ADVANCED AUTOMOTIVE MATERIALS: THE NEW DNA OF PERSONAL MOBILITY

Mark Verbrugge
Director, Chemical Sciences and Materials Systems Laboratory
Outline

- GM, GM R&D
- Automotive challenges and potential paths forward
  - Looking for a new automotive DNA
- Topics awaiting materials innovation
  - Electrified vehicles (focus on energy storage and conversion)
  - Lightweight materials
- Collaborative Research Laboratories
  - Case study: GM-Brown CRL
GENERAL MOTORS COMPANY

- Traces its roots to 1908
- Worldwide Employment: 207,000
- 2011 Worldwide Vehicle Sales: 9 million
- 2011 Global Vehicle Market: 11.9%
- 2011 Global Revenue: $150.3 billion
- 2011 Net Income: $7.6 billion
GM R&D HISTORY

- Central R&D organization for General Motors
- Organized in 1920 under Charles ("Boss") Kettering
- World's first automotive research organization
- Now employs an extended Global Network
THE FIRST 125 YEARS OF THE AUTO INDUSTRY:
EVOLUTION TO MODERN DESIGN

1886  
Karl Benz’  
Motorwagen –  
First Automobile

1908  
Henry Ford’s  
Model T –  
First Affordable  
Automobile

1927  
General Motors’  
LaSalle Began  
Modern Era  
of American  
Automotive Styling

1950
THE FIRST 125 YEARS OF THE AUTO INDUSTRY: KEY DRIVERS AND TECHNOLOGY ENABLERS

PRODUCT

Annual Model Change
Design Is King


~300,000 Units/Models
THE FIRST 125 YEARS OF THE AUTO INDUSTRY: KEY DRIVERS AND TECHNOLOGY ENABLERS

EXTERNALITIES

PRODUCT

Annual Model Change Design Is King

“Safety” Focus

“Oil Shock”


~300,000 Units/Models

TECHNOLOGY ENABLERS
AUTO INDUSTRY PROGRESS

- Reduced Emissions by 99%
- Improved FE by 180%/93%
- Reduced Fatal Crashes by 75%
- Improved Affordability by 30%
THE FIRST 125 YEARS OF THE AUTO INDUSTRY: KEY DRIVERS AND TECHNOLOGY ENABLERS

EXTERNALITIES

PRODUCT

Annual Model Change
Design Is King

“Safety” Focus

“Oil Shock”

“Gotta have” Design returns


~300,000 Units/Models

50,000-100,000 Units/Models

TECHNOLOGY ENABLERS
EVERYTHING BEGINS AND ENDS WITH GREAT PRODUCTS
The SUSTAINABILITY CHALLENGE of 21st Century Personal Mobility
TOP 10 MARKETS BY NEW VEHICLE SALES IN 2011

2011 Sales (M)
Emerging Markets 39.5
Mature Markets 36.5
World Total 76.0

China Growth (%)
vs. 2010 vs. 2005 vs. 2000
2% 325% 854%
PERSONAL MOBILITY MUST BE REINVENTED FOR THE 21st CENTURY

Data from U.S. Census Bureau and GM Global Market & Industry Analysis
CURRENT DNA

- Energized by Petroleum
- Powered Mechanically by Internal Combustion Engine
- Controlled Mechanically
- Stand-alone
- Totally Dependence on the Driver
- Vehicle Sized for Max Use – People and Cargo

NEW DNA

- Energized by Biofuels, Electricity, and Hydrogen
- Powered Electrically by Electric Motors
- Controlled Electronically
- “Connected”
- Semi/Full Autonomous Driving
- Vehicle Tailored to Specific Use
## TECHNOLOGY DRIVERS FOR THE 2\textsuperscript{ND} CENTURY OF PERSONAL MOBILITY

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Stretch Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>High-efficiency vehicles using low-cost renewable energy</td>
</tr>
<tr>
<td>Emissions</td>
<td>No tailpipe environmental impact</td>
</tr>
<tr>
<td>Safety</td>
<td>Vehicles that don’t crash</td>
</tr>
<tr>
<td></td>
<td>Autonomous driving</td>
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<tr>
<td>Congestion</td>
<td>Congestion-free routing</td>
</tr>
<tr>
<td></td>
<td>Megacity parking</td>
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<tr>
<td>Affordability</td>
<td>Personal mobility “for every purse and purpose”</td>
</tr>
</tbody>
</table>
ADVANCED PROPULSION TECHNOLOGY STRATEGY

- Improve Vehicle Fuel Economy and Emissions
- Displace Petroleum

Hydrogen Fuel Cell-Electric Vehicles
Battery-Electric Vehicles (including E-REV)
Hybrid-Electric Vehicles (including Plug-in HEV)
IC Engine and Transmission Improvements

Petroleum (Conventional and Alternative Sources)
Alternative Fuels (Ethanol, Biodiesel, CNG, LPG)
Electricity (Conv. and Alternative Sources)
Hydrogen
PROJECT DRIVEWAY

35-50 MILES GAS-FREE

2,400,000 MILES LOGGED
2011 CAR OF THE YEAR AWARDS AND TOP HONORS
VOLTEC PROPULSION SYSTEM

- 288-Cell, 16-kWh Battery
- 1.4L Engine
- DC Cables
- AC Cables
- Power Inverter
- Fuel Tank
- Half Shafts

35 MILES BATTERY Electric Driving + 344 MILES EXTENDED-RANGE Driving
2013 CHEVROLET SPARK BEV

Nanophosphate Lithium-ion Battery
Cathode (+) Oxides
- Layered – LiCoO₂, LiNiO₂
- Composite – Li₂MnO₃-LiNxMnyCozO₂
- Spinel – LiMn₂O₄
  - High Voltage Spinel – LiMn₁.₅Ni₀.₅O₄
- Silicates, Olivines – Li₂MSiO₄, LiFePO₄

Requirements
- Cost, safety, stability, conductivity

Anode (-)
- Carbon – LiC₆
- Silicon Composites and Alloys

Electrolyte
- LiPF₆ in Organic Carbonate Solvent
  - Need: Higher Voltage Stability
  - Protective layers? New salts/solvents?

Separator
- Ceramic-Coated Polymer
- Chemically Functionalized Polymer?

- Significant majority of the battery cost/volume/mass is in the cell materials
- Developments are needed in all four of the lithium-ion cell subcomponents
EVERYDAY DRIVERS

>6,000

MILES LOGGED

PRODUCTION-INTENT
FUEL CELL SYSTEM

>6,000
EVERYDAY DRIVERS

2,400,000
MILES LOGGED

- Zero emissions
- 350-mile range
- 3-minute H2 refueling

- Cost reduction
- Infrastructure deployment
REMAINING FUEL CELL VEHICLE CHALLENGES

Manufacturability/Simplification

Stack Manufacturability/Cost

- Seal processing time (stack, then seal)
  - Requires injection moldable seal

Novel plate designs/materials

- Photopolymer designs as framework
- Requires electronically conductive coatings

System Simplification/Cost

- Fuel Cell System
  - Reduction of sensors, actuators
  - State of health/life models

- H₂ Storage System
  - Materials cost (C'fiber, SS→Al)
  - Reduction of valves, fittings
VEHICLE WEIGHT AND FUEL ECONOMY

6% improvement in fuel economy for 10% mass reduction

- 0.4 mpg improvement per 100 lbs., for 3,500-lb. vehicle
- 0.5 km/L improvement per 100kg weight reduction, for 1500kg vehicle
# Advanced Materials for Lightweight Vehicles

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight Reduction vs. Low-Carbon Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-strength steel</td>
<td>15-25%</td>
</tr>
<tr>
<td>Glass-fiber composite</td>
<td>25-35%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>40-50%</td>
</tr>
<tr>
<td>Magnesium</td>
<td>55-60%</td>
</tr>
<tr>
<td>Carbon-fiber composite</td>
<td>55-60%</td>
</tr>
</tbody>
</table>
Lightweight materials can provide 35-60% weight reduction compared to steel.
MULTI-MATERIAL BODY – THE FUTURE

Mg-Intensive Front-end

Steel: 79 Parts; 84 kg
Mg: 35 Parts; 46 kg
(Eliminate 44 Parts and Save 38 kg - 45%)

Castings (15): 31 kg
Extrusions (3): 9 kg
Sheet Parts (17): 6 kg

AHSS Passenger Compartment

Composite Floor Pan
GREEN AND RECYCLED VEHICLE MATERIALS
GM’s Global R&D Network

Alliance Partner

USCAR
EUCAR

Suzuki

Affiliated Lab

HRL

OEMs

USCAR
EUCAR
Sandia

Government Lab

Strategic Partners

Suppliers

Start-ups

Individual Contracts

Collaborative Research Labs

Universities

U. of Michigan
Brown
Carnegie Mellon
IISc-Bangalore
M.I.T.
U. of Wisconsin
IIT-Kharagpur
SJTU-Shanghai

Global Sites

Australia
Canada
China
India
Israel
Japan
Korea
Russia

Science and Tech Offices

Warren
Bangalore
Honeoye Falls
Mainz-Kastel
Palo Alto
Herzliya
Shanghai
COLLABORATIVE RESEARCH LABORATORIES

- Strategic partnership in a key technology area for GM
- 5-year commitment
- Incorporates a group of professors in a large program vs. individual projects
- Encourages people exchange, sabbaticals, student interns, visits
- GM fully funds
- CRL co-directed
- Tasks and goals are defined together
GM/UNIVERSITY CRL STRUCTURE

- University
- GM/University Collaborative Research Lab
  - Lab Co-Directors
    - Focus on CRL Mission and Goals
      - Thrust Area 1
        - Co-Leaders
      - Thrust Area 2
        - Co-Leaders
      - Thrust Area 3
        - Co-Leaders
      - Thrust Area...
        - Co-Leaders
- Administrative Support
- GM R&D
GENERAL MOTORS – BROWN UNIVERSITY COLLABORATIVE RESEARCH LABORATORY FOR COMPUTATIONAL MATERIALS RESEARCH

From Atoms

To Autos

2005 to 2010
- Microstructure Based Computational Plasticity Modeling
- Elevated Temperature Deformation of Al and Mg Alloys
- Engineered Surfaces and Interfaces

Allan F. Bower,* William Curtin, Huajian Gao, K.-S Kim, Sharvan Kumar, Brian Sheldon, Vivek Shenoy, School of Engineering, Brown University, Providence RI

Josh Campbell, Louis Hector, Jr., Raj Mishra, Yue Qi, Anil Sachdev, Mark W. Verbrugge,* X. Xiao, Chemical Sciences and Material Systems Laboratory, General Motors R&D Center, Warren MI

*Co-Director
CRL Structure for our next 5-yr phase

Brown Univ.  
GM/Brown Collaborative Research Laboratory  
Lab Co-Directors  
GM R&D  
Multi-Scale Computational Design of Al and Mg Alloys and Steels  
Characterization of Irreversible Deformation and Fracture in Li-Insertion Electrode Materials

The importance of solid mechanics to the clarification of degradation processes that take place within lithium ion batteries prompted us to expand into this topic area for the CRL.
Technology Matrix for Strategic Planning

<table>
<thead>
<tr>
<th>Need/Potential for Proprietary Advantage</th>
<th>Weak</th>
<th>Moderate</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolutely</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acquire Capability</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Build Strength</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Do In-House</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Probably</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collaborate or Monitor Field</td>
<td></td>
<td></td>
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<tr>
<td>Spread/Share Risk, Find Partners, Collaborate, etc.</td>
<td></td>
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<tr>
<td>Do In-House</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Share Risk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not sure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outsource</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Candidates for a Virtual Business</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Leverage External Resources, Borrow, Barter, etc.</td>
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<td></td>
<td></td>
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<tr>
<td>Cash cow</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Not likely</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abandon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sell</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


In general, one should migrate to the diagonal.
From a firm perspective in growth mode

- It’s critical to move out of the R&D box as quickly as possible.
- The same is actually true for all states noted:
  - Stay in high-volume, resource-intensive production only when profitable
  - Advanced Engr & Mfg have high burn rates

### Strategic Partner, e.g., a CRL

<table>
<thead>
<tr>
<th>Need/Potential for Proprietary Advantage</th>
<th>Technical Capability Relative to Achieving Proprietary Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;D Capabilities</td>
<td>Weak</td>
</tr>
<tr>
<td>Advanced Engineering and Manufacturing</td>
<td>Moderate</td>
</tr>
<tr>
<td>Product Engr, Mfg.</td>
<td>Strong</td>
</tr>
</tbody>
</table>

#### Lesson Learned & Move On
- Abandon
- Collaborate or Monitor Field
- Leverage External Resources, Borrow, Barter, etc.
- Do In-House
- Share Risk
- Cash cow
- Sell

### Abbreviations
- CRL: Contract Research Laboratory

#### Graph

- **R&D phase**: Buying the option
- **Profit**
- **Time**
What really makes a CRL successful?

Collaboration
- Trust...cultivate a professional but low-risk environment to encourage ideation, roadmapping, project plans
- Problem selection...industrially relevant but in need of a research solution
- A champion on both sides (university and industry)
- Hard work by great people

Recognize the value of accomplishments

GM-Brown CRL Accomplishments.. 2005 to 2010
- Publications in Refereed Journal Articles.. 62
- GM Internal Reports
  - Development of lightweight Aluminum and Magnesium alloys with enhanced room temperature formability.. 6
  - Optimizing the microstructure and composition of Al and Mg alloys for elevated temperature forming.. 9
  - Developing engineered surfaces for wear-resistant linerless engines and coatings for dry drilling.. 12
  - Failure mechanisms understating of battery negative electrode materials.. 3
- Presentations.. 41
- Other key metrics.. students graduated, awards, external collaborations and linkages
Summary

- GM, GM R&D
- Automotive challenges and potential paths forward
  - Looking for a new automotive DNA
- Topics awaiting materials innovation
  - Electrified vehicles (focus on energy storage and conversion)
  - Lightweight materials
- Collaborative Research Laboratories
  - Case study: GM-Brown CRL