LONG-TERM TRENDS IN WORLDWIDE TRANSPORTATION

Gary Smyth, Ph.D.
Executive Director, North American Science Labs, Global R&D
GM’S LEADERSHIP IN ENABLING THE FEDERAL CLEAN AIR ACT

1970: Ed Cole announces emissions control program – driving unleaded gasoline nationwide in U.S.

1970: GM introduces no-lead-tolerant engines on all 1971 models in U.S. and Canada

1974: GM introduces catalytic converter on all 1975 models sold in U.S. and Canada

HISTORY OF EMISSION STANDARDS

**GM’S LEADERSHIP IN ENABLING THE FEDERAL CLEAN AIR ACT**

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PERSONAL MOBILITY MUST BE REINVENTED FOR THE 21st CENTURY

Data from U.S. Census Bureau and GM Global Market & Industry Analysis
TOP 10 MARKETS BY NEW VEHICLE SALES IN 2010

- **China Growth (%)**
  - vs. 2009: 33%
  - vs. 2005: 218%
  - vs. 2000: 735%

- **2010 Sales (M)**
  - Emerging Markets: 37.3
  - Mature Markets: 36.3
  - World Total: 73.6

**Vehicle Sales (M)**

- China
- EU
- U.S.
- Japan
- Brazil
- India
- Russia
- Canada
- S. Korea
- Australia

**Legend**

- **2010**
- **2009**
- **2005**
- **2000**
PETROLEUM SUPPLIES...

35% OF WORLD’S ENERGY

96% OF TRANSPORTATION ENERGY
64 mb/d of gross capacity needs to be installed between 2007 & 2030 – *Six times the current capacity of Saudi Arabia*

Source: IEA World Energy Outlook, 2010
MEGA TRENDS FOR FUTURE POWERTRAINS

ENERGY DIVERSITY

POWERTRAIN EFFICIENCY
ENERGY OPTIONS

Energy Resource:
- Oil (Conventional)
- Oil (Non-Conventional)
- Biomass
- Natural Gas
- Coal
- Renewables (Solar, Wind, Hydro)
- Nuclear

Conversion:
- Syngas

Energy Carrier:
- Liquid Fuels & CNG
- Electricity
- Hydrogen

Propulsion System:
- Conventional ICE: Gasoline/Diesel
- ICE Hybrid
- Plug-in Hybrid ICE
- Range-Extended EV
- Battery Electric
- Fuel Cell Electric

Electrification
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

Energy Diversity

Time
ADVANCED IC ENGINES

Achieve maximum fuel economy and minimum emissions potential for diverse range of application through synergistic integration of building block technologies

Downsized Boosting

Cylinder Pressure Sensing

Dilute Combustion

Electrification

Charge Boosting, Charge Dilution, Active Sensing, and Electrification will be the focus in the future
### ADVANCED IC ENGINES

**Megatrend: Particulate Control**
- Cooled EGR High CR Boosted BAS
- Stratified Charge
- HCCI

**Megatrend: Electrification**
- Boosted BAS (Stratified Charge or HCCI)

**Megatrend: Alternative Fuels**
- SIDI WG-Turbo BAS
- Stop/Start
- OHV-DICP
- 2-Step VVA
- Cam-in-Cam LIVC

<table>
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<tr>
<th>Current Production: OHC: PFI, Dual-Cam Phaser OHV: AFM</th>
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**Current Development**
- Advanced Innovation
- Exploratory

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- SIDI Boosted
- Stoichiometric SIDI
- Extended AFM for V6
- Current Production: OHC: PFI, Dual-Cam Phaser OHV: AFM
- Stop/Start
- OHV-DICP
- 2-Step VVA
- Cam-in-Cam LIVC
- Boosted BAS (Stratified Charge or HCCI)
- SIDI WG-Turbo BAS
- Cooled EGR High CR Boosted BAS
- Stratified Charge
- HCCI
DOWNSIZED TURBO GAS ENGINE

CHEVROLET CRUZE  1.4L TURBO ECOTEC
CHEVROLET EQUINOX WITH 32 MPG
CLASS-LEADING HIGHWAY FUEL ECONOMY

30% FUEL ECONOMY IMPROVEMENT WITH POWERTRAIN AND VEHICLE ENABLERS

- 2.4L SIDI L4 Ecotec Engine Replaced 3.4L V6
- 6-Speed Automatic with Optimized Shift and Clutch Control
- Rack Electric Power Steering
- Deceleration Fuel Cut-off
- Idle Speed Reduction
- Electronic Returnless Fuel System
- Aerodynamic Drag Reduction
- Regulated Voltage Control
- Optimized Tire Rolling Resistance
STOP-START SYSTEMS

Starter Motor
Electric Auxiliary Pump

[Image of car and engine components with labels]
HOMOGENEOUS-CHARGE COMPRESSION-IGNITION (HCCI)
Electrification of the vehicle adds opportunities for further combustion and engine optimization, energy diversity, different fuels, and novel IC engines.

Advanced/Novel IC Engines

Electrification
Different stages of the cycle can be separated into different working volumes.

Possible to optimize each stage individually, potential for heat loss management and exhaust energy recuperation.

Initial modeling shows potential for very high thermal efficiency.
ADVANCED IC ENGINES

Operating points on brake thermal efficiency map (%)

Throttled Gasoline

DCDE #1

DCDE #2

Brake Torque (Nm)

Engine Speed (RPM)
HYBRIDIZATION

GM Two-Mode Hybrids

Hybridization Upper Bound

Hybridization
• EV Operation
• Load Shifting
• Regeneration
• Stop/Start

Conventional Upper Bound

Improvements in Conventional Powertrain

Technology Implementation

Chevrolet Tahoe Hybrid
Chevrolet Silverado Hybrid
Toyota Prius IV
Ford Fusion
Buick LaCrosse eAssist™
Honda Insight
Opel Astra
Volkswagen Passat Bluemotion

HYBRID

Efficiency
2-MODE RWD HYBRIDS
HYBRIDIZATION

eAssist™ – Technology to Watch in 2011

- EV Operation
- Load Shifting
- Regeneration
- Stop/Start

Improve in Conventional Powertrain

- Hybridization Upper Bound
- Conventional Upper Bound

Technology Implementation

- Chevrolet Tahoe Hybrid
- Chevrolet Silverado Hybrid
- Toyota Prius IV
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- Buick LaCrosse eAssist™
- Honda Insight
- Opel Astra
- Volkswagen Passat Bluemotion
LACROSSE SEDAN WITH eASSIST™

- 2.4 L Ecotec Direct Injection 4-Cylinder Engine
- 15 kW Electric Motor-Generator
- Regenerative Braking
- Hydra-Matic 6-Speed Transmission
- 115 V Lithium-ion Integrated Battery
Advanced engines (e.g., HCCI, lean stratified) often run at the ragged edge of combustion stability
- Maximize efficiency (reduced pumping losses & heat transfer; favorable gas properties)
- Minimize engine-out NOx

Advanced engine development requires increasing knowledge and control of key processes
- Turbulent air flow
- Fuel sprays
- Mixing
- Combustion
- Emissions formation
- Aftertreatment

Relevant spatial/temporal scales for IC engines span 4 orders of magnitude
- ~10 µm – 100 mm; ~ 10 µs – 100 ms
Normal cycles: spark & flame move towards fuel in bottom of piston bowl (simulation and experiments)

Numerical Simulation

Flame kernel

Fuel (\(\Phi=1\))

4 normal cycles selected from 2000 cycles

60,000 pictures/second
2000 engine cycles
150 pictures / cycle
300,000 pictures
Misfire cycles: spark / early flame kernel move upward, away from fuel in bottom of piston bowl
RESEARCH CHALLENGES

- Characterizing, predicting and controlling stochastic cycle-to-cycle variation in in-cylinder processes (flow, spray, combustions, emissions)
- Surface chemistry and physics to enable high-efficiency, low-temperature catalysis and filtration
- Experiments and modeling of dense near-nozzle sprays and nozzle internal flow regions.
- High-pressure, dilute combustion
- Efficient, accurate reduced chemical kinetic schemes
- System integration tools using validated, reduced-order, reduced-complexity models for engine and aftertreament systems
  - Including real-time calibration, control and diagnostics
MODELING STOCHASTIC PROCESSES (SPRAY)

RANS

- Usual Reynolds-Averaged Navier-Stokes (RANS) CFD computes “average” events
- Blurs distinct local features seen in experimental snapshots
- Ignition, combustion and emissions formation depend on local conditions
- Cannot predict cycle-to-cycle variations

LES

- Large-Eddy Simulation predicts individual-cycle phenomena
- Much larger computational burden than RANS

Courtesy Prof. C. Rutland, GM / Univ. Wisconsin Collaborative Research Lab
LES: TURBULENT INTAKE FLOW INTO CYLINDER

Xiaofeng Yang
PSR Lab, GM R&D
UW CRL ACTIVITIES IN RESEARCH COMMUNITY

- Co-chair of Predictive Simulation for Internal Combustion Engines (PreSICE) Workshop
  - Primary support document for new DOE program
  - GM and UW-CRL provided primary support for stochastic processes writeup

- GM LES Working Group
  - Multi-institution effort to validate engine LES and develop modeling practices for engines
  - Primary participant

- Engine Combustion Network (ECN)
  - Primary participation with GM in development of new GDI spray program
  - Preliminary work on LES for GDI sprays
ADVANCED PROPULSION TECHNOLOGY STRATEGY

**Energy Diversity**

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

**Time**

1. **IC Engine and Transmission Improvements**
2. **Hybrid-Electric Vehicles (including Plug-in HEV)**
3. **Battery-Electric Vehicles (including E-REV)**
4. **Hydrogen Fuel Cell-Electric Vehicles**

**Improve Vehicle Fuel Economy and Emissions**

**Displace Petroleum**
ENERGY DIVERSITY – ETHANOL

OVER 6.5M VEHICLES WORLDWIDE

FLEXFUEL
E85 ETHANOL

Flexpower
BIOFUELS TECHNOLOGY ROADMAP

1st Generation | “Gen 1.5” | 2nd Generation | 3rd Generation | 4th Generation

Feedstock: Sugars, Starch → Cellulose
- Sugarcane
- Corn
- Sugarbeet, ...
- Cassava
- Sweet Sorghum
- Grasses
- Wood Biomass
- Cellulosic Waste

Fuels and Conversion Products
- Ethanol
- Ethanol
- Alcohols
- Green Hydrocarbons
- Biocrude to Refinery
- Pyrolysis Final Fuels

Feedstock: Oil-Seed/Waste Lipids → Algae
- Soybeans
- Palm Oil
- Rapeseed
- Tallow
- Waste Veg. Oil
- Jatropha
- Camellina
- etc.
- Algae
- Designer bacteria convert CO₂ directly to final fuel products
SANDIA/GM STUDY:
BIOMASS FOR 90B GALLONS OF ETHANOL

- Switchgrass
- Woody Crops
- Agricultural Residue
- Forest Residue
- Corn

2030 Land Use
- 44 M acres cropland as pasture and idle cropland
- 44 M acres non-grazed forest land
- No land use change for residues
- Equals 2006 corn ethanol acreage

Ethanol Production, Billion Gallons

2010 2014 2018 2022 2026 2030
INCREASING EFFICIENCY

- Displace Petroleum
  - Grid Connection

- Hybridization
  - EV Operation
  - Load Shifting
  - Regeneration
  - Stop/Start

- Improvements in Conventional Powertrain

Hybridization Upper Bound

Conventional Upper Bound
ELECTRIC VEHICLE WITH RANGE-EXTENDER

25-50 Miles of Battery Electric Drive

+ Hundreds of Miles Extended-Range Driving
VOLTEC PROPULSION SYSTEM

- Battery
- DC Cables
- Engine
- AC Cables
- Power Inverter
- Electric Drive Unit
- Fuel Tank
- Half Shafts
LITHIUM-ION BATTERY

- 16-kWh battery pack
- High energy, high power in minimized package
- 8-year/100,000-mile warranty
EVERYDAY DRIVERS
8,000 MILES LOGGED

PROJECT DRIVEWAY

PRODUCTION-INTENT FUEL CELL SYSTEM

8,000 EVERYDAY DRIVERS

2,000,000 MILES LOGGED
FUEL CELL VEHICLE DEMONSTRATIONS WITH THE MILITARY IN HAWAII

- One-year demonstration with all three services
  - Five vehicles per service
- Hydrogen refueling to be installed at each base
- Also evaluating utilizing vehicles as mobile generators (25 kW continuous)
- In partnership with The Gas Company and the State of Hawaii
APU MOTIVATION

- Why use an APU?
  - Customer-utility
    - Reduce range-anxiety
    - Provide “limp-home” capability
    - Improve cold weather functions (cabin heating, windshield defrost)
  - Reduce battery weight and cost

- Tradeoffs
  - ZEV capability (except fuel cell)
  - NVH

- Function
  - Dedicated onboard battery charger
  - No prime mover capability
  - Fixed power operation
Power density and efficiency are estimated assuming APU < 50.

For microturbines and Stirling engines, efficiency can vary largely with the type of alloys used, emission targets, packaging, and weight constraints, etc.

4-stroke piston ICEs and Wankel engines appear to be the most viable APU candidates for power ratings below 20 kW (considering cost and packaging limitations).
Battery improvement expected, but still lower density than liquid fuels

Hydrogen has significantly higher energy density than current batteries
By 2030, 60% of the world’s population will live in urban areas, up from 50% today.

Within 20 years, 80% of wealth will be concentrated in cities.

As the urban population increases, traffic congestion in large metro areas will become an even bigger issue.
LONDON’S POPULATION DENSITY PROFILE

Source: Mats Andersson, World Bank (2005)
NEW YORK’S POPULATION DENSITY PROFILE

Source: Mats Andersson, World Bank (2005)
SHANGHAI’S POPULATION DENSITY PROFILE

Source: Mats Andersson, World Bank (2005)
ROADMAP TO AUTONOMOUS DRIVING

Alerts/Warnings (No Control)
- Lane Departure Warning
- Traffic Sign Memory
- Forward Collision Alert
- Side Blind Zone Alert

On-Demand/Shared Control
- Freeway Assisted Driving (limited conditions) hands free, w/eyes on road
- Auto Lane Change
- Collision Avoidance w/Braking & Steering
- Increasing Autonomous and Avoidance Capability
- Integrated Sensing w/V2X Connectivity

Limited Intervention
- Full-Speed Adaptive Cruise Control (Stop & Go)
- Collision Mitigation Braking
- Low Speed Avoidance (Virtual Bumper)
- Lane Keep Assist

The Exponential Growth of Computing, 1900-2100

Today

Future

Calculations per Second

1,000 of Computing Buys

$1,000 of Computing Buys

All Human Brains

1 Human Brain

1 Mouse Brain

1 Insect Brain

Double Exponential Growth Through Two Centuries

Calculations per Second
AUTONOMOUS DRIVING

Forward Vision System
- Lane tracking
- Object detection
- Far IR Capability

Rear Vision System
- Object detection
- Far IR Capability

Enhanced Digital Map System

Side Blind-Zone Alert
Lane-Change Assist

Dedicated Short-Range Communication + GPS (V2V)

Ultrasonic Sensors

Dedicated Short-Range Communication + GPS (V2V)

Ultrasonic Sensors

Dedicated Short-Range Communication + GPS (V2V)
REINVENTING PERSONAL URBAN MOBILITY:
EN-V (ELECTRIC, NETWORKED VEHICLE)
SINO-SINGAPORE TIANJIN ECO-CITY
## TECHNOLOGY DRIVERS FOR THE 2\textsuperscript{ND} CENTURY OF PERSONAL MOBILITY

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<td>Low-cost renewable energy</td>
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<td>Emissions</td>
<td>No tailpipe environmental impact</td>
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<td>Safety</td>
<td>Vehicles that don’t crash</td>
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<td>Autonomous driving</td>
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