Mazda SKYACTIV-G Engine with New Boosting Technology

- ACC Symposium held on September 28 -

Reiji Okita
Mazda Motor Corporation
CONTENTS
1. Mazda's approach for environmental improvement
2. SKYACTIV-G Development Process
3. SKYACTIV-G 2.5L TC development
4. End message
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
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.
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 -**

**Well to Tank CO₂ emission of Electricity**
(without transmission efficiency)

<table>
<thead>
<tr>
<th>Country</th>
<th>CO₂ emissions by basic unit (kg-CO₂/kWh)</th>
<th>Breakdown of non-fossil energies</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>0.07</td>
<td>Nuclear: 76 Water: 60 New energy, others: 2</td>
</tr>
<tr>
<td>Canada</td>
<td>0.17</td>
<td>Nuclear: 15 Water: 13 New energy, others: 2</td>
</tr>
<tr>
<td>Italy</td>
<td>0.41</td>
<td>Nuclear: 10 Water: 5 New energy, others: 19</td>
</tr>
<tr>
<td>England</td>
<td>0.44</td>
<td>Nuclear: 19 Water: 8 New energy, others: 5</td>
</tr>
<tr>
<td>Japan</td>
<td>0.47</td>
<td>Nuclear: 19 Water: 7 New energy, others: 5</td>
</tr>
<tr>
<td>Germany</td>
<td>0.47</td>
<td>Nuclear: 18 Water: 8 New energy, others: 2</td>
</tr>
<tr>
<td>US</td>
<td>0.51</td>
<td>Nuclear: 15 Water: 3 New energy, others: 5</td>
</tr>
<tr>
<td>China</td>
<td>0.77</td>
<td>Nuclear: 12 Water: 5 New energy, others: 3</td>
</tr>
<tr>
<td>India</td>
<td>0.88</td>
<td>Nuclear: 12 Water: 5 New energy, others: 3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Car Type</th>
<th>Real World Electricity Consumption (kWh/100km)</th>
<th>Real World Fuel Consumption (L/100km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C car EV</td>
<td>21.2</td>
<td>5.2</td>
</tr>
<tr>
<td>C car SKYACTIV-G</td>
<td>21.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Specific electricity consumption at NEDC (kWh/100km):

- A car
- B car
- C car

F/E at NEDC (L/100km):

- A car
- B car
- C car

*Source: ADAC EcoTest NEU ab März 2012

*Note: Mazda3 2.0L SKYACTIV-G
1. Mazda’s approach for environmental improvement

- Well to Wheel

**Well to Wheel CO2 emission** ~Mazda Estimate

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

\[ 106 \sim 116 \text{ CO2-g/km} \]

**C car SKYACTIV-G**
- Fuel Consumption: 5.2 L/100km

(Well to tank + Tank to Wheel)

\[ 148 \text{ CO2-g/km} \]

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.
1. Mazda's approach for environmental improvement

**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
1. Mazda’s approach for environmental improvement

**How do we let the aim accomplish?**

“F/C improvement 20%～30%”
CONTENTS

1. Mazda’s approach for environmental improvement
2. SKYACTIV-G Development Process
3. SKYACTIV-G 2.5L TC development
4. End message
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

Heat energy balance vs. load

- Radiation, Misfiring loss
- Exhaust loss
- Cooling loss
- Pumping loss
- Mech. friction loss
- Effective work

Control factor

- Compression ratio
- Specific heat ratio
- Combustion period
- Combustion timing
- Heat insulation
- Mechanical loss
- Pressure difference b/w intake and exhaust
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**

![Chart showing torque levels and power sources for previous and new generations of CD-SUVs.

- **Previous Generation**
  - 2.3L T/C
  - 3.7L V6
  - 2.5L
  - 2.0L/1.8L
  - 1.6L/1.5L
  - 1.3L

- **New Generation**
  - V6 or I4 Boosted
  - 2.5L
  - 2.0L
  - 1.5L
  - 1.3L

**TIME-LINE**

- **TORQUE Nm**
  - 400
  - 200

**Previous Generation**

- 2.3L_T/C
- 3.7L_V6

**New Generation**

- V6 or I4 Boosted

**HIGH CR NA Inline four (4)**

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

1. Mazda’s approach for environmental improvement
2. SKYACTIV-G Development Process
3. SKYACTIV-G 2.5L TC development
4. End message
Scenario we selected L4 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

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

Mechanical Friction ~Calculation by Mazda

Displacement [cc]

Friction V 6-cyl.
Friction in-line 4-cyl.
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**

**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**

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

**Livengood-Wu integral**

\[
\int_{t=0}^{t=t_c} \frac{1}{\tau} P T \; dt = 1
\]

P: pressure (kPa)
T: unburned gas temp. (K)
X_EGR: EGR ratio
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
The concept of 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**

@1500rpm

- TDC Temp. Δ75K, $\epsilon=13.0$
- $\epsilon=10.5$
- BGR 7.0%
- BGR 2.5%
- BGR 0.0%

**“EGR” at mid/high rpm & high load**

@4000rpm

- $\epsilon=13$
- $\epsilon=10.5$
- EGR 18%
- EGR18%
- EGR25%

The follow is 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
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.
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.
Dynamic Pressure Turbo (DPT) Scavenging Effect
3. SKYACTIV-G 2.5L TC development

Dynamic Pressure Turbo (DPT) effect at low/high engine rev.

New Turbo Charger System
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

Low rpm
High load

Pressure
High pulsation

Pressure
Low pressure
Low pulsation

Valve : Close

No Scavenging condition & enough EGR required

Mid/High rpm

Pressure

Valve : Open

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

- Improved in mechanical friction and pumping Loss by Down sizing, V6 to I4
- Improved by Cooled EGR
- Improved by Scavenging

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

**Torque Curve**

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.

**Acceleration Characteristic**

- Quick response to accelerate instantly
- Strong response to accelerate intensively
- Continuous Max. G force to accelerate aggressively
3. SKYACTIV-G 2.5L TC development

SKYACTIV-G 2.5L with DPT $\lambda=1$ window

SKYACTIV-G 2.5L with DPT achieved wider range of $\lambda=1$ 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

1. Mazda's approach for environmental improvement
2. SKYACTIV-G Development Process
3. SKYACTIV-G 2.5L TC development
4. End message
● **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