

Development and Demonstration of Hydrogen Engine Vehicles Integrated with Toyota's Hybrid System for Light Commercial Vehicles

Yuto IKEDA

Powertrain Function Development Div.
TOYOTA MOTOR CORPORATION

TOYOTA

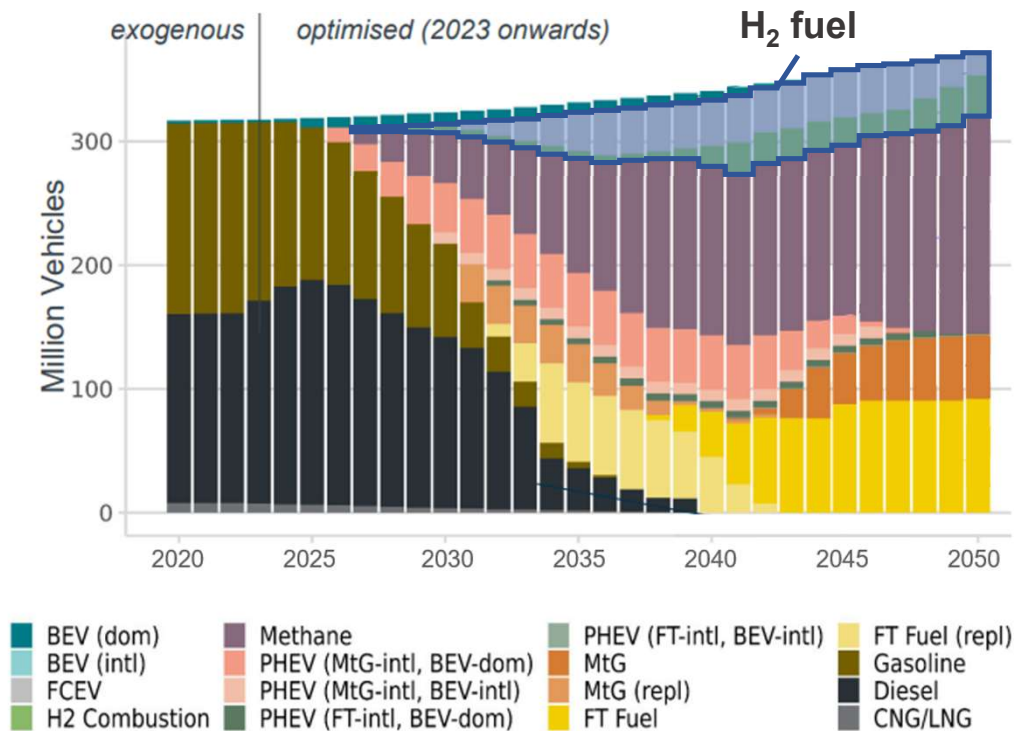
- 1. Introduction**
- 2. H₂ ICE Specification**
- 3. Technical Topics**
- 4. Vehicle Specifications**
- 5. Conclusion**

* H₂ ICE : Hydrogen engine

- 1. Introduction**
2. H₂ ICE Specification
3. Technical Topics
4. Vehicle Specifications
5. Conclusion

Toward Carbon Neutrality

Technology Scenario

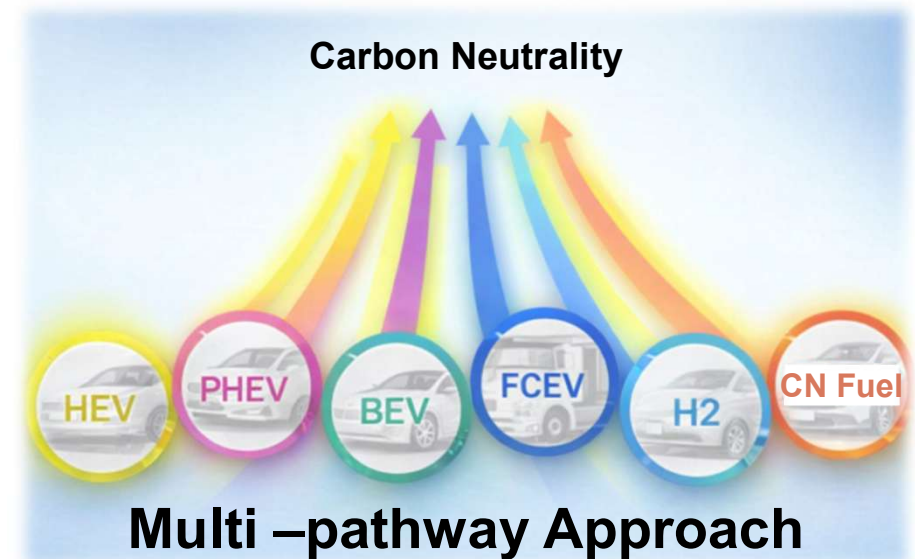


Source :
FVV, 2023 JSAE/SAE Powertrains, Energy and Lubricants International Meeting,
"Transformation of mobility to the GHG neutral post fossil age"

Advantage of H₂ fuel

- ✓ Enables temporary storage of renewable energy
- ✓ Transportable

TOYOTA strategy



Toyota promotes a multi-pathway strategy
Hydrogen is one of the options

Energy Density and Vehicle Suitability

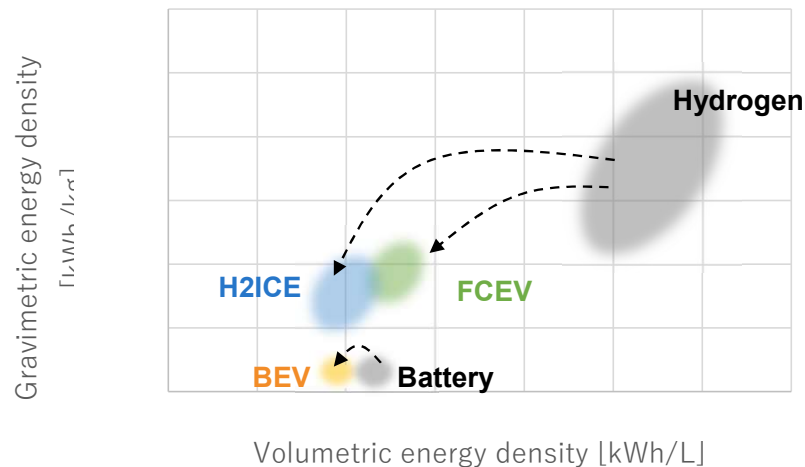
5/34

Why hydrogen fits large commercial vehicles

From stored energy to energy that reaches the wheels



Assumed T-t-W: BEV 85% / FCEV 45% / H2ICE 32%



After applying T-t-W efficiency, the volume gap closes - the mass gap does not
⇒ The value of hydrogen fuel is in **[mass]** rather than **[volume]**

Suitable vehicle

<BEV>

- Packaging freedom
- Existing charging grid



Advantage in small vehicles (energy)

<Hydrogen>

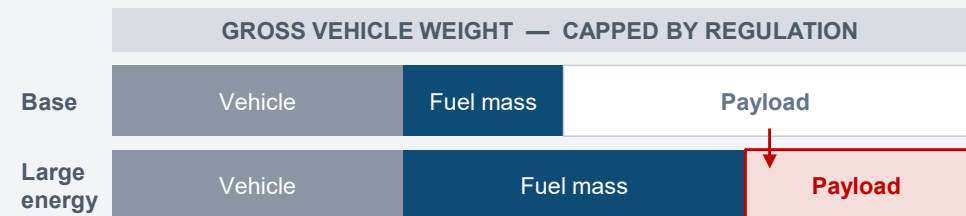
- Short refuelling time
- High gravimetric energy density (Payload)



Advantage in large vehicles (energy)

In between: either can be selected

Why payload decides in the large segment

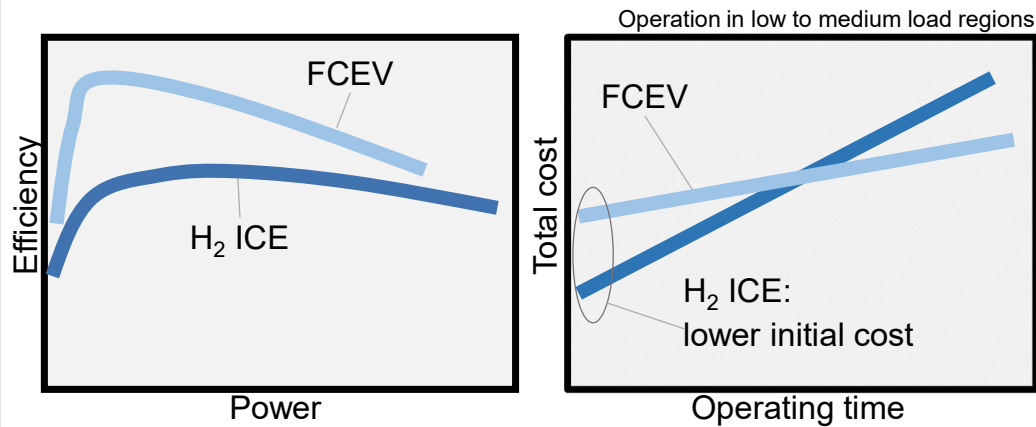


∴ In the large segment, gravimetric energy density is the deciding value

Hydrogen suits large commercial vehicles — thanks to gravimetric energy density

Advantage of H₂ ICE

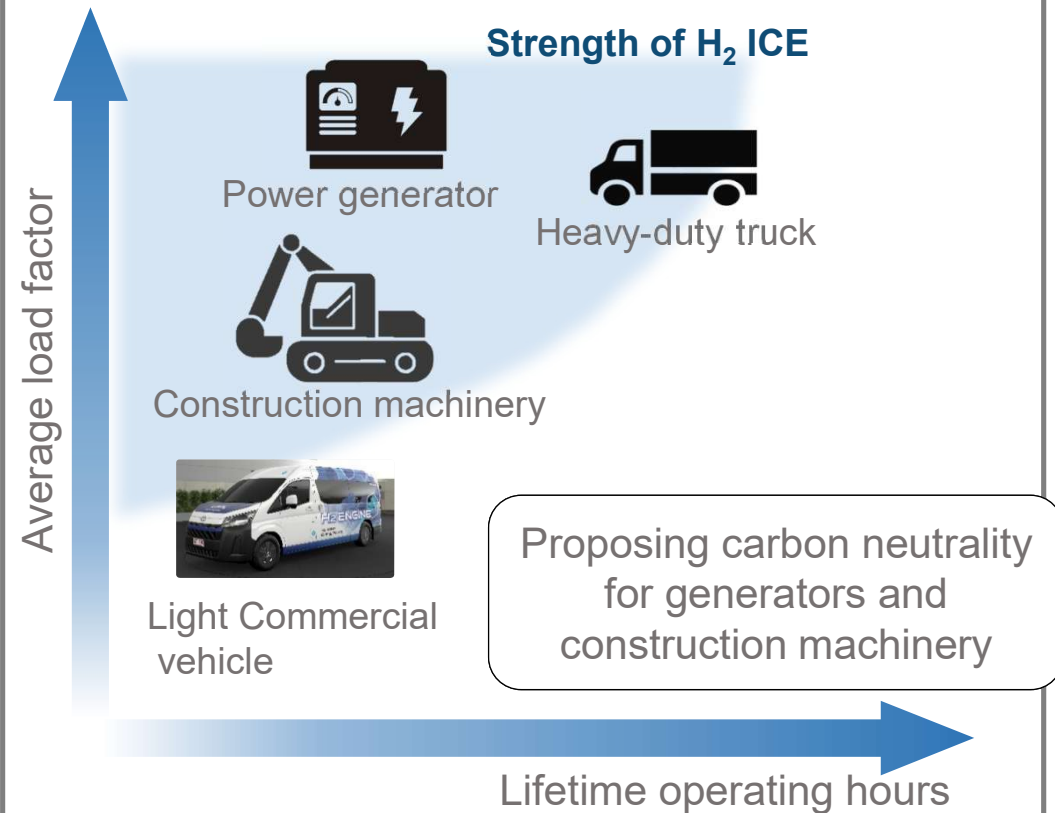
Characteristics



Efficiency at high-load
H₂ ICE $\geq$ FCEV

Cost for short operation time
H₂ ICE < FCEV

Future potential



- ✓ Advantages in high-load performance and initial cost
- ✓ Consider non-automotive applications

Development steps for H₂ ICE

7/35



Commercialization



STEP 01 H₂ race

- ✓ Identify H₂ combustion
- ✓ High performance by race-only engine



STEP 02 Test vehicle

- ✓ Transfer from race to Production
- ✓ Improve and optimize H₂ combustion



STEP 03 On-road test

- ✓ Meeting emission regulation
- ✓ High reliability and Durability



STEP 04 Performance Enhancement

- ✓ High Dynamic Performance
- ✓ Expanded Operating Range
 - ↳ Enabled by H₂ ICE Hybridization



Development Target

Reliability

- ✓ Safety First

Performance

- ✓ Match base vehicle performance

Feasibility

- ✓ Utilize existing assets

Validate combustion in racing and transfer them to commercialization

1. Introduction
- 2. H₂ ICE Specification**
3. Technical Topics
4. Vehicle Specifications
5. Conclusion

Base engine for H₂ conversion

V35A-FTS

High speed combustion

- Long stroke (S/B ratio=1.17)
- High efficiency IN/EX port
- Laser clad valve seat (IN)

- High efficiency water cooled intercooler

High rigidity structure

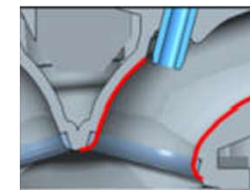
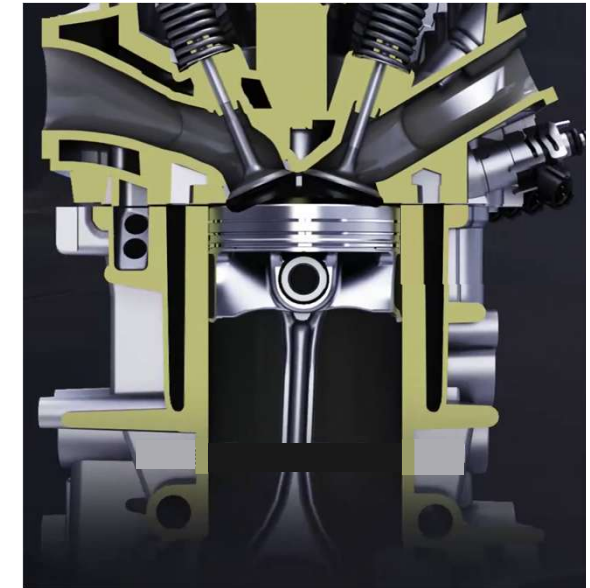
- Ladder frame (Crankcase)
- High rigidity crankshaft
- High strength forged connecting rod

High efficiency Twin turbocharger

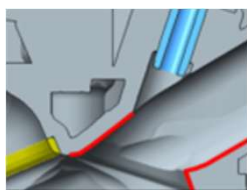
- Electro-mechanical wastegate valve



Engine	V35A-FTS
Engine Type	V type 6 cylinder
Fuel	Gasoline
Displacement [cc]	3445
Bore × Stroke [mm]	Φ85.5 × 100
Compression Ratio	10.4
Max. power [kW]	260
Max. torque [Nm]	650
Turbocharger	Single scroll turbo ×2
Intercooler	Water-cooled



Press-fit
valve seat

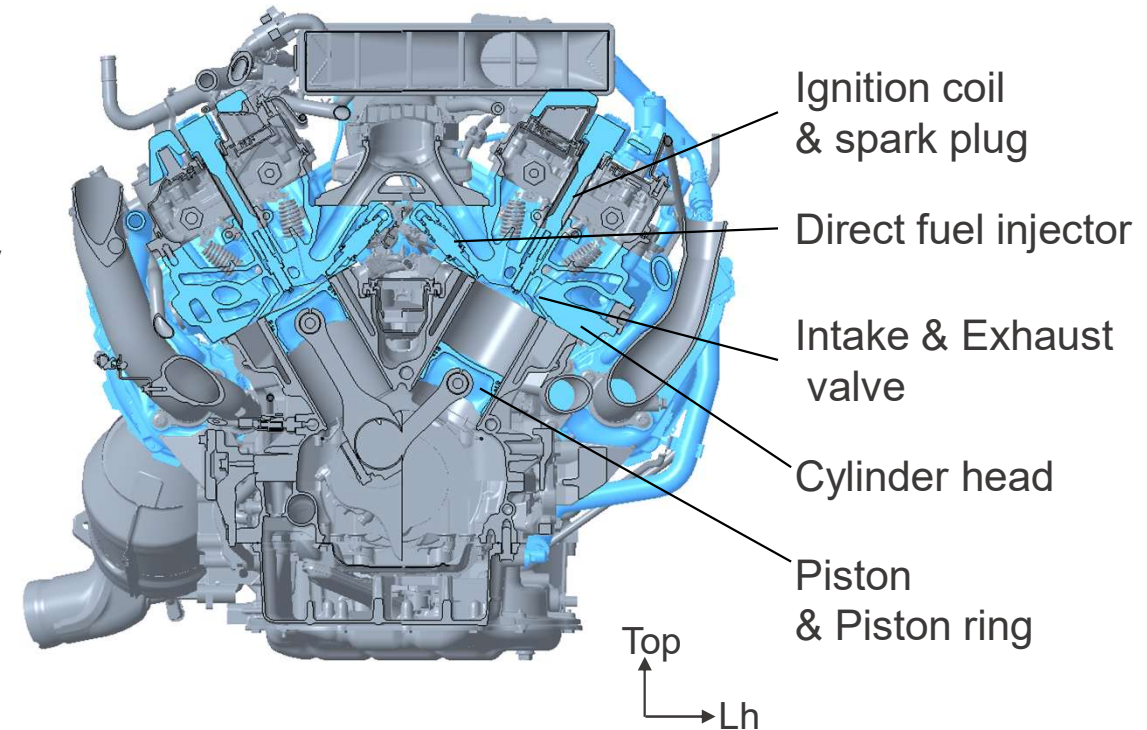
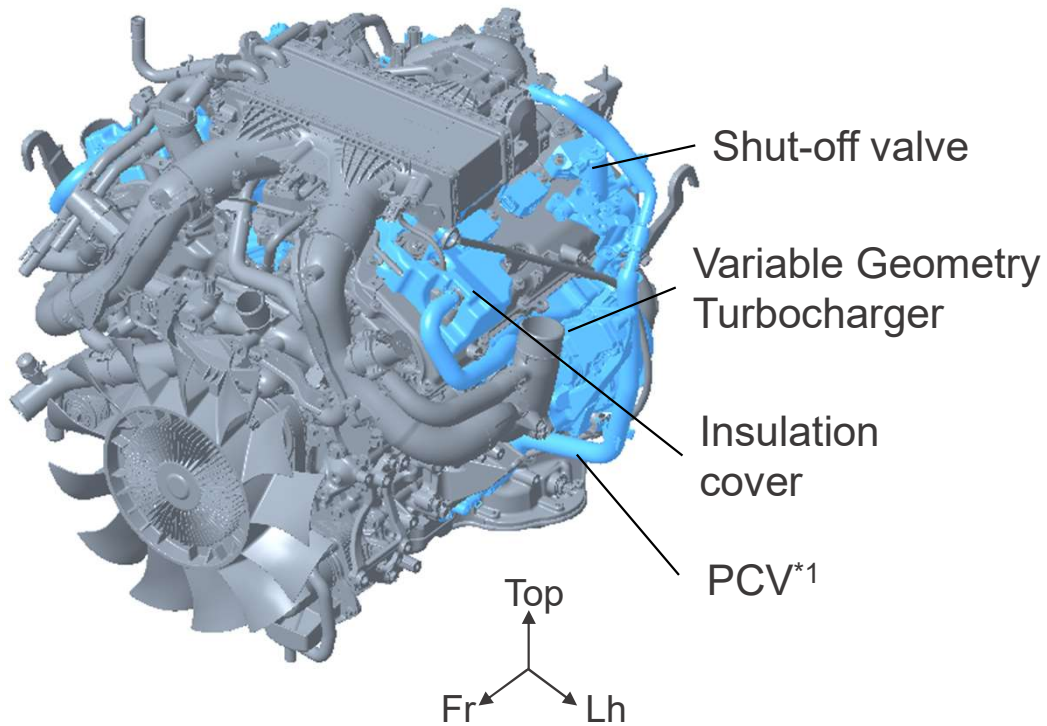


Laser clad
valve seat

Select the optimal base engine to meet development target

Changes from the base engine

Minimize new components for H₂ ICE



*1 Positive Crankcase Ventilation

95% of parts carried over from the base engine

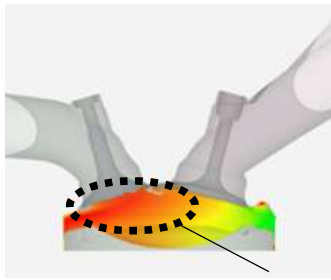
Combustion concept

Target

Lean combustion + mixture homogeneity

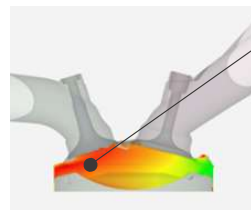
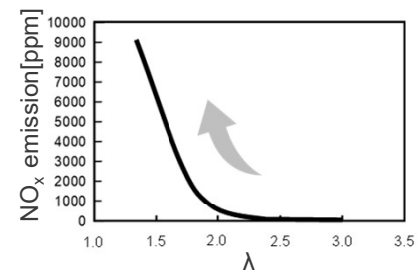
Bad $\longleftrightarrow$ Good

Rich
Lean



Local rich area

NO_x emission up + Thermal efficiency down

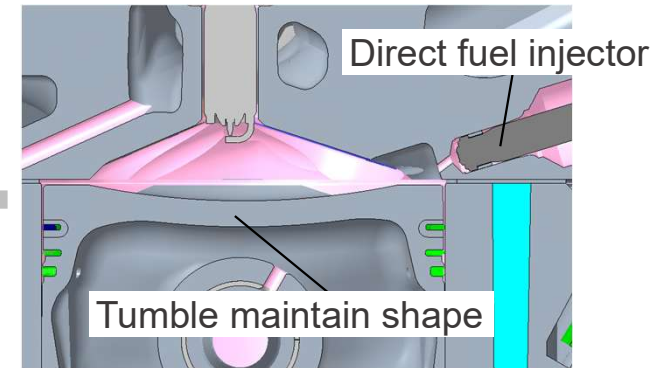


Rich area
High temperature
Cooling loss up

Combustion chamber spec.



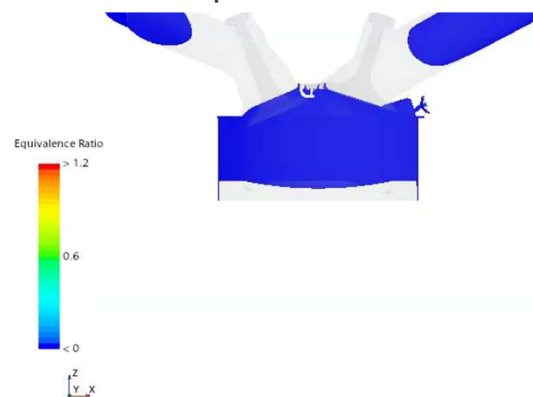
High tumble port



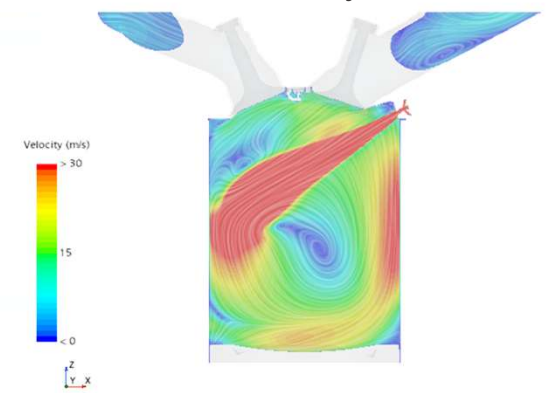
Direct fuel injector

Tumble maintain shape

Equivalence ratio

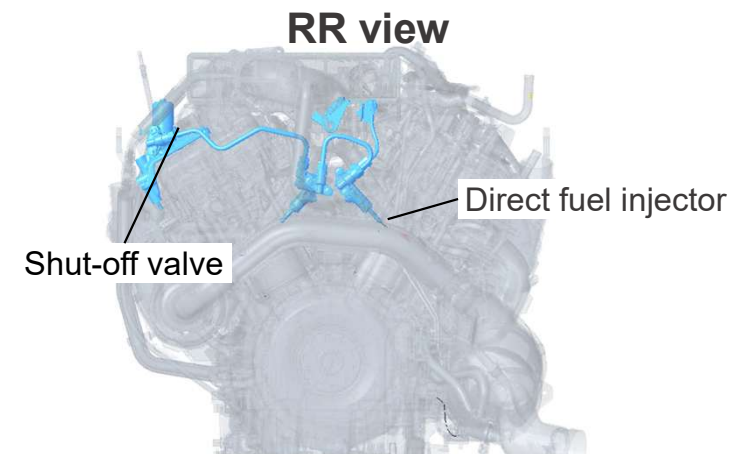
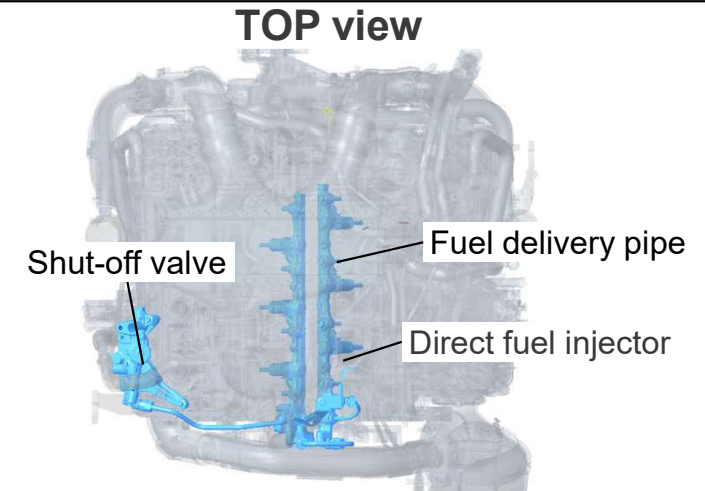
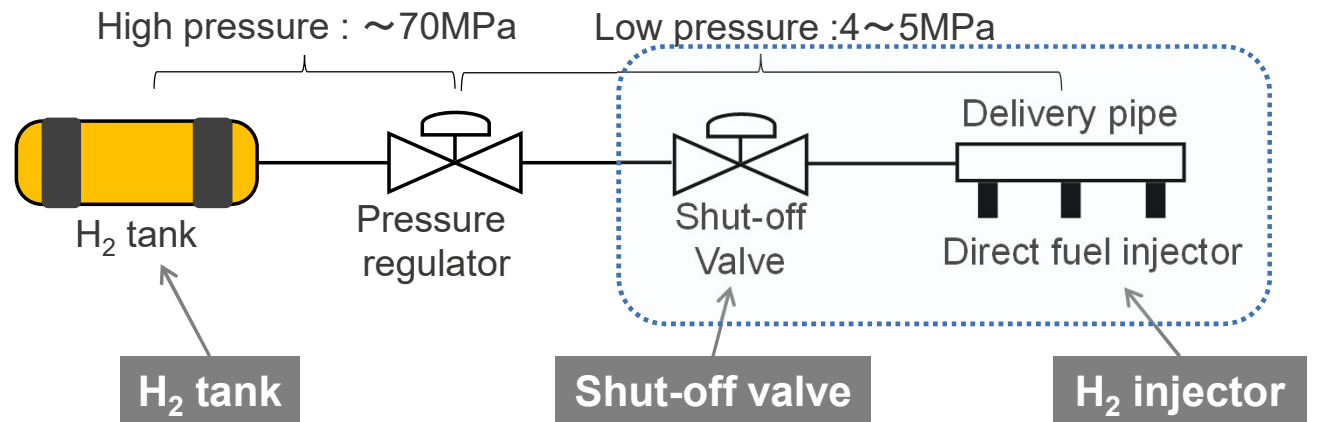


Velocity



Improved mixture homogeneity by DI and high tumble to balance performance and emissions

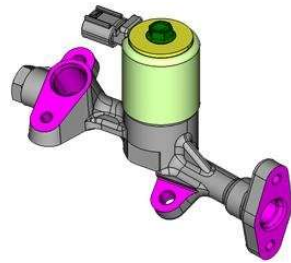
Fuel supply system



- ✓ FCEVs H₂ tank (for MIRAI)
- ✓ 3 tanks in total
- ✓ 6.2kg H₂



- ✓ Stop fuel supply during failure or engine shutdown

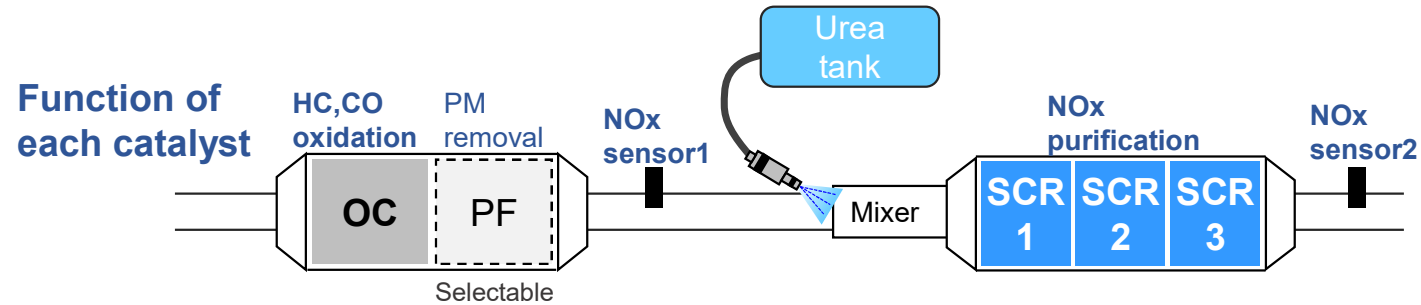


- ✓ Based on gasoline injector
- ✓ w/o lubrication system for wear



Use mass-production parts to minimize new components for H₂ ICE

Exhaust system

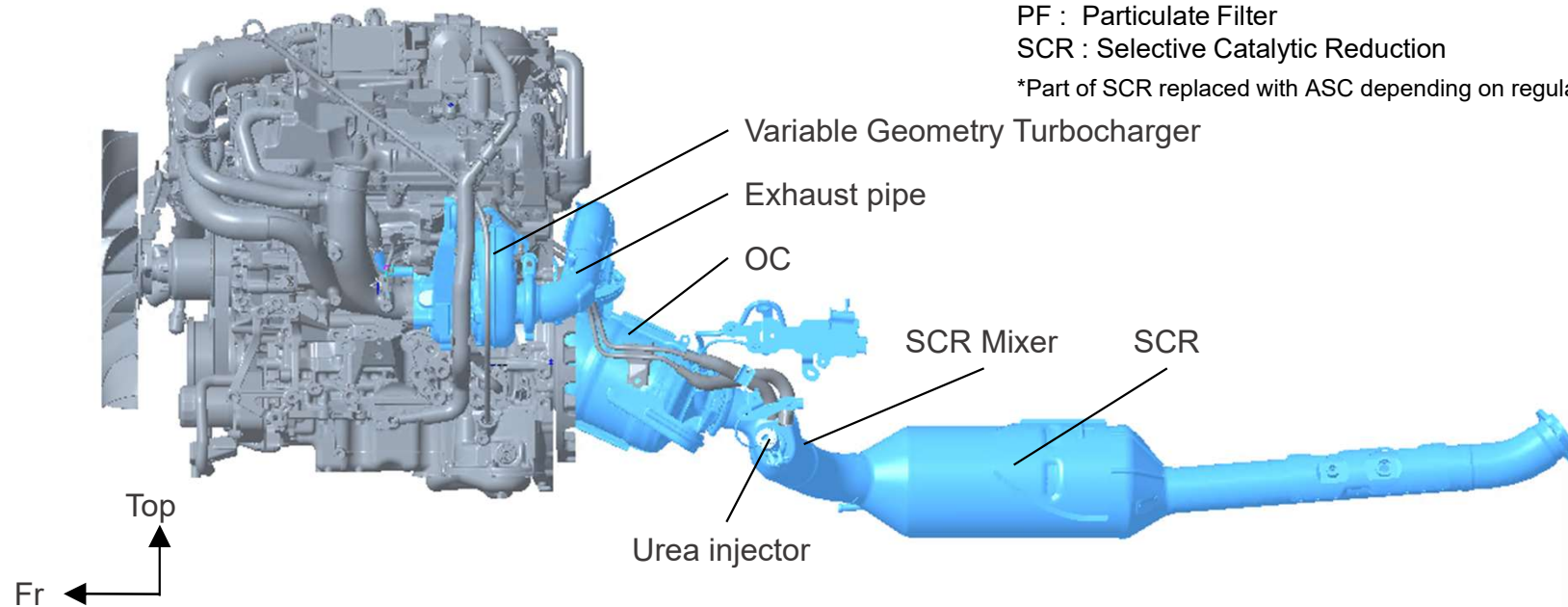


OC : Oxidation Catalyst

PF : Particulate Filter

SCR : Selective Catalytic Reduction

*Part of SCR replaced with ASC depending on regulation level



Use mass-production parts to minimize new components for H₂ ICE

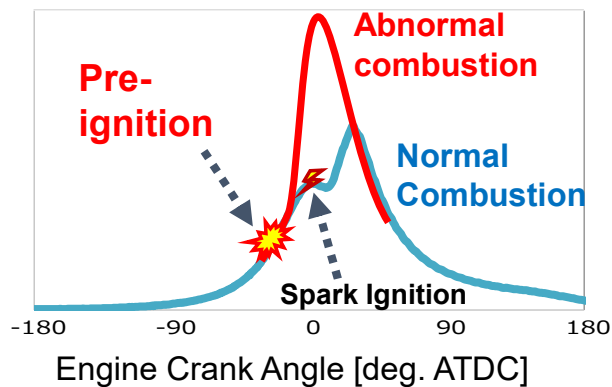
1. Introduction
2. H₂ ICE Specification
- 3. Technical Topics**
4. Vehicle Specifications
5. Conclusion

Main Technical Topics for H₂ ICE

15/34

Topic1

Abnormal Combustion



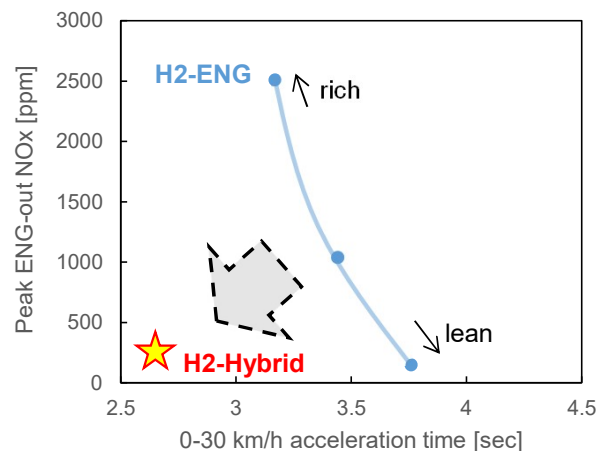
High ignitability due to wide flammability limits and low minimum ignition energy

risk of component damage

Pre-Ignition Detection

Topic2

Torque Response



Low NOx
(High lambda)

Trade-off

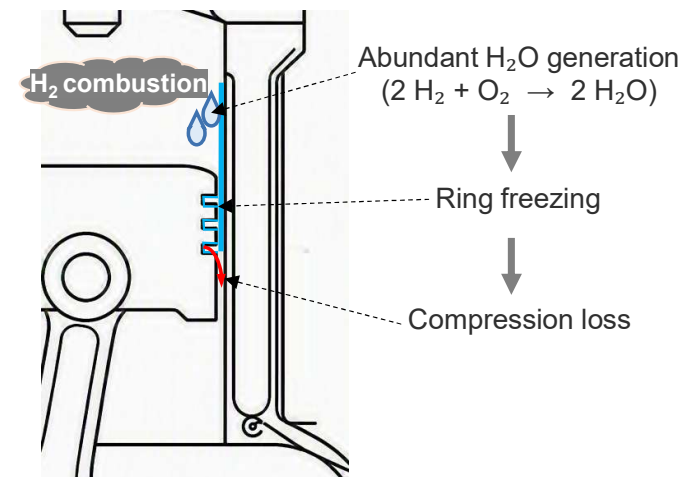
Fast boost and
torque build-up

Reduced Drivability

Hybrid Technology Utilization

Topic3

Cold-Start Performance



H₂ combustion produces abundant H₂O; at cold start it freezes around the piston rings.

Cold-start failure

Topics 1 : Abnormal Combustion(Pre-ignition)

16/34

Physical-property gap between H_2 and gasoline makes pre-ignition easy

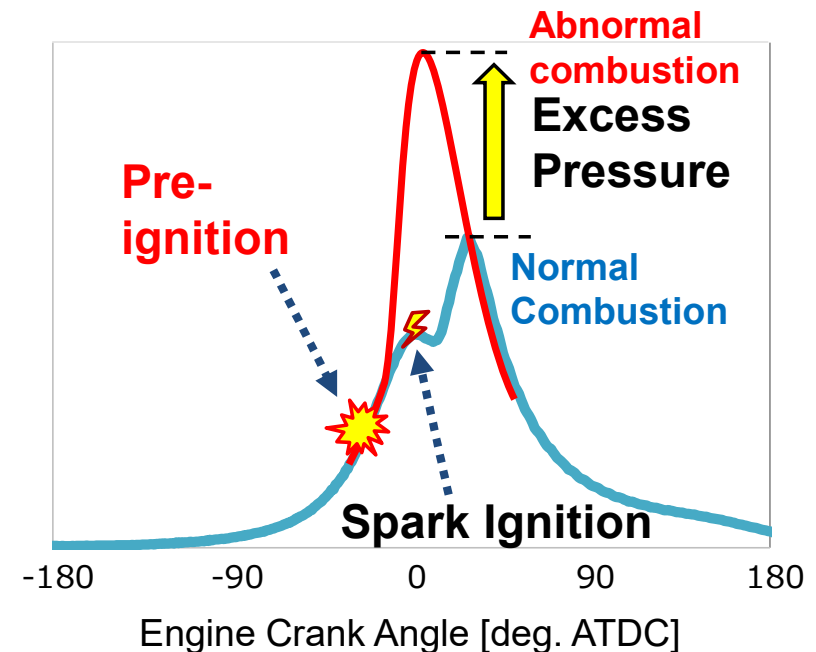
Properties of hydrogen and gasoline

		H_2	Gasoline
Molecular weight	g/mol	2	70~90
Density	kg/m ³	0.084	740
Diffusion coefficient (in Air)	m ² /s	6.66×10^{-5}	0.5×10^{-5}
Flammable range: λ	-	0.14~10	0.49~2
Minimum ignition energy	mJ	0.02	0.25
Frame speed	m/s	2.65	0.4~0.5

Key H_2 differences

Reference)
JOURNAL OF JAPAN SOCIETY FOR SAFETY ENGINEERING vol.44 No.6(2005)
The Institute of Electrical Installation Engineers of Japan Vol36 April (2016)
Isao Abe: Physical and Chemical Properties of Hydrogen, Hydrogen Energy System
Vol.27, No1(2002)

In-cylinder Pressure : Pre-ignition



H_2 enhances combustion

but its wide flammability and very low ignition energy can trigger Pre-ignition

Topics 1 : Abnormal Combustion(Pre-ignition)

17/34

Pre-ignition is classified by its cause as follows:

Item	In-cylinder Pressure	Main Causes	Damage risk	Approach
Early Pre-ignition	Injection-synchronized pre-ignition 	1) After-burning of residual hydrogen near injector tip 2) Oxidation and exothermic reaction of injector insertion aid under high temperature	High	Prevention
	Injection-unsynchronized pre-ignition 	Unintended spark discharge of the spark plug	High	Prevention
Late Pre-ignition		1) Residual high-temperature gas in spark plug tip pocket 2) Influence of oil-derived deposits suspended in combustion chamber	Low	Suppression
Runaway Pre-ignition		Maintaining elevated temperature due to prior abnormal combustion	High	Prevention

*Pre-ignition: the mixture auto-ignites before the spark timing — not triggered by the spark plug

Target for **high**-damage-risk pre-ignition:
“Prevent / keep Detectable”

✓ **Prevention** do not let it occur

- ✓ Reduce injector-tip sac volume
- ✓ Switch to an oxidation-resistant assembly lubricant

+

✓ **Detection** catch it if it occurs

- ✓ Detection via crank speed fluctuation

⇒ **Method shown on the next slide**

Prevent high-damage-risk pre-ignition — and keep it detectable

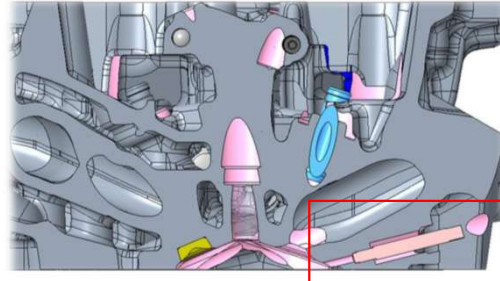
Topics 1 : Abnormal Combustion(Pre-ignition)

18/34

In racing, pre-ignition was detected by adding an in-cylinder pressure sensor (CPS)

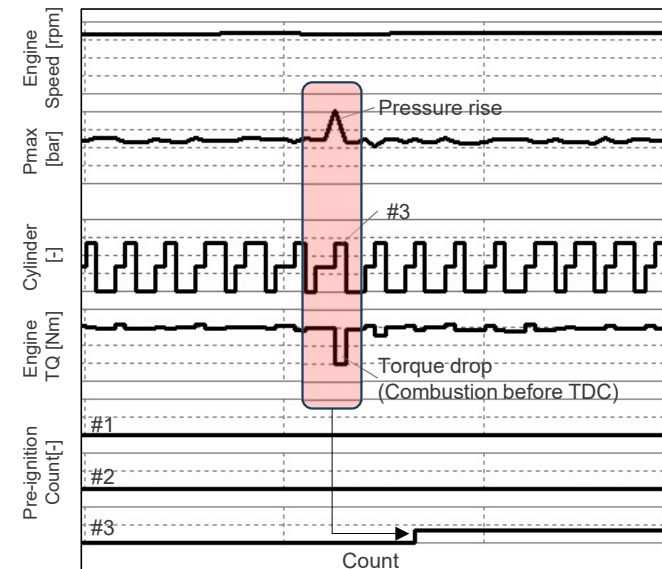


Race activity



Dedicated boss in cylinder head

Item	CPS	Reason
Detection	○	Direct in-cylinder pressure → clear, easy judgement
Reliability	✗	Exposed to combustion gas → thermal load, deposit, drift
Cost	✗	One sensor per cylinder + amplifier / analysis unit
Packaging	✗	Dedicated boss in cylinder head → layout constraints



Detection must be secured with the existing hardware
⇒ Next slide

Accurate, but reliability and cost trade-offs are too large for production

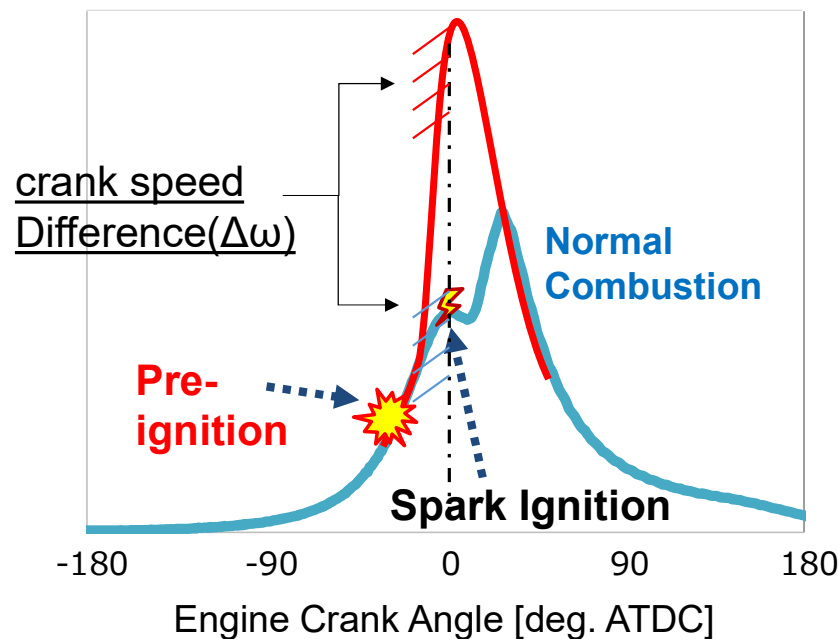
Topics 1 : Abnormal Combustion(Pre-ignition)

19/34

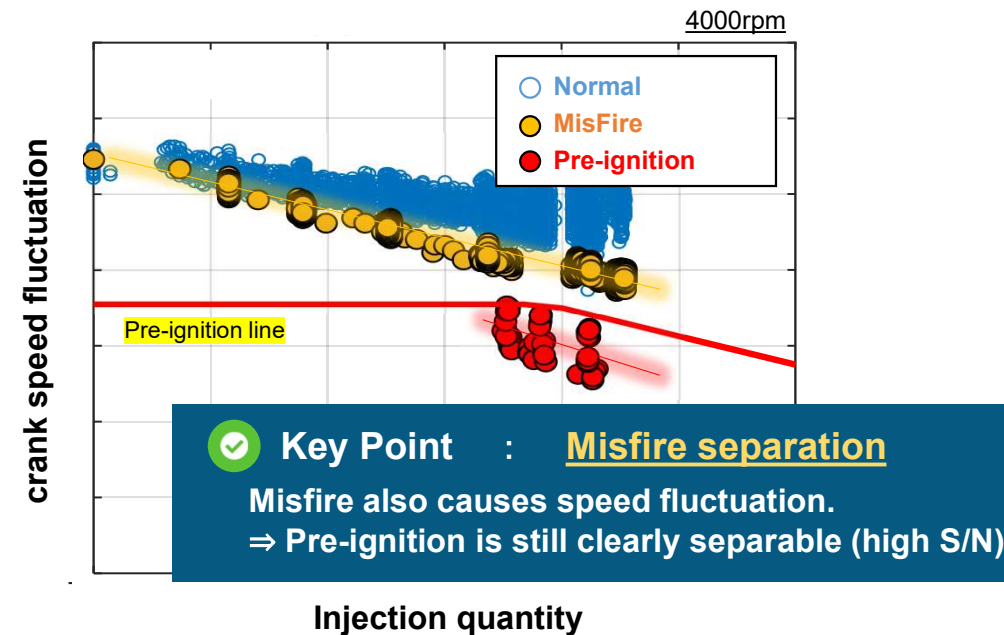
Pre-ignition is detected from crank speed fluctuation

↳ Focusing on the speed difference during compression — no additional sensor needed (no CPS)

In-cylinder Pressure : Pre-ignition



Detection index : Clear separation (high S/N)

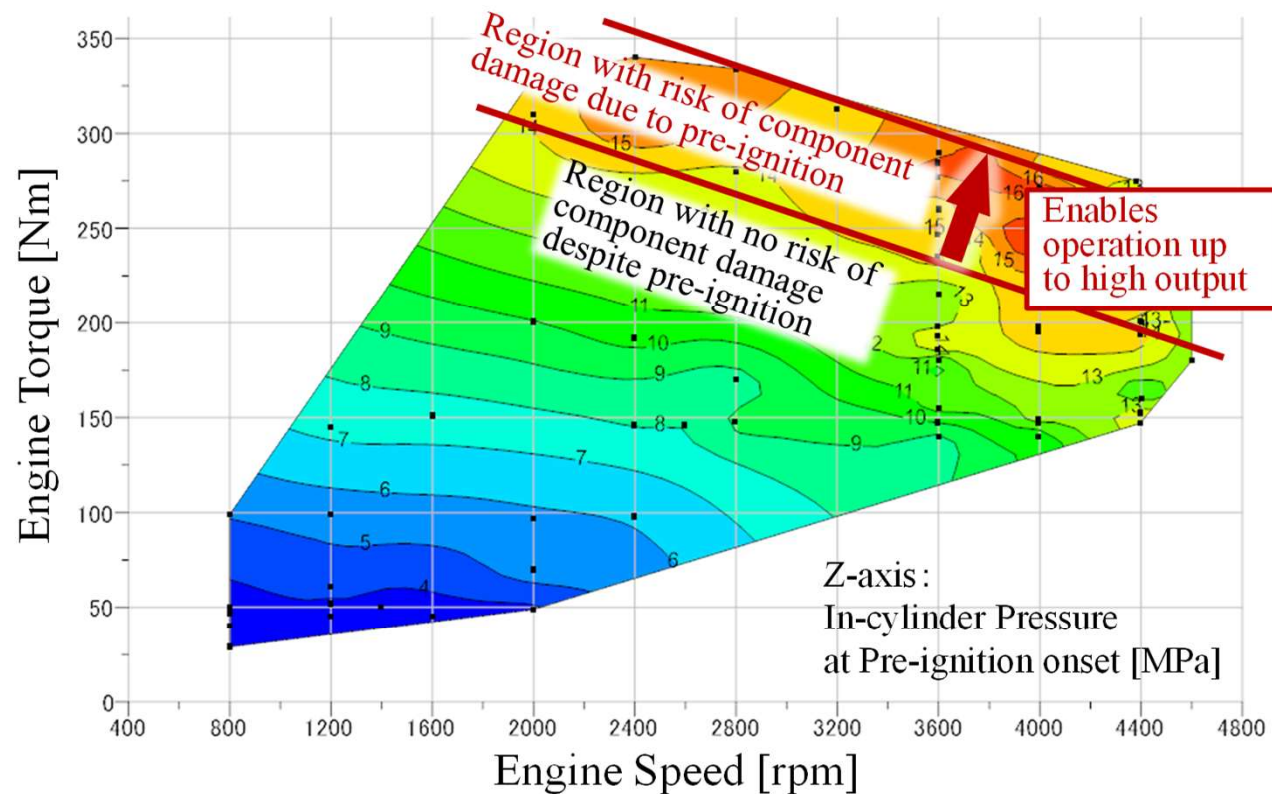


**Pre-ignition detection established with the existing sensor
⇒ Reliability secured even if it occurs**

Topics 1 : Abnormal Combustion(Pre-ignition)

20/34

*Preventing damage-risk pre-ignition — with fail-safe detection as backup
⇒ the full operating range is used without restriction*



**Operating range expanded to high load without restriction,
achieves the engine's full output potential**

Topics 2 : Transient Torque Response

21/34

Hydrogen Engine Characteristics

High-lean combustion

Low engine-out NOx via $\lambda \approx 2.4$ operation

High air demand

Boosted operation needs large air mass

Air-path driven torque

Torque rise depends on boost response



Commercial-Vehicle Requirements

Urban stop-and-go service

Repeated acceleration in urban routes



Heavy-load operation

High payload and towing loads



Delivery route operation

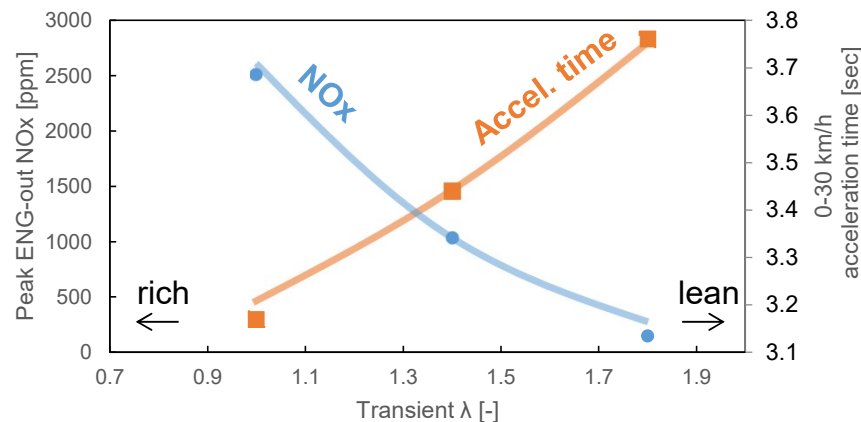
Frequent launches after short stops



Lean air-path torque × frequent accel. → transient response is the key challenge

Topics 2 : Transient Torque Response

The Enrichment Trade-off



Faster torque response

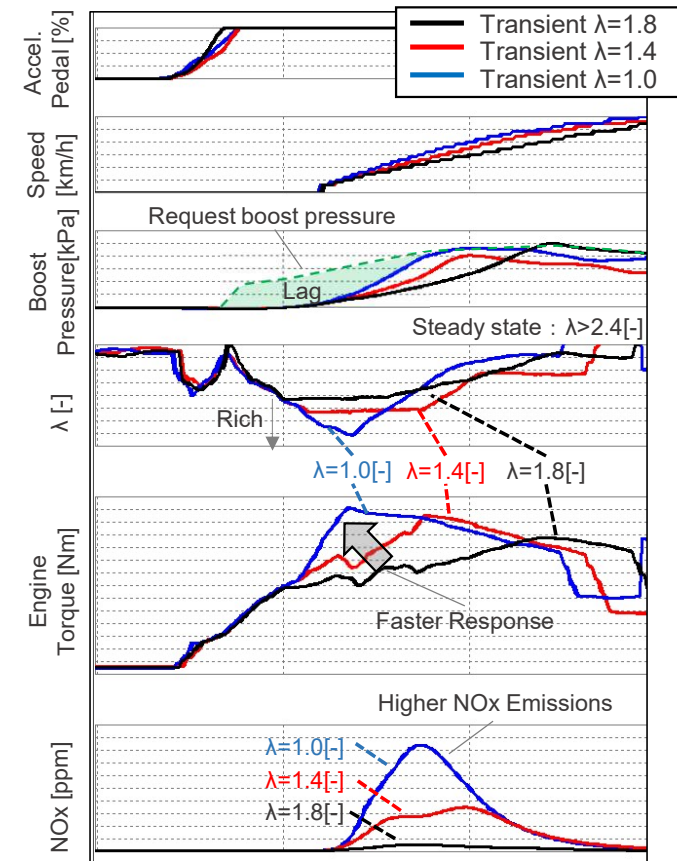
Richer transient λ speeds boost & torque build-up



NOx exceeds the Target

Rich operation drives engine-out NOx above the allowable level

Regain response while staying lean → ① VGT + VVT ② Hybrid

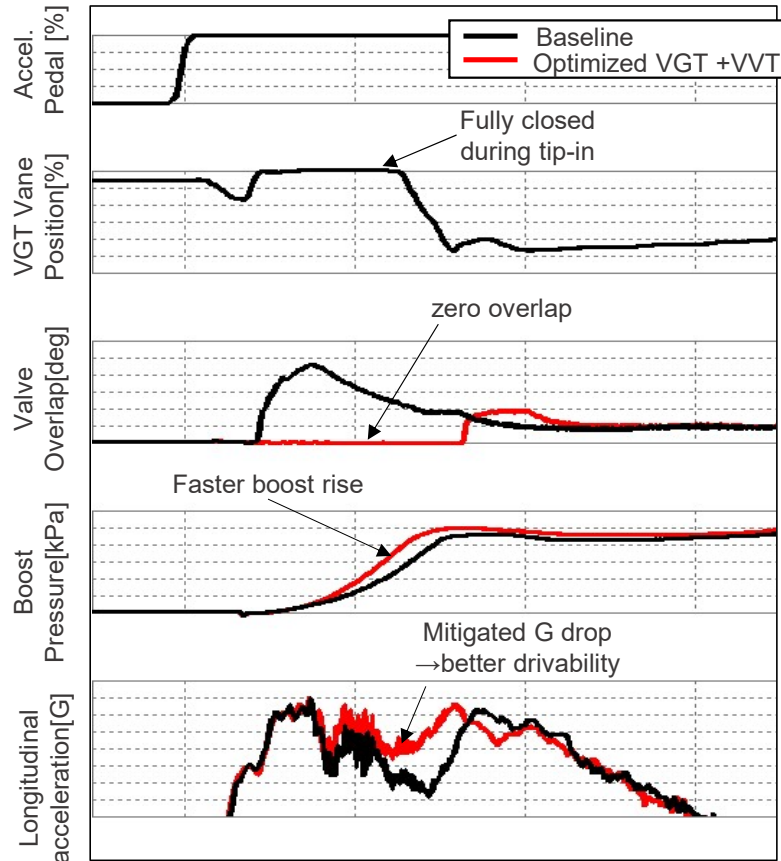


Faster acceleration response is balanced against low NOx operation

Topics 2 : Transient Torque Response

23/34

Countermeasure ① : VGT & VVT optimization



Cause-and-effect chain

1 Accelerator tip-in

2 High air demand (lean, boosted)

3 Insufficient exhaust energy $P(\text{exh}) > P(\text{int})$

4 Exhaust-gas reversion at overlap

5 Reduced effective charging

6 Delayed boost & torque



VGT — close vanes during tip-in

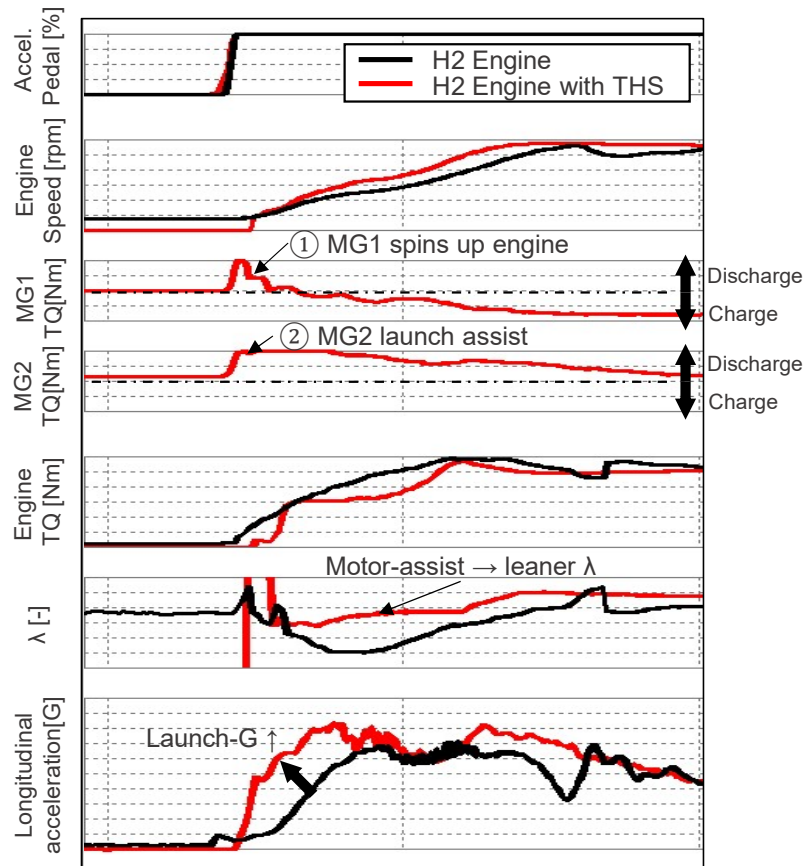
VVT — command zero valve overlap

VGT vane close + zero overlap → faster boost & torque, better drivability

Topics 2 : Transient Torque Response

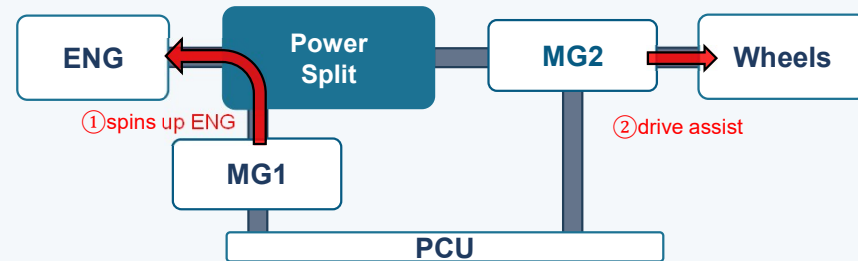
24/34

Countermeasure ② : Hybrid powertrain (THS)



How hybrid restores launch response

Power-split device (THS)



① MG1 covers engine inertia

At tip-in MG1 instantly lifts engine speed, so torque build-up is not limited by engine/turbo inertia.

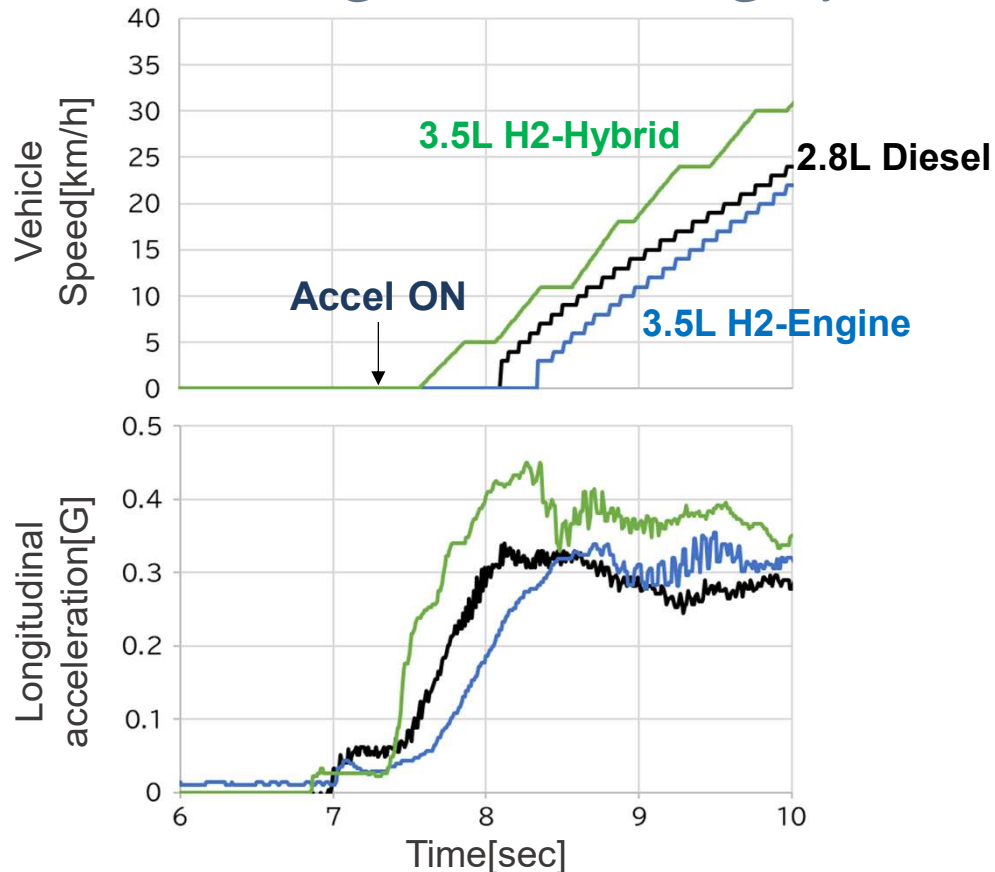
② MG2 assists launch torque

MG2 adds drive torque during launch, filling turbo-lag and allowing leaner λ → lower NOx.

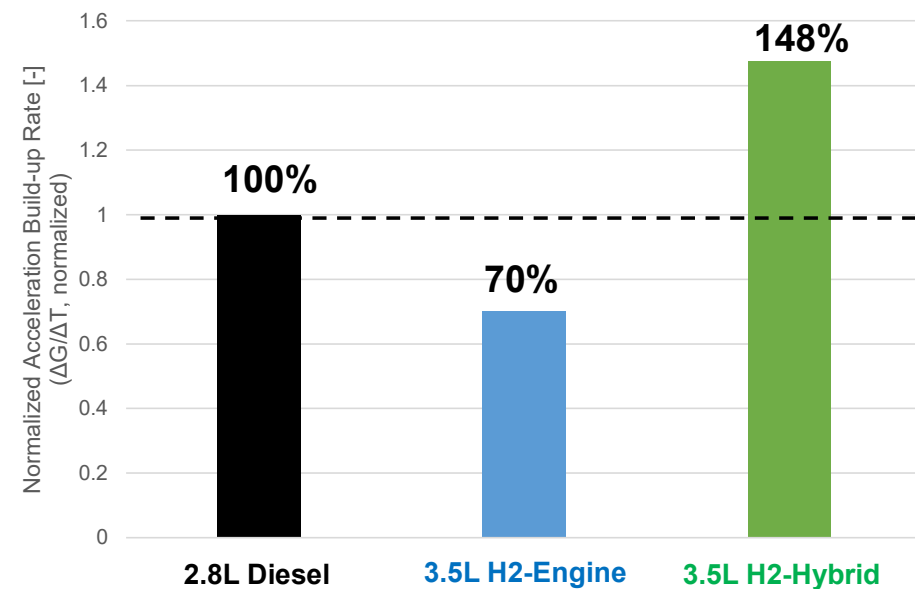
THS motor assist → faster launch-G while keeping λ lean (NOx reduced)

Topics 2 : Transient Torque Response

Countermeasures ① VGT+VVT and ② Hybridization combined — evaluated on the vehicle launch



Hybrid restores Diesel-Equivalent Response



**Hybridization surpasses diesel launch response
+48% vs. diesel (vs. -30% for H₂ engine alone)**

Topics 3 : Cold-Start Performance

26/34

Hydrogen combustion generates far more water than gasoline; in cold, short-trip use this water becomes a start-reliability risk.

More water is produced by design



Water (H₂O) is the primary combustion product of hydrogen – there is no carbon, so almost all fuel energy ends up as water vapour.

Relative water produced per unit energy

Gasoline ×1.0

Hydrogen ≈×2.5

≈ 2.5× the condensate of gasoline

Higher water

→ higher risk of freezing, corrosion and oil dilution.

Focus of this presentation



Repeated short-trip operation

Vehicles are frequently shut down before the engine reaches full warm-up.



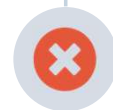
Condensate accumulates

Water films the bore wall and collects in the top piston-ring groove.



Cold soak → freezing

During a sub-zero soak the trapped water freezes and the ring loses its gas seal.



Start failure

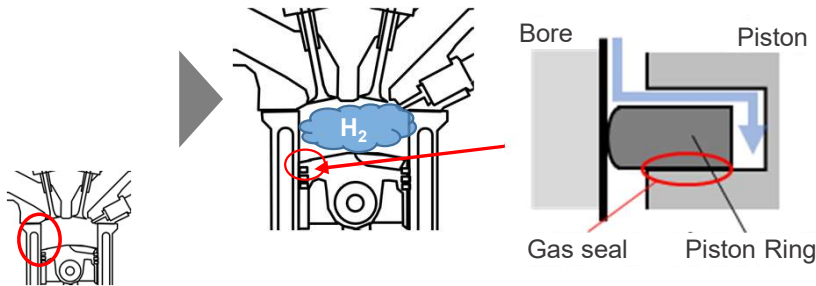
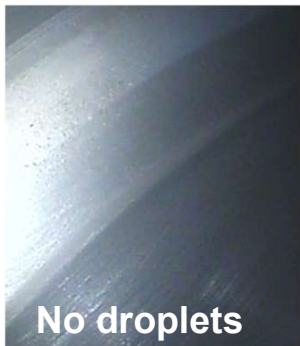
Compression leaks past the frozen ring → the engine cannot fire.

Topics 3 : Cold-Start Performance

27/34

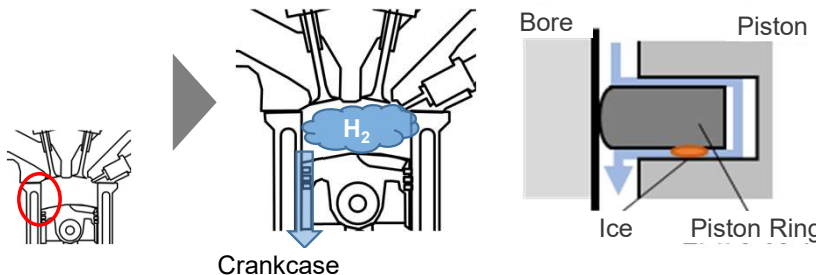
Mechanism verified on the engine: trapped water freezes and breaks the ring seal → start failure

Stopped **after** warm-up



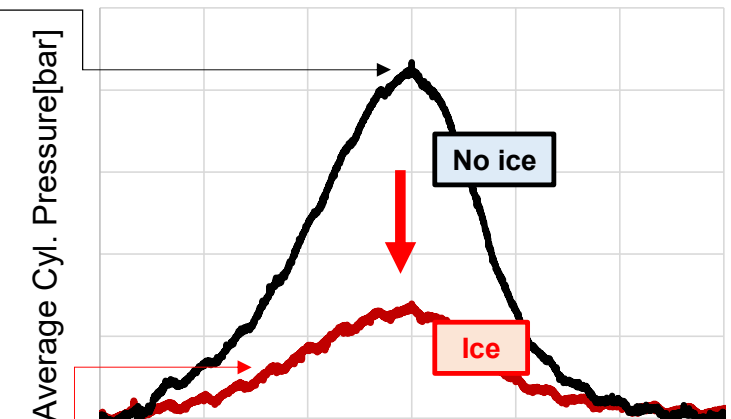
-30 °C cold-soak start-up

Stopped **before** warm-up



Normal

Fault



Compression loss → no start

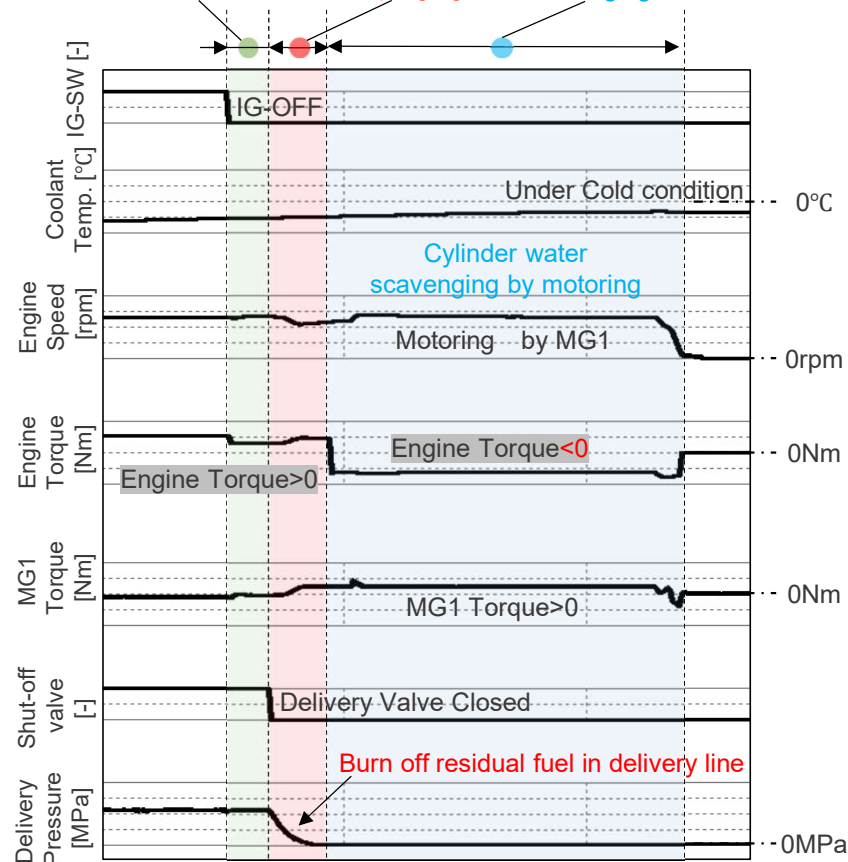
Stop before warm-up → cold soak → ring freezing → compression loss → no start

Topics 3 : Cold-Start Performance

Countermeasure : Scavenging control enabled by HEV engine motoring

Shutdown Sequence

【IG-OFF】→【Leak check】→【Fuel purging】→【Scavenging】



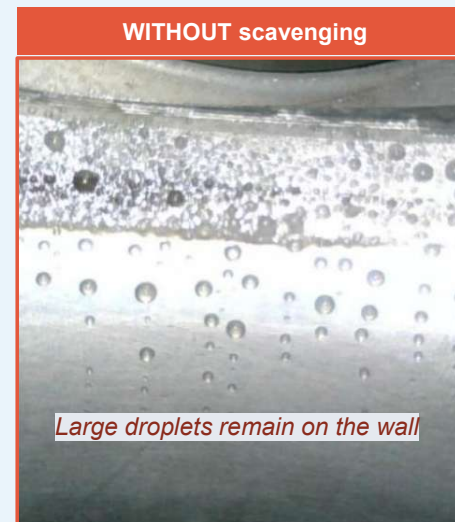
How the control works



Motoring at stop

At IG-Off the MG spins the engine (no fuel/spark) to pump air through the cylinders.

In-cylinder wall after stop (-10°C, 30sec Idle)

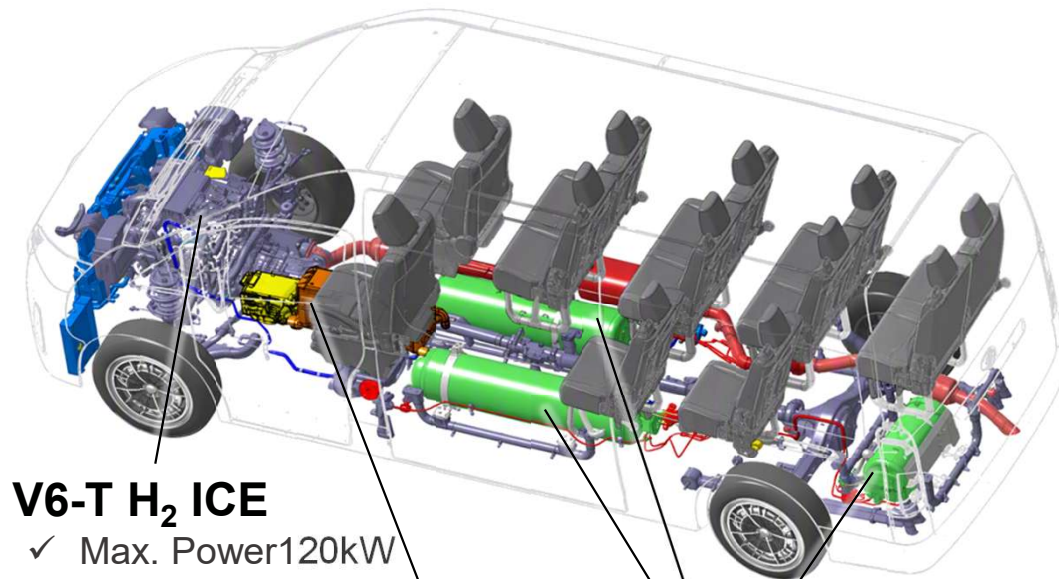


Reliable cold start ensured down to -30 °C

1. Introduction
2. H₂ ICE Specification
3. Technical Topics
- 4. Vehicle Specifications**
5. Conclusion

H₂ ICE & Vehicle Specifications

30/34



V6-T H₂ ICE

✓ Max. Power 120kW

HV Battery

✓ Max. Power 132kW

H₂ tank

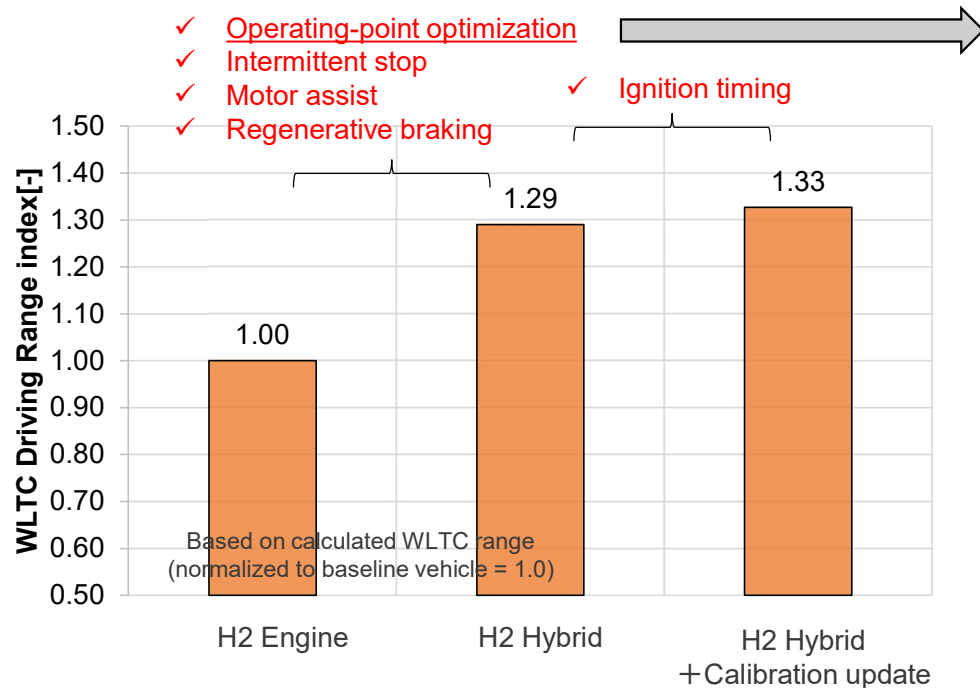
- ✓ use FCEVs h2 tank
- ✓ 3 tanks in total
- ✓ 6.2kg H₂

H ₂ Engine	Engine Type	V type 6 cylinder
	Displacement [cc]	3445
	Fuel	Compressed H ₂
	Bore × Stroke [mm]	Φ85.5×100
	Compression Ratio	10.4
	Max. power [kW]	120
	Max. torque [Nm]	354
	Max. engine speed [rpm]	4400
Battery	Combustion concept	lean combustion
	Battery type	Lithium-ion battery
Motor	Capacity [Ah]	4.3
	Max. power [kW]	132
Vehicle	Max. torque [Nm]	300
	Body size (L×W×H)[mm]	5915×1950×2280
	Gross vehicle weight[kg]	3820
	Emission Level	Euro7
	Towing Capacity[kg]	1500

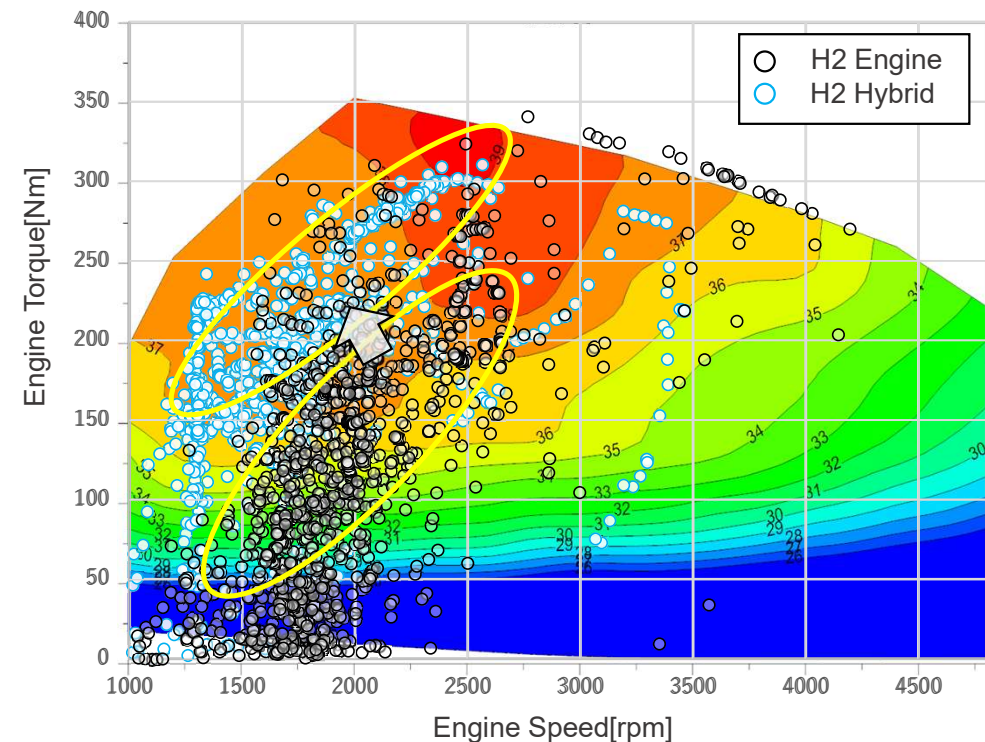
H₂ ICE & Vehicle Specifications

31/34

Driving Range Improvement



HEV conversion shifts to higher-efficiency operating points



Hybridization improves driving range by 33%

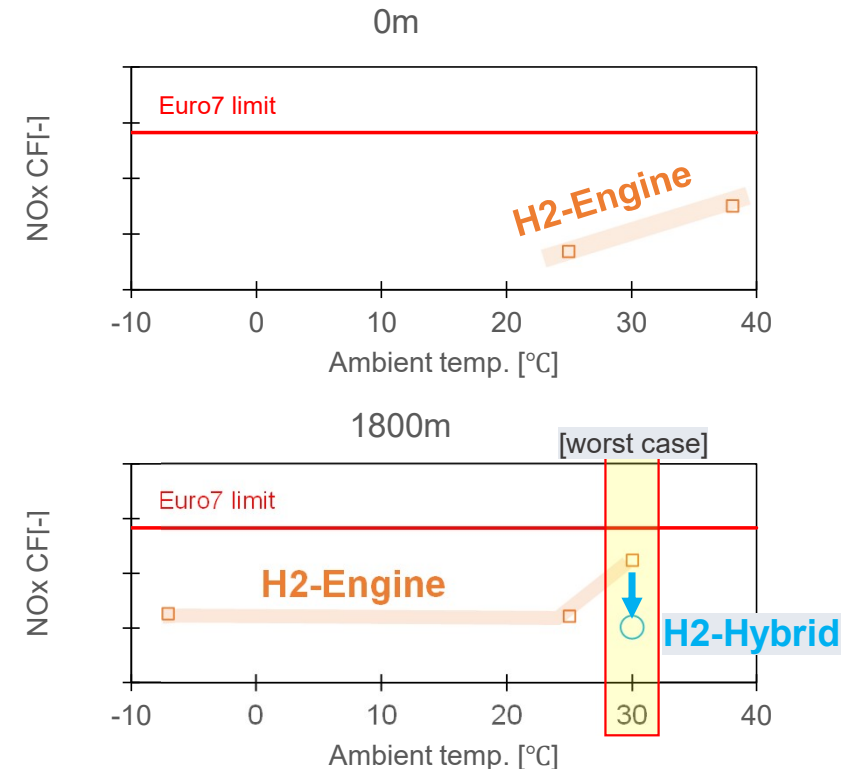
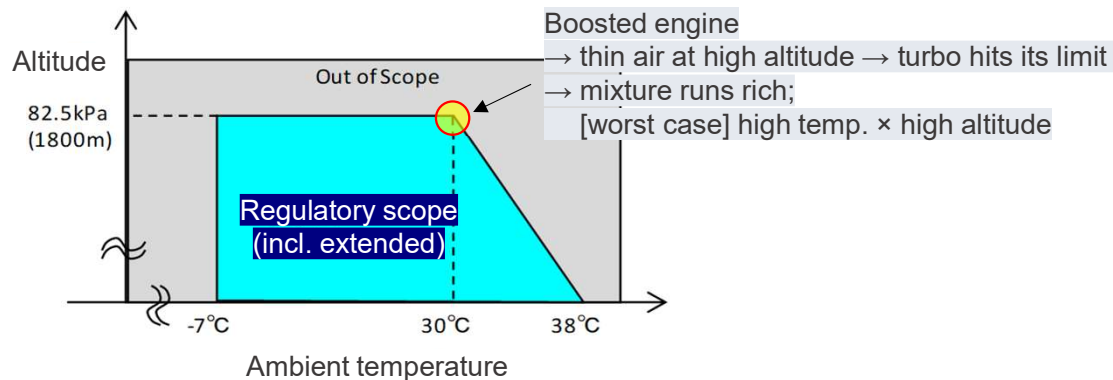
H₂ ICE & Vehicle Specifications

32/34

Vehicle Emissions — Real Driving Emission (RDE)

↳ Confirmed to stay within the regulatory limit across the following ambient conditions

Item	Specification (assumed heavy-duty)
Vehicle category	M2
Weight class / regime	Heavy-duty (ref. mass > 2,610 kg)
Regulation / stage	Euro7
Pollutant	NOx
Metric / test	Conformity Factor
Boundary conditions	Ambient temp. -7 to 35 ° C / altitude up to 1,300 m



Euro7 compliance achieved
— validated at the worst case (high temp. × high altitude)

1. Introduction
2. H₂ ICE Specification
3. Technical Topics
4. Vehicle Specifications
- 5. Conclusion**

Conclusion

34/34

Toyota is developing H₂ ICE as part of a multi-pathway approach to carbon neutrality.

Abnormal Combustion

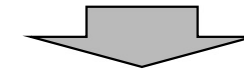
Manage pre-ignition risk and expand usable operating range.

Torque Response

Use motor assist to recover launch performance while keeping lean combustion.

Cold start

Use motor-driven scavenging to improve start reliability.



Pre-Ignition Detection

Provides an additional layer of reliability

Hybrid Technology Utilization

Feasible without it ,
hybridization makes these barriers far easier to solve

**Technology demonstration is underway in Europe
— driving further development —**