The Future for the Internal Combustion Engine and the Advantages of Octane

DAVE BROOKS
Director, Global Propulsion Systems
R&D Laboratories
GM Research & Development
ZERO CRASHES
ZERO EMISSIONS
ZERO CONGESTION
KEY DRIVERS OF THE TRANSFORMATION

INTERNAL COMBUSTION ENGINE
EVOLUTION FROM TRANSPORTATION TO MOBILITY

ELECTRIC | CONNECTED | SHARED | AUTONOMOUS

“The future we’ve been saying is coming so fast – is already upon us”
## REGULATORY REQUIREMENTS
OUTLOOK FOR GLOBAL FUEL ECONOMY AND GREENHOUSE GAS REGULATIONS
PATHWAY TO NET-ZERO CO2 TRANSPORTATION

<table>
<thead>
<tr>
<th>Country</th>
<th>MPG</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>54.5</td>
<td>2025</td>
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<tr>
<td>China</td>
<td>56.0</td>
<td>2020</td>
</tr>
<tr>
<td>Europe</td>
<td>68.8</td>
<td>2021</td>
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</table>

Source: GM Public Policy
GLOBAL FUEL ECONOMY / CO₂ OUTLOOK

CO₂ Emissions on MVEG-B drive cycle (gCO₂/km)

Industry Targets normalized to EU drive cycle with units converted
Dashed lines indicate proposed (not yet final) regulation

U.S.*

More Stringent

Source: GM Energy Center, October 2017
EFFICIENCY IMPROVEMENTS

- Downsized Turbo Engines
- Multi-speed Transmissions
- Stop/start + eAssist Light
- Electrification
- Electrification of Propulsion System
- Next Generation Fuels
HISTORICAL TRENDS IN FUEL & ENGINES

Ref: ORNL - A Historical Analysis of the Co-evolution of Gasoline Octane Number and Spark-Ignition Engines
Liquid combustion fuels, largely derived from petroleum, will continue to dominate in global light-duty transportation through mid-century.

As such, it is critical that fuels evolve to maximize the potential of future high efficiencies engines.

Source: GM R&D compiled with public data (population, urbanization, GDP growth rate projections)
WHAT NEXT? THE CO2 CHALLENGE

Meeting future CO2 regulations while delivering vehicles that customers want and can afford ……

<5% MY2014 vehicles in the US meet MY2025 CO2 and all make use of are advanced powertrains

... will require the synergistic integration of fuels and engine technologies

THE ENGINE CHALLENGE

To maximize engine efficiency we must focus on minimizing loss mechanisms and maximizing work recovery ...

Aggressively downsize to reduce parasitic losses
  o Key enablers are advanced boost systems and increased knock tolerance - more knock resistant fuels

Migrate to compression ratios between 13 & 14 to maximize work extraction without incurring major parasitic losses
  o Key enablers are variable valve actuation and increased knock tolerance - more knock resistant fuels

Migrate to high levels of charge dilution to minimize heat losses and maximize work extraction
  o Key enablers are increased EGR tolerance and Lean, Low Temperature Combustion - more reactive fuels

Maintaining modest peak pressure levels to avoid incurring major parasitic losses
  o Key enablers are homogeneous stoichiometric operation at WOT with rated speed above 6000rpm
THE ENGINE CHALLENGE

Downsizing is critical to enhancing vehicle level fuel economy and thus fuels that maximize resistance to knock are critical -- enabling increased compression ratios and more advanced combustion phasings at high loads – to maximizing the benefits.
THE ENGINE CHALLENGE

High levels of charge dilution and lean, low temperature combustion at low loads are critical to enhancing vehicle level fuel economy and thus fuels with good low load reactivity are critical—but, not at the expense of full load performance.
THE ENGINE CHALLENGE

At equal performance, GDI-like engines that operate lean, LTC at full load degrade specific output and vehicle level fuel economy. To maximize fuel economy, it is critical to synergistically blend aggressive downsizing (stoichiometric operation at full power) with lean, low temperature combustion at part load.
To maximize efficiency, we need a better fuel.

To maximize SI Engine potential the fuel should have high knock resistance at high loads and good reactivity at low loads, the fuel should have the following properties:

- High knock resistance with high sensitivity
  - High RON and High Sensitivity
- Low variability across the marketplace
  - RON, Sensitivity, T90, ........
- Near-zero sulfur, <10 ppm (lower is better)
- Good low temperature catalyst reactivity
- Low propensity to soot

† We don’t need a new fuel, we need an improved gasoline with high RON (>98), high Sensitivity (>12) and low variability
The Fuels Challenge – Sensitivity

High sensitivity fuels are relatively stable at low temperatures, but react rapidly at high temperatures.

- **Typical High Sensitivity Fuel** (e.g. Ethanol)
  - High RON
  - Increasing Sensitivity
  - Decreasing Reactivity
  - Knock Resistance (High Load and WOT)

- **Typical Low Sensitivity Fuel** (e.g. 100 PRF)
  - Low MON
  - Increasing Sensitivity
  - Increasing Reactivity
  - Compression Ignition (Low Load)

Sensitivity = RON - MON
THE FUELS CHALLENGE – OCTANE INDEX

Octane Index (OI = RON - K*Sensitivity) is a good measure of fuel performance when “K” is adjusted to the engine/combustion mode.

“K” characterizes the temperature, pressure trajectory associated with a specific engine/combustion mode.

Gasoline Spark Ignition (conventional)

**Knock Resistance** - high pressure, low temperature condition

*K is negative* - Sensitivity increases Octane Index and “degrades reactivity”

*K ~ -1 for Boosted, High Load, WOT*

Gasoline Low Temp Combustion (e.g. HCCI)

**Compression Ignition** - low pressure, high temperature condition

*K is positive* - Sensitivity decreases Octane Index and “increases reactivity”

*K ~ +2 for Lean, Part Load LTC/HCCI*
THE FUELS CHALLENGE

The ideal fuel is a high RON (>96), high Sensitivity (>12) alternative to regular grade gasoline for both near-term Boosted SI Engines and long-term LTC/HCCI Engines - Sensitivity is key.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>RON</th>
<th>MON</th>
<th>Sensitivity</th>
<th>AKI</th>
<th>Boosted SI WOT (K=1)</th>
<th>Part Load LTC (K=2)</th>
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<tbody>
<tr>
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<td>83</td>
<td>8</td>
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<td>92</td>
<td>6</td>
<td>95</td>
<td>104</td>
<td>86</td>
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</table>

- Raising RON at a fixed Sensitivity reduces the Knock gains and stifles LTC.
- Raising RON and Sensitivity together maximizes the near and long term gains.
- Raising RON at the expense of Sensitivity reduces the Knock gains and stifles LTC.

Major Knock gains while enabling part load LTC.

Need to minimize the impact of low sensitivity blending streams.
THE FUELS CHALLENGE

The ideal fuel is a high RON (>96), high Sensitivity (>12) alternative to regular grade gasoline that leverages high sensitivity blending components. Need to minimize the impact of low sensitivity paraffinic fuels.

<table>
<thead>
<tr>
<th>Fuels Comparison</th>
<th>RON</th>
<th>MON</th>
<th>Sensitivity</th>
<th>AKI</th>
<th>Comp. Ign.</th>
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</table>

Need to minimize the impact of low sensitivity paraffinic fuels.
THE PRAGMATIC APPROACH – “THE IDEAL ENGINE & FUEL COMBINATION”

- Integration of aggressive downsize boosting with lean, low temperature combustion
- Downsize boosting mega-trend, operating with homogeneous, stoichiometric combustion at high loads to maximize specific output and minimize parasitic losses
- Introduce lean, low temperature combustion at low loads to maximize vehicle level fuel economy by reducing heat losses and maximizing work extraction
- Need a fuel that has excellent knock resistance at high loads and good autoignition reactivity at low loads
- Ideal fuel has High RON (100), High Sensitivity (14) and low variability to support the synergistic integration of downsizing and lean, low temperature combustion
- Highly integrated & electrification of propulsion systems to maximize energy recovery and optimize drive quality
AUTOMOBILE MANUFACTURER FUEL NEEDS

► Improve fuel efficiency and opportunity to make fuel part of the CO₂ solution
► Extend high volume market viability of highly cost effective internal combustion engine powertrains
► Near term availability (2020-2022) and long term viability
► Focus on fuel properties rather than fuel formulation
► Evaluate CO₂ emissions from a well-to-wheels approach
► Fuel value proposition needs to be attractive to the customer
► Fuel producers commit to supply high octane fuel, and OEMs commit to produce engines/vehicles optimized to use it
► Legacy fleet and infrastructure considered, primary focus is on future fleet
THE IMPORTANCE OF
A NEW NATIONAL FUEL

Combine Higher octane with new engine designs to...

- Meet fuel economy targets while providing better value to consumers and society
- Extend the horizon of internal combustion engines using liquid fuels
- Provide consumers what they want – from affordability to performance
I believe the auto industry will change more in the next 5 to 10 years than it has in the last 50

Mary Barra
CEO and Chairman of General Motors
THANK-YOU

GENERAL MOTORS