A Study on the impact of Driving Trace Index (DTI) on fuel economy in Korea

26 Sep. 2019

KOTSA, The Republic of KOREA
(Korea Transportation Safety Authority)
1. Background

2. Definition of DTI (Driving Trace Index)

3. Information of Test equipment

4. DTI resulting from drive trace on F.E.

5. Conclusions
1. Background

**CO₂ gap between Lab vs. RDE**

**CO₂ Gap caused major factor**
- Vehicle mass / aerodynamics / rolling resistance
- Ambient temp. / road grade
- Additional EL. Aux (A/C excl.)
- A/C use / Traffic conditions

**CO₂ Gap Lev. (AVL, 2015)**
- Certification: 7.6 L/100 km
- RDE: 8.8 L/100 km (+16%)
- Worst condition: 12.6 L/100 km (+65%)

- +3.5%: Annual temp. variation
  - 15% @ 4°C (1.3%)
  - 50% @12°C (1.5%)
  - 25% @20°C (0.35%)
  - 10% @ 28°C (-0.25%)

- +2.2%: Real world aerodynamics & side winds

- +3.2%: 100 kg extra mass (occup. rate 1.5 & extra loads)

- +2.4%: Lower Energy Class (+1.7%)
- Maintenance (+0.2%)
- Winter tyre (+0.2%)
- Wet road (0.3%)

- +2.5%: 0.25% avg. grade

- +5%: A/C use

- +5%: Additional elec. consumers (A/C excl.)

- +5%: Additional EL. Aux.

- +5%: Road Grade

- ±15%: Traffic conditions

**Type approval = 100%**

**Need to establish a fuel economy criteria methodology for reducing Gap between CO₂ (fuel economy) certification and actual measurements**

<Source: Progress in Energy and Combustion Science, 2017>
1. Background

Driving cycle trace indices in WLTP (UNECE/WP.29/GRPE)

- **ASCR**
- **IWR**
- **RMSSE**

*Source: WLTP-11-21e, 2015*

- **IWR**: -2.0 ~ +4.0%
- **RMSSE**: 0.8 or 1.3 km/h less than sampling rate: 10 Hz

- **Possible criterion**

*Source: WLTP-11-22e, 2015*

- **Need to select indices and set criteria for Drive trace in line with international trends**
### 2. Definition of DTI (Driving Trace Index)

#### Driving quality evaluation (DQE) indices (SAE J2951)

<table>
<thead>
<tr>
<th>Index</th>
<th>Evaluation</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Rating (ER)</td>
<td>Change rate on the cycle energy</td>
<td>ER is defined as the percent difference between the total driven and target cycle energy.</td>
</tr>
<tr>
<td>Distance Rating (DR)</td>
<td>Change rate on the distance</td>
<td>DR is defined as the percent difference between the total driven and scheduled distance.</td>
</tr>
<tr>
<td>Energy Economy Rating (EER)</td>
<td>Change rate on the distance per energy</td>
<td>EER is defined as the percentage difference between the distance per unit cycle energy for the driven and target traces.</td>
</tr>
<tr>
<td>Absolute Speed Change Rating (ASCR)</td>
<td>Change rate on the integral of the absolute magnitude of acceleration</td>
<td>ASCR is defined as the percentage difference between the ASC for the driven and target traces.</td>
</tr>
<tr>
<td>Inertial Work Rating (IWR)</td>
<td>Change rate on the inertial work</td>
<td>IWR is defined as the percentage difference between the inertial work for the driven and target traces.</td>
</tr>
<tr>
<td>Root Mean Squared Speed Error (RMSSE)</td>
<td>Speed deviation</td>
<td>RMSSE provides the driver’s performance in meeting the schedule speed trace throughout the test cycle in terms of the Root Mean Squared Speed Error.</td>
</tr>
</tbody>
</table>

\[
ER = \frac{CE_D - CE_T}{CE_T} \times 100
\]

\[
CE_D = \sum_{i=1}^{n} \left( 1.015 \cdot ETW_i \cdot e_a + F_i + F_i V_i + F_i^2 V_i^2 \right) \cdot e_d
\]

\[
v_a = \frac{1}{2} \sqrt{\frac{2}{c_i} - 1} \cdot V_i
\]

\[
e_d = \frac{V_{a, t-1} - V_{a, t-1, d}}{0.2}
\]

\[
DR = \frac{D_D - D_T}{D_T} \times 100
\]

\[
D_D = \sum_{i=1}^{n} d_d
\]

\[
EER = \left[ 1 - \frac{DR}{100 + 1} \right] \cdot 100
\]

\[
ASCR = \frac{ASC_D - ASC_T}{ASC_T} \times 100
\]

\[
ASC_D = 0.1 \sum_{i=1}^{n} |a_d|
\]

\[
IWR = \frac{IW_D - IW_T}{IW_T} \times 100
\]

\[
IW_D = \sum_{i=1}^{n} |w_{D, i} - L_i|
\]

\[
W_{D, i} = F_{D, i} - F_i \cdot e_d = 1.015 \cdot ETW_i \cdot e_a \cdot V_i \cdot 0.1
\]

\[
RMSSE = 3.6 \sqrt{\frac{\sum_{i=1}^{n} (V_{D, i} - V_{T, i})^2}{N}}
\]
3. Information of Test equipment

◆ Fuel economy test modes: FTP-75 (city) + HWFET (highway) mode

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>FTP-75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (sec)</td>
<td>505</td>
<td>867</td>
<td>505</td>
<td>1877</td>
</tr>
<tr>
<td>Distance (km)</td>
<td>5.78</td>
<td>6.21</td>
<td>5.78</td>
<td>17.77</td>
</tr>
<tr>
<td>Avg. speed (km/h)</td>
<td>41.2</td>
<td>25.9</td>
<td>41.2</td>
<td>34.1</td>
</tr>
<tr>
<td>Max. speed (km/h)</td>
<td>91.2</td>
<td>55.2</td>
<td>91.2</td>
<td>91.2</td>
</tr>
<tr>
<td>Max. acceleration (m/s²)</td>
<td>1.48</td>
<td>1.48</td>
<td>1.48</td>
<td>1.48</td>
</tr>
<tr>
<td>Idle fraction (%)</td>
<td>19.6</td>
<td>18.4</td>
<td>19.6</td>
<td>19.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cycle</th>
<th>HWFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (sec)</td>
<td>765</td>
</tr>
<tr>
<td>Distance (km)</td>
<td>16.51</td>
</tr>
<tr>
<td>Avg. speed (km/h)</td>
<td>77.7</td>
</tr>
<tr>
<td>Max. speed (km/h)</td>
<td>96.4</td>
</tr>
<tr>
<td>Max. acceleration (m/s²)</td>
<td>1.43</td>
</tr>
<tr>
<td>Idle fraction (%)</td>
<td>0.7</td>
</tr>
</tbody>
</table>
4. DTI resulting from drive trace on F.E.

Fuel economy (FE) variation depending on drive trace method

- **Test conditions by Driving trace method(Base, Soft & Hard)**
  - Base, Soft & Hard condition test times: each 5 / 3 / 3
  - Speed tolerance range: Total of 5 separated by ±1 km/h & ±2 km/h
  - DQE index calculation: 10 Hz measurement data / ETW / Road load

<table>
<thead>
<tr>
<th>Test mode</th>
<th>Soft (2 kph)</th>
<th>Soft (1 kph)</th>
<th>Base</th>
<th>Hard (1 kph)</th>
<th>Hard (2 kph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP-75</td>
<td>5.2</td>
<td>4.0</td>
<td>0.0</td>
<td>-2.9</td>
<td>-5.9</td>
</tr>
<tr>
<td>HWFET</td>
<td>3.8</td>
<td>2.1</td>
<td>0.0</td>
<td>-1.6</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

Need to selection of the DQE indices and introduction of appropriate criteria

- **Evaluation of fuel economy change by Driving trace method(FTP-75)**
  - Soft & Hard (2 km/h) conditions relative to Base: Each 5.2% / 5.9% difference in average fuel economy (In both cases, fuel economy tolerances greater than ~5%)
  - The fuel economy effects of both Soft & Hard conditions are similar

- **Evaluation of fuel economy change by Driving trace method(HWFET)**
  - Soft & Hard (2 km/h) conditions relative to Base: Each 3.8% / 1.1% difference in average fuel economy (In both cases, fuel economy tolerances greater than ~5%)
  - This means that the fuel economy sensitivity is lower than that of FTP-75 according to the Driving trace method
  - Soft conditions also have a greater impact on fuel economy than Hard conditions
Analysis of DQE index and fuel economy depending on drive trace (FTP-75 mode)

FE change rate (%) depending on the DQE indices

2σ Error bar graph for avg. value of DQE index

Distinguishable according to the Driving trace methods
- DR: Base & Hard condition indistinguishable
- ER: Base & Soft condition indistinguishable
- RMSSE, IWR (ASCR), EER: Base & Soft or Hard condition distinguishable
Analysis of DQE index and fuel economy depending on drive trace (HWFET mode)

- DR: Base & Soft or Hard condition indistinguishable
- ER, EER: Base & Soft (1kph) condition indistinguishable
- RMSSE, IWR (ASCR): Base & Soft or Hard condition distinguishable

In HWFET mode, fuel economy sensitivity is reduced under hard conditions

FE change rate (%) depending on the DQE indices
### 4. DTI resulting from drive trace on F.E.

Each DQE index variation depending on drive trace method in **FTP-75 and HWFET modes**

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Index</th>
<th>RMSSE (km/h)</th>
<th>DR (%)</th>
<th>ER (%)</th>
<th>EER (%)</th>
<th>ASCR (%)</th>
<th>IWR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FTP-75</strong></td>
<td>Soft (2 kph)</td>
<td>1.85~1.99</td>
<td>1.59~1.88</td>
<td>-0.41~0.80</td>
<td>-2.01~1.07</td>
<td>-1.96~0.60</td>
<td>-0.86~0.39</td>
</tr>
<tr>
<td></td>
<td>Soft (1 kph)</td>
<td>1.55~1.62</td>
<td>1.14~1.22</td>
<td>0.21~0.62</td>
<td>-1.01~0.60</td>
<td>0.07~0.69</td>
<td>1.35~2.59</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>0.50~0.77</td>
<td>-1.10~0.28</td>
<td>-0.18~1.35</td>
<td>0.92~2.29</td>
<td>2.22~3.53</td>
<td>3.12~5.23</td>
</tr>
<tr>
<td></td>
<td>Hard (1 kph)</td>
<td>1.25~1.31</td>
<td>-1.12~0.81</td>
<td>1.88~3.21</td>
<td>2.95~3.89</td>
<td>4.64~6.16</td>
<td>7.34~9.68</td>
</tr>
<tr>
<td></td>
<td>Hard (2 kph)</td>
<td>1.55~1.90</td>
<td>-1.09~0.43</td>
<td>4.3~5.76</td>
<td>5.17~5.85</td>
<td>7.13~9.17</td>
<td>10.54~14.12</td>
</tr>
<tr>
<td><strong>HWFET</strong></td>
<td>Soft (2 kph)</td>
<td>0.98~1.13</td>
<td>0.02~0.44</td>
<td>-0.89~0.05</td>
<td>-0.99~0.48</td>
<td>-8.98~6.82</td>
<td>-10.82~7.62</td>
</tr>
<tr>
<td></td>
<td>Soft (1 kph)</td>
<td>0.80~0.89</td>
<td>0.05~0.14</td>
<td>-0.09~0.31</td>
<td>-0.24~0.27</td>
<td>-3.52~1.69</td>
<td>-3.70~2.01</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>0.37~0.49</td>
<td>-0.22~0.13</td>
<td>0.19~1.03</td>
<td>0.14~0.90</td>
<td>0.37~3.07</td>
<td>0.58~3.73</td>
</tr>
<tr>
<td></td>
<td>Hard (1 kph)</td>
<td>0.71~0.78</td>
<td>-0.06~0.06</td>
<td>2.89~3.20</td>
<td>2.82~3.17</td>
<td>12.76~13.59</td>
<td>15.37~15.93</td>
</tr>
<tr>
<td></td>
<td>Hard (2 kph)</td>
<td>0.65~0.72</td>
<td>-0.13~0.09</td>
<td>1.69~2.69</td>
<td>1.75~2.71</td>
<td>9.69~11.31</td>
<td>11.45~13.74</td>
</tr>
</tbody>
</table>
Estimation of DQE index criteria through statistical analysis

- Analyze DQE Indices statistics
  - Leverage a total of 77 Base driving data
  - Setting the 2σ probability distribution interval of normal and average values
  - FTP-75 mode: separated by phase

- RMSSE regular distribution analysis
  - In FTP-75 mode compared to HWFET, less dispersion and move to the right
  - In FTP-75 mode, the average value and dispersion are large in P1→ Consider this to be due to a delay in response performance due to non-heating
4. DTI resulting from drive trace on F.E.

Estimation of DQE index criteria through statistical analysis

- **IWR (ASCR) regular distribution analysis**
  - Less dispersion in FTP-75 mode compared to HWFET (Excellent normality in FTP-75 mode)
  - For FTP-75 mode, the mean value and dispersion → Judging by frequent acceleration and deceleration of P2 sections

- **Analyze DQE Indices statistics**
  - Leverage a total of 77 Base driving data
  - Setting the $2\sigma$ probability distribution interval of normal and average values
  - FTP-75 mode: separated by phase

**2$\sigma$-probability distribution segment & average value**
Estimation of DQE index criteria through statistical analysis

- **Analyze DQE Indices statistics**
  - Leverage a total of 77 Base driving data
  - Setting the $2\sigma$ probability distribution interval of normal and average values
  - FTP-75 mode: separated by phase

- **EER regular distribution analysis**
  - Less dispersion in HWFET mode compared to FTP-75 (Excellent normality in HWFET mode)
    - Reverses the regularity characteristics of IWR (ASCR)
  - For FTP-75 mode, the mean value and dispersion → Judging by frequent acceleration and deceleration of P2 sections

**4. DTI resulting from drive trace on F.E.**

MOLIT
Ministry of Land, Infrastructure and Transport

KOTSA
Korea Transportation Safety Authority
## 4. DTI resulting from drive trace on F.E.

### Results of statistical analysis and suggestions of the appropriate criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>RMSSE (km/h)</th>
<th>DR (%)</th>
<th>ER (%)</th>
<th>EER (%)</th>
<th>ASCR (%)</th>
<th>IWR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FTP-75</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal probability (2σ)</td>
<td>0.75</td>
<td>-0.52~0.44</td>
<td>-1.86~2.57</td>
<td>-1.56~2.33</td>
<td>-1.72~3.54</td>
<td>-3.09~5.36</td>
</tr>
<tr>
<td>(+) Estimated range</td>
<td>0.77~1.25</td>
<td>-0.28~1.14</td>
<td>1.35~1.88</td>
<td>2.29~2.95</td>
<td>3.53~4.64</td>
<td>5.23~7.34</td>
</tr>
<tr>
<td>Criteria proposal strict</td>
<td>0.75</td>
<td>-</td>
<td>-</td>
<td>0.92~2.29</td>
<td>2.22~3.53</td>
<td>3.12~5.23</td>
</tr>
<tr>
<td>Criteria proposal flexible</td>
<td>0.75</td>
<td>-</td>
<td>-</td>
<td>-0.60~2.33</td>
<td>0.69~3.54</td>
<td>2.59~5.36</td>
</tr>
<tr>
<td><strong>HWFET</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal probability (2σ)</td>
<td>0.73</td>
<td>-0.33~0.20</td>
<td>-1.28~1.33</td>
<td>-1.00~1.18</td>
<td>-3.88~9.11</td>
<td>-5.05~11.68</td>
</tr>
<tr>
<td>(+) Estimated range</td>
<td>0.46~0.65</td>
<td>-</td>
<td>1.03~1.69</td>
<td>0.90~1.75</td>
<td>3.07~9.69</td>
<td>3.73~11.45</td>
</tr>
<tr>
<td>Criteria proposal strict</td>
<td>0.46</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.37~3.07</td>
<td>0.58~3.73</td>
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<td>Criteria proposal flexible</td>
<td>0.65</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-1.69~9.11</td>
<td>-2.01~11.45</td>
</tr>
</tbody>
</table>
Analysis of correlation between IWR and ASCR

- **Leverage a total of 77 Base operating data**
- **When comparing determinant (R2) the correlation between the two Indexes is very large**
  - FTP-75 Mode (R2): 0.9826
  - HWFET Mode (R2): 0.9975
- **IWR provides a more quantitative driving quality scale compared to ASCR**
  - ASCR does not detect changes in driving path as it represents the degree of change in speed
  - IWR, on the other hand, takes into account the effects of inertia work expressed in engine power.

**Linear regression model for FTP-75 mode**

\[ y(x) = 0.6167635x + 0.2082124 \]
\[ R^2 = 0.9826 \]

**Linear regression model for HWFET mode**

\[ y(x) = 0.7750253x + 0.0452439 \]
\[ R^2 = 0.9975 \]
5. Conclusions

- Impact of driving quality evaluation (DQE) indices resulting from drive trace on fuel economy

- Driving quality evaluation (DQE) indices (ER, DR, EER, ASCR, IWR, RMSSE) depending on drive trace (soft, base, hard driving) in reference to SAE J2951 were evaluated and the impact of each index on fuel economy was analyzed

- HWFET mode is less sensitive to fuel economy variation depending on drive trace than FTP-75 mode in Soft or Hard driving condition when compared with Base driving

- The estimated range of DQE indices present between Base driving condition and Soft or Hard driving conditions is selected, and the area overlapping the 2σ-probability distribution segment of the population are approached from two different perspectives (strict and flexible) to propose a range of appropriate criteria

✓ When strict criteria are applied, in FTP-75 and HWFET modes respectively, RMSSE (km/h) is 0.75 and 0.46; ASCR (%) 2.22~3.53 and 0.37~3.07; IWR (%) 3.12~5.23 and 0.58~3.73; and EER (%) 0.92~2.29 in only FTP-75 mode

✓ When flexible criteria are applied, in FTP-75 and HWFET modes respectively, RMSSE (km/h) is 0.75 and 0.65; ASCR (%) 0.69~3.54 and -1.69~9.11; and IWR (%) 2.59~5.36 and -2.01~11.45

✓ IWR and ASCR were confirmed to have a close correlation to each other (R² ≥ 0.982), and it was suggested that IWR is more reliable than ASCR as quantitative DQE index

➢ The proposed criteria of each DQE index can be used for the amendment of domestic fuel economy regulation, and applied to reduce the gap between laboratory and real road by excluding the flexibility of the driver’s skill.
Thank you very much ! !

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