Simulation Assists Vehicle and Powertrain Optimization and Component Selection

Thomas Morel
Gamma Technologies

SAE 2011 Electronic Systems for Vehicle Propulsion Symposium
November 8-9, 2011, Troy, MI
Focus on Efficiency

• The trend for Vehicles and Powertrains is an increasing focus on energy efficiency

• Contributions towards improved energy efficiency are sought to come from many directions, often including electronic systems

• The engineers’ ingenuity is on display, when one surveys the ever-increasing number of innovative solutions, each of which offers some degree of efficiency improvement
Energy Efficiency Opportunities

• Among the most important contributors of efficiency benefits are expected to be:
  – engine combustion
  – electrification (hybrids, EVs, other components)
  – transmissions (MT, DCT, AT, CVT)

• Important contributions also offered by many other devices and components of the vehicle system:
  – boosting, thermal management, VVA, cam-phasers, CAC and EGR cooling, start-stop, pumps, fans, ….

• In fact almost all parts of a vehicle are now being scrutinized and re-considered in innovative ways
Electronic Systems Lead the Way

• Most of the new innovations are enabled by the expanding power of electronic systems

• It is the electronic control that gives rise to many new possibilities, and the ensuing myriad of combinations

• These are of course good news in general, but…
Electronic Systems Lead the Way

• Most of the new innovations are enabled by the expanding power of electronic systems

• It is the electronic control that gives rise to many new possibilities, and the ensuing myriad of combinations

• These are of course good news in general, but…

The fact is that the plethora of available building blocks and their combinations has created a very significant challenge for designers of vehicle systems
Electronic Systems Lead the Way

• It has become more and more difficult to examine all of these combinations and properly design and optimize them for maximum benefit

• The well established existing test approach is too costly and time consuming

• The previous simulation methods are too narrow and limited (they do not include important subsystems and include too few interactions)

• And are increasingly seen as no longer sufficient

• A new approach is needed and is on the way
Integrated System Analysis

- Vehicle system has many components:

- To assess and maximize the benefits of the new technologies, the industry is today turning to a comprehensive integrated analysis, which takes into consideration the entire system.
Integrated Analysis: Benefits

- Eases collaboration between departments and disciplines
- Eliminates labor and inaccuracy of transfer of boundary conditions
- Essential for transient system analysis (driving cycles, extreme maneuvers, warm-up, control response)
- Comprehensive system analysis is also well suited for the selection of specific components
Accounts for two-way interactions between subsystems

For example the engine supplies boundary conditions to most of the subsystems, and receives back fueling, thermal inputs for the CAC and friction, torques, etc.
Building an Integrated Model I

- The general idea of building an integrated model is based on the principle of parallel simulation of subsystems -- connecting models of various subsystems and have them interchange computed quantities (torque, speed, heat, etc...) at every time step

- Since the different subsystems are most often the responsibility of separate departments (which often use separate CAE tools), the first approach logically focuses on co-simulation of these tools

- This requires a linkage software (e.g. Simulink or others) or a socket communication
While co-simulation is the expeditious method, not requiring any tool change in the cooperating departments, it also has a lot of limitations (not all quantities are available for data transfer, problems in version synchronization, speed of calculation, difficult collaboration).

These limitations can be greatly reduced by departments agreeing to use a common system where possible, and use co-simulation only where necessary.
Examples of New Methodology

• Models combine some or all of the following:

Always:
– vehicle
– engine
– Transmission

Frequently also VTM:
– coolant circuit
– CAC + EGR coolers
– underhood module

Increasingly added:
– HVAC
– oil + other cooling circuits
– aftertreatment
– hybrid/EV components
– electrical systems
– hydraulics
– fuel injection
Examples of New Methodology

• Models combine some or all of the following:
  
  **Always:**
  – vehicle
  – engine
  – Transmission

  **Increasingly added:**
  – HVAC
  – oil + other cooling circuits
  – aftertreatment

  **Frequently also VTM:**
  – coolant circuit
  – CAC + EGR coolers
  – underhood module
  – hybrid/EV components
  – electrical systems
  – hydraulics
  – fuel injection

• Examples of what can be accomplished by large scale integrated modeling will be shown demonstrated on a single computational platform GT-SUITE  
(However, the examples could also be structured with parts of the system co-simulated by other software tools)
Fairly typical application is comparing two engine design alternatives for example here:

- Baseline engine
- Same engine with cylinder deactivation
  - Effect on warmup and fuel efficiency
  - Evaluated over FTP cycle

Includes:
- Vehicle, engine, cooling passages and cooling circuit, control
- Completely integrated and solved together
Integrated System Model

2.2L 4-Cylinder SI Engine with Cylinder Deactivation

- Shows integration of GT-POWER, COOL, and DRIVE
- The integrated model follows the Highway Fuel Economy Test FTP driving cycle after a 30 second engine warm-up
- Pump speed controlled to maintain a 2 K temperature increase across the engine
- Fan speed controlled to maintain an engine inlet coolant temperature of 365 K
- Cylinder deactivation from 4-cylinders to 2-cylinders
- Cylinder deactivation logic involves the following:
  1. Fuel cutoff to cylinders 2 and 3
  2. Intake and exhaust valves are closed for cylinders 2 and 3
- Deactivation occurs when the following criteria are met:
  1. BMEP is \(\geq 15\%\) of maximum load (4-cylinders), and
  2. Vehicle speed is \(\geq 60\) kph
- Reactivation occurs when either of the following criteria are met:
  1. BMEP is \(\geq 75\%\) of maximum load (2 cylinders), or
  2. Vehicle speed is \(\leq 40\) kph
Engine Model

To Transmission

Intake

Exhaust
Vehicle Model

From Engine
Driver Module

- Clutch
- Brake
- Accelerator
- Gearshift

Idle Control
Driveaway
Detail: Control Elements
Cylinder Head/Block Cooling

FE Model of Cylinder Structure

Head

Block

Pump
Coolant Heat Transfer Rate, per Cylinder

Base case:
all cylinders have about the same heat to coolant, small differences cyl-to-cyl

Deactivation:
Active cylinders run hotter than in the base case, while the two deactivated cylinders get heated only when producing work.
Heat Transfer Rates From Engine and Radiator

Difference:
With deactivation there is less overall heat transfer.
Warm-Up of Baseline Engine

After 40 sec
Cycle at ~40 sec
Base Model

After 200 sec
Cycle at ~200 sec
Base Model

After 500 sec
Cycle at ~500 sec
Base Model
Warm-Up of Engine with Cylinder Deactivation

After 40 sec

After 200 sec

After 500 sec
Pump/Fan Power

Difference:
Less pump and fan power required
## Summary Output: Fuel Economy

<table>
<thead>
<tr>
<th>Highway FTP Cycle</th>
<th>Base Model</th>
<th>Cylinder Deactivation</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Economy [mpg]</td>
<td>33.09</td>
<td>36.76</td>
<td>11.12</td>
</tr>
</tbody>
</table>
Effects of Environment and of Cooling System Components

- Again: Vehicle, engine, cooling passages and cooling circuit, control
- Add: Underhood Cooling Module, containing:
  - EGR cooler - water cooled
  - A/C condenser heat load imposed
  - Radiator, fan
  - UHM discretized into 12 x 9 grid
  - 0.1 sec time step

- FTP-72 Driving Cycle
- Calculation speed: 4.5 x RealTime
Underhood Cooling Module

- Underhood components modeled within a 3-D graphical environment
Heat Exchangers meshed automatically
• Air Space meshed into a 3-D set of volumes
Module Inserted into a Full System Model

Fast-running Engine Model
Module Inserted into a Full System Model

Fast-running Engine Model

Drop in and connect
Effect of Environment: High Altitude

Comparison of the effect of high altitude (2700 m) compared to the baseline. It shows the evolution of the coolant temperature entering the block (left) and the thermostat lift (right).
Component Selection: Electrically Driven Fan and Pump

Improved engine cooling by use of electrically powered fan and coolant pump, coupled with their electronic control, showing the fan power (left) and the coolant temperature entering the block (right).
Reducing the volume of the coolant speeds up the response of the system and its warm-up.
Example 3: Transient Drive Cycle SC03

Government fuel economy standards now include driving cycles with A/C on.

EPA SC03 Supplemental Federal Test Procedure (SFTP) with Air Conditioning
Motivation for A/C Modeling

A/C is significant power consumer
Motivation for A/C Modeling

A/C is significant power consumer
Add: **A/C System:**

- R134a
- Single evaporator system
- High-side receiver/dryer
- TXV set to maintain 7°C superheat

**Vehicle/Engine Highlights:**

- Front wheel drive passenger car
- Manual transmission
- 3.5 L 4-cylinder turbo diesel engine
Example: Transient Drive Cycle SC03

Mean Value Engine

A/C System

Vehicle and Driver following SC03 Cycle
A/C System Subassembly
Evaporator Subassembly

Air In

Refrig In

Evaporator-capact-1

Evaporation Pipe_1

Refrig Out

Evaporation Pipe_2

Air Out, to Cabin
Evaporator HX Subassembly

Air In

Refrig In

Air Out

Refrig Out

(10 x 2 Rows)
Results for SC03 Driving Cycle

Vehicle Speed

Engine Speed

Compressor Massflow

Compressor Power
Results for SC03 Driving Cycle

Condenser Sub-cooling

Evaporator Super-heat

Cooling Capacity

Average Gas Mileage
Summary and Outlook

• Vehicle systems have become too complex to design by merely assembling sub-systems and by subsequent test iterations.

• Tools are now available to allow designers to achieve the optimum results from combination of the best available components and technologies by upfront simulation.
Summary and Outlook

- The industry has taken a note and all OEMs are now focusing on implementation of methods for vehicle system analysis which includes as its basis: **engine, vehicle and thermal management**, optionally complemented by other sub-systems.

- Surveying the trends of the industry one can safely predict a rapid growth of large-scale simulations of vehicle systems coupled with multivariate optimization.

- The models used will be increasingly detailed to allow **optimized system matching, selection of specific components** and **control development**.