Reinventing the Automobile

EDF-Alliance Executive Workshop
Columbia University
October 11, 2011

Lawrence D. Burns

Global Automobile Transportation

- 850 M cars and trucks
- ≈ 70 M new vehicles per year
- Significant growth likely
  - Emerging markets
  - Especially China
- Enormous Inertia
  - Scale
  - Co-dependent infrastructure (Energy, Roads, Traffic Controls)

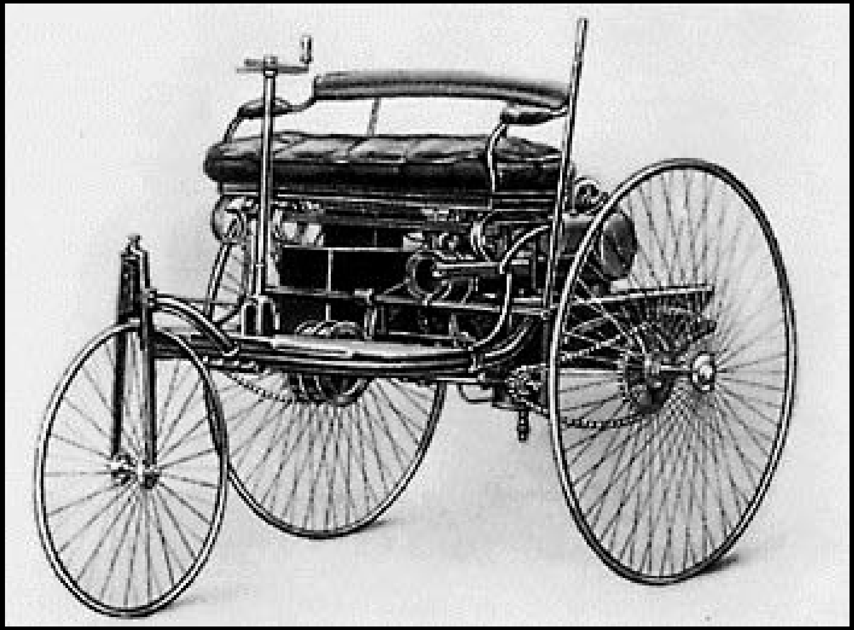
Freedom

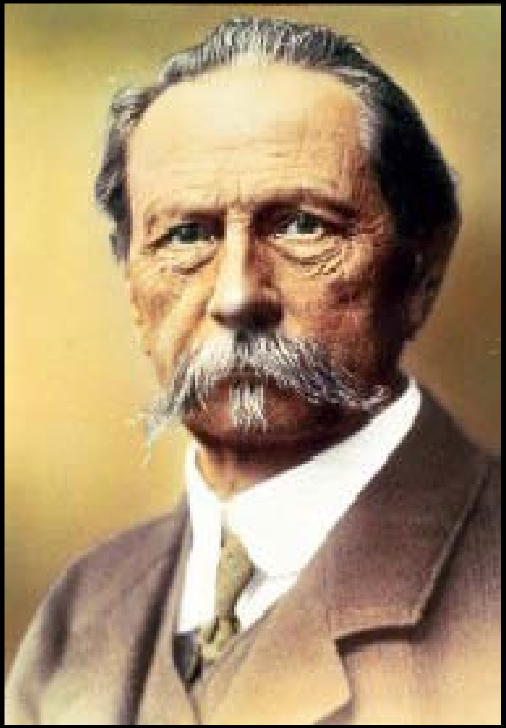
Challenges

- Energy: 95% dependent on oil
- Environment: CO_2 emissions
- Safety: 1.2 M roadway fatalities worldwide
- Congestion: Severe traffic delays

1886: From Horses to Horsepower

Karl Benz Granted Patent for First Gasoline Powered Automobile





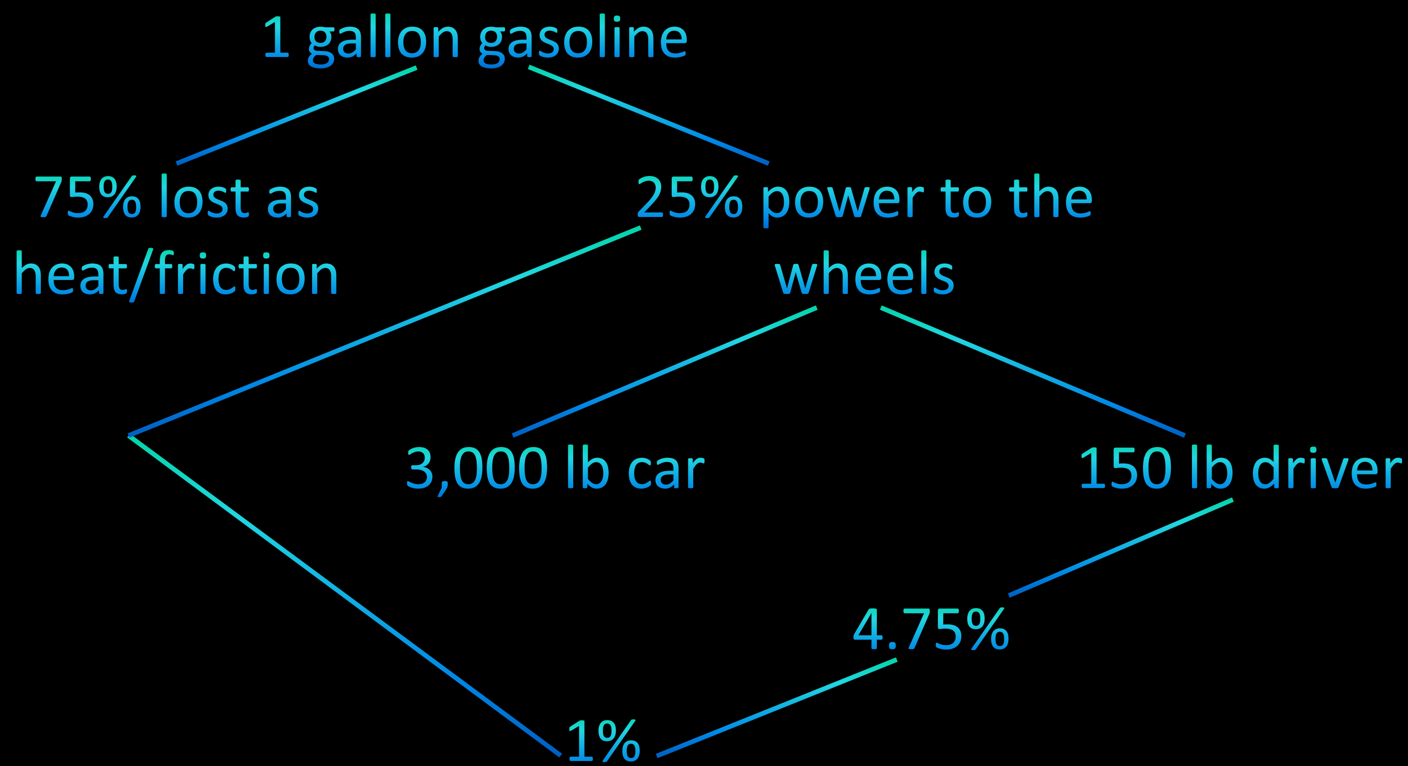
Historical Automotive “DNA”

- Mechanical Drive
- Combustion Engines
- Oil-based Fuels
- Mechanical & Hydraulic Controls
- Human Operated
- Stand-alone

Likely Unsustainable

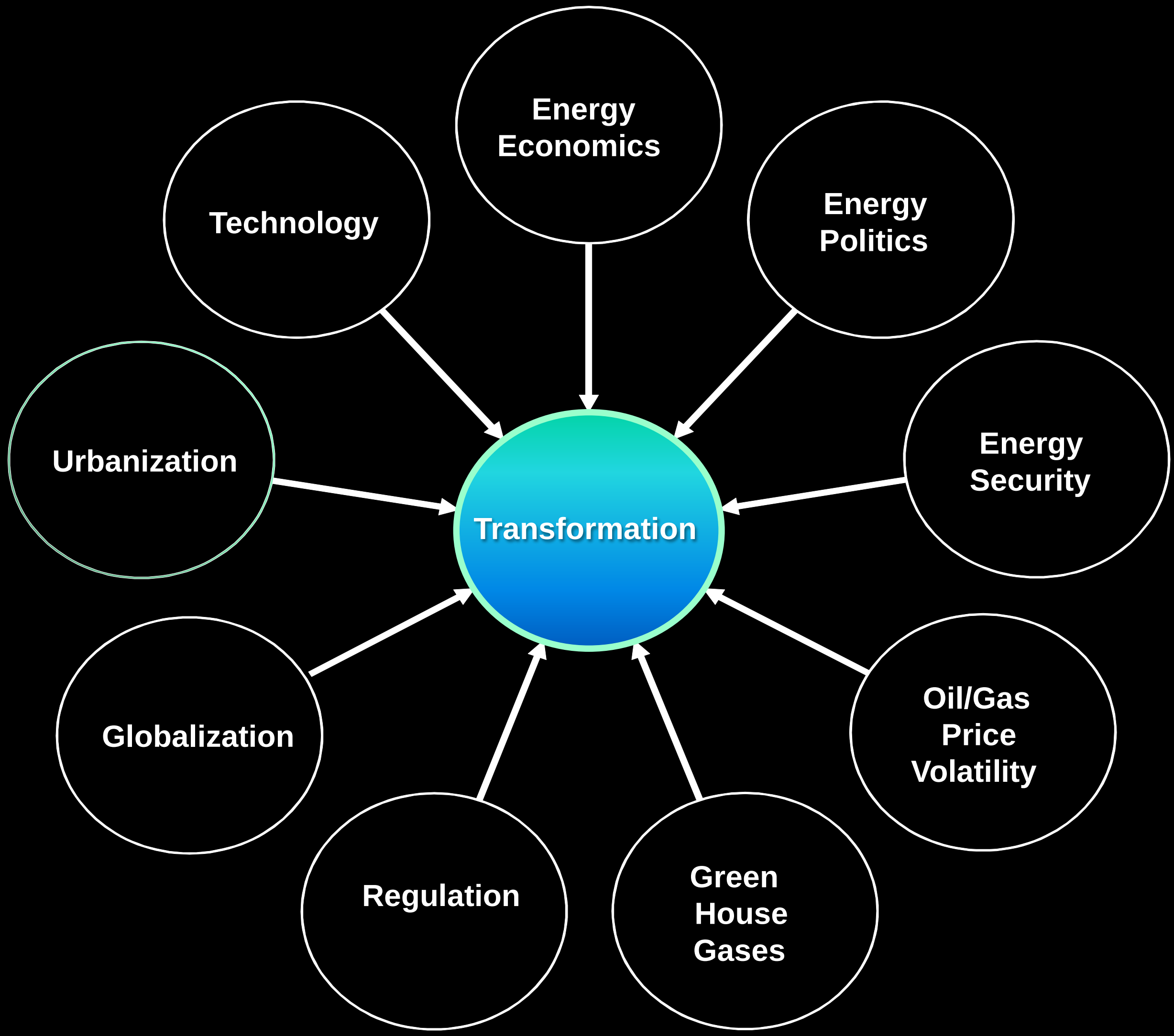
"Pop" Quiz

How much of the energy in a gallon of gasoline is used to move the driver of a car? 1%!

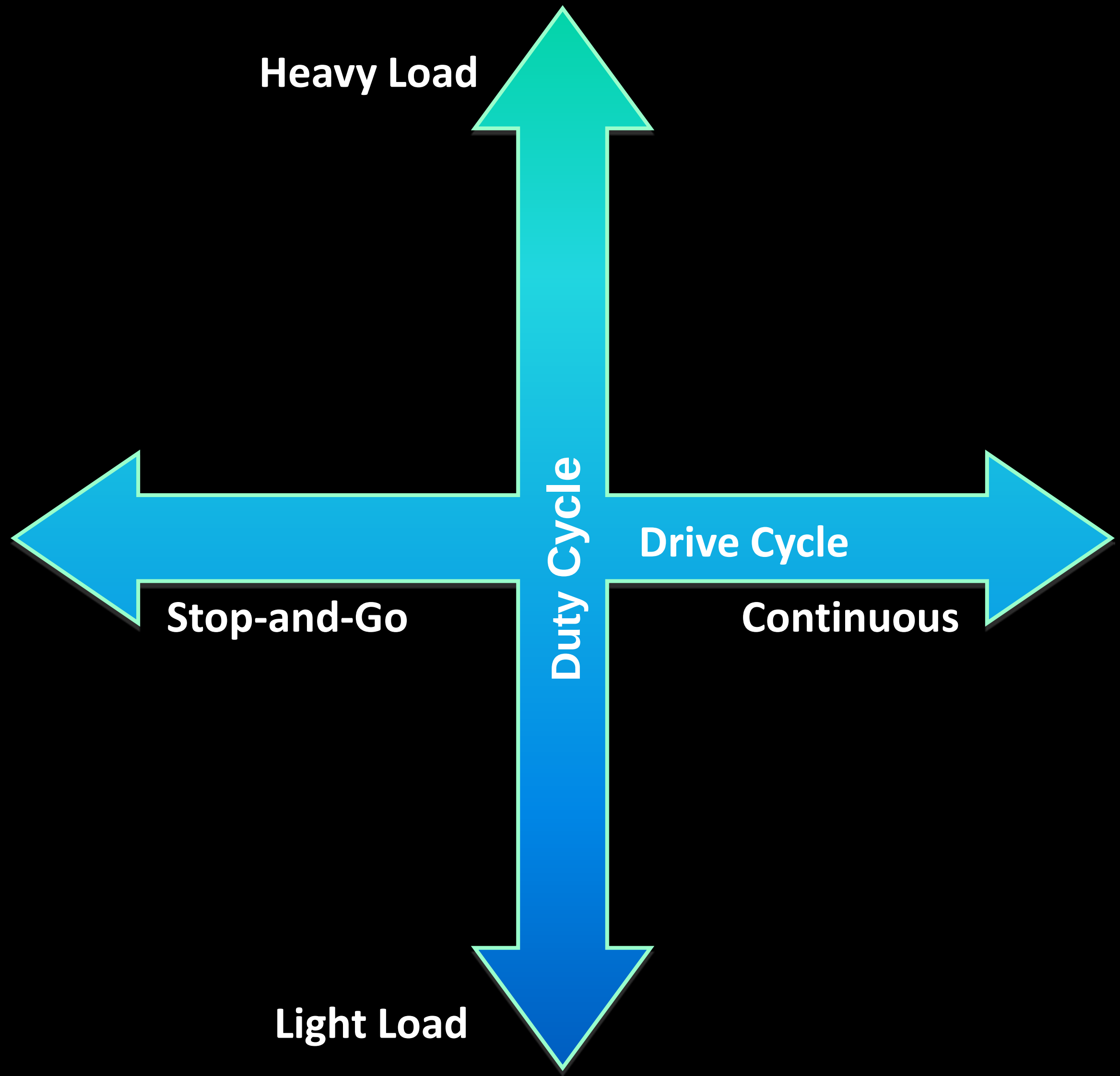


We have a system design opportunity not an energy problem!

Multiple Drivers of Change



Range of Consumer Needs



New Automotive “DNA”

- Electrical Drive
- Electric Motors
- Diverse Energy Sources
- Electronic & Digital Controls
- Autonomously Operated
- “Connected”

Transformational Change

Historical "DNA"

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New "DNA"

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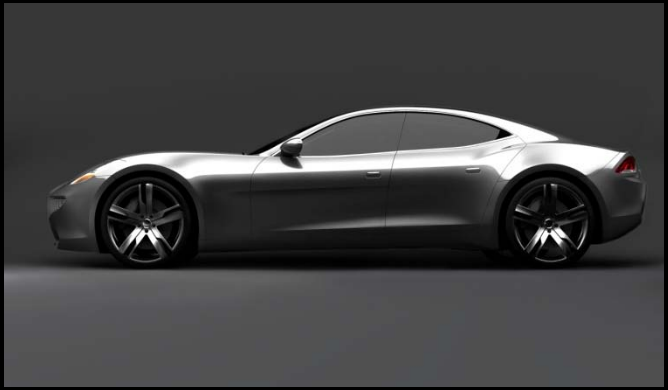
Electric Vehicles are Here!

Example Plug-In EVs

Extended Range

Chevrolet Volt



Fisker Karma

Pure Plug-In

Ford Focus EV

Tesla S-Model

Nissan Leaf

Example Fuel-Cell Electric Vehicles

Daimler B Class F-Cell

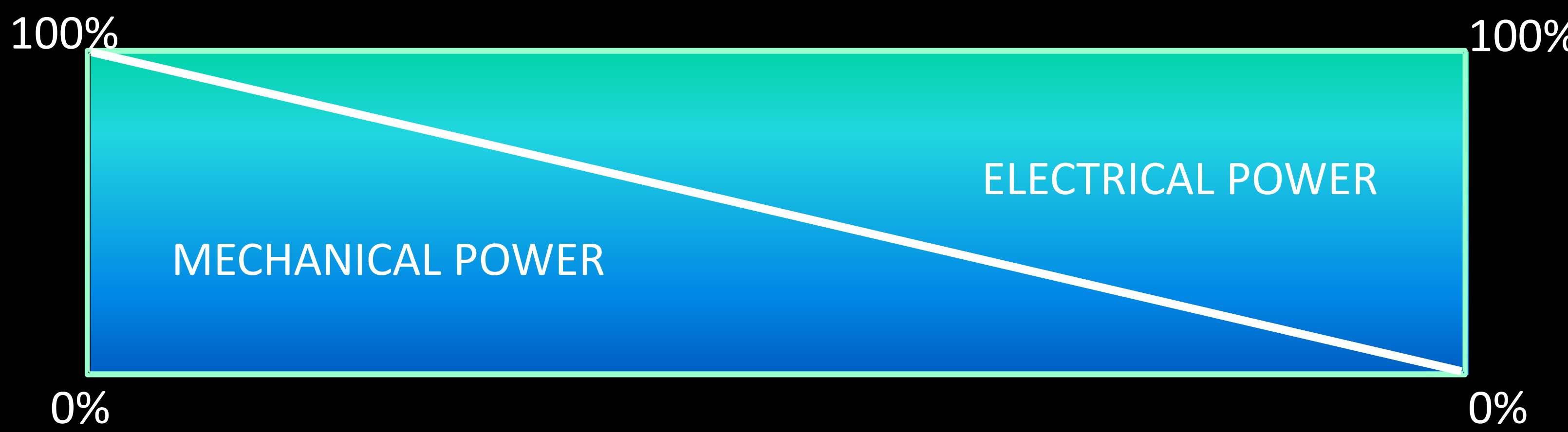
Honda Clarity

Hyundai Tucson ix35 FCEV

Toyota Highlander FCV

Chevrolet Equinox Fuel Cell

Vehicle Electrification



Internal Combustion Engine (ICE)

Hybrid (HEV)

PlugIn Hybrid (PHEV)

Extended Range Electric (EREV)

Battery Electric (BEV)

Fuel Cell Electric (FCEV)

Mechanical Drive

Mechanical Drive with Electrical Assist

Electrical Drive with Mechanical Assist

Electrical Drive

<u>Interdependent</u> Battery Challenges

- Cost
- Durability
- Safety
- Mass
- Size
- Recharge Time
- Infrastructure

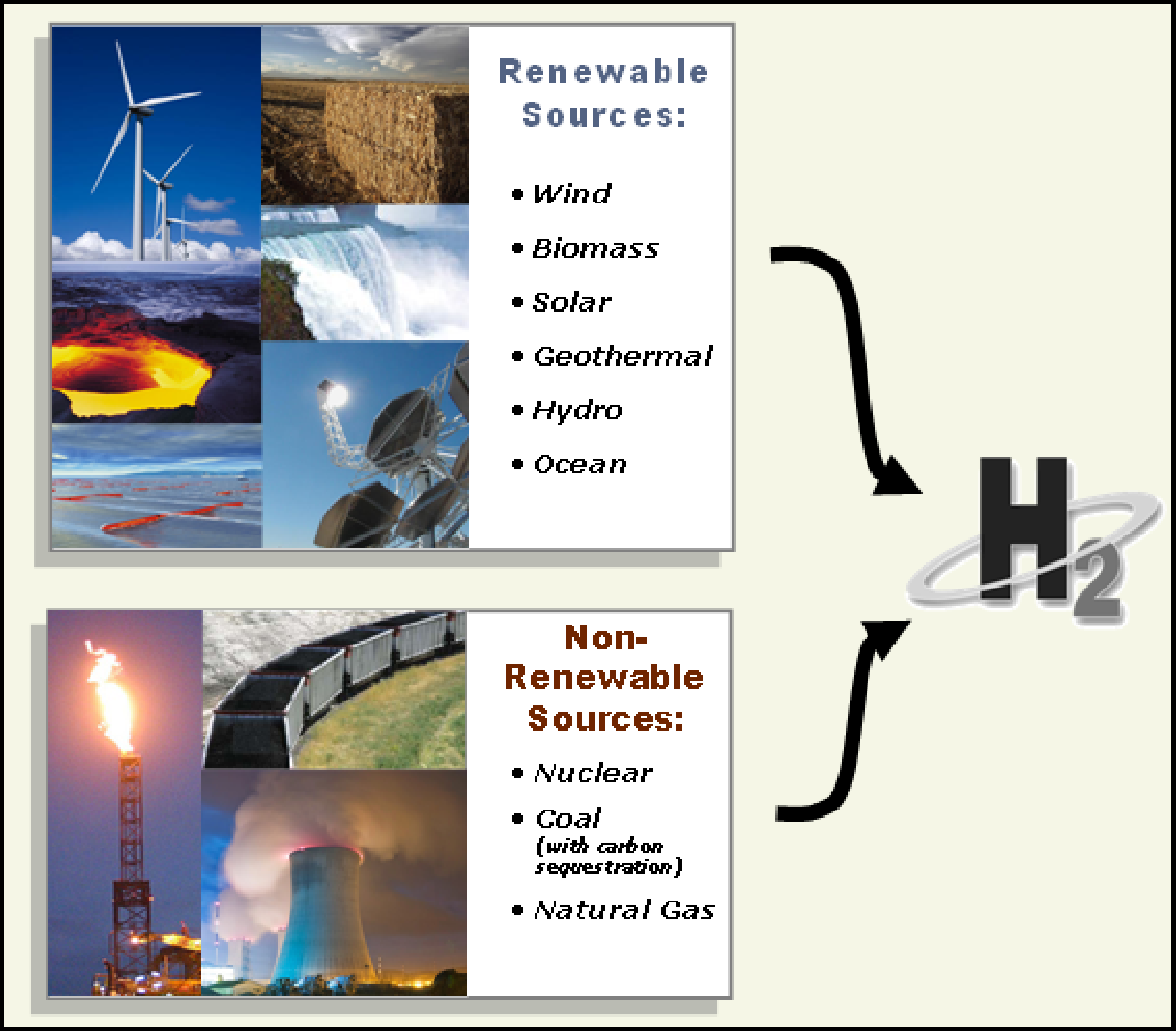
Important Factors to Keep in Mind

- Advanced batteries must mature
  - 3 commercial learning cycles
    - 10 to 12 years
    - "Market tipping point"
      - Customer Value > Market Price > Supplier Cost
  - Significant change from Gen 1 to Gen 3
- Significant grid investment for high volumes
- Wide range of customer requirements

Hydrogen Fuel Cell Technology

- **Can power family-sized vehicles**
- **Zero emissions & zero petroleum**
- **Compared to internal combustion engine:**
  - More than twice as efficient
  - Comparable precious metal content
  - Comparable durability, range (300 miles), performance & refueling time
  - 60% fewer parts
  - 90% fewer moving parts
- **Cold & hot operation capability**

Hydrogen Can be Made from a Wide Variety of Energy Sources



Shared Technology Building Blocks for Vehicle Electrification

- Motors
- Power electronics
- Controls
- Plug-in batteries
  - anodes, cathodes, separators, electrolytes
  - rechargers
- Hydrogen batteries
  - fuel cells
  - hydrogen storage
- Cooling systems
- Connectors and seals
- Advanced materials

Another “Pop” Quiz

How far can you drive on…

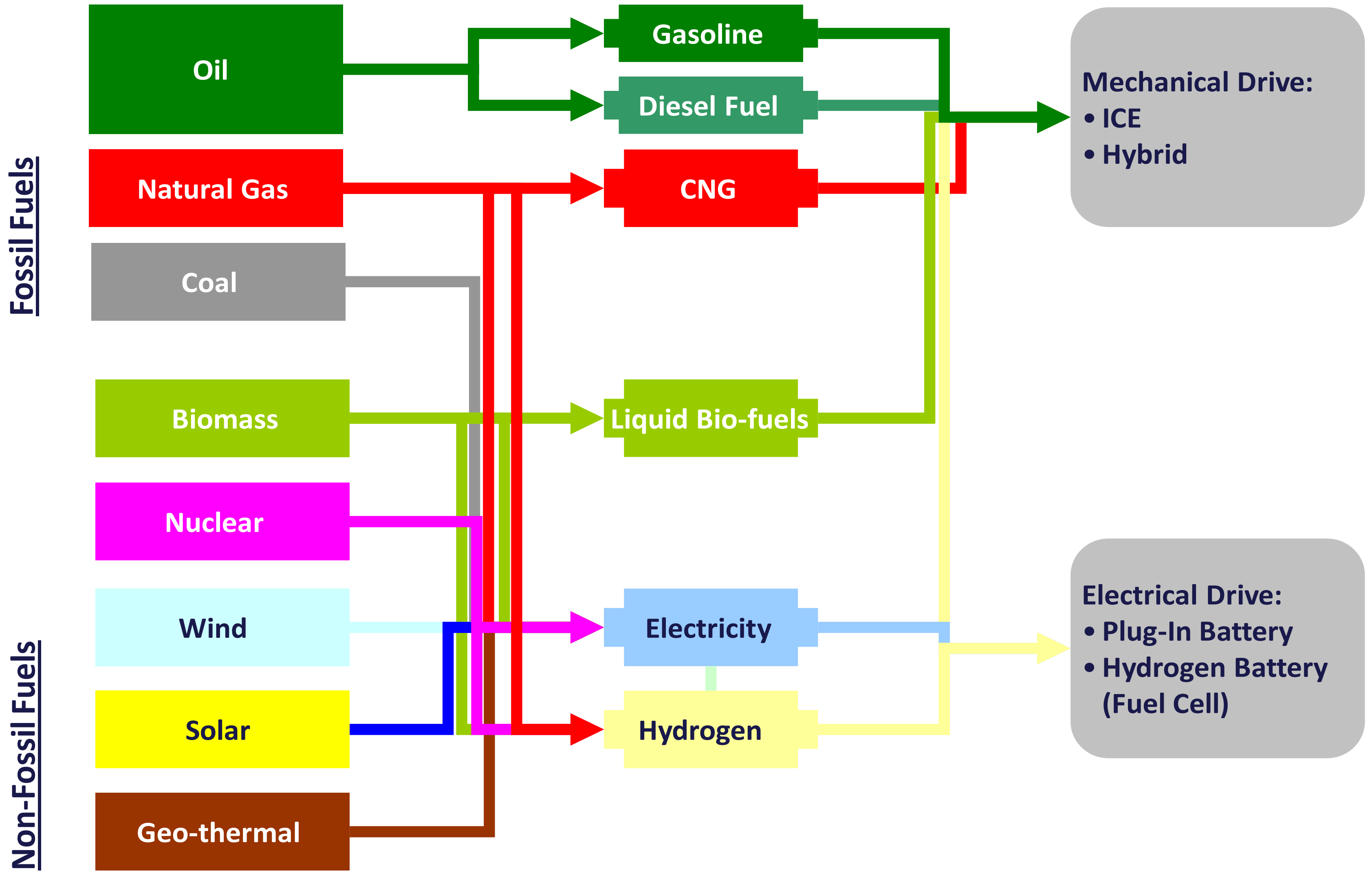
- The amount of gasoline you can pump in one hour? 7,000 miles
- The amount of compressed hydrogen you can pump in one hour? 5,000 miles
- The amount of electricity you can store in a battery in one hour?

Another "Pop" Quiz

How far can you drive on…

- The amount of gasoline you can pump in one hour? 7,000 miles
- The amount of compressed hydrogen you can pump in one hour? 5,000 miles
- The amount of electricity you can store in a battery in one hour?
  - 5 miles with 120V outlet
  - 20 miles with 240V outlet

Road Transportation Energy Supply



Non-Oil Energy Pathways

Natural Gas

- Compressed or Liquid → ICE
- Burn → Electricity → Plug-in EV
- Reform → Hydrogen → Fuel Cell EV or ICE

Biomass

- Liquid → ICE
- Burn → Electricity → Plug-in EV
- Reform → Hydrogen → Fuel Cell EV

Wind or Solar

- Electricity → Plug-in EV
- Electrolysis → Hydrogen → Fuel Cell EV

Energy Diversity Challenge

- Not a question of invention or know-how

- A “chicken and egg” challenge
  - Co-dependence of vehicles and energy supply
- An economic challenge
  - Capital required for infrastructure
  - Produce alternatives at competitive costs

Connected Vehicles are Here!

&

Autonomous Vehicles are Coming!

Google Cars Drive Themselves in Traffic

Autonomous Vehicles Are Compelling

- More value from time in vehicles
  - ”driving is a distraction!”
  - 1 hr/day X $25/hr X 250 days/yr = $6,250/yr
  - 1 hr/day X $50/hr X 250 days/yr = $12,500/yr

- Vehicles that don’t crash
  - eliminate roadway fatalities, injuries and property damage
  - enable lighter vehicles

- Lighter vehicles
  - enhance energy efficiency
  - enable better use of batteries (both plug-in and hydrogen)

Mobility Internet

- Enhances how people and goods move around and interact
- Does for vehicles what the Information Internet did for computers
- Manages huge amounts of spatial and temporal "connectivity" data
  - people
  - goods
  - vehicles
  - infrastructure
- Coordinates precisely
  - "millimeters and milliseconds"
  - "mega-meters and hours"
- Optimizes
  - safe traffic flow
  - road space use
  - parking space use
  - shared vehicles
  - commercial fleets
  - energy supply
- Creates opportunities for innovative "apps"

Design Transformation

Electric drive and “connected”/autonomous vehicles enable a transformation in vehicle design

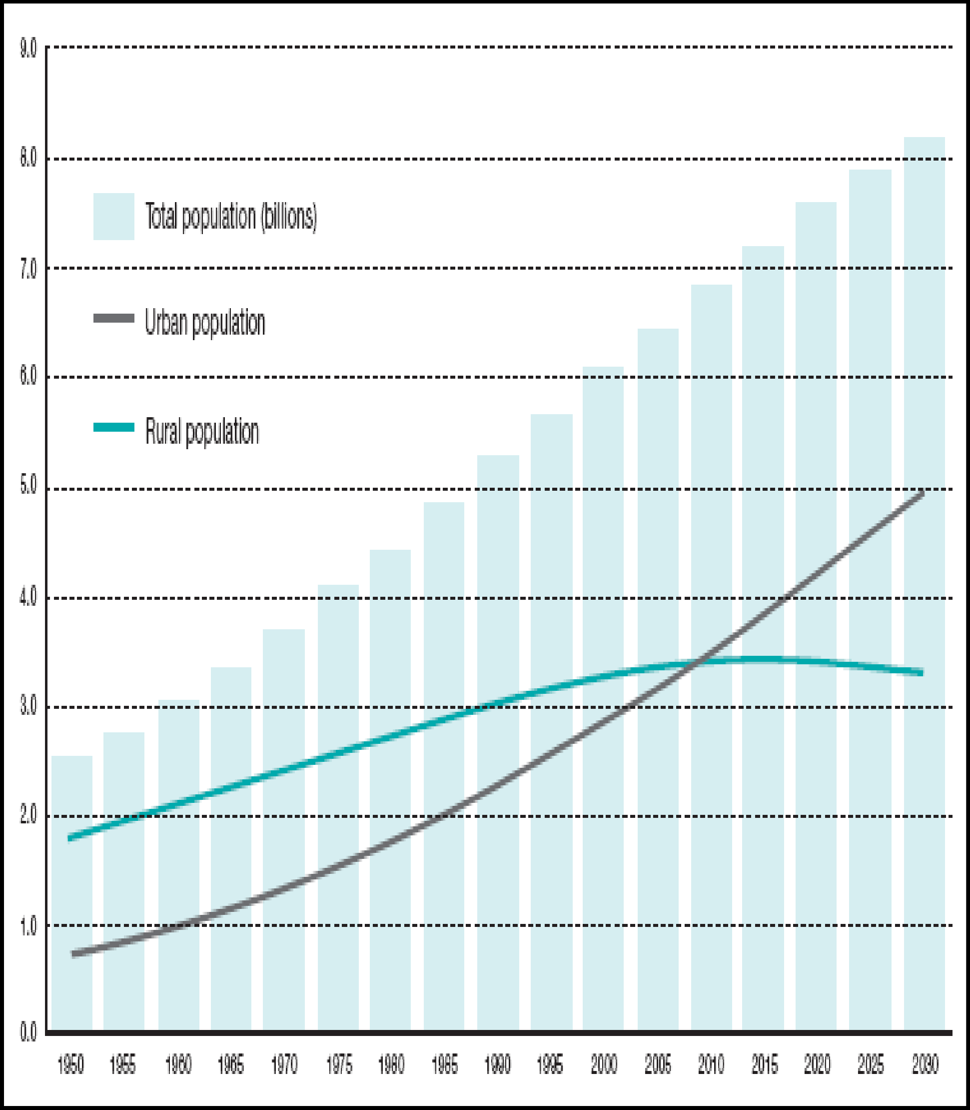
- Wheel motors
- “By-wire” controls
- Fewer parts
- New proportions
- Less Mass

AUTONOMY

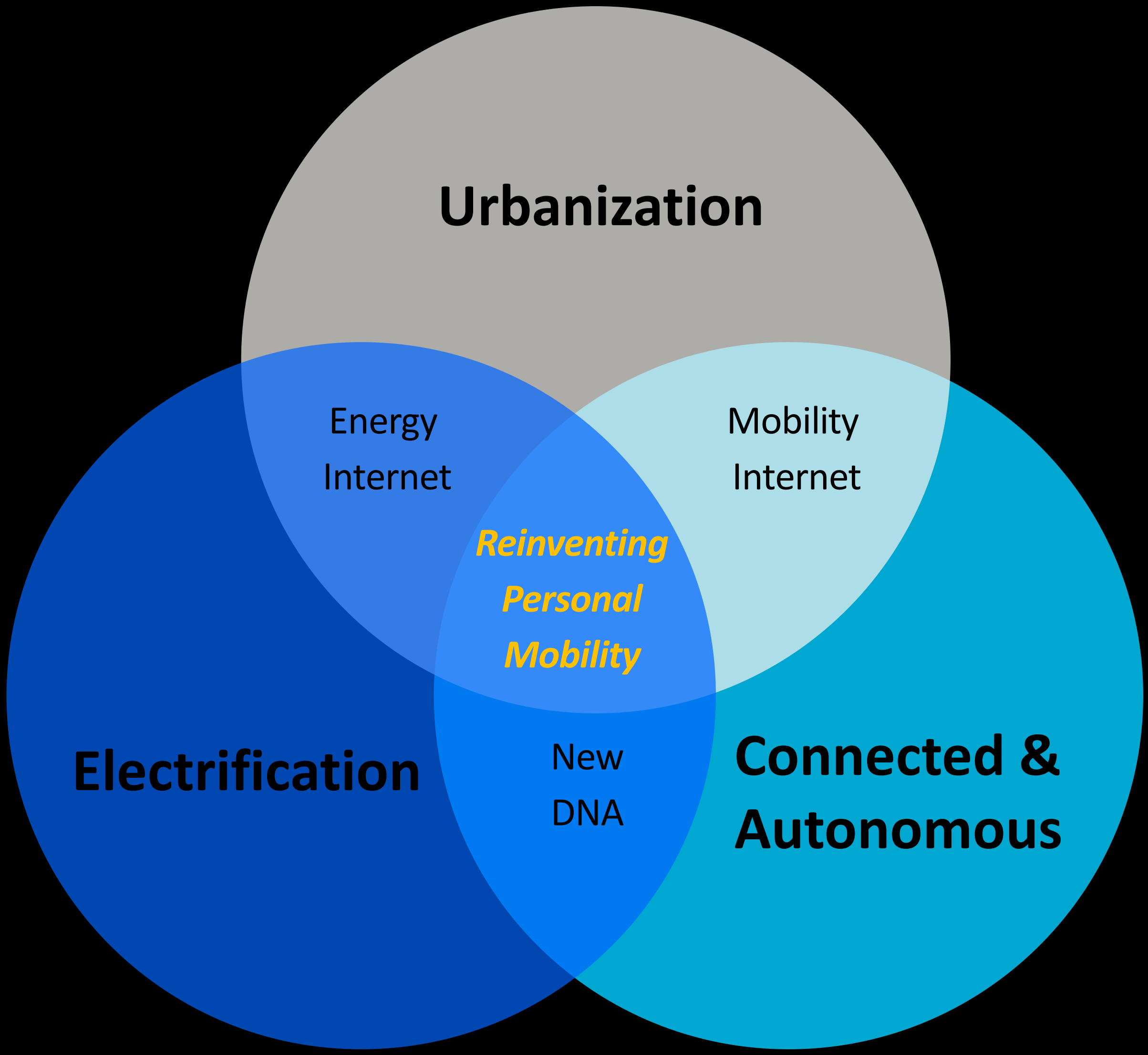
AUTONOMY


AUTONOMY

Megatrend Urbanization



Reinventing Personal Mobility



Reinventing the Automobile

Personal Urban Mobility for the 21st Century

William J. Mitchell, Christopher E. Borroni-Bird, and Lawrence D. Burns

15 X

10 X

5 X

5 X

0 X

Transformational Synergy

Information Internet

+

Energy Internet

+

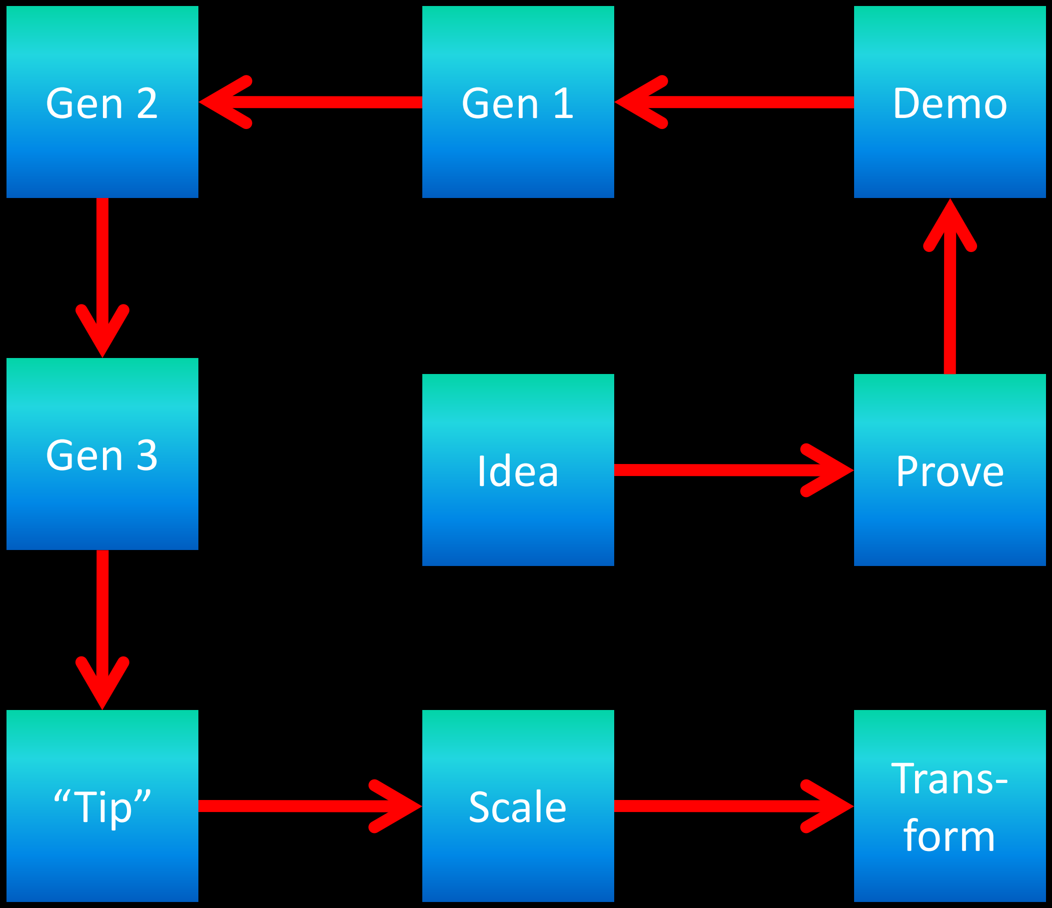
Mobility Internet

Transformational Change in
How We Live Our Daily Lives

Realizing the Opportunity

- Common understanding and collective will
- “System-of-Systems” approach
- “And” not “Or” mindset
- Value > Price > Cost
- Fashion and FUNction
- Commercial learning cycles

Learning is Key to Transformational Change



Learn about technology, customers and supply processes

The Whole is More Than the Sum of the Parts

Converging Ideas

Electrically Driven & Connected

+

Mobility Internet

+

Clean, Smart Energy

+

Pricing Markets

=

Transformational Change in Personal Mobility

- Zero emissions
- Renewable Energy
- Crash Avoidance
- Safe Social Networking While Driving
- Fun Driving and Autonomous Driving (When Desired)
- Fashionable Design
- Shorter, More Predictable Urban Travel Times
- Space-and Time-Efficient Parking
- Increased Roadway Throughput
- Quieter Cities
- Safer Pedestrians & Bicyclists
- More Equitable Access
- Lower Cost

=

Enhanced Freedom

+

Sustainable Mobility

+

Sustainable Economic Growth and Prosperity

New Technology "Improves" Existing Technology

- Aluminum has driven improvements in steel auto bodies
- Electric vehicles are driving improvements in internal combustion engines
- Plentiful natural gas will drive improvements in coal and renewables

Technology and Geo-Political Leverage

- Proven transformational options can impact geo-political dynamics prior to large scale transformation
- To show OPEC it has a viable and scalable option to importing oil, the United States should
  – deploy 10,000 electric vehicles (fuel cell and/or plug-in)
  – in one U.S. community
  – using plentiful U.S. natural gas & bio-mass as a source of hydrogen and electricity

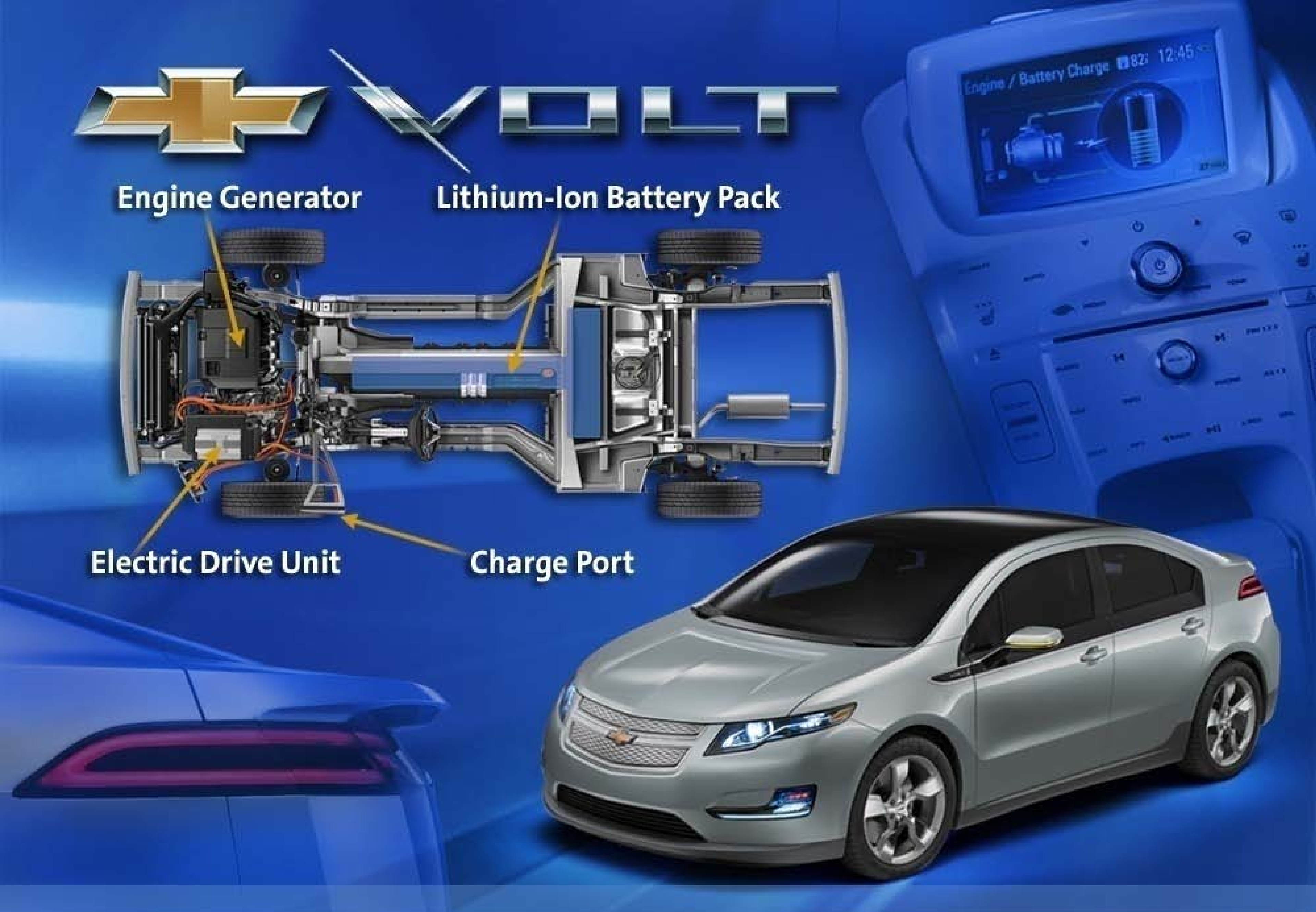
Risks of Disruption

- Examples of Industries that have been disrupted
  - Photography
  - Media
  - Entertainment
  - Computer
  - Telecom
  - Television
  - Pharmaceutical
- Incumbents Rarely Do Well When Industries Disrupt
- Transportation and Energy Sectors are Ripe for Disruption
  - Enormous Inertia of Installed Base Reduces Risks

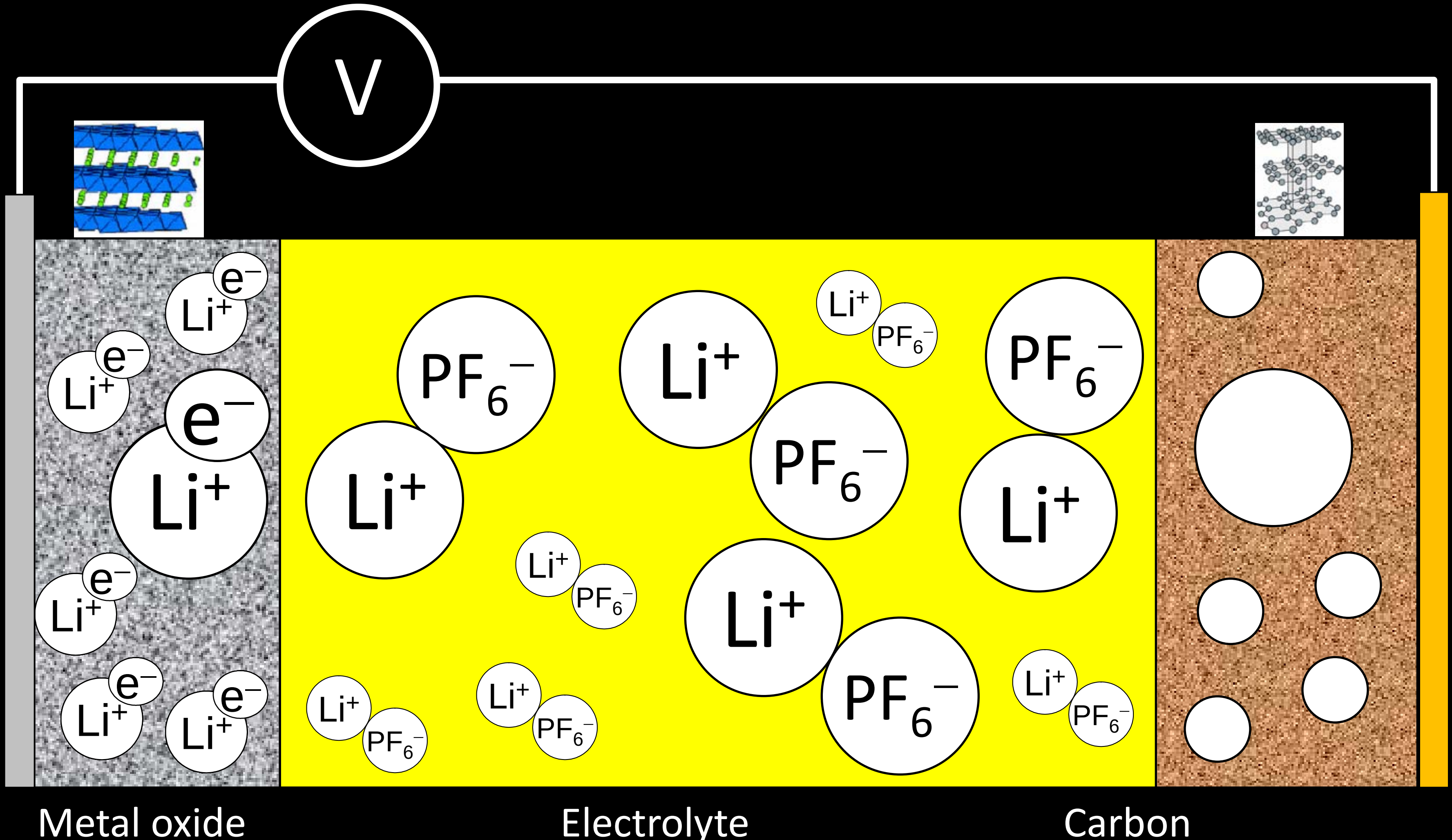
Summary

- The <u>convergence</u> of transportation, energy, communications and information technology will
  - be transformational
  - enhance ours lives
  - create significant business growth and shareholder value
- The transportation and energy industries are now as ripe for disruption as the telecom, photography, television, computer, media and pharmaceutical industries once were

Back-ups


VOLT
Engine Generator
Lithium-Ion Battery Pack
Electric Drive Unit
Charge Port
Engine / Battery Charge
12:45

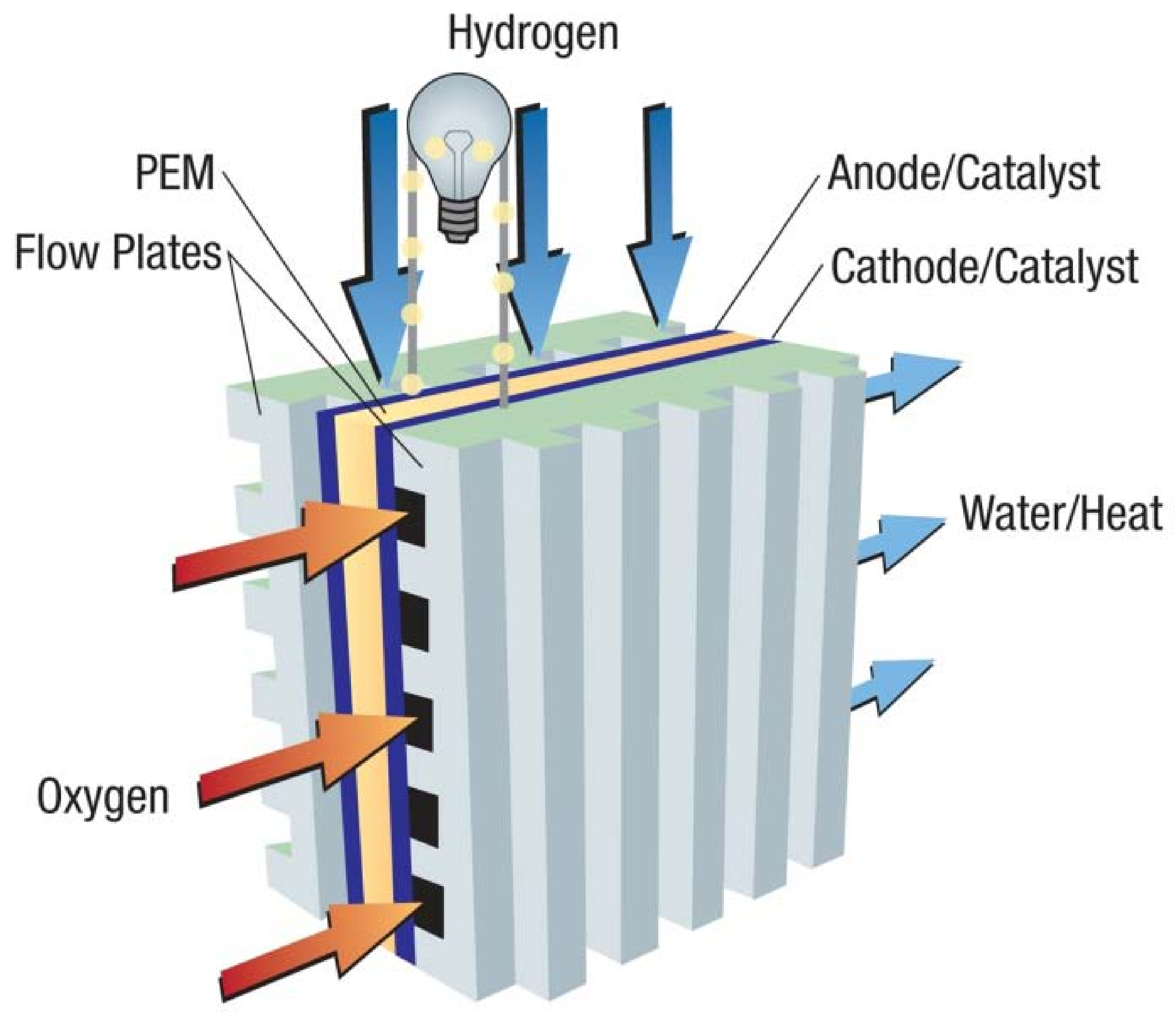
Charge Mechanism (Reverse of Discharge)



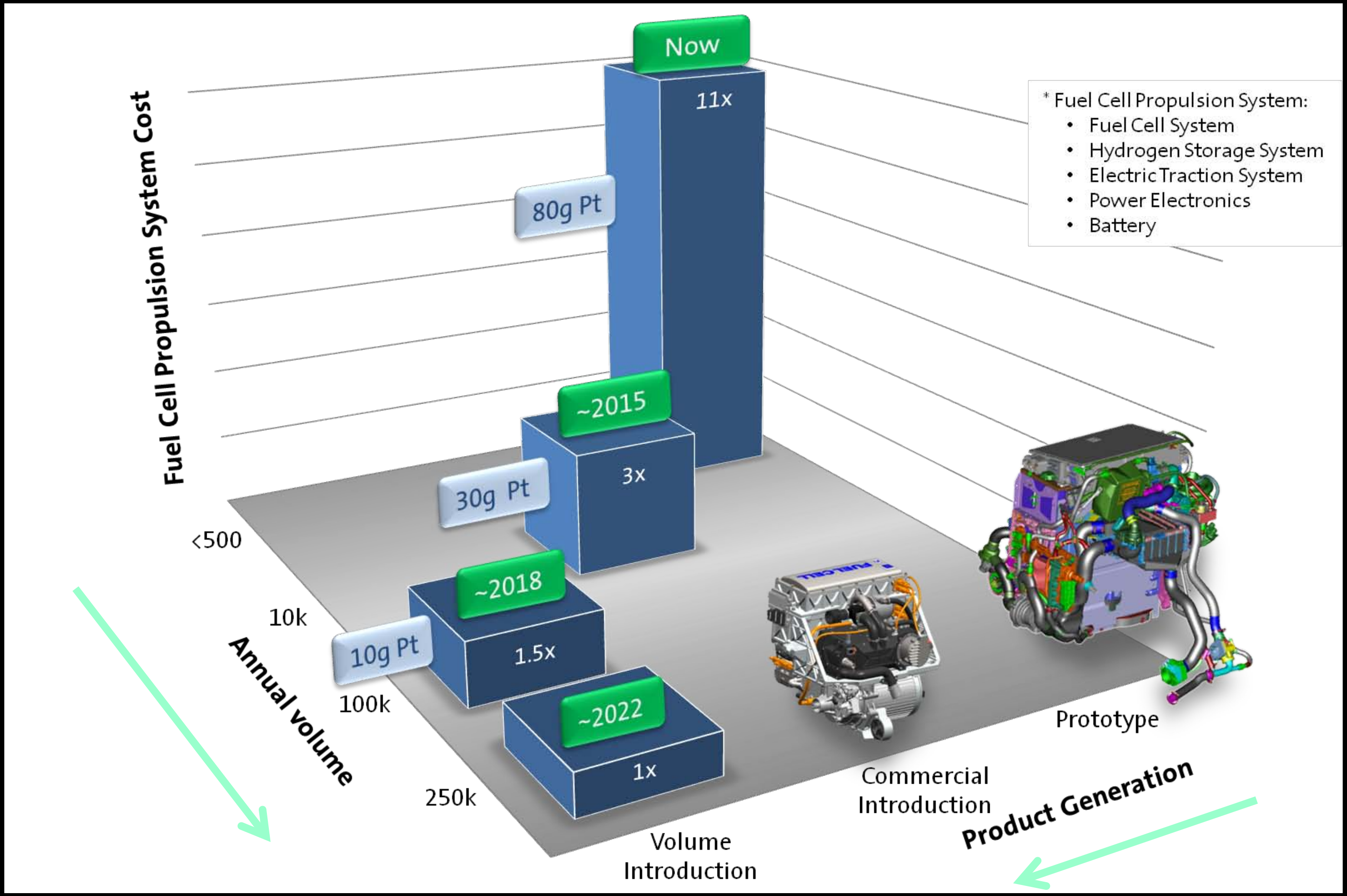
Cathode is full of lithium at the end of discharge

By putting energy into the cell, lithium is forced out of the metal oxide (positive) and into the carbon (negative).

Hydrogen Fuel Cell Technology



Cost Glide Path: *Example from GM*



Clear roadmap to automotive competitive costs requires multiple learning cycles & scale volume

“Connected” Vehicles

- GM OnStar, Ford Sync,….
- Vehicle-to-Vehicle/Pedestrian/Location
  - GPS + Stability Control + Wireless Communication
- Enhanced
  - Safety
  - Convenience
  - Traffic Flow and Parking
  - Vehicle Service and Insurance
  - Information and Entertainment

Vehicles That Drive Themselves

Where am I?

GPS + Digital Maps

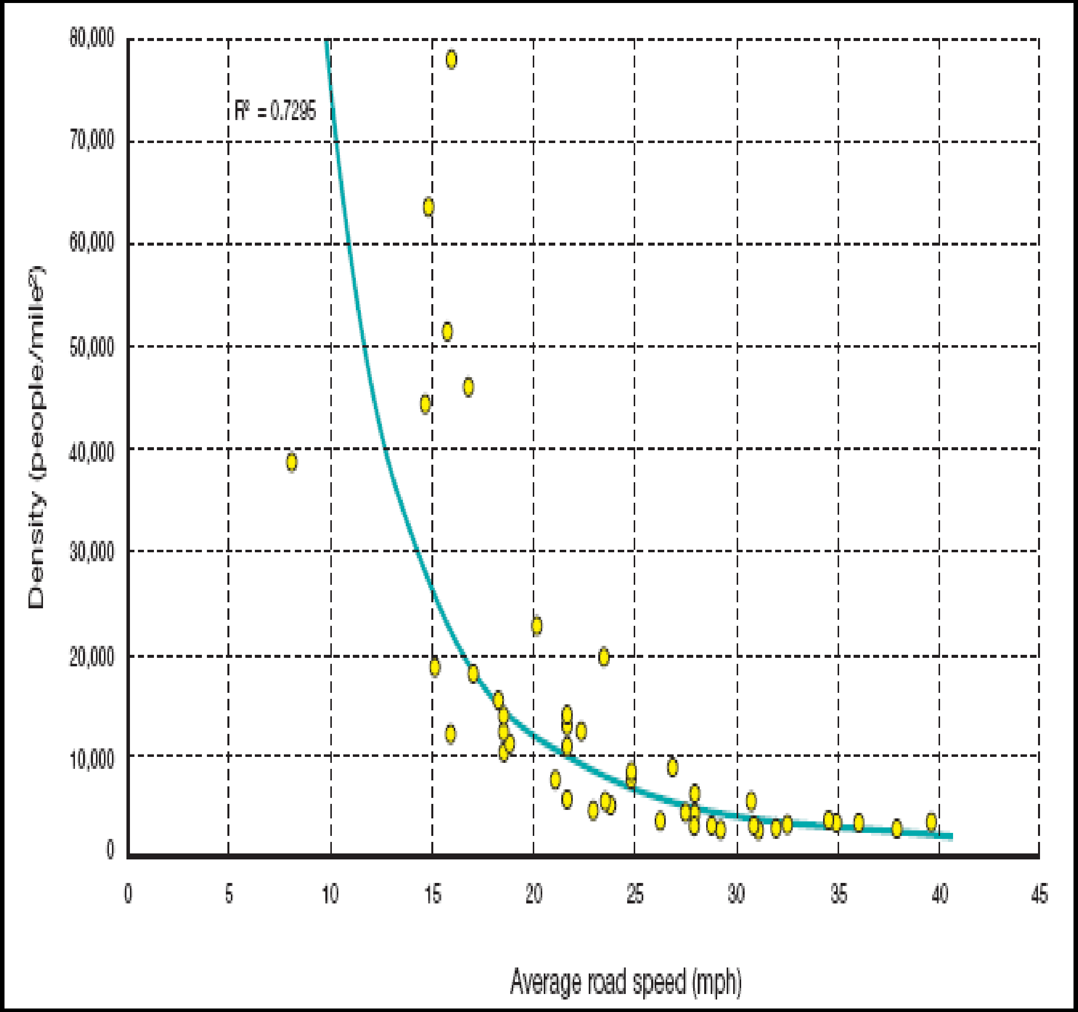
What's around me?

360^{0} Sensing (Sensors + "V2V")

Take me where I want to go:

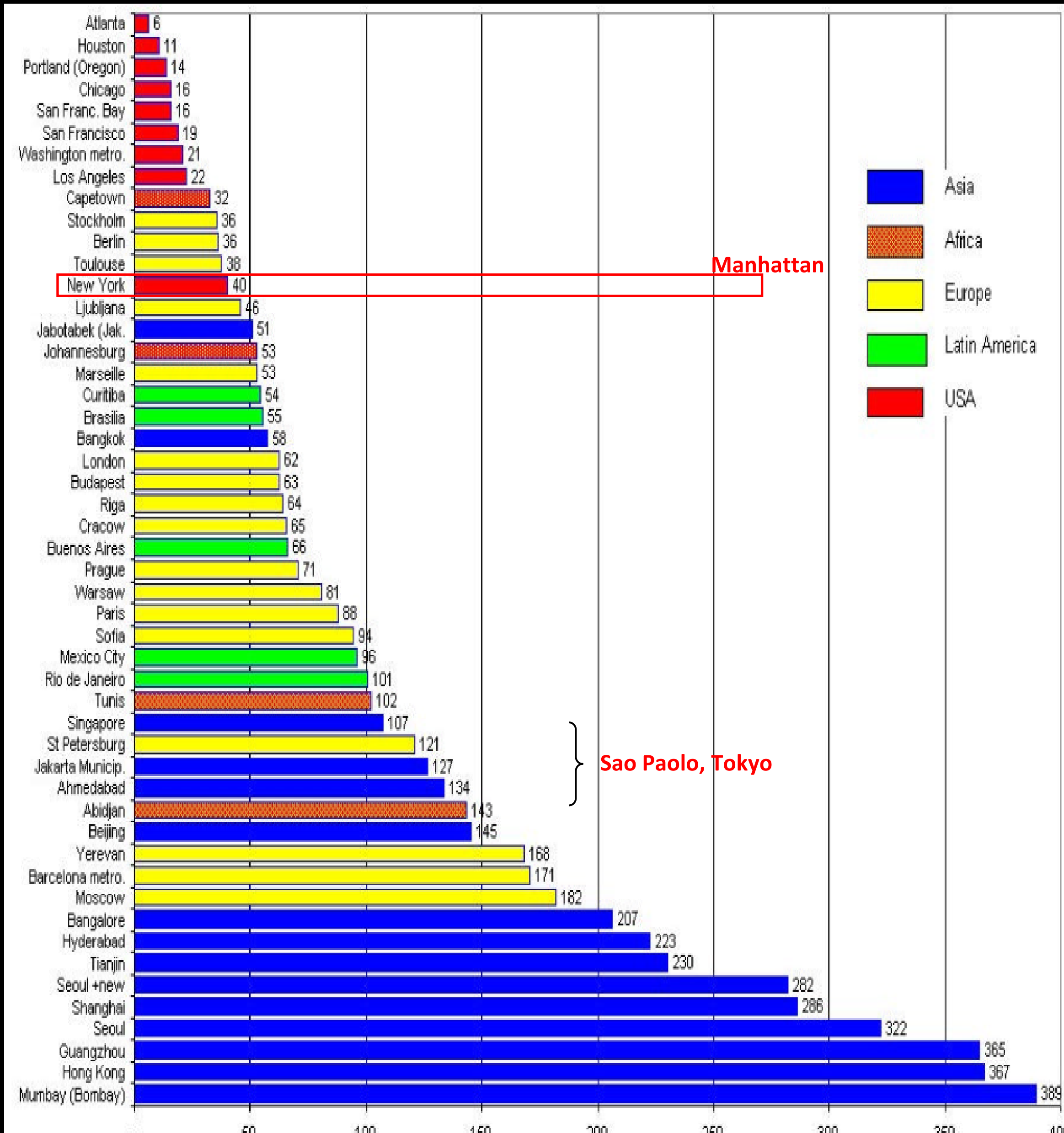
Software Algorithms + electronic controls & actuators

Population Density and Traffic Speed



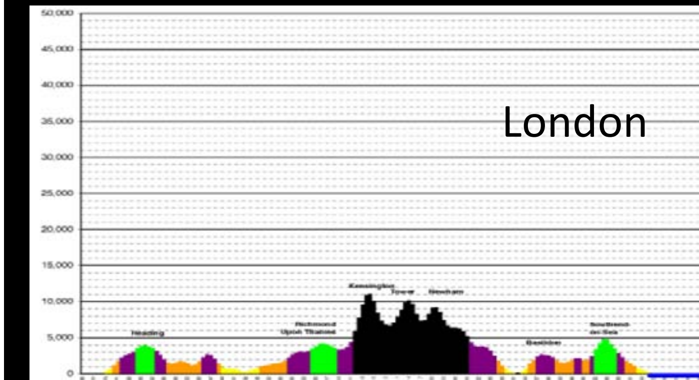
Source: data from Jeffrey R. Newman, Felix B. Laube (eds) (2002)

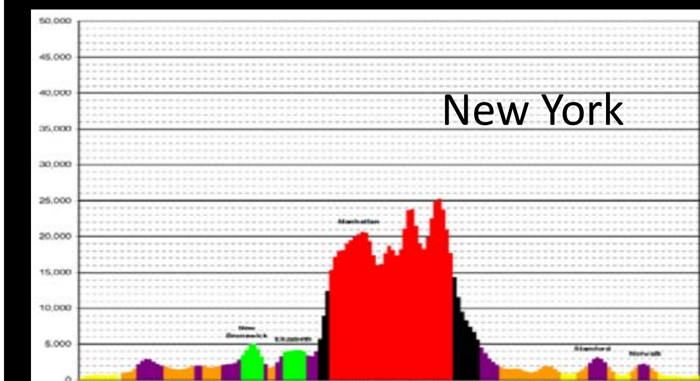
Developing Cities are the Most Densely Populated

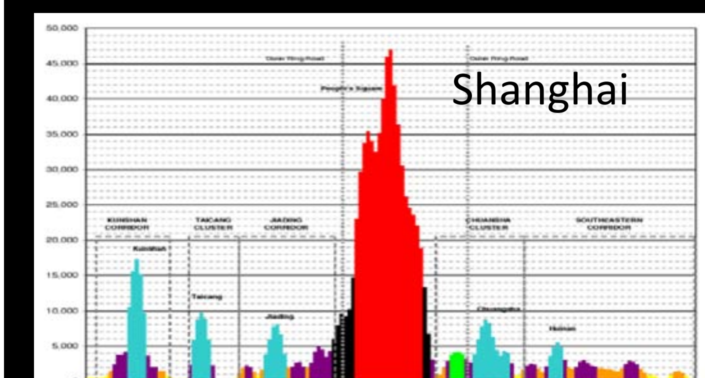


Population density (people/hectare)

100,000/ sq.mile







Source: Alain Bertaud (2002)

The Value Creation Curve