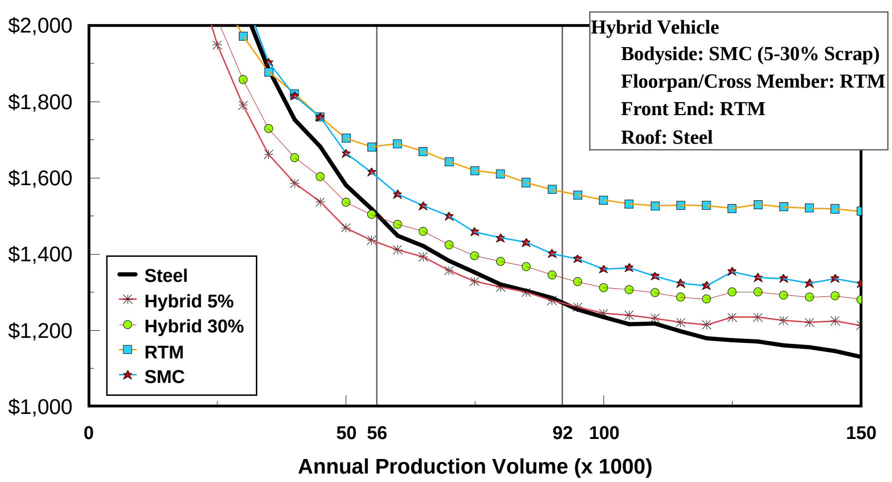
Individual Subsystems: Floorpan/Cross Member



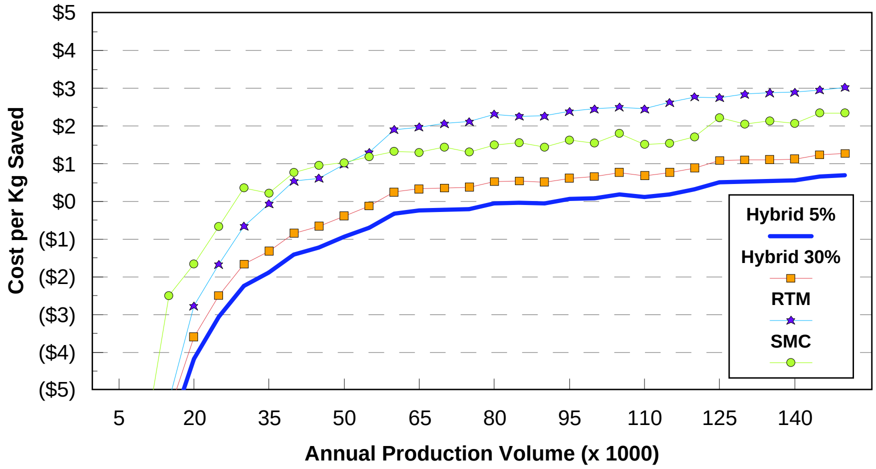
Hybrid Vehicle Scenarios



Hybrid Vehicle Scenarios



Hybrid Vehicles: Cost per Kilogram Saved



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