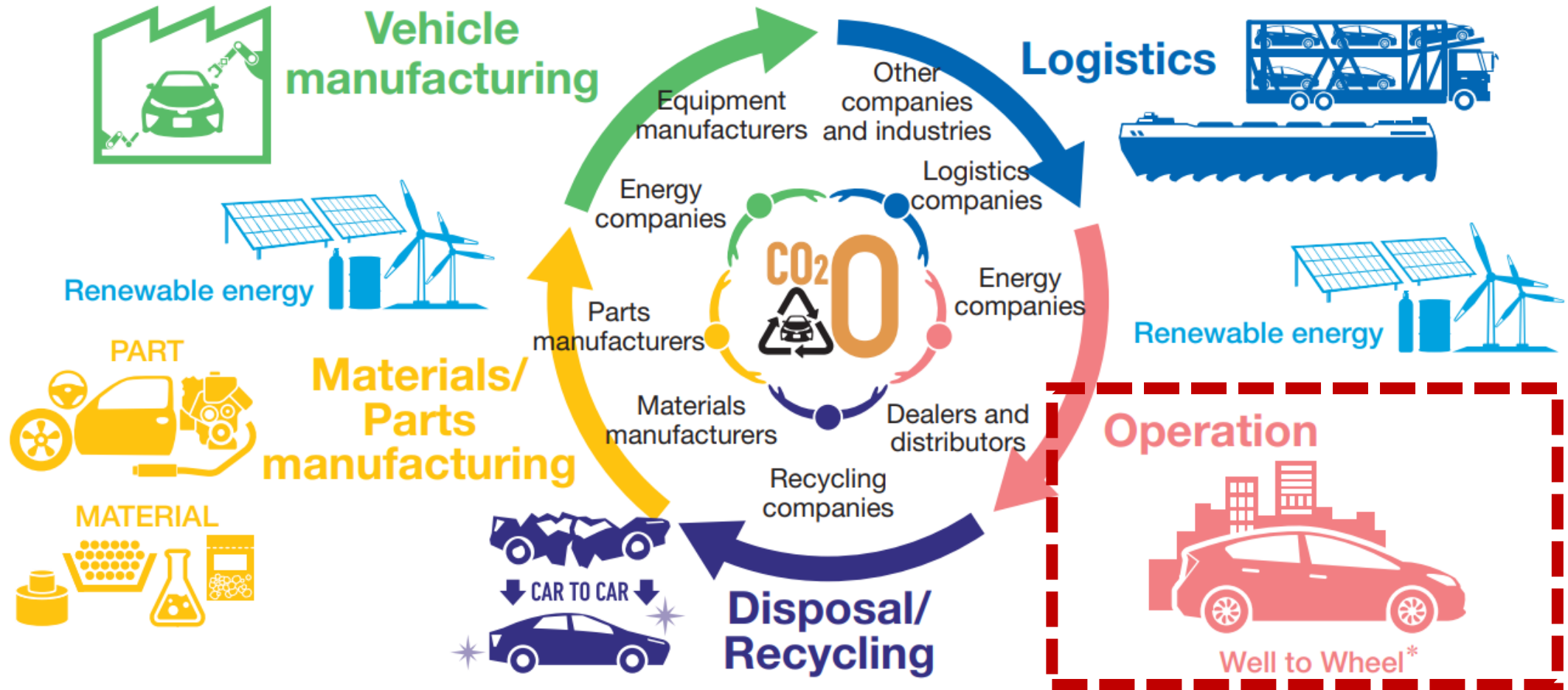


The Effect of Mid-Level Ethanol Blends on Fuel Economy, Performance, Emissions, Reliability, and Well-to-Wheel CO₂ in Gasoline Engine

Naoyoshi Matsubara, Kenji Sugata, Takashi Koyama, Yuta Ochi,
Mizuki Aoki, Keiju Tomoda, Kohei Kodama, Masakiyo Kojima

Toyota Environment Challenge 2050

Aim to achieve CN throughout the vehicle life cycle



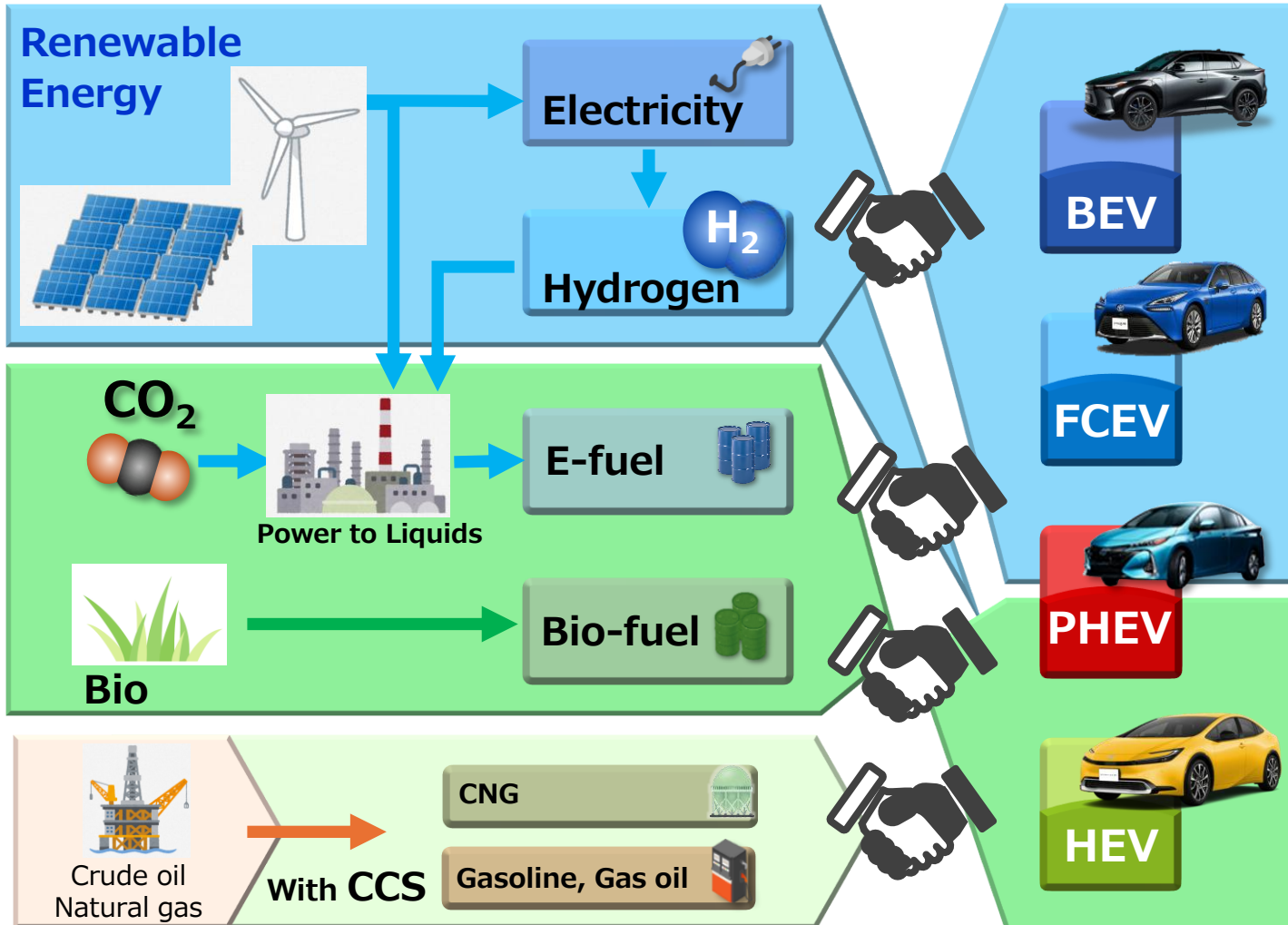
* In addition to greenhouse gas (GHG) emissions during vehicle operation, GHG emissions from fuel and electricity production are also included. (The emissions of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) vary depending on the power source mix and hydrogen production methods)

Multi-pathway Strategy of Powertrain

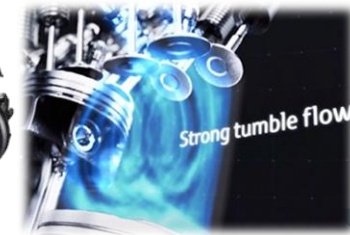
Both Engine and Fuel technologies are essential for achieving CN

Various Energy & Fuel Source

Various Powertrains



Engine Technologies



High Thermal Efficiency

CO₂



Fuel Technologies



- High thermal efficiency
- Low emission

CO₂



Utilization of Ethanol



Sources: Inspire SGS. Ethanol Mandates and Average Content in Gasoline. Jan. 2024. ePure. Overview of Biofuels Policies and Markets across the EU. Feb. 2023.

Note: Some countries only have maximum % blending policies.

[USGC publishes new ethanol infographics | SAF Magazine](https://safmagazine.com/articles/usgc-publishes-new-ethanol-infographics)

<https://safmagazine.com/articles/usgc-publishes-new-ethanol-infographics>

Ethanol Characteristics

Ethanol has significantly different characteristics from Gasoline

Property	Gasoline	Ethanol	
Molecular	C4~C12	C ₂ H ₅ OH	Lower Carbon number Hydroxy group
Molecular weight [g/mol]	70~90	46	
Density [kg/m ³]	0.740	0.789	
Stoichiometric air fuel ratio [-]	14.6	9.0	Higher fuel injection amount
Flammable range [vol%]	2~10	3.3-19	
Flame propagation speed [m/s]	0.4~0.5	0.6	
Research octane number [-]	92	111	Higher knock propensity
Adiabatic flame temperature [K]※	2291	2235	Lower cooling loss
Latent heat of evaporation [kJ/kg]	420	845	
Boiling point [deg. C]	30-180	79	Poor evaporation in cold condition
Lower heating value [MJ/kg]	43	26.8	Lower driving range

※ Ethanol and S5R gasoline surrogate were calculated
under condition of 298K, 1 atm, stoichiometric with SIP Gd2.01 [6]

Challenge and Objective

Challenge

It is important to understand the effect of Ethanol blend ratio. However, study of Mid-level ethanol blend (E10-E40) effect on current engine is still at the early stage.



Objective

To clarify the MLEB effect on performance, fuel economy, emissions, and reliability with current turbo-charged engine

Test Engine

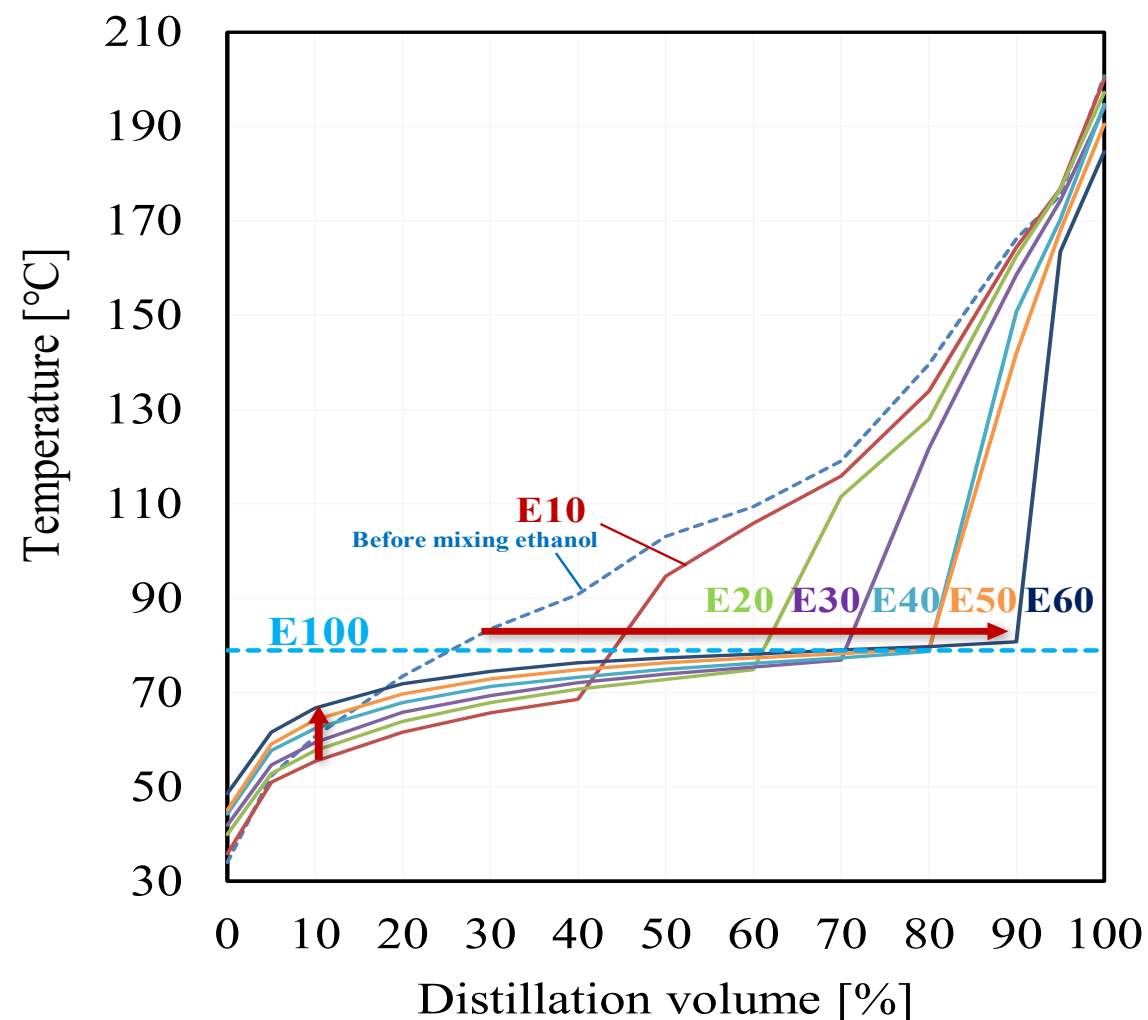


Engine	T24A-FTS
Engine type	Inline 4-cylinder, turbocharged
Displaced volume	2393 cc
Stroke	99.5 mm
Bore	87.5 mm
Compression ratio	11.0:1
Injection system	Direct injection (DI) and Port fuel injection (PFI)
Representative vehicle	 Tacoma

Test Fuel Property

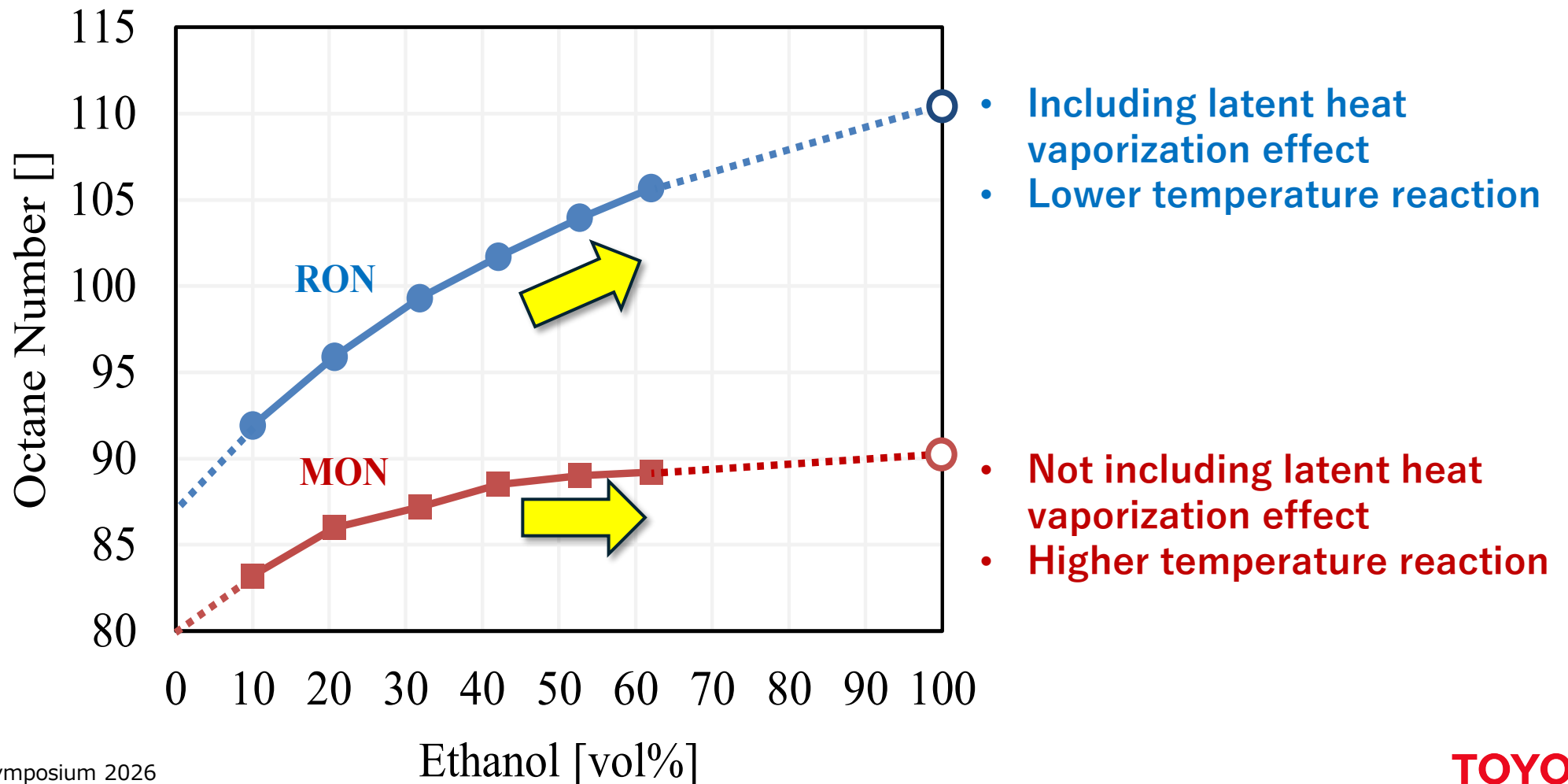
Mixing ethanol base on E10 fuel in USA

term	unit	Base E10	E20	E30	E40	E50	E60	E100
RON	-	91.9	95.9	99.3	102.2	No data	No data	No data
MON	-	83.2	86	87.2	88.5	89	89.2	No data
RVP@37.8℃	kPa	63.1	59.8	58.9	54.4	52.8	49.1	No data
Density@15℃	kg/m3	0.740	0.745	0.752	0.757	0.763	0.769	0.813
IBP	℃	35.8	40	41.9	44.3	45.1	48.6	No data
T5	℃	51	52.8	54.7	57.8	59.1	61.6	No data
T10	℃	55.5	57.7	59.4	62.4	64.2	66.8	No data
T20	℃	61.6	63.9	65.8	67.9	69.7	71.9	No data
T30	℃	65.7	67.9	69.4	71.3	72.9	74.5	No data
T40	℃	68.6	70.7	72.1	73.3	74.9	76.3	No data
T50	℃	94.7	72.8	73.9	75	76.3	77.4	No data
T60	℃	105.9	74.8	75.4	76.2	77.4	78.2	No data
T70	℃	115.9	111.6	76.9	77.4	78.3	79.1	No data
T80	℃	133.9	128	121.8	78.7	79.3	79.8	No data
T90	℃	164.4	162.5	158.6	150.7	141.9	80.8	No data
T95	℃	176.8	176.7	174.3	170.3	167.9	163.5	No data
FBP	℃	200.1	197.2	194	194.7	190.5	184.6	No data
Distillation Residue	vol%	0.7	1.1	1.1	0.9	1.0	1.3	No data
Unwashed gum	mg/100 ml	No data	2.6	3.1	0.9	0.8	0.0	No data
Washed gum	mg/100 ml	0.5	0.24	0	0	0	0	No data
Olefins	vol%	6.5	6.32	5.12	4.22	3.64	2.97	No data
Aromatics	vol%	23.7	18.47	16.47	13.38	11.56	8.94	No data
Ethanol	vol%	10	21	32	42	53	62	96
H/C	-	1.96	2.04	2.14	2.21	2.31	2.42	3.1019
O/C	-	0.03	0.07	0.11	0.16	0.21	0.25	0.5521
A/F	-	14.0	13.3	12.7	12.1	11.5	11.0	8.6
Water	ppm	No data	324	228	325	281	296	4400
Sulfur	ppm	11	9	8	6	5	5	No data
NHV	kJ/kg	41410	39490	37940	36140	34220	32480	24730



Octane Number

RON increases monotonically
MON increase slow down above E40



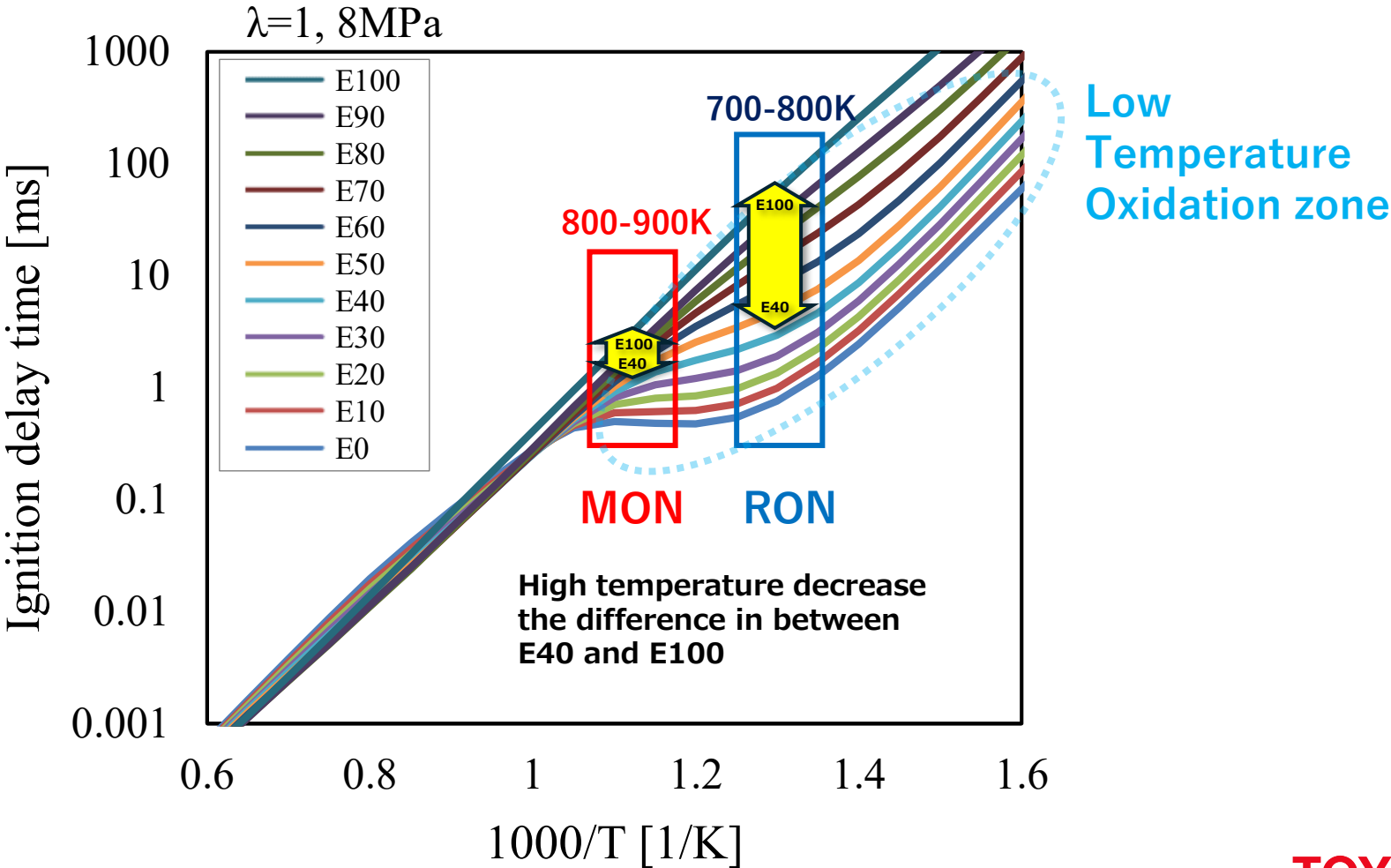
Ignition Delay Time

Ethanol suppresses Low temperature oxidation reaction.
The reaction effect is not significant in higher temperature condition

Chemkin-Pro
zero-dimensional detailed
reaction calculation

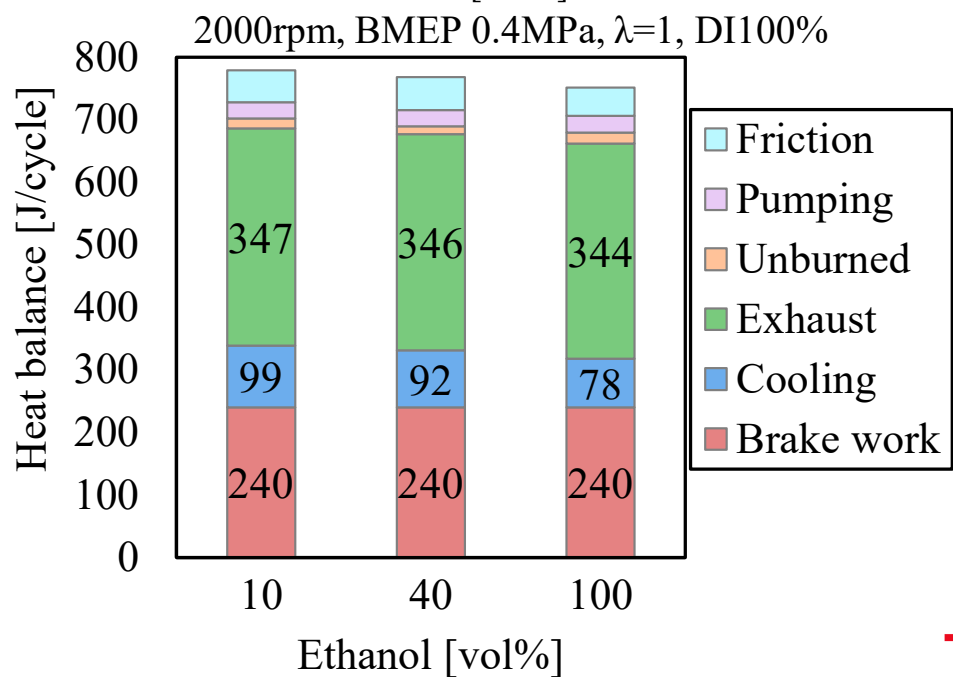
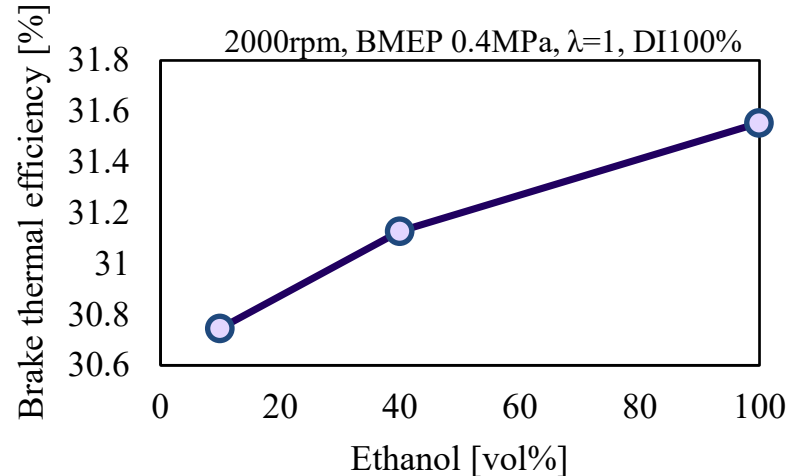
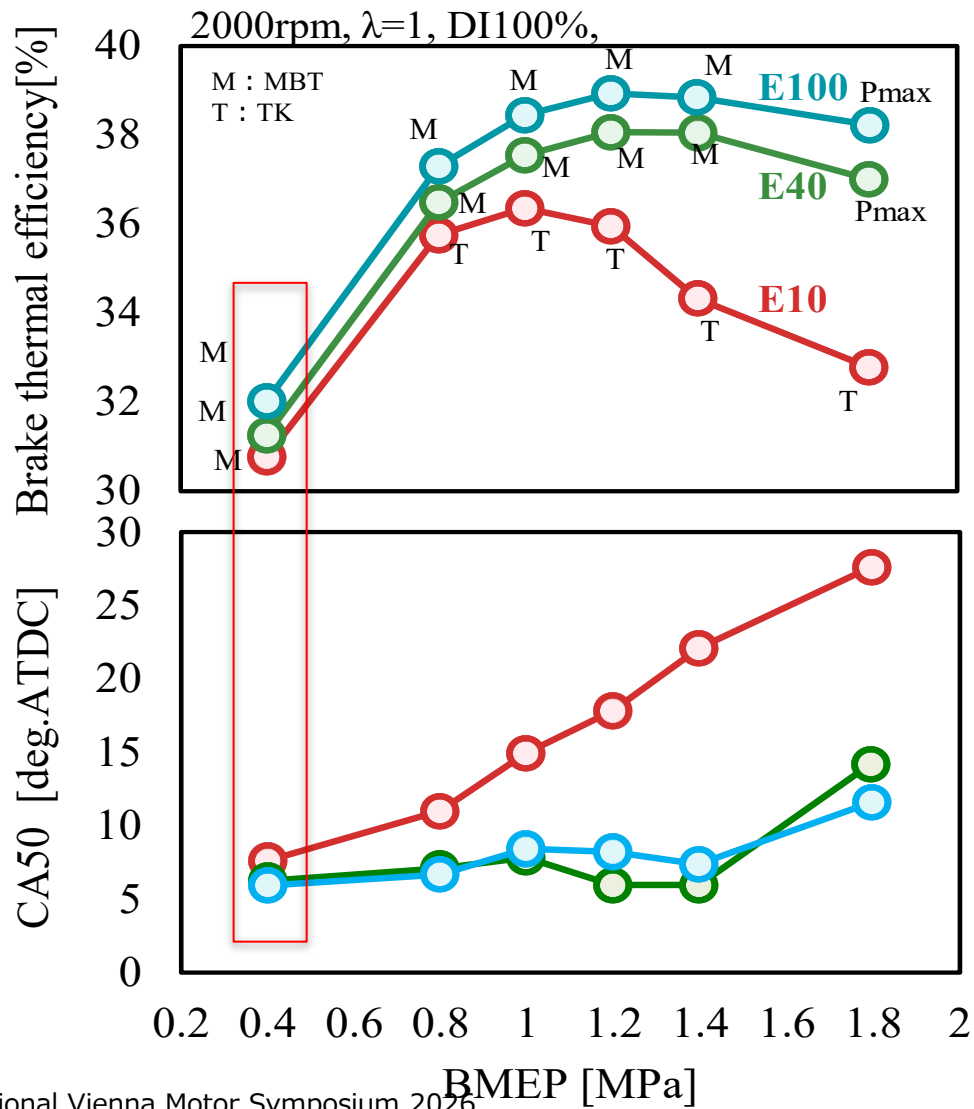
Surrogate fuel of E10

Molecules	mol%
N-pentane	9.2
Heptane	9.5
2_3-dimethylbutane	9.2
iso-octane	7.9
Xylenes	11.5
Trimethylbenzenes	4.7
Toluene	6.3
Methylcyclopentane	12.6
Hexene	9.2
Ethanol	19.8



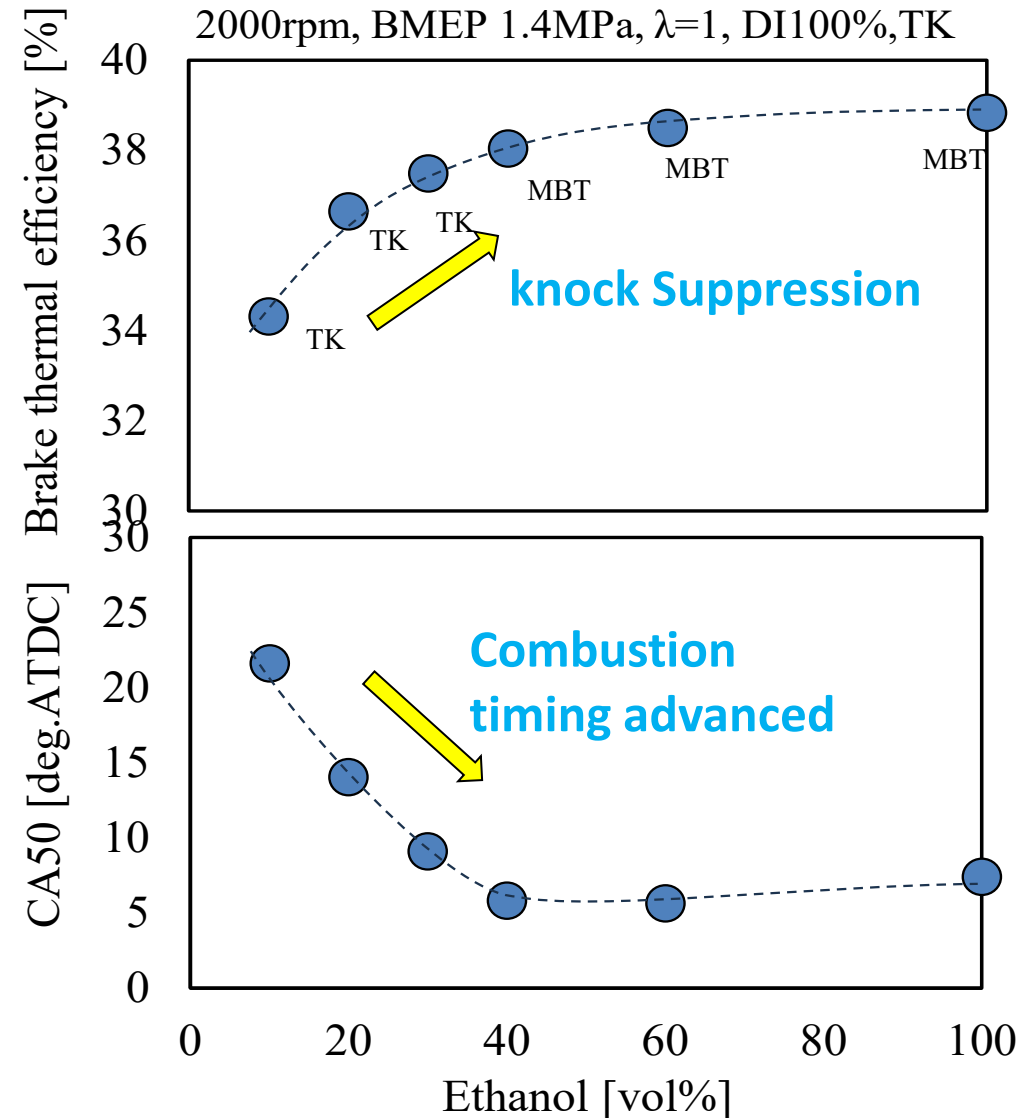
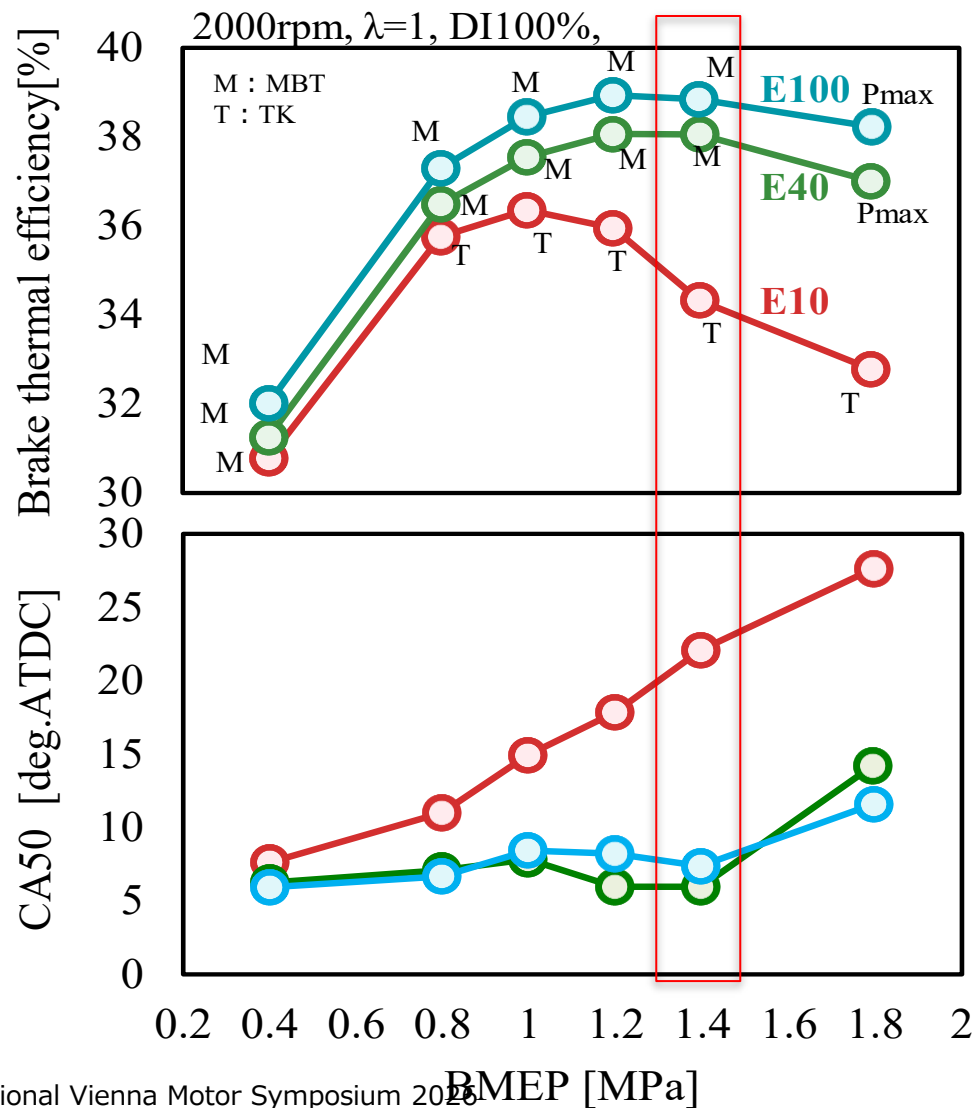
Thermal Efficiency in Low Load

Thermal efficiency increase with Ethanol blend ratio due to lower cooling loss



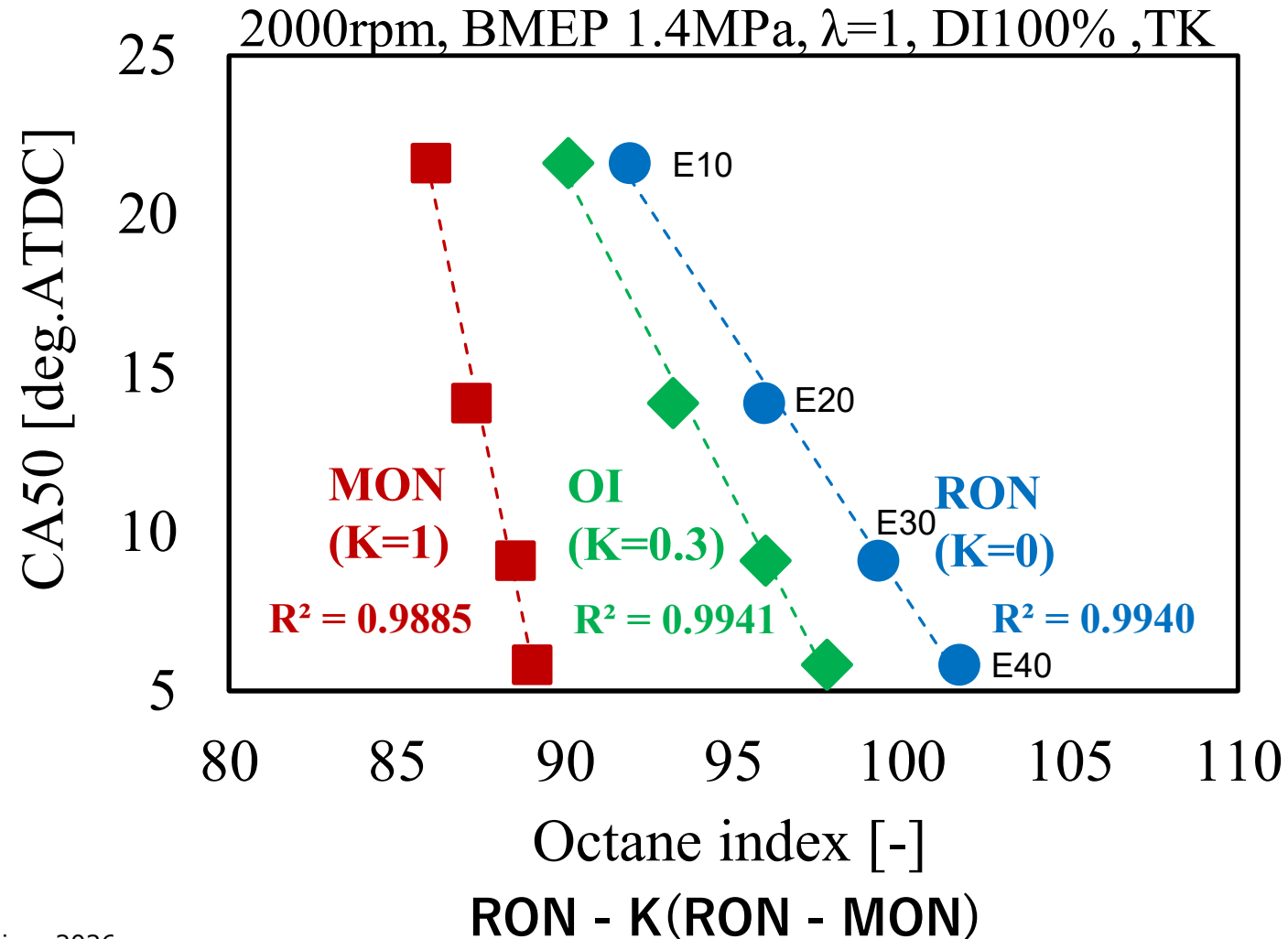
Thermal Efficiency in High Load

The knock mitigation effect is significant from E10 to E40



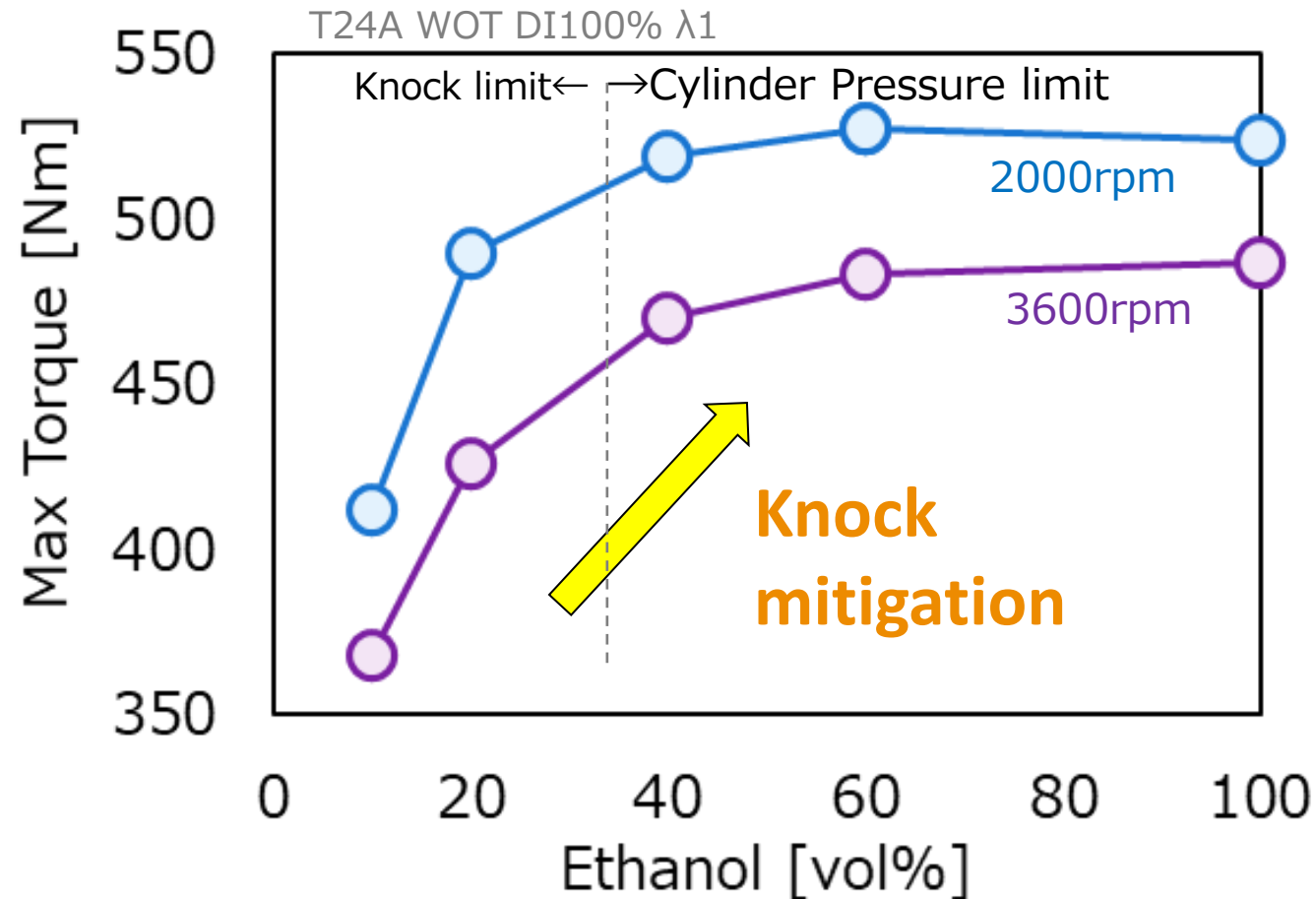
Octane Index

RON has greater effect on knock



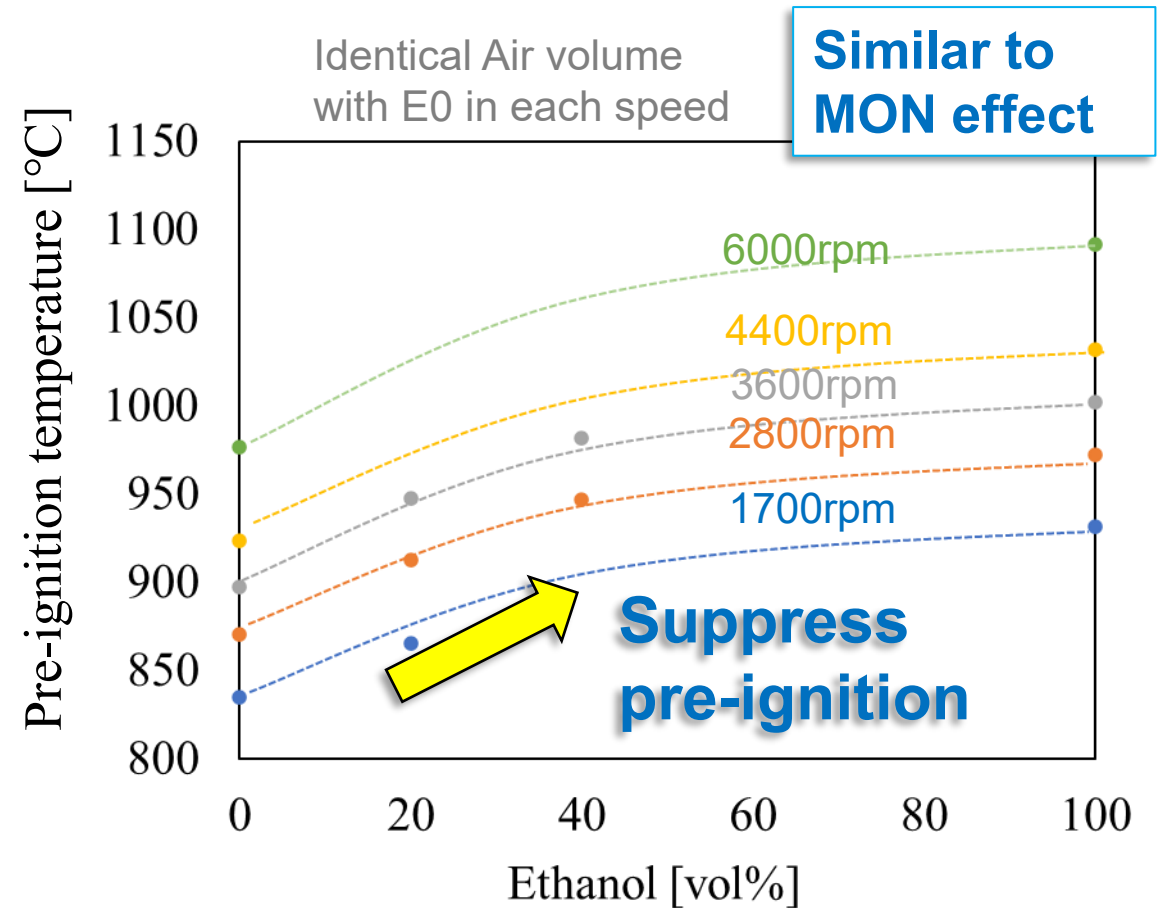
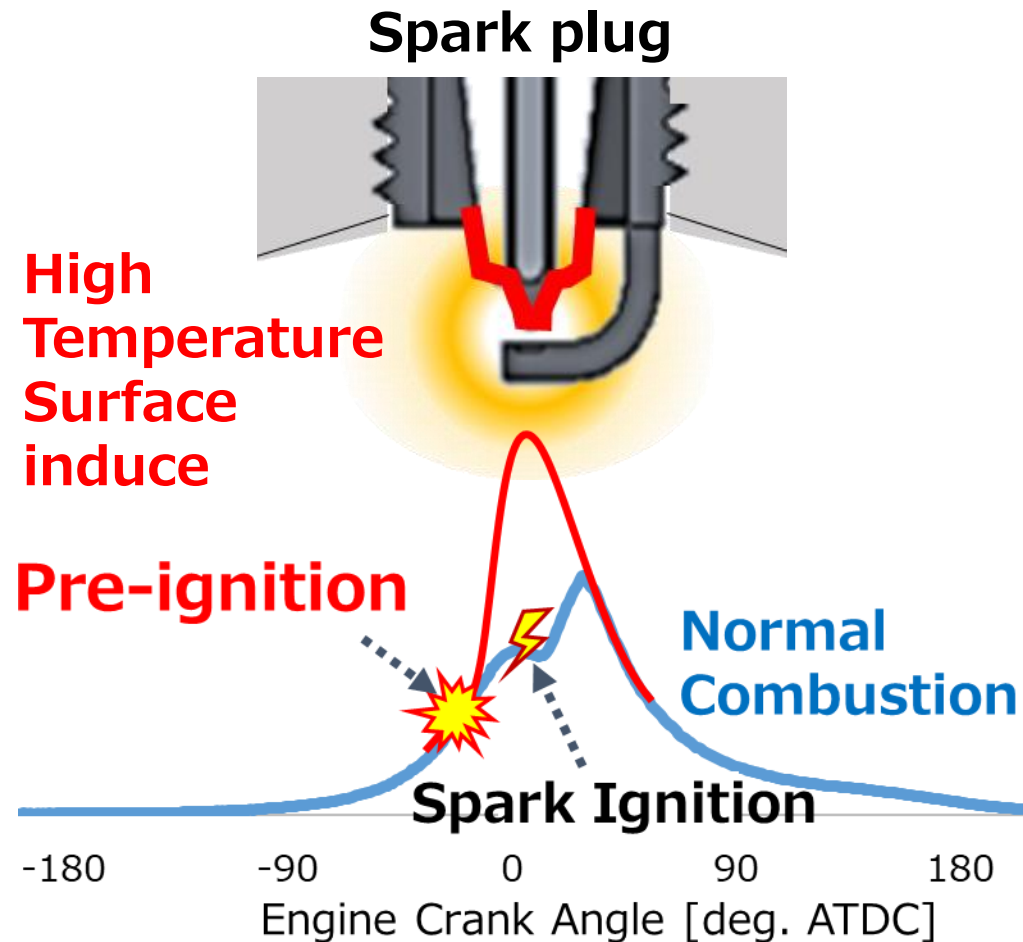
Maximum Torque

The knock mitigation effect is significant from E10 to E40



Hot Surface Pre-ignition

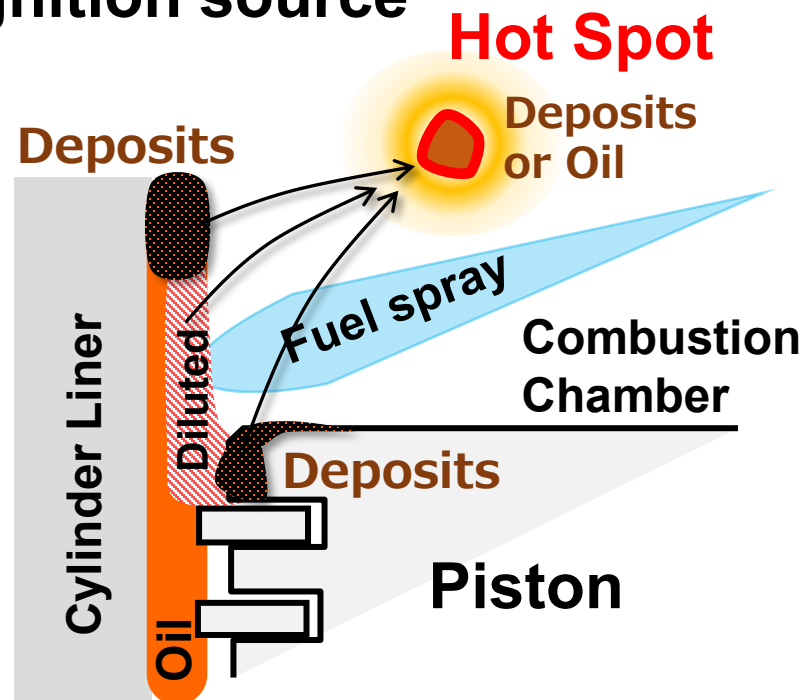
Ethanol suppresses pre-ignition significantly up to 40%



Low Speed Pre-Ignition (LSPI)

Ethanol suppresses Pre-ignition significantly up to 40%

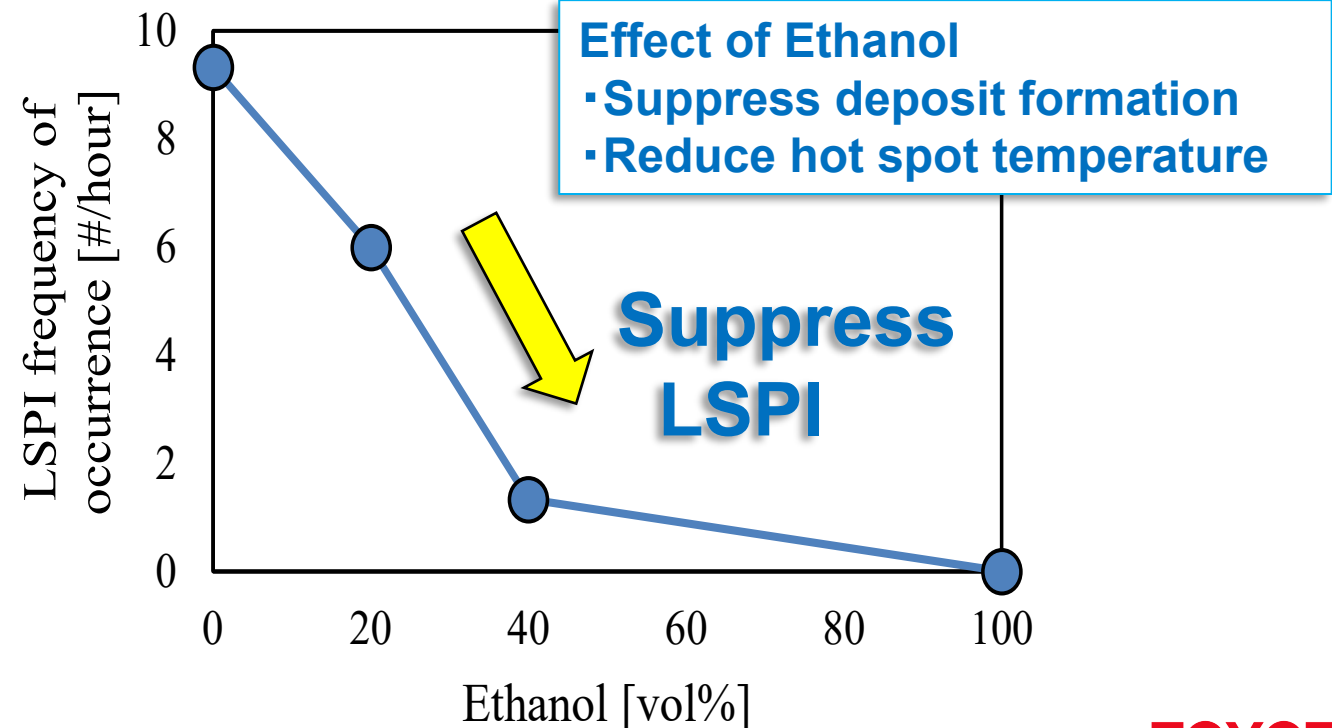
Cylinder wall wetting increase deposits which become ignition source



Mayer, M., Hofmann, SAE2016-01-0719 reported
Ethanol increases dilution and LSPI
 →How about same dilution?

T24A 1700rpm 450Nm, Same Air volume, Coolant 60°C, Oil with calcium

Same oil dilution since same timing of end of injection



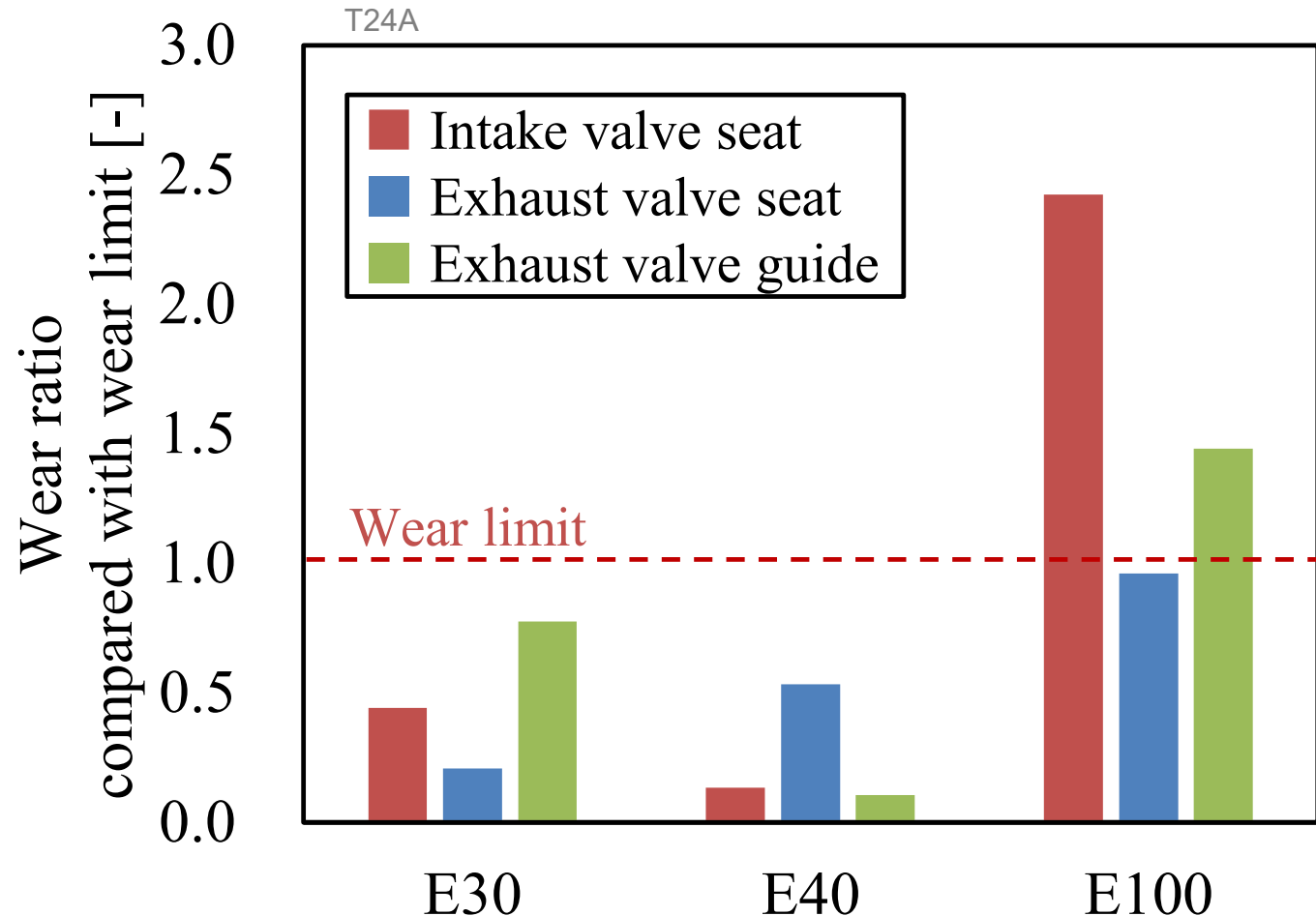
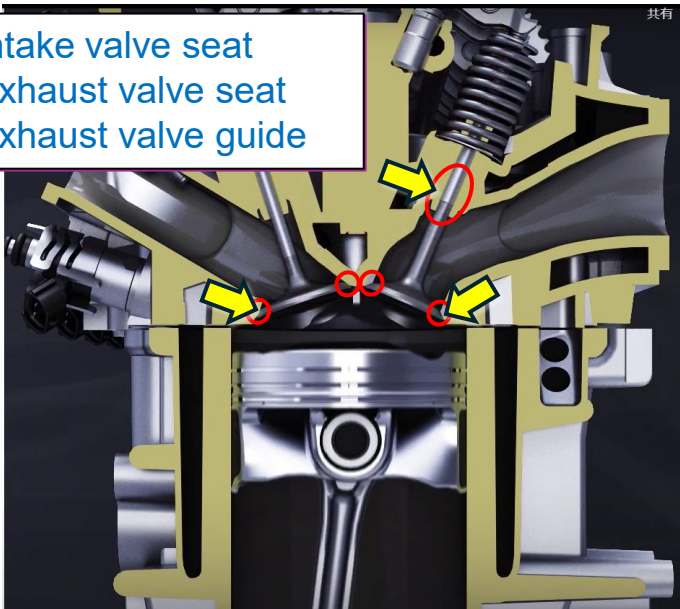
Reliability

No critical wear issue appeared up to 40% in durability test

Comprehensive durability test

Repeated low and high coolant temperatures and high load conditions, combined with idle and stop conditions. Over a period of 300 hours

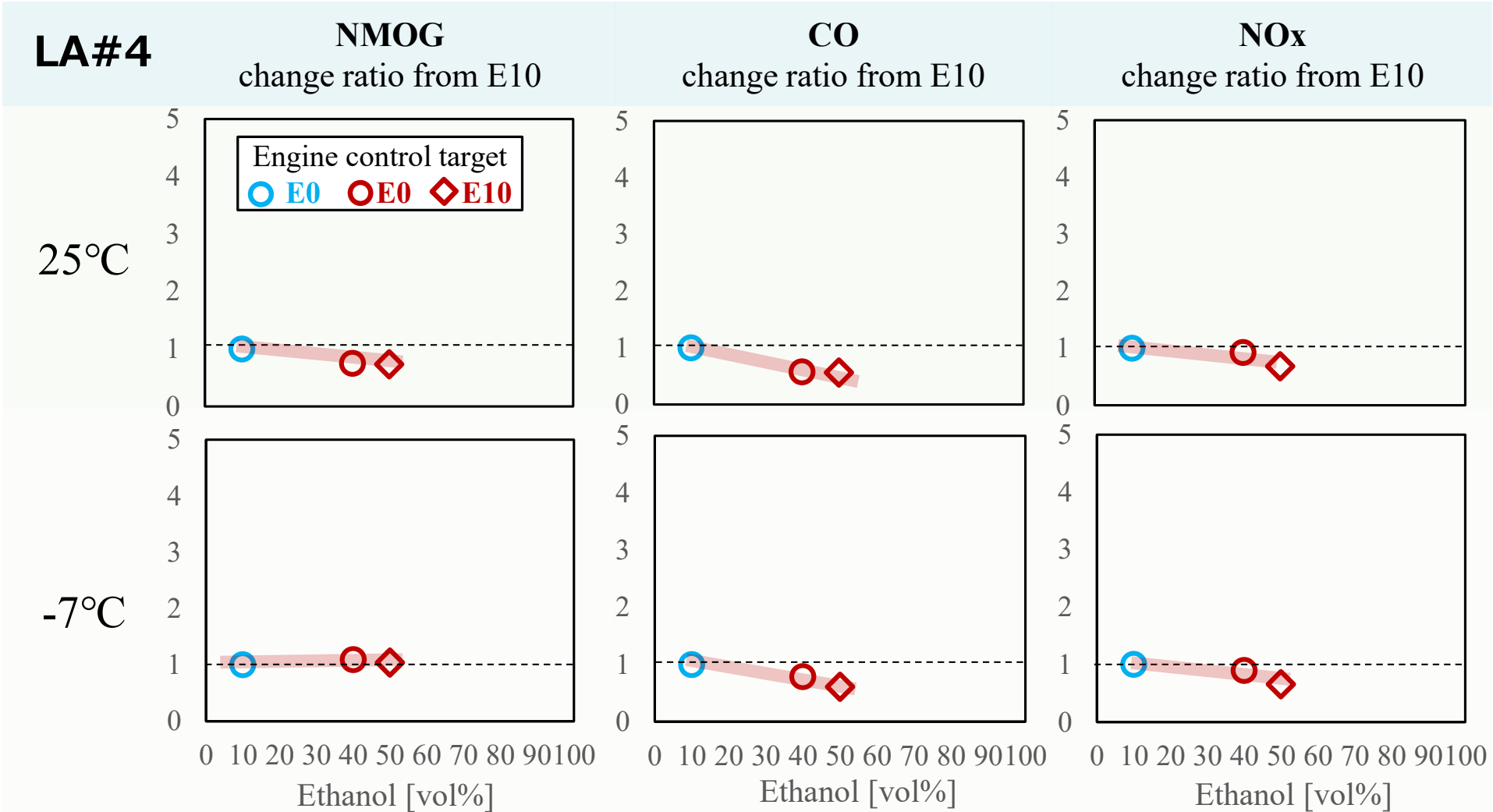
- Intake valve seat
- Exhaust valve seat
- Exhaust valve guide



Vehicle Emissions

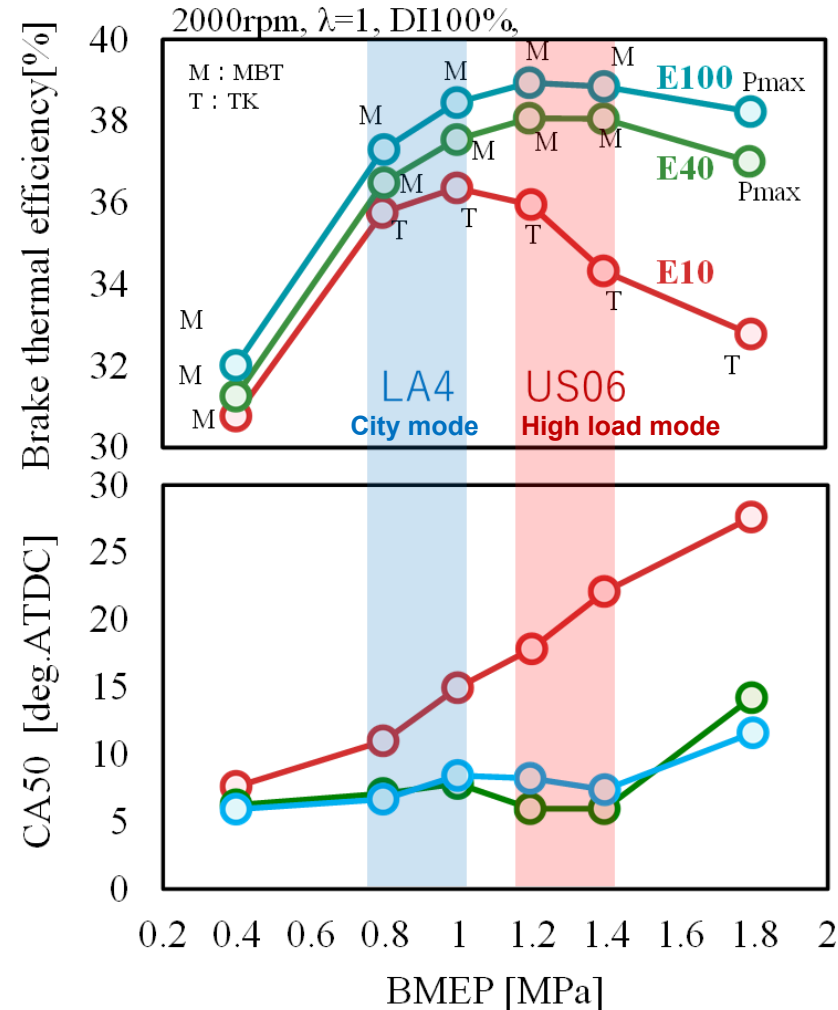
No critical emissions issue at 40% gap between engine control and fuel

Corolla Cross
M20A (2L,NA)

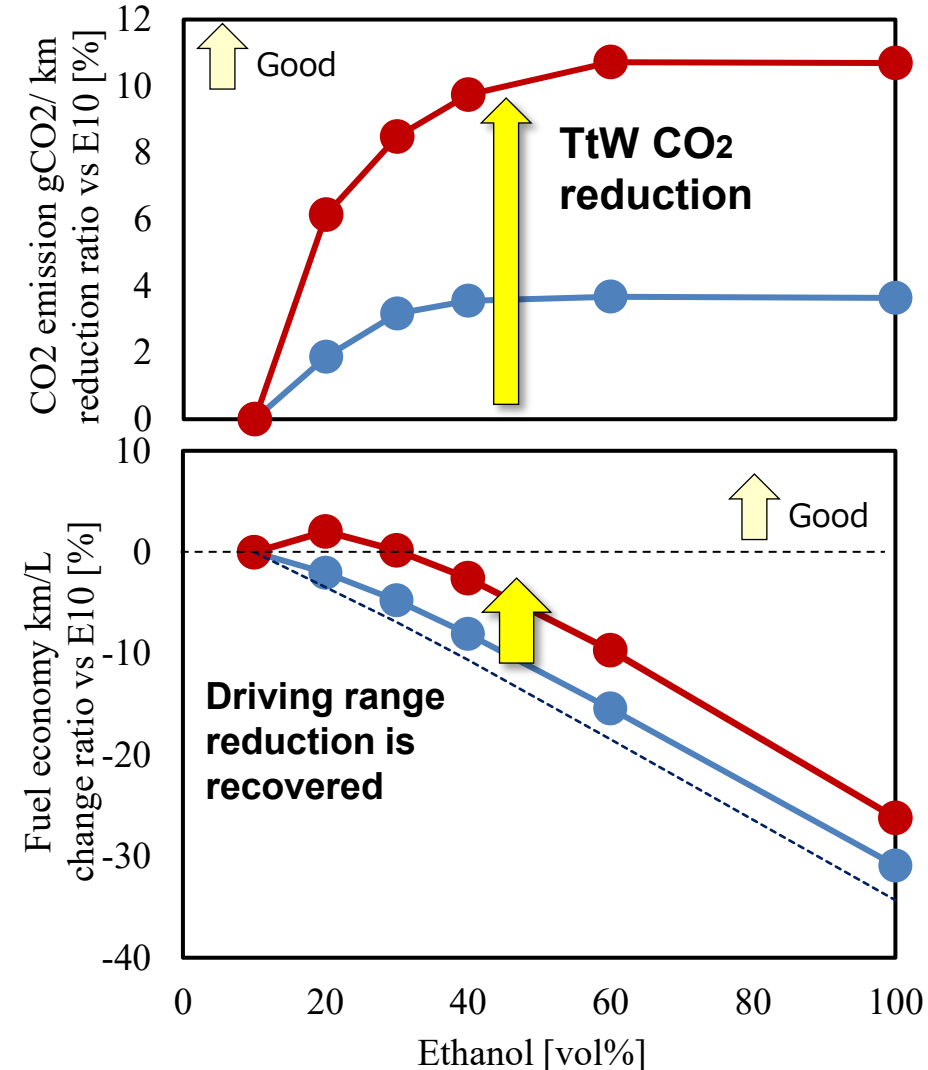


Tank to Wheel CO₂ and Driving Range

Up to E40, TtW CO₂ decreased and driving range reduction is almost recovered

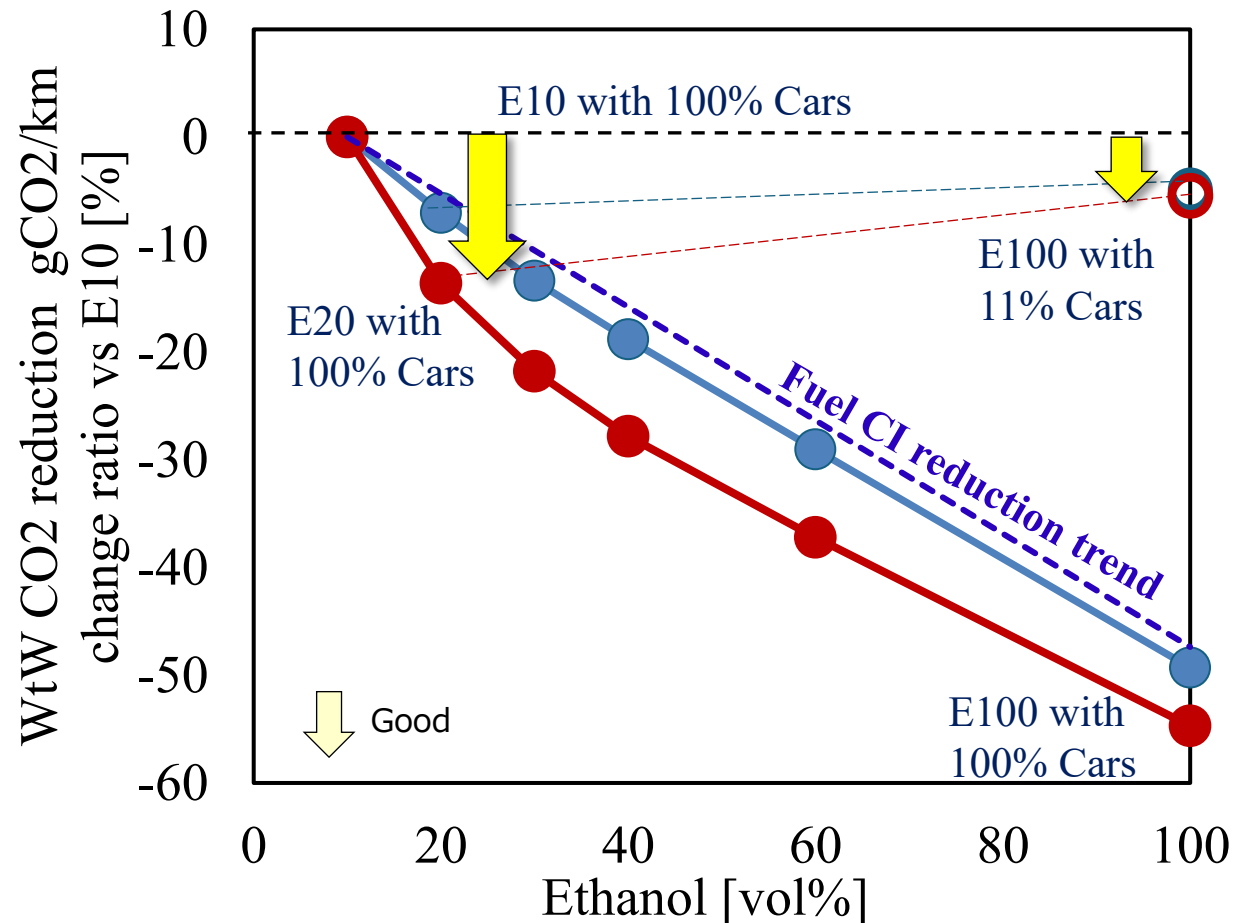


Tacoma T24A 1M-HEV



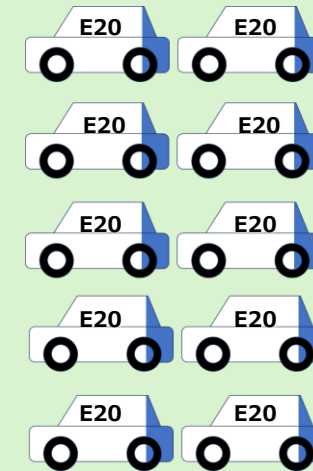
Well to Wheel CO₂

Considering the same amount of ethanol, improving thermal efficiency in a larger number of cars with lower ethanol blend ratio results in greater WtW CO₂ reduction than using it in fewer cars with higher ethanol blend ratio.

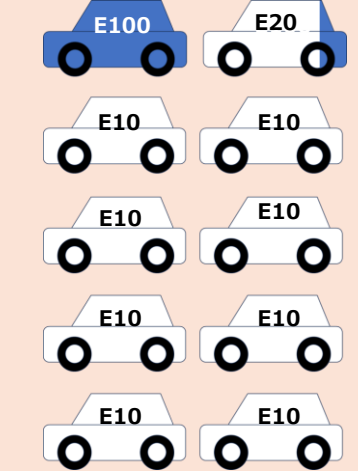


Lower CO₂

E20 x 10cars



E100 x 1.1cars



Summary

Investigated the Mid-level ethanol effect on a modern turbocharged gasoline engine

■ **Up to 40%**, **increased ethanol improves** thermal efficiency, maximum torque and pre-ignition **without critical issues** of emissions, durability, or driving range, when utilizing ethanol knock mitigation potential.

■ **Above 40%**, the improvement decreases significantly.
Hardware change is needed to utilize ethanol potential further .

■ Improving efficiency with mid level ethanol blends across many vehicles reduces WtW CO₂ emissions more than high blends in a few vehicles.