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

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GENERAL MOTORS


ZERO CRASHES
ZERO EMISSIONS
ZERO CONGESTION
GMC
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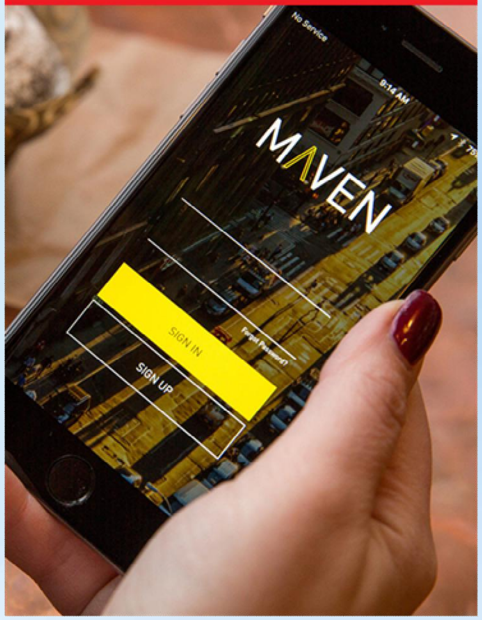
KEY DRIVERS OF THE TRANSFORMATION

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

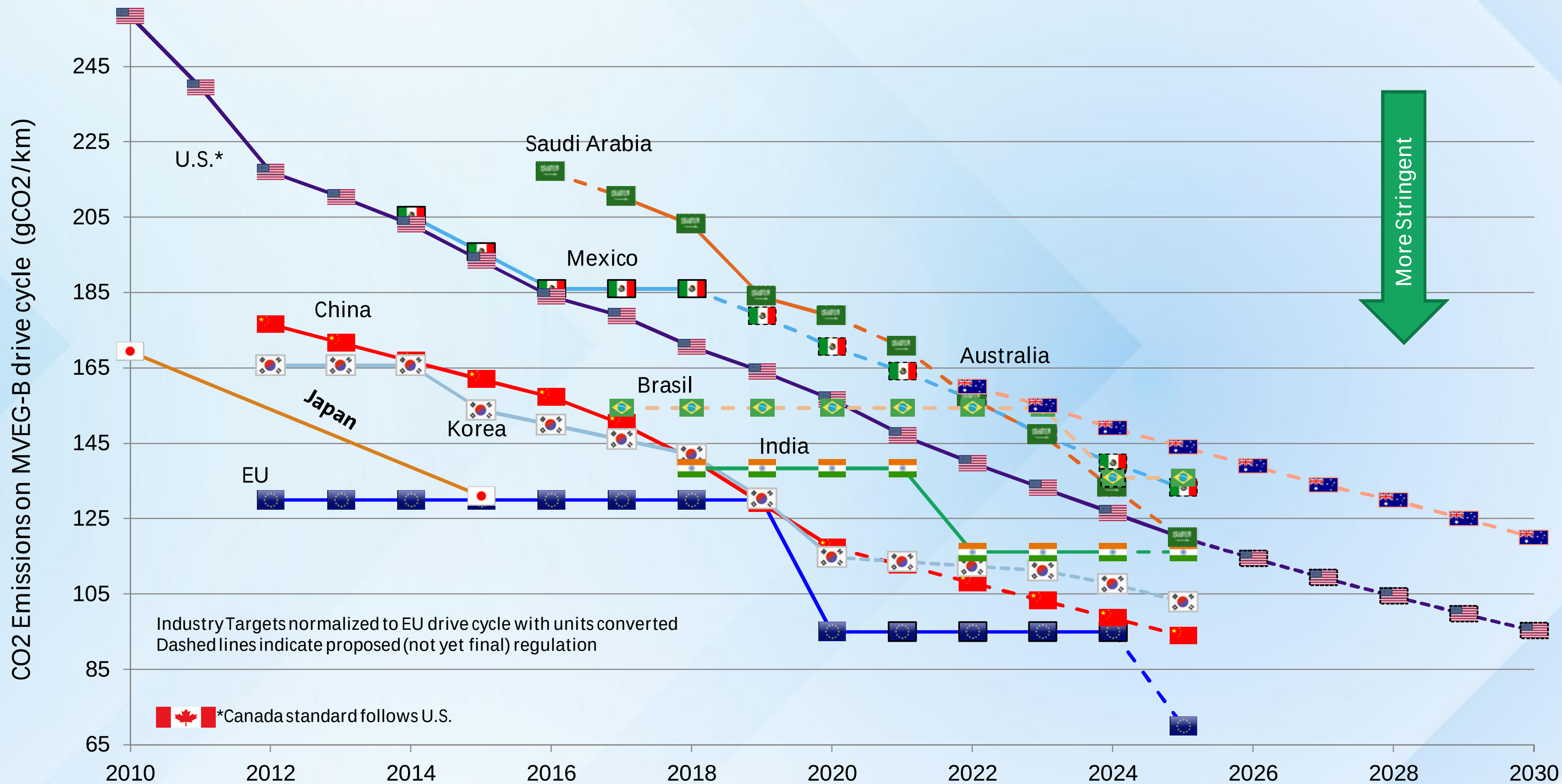
OUTLOOK FOR GLOBAL FUEL ECONOMY AND GREENHOUSE GAS REGULATIONS

PATHWAY TO NET-ZERO CO2 TRANSPORTATION

	MPG	YEAR
United States	54.5	2025
China	56.0	2020
Europe	68.8	2021

Source: GM Public Policy

GLOBAL FUEL ECONOMY / CO_2 OUTLOOK

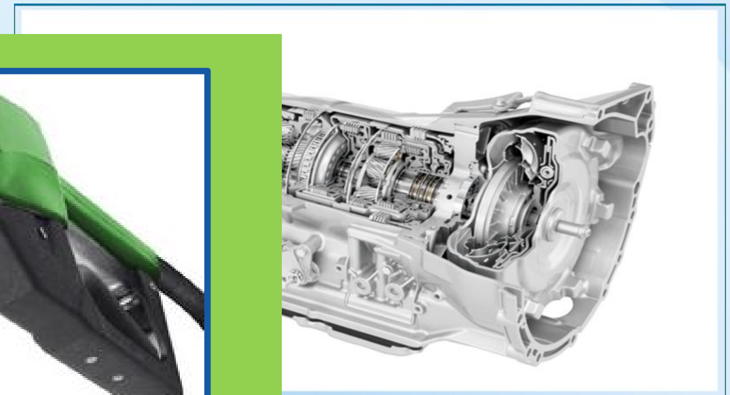


Source: GM Energy Center, October 2017

EFFICIENCY IMPROVEMENTS

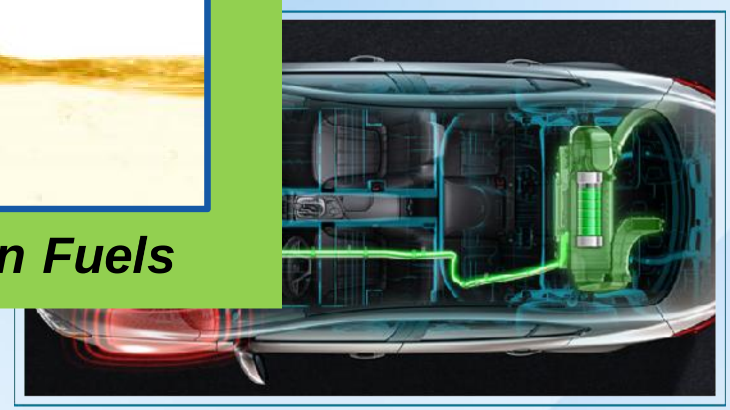
Downsized Turbo E

Next Generation Fuels



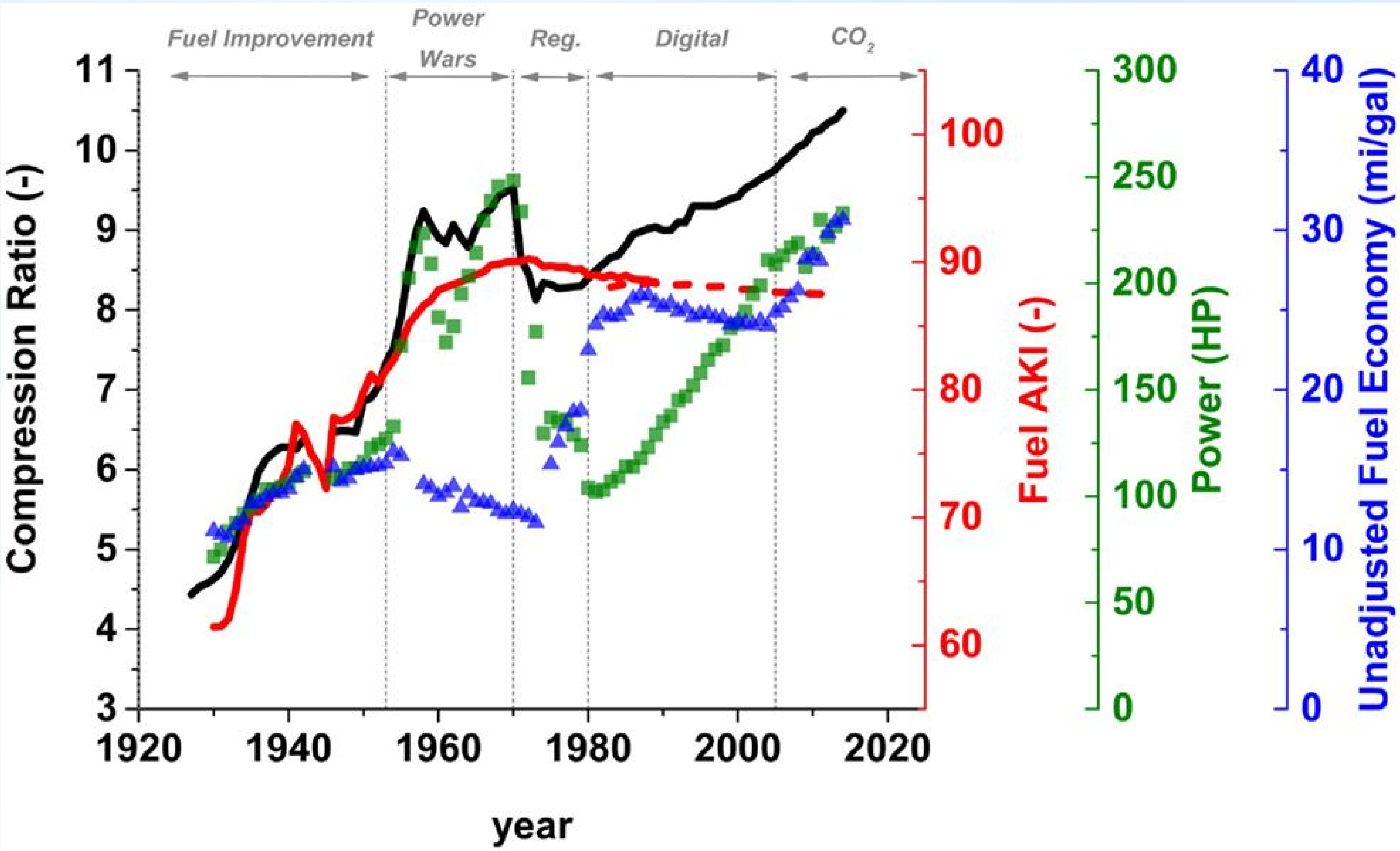
eed Transmissions

Stop/start + eAssist Light Electrification



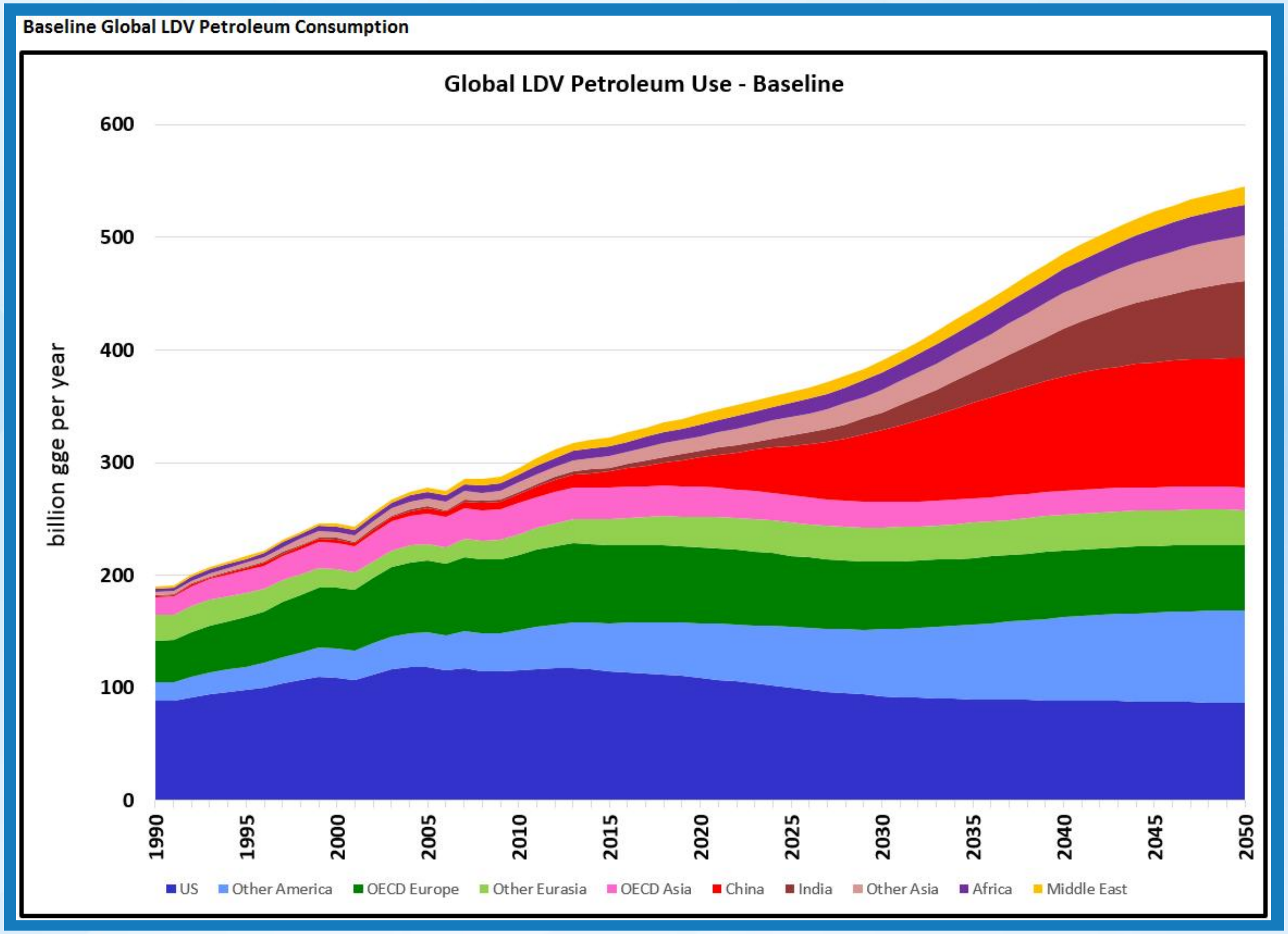
Electrification of Propulsion System

HISTORICAL TRENDS IN FUEL & ENGINES



Ref: ORNL-A Historical Analysis of the Co-evolution of Gasoline Octane Number and Spark-Ignition Engines

FUEL USAGE - MODELED GLOBAL LDV PARC PETROLEUM



Liquid combustion fuels, largely derived from petroleum, will continue to dominate in global light-duty transportation through mid-century

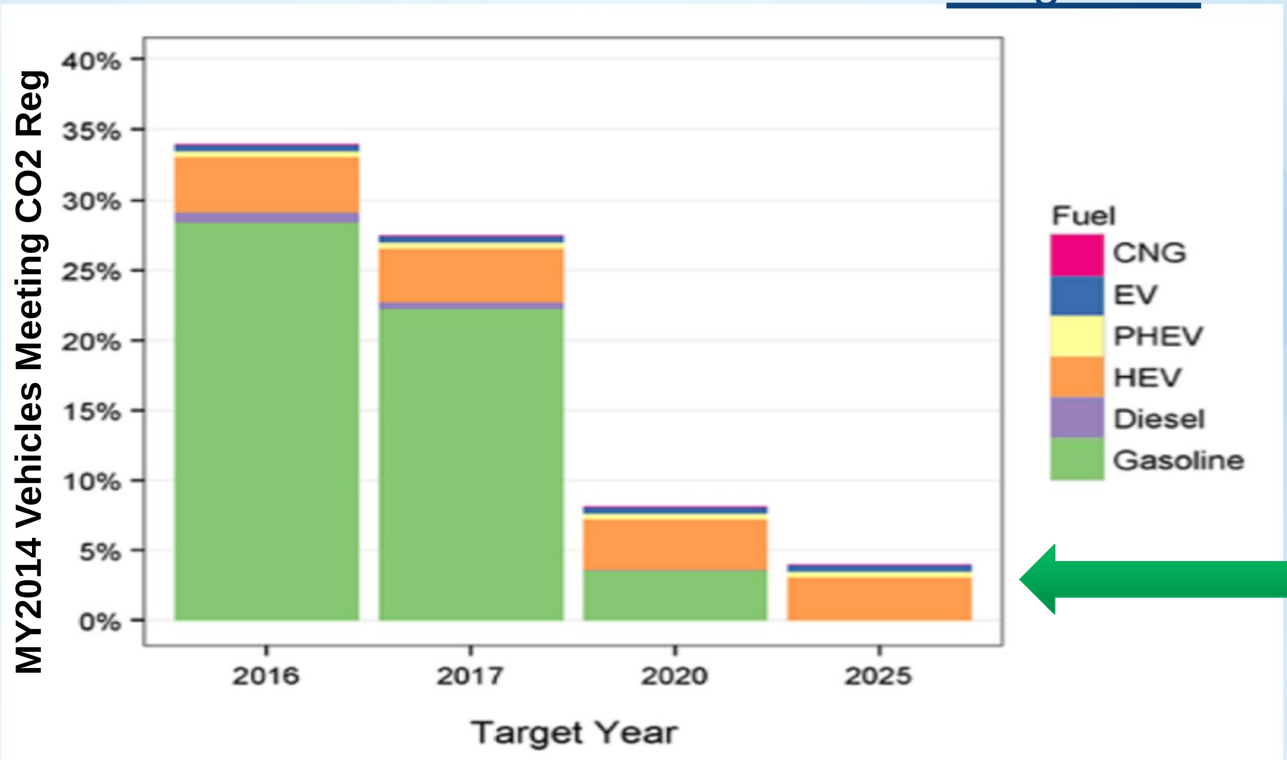
As such, it is critical that fuels evolve to maximize the potential of future high efficiencies engines

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……

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



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

Source: EPA US Light-Duty Automotive Technology, Carbon Dioxide Emissions and Fuel Economy Trends: 1975 Through 2014

THE ENGINE CHALLENGE

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

Aggressively downsize to reduce parasitic losses

- 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

- 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

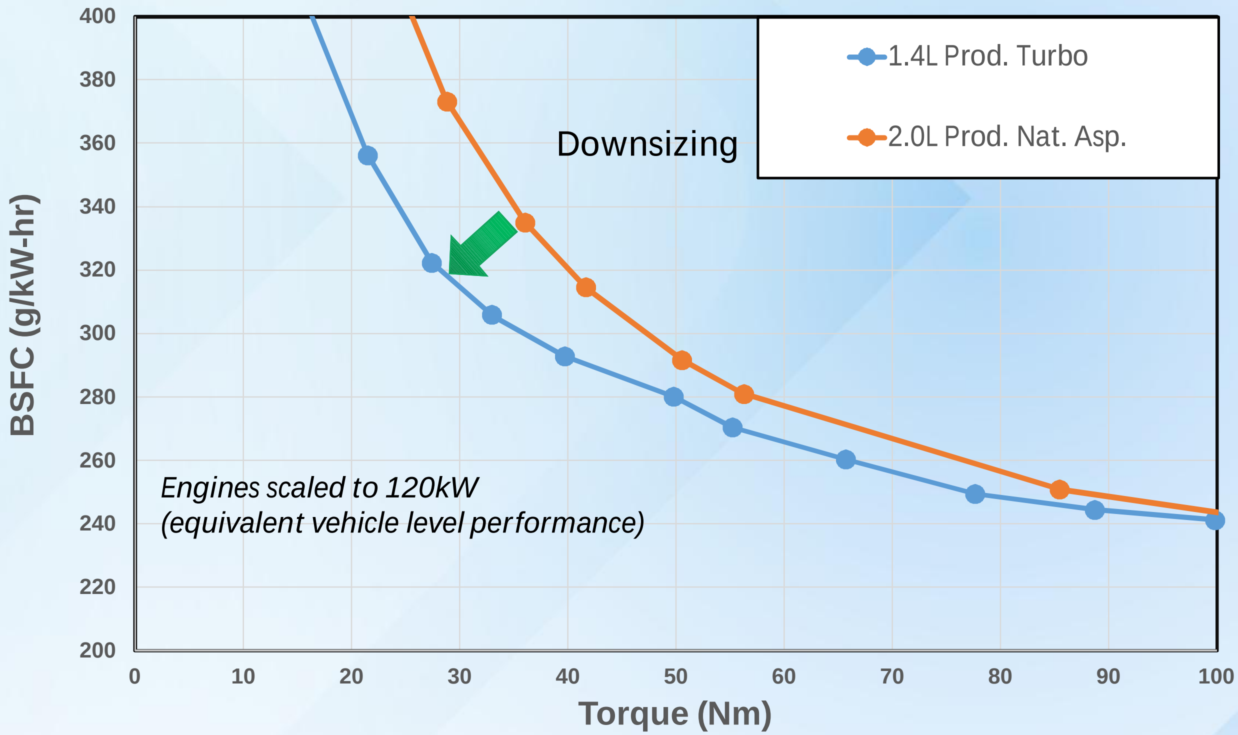
- Key enablers are increased EGR tolerance and Lean, Low Temperature Combustion – *more reactive fuels*

Maintaining modest peak pressure levels to avoid incurring major parasitic losses

- Key enablers are homogeneous stoichiometric operation at WOT with rated speed above 6000rpm

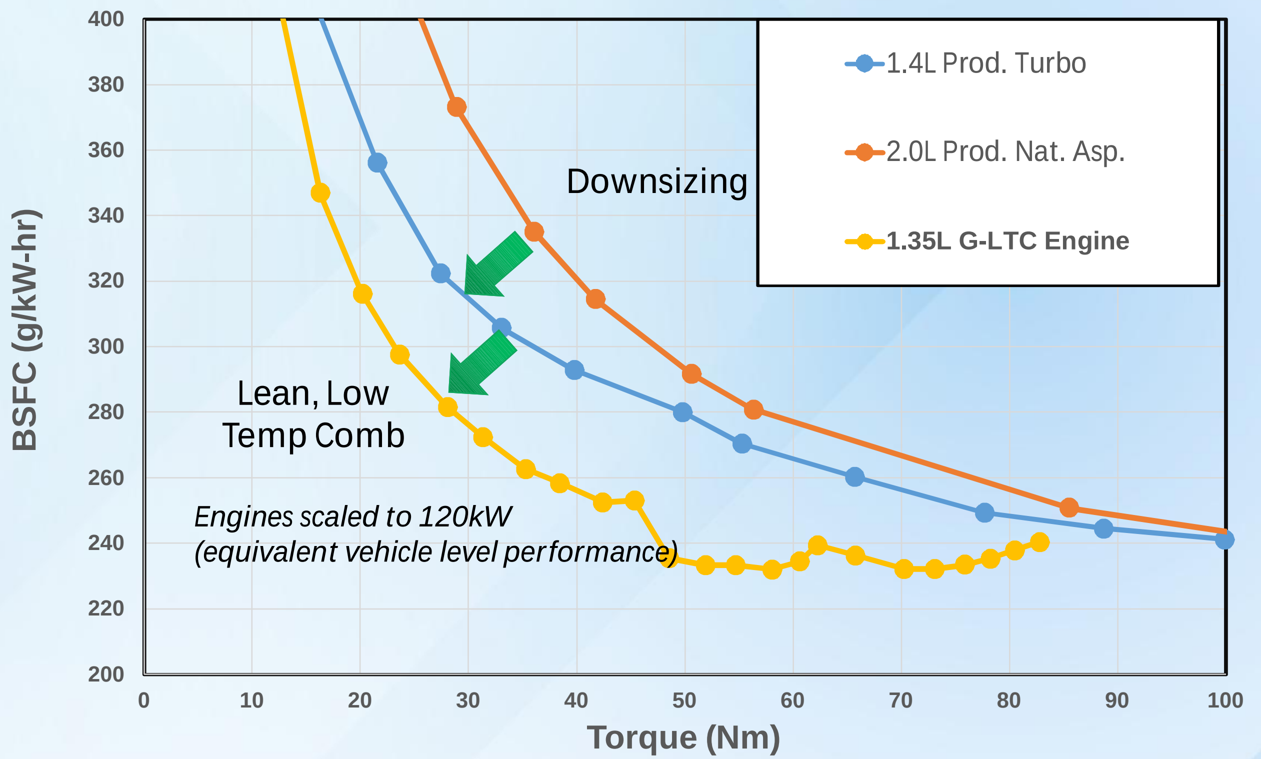
THE ENGINE CHALLENGE

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



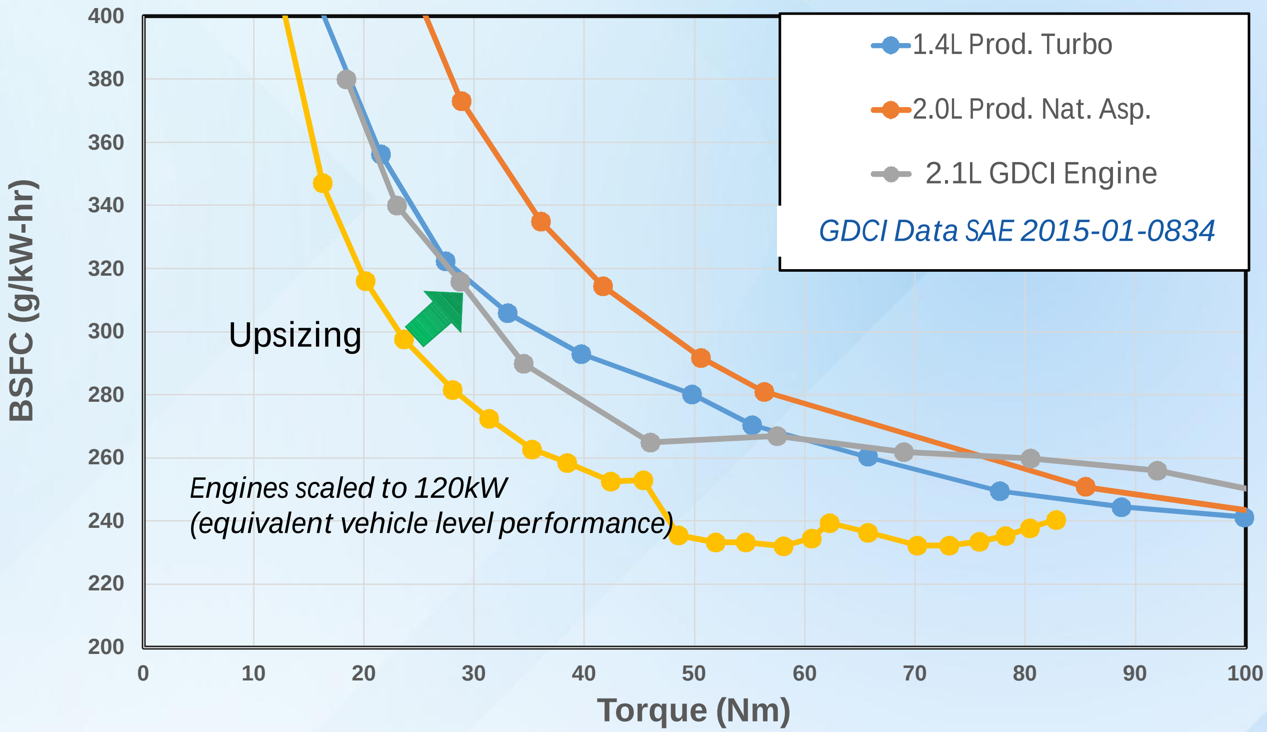
THE ENGINE CHALLENGE

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, GDCI-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



THE FUELS CHALLENGE – EFFICIENT & CLEAN IC ENGINES

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

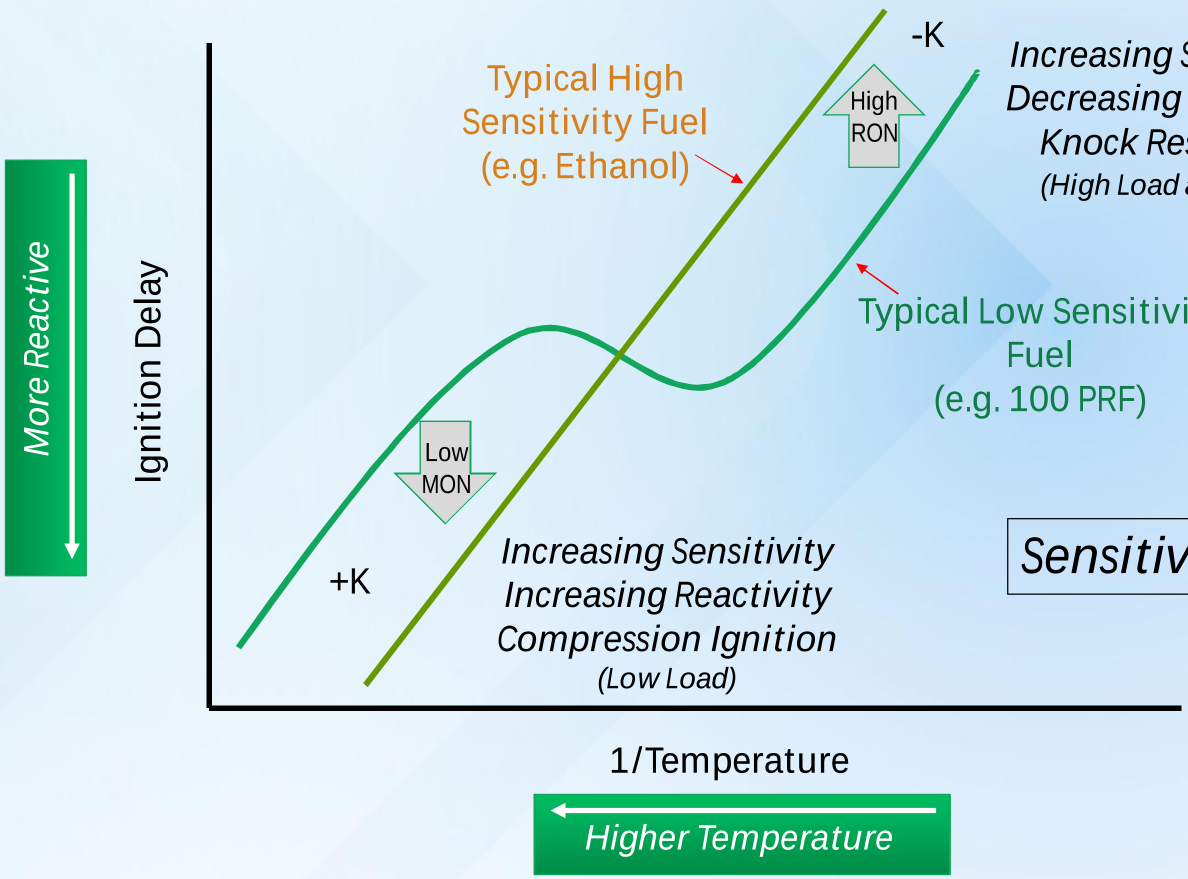
- Ø High knock resistance with high sensitivity
  - o High RON and High Sensitivity
- Ø Low variability across the marketplace
  - o RON, Sensitivity, T90, ...
- Ø Near-zero sulfur, < 10 ppm (lower is better)
- Ø Good low temperature catalyst reactivity
- Ø Low propensity to soot

RON>98 S>12
MON<88

à 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.



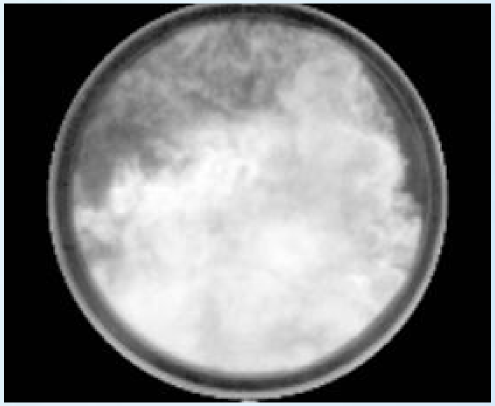
Sensitivity = RON-MON

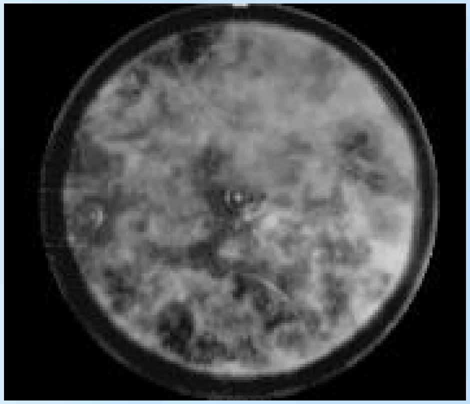
THE FUELS CHALLENGE – *OCTANE INDEX*

*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)





Gasoline
Low Temp
Combustion
(e.g. HCCI)

Knock Resistance – high pressure, low temperature condition

K is negative – Sensitivity increases Octane Index and "degrades reactivity"

K ~ -1 for Boosted, High Load, WOT

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

					Octane Index	
Fuel	**RON**	**MON**	**Sensitivity**	**AKI**	**Boosted SI WOT (K=-1)**	**Part Load LTC (K=2)**
US Regular Grade	91	83	8	87	99	75
Improved Gasoline	96	84	12	90	108	72
Desired Gasoline	100	86	14	93	114	72
Fixed Sensitivity Fuels	94	86	8	90	102	78
	96	88	8	92	104	80
	98	90	8	94	106	82
Fixed MON	94	84	10	89	104	74
	96	84	12	90	108	72
	98	84	14	91	112	70
Decreasing Sensitivity Fuels	94	84	10	89	104	74
	96	88	8	92	104	80
	98	92	6	95	104	86

major Knock gains while enabling part load LTC

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

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 leverages high sensitivity blending components

Fuels Comparison					Octane Index	Octane Index
Fuel Type	**RON**	**MON**	**Sensitivity**	**AKI**	**Comp. Ign.**	**SI-Knock**
Regular Grade Gasoline (US)	91	83	8	87	75	99
GM Desired Gasoline	100	86	14	93	72	114
Alcohols						
Methanol	106	92	14	99	78	120
Ethanol	107	89	18	98	71	125
Aromatics						
Toluene	120	109	11	114.5	98	131
Ethyl-Benzene	111	98	13	104.5	85	124
Olefins						
Pentene	91	77	14	84	63	105
Iso-Octene	>100	86	>14	>93	<72	>114
Cyclo-Parafins						
Cyclo-Pentane	101	85	16	93	69	117
Cyclo-Hexane	84	78	6	81	72	90
Parafins						
Pentane	62	63	-1	62.5	64	61
Hexane	25	26	-1	25.5	27	24
Iso-Pentane	93	90	3	91.5	87	96
Iso-Hexane	100	100	0	100	100	100

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 CO_2 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 CO_2 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

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