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Integrated Modeling Approach for Highly electrified HEV. Virtual Design and Simulation Methodology for Advanced Powertrain Prototyping.

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Abstract

Nowadays car development time from concept approval to Job 1 is between 2 and 5 years (with an average of 3 years), but in the coming years is necessary to reduce it in order to achieve the optimal 12-month car. On the other hand the penetration rate of alternative powertrains (electric, hybrid) is growing quickly, increasing the complexity of the vehicle and therefore development time cycle. Presented architecture and methodology in this paper, is based on virtual modelling of system/components, giving the possibility of an integrated vehicle virtual simulation, and also allowing the substitution of system/component models for real hardware (Hardware-In-the-Loop, HiL), or even using the entire vehicle model in a driving simulator searching for Human-In-the-Loop (HuiL) approaches. As far as the modelling represent the real system/components with accuracy, the use of these vehicle integrated virtual models will be more useful, allowing reduce the development time and also increasing vehicle overall quality.

Keywords: HEV, Powertrain, Modeling, Simulation, Control system

1 Introduction

Recently, a great deal of interest has appeared around improving the efficiency, reducing emissions and consumptions to operate vehicles. One solution, which is currently gaining acceptance, is to move from conventional powertrains based in internal combustion engines burning fossil fuels, to alternative powertrains operating in so called Hybrid Electrical Vehicles (HEV). There are some different powertrain configurations in HEVs, all of them have an electrical drive system as one of the power sources, increasing their importance depending of the considered degree of hybridization. Aspects like energy efficiency, emissions, vehicle performance, range in Km, and total cost, depend on the design of the powertrain system and the control strategy employed. In HEV the Know-How in electrical components, like energy storage systems (batteries, super-capacitors, etc.) electric machines, power inverters, control systems, etc., is the key factor in the electrical powertrain design stage. Components are more and more complex and it's strongly recommended the use of advanced tools for the modeling and simulation in the conceptual and preliminary design stages, to analyze the behavior of all these components integrated in the HEV powertrain. Once general powertrain architecture is defined, in the detail design stage model based studies are mandatory to implement advanced control and optimization strategies for the management of the different energy sources.

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Improvements in efficiency, emissions and consumptions are possible taking into account the driver intentions and the environment information obtained through external perception or communication technologies installed in the vehicle. In addition, the dynamic response of the components in electrical powertrain is quite different from conventional. For example, electrical motor torque Vs speed characteristic makes necessary the design of new drive control strategies, so that the driver has the same or even better vehicle drivability, comfort and safety. The use of Human in the Loop (HuiL) methodology (driving cycles simulations over virtual scenarios) is very interesting in the detail design stage to analyze the driver requirements and the dynamic response of the vehicle as a whole.
Fig. 1 shows the layout of a Test Bench presented in this article for HEV virtual design and advanced powertrain prototyping. In next sections models architecture and virtual design methodology are explained to illustrate the benefits using model based design and advanced simulations techniques to achieve rapid powertrain prototyping.

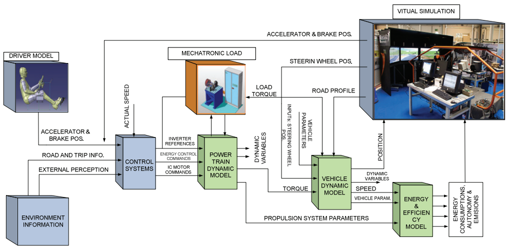

Figure1: Test Bench model based architecture

2 Models Architecture for HEV virtual design

In this section, models architecture for Hybrid and Electric Vehicles is presented. Different model topologies are appropriated depending of the actual design stage on the project.

- Models with backward-facing topology and numerical simulations in the conceptual and preliminary design stages for powertrain components requirement definitions and energy management strategies exploration.
- Dynamic models with forward-facing topology together with hardware and human in the loop simulations in the preliminary and detail design stages for the development of electronic control systems related with the electric motors control (propulsion, traction) and the power and energy management systems.

2.1 Backward models. Driving cycles simulations.

Drive cycle simulations of longitudinal vehicle models is an important tool to evaluate energy consumptions, efficiency and emissions in the conceptual design of power-trains [1]. In the early design stages many simulations are required for power-train configuration optimization and also for the conceptual development of HEV hybridization and energy management strategies [3]. Simulation time is too low so this model topology and simulations can be used together with advanced non-linear searching methods (direct search, evolutionary algorithms, etc.) in design exploration and optimization loops to achieve optimal HEV power-train configurations and energy control strategies. Multi-objective optimization problem formulations for power-train design (high energy efficiency, high range, high performance, high drivability, active safety, high component durability, low cost, low consumptions, low emissions, etc.), can be solved using this tool as fitness function to evaluate some of the pursued objectives in the searching method loop iteration.
Simulation with this models uses vehicle speed and acceleration (drive cycle) to calculate required torques and speeds backwards through the driveline. In the case of study analyzed here (electric vehicle battery powered with an ICE based range extender) energy consumption of battery and fuel consumption of ICE range extender are calculated for a defined drive cycle profile (vehicle speed Vs time). The model consists of static equations and efficiency maps of the power-train components. Fig. 2 shows backward model architecture.

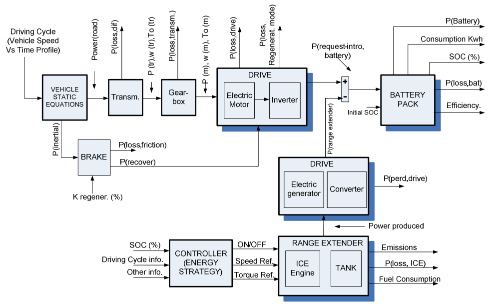

Figure 2: Backward model block diagram.

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Static equations representing the longitudinal movement of the vehicle from the driving cycle are presented in (1). It is founded upon a parametric description of the well-known road load equation [2].

$$\begin{aligned} P_{road} &= P_{aero} + P_{roll} + P_{accel} + P_{grade} \\ &= \frac{1}{2}\rho C_D A v^3 + C_{RR} m_{total} g v + \\ &+ k_m m_{total} a v + m_{total} g Z v \end{aligned} \qquad (1)$$

Where P_{road} is the road load power (W), v is the vehicle speed (m/s), a is the vehicle acceleration (m/s^2), p is the density of air (Kg/m^3), C_D is the aerodynamic drag coefficient, A is the vehicle frontal area (m^2), C_{RR} is the rolling resistance coefficient, m_{total} is the total vehicle mass (Kg), g is the gravitational acceleration (9.81m/s^2), Z is the road gradient (%) and K_m is a factor corresponding for the rotational inertia of powertrain. If P_{road} = 0, P_{accel} (inertial forces) compensates power losses of P_{aero}, P_{roll} and P_{grade}. If P_{road} > 0 the powertrain will must to supply power and with P_{road} < 0 the powertrain could recover energy (regenerative brake) depending of the powertrain absorption capacity and efficiency in the recovery or regenerative mode. At this level power losses corresponding to the vehicle lateral forces have not been taken into account. Theoretically influence of the lateral forces in energy consumption is low with respect of the longitudinal forces. In next subsection we present a forward-facing full vehicle dynamic model with both, longitudinal and lateral dynamic effects, developed over the same integrated test bench. Comparative results studies about the influence of both dynamics in energy consumptions can be made using the two model topologies, backward with no dynamics (only steady states) and forward topology with longitudinal and lateral dynamic effects calculations.

Models for electric drives and ICE are based in efficiency maps (obtained in the components characterization phase) implemented over lookup tables. For the battery, we use the well-known Peukert model of battery behavior [5]. Although this method is not very accurate at low currents, for higher currents it models battery behavior well enough. Equation (2) shows the apparent or effective charge removed from the battery where CR_n is the total charge removed in n_{th} step of the simulation, At is the step time in seconds, I is the current flowing, and k is the *Peukert* coefficient obtained in the characterization phase of battery pack. Equation (3) shows the calculation of the charge supplied by the battery to the electric vehicle. Knowing the depth of discharge of the battery is necessary to estimate the battery open circuit voltage using a polynomial function obtained in the characterization phase of the battery pack. Finally, battery terminal voltage can be calculated taking in account battery internal resistance and the current flowing from the battery.

$$CR_{n+1} = CR_n + \frac{At \times I^k}{3600} Ah \qquad (2)$$

$$CS_{n+1} = CS_n + \frac{At \times I}{3600} Ah \qquad (3)$$

2.2 Forward model. Longitudinal and lateral vehicle dynamic model

In forward dynamic simulation differential equations of longitudinal and lateral vehicle dynamics are solved using the throttle, brake and steering wheel positions as inputs, and vehicle speed and position as outputs. In this process, torque, speed, and power forward through the driveline are calculated so energy consumptions also can be known. This kind of model requires controllers, and a driver (driver model or real driver) to track a given drive cycle or to drive over a virtual scenario as we'll see in next sections. Differential equations to be solved, typically gives an order of magnitude longer simulation times than what is typical for the backward approach. However, dynamic effects and limit conditions are included in simulations making the modelling and simulation more accurate and realistic. Fig. 3 shows the forward facing model architecture.

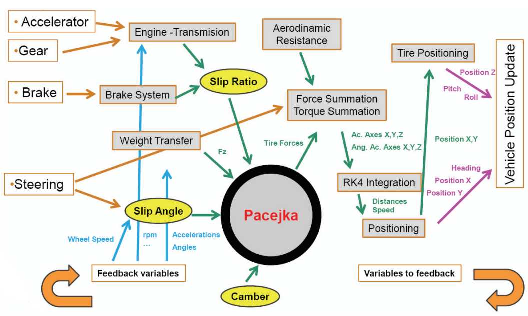

Figure 3: Lateral and longitudinal model block diagram.

Both, longitudinal and lateral vehicle dynamic responses are considered together with powertrain

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components dynamic effects. Tire data and modelling approach of road-tire contact has been also considered by using the Pacejka model approach that provides very accurate results of the forces involved [7]. The model target is to calculate the vehicle speed and position as well as some important dynamic variables like forces, torques, slip angles, lateral accelerations, vertical axis loads, power and speeds, etc., forward through the driveline. These variables are involved in the differential equations that define the vehicle dynamic response (roll stiffness, weight transfer and vehicle model) according to the inputs, i.e. acceleration and brake pedal position, steering wheel position, and vehicle parameters, i.e. tire parameters, geometry, roll centre, inertias, weight, powertrain parameters, etc. Differential equations are solved using an advanced and fast integration solver (Runge Kutta based method). Model has been implemented in LabView™, over a multi-core technology Computer. Model modular development has been very important [4]. Thus, dynamic sub-models corresponding to the vehicle powertrain components can be swapped by the real electric components easily through fast inputs/outputs and communications signals, allowing us real Hardware or even Powertrain in the Loop simulations approach (HiL, PoiL) to test and calibrate the powertrain components as we can see in next section.

3 Test Bench. Models integration and simulation possibilities

Fig. 4 shows HEV final test bench architecture layout, with some of the powertrain sub-models of the full forward dynamic model swapped by real powertrain electric components. Figure 5 shows the physical coupling detail of the two motors (traction and mechatronic load).

In this case, two motors with a physical coupling were running, one working as a load and the other as a traction drive [6]. Torque reference commands of load drive and traction drive, were calculated by the vehicle dynamic forward model. Torque command reference of the traction drive is calculated according with the acceleration and braking signals requested from the driver. In each simulation time step, forward dynamic model also calculates the wheel resistance torque (aerodynamic, rolling, lateral and longitudinal acceleration, grade) in the powertrain axis reference. This torque is sent to the load drive as torque reference command. Electric drives responses feedback signals were sent back to the model to be used in the vehicle forward lateral and longitudinal dynamic response calculation.

Test bench architecture is completed with the integration of an advance driving simulator platform, SCANeR[1] II, allowing driving cycle simulations using a human driver over virtual scenarios with a Driver or Human in the Loop approach (HuiL). Only the virtual scenarios advanced tools and graphical representation are used. Through a fast communication network and software component communication modules, provides by OKTAL, we have been able to integrate the HEV forward dynamic model (developed in LabView™) into the SCANeR II driving simulator platform.

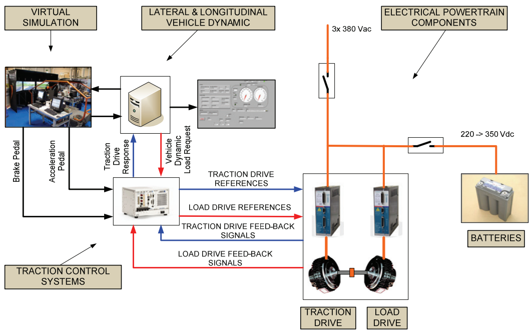

Figure 4: HEV Test Bench architecture and layout.

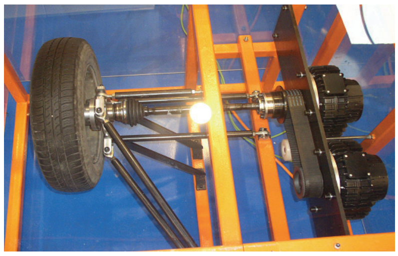

Figure 5: Detail of physical coupling between traction and mechatronic load motors.

4 Powertrain prototyping. Virtual design and simulation.

In this section the existing relation and uses of the presented test bench integrated architecture (models, components), with the pursued objectives

[1] SCANeR II. Registered trademark of RENAULT and OKTAL. Comprehensive driving simulation software package developed by the Vehicles Simulation and Perception Research group of RENAULT and OKTAL.

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in the actual design stage (conceptual, preliminary or detail) will be explained.

4.1 Hardware and Human in the Loop simulation over virtual scenarios.

In this section we present some simulations using the test bench presented in this article. For these simulations we have selected an electric vehicle with 930Kg of mass, 1,909m^2 of frontal section, 0,344 of aerodynamic drag coefficient and 0,5m of tire diameter. Appropriated parameters related with the vehicle geometry, roll centres, *Pacejka* tire coefficients [7], inertias, suspension parameters, etc., have been also selected. Electric motor power is 45Kw with a base speed of 1000rpm and 470Nm of maximum Torque below base speed. Energy of battery is 12 KWh and the electric vehicle is provided with an ICE based range extender of 10 Kw.

Firstly forward facing model and simulation was selected. A real driver drove over a virtual scenario of 4Km (urban and extra urban mix circuit) selected in the advanced virtual driving simulator SCANeR II, fig. 6, (Human in the Loop). Electric drive sub-model was swapped by the real one as we have explained in section 3 of this article. Some important dynamic variables were logged to help us in the adjustments of control systems [6] (electric drive control loops adjustments, transfer function from pedal position to electric drive torque reference calculation, etc.), fig. 7.

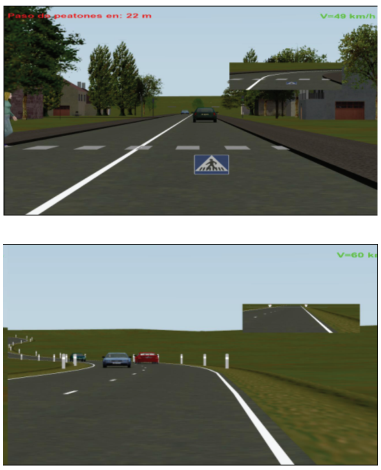

Figure 6: Virtual driving scenario. SCANeR II.

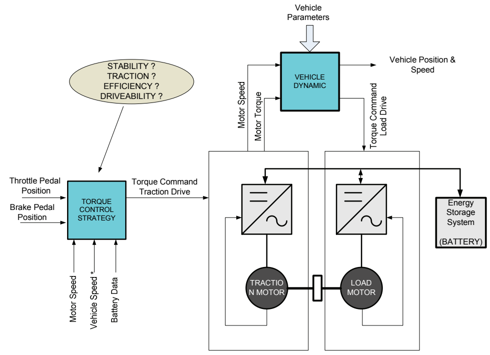

Figure 7: Control systems adjustments.

Next graphs, Fig. 8 to Fig. 14, show some dynamic variables logged during Human in the Loop simulation to be used for analysis and re-design of some aspects of the electric powertrain control systems.

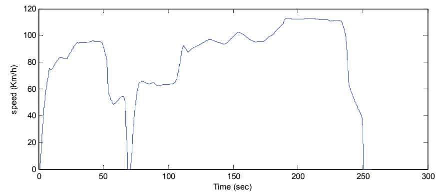

Figure 8: Vehicle speed.

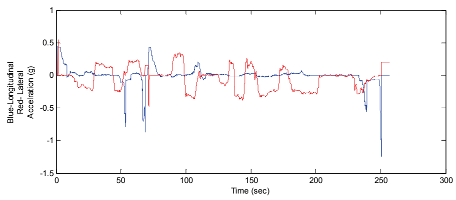

Figure 9: Lateral & Longitudinal acceleration.

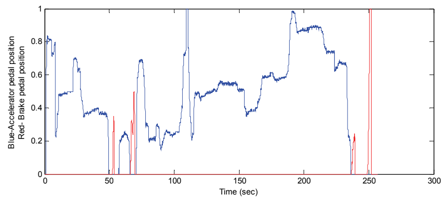

Figure 10: Accelerator and Brake pedal position.

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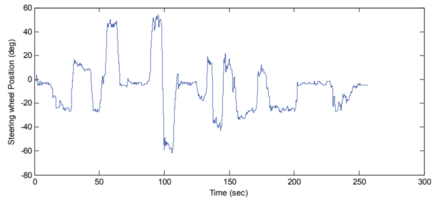

Figure 11: Steering wheel position

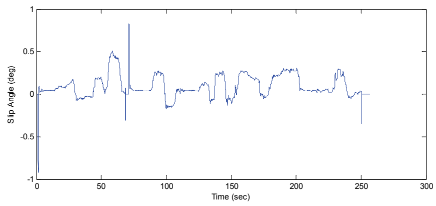

Figure 12: Slip angle.

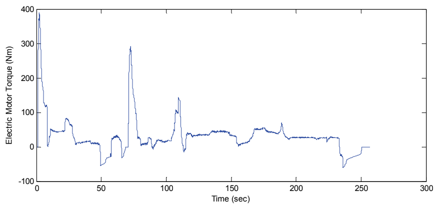

Figure 13: Torque in Electric Drive

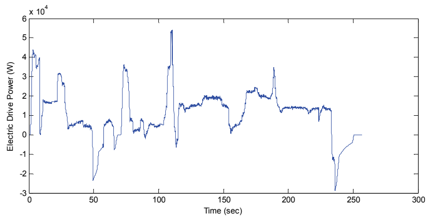

Figure 14: Power in electric drive.

Fig. 15 shows de battery energy consumption in Wh. In Fig. 16 we can see the SOC (state of charge, %), over this driving scenario, evaluated by the forward facing type simulation.

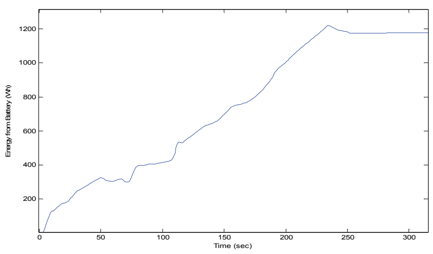

Figure 15: Battery energy consumption.

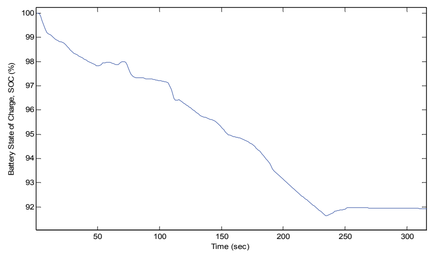

Figure 16: State of Charge of the Battery.

Now, we will test the backward facing model described in section 2.1 of this article. To do that we use the driving cycle logged while the driver was driving over the same virtual scenario, Fig. 6. This driving cycle corresponds to the graph shown in Fig. 8. Remember that in backward simulation only the static equations corresponding to the longitudinal vehicle model are used. Vehicle and powertrain parameters are the same as in forward simulation. Results about the energy consumption and State Of Charge of battery are presented in Fig. 17.

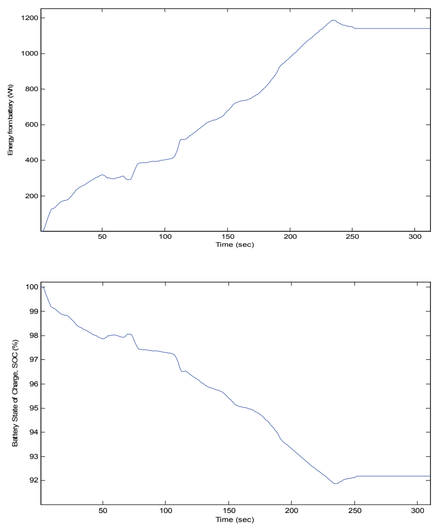

Figure 17: Battery consumption variables logged during backward simulation.

Note the accuracy of backward model based simulation in terms of battery energy consumption. In forward model based simulation, energy consumption in battery was 1.18 KWh while in backward model based simulation was 1.14 KWh. Using forward model approach, longitudinal and lateral dynamic effects (not only steady states) have been taken into account. Also a more

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accurate model approach of tire road contact has been used. Backward model based simulation has enough accuracy in the energy consumption estimation. Simulation time using backward models has been too low and it's a great advantage for the uses in the early design stages due to many simulations are required for the optimization of powertrain configuration. HEV forward model based approach considers subsystems dynamic effects, subsystems limit conditions and presents more accuracy in power and energy calculations. Simulation time required is high. In the example presented here, simulation time was almost 300 sec due to it was a real time simulation with a real driver driving over a virtual scenario (Human in the Loop simulation). Some variables could be logged during the simulation to analyze aspects related with energy efficiency, drivability, stability, propulsion/traction responses, etc., and used for the rapid prototyping and adjustments of powertrain control systems. Thus the use of dynamic model in forward topology is crucial and very appropriate in preliminary and detail design stages.

5 Conclusion

Virtual design methodology based on integrated model approach architecture (with HiL), and the possibilities of "close to real" testing added by the driving simulator (HuiL), has been presented as innovative approach in terms of design and developing time reduction. Uses of Backward and Forward model topologies have been discussed regarding with the HEV powertrain design stages. Backward model based simulation has enough accuracy in the energy consumption estimation. Simulation time is too low and it's a great advantage for the uses in the early design stages due to many simulations are required for the optimization of powertrain configuration. HEV forward model based approach considers lateral and longitudinal vehicle dynamics, subsystems dynamic effects, subsystems limit conditions and presents more accuracy in power and energy calculations.
Test bench presented here, allows us real time simulations with a real driver driving over virtual scenarios (Human in the Loop simulation approach, HuiL). In addition, electric powertrain subsystem models can be swapped easily by the real components for testing and calibration (Hardware or even Powertrain in the Loop, HiL). Some variables could be logged during the simulation to analyze aspects related with energy efficiency, drivability, stability, propulsion / traction responses, four wheels drive electrical concepts, etc. These important variables are used for the rapid prototyping and adjustments of powertrain control systems considering the combined effects of lateral and longitudinal dynamics. Thus, the use of this forward model based test bench is crucial and very appropriate in preliminary and detail design stages of the future powertrain for hybrid and electric vehicles.
As final resume and conclusion, fig. 18 shows all aspects and concepts on which we have been talking about along this article. This schematic view - based on the well known "V" design process cycle - give us the possibility to illustrate, in an easy way, the methodology used for Hybrid and Electric Vehicles powertrain rapid prototyping.

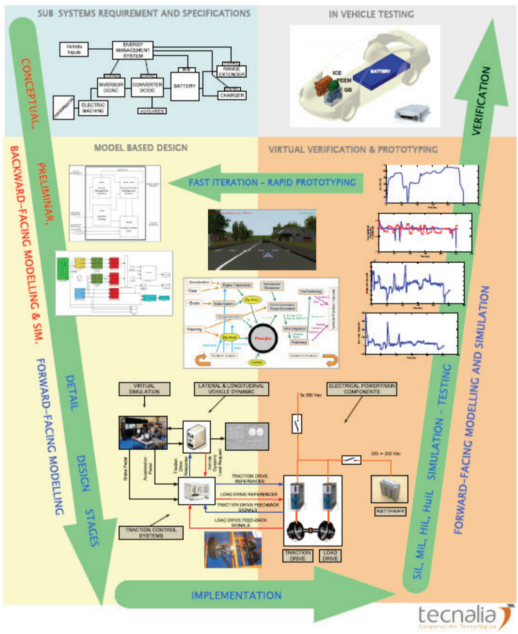

Figure 18: Virtual Design and Simulation Methodology. "V" Design Process Cycle

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