Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Lars Nielsen
Vehicular Systems, Linköping University
SVEA, May 20, 2015
Drive cycle research – two main questions

**Goal:** driving cycles as an **engineering tool** in vehicle design

EU Bulletin Transportation and Environment “In fact, NOx emissions have not seen a significant reduction in the last 13 years ... practice known as “cycle beating””

How to define similar but not the same (equivalence)?

How to use databases of driving data?
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

• Equivalence (similar but not the same)
• Computational formulation
• Database characterization by Markov process
• Two-step process to find representative driving cycles with proper excitation
Equivalence

• Similarity should be related to traction
• Mean Tractive Force (MTF) as defined by Guzzella and Sciaretta
• Using MTF components better related to traction
• Efficient algorithms
Equivalence

Mean Tractive Force (MTF) as defined by Guzzella and Sciaretta

• NEDC with marked traction mode regions where the powertrain needs to deliver positive power to the wheels.
Equivalence

\[ F(t) = F_{\text{air}} + F_{\text{roll}} + F_{\text{m}} \]

The tractive force at the wheels and its components

\[ F_{\text{air}} = \frac{1}{2} \rho_{\text{a}} c_{\text{d}} A_f v^2(t) \]

\[ F_{\text{roll}} = mg c_r \]

\[ F_{\text{m}} = ma(t) \]
Equivalence

Define MTF and characterizing parameters

\[ \bar{F}_{\text{trac}} = \frac{1}{x_{\text{tot}}} \int_{t \in \tau_{\text{trac}}} F(t)v(t) \, dt, \]

\[ \bar{F}_{\text{trac}} = \bar{F}_{\text{air}} + \bar{F}_{\text{roll}} + \bar{F}_{m} \]

\[ \bar{F}_{\text{air}} = \frac{1}{x_{\text{tot}}} \int_{t \in \tau_{\text{trac}}} \frac{1}{2} \rho_{a} c_{d} A_{f} v^{3}(t) \, dt = \frac{1}{2} \rho_{a} c_{d} A_{f} \alpha(v(t)) \]

\[ \bar{F}_{\text{roll}} = \frac{1}{x_{\text{tot}}} \int_{t \in \tau_{\text{trac}}} m g c_{r} v(t) \, dt = m g c_{r} \beta(v(t)) \]

\[ \bar{F}_{m} = \frac{1}{x_{\text{tot}}} \int_{t \in \tau_{\text{trac}}} m a(t)v(t) \, dt = m \gamma(v(t)) \]
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Picture of the engine test stand that has been used in the hardware-in-the-loop simulation.

Overview of the hardware-in-the-loop simulation in a forward simulation approach.

Experiments show that using the three MTF components is significantly better than just the total (MTF)
Equivalence

Definition of characterizing parameters \( \alpha, \beta, \gamma \)

\[
\alpha(v(t)) = \frac{F_{\text{air}}}{\frac{1}{2} \rho_a c_d A_f} = \frac{1}{x_{\text{tot}}} \int_{t \in \tau_{\text{trac}}} v^3(t) \, dt \\
\beta(v(t)) = \frac{F_{\text{roll}}}{mgc_r} = \frac{1}{x_{\text{tot}}} \int_{t \in \tau_{\text{trac}}} v(t) \, dt = \frac{x_{\text{trac}}}{x_{\text{tot}}} \\
\gamma(v(t)) = \frac{F_m}{m} = \frac{1}{x_{\text{tot}}} \int_{t \in \tau_{\text{trac}}} a(t)v(t) \, dt
\]
Equivalence

Define equivalence

\[ v_1(t) \sim v_2(t) \]

as equal characterizing parameters

\[ \alpha(v_1(t)) = \alpha(v_2(t)) \]
\[ \beta(v_1(t)) = \beta(v_2(t)) \]
\[ \gamma(v_1(t)) = \gamma(v_2(t)) \]

In general

- Add more equality constraints
  - e.g. equal average jerk
  - ...
- Add inequality constraints e.g.
  - Maximum speed
  - Maximum torque (speed dependent)
  - Maximum power (speed dependent)
  - ...
Equivalence

In general: for a vector, \( \theta \), of characterizing parameters fulfill equality constraints and inequality constraints

\[
\begin{align*}
h(v, \theta) &= 0 \\
g(v) &< 0
\end{align*}
\]

Additional possibility

Add criterion \( f(v) \), e.g. minimum total jerk

\[
\begin{align*}
\min f(v) \\
\text{subject to} \\
h(v, \theta) &= 0 \\
g(v) &< 0
\end{align*}
\]

Matlab fmincon 1-2 minutes
Equivalence

Incorporates interactivity

NEDC (dashed) with a NEDC equivalent version (solid) where a specified speed profile have been incorporated at \( t=[1072,1088] \).
Equivalence

NEDC (dashed) and its equivalent version to FTP75 (solid)

- The mean speed in the FTP75 is higher than in the NEDC, (34.1 vs 33.6 km/h)
- Nevertheless, to fulfill the constraints the vehicle speed need to be reduced during the traction regions, as can be seen in the figure
Equivalence

Summing up:

• Equivalence concept that captures similar but not the same, with similarity related to traction

• Hard-ware-in-the-loop experiments shows that using the three MTF components is significantly better than just the total (MTF)

• General methodology with surprisingly(?) efficient algorithms
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

- Equivalence (similar but not the same)
- Computational formulation
- **Database characterization by Markov process**
- Two-step process to find representative driving cycles with proper excitation
## Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Database from Volvo – 466 trips in west Sweden

<table>
<thead>
<tr>
<th>Category</th>
<th>Limits [km]</th>
<th>#Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>$0 &lt; x &lt; 14$</td>
<td>409</td>
</tr>
<tr>
<td>Medium</td>
<td>$14 &lt; x &lt; 32$</td>
<td>42</td>
</tr>
<tr>
<td>Long</td>
<td>$32 &lt; x$</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Limits [km/h]</th>
<th>#Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>$0 &lt; v &lt; 40$</td>
<td>328</td>
</tr>
<tr>
<td>Mixed</td>
<td>$40 &lt; v &lt; 72$</td>
<td>133</td>
</tr>
<tr>
<td>Highway</td>
<td>$72 &lt; v$</td>
<td>5</td>
</tr>
</tbody>
</table>
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Markov process as state machine

Markov process represented by state transition matrix

\[
\begin{array}{cc}
A & E \\
\hline
A & 0.6 & 0.4 \\
E & 0.7 & 0.3 \\
\end{array}
\]
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Generate Markov transition matrix from data

\[
\begin{align*}
AA: \frac{7}{7+6} &= 0.54; \quad AE: \frac{6}{7+6} &= 0.46
\end{align*}
\]
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Generate Markov transition matrix from the selected data in the database
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Generate representative driving cycle
- Use Markov matrix to generate candidate
- Correct in ensemble i.e. over many
- However, individual realization may be non-representative
- Thus, needs a selection to confirm
- Thresholds on wellness of fit
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Generate representative driving cycle

Left part of figure
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

• Equivalence (similar but not the same)
• Computational formulation
• Database characterization by Markov process
• Two-step process to find representative driving cycles with proper excitation
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Basic idea – combine Markov generation with equivalence transformation

Here the three MTF components in selection criterion
Minimum jerk is used in transformation step
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Should be retuned thanks to improved transformation
Now few minutes to few hours in left step, and minutes in right step.

Result is a representative driving cycle that is equivalent with desired excitation (at the wheels)
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

From the category Mixed in Volvo database

- a generated CDC (dashed) with similar MTF components as the NEDC (4%, 1%, 17%)
- and the transformed EqDC (solid) equivalent to NEDC.
Using Real-world Driving Databases to Generate Driving Cycles with Equivalence Properties

Summing up:

• Equivalence concept that captures similar but not the same, with similarity related to traction
• Computational formulation gives general methodology with efficient algorithms
• Effective use of databases
• Result is a representative driving cycle that is equivalent with desired excitation (at the wheels)
Model Based Engineering

Recent book (2014)

Explains model blocks
Models available on our web site