Sustainable Fuels and Clean Vehicles

Light-Duty SI Engine Technologies and the Impact of Higher Carbon Alcohol Fuels

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Spark-ignition engines undergoing rapid development and technology integration

- Direct-injection, advanced ignition, charge control via flexible cam systems, and boosting – downsizing – downspeeding,
- Ethanol an important US biofuel as a blend over the past decade
- US Renewable Fuel Standard (RFS2) requires an increase in the use of advanced biofuels of up to 36 billion gallons by 2022.
- Longer chain alcohols, cellulosic ethanol and synthetic biofuels, can meet demand while adhering to the RFS2 corn-based ethanol limitation.
- Higher carbon number alcohols can be utilized to improve the energy content, knock resistance, and petroleum displacement of alcohol blends in comparison to higher ethanol blends (>E15)

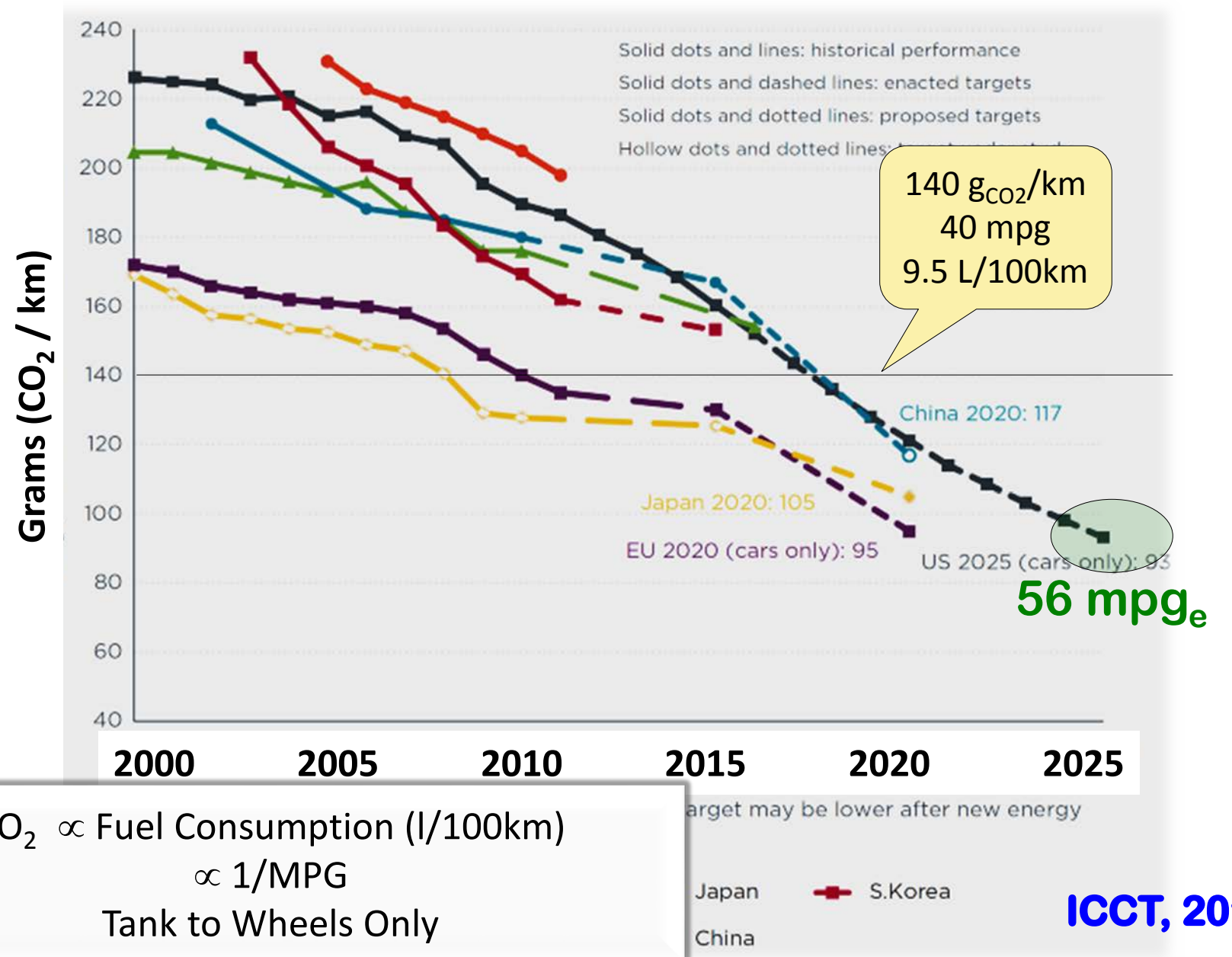
FUEL CONSUMPTION

(CO_2 EMISSIONS)

REGULATED EMISSIONS

(NO_X, HC, CO, PM)

CO_2 (Fuel Consumption) Regulations

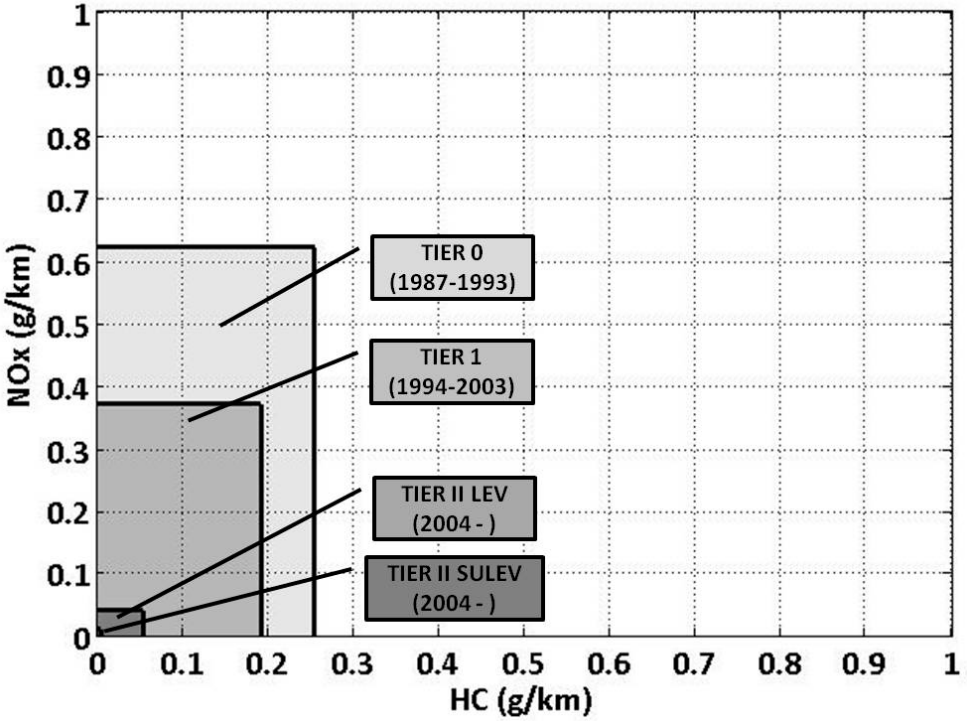


CO_2 ∝ Fuel Consumption (l/100km)
∝ 1/MPG
Tank to Wheels Only

ICCT, 2012

Emissions Regulations

US Emission Standards*



PZEV = SULEV levels with no evaporative emissions

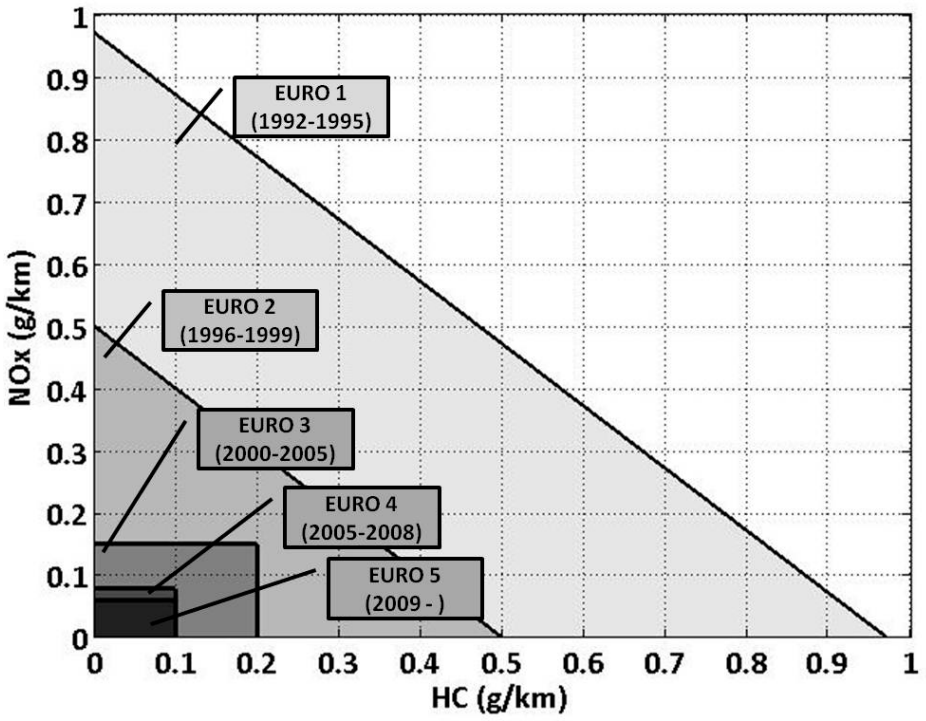
*Standards in g/mi converted to g/km

EPA Tier II - Different Bins

Must Meet Fleet Average

CARB LEVIII → EPA TIER III

European Emission Standards



Different standards for gasoline and diesel

Euro 6 (PM + PN)

Emissions Standards – Future US

US Tier II

120,000 Miles

Phase in: 2004-2009

Emission Category	NMOG +NOx	PM
8	325	20
7	240	20
6	190	10
5	**160**	**10**
4	110	10
3	85	10
2	**30**	**10**
1	0	0

* mg/mile

Fleet Average

Fuel Sulfur: 30 ppm

CARB LEV III

150,000 Miles

Phase in: 2015-2025

Emission Category	NMOG +NOx	PM†
LEV160	160	10
ULEV125	125	10
ULEV70	70	10
ULEV50	50	10
SULEV30	**30**	**10**
SULEV20	20	10

* mg/mile

Extremely low emissions gasoline vehicles since 2004 (SULEV)

US Tier III (Proposed)

150,000 Miles

Phase in: 2017-2025

Emission Category	NMOG +NOx	PM
Bin 160	160	3
Bin 125	125	3
Bin 70	70	3
Bin 50	50	3
Bin 30	**30**	**3**
Bin 20	20	3
Bin 0	0	0

Fleet standard reduction of 5x (160 → 30)

Bin 160 = Tier II Bin 5

Bin 30 = Tier II Bin 2

Emission Standards – EU & China

EU Emissions Standards

EURO5 (2009) Beijing (2013)

EURO6 (2014)

Emission Category	HC +NOx		
4 (CI)	483		
4 (SI)	290		NA
5 (CI)	370	8	NA
5 (SI)	257	8	NA
6 (CI)	274	8	$10 \cdot 10^{11}$
6 (SI)	257	8	$10 \cdot 10^{11}$

China EURO iles

High NO_X and Differing CI / SI Emissions Standards Promote diesel LDV

Higher Diesel Fuel Quality

* mg/mile

Fuel Sulfur: <10 ppm (2009)

Cetane #: 51

LEV III == SULEV
LEV III << EURO6

US Tier III (Proposed)

150,000 Miles

Phase in: 2017-2025

Emission Category	NMOG +NOx	PM
Bin 160	160	3
Bin 125	125	3
Bin 70	70	3
Bin 50	50	3
Bin 30	**30**	**3**
Bin 20	20	3
Bin 0	0	0

* mg/mile

Fleet Average by 2025

Fuel Sulfur: 10 ppm

Bin 160 = Tier II Bin 5

Bin 30 = Tier II Bin 2

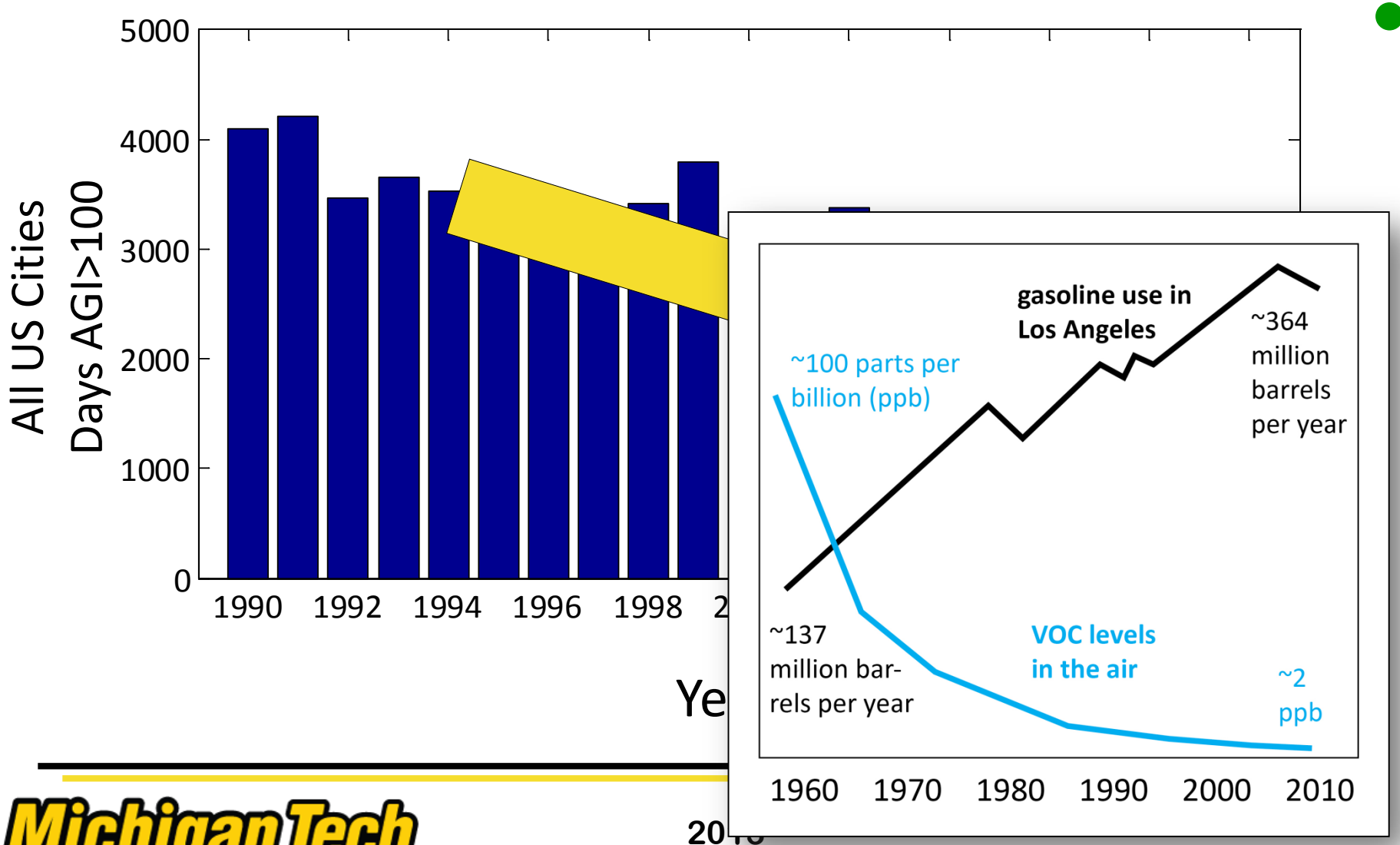
Air Quality Index

AQI (Rating)		Classification (Rating)	PM_{10} (ug/m^3)		$PM_{2.5}$ (ug/m^3)		NO_2 (ppm)	
0	50	Good	0	54	0	15.4	0	-
51	100	Moderate	55	154	15.5	40.4	-	-
101	150	Unhealthy (Sensitive)	155	254	40.5	65.4	-	-
151	200	Unhealthy	255	354	65.5	150.4	-	0.64
201	300	Very Unhealthy	355	424	150.5	250.4	0.65	1.24
300	401	Hazardous	425	504	250.5	350.4	1.25	1.64
401	500	Hazardous (No data)	505	604	350.5	500.4	1.65	2.04

US EPA
Guidelines for the Reporting of Daily Air Quality - the Air Quality Index (AQI)
EPA-45/B-06-001
May 2006

Air Quality – US

US Tier 0 → US Tier I → US Tier II → CARB LEV III / US Tier III



http://www.noaanews.noaa.gov/stories2012/20120809_laairqualitystudy.html

LDV POWERTRAIN TECHNOLOGIES

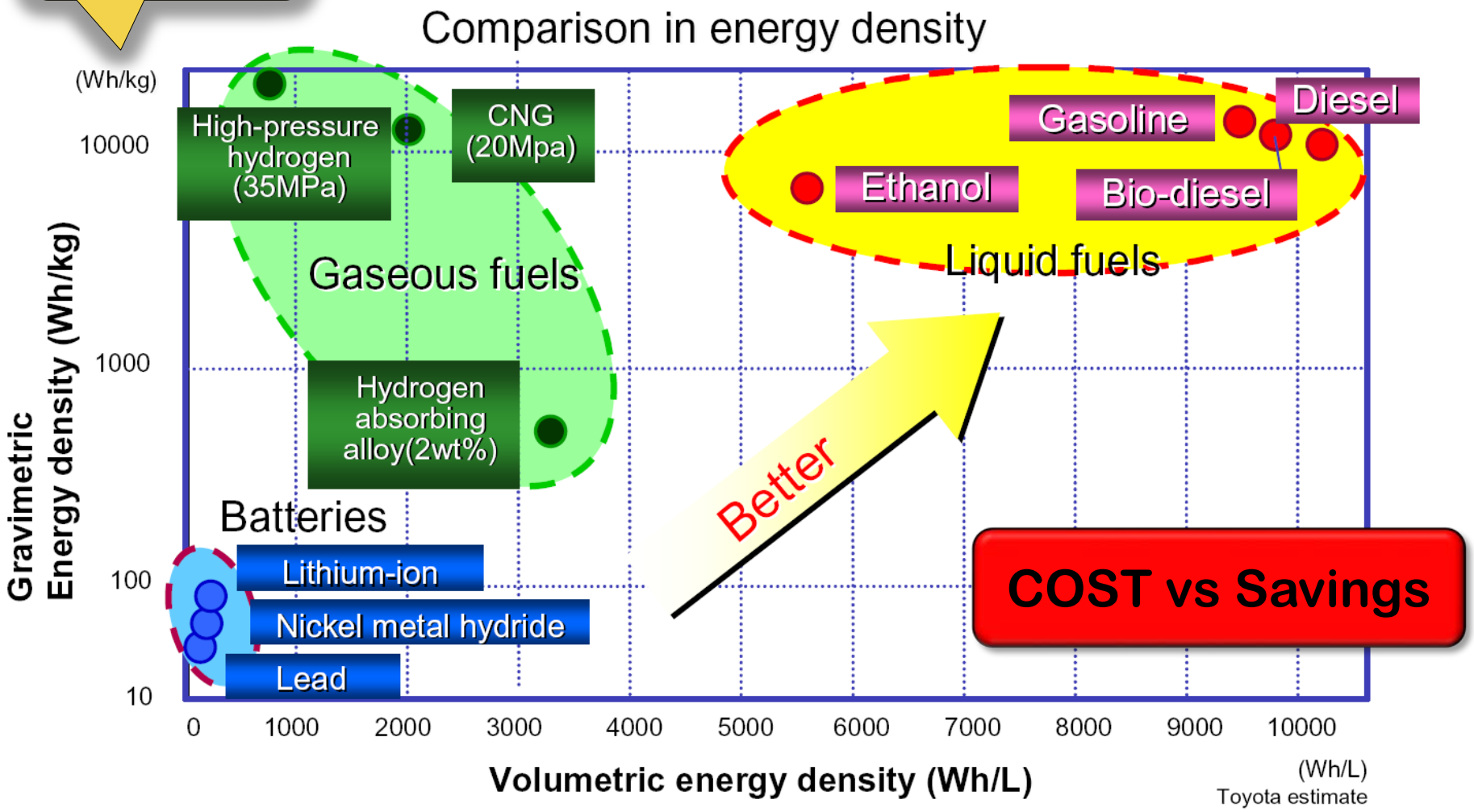
SAE TECHNICAL PAPER SERIES
2008-01-0456

Study on the Potential Benefits of Plug-in Hybrid Systems

Masayuki Komatsu, Toshifumi Takaoka, Tetsuhiro Ishikawa, Yuujin Gotouda and Naoto Suzuki
Toyota Motor Corporation
Tamaki Ozawa
Toyota Technical Development Corporation

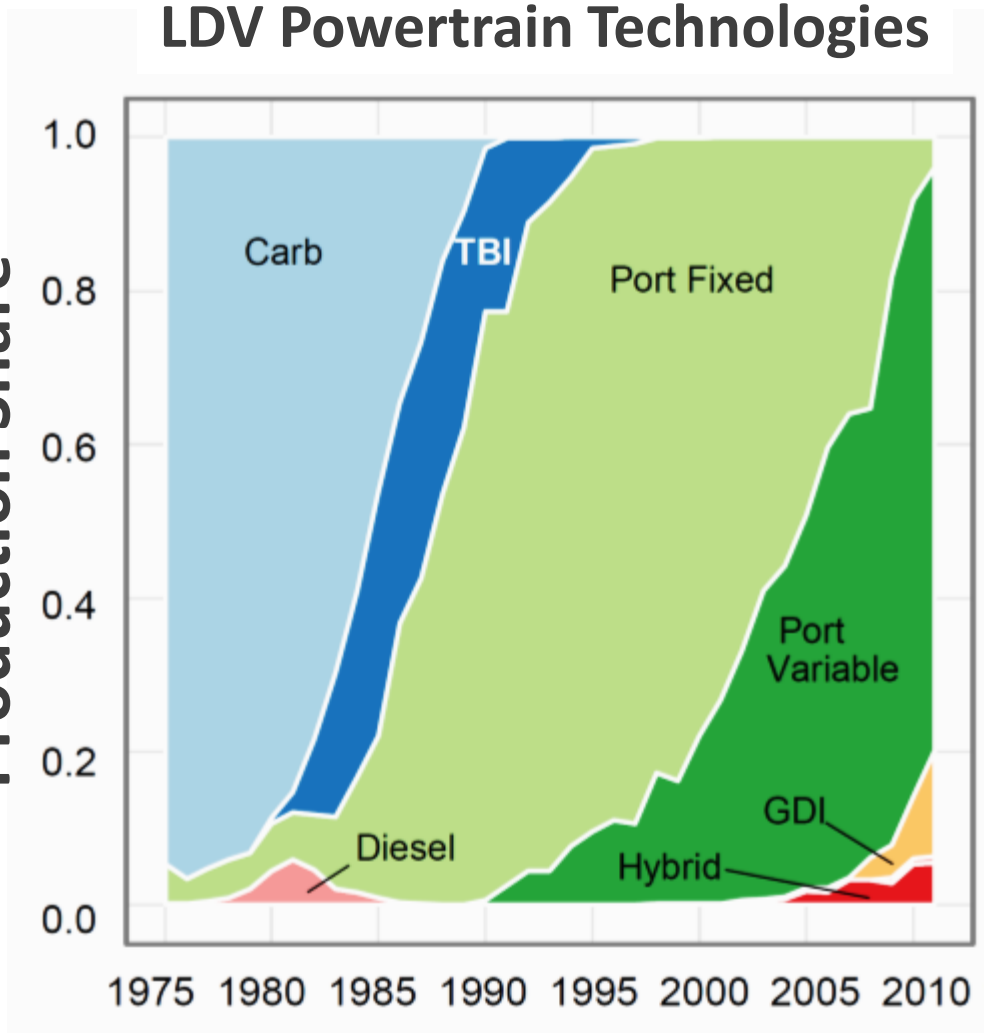
Vehicle Energies

Log Scale



Battery density constraints 1-charge range of pure EV.
Combine HV and EV to reduce fuel consumption of HV.

US Spark-Ignition Engines

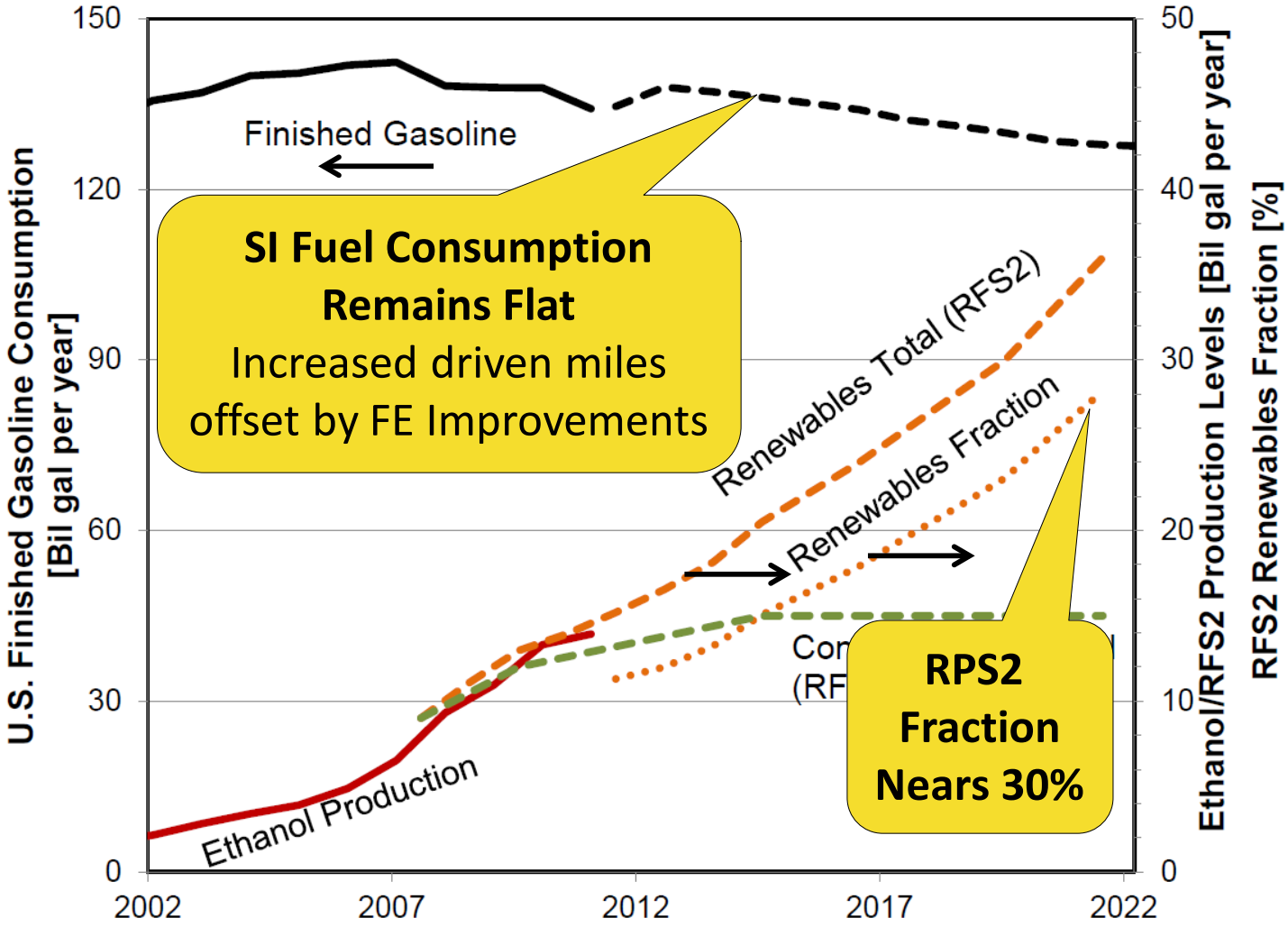


SI engines dominate US and will like continue to dominate LDV powertrains for the next several decades

- **Lowest cost**
- **Lowest emissions**
- Diesel vs gasoline fuel cost differential will likely widen
- Fuel Flexibility: Ethanol, **NG, …**
- Synergies with HEV's
- Improving efficiency; **however, disadvantage to CI**
  - **Further enhancement required**

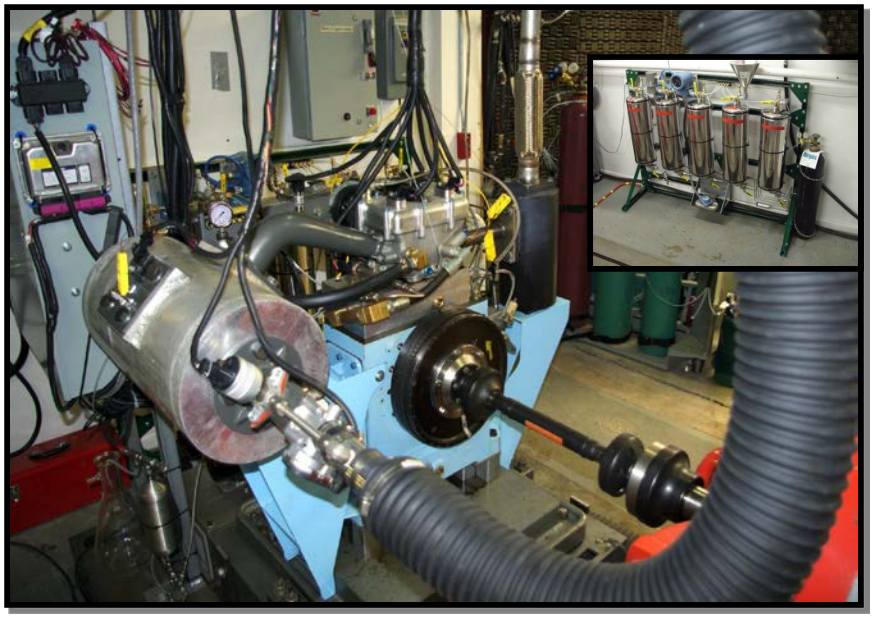
ALTERNATIVE FUELS FOR SI ENGINES

US Renewable Fuels



Ethanol Blends Characterized and Modeled

- Crank start combustion and emissions
- Compression Ratio – Impacts & optimization
- High Dilution (Cam Phasing and Cooled EGR)
- Predictive combustion for engine simulation
- Ignition systems



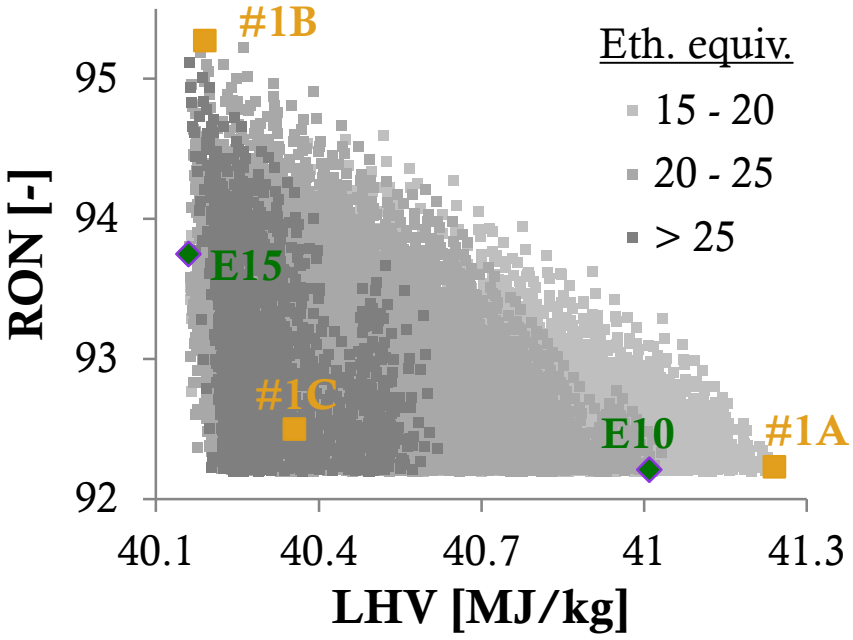
	E00	E10	E20	E50	E85
CR 11.0	√	√	√	√	√
CR 12.5	√	√	√	√	√
CR 14.0	√	√	√	√	√
CR 15.5	√	√	√	√	√
CR 17			√	√	√
CR 18.5				√	√

Alcohol Properties

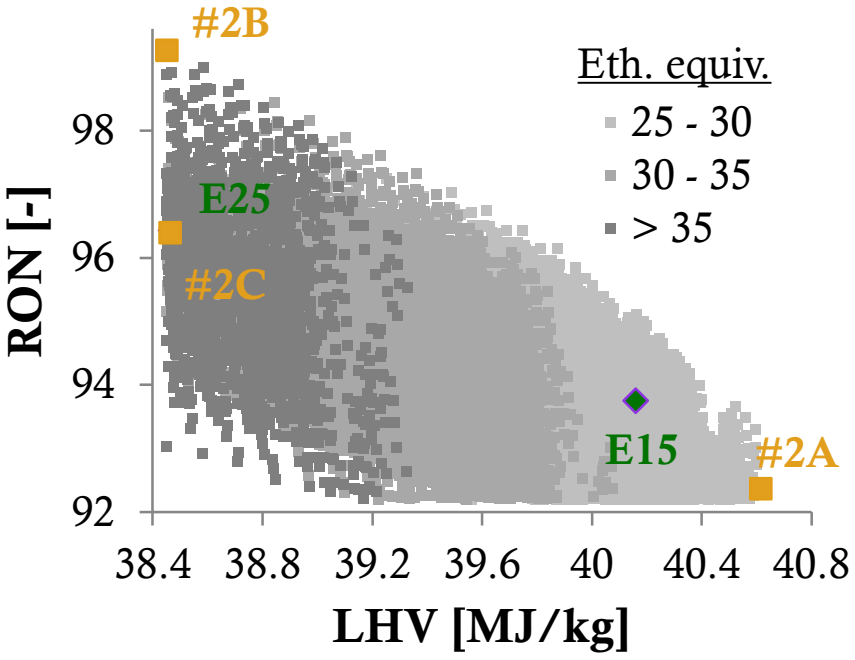
	Density kg/m^3	HoV kJ/kg	LHV MJ/kg	Oxygen wt%	RON -	MON -	RVP kPa (psi)
EEE	742	351*	42.9	0	97.1	88.7	62.1 (9.0)
BOB	753	n/a	42.7	0	88.6	81.0	40.0 (5.8)
ethanol	789	920	25.5	34.7	107.4	88.2	17.4 (2.5)
n-propanol	803	792	30.2	26.6	104.9	87.8	8.5 (1.2)
iso-propanol	786	757	29.7	26.6	112.5	96.7	13.3 (1.9)
n-butanol	810	708	32.9	21.6	98.3	84.4	10.1 (1.5)
iso-butanol	802	686	32.7	21.6	105.1	89.3	6.3 (0.9)
n-pentanol	814	647	34.7	18.1	85.8	75.9	3.7 (0.5)
iso-pentanol	810	617	34.5	18.1	98.8	86.8	2.8 (0.4)
n-hexanol	814	486	36.0	15.7	69.3	64.1	2.8 (0.4)

* actual value not available, value shown is typical for gasoline

Optimal Alcohol Blends



Can exceed E10 LHV, E15 RON, or E25 PD.



Can exceed E15 LHV, E25 RON, or E35 PD.

Summary

Combined CO_2 and Emissions Reduction – Challenges & Opportunities for LDV

- Emissions reduction factor in improving air quality
- SI engines can meet current and future emissions regulations (NMOG/NO_X/PM) but significant reduction in CO_2 required.
  - Advanced engine technologies
  - Alternative fuels including alcohol blends (CO_2 credits)
  - Electrification (HEV) and vehicle technologies (light weight materials, advanced trans, …)

THANK YOU