Emerging Powertrain Technologies and Future Challenges & Opportunities for Simulation

Prof. Federico MILLO - Politecnico di Torino

European GT-Conference 2019
Steigenberger Airport Hotel – Frankfurt am Main, DE
October 7 – 8, 2019
Introduction

CALL FOR SIMULATION

- CO₂ targets set by EC will be reduced from 95 g/km in 2020 down to 59 g/km in 2030
  - Unprecedented rate of improvement of ICEs efficiency will be needed, as well as unprecedented rate of deployment of powertrain electrification

- For pollutant emissions, Euro 6d will be fully enforced in 2020, with RDE (Real Driving Emissions) Conformity Factors of 1
  - Virtual RDE Conformity Factors assessment
Introduction

CALL FOR SIMULATION

- Reduction of **time to market**

- **Integration of simulation in the V-cycle workflow**

  ![V-cycle workflow diagram](image)

  Source: Syed Wahiduzzaman: Meeting Future Emissions Challenges Using System, 2018

- **Investigation of different concepts in short terms**

- **Physical models** to cover technological breakthroughs

- DoE and extensive exploitation of **optimization algorithms**

Source: Frederic Ravet: Crucial needs for efficient simulations in automotive industry, 2019
INTEGRATED VEHICLE MODEL

Nowadays Simulation
Nowadays Simulation

INTEGRATED VEHICLE MODEL

OPPORTUNITIES
• REAL DRIVING EMISSIONS
• FULL VEHICLE VALIDATION

COMPUTATIONAL POWER
• INTEGRATED VEHICLE SIMULATION

Source: Syed Wahiduzzaman: Meeting Future Emissions Challenges Using System, 2018

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07-10-2019
Internal Combustion Engine

INTEGRATED VEHICLE MODEL

INTERNAL COMBUSTION ENGINE

- Efficiency enhancement
- Combustion & Emissions models
Internal Combustion Engine

**INTEGRATED VEHICLE MODEL**

**INTERNAL COMBUSTION ENGINE**

- Efficiency enhancement
- Combustion & Emissions models

**VIRTUAL CALIBRATION**

- **Multi-model** and **Multi-Core** simulations
- Development of physical models of automotive powertrains
- Setup of a suitable HiL system with FPGA processing unit
Virtual Calibration

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**Trade-off**

**BSFC - CN**

**Pressure**

**Injection rate**

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**Trade-off**

**BSFC - BSNOx**

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**Internal Combustion Engine**

**INTEGRATED VEHICLE MODEL**

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**INTERNAL COMBUSTION ENGINE**

- Efficiency enhancement
- Combustion & Emissions models

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**ASSESSMENT OF CO\textsubscript{2} REDUCTION TECHNOLOGIES**

<table>
<thead>
<tr>
<th>Technology</th>
<th>FC / CO\textsubscript{2} Benefit</th>
</tr>
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<tbody>
<tr>
<td>Direct Injection</td>
<td>1.5%</td>
</tr>
<tr>
<td>c-EGR</td>
<td>2 – 5%</td>
</tr>
<tr>
<td>High CR (Atkinson cycle, c-EGR, DI, VVT)</td>
<td>10 – 14% (\textsuperscript{1})</td>
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<tr>
<td>Miller cycle (Turbocharged Atk., c-EGR)</td>
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<td>Dyn. cylinder deactivation (+ VVL)</td>
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<td>10%</td>
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<tr>
<td>Water Injection</td>
<td>5 – 7%</td>
</tr>
<tr>
<td>Lean-burn gasoline</td>
<td>10 – 20%</td>
</tr>
<tr>
<td>HCCI w/ spark assist</td>
<td>20 – 30% (\textsuperscript{4})</td>
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Source: Johnson, T., Joshi, A. “Powertrain Alternatives to Low-Carbon Transportation”, ANFIA and SAE Torino 2018

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Water Injection Technology

- High latent heat of vaporization
- Lower charge temperature at spark timing
- **Performance** increase
  - less retarded spark timing
- **Fuel economy** improvement
  - higher compression ratio
  - mixture enrichment reduction
**Water Injection Technology**

**Experimental activity**
- Port water injection system (low engine architecture impact)
- Higher compression ratio

**CFD-3D model**
- Optimization of water spray targeting and location
- Model calibration and validation

**CFD-0D/1D model**
- Predictive combustion model
- Knock model calibration as a function of W/F ratio

**CFD-0D/1D VEHICLE model**
- Assessment of BSFC benefits over driving cycles
- Assessment of water consumption
Water Injection Technology

- Experimental activity
  - Port water injection on low engine architecture
  - Higher compression ratio

- CFD-3D model
  - Optimization of water spray targeting and location
  - Model calibration and validation

- Imposed CCV

- Knock Mitigation Strategy
  - Water Injection
    - Water Consumption
  - Spark Retard
    - Efficiency penalty

- Water Injection Technology

- Knock Mitigation Techniques for highly boosted downsized SI engines”, 2017 SIA Powertrain Conference

- CFD-0D/1D VEHICLE model
  - Assessment of BSFC benefits over driving cycles
  - Assessment of water consumption

- SITurb

- KNOCK MODEL

Evaluate knock occurrence probability during transients

Mimic ECU Knock Control Strategy in GT
Larger flame area leads to a faster burn rate and higher cylinder pressure.

Internal Combustion Engine

**INTEGRATED VEHICLE MODEL**

### INTERNAL COMBUSTION ENGINE

- Efficiency enhancement
- Combustion & Emissions models

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*Source: Johnson, T., Joshi, A. “Powertrain Alternatives to Low-Carbon Transportation”, ANFIA and SAE Torino 2018*
Turbulent Jet Ignition

TECHNOLOGY OVERVIEW

Pre-chamber TJI system includes:

- Small pre-chamber (1-5% of main combustion chamber)
- Multiple-orifice nozzle connecting pre-chamber to main chamber
- 2 injectors
  - 1 injector (DI or PFI) to fuel the main chamber ($\lambda >> 1$)
  - 1 injector (DI) to fuel the ignition chamber ($\lambda = 1$)

Pre-chamber turbulent jet ignition enables ultra-lean operations ($\lambda \approx 2.0$) of SI engines with:

- Stable combustion process
- High Brake Thermal Efficiency
- Low NOx emissions

Ultra-lean engine operations yield to:

- Lower mean combustion temperature
- Knock mitigation
- In-cylinder heat losses reduction
- Pumping work reduction through de-throttling effect

TECHNOLOGY BENEFITS

CHALLENGES AND OPPORTUNITIES

- Explore the effects of the pre-chamber geometry design in terms of volume, nozzle and hole geometrical characteristics
- Development of models to phenomenologically describe mixture preparation, turbulence evolution, flame area enhancement, burn rate development

Source: Benjamin Hibberd: "Path to EU7 – MAHLE MJI". Engine Expo Europe, Stuttgart 2019
INTERNAL VEHICLE MODEL

EXHAUST AFTERTREATMENT SYSTEM

- Urea dosing
- Heating strategies
- Hardware sensitivity
Challenges and opportunities

- To **develop** flexible and **robust simulation tools** for characterizing complex aftertreatment systems
- To **optimize** such **architectures** while minimizing costs and time-to-market
1. Catalysts samples extraction and experimental campaign

2. Model development and calibration using evolutionary algorithms

3. Model upscaling and validation over engine data (driving cycles)

EXHAUST AFTERTREATMENT MODELING

Main Applications
- Sensitivity analyses (PGM loading, catalyst dimensions, …)
- Development of control strategies
- Exhaust line architecture optimization
- Virtual test bench

1D CFD Aftertreatment Models
- Optimal Accuracy/CPU tradeoff
- Relatively easy to calibrate
- High flexibility

Main Applications
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Electrification

INTEGRATED VEHICLE MODEL

ELECTRIFICATION

- Hybrid topologies
- Electric auxiliaries
- eDrive

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<td>Start-stop</td>
<td>2 – 5%</td>
</tr>
<tr>
<td>Mild (48V, other)</td>
<td>10 – 20%</td>
</tr>
<tr>
<td>Full</td>
<td>25 – 30%</td>
</tr>
<tr>
<td>Plug-in</td>
<td>65 – 75%</td>
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Source: Johnson, T., Joshi, A. "Powertrain Alternatives to Low-Carbon Transportation", ANFIA and SAE Torino 2018

Source: Els, P. "48V Issues and Prospects, unlocking the opportunities", Autelligence, 2017
Electrification

**INTEGRATED VEHICLE MODEL**

**ELECTRIFICATION**

- Hybrid topologies
- Electric auxiliaries
- eDrive

**ENERGY MANAGEMENT STRATEGIES**

- Global vs Instant optimization
- Multi-objective minimization (NOx, CO₂, noise, …)
**Vehicle Model:**
- Developed in Matlab
- It relies on a kinematic approach
- It is based on a backward methodology
- 0D black box model of both engine and electric machines

**Mission Profiles**
- Choosing a distance of about 70 km as optimization horizon, more than 90% of daily trips travelled in Europe is taken into account.

**Target:**
Minimization of the Overall CO₂ emissions of the vehicle

\[ f = \frac{\mu CO_2}{\mu_{fuel}} \int_0^T m_f(t, u(t)) \; dt + \frac{1}{\eta_{chg} \cdot \eta_{grid}} \cdot CIE \cdot \Delta SOC \cdot E_{batt} \]

**Dynamic Programming Optimization**
Based on the Bellman optimality principle, it is able to define the best strategy which minimizes the defined performance index.

**Electrification**

Since it requires the a-priori knowledge of the mission profile cannot be implemented in a real ECU, but it allows evaluating an upper bound to fuel economy potential of a hybrid vehicle.

Comprensive vehicle model for the control **calibration** and **validation** of the energy management strategy of a **P0 BSG 48 V Mild Hybrid system**

Source: Zanelli, A., Millo, F., et al., "Comprehensive 48 V diesel mild hybrid vehicle model for energy management control system calibration and validation," European GT Conference, 2018
Electrification

INTEGRATED ENERGY MANAGEMENT STRATEGY

Integration of the electric auxiliaries power in the Energy Management Strategy

- Performance improvement and CO₂ reduction:
  - eSupercharger
  - eTurbocharger

- Pollutant emission reduction:
  - eCatalyst
  - eSupercharger

- Thermal Management and CO₂ reduction:
  - eWater Pump
Electrification

INTEGRATED VEHICLE MODEL

ELECTRIFICATION

- Hybrid topologies
- Electric auxiliaries
- eDrive

COMPONENTS SIZING

- Powertrain architecture
- Internal combustion engine
- Battery pack
- Electric motor / generator
- Energy management system

ENERGY MANAGEMENT STRATEGIES

- Global vs Instant optimization
- Multi-objective minimization (NOx, CO₂, noise, …)
Electrification

COMPONENT SIZING

- ICE
- Battery
- EMG
- Transmission
- 

Powertrain Architecture

- Series
- Parallel
- Power-split

Design Strategy

- Government
- OEM
- Consumer

Dynamic Programming

Powertrain Software

ECMS
MPC
Rule-based
Electrification

COMPONENT SIZING
**Genetic Algorithm approach**

- **Initial Population**
- **Fitness**
- **Selection**
- **Crossover**
- **Mutation**
- **New Population**
- **Fitness operators:**
  - transform the cost function value into a measure of relative fitness.
  - In this case, proportional fitness assignment was used.

**GA operators:**
- **Selection:** determining the number of offspring;
- **Crossover:** producing new individuals from their parental genes;
- **Mutation:** randomly applied with low probability, modifying elements in the chromosomes.

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Long Term Perspectives

WHAT’S NEXT?

• Smart mobility
• Connected and Automated Vehicles
• Distance based optimization
What’s Next?

SMART MOBILITY

- Interactive Signage
- Smart Lighting
- Connected and Automated Vehicles
- Smart Traffic Lights
- 5G Network
- Environmentally Friendly
What’s Next?

V2X INFORMATION

Vehicle-To-Infrastructure

V2I + V2V = V2X

Vehicle-To-Everything

Vehicle-To-Vehicle

Source: Rizzoni, G., 8th IFAC symposium on AAC, June 2016

Trip Data from GPS

Source: Rizzoni, G., 8th IFAC symposium on AAC, June 2016
What’s Next?

V2X FOCUS

Exploiting V2X Connections

Enhance the Fuel Economy of Hybrid Electric Vehicles (HEVs)

How?

V2V & V2X sensors provide surrounding environment and look-ahead information

Design of an Energy Management System (EMS) capable of a synergic coupling between global optimization strategies and Connected and Automated Vehicles (CAV) information

www.dcaiti.tu-berlin.de/research/simulation/
Time Based Optimization

State Variables: \[ x = [SOC(t)] \]

Control Variables: \[ u = \begin{bmatrix} T_{eng}(t) \\ T_{EM}(t) \end{bmatrix} \]
What’s Next?

DISTANCE BASED OPTIMIZATION

Distance Based Optimization

State Variables:

\[ x = \begin{bmatrix} V_{veh}(s) \\ SOC(s) \end{bmatrix} \]

Control Variables:

\[ u = \begin{bmatrix} T_{eng}(s) \\ T_{EM}(s) \end{bmatrix} \]
What’s Next?

DISTANCE BASED OPTIMIZATION

EMS tasks:
- Route Optimization
- Powersplit Optimization
- Speed Profile Optimization
- CO₂ Minimization

Implementation of the EMS on a virtual test rig developed in GT-SUITE environment

Source: G. Rizzi et al., 2017 IEEE Conference on Control Technology and Applications (CCTA)
Conclusions

**CO₂ emission targets and Real Driving Emissions** will be the main drivers in the next future

A significant growth of **powertrain** variety and complexity is expected

Development of **new technologies** with an unprecedented pace is requested

**Virtualization is the key!**

Source: Morey, B. "Powertrain to 2030, trends and risks", Autelligence, 2019
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➢ Mr. Giuseppe DI PIERRO
➢ Mr. Alessandro TANSINI

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