Vehicle Energy Management (VEM) methodology for energy management evaluations

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Contents

• Introduction

• Vehicle Energy Management (VEM) methodology

• Gasoline application

• Diesel application

• Conclusions
A new challenge for next years

Not only CO₂ emissions…

Penalties will reach 95 € per g/km

EU target ➔ full transport de-carbonization by 2050

… but also pollutants.
A new challenge for next years

A new development path urges...

- Innovative concepts and devices
- New strategies
- Powertrain and Vehicle integration
- Transient / Cycles operation
- Hybrid/Electric concepts

Source: ERTRAC – Future ICE Light and Heavy Duty Powertrain Technologies – 2016
ERTRAC is the European Road Transport Research Advisory Council
A new challenge for next years

Virtual Analysis is time & cost saving vs experimental tests

**1st way:** co-simulation
- Time saving: allow the use of existing models
- Tool-diversity saving: models and Depts. competences
- Co-simulation issues
- High licenses cost

**2nd way:** main-tool simulation
- Engine models in GT-SUITE
- Low licenses cost (all libraries included in GT-SUITE license)
- Co-simulation allowed
- Time requested to convert previous existing models

**Scope:** create a dynamic virtual test bench of the entire vehicle system to support scenarios evaluation.

FCA is presenting a “2nd way” experience by using GT-SUITE
Contents

- Introduction

- **Vehicle Energy Management (VEM) methodology**
  - Gasoline application
  - Diesel application
- Conclusions
Vehicle Energy Management (VEM) methodology definition

VEM model

Inputs
- Vehicle mission
- Engine and other systems control strategies

Outputs
- Engine operation and thermal behavior
- Engine systems operation
- Vehicle response

Main features:
- Dynamic engine model (performance + thermal)
- Powertrain coolant and lubricant circuits
- Vehicle and driveline

For each part:
- Operational outputs
- Temperatures
- Flow rates
- Pressures
- Energy balances

VEM as a virtual dynamic test bench for energy flow analysis and optimization in an integrated powertrain/vehicle system

* not yet implemented
** for AT only
Contents

- Introduction
- Vehicle Energy Management (VEM) methodology
- Gasoline application
- Diesel application
- Conclusions
Gasoline application: VEM model status and validation

- Current gasoline model

The model has been developed thanks to a close synergy between PWT and Vehicle Depts. in CRF.

- Validation over NEDC

The model has been developed thanks to a close synergy between PWT and Vehicle Depts. in CRF.
Gasoline application: Engine Fast Running Model

Engine performance Fast Running Model (FRM)
Large effort put on this subsystem to build a stable and well-validated engine FRM to simulate fuel map

GT-SUITE detailed model
Detailed model:
full load engine model
correlation through experimental data

Features:
- best accuracy in results
- best flow dynamics representation
- high CPU time

GT-SUITE FRM model
Complete FRM model:
Full and partial load engine model generation with a step-by-step volumes/discretization reduction (err: ±5% vs detailed model) and DOEs

Features:
- slightly less accurate results
- flow dynamics saved but worse accuracy
- reduced CPU time 8-12 times

Engine BSFC map
Mean FRM accuracy vs Exp. ± 2% (detailed mod. ± 1%)

Key points
• Predictive combustion.
• MultiAir lifts optimization.
• Predictive heat exchange.
• Dedicate idle point calibration.
Gasoline application: Engine Thermal-Structural model

Engine Thermal-Structural

Core subsystem to be built in order to determine correct and predictive heat exchange to coolant/oil and structure

Model contribution to boundaries generation for CHT analyses
Gasoline application: Coolant circuits model

HT and LT coolant circuits

- High and Low Temperature coolant circuit model build-up from CAD model by mean of GEM3D tool
- The heat exchangers (all predictive) identified using the available datasheets
- Coolant flow rate on single branches calibrated using the FCA official test bench measurements

Relative error between the simulation and the measurement

<table>
<thead>
<tr>
<th>Engine speed (rpm)</th>
<th>1000</th>
<th>1500</th>
<th>2500</th>
<th>3500</th>
<th>4500</th>
<th>5500</th>
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<tbody>
<tr>
<td>Open Thermostat</td>
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<tr>
<td>Oil cooler/Cabin heater</td>
<td>-0.07</td>
<td>-0.05</td>
<td>-0.05</td>
<td>-0.05</td>
<td>-0.04</td>
<td>-0.03</td>
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<tr>
<td>Tank</td>
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<td>-0.06</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.05</td>
<td>-0.08</td>
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<tr>
<td>Turbocharger</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Closed Thermostat</td>
<td></td>
<td></td>
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<tr>
<td>Oil cooler/Cabin heater</td>
<td>-0.07</td>
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<td>-0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Radiator</td>
<td>0.00</td>
<td>-0.04</td>
<td>0.01</td>
<td>0.00</td>
<td>-0.01</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

Results: ± 2% coolant flow rate mean error (model vs exp flow)
Gasoline application: Oil circuit and Underhood models

Oil circuit & Underhood

Oil circuit

- Simplified oil circuit
- Total volume respected and predictive oil cooler characteristic from test bench.

Underhood

- Simplified underhood for engine vane temperature and heat exchange.
- System modeled by using GT-SUITE 1D-Airflow, calibrated with 3D-CFD instead of COOL3D.
Gasoline application: Driveline and Vehicle models

Transmission, Vehicle & Driver

Key idea
Integrating a complete driveline with driver approach included and an engine Fast Running Model

Criticalities faced
- Idle control (residual torque management)
- Dynamic integration (flywheel and components inertia)
- Engine dynamic control (throttle, wastegate, spark advance)
- Driver optimization

Results:
- Real experimental tests conditions, through Driver model.
- Engine adapting/predictive behavior thanks to FRM instead of map
1st use example: coolant thermal management on NEDC

**Vehicle Energy Management (VEM) methodology for energy management evaluations**

VEM model results fit with good approximation the experimental tests

**Faster coolant warm-up in the best strategies**

![Controlled Coolant Valve](image1.png)

![Enthalpy Storage Tank](image2.png)

**Coolant temperature [°C]**

- VEM baseline
- VEM - CCV
- VEM - Enthalpy storage

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**Average Temperature, Part Thermostat**

**Temperature [°C]**

**Time [s]**
2\textsuperscript{nd} use example: oil thermal management on NEDC (1/2)

Scope: to evaluate some innovative concepts to accelerate oil warm-up, increasing FE by reducing frictions.

- **Oil by-pass in the oil cooler**

  Positive effect of the oil cooler on oil warm-up acceleration.
Heat addition to oil – sensitivity study

Temperature [°C]

Possible heat sources
- Enthalpy Storage Tank (EST)
- Heat recovery
- Electric resistance

Estimation of Enthalpy Storage Tank volume

Possible EST installation issues

<table>
<thead>
<tr>
<th>EST volume [% of current total oil volume]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
</tr>
<tr>
<td>P2</td>
</tr>
<tr>
<td>P3</td>
</tr>
</tbody>
</table>

Total energy needed, from heat-to-oil and warm-up time
Case study: replace mechanical coolant pump with an electrically driven one.
Application: electrified powertrain (e.g.: BSG or HEV).

VEM results over NEDC

In this specific case the sole replacement of the mechanical pump does not result in appreciable FE improvement.

An electrical pump should be used to optimize engine warm-up through appropriate control strategies.
Contents

• Introduction
• Vehicle Energy Management (VEM) methodology
• Gasoline application
• **Diesel application**
• Conclusions
FCA V6 3.0 L Diesel - Engine Overview

ENGINE HIGHLIGHTS

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL DISPLACEMENT</td>
<td>2987 cm³</td>
</tr>
<tr>
<td>CONFIGURATION</td>
<td>V6 - 60°</td>
</tr>
<tr>
<td>MAX TORQUE</td>
<td>600 Nm @ 1800 rpm</td>
</tr>
<tr>
<td>MAX POWER</td>
<td>200 kW @ 4000 rpm</td>
</tr>
<tr>
<td>INJECTION SYSTEM</td>
<td>Solenoid – 2000 bar</td>
</tr>
<tr>
<td>TURBOCHARGER</td>
<td>Single VGT</td>
</tr>
<tr>
<td>EGR SYSTEM</td>
<td>LP and HP circuit</td>
</tr>
</tbody>
</table>
Diesel application: VEM model status and validation

Main Features

- Model generated through the integration of pre-existing submodels
- Information between subsystems exchanged via thermal and mechanical connections
- Good correlation with experimental data for temperatures and fuel consumption
- Vehicle part is missing due to lack of data.
Diesel application: Engine Fast Running Model

Main Features

- Full and partial load calibration on experimental data and measurements
- PID controllers integrated in ECU (Injection, Boost, EGR, VSA…)
- Advanced friction modeling: $\text{FMEP} = f(\text{Toil})$ → Engine warm-up effect on fuel consumption
- Original engine model simplified to reduce runtime
Diesel application: Coolant circuit and Radiator

Main Features
- Model built from CAD 3D geometry
- Implicit solver → Reduced runtime
- Model calibrated on data from coolant circuits testbench (Flow rate ±5%)
- Heat exchangers, pump and thermostat physics modeled → Warm-up prediction
- Experimental characterizations for pressure drop and heat rejection
Diesel application: Oil circuit

Main Features

- Model built from CAD 3D geometry
- Mean value bearing maps (Crankshaft, Conrods, Camshafts)
- Implicit solver → Reduced runtime
- Experimental data available for model calibration (Pressure ±0.1 bar)
- Pump absorption dependent on oil temperature
- Heat exchange with coolant, engine block and crankcase environment
Main Features

- Model built from CAD 3D geometry
- Thermal masses involved in engine warm-up
- Fluid-to-solid and solid-to-solid heat transfer calibrated on CHT calculations and experimental measurements
- All surfaces belonging to engine block and head have thermal connections with fluids and/or solids
Driving cycles simulation - Overview

Key Points

- Engine integrated model requires some inputs from the testbench (Engine speed/load, ECU maps)
- ATS light-off temperature defines the switch between different ECU calibrations (EGR split, injection strategy…)
- WLTC cycle still to be implemented, work in progress…

<table>
<thead>
<tr>
<th>CYCLE</th>
<th>ENGINE SPEED</th>
<th>OPERATING POINTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEDC</td>
<td>![Graph]</td>
<td>![Graph]</td>
</tr>
<tr>
<td>FTP</td>
<td>![Graph]</td>
<td>![Graph]</td>
</tr>
<tr>
<td>HIGHWAY</td>
<td>![Graph]</td>
<td>![Graph]</td>
</tr>
<tr>
<td>WLTC</td>
<td>![Graph]</td>
<td>![Graph]</td>
</tr>
</tbody>
</table>
Driving cycles simulation - ECU and model controls

**Main Features**
- Engine speed measured at testbench is imposed in the model → Model running in Speed Mode.
- Brake torque is set as target for the injection PID controller.
- The switch between Engine Operating Modes (EOM) is defined by temperature at SCR Inlet.
- Strategies and maps dependent on EOMs (EGR split, injection, boost...) need to be implemented in GT-Power model.

**ECU Controls**
- Torque
- Injection / Combustion
- EGR (HP and LP)
- Boost (VGT Rack)
- Backpressure Throttle
- VSA (Swirl Flaps)
- TVA
- EGR Cooler bypass

**Torque Control**
- Torque TGT (Dyno)
- Torque ACT (GT)
- Controller Output

**Temperature @ SCR Inlet**
- EOM 1
- EOM 2
- EOM 3
- EOM 4

**EGR Split – HP/LP**
- HP-EGR Rate
- LP-EGR Rate
Sensitivity evaluation of thermal management devices on NEDC

**SWITCHABLE WATER PUMP (SWP)**

Pump flow is shut-off by means of a **throttle valve** placed on pump outlet. A small coolant leakage is allowed (quasi-zero flow).

**Coolant Temperature**

**Fuel Consumption**

Total FC reduction in NEDC cycle = **0.6%**

**VARIABLE DISPLACEMENT OIL PUMP (VDOP)**

A PID-controlled valve sets pump displacement in order to control oil pressure inside main gallery. Different control maps can be implemented.

**Oil Pump Torque**

**Fuel Consumption**

Total FC reduction in NEDC cycle = **0.2%**

**OIL COOLER BYPASS**

At low oil temperature the cooler is bypassed, reducing pump power absorption from the crankshaft, while oil flow rate at main and conrod bearings is increased.

**Oil Temperature**

**Oil Pump Torque**

Total FC reduction in NEDC cycle ~ **0%**
Resuming diesel experience

• An integrated model for FCA V6 3.0 L Diesel engine has been set up in GT-SUITE environment.

• The model includes 4 sub-models, each one calibrated on experimental data:
  - Engine performance
  - Cooling system (cooling circuit + radiator)
  - Oil circuit
  - Engine thermal-structural

• The model is currently used to simulate different driving cycles, both European and American, in order to predict engine warm-up and total fuel consumption.

• Some thermal management devices have been tested by means of engine integrated model, showing interesting results in terms of fuel economy.
Contents

• Introduction
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• Gasoline application
• Diesel application
• Conclusions
**VEM outlook in next years**

**VEM as a virtual dynamic test bench** for energy flow analysis and optimization in an integrated powertrain/vehicle system

<table>
<thead>
<tr>
<th>Field</th>
<th>Capability</th>
<th>Application potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powertrain</td>
<td>• Fluid-dynamics and thermal analysis</td>
<td>• Engine thermal behavior evaluations</td>
</tr>
<tr>
<td></td>
<td>• Lubrication circuit analysis</td>
<td>• Powertrain auxiliaries analysis</td>
</tr>
<tr>
<td></td>
<td>• Auxiliary load simulation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Driveline/Transmissions</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>• Heat exchangers and new layouts evaluation/sizing</td>
<td>• Engine encapsulation</td>
</tr>
<tr>
<td>management</td>
<td>• Powertrain thermal management</td>
<td>• Coolant/oil heat storage</td>
</tr>
<tr>
<td></td>
<td>• Circuits pressure drop analysis</td>
<td>• New circuit layouts and components</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pumps evaluation</td>
</tr>
<tr>
<td>Controls</td>
<td>• Engine strategies</td>
<td>• Catalyst light off, Stop&amp;Start, cut-off</td>
</tr>
<tr>
<td></td>
<td>• New vehicle systems operation solutions</td>
<td>• EGR management</td>
</tr>
<tr>
<td>Vehicle</td>
<td>• Sensitivity studies (weight, loads, aerodynamic)</td>
<td>• Low circuit and WCAC evaluations</td>
</tr>
<tr>
<td></td>
<td>• Aerothermal devices</td>
<td>• ATB, cool-down, HVAC, AGS</td>
</tr>
<tr>
<td>Benchmarking</td>
<td>• Engine benchmarking</td>
<td>• Split-cooling</td>
</tr>
<tr>
<td></td>
<td>• Concepts evaluation</td>
<td>• Different cooling layouts evaluation</td>
</tr>
<tr>
<td></td>
<td>• Vehicle benchmarking</td>
<td></td>
</tr>
</tbody>
</table>

**Open points**
- CPU time vs accuracy
- Gasoline model stability
- Diesel predictive combustion
- Simil-ECU controls
- Hot and cold frictions
- VVT modelling

**Future possible integrations**
- Emissions by ATS model
- HVAC model
- Hybrid systems
- RDE cycles
Acknowledgments

Thank you for the attention

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