Chip Simulation for Virtual ECUs

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Virtual ECUs and Applications
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Contents

- **Background**
  - Concept of model based simulation environment
  - Engine simulation model
    - ECU model
    - Combustion model
    - Catalyst model
  - RDE simulation combined with vehicle simulation model
- **Summary**
2018 model new Civic

Fuel economy (CO₂) Modified NEDC
91 g/km (6MT, Sedan)
93 g/km (6MT, Hachback)
109 g/km (9AT)

1.6L diesel engine

Exhaust emissions
Euro6d-TEMP

Passed RDE regulation and achieved 91 g/km
## RDE definition

<table>
<thead>
<tr>
<th></th>
<th>Chassis dynamometer</th>
<th>RDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle speed profile</td>
<td>Fixed</td>
<td>Depends on vehicle, driver, route, and traffic</td>
</tr>
<tr>
<td>Environment (Ta, Pa)</td>
<td>Fixed</td>
<td>Depends on season, weather, wind, and altitude</td>
</tr>
<tr>
<td>Road load force</td>
<td>Straight, w/o gradient (w/o PEMS)</td>
<td>Depends on curves, altitude, road surface, passengers, and baggage (with PEMS)</td>
</tr>
<tr>
<td>Repeatability</td>
<td>with</td>
<td>w/o</td>
</tr>
</tbody>
</table>

**Difficulty to check RDE performance at all conditions during development**
## Method for calibration and validation

### Necessity of model utilization for efficient development

<table>
<thead>
<tr>
<th>Validation in real world</th>
<th>Easy to simulate and calibrate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tests on road</strong></td>
<td><strong>Chassis dynamometer (vehicle) + vehicle simulation</strong></td>
</tr>
<tr>
<td>PEWS</td>
<td><img src="image1" alt="Chassis dynamometer" /> <img src="image2" alt="Engine test bed" /> <img src="image3" alt="Model" /></td>
</tr>
</tbody>
</table>

Vehicle simulation: consideration of road load force change due to curves, altitude, and road surface (weather, wind)
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- Summary
Flowchart of model utilization

Vehicle simulation
(NEDC, WLTC, RDE) etc.

Engine simulation

Dynamic statistical combustion model

Vehicle model
Driver model
Route model
Traffic model

Vehicle test

Calibration target

Base maps, environmental corrections, controllers, aftertreatment control etc.

Simulation and optimization

Verification

Vehicle test

Coupling of vehicle simulation and engine simulation

Ne, Te, Gear, V, etc.

ECU model

Catalyst model

Synthetic gas flow test bed

Base maps, environmental corrections, controllers, aftertreatment control etc.

Calibration target
Engine simulation model

Combination of ECU, combustion, and catalyst models

Vehicle simulation

ECU model

Combustion model

(Combustion model
(Dynamic data based statistical model)

Catalyst model

(LNT physical model)

Inputs:
- Ne (Engine speed)
- Te (Brake torque)
- Main injection timing
- Fuel injection pressure
- VGT opening
- HP-EGR valve opening
- LP-EGR valve opening
- Intake throttle valve opening
- Intake shutter valve opening
- Tw (Coolant temperature)
- Ta (Ambient temperature)
- Pa (Ambient temperature)
- Combustion mode signal

Outputs:
- Emissions, temperatures, etc. including sensor values fed back to the ECU model

Vehicle simulation Inputs:
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Vehicle simulation Outputs:
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Vehicle simulation

ECU model

Combustion model

Catalyst model

Combination of ECU, combustion, and catalyst models

Combustion model (Dynamic data based statistical model)
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Chip simulation for virtualize an ECU

Control logic part (Reuse possible)
- Control specification
- Scheduler
- Variables setting
- MAP file
- HEX for ECU

Driver part (CAN, AD, etc.)
- Driver file
- MAP file
- Variables setting
- HEX for ECU

Virtual ECU (Chip simulation)
- MATLAB/Simulink
- S-function spec.
- Driver file
- HEX
- Variables setting
- MAP file
- Control specification
- Scheduler

Real ECU
- Control logic part (Reuse possible)
- Driver part (Reuse impossible)
- Virtual ECU (Chip simulation)
- Simulation based on HEX without control model and C code

Simulation based on HEX without control model and C code
## Combustion modeling approach

<table>
<thead>
<tr>
<th>Physical model (0D-3D)</th>
<th>Statistical model (Empirical model, DoE model)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Use case:</strong> concept study, advanced research</td>
<td><strong>Use case:</strong> calibration, validation</td>
</tr>
</tbody>
</table>

### Comparative Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Physical Model</th>
<th>Statistical Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Necessity of parameters tuning based on measurement data</td>
<td>Necessity of engine hardware and training data</td>
<td></td>
</tr>
<tr>
<td>Higher number of adjustment parameters</td>
<td>Higher number of adjustment parameters</td>
<td></td>
</tr>
<tr>
<td>High predictive accuracy even at model extrapolation region</td>
<td>High predictive accuracy at model interpolation region</td>
<td></td>
</tr>
<tr>
<td>High dimension -&gt; low calculation speed</td>
<td>High calculation speed</td>
<td></td>
</tr>
<tr>
<td>Suitable for engine hardware development and phenomenological analysis</td>
<td>Suitable for model based engine calibration (optimization)</td>
<td></td>
</tr>
</tbody>
</table>

Statistical model is suitable for efficient calibration at later stage of development.
Advantage of dynamic DoE model

- Steady state DoE model
  - Steady state prediction
  - Model fitting based on averaged measurement data

- Dynamic DoE model
  - Transient prediction including time lag of measurement apparatus
  - Model fitting based on recorder measurement data
Dynamic DoE for combustion model

Space filling methodology for the Gaussian Process Modeling (GPM)
Model structure for learning time dependent behavior:
Regression model with additional inputs and outputs from past time steps

Reference:
T. Huber, M. Hanselmann, and T. Kurse: Use of Data Based Models to Predict Any RDE Cycles - Challenges, Experiences and Results, 8th Emission Control Conference, Dresden (2016)
Predictive accuracy of engine model

Achievement of quantitative emissions prediction at RDE
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**RDE-compliant virtual engine calibration**

- **Requirement**
  - Regulation change
  - Vehicle simulation
  - ECU modeling

- **Allocate req. to function**
  - Virtual engine calibration
  - Virtual prototype validation

- **Engine emission simulation**

- **Verification**
  - Powertrain dynamic test bed

- **Validation**
  - Vehicle

**Utilization of virtual calibration and validation**
Vehicle simulation for RDE route

Generation of vehicle speed by vehicle, driver, route, and traffic models
Model based RDE performance evaluation

Vehicle, driver, route, and traffic models
- Vehicle simulation
Vehicle speed, engine speed, brake torque, and gear shift position
- Engine simulation
NOx, Soot, CO₂ etc.

Vehicle, driver, route, and traffic models
- Vehicle simulation
Vehicle speed, engine speed, brake torque, and gear shift position
- Engine simulation
NOx, Soot, CO₂ etc.

Achievement of emission prediction with vehicle and engine simulation
Evaluation of emission robustness

Validity confirmation of hardware selection and calibration data settings

Total (Urban+Rural+Motorway)

Simulation

NOx tailpipe emissions (g/km)

Frequency distribution (*)

Total (Urban+Rural+Motorway)

Urban

6MT

9AT

6MT

20
Summary

It is a challenge to sufficiently validate RDE performance under all conditions through road tests during vehicle development due to wide range of validating conditions.

A model based development technology was established to simulate, verify and calibrate the emissions performance of a vehicle.

RDE performance could be accurately predicted by coupling a vehicle driving simulation with an engine simulation that includes an ECU model, combustion model (dynamic data based statistical model), and exhaust aftertreatment catalyst model.

Use of the simulation model enabled robust validation of RDE performance under various conditions that assume driving on actual roads.

Thank you very much for your kind attention.