Mazda’s Approach for Developing Engines from a Perspective of Environmental Improvement

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Contents

- Improving thermal efficiency of ICEs
- Goal of SKYACTIV engines
- SKYACTIV engines: 1st step
- SKYACTIV engines: Next step
- Investigation results of boosted downsizing engines and future strategy for engine displacement
Fuel Economy Improvement = Loss reduction
All technologies for improving fuel economy must overcome these seven controlling factors.
Gasoline engine and diesel engine will look similar in the future.
• Improving thermal efficiency of ICEs

• Goal of SKYACTIV engines

• SKYACTIV engines: 1st step

• SKYACTIV engines: Next step

• Investigation results of boosted downsizing engines and future strategy for engine displacement
Specific CO2 emissions of electric power generation

Specific CO2 emission from electric power generation is assumed to be 0.5kg-CO2/kWh.
**Goal of SKYACTIV engines**

Fuel consumption reduction target for ICE powered vehicle in real world

Electric power consumption of C car in the real world: 21.2kWh/100km.
Fuel consumption of Mazda 2L C car in the real world: 5.2L/100km
Goal of SKYACTIV engines

Fuel consumption reduction target for ICE powered vehicle in real world

Average

Mazda3  2.0L = 5.2L/100km

Target; 4L/100km

4.2L/100km

4L/100km

3.8L/100km

3L/100km

21.2kwh/100km = C car in the real world

LCA considering just Li-ion Battery manufacturing 2 ton (minimum estimation ever found) CO2 for 20kWh battery

Lifetime mileage assumed 200,000km

Target for Mazda 3  5.2L/100km  →  4L (3.8L-4.2L)/100km

Around 25% fuel consumption reduction required
Real-world CO2 emissions (In Japan)

Evaluation condition: Weighted average of results of below 3 tests, considering Japanese ambient temperature distribution in a year

1. JC08 Hot  ambient temperature 25°C  air conditioner 25°C AUTO
2. JC08 Hot  ambient temperature 37°C  air conditioner 25°C AUTO
3. JC08 Cold  ambient temperature -7°C  air conditioner 25°C AUTO

Average energy consumption = JC08H 25°C — ((JC08H 25°C — JC08H 37°C) *0.2 + (JC08H 25°C — JC08C -7°C) *0.3)/4

Fuel economy of internal combustion engines needs to be reduced by approx. 26%((126-93)/126=0.26) to attain the EV-level CO2 emissions.
• Improving thermal efficiency of ICEs

• Goal of SKYACTIV engines

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The most distinctive feature of 1st step gasoline engine is world highest compression ratio.
**Full load Performance**

Improving low- and mid-end torque in spite of a high compression ratio and achieve superior driving.

**SKYACTIV engines: 1st step**
SKYACTIV engines: 1st step

Compression ratio vs. RON

Performance enhanced together with high compression ratio
SKYACTIV engines: 1st step

SKYACTIV-G surpasses competitors’ all new engines including 30% downsized engines in fuel efficiency.
SKYACTIV-G made a large improvement in performance over conventional engines.
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SKYACTIV engines: Next step

Roadmap to the goal of ICE

Gasoline engine and diesel engine will look similar in the future.
SKYACTIV engines: Next step

Walk of efficiency improvement

Light load: 2000rpm – IMEP290kPa

There is room for improving thermal efficiency in the light load range:
Approx. 30% for diesel engines  Approx. 40% for gasoline engines
It seems possible for ICEs to attain a 25% fuel economy improvement, which is the target to attain the EV-level CO2.
Hybridization requirement on electric device capacity

Regenerative energy just delivers 10-30% of vehicle driving energy

Motor drive using electricity generated by engine = Large battery and large motor required
When Mazda’s next-generation engines are hybridized, small-sized motor and battery are sufficient enough to power engines.
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Investigation results of boosted downsizing engines

Prediction of BSFC

At low load, 1L boosted engine with usual CR=10 shows better BSFC than 2.5L NA, but at mid. and high load, 2.5L engine shows much better BSFC than 1L boosted engine.
Investigation results of boosted downsizing engines

Mode fuel distribution map

Downsizing is favorable for NEDC-mode fuel economy
SKYACTIV engines are better than boosted downsizing engines in the real world fuel economy.
**Investigation results of boosted downsizing engines**

Comparison between 2L SKYACTIV and 1L and 1.4L boosted D/S

2L SKYACTIV engine can be superior to 1.4L boosted D/S engine with a cylinder deactivation system, and 1L 3 cylinder boosted D/S engine in all operational ranges.
Even 2.5L SKYACTIV engine can be superior to 1.4L 4-cylinder boosted D/S engine with a cylinder deactivation system, and 1L 3 cylinder boosted D/S engine in all operational ranges.
**Investigation results of boosted downsizing engines**

**Cost**

Base engine (Direct Injection) → Boosted D/S → SKYACTIV-G

- Turbocharger
- Intercooler & piping
- Strengthened piston, con-rod, crankshaft, block, head
- Electric VCT
- 4-2-1 exhaust

Boosted downsizing engines require extra expensive devices.
Future strategy for engine displacement

Target of lean burn

Excess air ratio vs. thermal efficiency

- Indicated thermal efficiency (%)
- Excess air ratio
- IMEP
  - 900kPa
  - 600kPa
  - 300kPa

2000rpm
CR = 14
Combustion duration = 35°

Expanding $\Lambda > 2.2$ is required for the compatibility of both efficiency and no NOX after-treatment
Future strategy for engine displacement

Lean burn capable area against displacement

Large Disp. NA can enlarge lean-burn area wider than boosted downsizing. Boosted Upsizing for wide lean-burn area is recommendable.
Examination of fuel economy
# Examination of fuel economy

## Average mileage/year

<table>
<thead>
<tr>
<th>Country</th>
<th>Mileage/year (km)</th>
<th>Vehicle age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>9,896</td>
<td>5.84</td>
</tr>
<tr>
<td>United States</td>
<td>18,870</td>
<td>8.30</td>
</tr>
<tr>
<td>England</td>
<td>14,720</td>
<td>6.20</td>
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<tr>
<td>Germany</td>
<td>12,600</td>
<td>6.75</td>
</tr>
<tr>
<td>France</td>
<td>14,100</td>
<td>7.50</td>
</tr>
</tbody>
</table>

Ref. report from investigative commission on clean diesel passenger car growth: future prospect  July 2008

Averaged mileage/year is somewhere between 10,000 and 15,000 km. (US excluded.)
### Real world fuel economy (US)

#### Midsized cars

<table>
<thead>
<tr>
<th>Fuel economy (mpg)</th>
<th>COMBI</th>
<th>CITY</th>
<th>HWY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong> Ford Fusion SE Hybrid</td>
<td>39</td>
<td>35</td>
<td>41</td>
</tr>
<tr>
<td><strong>2</strong> Toyota Camry Hybrid XLE</td>
<td>38</td>
<td>32</td>
<td>43</td>
</tr>
<tr>
<td><strong>3</strong> Volkswagen Passat TDI SE</td>
<td>37</td>
<td>26</td>
<td>51</td>
</tr>
<tr>
<td><strong>4</strong> Hyundai Sonata Hybrid</td>
<td>33</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td><strong>5</strong> Mazda6 Sport</td>
<td>32</td>
<td>22</td>
<td>44</td>
</tr>
<tr>
<td><strong>6</strong> Nissan Altima 2.5 S (4-cyl.)</td>
<td>31</td>
<td>21</td>
<td>44</td>
</tr>
<tr>
<td><strong>7</strong> Honda Accord LX (4-cyl.)</td>
<td>30</td>
<td>21</td>
<td>40</td>
</tr>
<tr>
<td><strong>8</strong> Chevrolet Malibu Eco</td>
<td>29</td>
<td>20</td>
<td>41</td>
</tr>
<tr>
<td><strong>9</strong> Toyota Camry LE (4-cyl.)</td>
<td>27</td>
<td>19</td>
<td>41</td>
</tr>
<tr>
<td><strong>10</strong> Hyundai Sonata GLS</td>
<td>27</td>
<td>18</td>
<td>39</td>
</tr>
<tr>
<td><strong>11</strong> Subaru Legacy 2.5i Premium</td>
<td>26</td>
<td>18</td>
<td>35</td>
</tr>
<tr>
<td><strong>12</strong> Chevrolet Malibu 1LT</td>
<td>26</td>
<td>17</td>
<td>38</td>
</tr>
<tr>
<td><strong>13</strong> Toyota Camry XLE (V6)</td>
<td>26</td>
<td>17</td>
<td>37</td>
</tr>
<tr>
<td><strong>14</strong> Honda Accord EX-L (V6)</td>
<td>26</td>
<td>16</td>
<td>39</td>
</tr>
</tbody>
</table>

#### COMPACT CARS Overall mpg = 29 or higher

<table>
<thead>
<tr>
<th>Fuel economy (mpg)</th>
<th>COMBI</th>
<th>CITY</th>
<th>HWY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong> Honda Civic Hybrid</td>
<td>40</td>
<td>28</td>
<td>50</td>
</tr>
<tr>
<td><strong>2</strong> Volkswagen Jetta Hybrid SE</td>
<td>37</td>
<td>29</td>
<td>45</td>
</tr>
<tr>
<td><strong>3</strong> Volkswagen Jetta TDI</td>
<td>34</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td><strong>4</strong> Mazda3 i Touring sedan</td>
<td>33</td>
<td>23</td>
<td>45</td>
</tr>
<tr>
<td><strong>5</strong> Chevrolet Cruze Turbo Diesel Mazda3 i Grand Touring hatchback</td>
<td>33</td>
<td>22</td>
<td>49</td>
</tr>
<tr>
<td><strong>6</strong> Toyota Corolla LE Plus</td>
<td>32</td>
<td>23</td>
<td>43</td>
</tr>
<tr>
<td><strong>7</strong> Ford Focus SE SFE</td>
<td>31</td>
<td>21</td>
<td>43</td>
</tr>
<tr>
<td><strong>9</strong> Volkswagen Jetta SE (1.8T)</td>
<td>30</td>
<td>21</td>
<td>39</td>
</tr>
<tr>
<td><strong>10</strong> Nissan Sentra SV</td>
<td>29</td>
<td>21</td>
<td>38</td>
</tr>
<tr>
<td><strong>11</strong> Honda Civic EX</td>
<td>29</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td><strong>12</strong> Hyundai Elantra GLS</td>
<td>29</td>
<td>20</td>
<td>39</td>
</tr>
<tr>
<td><strong>13</strong> Dodge Dart Rallye</td>
<td>29</td>
<td>19</td>
<td>41</td>
</tr>
</tbody>
</table>

**Fuel economy of HEV is superior, however,…**
Examination of fuel economy

Fuel cost / year
assuming 19,000km/year  gasoline price; 3.8$/gallon

- Mid size cars
  - 1400-1150 = 250$/year
- Compact cars
  - 1358-1121 = 237$/year

Average drive cannot payoff the price increase by HEV by superior fuel economy
Summary

- We created roadmaps toward the ideal ICE and are steadily advancing developments accordingly.
- We introduced the world’s highest compression ratio into the gasoline engines at the first step.
- We believe that our approach is more reasonable than the boosted downsizing approach from a perspective of real-world fuel economy and cost.
- We believe that hybrid-level fuel economy is achievable with just improving ICE technologies and that EV-level CO2 emissions is also achievable with improved ICE and simple hybrid technologies.
- We believe that the EV-level of well-to-wheel CO2 emissions is achievable with approx. 25% improvements from that of the current SKYACTIV. Once EVs have held a large share of the market, tremendous amount of electricity will have to be generated. As a result, EVs will be unable to obtain benefits from the current electric price due to the electric price increase.
- We regard large engine displacement as a cost free turbocharger, and plan to maximize its advantage and increase engine displacement.
- If expensive technologies which only improve fuel economy are offered to our customers, they cannot pay off high vehicle prices. Therefore, we continuously offer technologies together with additional values, such as driving pleasure.
Thank you for your attention!