

Multi Attribute Optimization: Fuel Consumption, Emissions and Driveability

Kazuhiko Gotoh
Toyota Motor Corporation

Jerome Ceppi and Nicolas Sabatier
LMS Imagine

Yukisada Tsuchida
LMS Japan

ABSTRACT

In making our products more attractive, it is becoming increasingly important to balance multiple areas of performance, such as fuel economy, emissions and drivability. Customer expectations and government legislations, to protect global environment, strongly increase the work complexity of auto firms in order to release high quality and eco-friendly vehicles. The balancing between several target is becoming a key factor in the car design:

- respect current (and anticipate future) emission limits
- optimization of fuel consumption
- insure high level of drivability
- maintain acceptable(or increase) performances
- sustain acceptable cost, reliability, etc.

From recent emissions limitations, engine cold start (at the beginning of driving cycle) plays a major role in the total amount of pollutants. Especially, achievements of HC limitations are a big challenge for vehicles with a conventional spark ignition engine. Several options are studied by auto firms such as (but not limited):

- down-sizing
- additional technologies on injection systems (for example direct injections)
- additional technologies on post-treatment systems (for example secondary air injection or HC/NOx trap, etc.)
- additional technologies on the engine actuators and geometries (for example Variable Valve Timing, Variable Valve Actuation, Variable Valve Lift, variable compression ratio, variable tumble systems, etc.)
- additional technologies on the air path systems (for example overcharging, low pressure EGR loop, etc.)

These options need to be evaluated from auto firms with respect to the final cost, development time, complexity, reliability, etc... For this kind of compromise, system simulation physical model based becomes helpful. This paper describes about the development of a multi attribute full vehicle model and a new approach to find the best compromise between performance, fuel consumption and emissions.

CITATION: Gotoh, K., Ceppi, J., Sabatier, N. and Tsuchida, Y., "Multi Attribute Optimization: Fuel Consumption, Emissions and Driveability," *SAE Int. J. Passeng. Cars - Mech. Syst.* 5(1):2012, doi:10.4271/2012-01-0946.

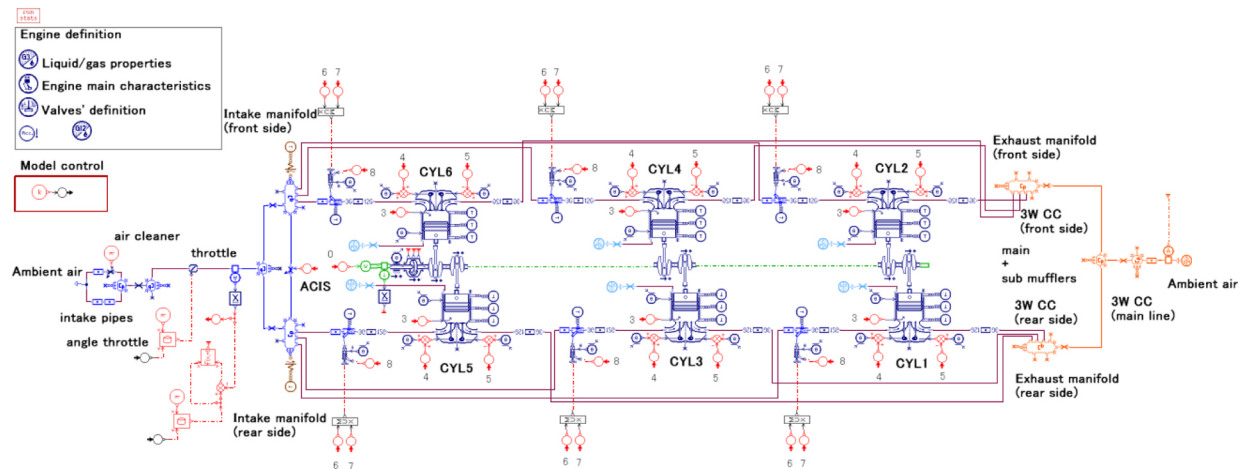


Figure 1. V6 Engine high frequency model

INTRODUCTION

In this context of multi attribute optimization, where compromises have to be defined in order to achieve adequate performance, fuel consumption, emissions, drivability, reliability, etc., system simulation based on physical models becomes more and more important. In order to develop a multi attribute full vehicle model, We have decided to use a multi physic simulation platform with industrial development and support, i.e. LMS Imagine.Lab AMESim. This 1D software is supported by LMS Engineering Services in order to follow auto firms and their suppliers in making studies with this software. LMS Imagine.Lab AMESim is a state of the art software developed with several partnerships such as IFP Energies nouvelles for the engine related subjects.

In this multi physic platform, several levels of modeling are available for most of the components. For example, we will see in this paper that the engine could be simulated with a high frequency model (i.e. crank angle based) for some purpose, with a mean value engine model or a map based for other purpose. System simulation consists in choosing the required level of detail depending on the topics. For example, we will see below that high frequency engine model has been used to estimate cylinder pressure, torque and emissions in details and also for drivability study. On the other hand, a mean value engine has been used when simulating NEDC cycles for cumulative emissions and fuel consumption.

The following topics are covered within this paper manuscript:

- high frequency model
- drivability model
- sensitivity analysis
- driving cycle analysis

HIGH FREQUENCY MODEL

In this part we will show a high frequency model of V6 engine that has been built in LMS Imagine.Lab AMESim

with the IFP Energies nouvelles engine library (see Figure 1). Simulation results and correlation with engine testing are shown for both performance (cylinder pressure, torque) and emissions.

The combustion model based on the latest developments of CFM (Coherent Flame Model, see Ref. 15) has proved to give very good results with a high degree of predictivity.

The calibration of the model is done on only one operating point (700 rpm; Air/Fuel 12.5; Spark Advance 20°) with closed valves (i.e. during combustion). If we look at cylinder pressure (see Figure 2), the high frequency model achieves pretty good correlation. Red curve is from simulation and green measured on the test bench for all Figures below.

Then, the predictivity is analyzed for different spark advance and different Air Fuel Ratio without any fine tuning, see Figure 3 & 4.

In terms of emissions, the Figure 5 presents the results at 700rpm with A/F of 14.5 during a spark advance sweep. Points are measurement data with an error bar of $\pm 25\%$, solid lines represent the AMESim results with the latest CFM combustion model. NO_x, CO and CO₂ tendencies could be reproduced by the model. HC sensitivity (vs. Spark Advance) could not be reproduced even if the level is correct. If we look results at constant SA of 23°CA (see Figure 6), the AFR effect is correctly predicted by the model including the HC with the latest CFM combustion model.

During engine control unit calibration done at the test bench, several sweeps of spark advance and air fuel ratios are done in order to find the optimum values in terms of torque, fuel consumption and emissions. Even after calibrating only one point on the model, precision and predictivity were sufficient to predict the optimum calibration zone (A/F and SA). Meaning this kind of high frequency model could reduce the calibration time at engine test bench, greatly reducing cost and saving precious time. We will see below that the model can also predict auto-ignition in the higher engine speed and load area. Our methodology was to fine

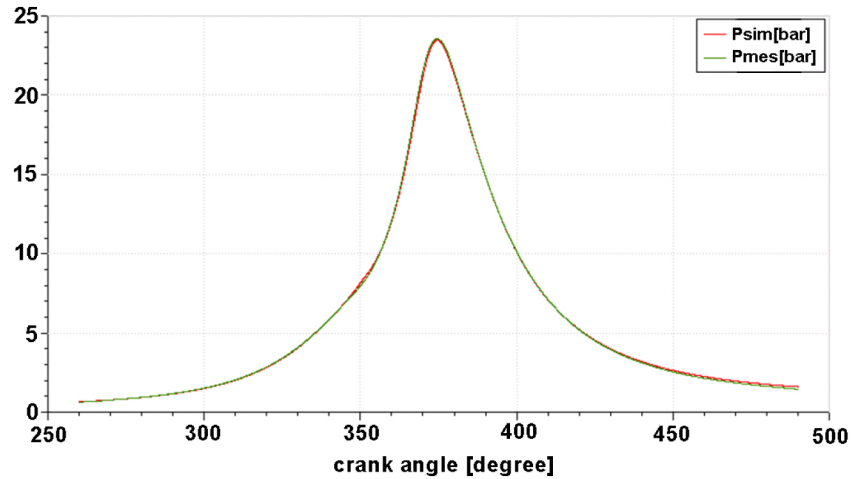


Figure 2. Cylinder pressure trace @ 700rpm; A/F 12.5; 20° SA

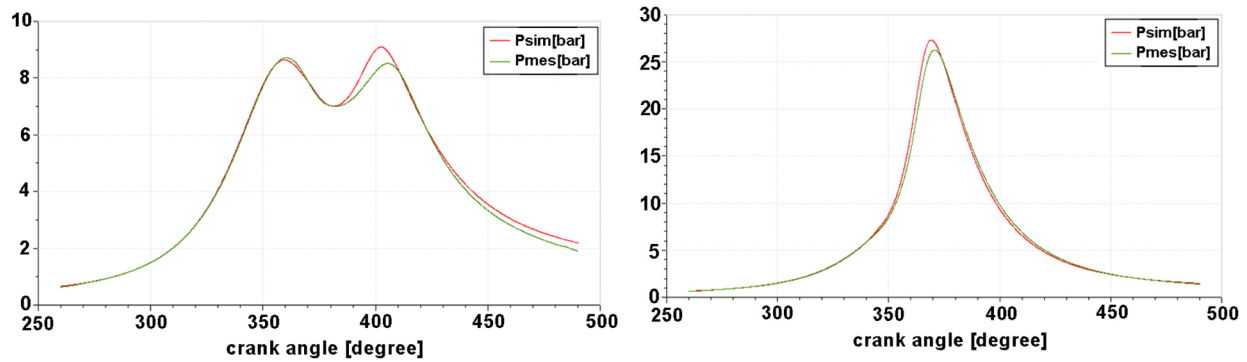


Figure 3. Cylinder pressure trace @ 700rpm; A/F 12.5; -2° & 25° SA

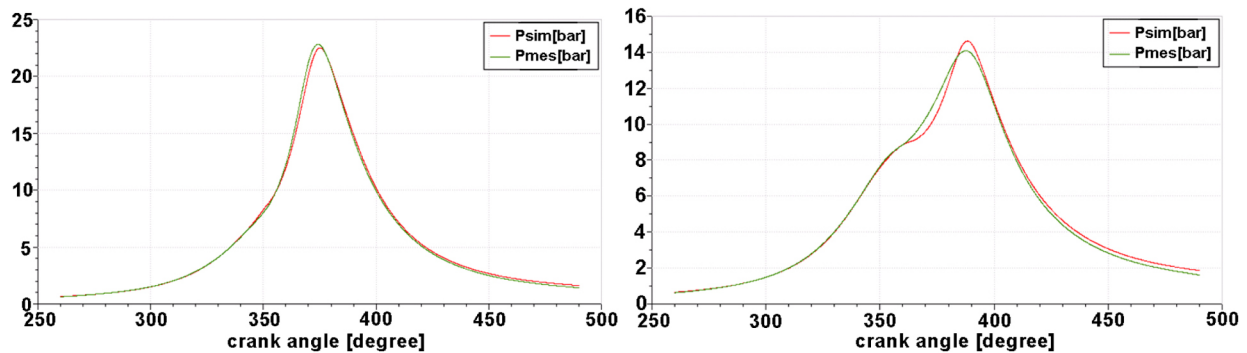


Figure 4. Cylinder pressure trace @700rpm; A/F 14.5; 21° SA and A/F 10.5; 11° SA

tune the CFM combustion model on several points in order to be fully representative of the full engine range (engine speed & load). We focused our work on the following points:

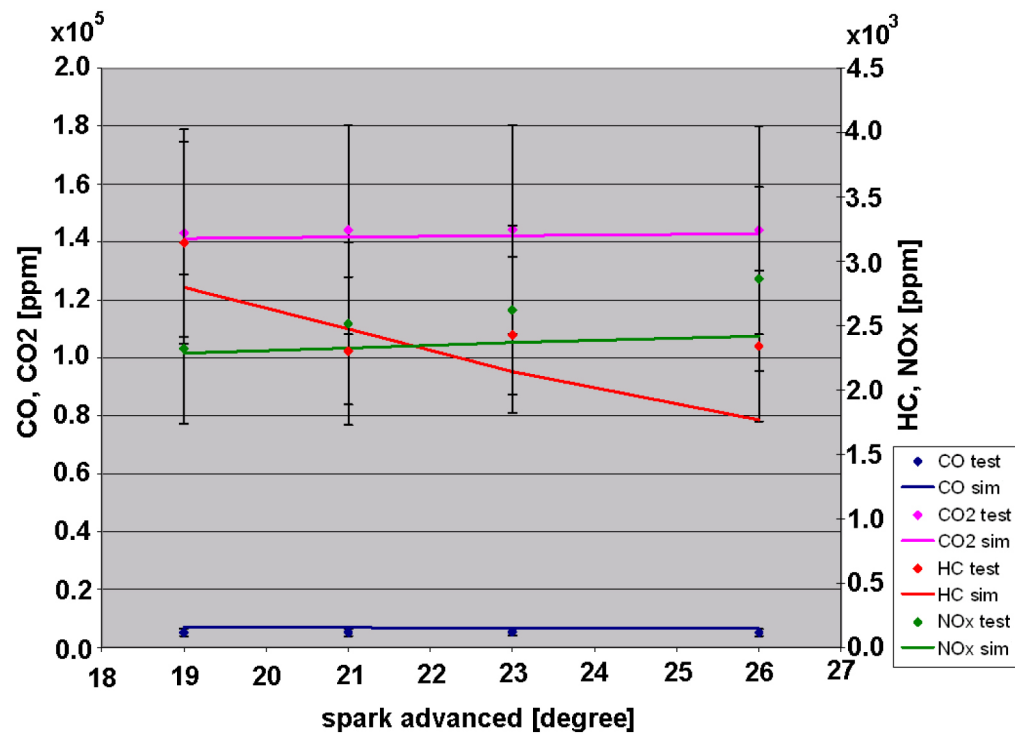


Figure 5. Emissions @700rpm; A/F 14.5

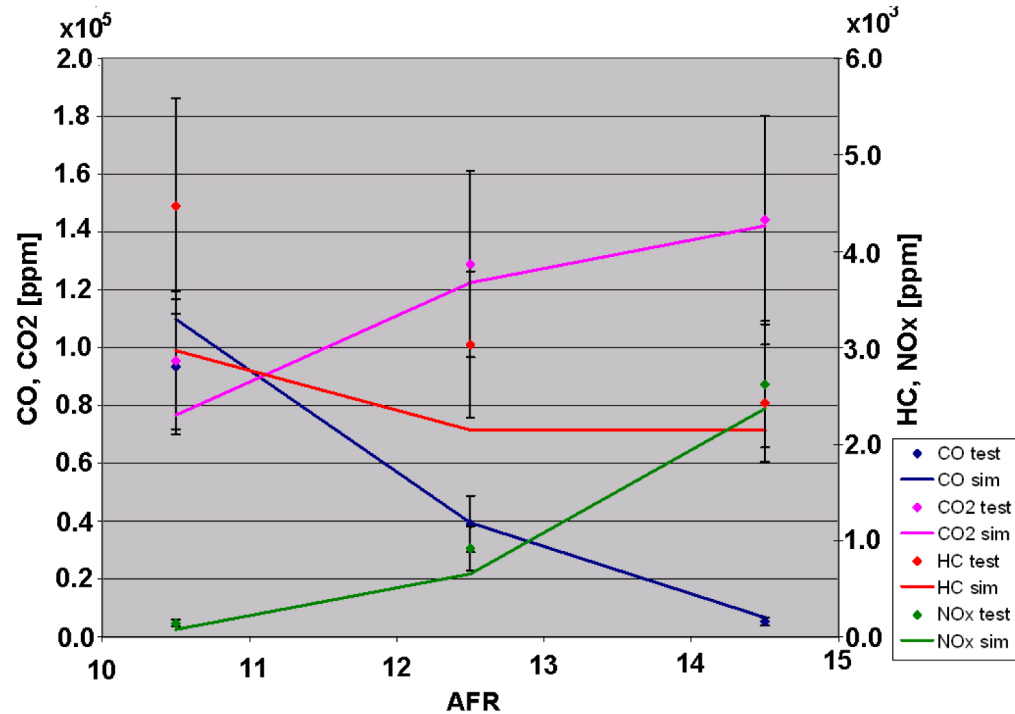


Figure 6. Emissions @700rpm; 23° SA

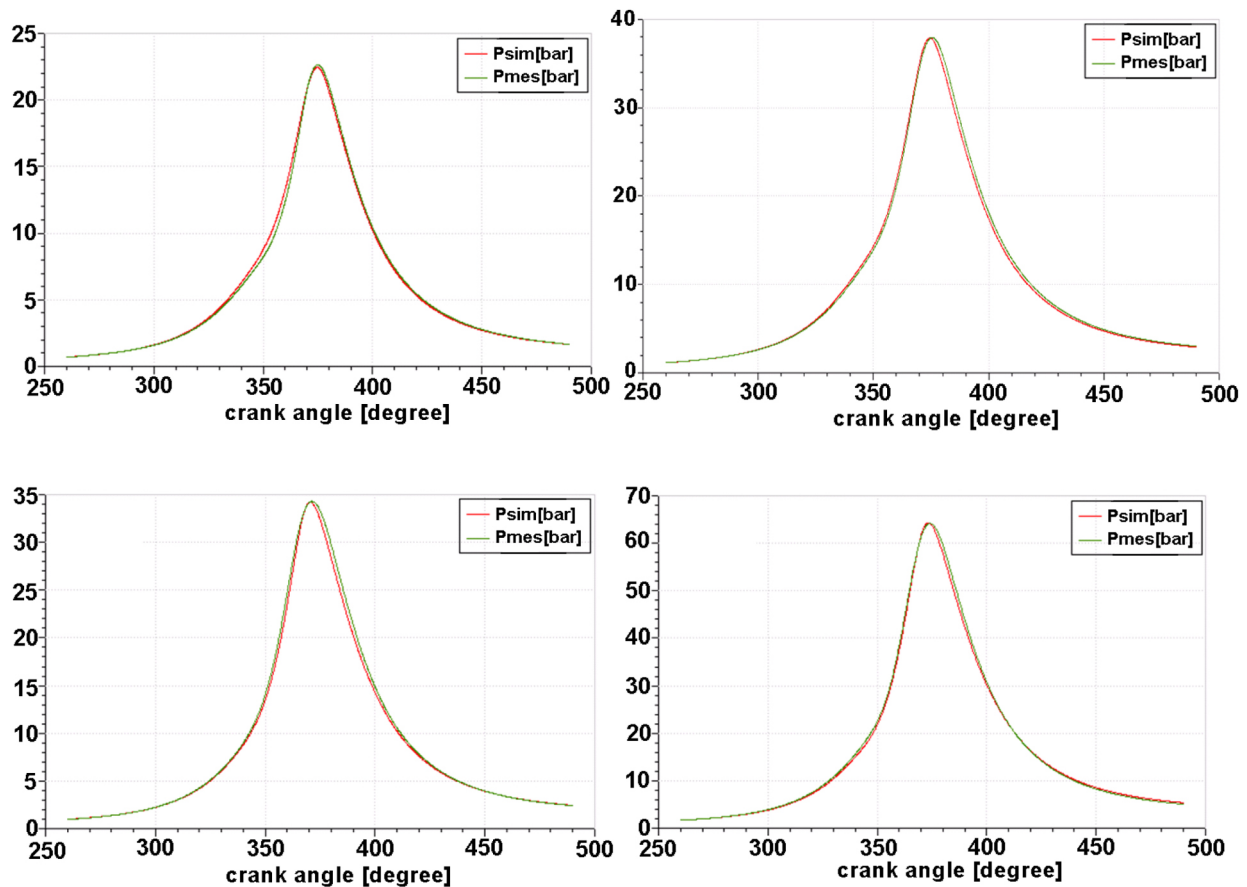


Figure 7. Cylinder pressure traces @800rpm; 1200rpm; 2400rpm; 3600rpm

@	* 3 points	800 rpm,	BMEP from 0.83 to 3.15 bars
@	* 5 points	1200 rpm,	BMEP from 0.87 to 6.28 bars
@	* 3 points	1800 rpm,	BMEP from 1.64 to 8.02 bars
@	* 6 points	2400 rpm,	BMEP from 0.56 to 7.82 bars
@	* 5 points	3600 rpm,	BMEP from 0.36 to 10.9 bars
@	* 5 points	5200 rpm,	BMEP from 0.91 to 10.25 bars

After this calibration process, the CFM combustion model is able to reproduce accurately the in-cylinder pressures over the full engine range. Few results are presented below in [Figure 7](#).

Looking at optimum torque vs. spark advance sweep, simulation give good results (red points on the [Figure 8](#)),

meaning able to refine the area of optimum. In this case, model was fine tuned on a single SA value (44° @2400rpm & 30° @3600rpm) and the SA sweep was purely predicted by the model and compared to the measurements.

At 3600rpm simulation predicted an optimum spark advance around 30°. In the [Figure 9](#), one can notice that knock is predicted to appear from 31-32°, meaning final optimum engine ECU calibration has been correctly predicted by the model. Moreover, this engine operating point is the first with rich mixture (all low end region is set at stoichiometry) and the CFM combustion model is able to predict that the engine is more sensitive to knock with stoichiometric mixture (knock appear from 27-28° with 14.5 AFR).

Concerning emissions, latest CFM combustion model gave very good results. [Figure 10](#) shows the emissions on the calibrated engine operating points at 1200rpm and 5200rpm. Points are measurement data (the vertical bars represent the +/- 25% accuracy), solid lines represent the AMESim latest CFM combustion model.

All emissions: CO, NOx, CO2 and HC are correctly predicted vs. load. Latest CFM combustion model slightly improves the situation for HC. Global correlation can be seen