

Analysis of Various Operating Strategies for a Parallel-Hybrid Diesel Powertrain with a Belt Alternator Starter

Edoardo Morra and Ezio Spessa
Politecnico di Torino

Claudio Ciaravino and Alberto Vassallo
General Motors Company

ABSTRACT

The sustainable use of energy and the reduction of pollutant emissions are main concerns of the automotive industry. In this context, Hybrid Electric Vehicles (HEVs) offer significant improvements in the efficiency of the propulsion system and allow advanced strategies to reduce pollutant and noise emissions.

The paper presents the results of a simulation study that addresses the minimization of fuel consumption, NO_x emissions and combustion noise of a medium size passenger car. Such a vehicle has a parallel-hybrid diesel powertrain with a high-voltage belt alternator starter. The simulation reproduces real-driver behavior through a dynamic modeling approach and actuates an automatic power split between the Internal Combustion Engine (ICE) and the Electric Machine (EM). Typical characteristics of parallel hybrid technologies, such as Stop&Start, regenerative braking and electric power assistance, are implemented via an operating strategy that is based on the reduction of total losses.

After model calibration and validation against available experimental data, various Hybrid Operating Strategies (HOS) have been examined. These are investigated over the New European Driving Cycle (NEDC) and the Artemis Urban Cycle (AUC) in terms of fuel economy, NO_x emissions and combustion noise. Finally, optimal calibrations are suggested as the best compromise between all the analyzed targets.

CITATION: Morra, E., Spessa, E., Ciaravino, C. and Vassallo, A., "Analysis of Various Operating Strategies for a Parallel-Hybrid Diesel Powertrain with a Belt Alternator Starter," *SAE Int. J. Alt. Power.* 1(1):2012, doi:10.4271/2012-01-1008.

INTRODUCTION

In response to the more stringent international standards concerning the environmental impact of the road traffic, automobile manufacturers are currently developing new vehicle concepts featuring lower emissions and fuel consumption ([1,2]). One promising approach is the partial electrification of traditional powertrains: Hybrid Electric Vehicles (HEVs). These innovative systems attempt to couple the advantages of traditional vehicles with electric propulsion. However, the resulting powertrain is complex and requires a suitable operating management strategy to properly exploit the expected benefits. ([3,4,5]). In this framework, simulation can play a significant role to properly identify the optimal hybrid operating management strategy.

In this paper, the fuel economy, NO_x emissions and combustion noise of a parallel hybrid architecture are analyzed through a dedicated numerical code. The model reproduces real-driver behavior and, taking into account

battery performance limitations, determines the power split between the Internal Combustion Engine (ICE) and the Electric Machine (EM).

As far as the powertrain layout is concerned, the traditional starter has been replaced with a high-voltage Belt Alternator Starter (BAS) in a light-duty diesel engine passenger car. The design of the resulting drivetrain is very similar to that of a traditional vehicle. Moreover, engine Stop&Start, regenerative braking, electric boosting and ICE load point shift are enabled.

Among the most common Hybrid Operating Strategies (HOS) that are available in the literature, the adopted approach is based on the reduction of total losses ([6]).

SIMULATION MODEL

The simulation model was developed using GT-Drive software, a Gamma Technologies Inc. tool for the zero-dimensional simulation of vehicles and powertrains ([7]). A

coupled code in Matlab environment was also required to implement the hybrid operating strategy ([8]).

Figure 1 shows a schematic overview of the considered hybrid powertrain. The electric machine is a Belt Alternator Starter (BAS), it is powered by the battery through the inverter and is mechanically linked to the ICE crankshaft through a V-shaped multi-rib belt. The ICE and EM supply torque directly to the wheels via the conventional driveline. No clutch is installed between the ICE and the EM. Although this provides a simplified and cost-effective solution, it is obviously a constraint for the regenerative braking and electric mode.

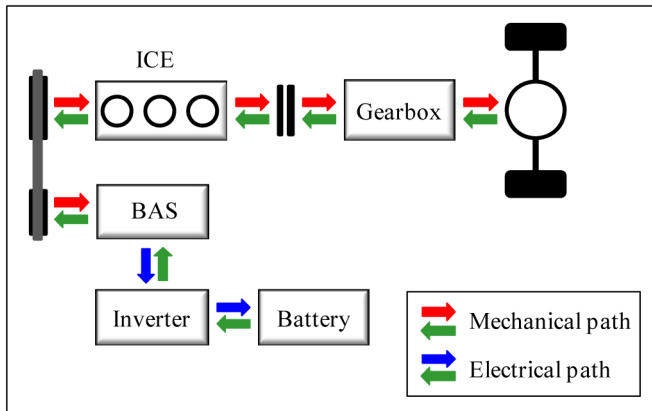


Figure 1. Layout of the considered hybrid powertrain

The ICE has been modeled on the basis of experimentally derived look-up tables, in which the fuel consumption, pollutant emissions and combustion noise are mapped as functions of the engine speed and BMEP. A semi-empirical correlation is used to reproduce coolant temperature time-histories during ICE warm-up ([9]).

The electric machine is a 3-phase AC induction motor/generator. Its total efficiency includes friction and electro-mechanical conversion losses, and it is obtained from experimentally-derived look-up tables as a function of the EM speed, torque and battery open circuit voltage ([10]). The entire electro-mechanical system, made up of an electric machine and power converter, will hereafter be referred to as Motor Generator Unit (MGU).

The electric energy storage system is a lithium battery pack with forced air cooling. It is described by means of an equivalent electric circuit ([11]). Battery operating constraints have been taken into account on the basis of the State Of Charge (SOC) and temperature.

The driveline is modeled according to the component inertias, efficiencies and speed ratios. Moreover, specific attention has been paid to the gearbox, due to its key role in the transmission losses. Its instantaneous efficiency is modeled as a function of the gear number, input torque, input speed and oil temperature, on the basis of available experimental characterizations of the component. Finally, the effects of change in the gear-box oil temperature have been taken into consideration by means of a simplified zero-

dimensional thermal model, which does not include modeling of the shaft and bearing pre-load change as a function of the temperature gradient in the gearbox. While accounting for shafts and bearing preload is an important feature in detailed gearbox simulation models, the authors believe that, in the framework of a more general powertrain system modeling, a zero-dimensional gearbox model represents a balanced approach to capture the influence of the vehicle time-history on the traction power at the ICE shaft.

For further details on the simulation setup, please refer to ([12]). The paper, by the same authors, deals with an overview of both the simulation layout and the control logic, but it only takes into consideration the optimization of the powertrain efficiency.

CONTROL LOGIC

The virtual driver identifies the required traction power through a dynamic feedback to the difference between the target and the actuated vehicle speed. The Hybrid Operating Strategy (HOS) selects the power split between the ICE and the EM in function of predefined optimization criteria. The adopted approach deals with the minimization of total power losses $P_{tot,i}$ ([6,12]), which are determined at each time-step as:

$$P_{tot,i} = c_1 P_{ICE,i} + c_2 P_{T(ICE),i} + c_3 P_{MGU,i} + c_4 P_{SOC,i} + c_5 P_{NOx,i} + c_6 P_{Noise,i} \quad (1)$$

$P_{ICE,i}$ represents the ICE energy losses and is defined as the difference between the chemical power of the fuel and the brake power.

$P_{T(ICE),i}$ describes the ICE thermal losses. It takes into consideration that the ICE warm-up is slowed down if part of the traction power is supplied by the MGU, and that frictions are increased until the engine reaches fully warmed operating conditions. It is defined considering the semi-empirical formulation for the ICE coolant temperature ([9]):

$$P_{T(ICE),i} = \left(\frac{\theta_{ICE,warm} - \theta_{ICE}}{\theta_{ICE,warm} - \theta_{ICE,cold}} \right)^2 \cdot P_{batt} \quad (2)$$

$P_{MGU,i}$ characterizes MGU and battery power losses and, in the case of motor mode, it is equal to the difference between the chemical power of the battery and the electric machine brake power (vice versa in the case of generator mode).

$P_{SOC,i}$ controls the battery state of charge. It introduces fictitious losses that are proportional to the deviation of the actual SOC from the target SOC:

$$P_{SOC,I} = C_{SOC,I} \cdot (P_{batt} - P_{batt,shift}) \quad (3)$$

As shown in Figure 2, both $C_{SOC,I}$ and $P_{batt,shift}$ depend on the battery SOC. The values of the SOC at the bottom, low, high and top levels, as well as the corresponding $P_{batt,shift}$ and $C_{SOC,I}$ values, should be tuned according to the considered vehicle mission.

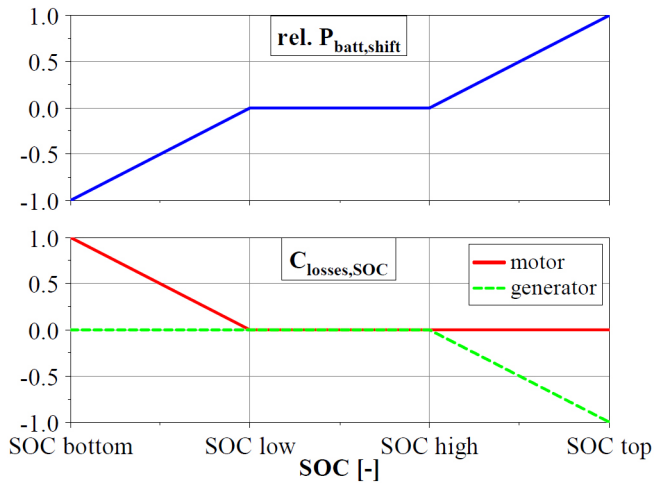


Figure 2. Battery: SOC losses

$P_{NOx,I}$ is responsible for the minimization of the NO_x emissions. It is defined as the NO_x mass flow rate multiplied by a scale factor:

$$P_{NOx,I} = 10^6 \cdot m_{NOx} \quad (4)$$

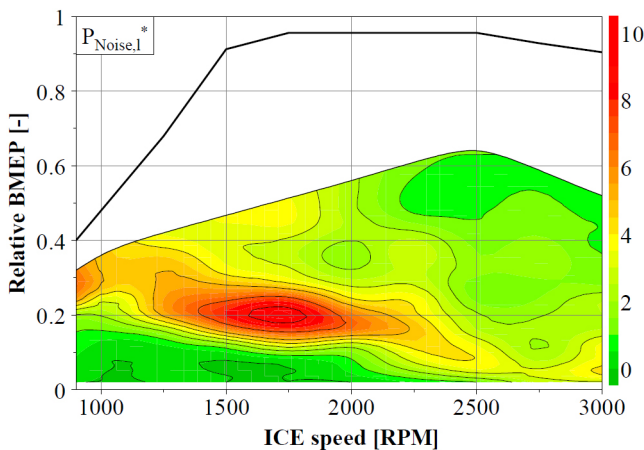


Figure 3. ICE: $P_{Noise,I}^*$ map

$P_{Noise,I}$ limits the ICE Combustion Noise (CN). It is characterized by a different structure than the other terms, since the target no longer represents the best reduction in the

total consumption or the total emissions. Its goal is to guarantee a combustion noise as close as possible to the target, i.e. to minimize the difference between the target and the actual combustion noise multiplied by a scale factor and expressed in power law (Figure 3):

$$P_{Noise,I}^* = 10^{0.1 \cdot (Noise_{Actual} [dB] - Noise_{Target} [dB])} \quad (5)$$

The target combustion noise is defined according to the specific vehicle application, as a balance between driving comfort and the fuel economy that the engine needs to deliver (therefore, depending on the vehicle application, a certain engine may be subjected to different combustion noise targets). Figure 3 underlines how the operating points in a Diesel engine that are more difficult to calibrate from a CN point of view, are characterized by intermediate loads and low speeds. This stems from the features of the diesel combustion process itself that exhibits a large premixed fraction, due to the combination of high EGR rates (emissionization constraints), quite high fuel injected quantities (engine load) and high residence time (low engine speed) ([14]).

CN is perceived in a different way depending on the vehicle speed. Aerodynamic drag and tire rolling are irrelevant at low speeds and combustion noise has a stronger impact.

$$\begin{cases} P_{Noise,I} = \left(1 - \frac{V_{car}}{50 \left[\frac{km}{h} \right]} \right)^3 \cdot P_{Noise,I}^*, & V_{car} \leq 50 \left[\frac{km}{h} \right] \\ P_{Noise,I} = 0, & V_{car} > 50 \left[\frac{km}{h} \right] \end{cases} \quad (6)$$

Eq. (6) considers a cubic relationship of the CN loss with respect to the vehicle speed, in order to stress the low vehicle speed area. It is assumed that the combination of tire rolling and aerodynamic noises are dominant over combustion noise above 50 [km/h] ([14]), therefore no optimization of the combustion noise is actuated for velocities higher than such a limit. These limits and assumptions are naturally highly dependent on the specific application, and can thus be tuned accordingly.

The $c_1 - c_6$ coefficients in Eq. (1) are tuning parameters that have to be determined in order to optimize the considered targets and to limit battery exploitation within the acceptable range. Their values are constant for any defined mission profile.

ASSESSMENT OF THE MODEL

The model has been assessed with reference to experimental tests that were carried out at the Internal