Mazda SKYACTIV-G Engine with New Boosting Technology

*- **ACC Symposium** held on September 28 -*

Reiji Okita
Mazda Motor Corporation

28, Sep. 2016

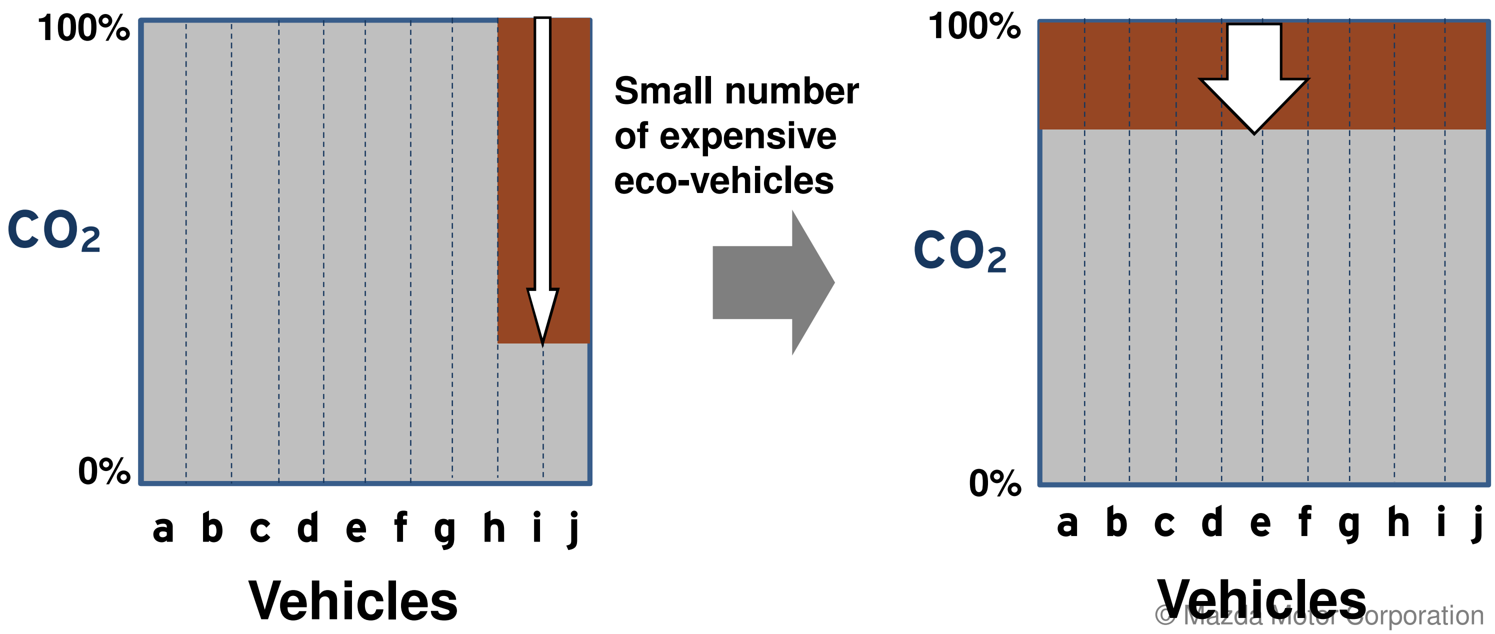
CONTENTS

1. Mazda's approach for environmental improvement

Mazda's Long-term Vision "Sustainable Zoom-Zoom"

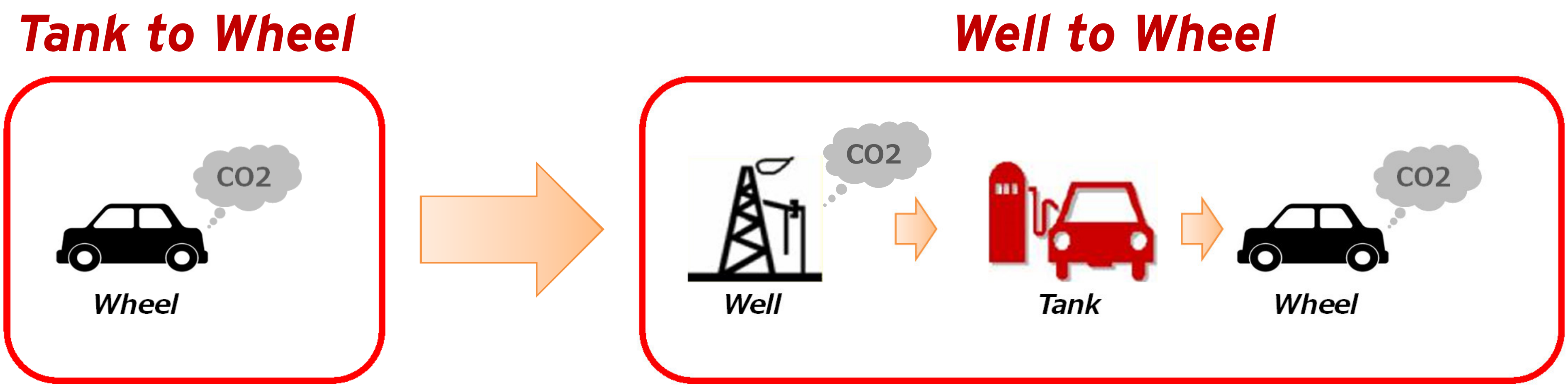
Provide all the customers with driving pleasure,
Also, Mazda considers the best contribution to the environment is to
incorporate superior and fairly valued technologies into every car model
rather than expensive eco technologies to limited models

Mazda's approach



Why we believe so ?

1) Market forecast
2) Difference between Well-to-Wheel CO2 emissions of EV and ICE

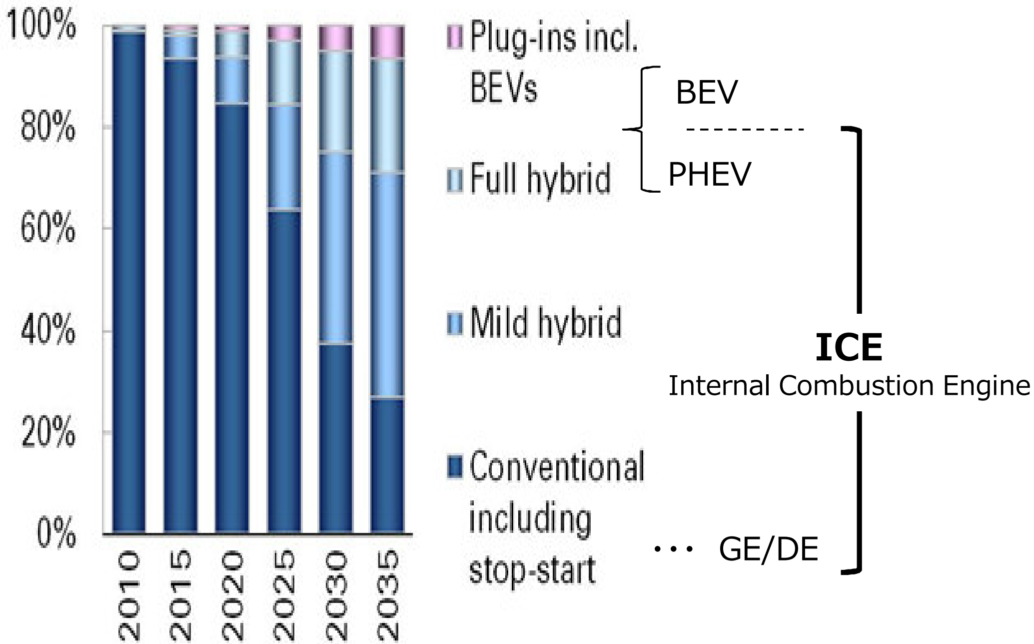


1. *Mazda's approach for environmental improvement*

- Market forecast-

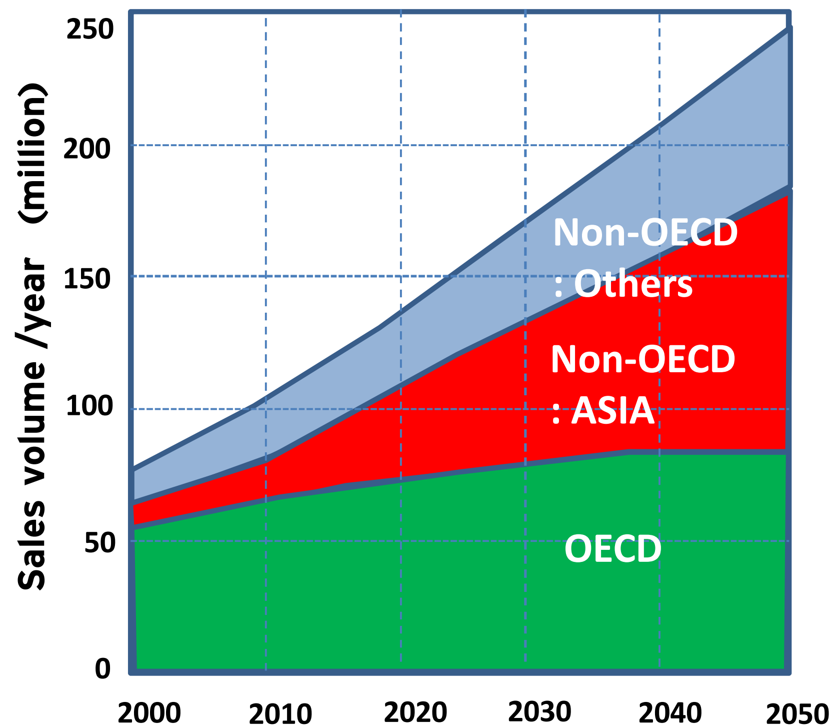
Vehicle Sales by type

Ref. BP Energy Outlook 2035



Vehicle Sales Volume by region

Ref. Marubeni Research Institute



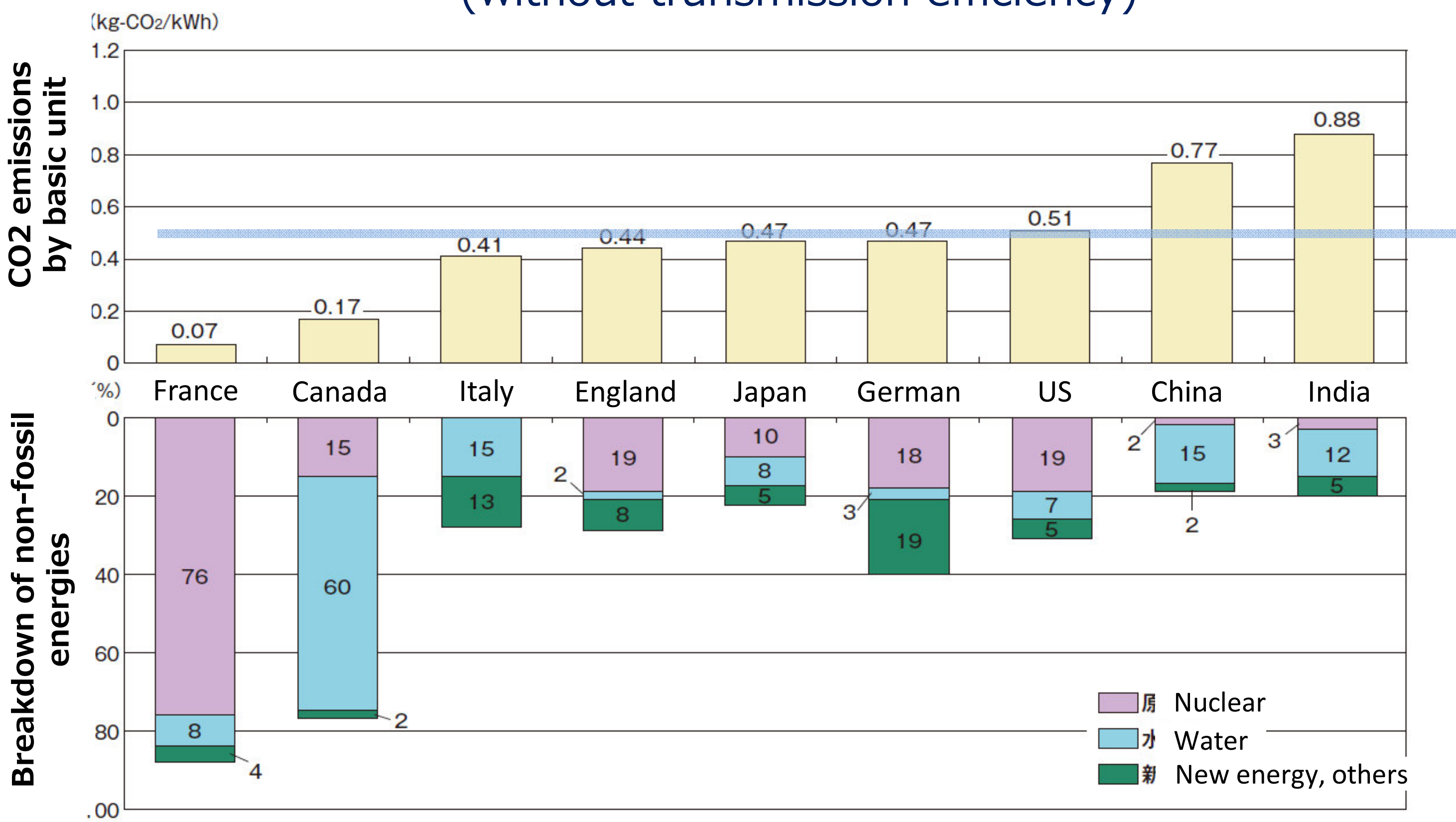
Most of power source of a car which will increase in future are internal combustion engines. It will not be possible to make a contribution for environment without improving internal combustion engines.

1. Mazda's approach for environmental improvement

- Well to Wheel -

Well to Tank CO2 emission of Electricity

(without transmission efficiency)



Well to Tank of Fuel in Japan

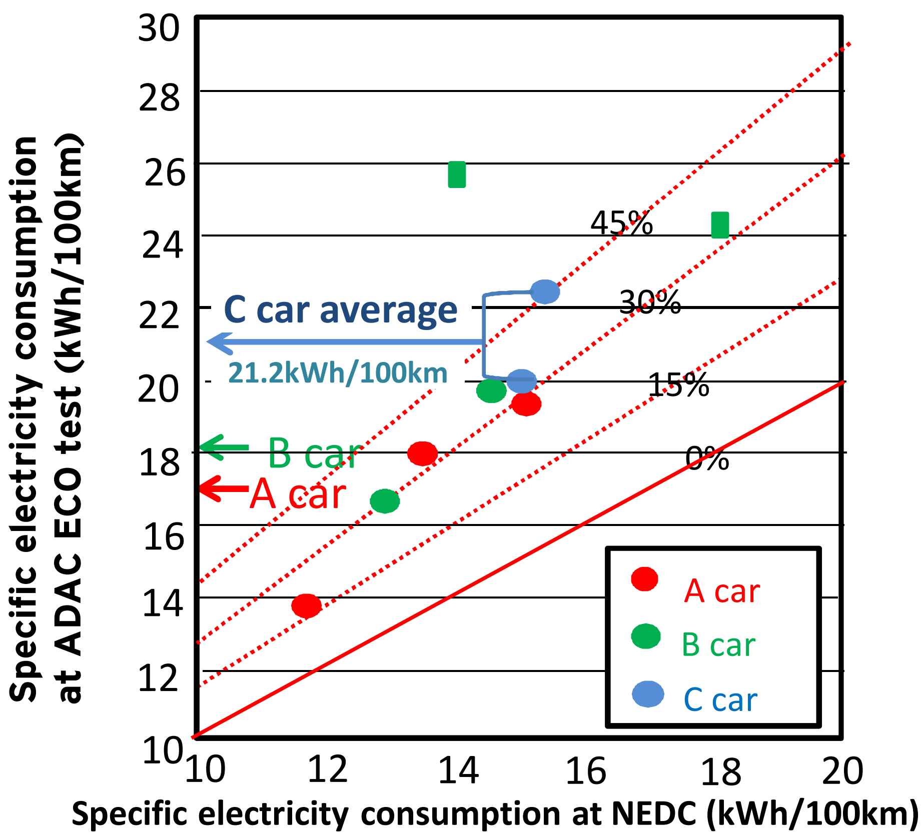
0.37kg-CO2/L

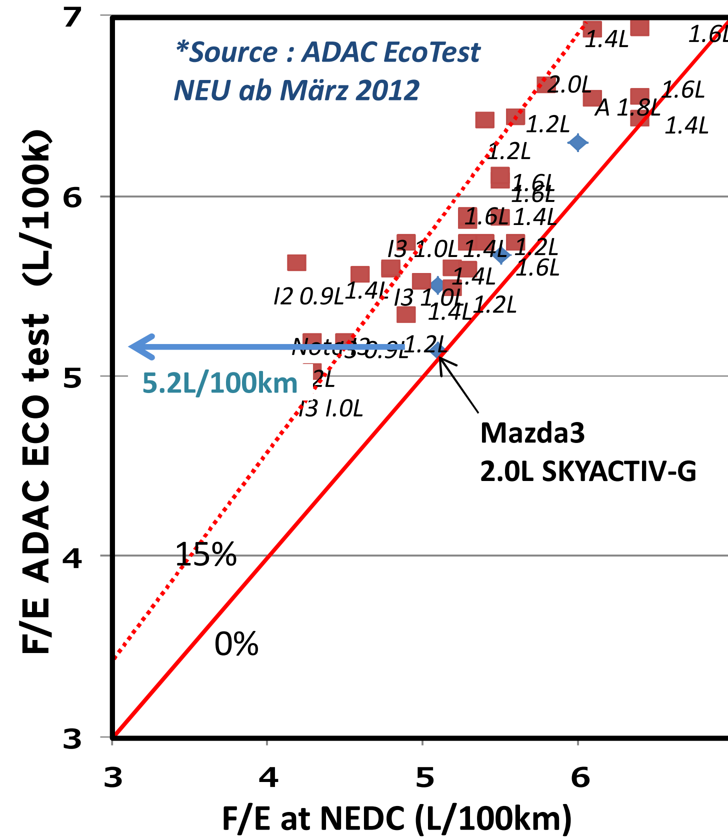
We assume that global average of specific CO2 emission in electric power generation is 0.5kg-CO2/kWh

1. Mazda's approach for environmental improvement

- Well to Wheel -

Electricity Consumption and Fuel Consumption





C car EV Real World Electricity Consumption : 21.2kWh/100km
C car SKYACTIV-G Real World Fuel Consumption : 5.2L/100km

1. Mazda's approach for environmental improvement

- Well to Wheel

Well to Wheel CO2 emission ～Mazda Estimate

C car EV

Electricity Consumption: 21.2kWh/100km
Specific CO2 emission : 0.5 CO2-kg/kWh
+ LCA considering Li-ion Battery: 1.0kg/100km

106 ～ 116 CO2-g/km

C car SKYACTIV-G

Fuel Consumption : 5.2L/100km

(Well to tank + Tank to Wheel)

148 CO2-g/km

20% - 30%

If the fuel consumption could be improved by 20%-30%, CO2 emission level of the vehicle powered by ICE could be equal to that of EV.

Potential of the improvement
Well to Wheel CO2 emission with ICE

Current efficiency of Tank-to-Wheel

- *EV : 80%-90%*
- *ICE: max. 30% - 40%*

*There is still **Large potential** of improvement in ICE,*
*also **hybridization** gives further improvement on ICE*

How do we let the aim accomplish ?

"F/C improvement 20%～30%"

CONTENTS

2. SKYACTIV-G Development Process

Innovative High Thermal Efficiency

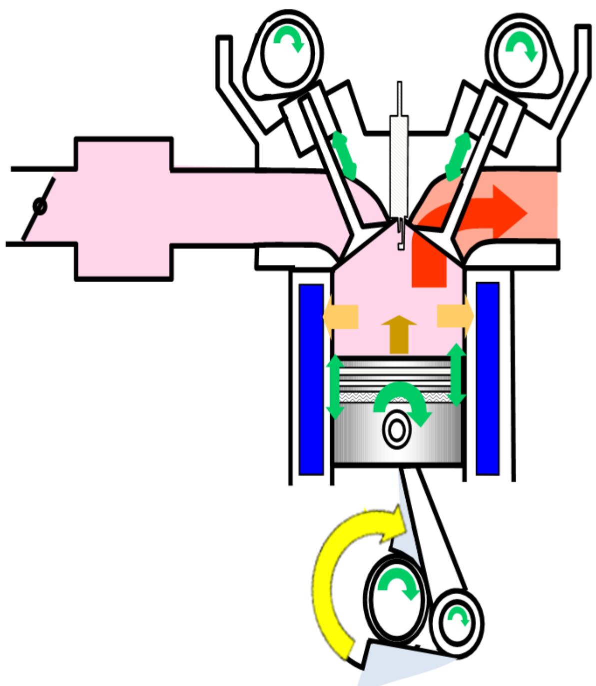
The energy of the fuel is converted to power that moves the vehicle.

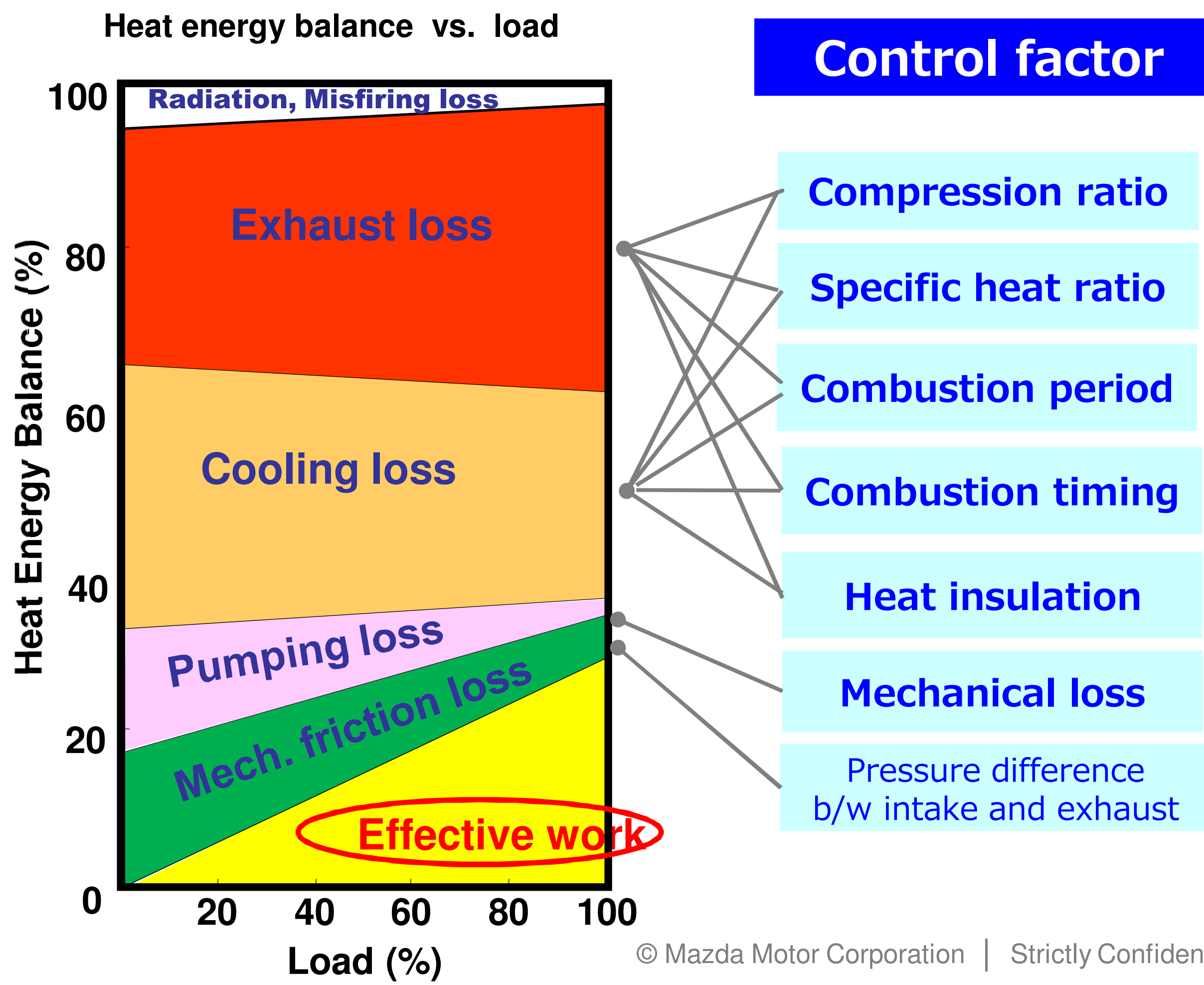
Maximize

- Improvement of driving force
- Improvement of fuel economy
- Decrease of poisonous substance in exhaust gas

2. SKYACTIV-G Development Process

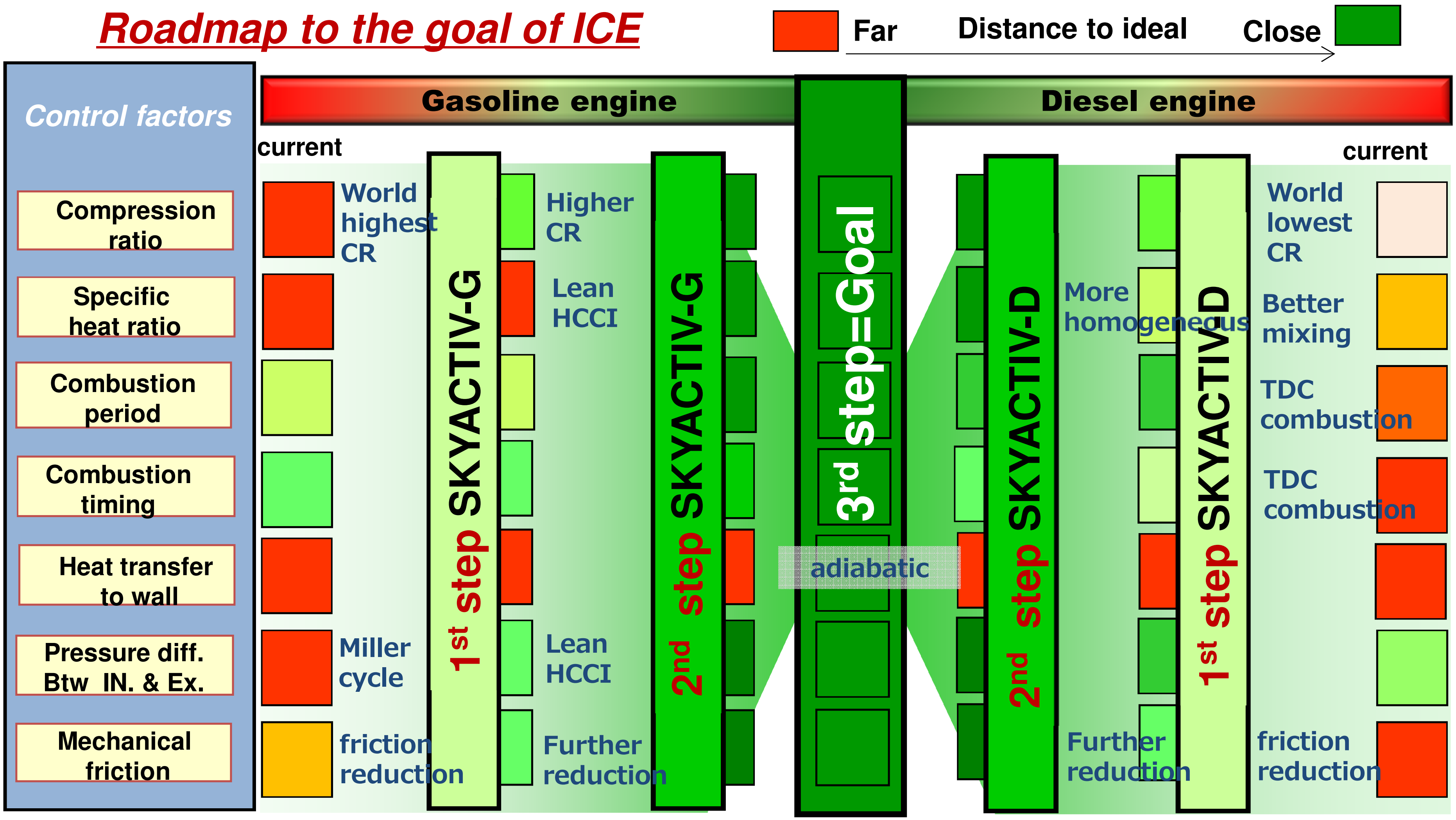
High-efficient Engine ← Minimize Losses





2. SKYACTIV-G Development Process

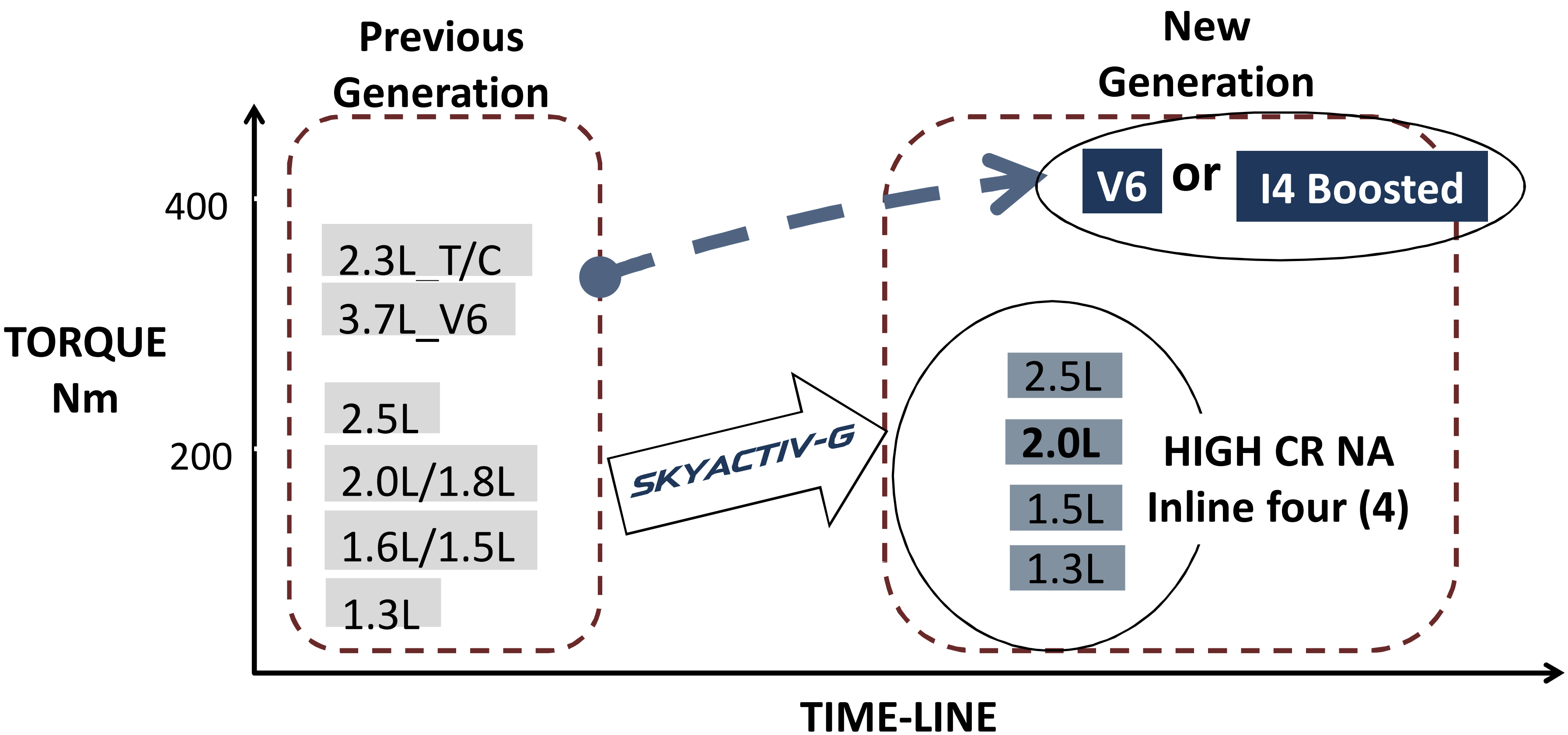
Roadmap to the goal of ICE



Gasoline and diesel engines will look similar in the future.

3. SKYACTIV-G 2.5L TC development

Power Source for CD-SUV



Alternative delivering torque higher than 400Nm on a large SUV is, V6 Natural Aspirated or Boosted I4 downsized.

CONTENTS

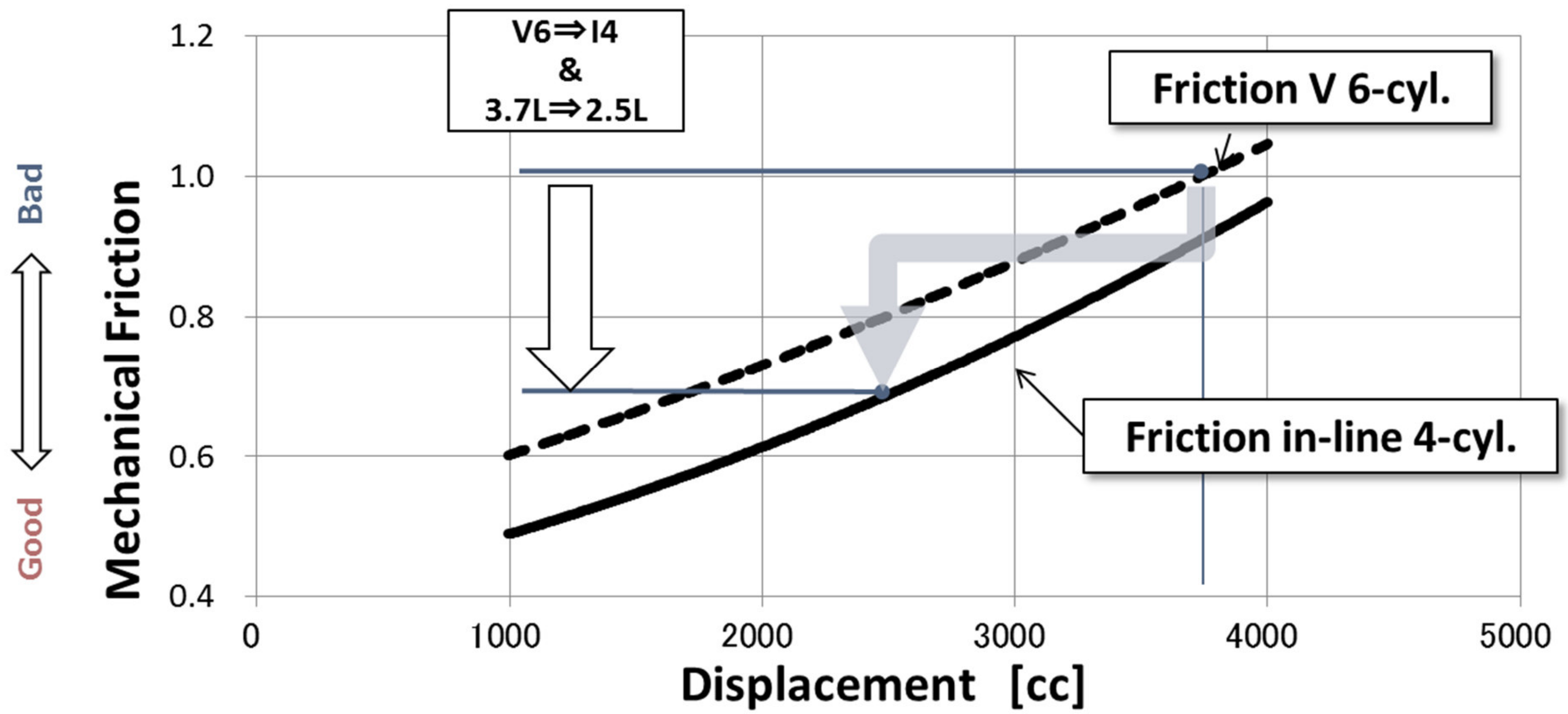
Scenario we selected I4 boosting, not V6 NA.

3. SKYACTIV-G 2.5L TC development

Advantage of I4 boosted

Effect of Downsizing V6 3.7L ⇒ Boosted I4 2.5L

Mechanical Friction ～*Calculation by Mazda*



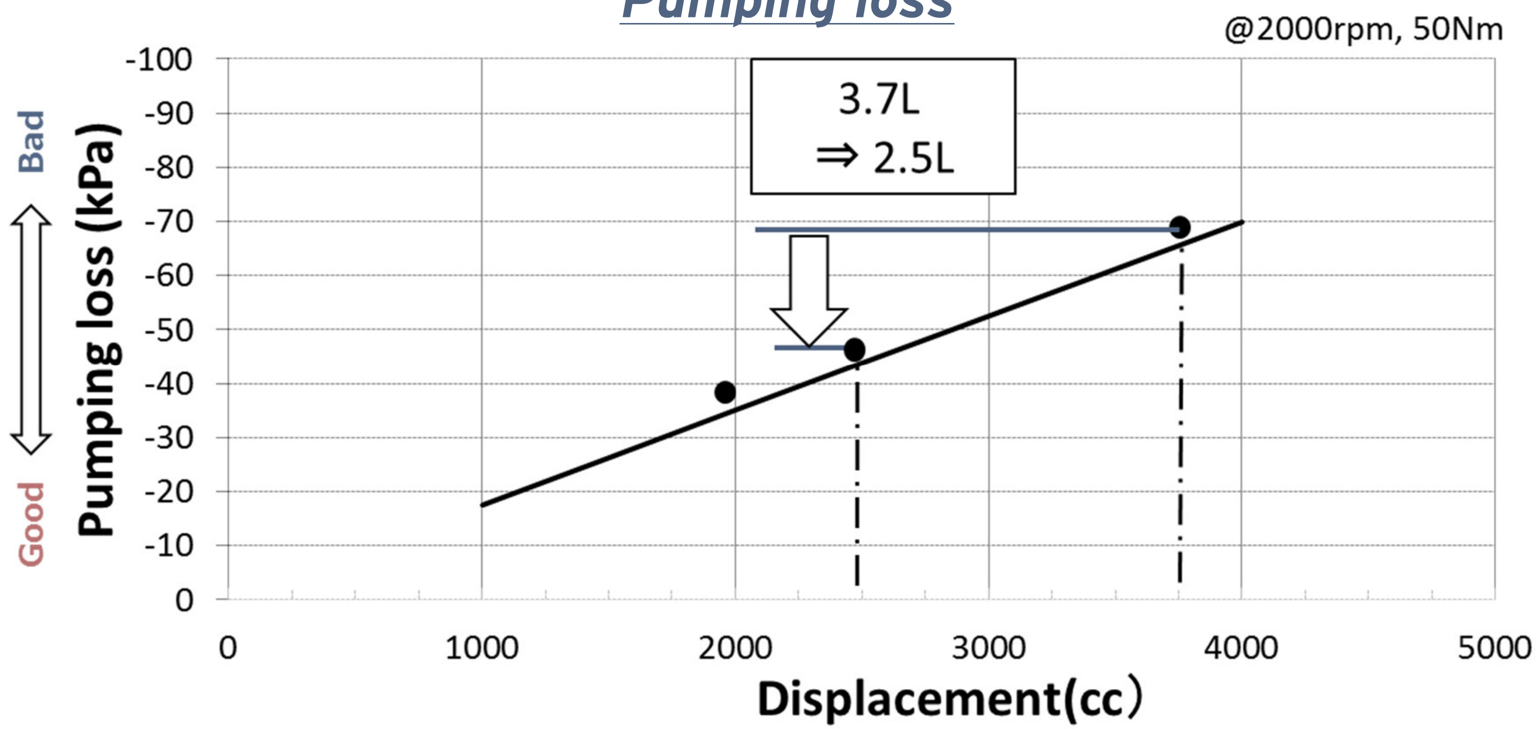
Compared to V6 3.7L, boosted I4 2.5L achieves:
- 30% less mechanical friction with fewer cylinders (6 to 4) and less displacement

3. SKYACTIV-G 2.5L Turbocharged (TC) Engine Development

Advantage of I4 boosted

Effect of Downsizing V6 3.7L ⇒ Boosted I4 2.5L

Pumping loss



Compared to the V6 3.7L, the boosted I4 2.5L achieves:
- 30% less pumping loss with less displacement.

3. SKYACTIV-G 2.5L TC development

		V6-NA	I4-Boosted
Performance	Torque at low rpm		Better
	Quick Response	Better	
Real World F/E	Compression Ratio	Better	
	Mechanical Friction		Better
	Pumping Loss		Better
Weight			Better
Cost			Better

BREAK THROUGH

I4 boosted concept has superior mechanical friction and pumping loss, while it is inferior fuel efficiency due to lowered compression ratio, and acceleration response.

3. SKYACTIV-G 2.5L TC development

Key issue to realize I4 boosted with high compression ratio is
Knocking Resistance Improvement

Evaluation Tool
for calculation of knocking resistance

Ignition delay

$$\tau = 8.449\text{x}10^{-5} \left(\frac{P}{T}\right)^{-1.343} (1-X_{EGR})^{-0.8881} \exp\left(\frac{5266}{T}\right)$$

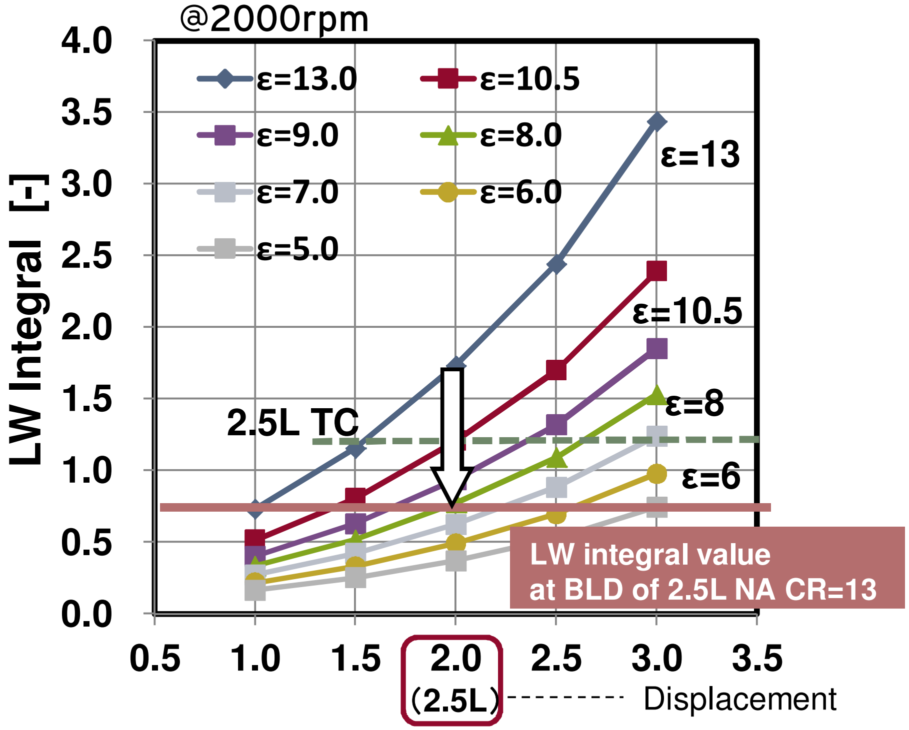
Livengood-Wu integral

$$\int_{t=0}^{t=tc} (1/\tau)_{P,T}\ dt=1$$

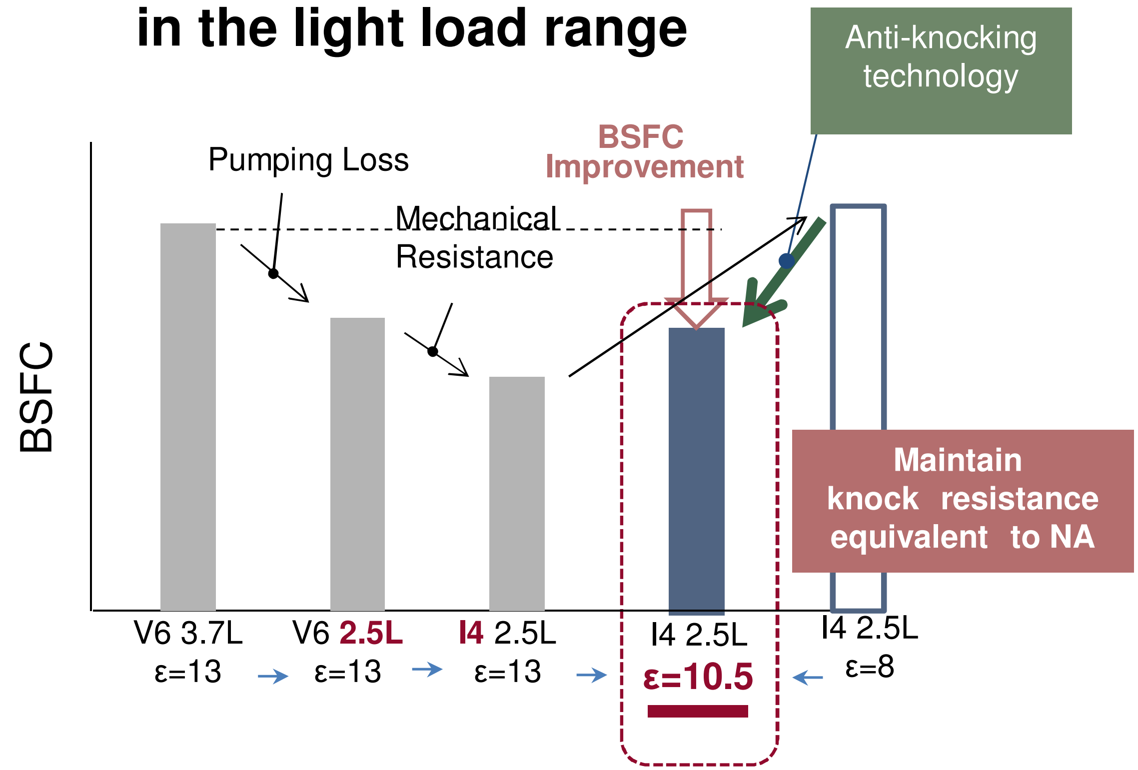
P: pressure (kPa)
T: unburned gas temp. (K)
X_EGR : EGR ratio

3. Breakthrough Point to Realize I4 Turbocharging Concept

Compression ratio setting in the high load range



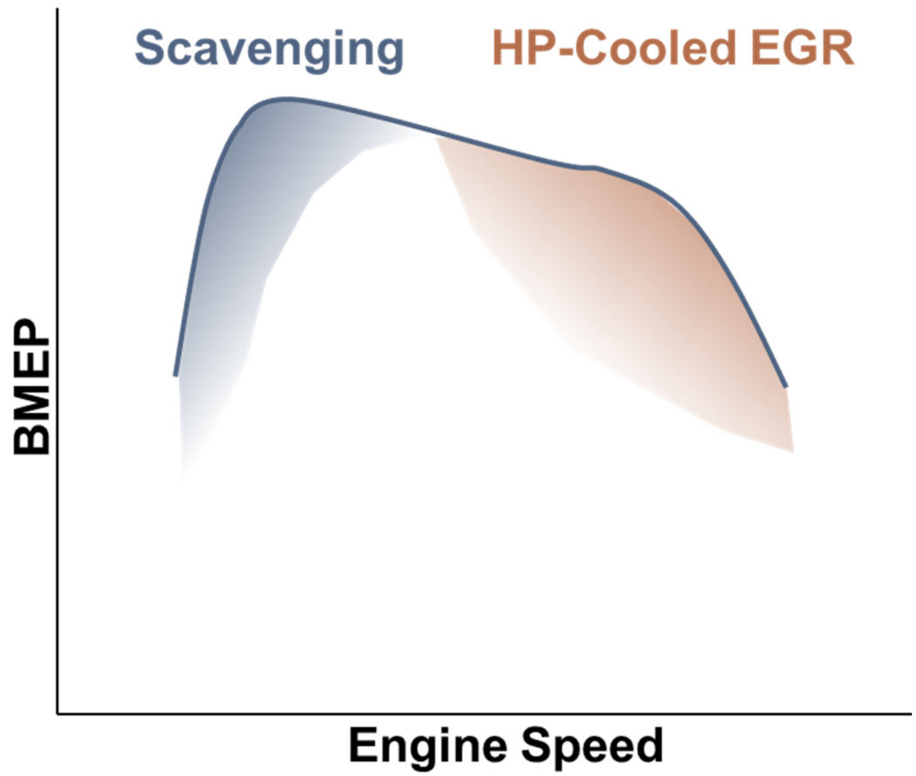
Compression ratio setting in the light load range



To keep the advantage of I4 turbocharged engine for the mechanical friction and pumping loss, the compression ratio must be kept around 10.5.

Cascaded targets to realize compression ratio, 10.5

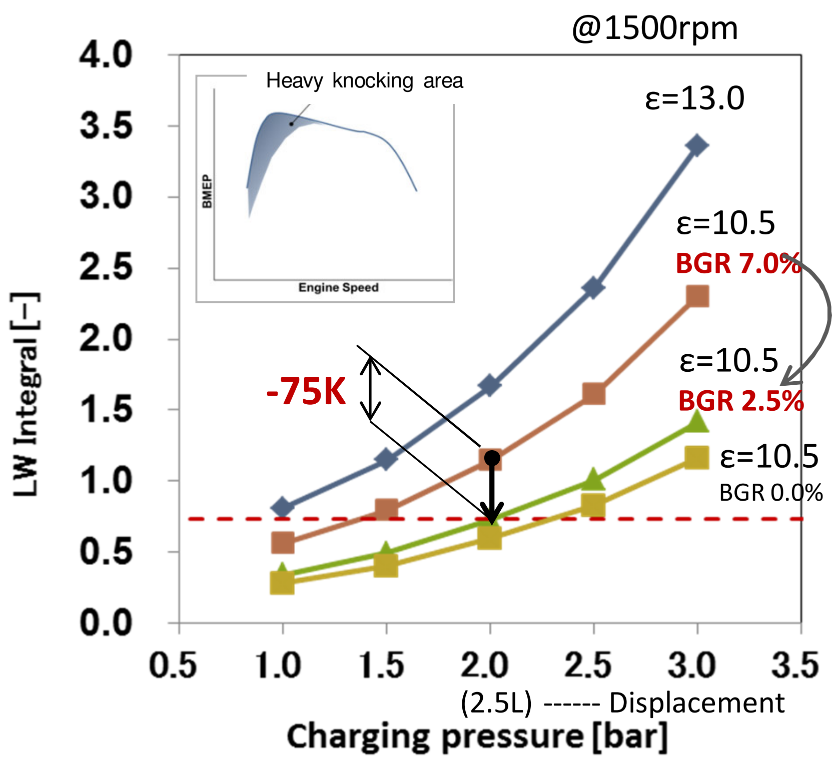
3. SKYACTIV-G 2.5L TC development



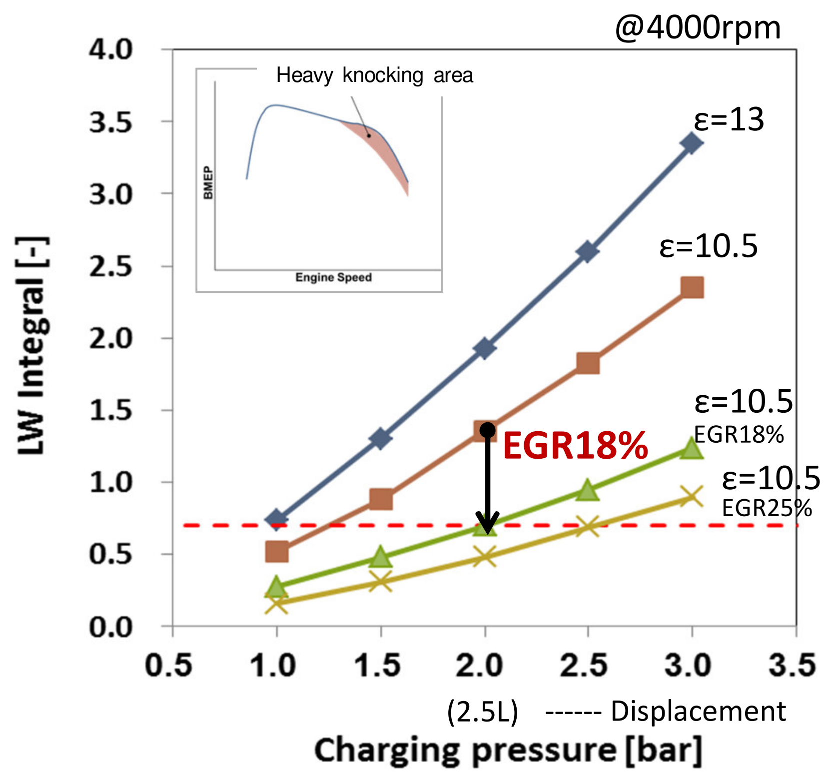
The concept o improve knock resistance at high loads, encouraging "scavenging" for low speed and introducing EGR for mid/high speed.

4. Setting Functional Targets and Appropriate Displacement

"Scavenging" at low rpm/high load



"EGR" at mid/high rpm & high load



The follows are necessities for the turbo charged 2.5L engines(CR 10.5/boost pressure 2.0bar) to ensure the knock resistance equivalent to 2.5L NA engines(CR 13.0) .

- ***low rpm/high load :*** *TDC Temp.Δ75K, BGR* 7.0% →2.5%*
- ***mid/high rpm & high load:*** *EGR ratio 18%*

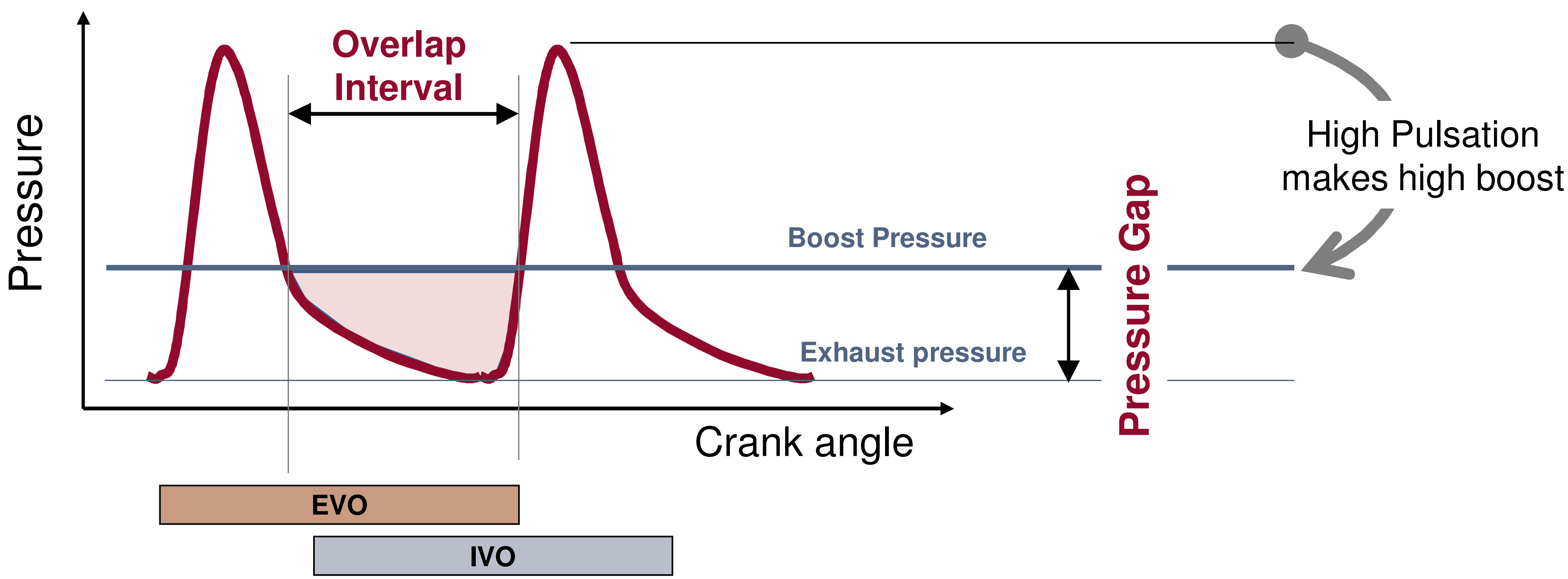
*: BGR = Residual gas ratio

Specific Measures to achieve cascaded specific targets

3. SKYACTIV-G 2.5L TC development

- Scavenging -

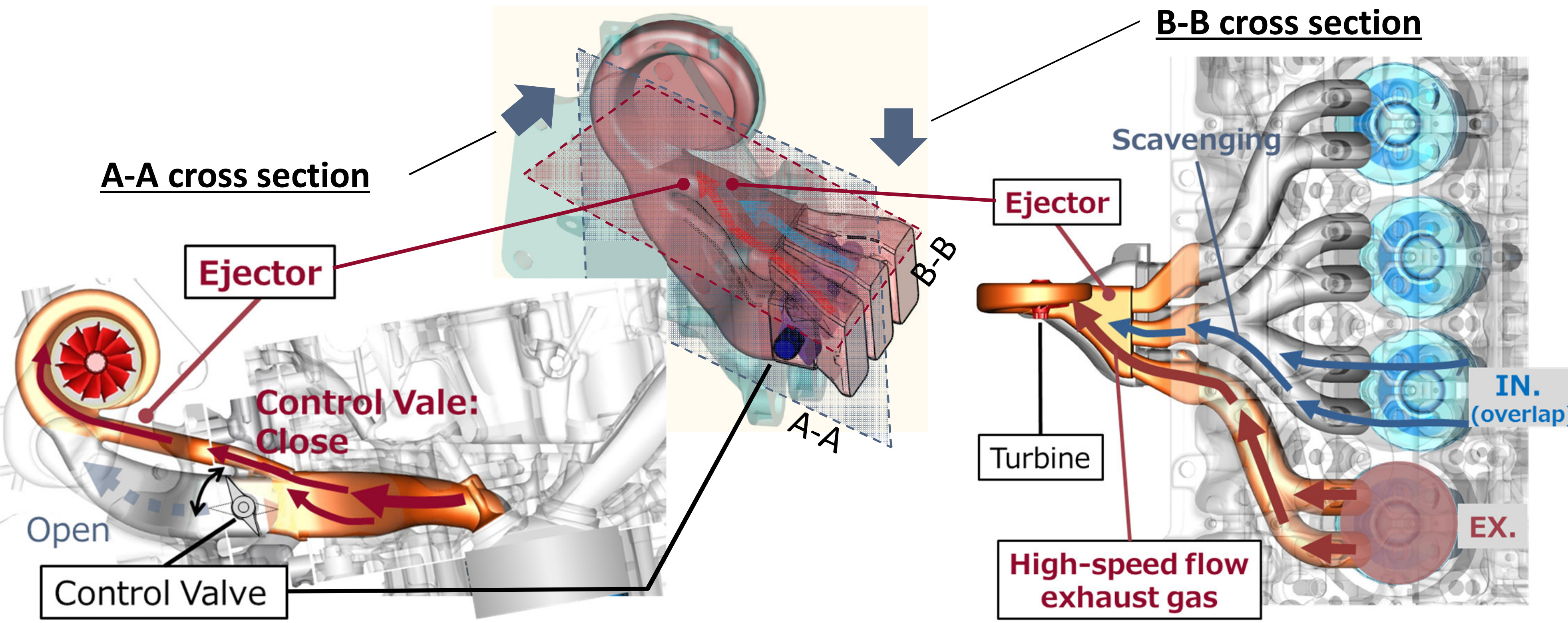
Exhaust Pulsation of a Turbocharged Engine



For strong scavenging, a large gap of pressure and long overlap interval are necessary, while the boost pressure exceeding over exhaust gas pressure.

3. SKYACTIV-G 2.5L TC development

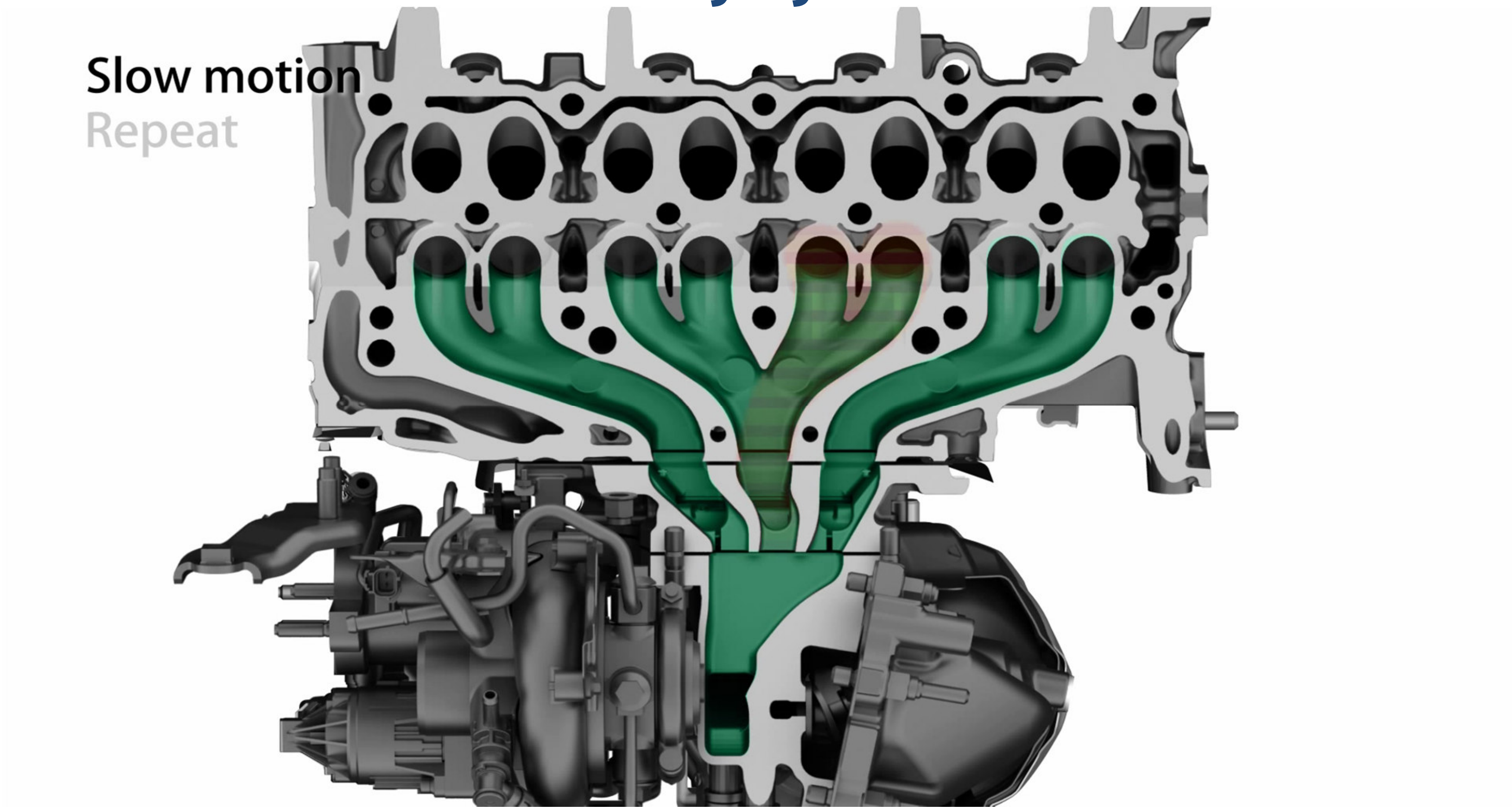
Dynamic Pressure Turbo (DPT) Structure



To realize scavenging concept, 4-3-1 exhaust was adopted so that the volume of four exhaust passages are minimized evenly. Each passage is divided into primary and secondary in order to encourage turbine rotation and scavenging effect.

3. SKYACTIV-G 2.5L TC development

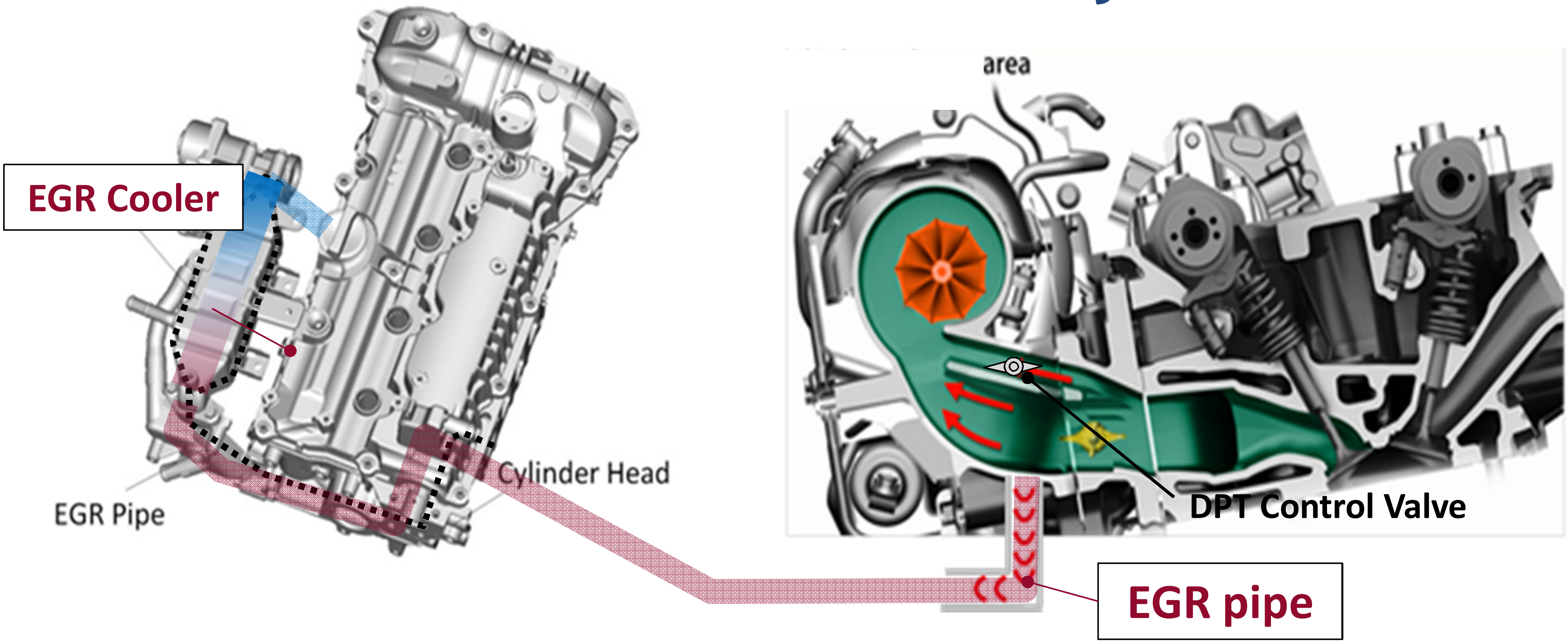
Dynamic Pressure Turbo (DPT)
Scavenging Effect



3. SKYACTIV-G 2.5L TC development

3. SKYACTIV-G 2.5L TC development

HP-Cooled EGR Passage

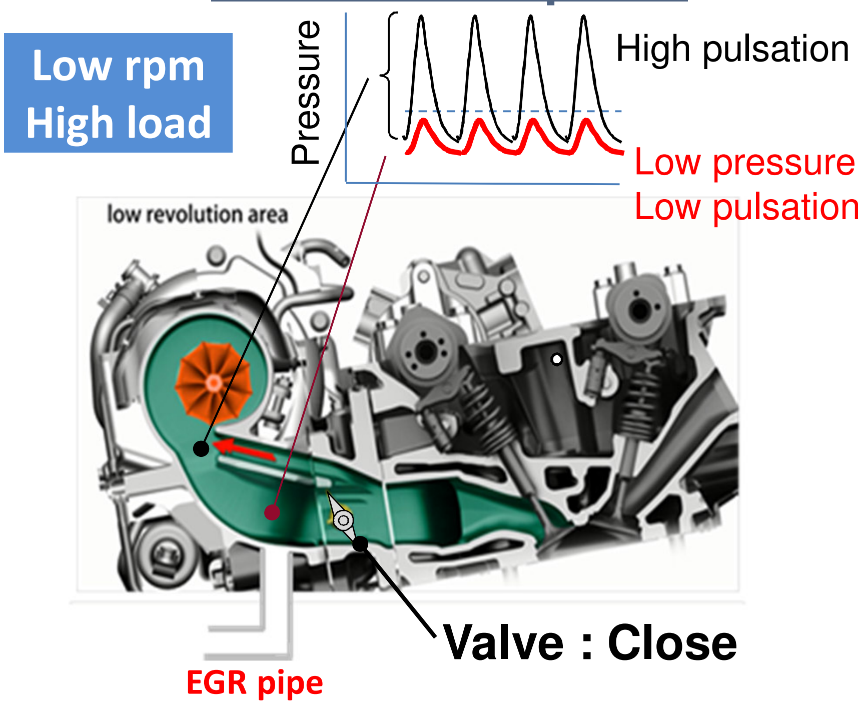


EGR gas is pulled through EGR outlet placed at down stream of the control valve, and brought to EGR cooler.

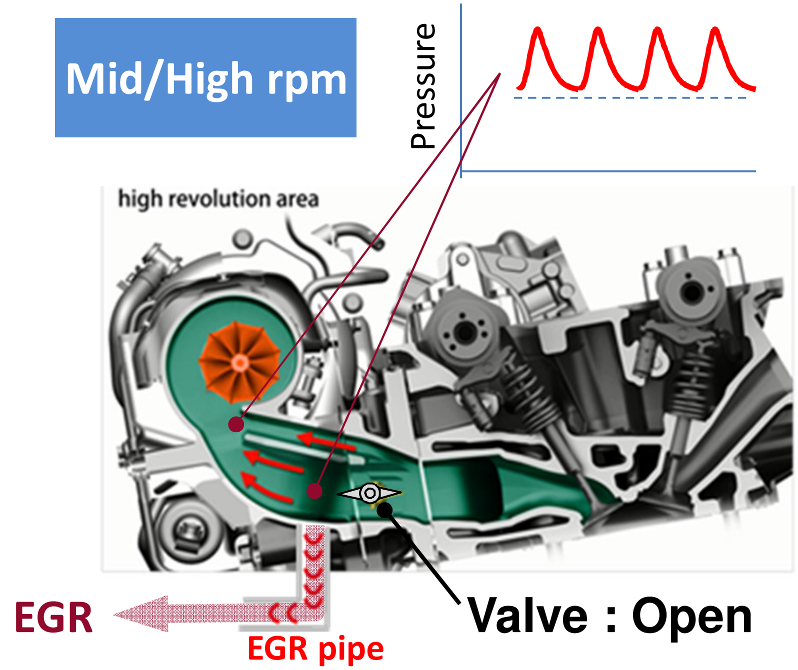
3. SKYACTIV-G 2.5L TC development

Function of EGR Pipe Location

Scavenging condition & no EGR required



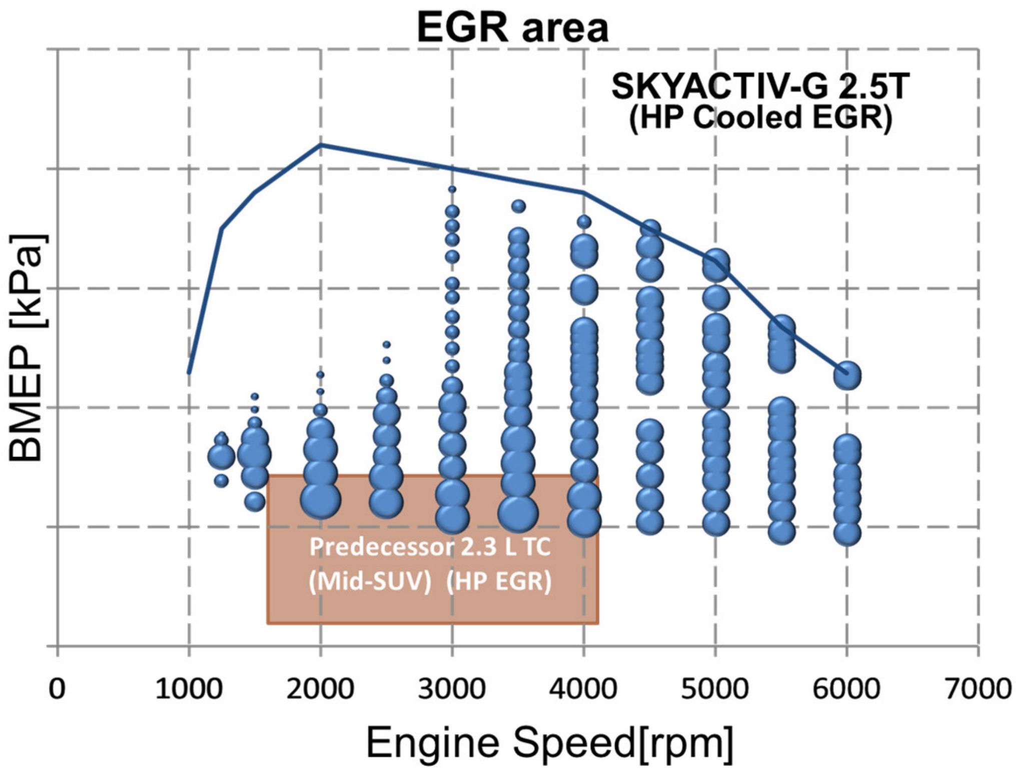
No Scavenging condition & enough EGR required

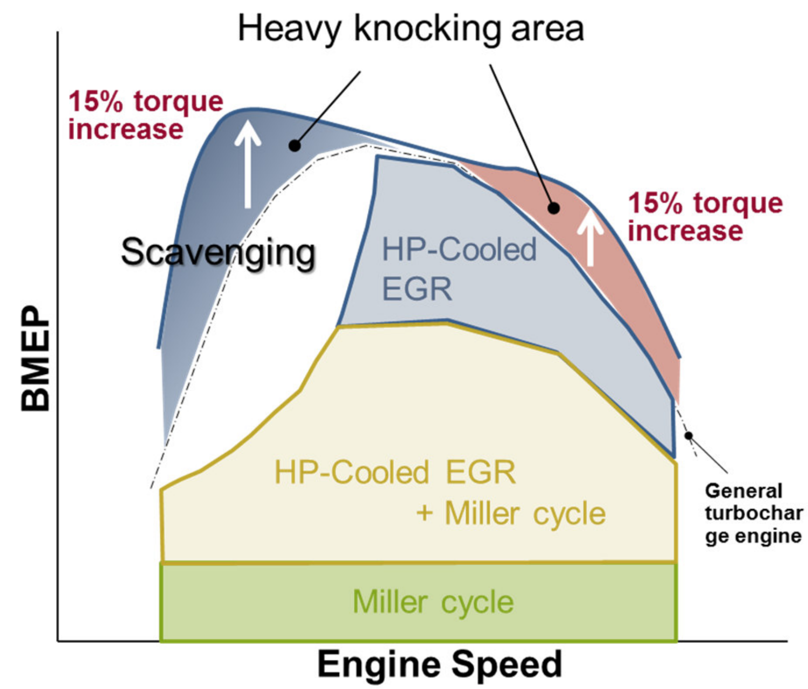


EGR passage does not disturb "scavenging" effect when it is required, but able to provide sufficient amount of EGR with transient accuracy.

3. SKYACTIV-G 2.5L TC development

Scavenging and EGR Area



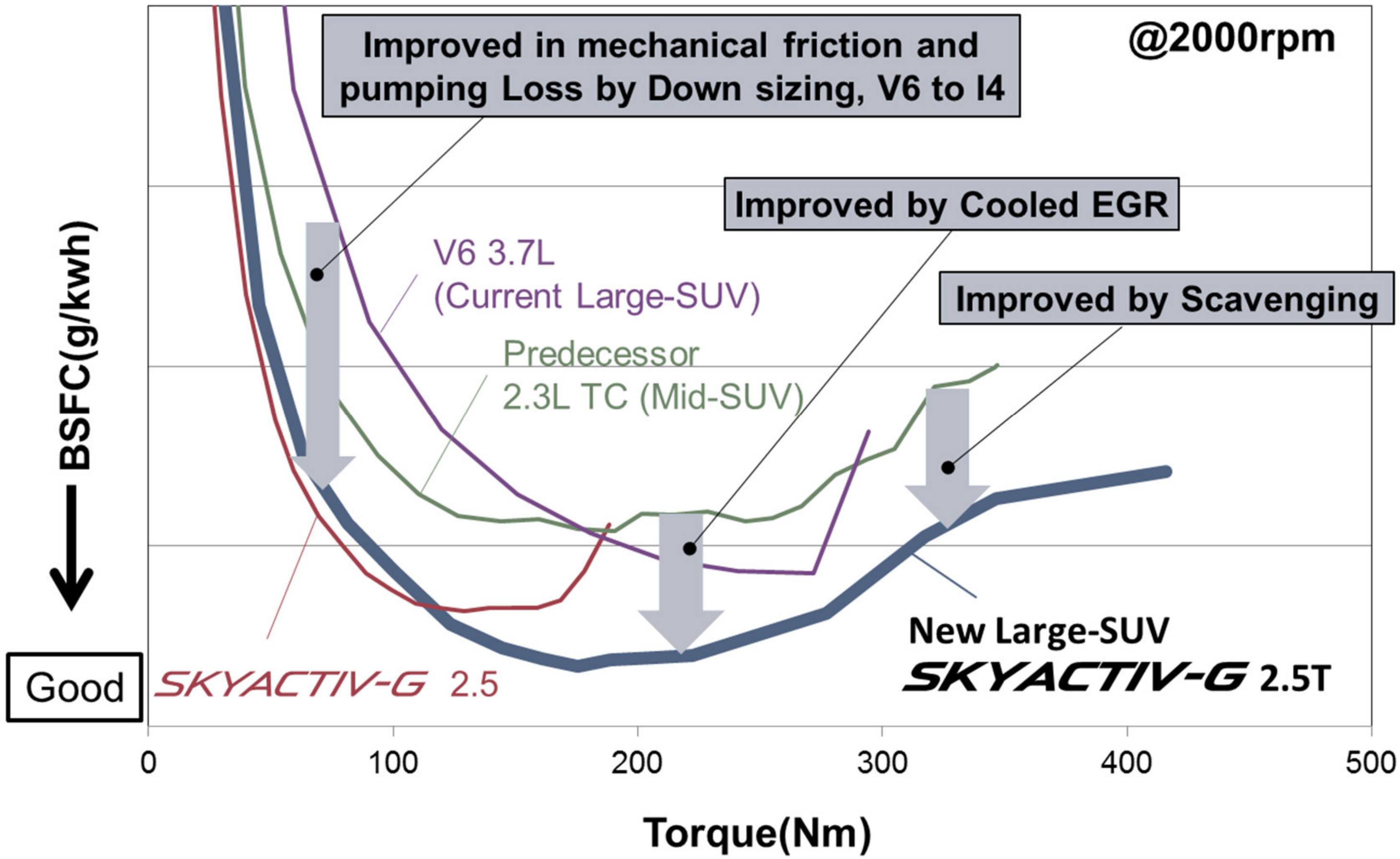


SKYACTIV-G with DPT achieved to enable high scavenging under low engine speed, as well as introduce high amount of EGR in wider engine operation range, led significantly low fuel consumption performance.

Achievements

3. SKYACTIV-G 2.5L TC development

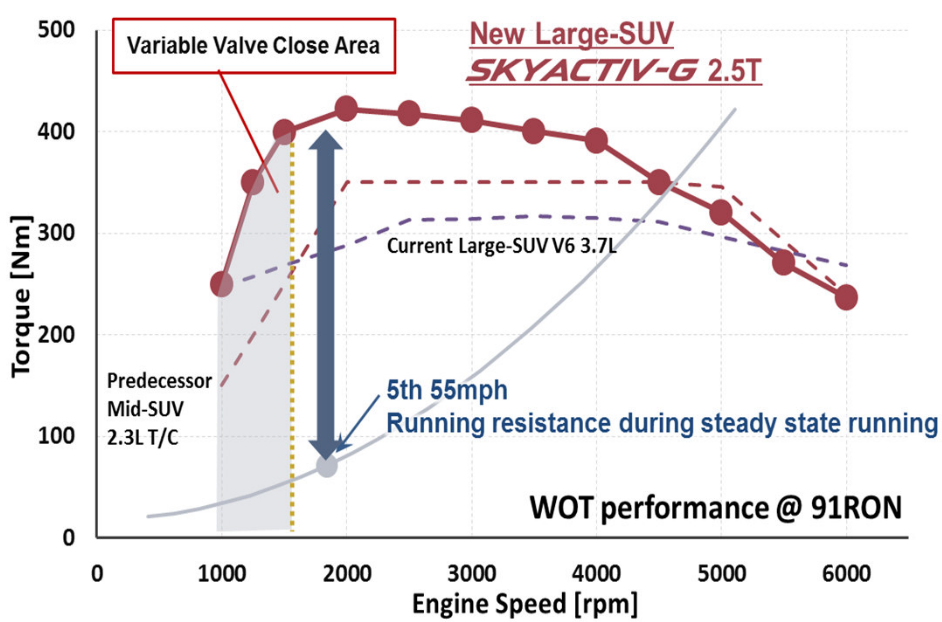
Reduction in Fuel Consumption



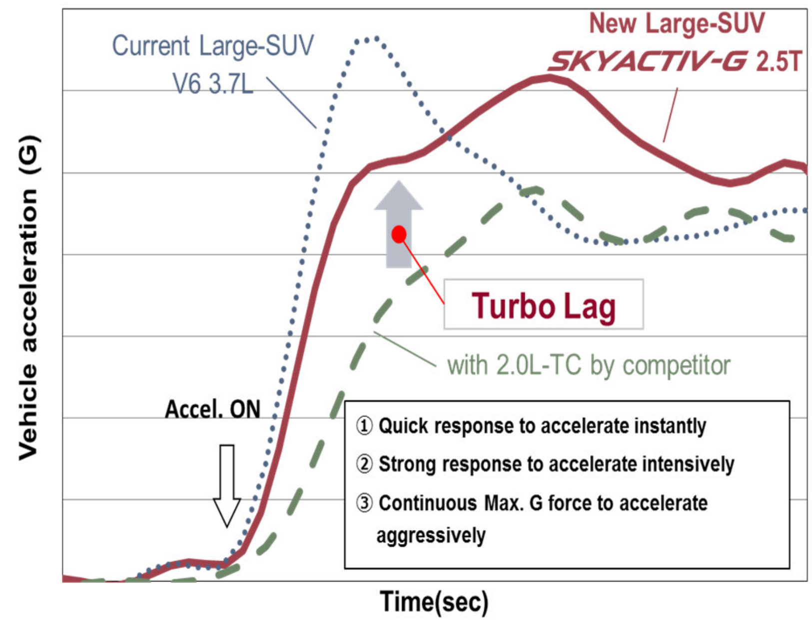
SKYACTIV-G 2.5L with DPT improves the fuel efficiency over a whole range.

3. SKYACTIV-G 2.5L TC development

Torque Curve

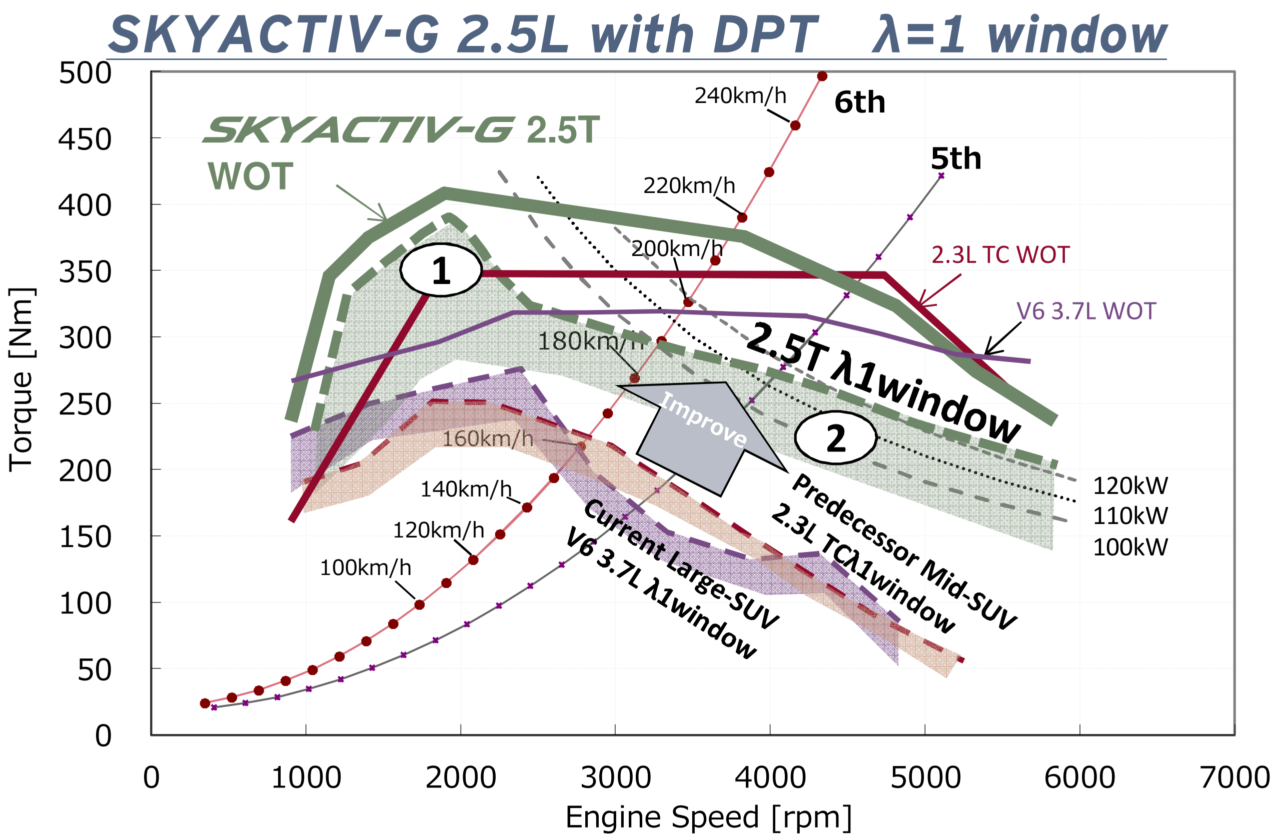


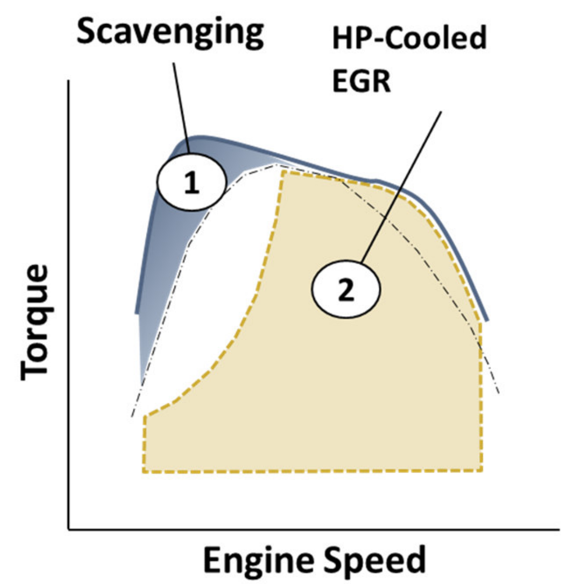
Acceleration Characteristic



SKYACTIV-G 2.5L with DPT achieved significantly higher torque than predecessor from low engine speed under 91RON, as well as much shorter turbo lag.

3. SKYACTIV-G 2.5L TC development





SKYACTIV-G 2.5L with DPT achieved wider range of λ=1 window, real-world fuel consumption has been improved by 30% from the predecessor model.

3. SKYACTIV-G 2.5L TC development

Summary

Mazda 2.5L SKYACTIV-G Engine with "Dynamic Pressure Turbo" and "HP cooled-EGR" brought the following benefits:

1. ***Acceleration response comparable to that of large-displacement naturally aspirated engine***
2. ***Low fuel consumption at middle and high loads.***
3. ***The maximum torque of 420 Nm at low speed, 2000rpm***

CONTENTS

- ***ICE has still enough potential to improve its thermal efficiency.***
- ***Mazda continues to improve ICE performance targeting to equal CO2 emission level as EV's.***

Thank you for your kind attention