AN ALTERNATIVE HYBRID AUTOMOTIVE POWERTRAIN SYSTEM

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Abstract. *This paper considers the problem of hybrid fuel-electrical automotive powertrain systems. The work presents an overview of the existent commercial alternatives and the research lines in this field. Hybrid vehicles are then further classified according to its functionality and main elements. A case study is then developed, where an alternative hybrid configuration is proposed, considering economical, environmental and technical issues. Simulation results using ADVISOR 2002 validate the viability of the proposed alternative, allowing also a comparison of the proposed solution to industrial options. Further results and analysis seek to evaluate the behavior of the new configuration in respect to emissions, cost and technical viability.*

Keywords*: vehicles, powertrain systems, hybrid vehicles, vehicle simulation, advisor 2002.*

1. Introduction

A number of automakers see fuel cell powered vehicles (FC-EVs) as the ultimate route to achieve a sustainable long-term alternative propulsion system. However, commercial production of FC-EVs is still some years away since some basic technological questions like how to safely produce hydrogen and store it on board are still unanswered. On the other hand, vehicles equipped with a hybrid drivetrain (HEVs) are already being developed by some automakers as a commercial product. Thereby in a short-term vision, HEVs may lead to the next vehicle generation.

HEVs offer the possibility of combining the advantages of EVs zero emissions in sensitive places, while offering a nearly unlimited long-distance capability by utilizing a standard internal-combustion engine (ICE).

This paper considers some possibilities to solve the problem of hybrid automotive powertrain systems consisting of a regular fuel powered internal combustion engine (ICE) coupled with one or more electrical machines (EM). The work presents an overview of the existent commercial alternatives and the research lines in this field, covering architectural configurations, systems and functionalities of hybrid vehicles.

A case study is then developed, where an alternative hybrid configuration is proposed, considering economical, environmental and technical issues. Simulation is performed using ADVISOR 2002, a public software developed at National Renewable Energy Laboratory (NREL) of the Department of Energy (DOE) of the United States of America since 1998. Results validate the viability of the proposed alternative, allowing also a comparison of the proposed solution to industrial options. Further results and analysis seek to evaluate the behavior of the new configuration in respect to emissions, cost and technical viability.

2. Hybrids Classification

Early ages hybrid vehicles were classified according to the architectural configuration of their propulsion components. This classification, still generally accepted, defines if the hybrid vehicle is assembled in a “Series” or “Parallel” configuration (Nedungadi, 1999 and Rahman, 2000).

In the series configuration, there is no direct connection between the ICE and the wheels. The ICE powers a generator, which feeds an electrical storage system, usually a battery, which is the source of energy for one or more EMs. The EMs only drive the vehicle (Nedungadi, 1999).

In the parallel configuration, there is a direct connection between the ICE and the wheels. This allows a more direct and efficient transfer of mechanical energy from ICE and EM to vehicle wheels (Nedungadi, 1999). In general, among several options for parallel configuration, the ICE drives the wheel and a generator, which feeds a battery to store the energy to be used by one or more EMs. In specific cases, EMs work as generators themselves supplying energy to be stored in batteries (Nedungadi, 1999).

Divergences regarding traditional classification concealed the fact that the mechanical connection is not the more logical classification methodology. As a result, another method was created to classify hybrid propulsion systems. It was based in mission type the system is designed. The classification, based on “mission” divides hybrids vehicles in three classes: mild hybrids, power hybrids and energy hybrids (Ronning, 1999).

Light or mild hybrid vehicles present the lowest additional cost to the propulsion system, with moderate effects in fuel consumption. The EM is an integrated starter/generator (ISG), which can be driven by a belt or assembled in the ICE crankshaft. Batteries usually have voltage lower than 60V and electric power around of 5kW (Ronning, 1999).

Medium or power hybrid vehicles present a substantial cost associated to the propulsion systems and a significant share of electrical propulsion in vehicle's total propulsion. Power flows from or to batteries in range between 20 and 40kW, although with a small energy storage capacity. They are capable of recapturing more aggressively the vehicle's kinetic energy in a process known as regenerative breaking. This capacity is due to the design of electrical motors, inverters and batteries, which can handle higher levels of power (Ronning, 1999 and Walters, 2001).

Energy hybrid vehicles employ energy storage systems with higher power and high energy levels, capable to provide enough power and energy to drive the vehicle for about 100km, reaching up to 70kW of power (Ronning, 1999).

3. Systems and Functionalities

In this section a quick overview and a short analysis of typical elements of a hybrid powertrain system is presented.

3.1. Electrical Machines

Electrical machines with Nd-Fe-B permanent magnet (PM) excitation are recognized to be the most suitable candidates for the HEV generator applications. Several configurations of magnetic circuits can be identified in the broad category of Permanent Magnets (PM) machines. Recent applications demonstrate the increasing attention for slotless-winding axial-field PM machine (AFPM) topology. Use of a slotless winding arrangement presents unique features including the elimination of stator teeth losses, torque pulsation, acoustic noise and high-frequency losses in the solid-rotor structure. Adoption of such a particular PM machine arrangement in ICE-driven generators allows higher torque per volume density and higher efficiency compared to conventional machine topologies (Crescimbini, 2003). Nowadays, the permanent magnet machine and the induction machine are both commonly considered for hybrid applications. Since magnet costs are due to decrease in the future, a shift towards PM machines is expected (Walters, 2001).

3.2. Inverters and Power Control Systems

Inverters are devices used in hybrid vehicles to boost the voltage from the battery and convert this boosted DC power into AC power for driving the motor (Toyota, 2003a). The strategy for future power inverters will have to move towards the ideal inverter with minimal losses and a small package size. Unless new device technologies emerge, high voltage applications will use semiconductor switching technology with Insulated Gate Bipolar Transistor (IGBT) due to its relatively high switching frequency capability and low losses. Low voltage systems will consider metal oxide semiconductor field effect transistors (MOSFETs) for lower resistance characteristics and lower cost. The future machine controller will guarantee the higher possible efficiency and ensure that the desired response characteristics of the drive can be met. For many applications, a vector control based strategy is appropriate due to the need for relatively fast response characteristics. However, as the Toyota Prius has demonstrated, other systems may not require that level of response and a combination of several control strategies can be successfully employed (Walters, 2001).

Studies demonstrate the viability of using single phase, high frequency alternate current (AC) systems due to its superiority rather than direct current (DC) systems (Bose, 1996). High frequency AC has the singular advantage of soft-switching of the devices at zero voltage with consequent switching loss elimination, higher reliability, less electro-magnetic interference, absence of acoustic noise and less acceleration stress on EM insulation. The distribution voltage, which is independent of battery voltage, can be isolated and regulated to a higher level, which permits optimal design of battery, converters and the EMs. Although the system needs the additional resonant inverter and high frequency step-up transformer, the latter can make the auxiliary power supplies for the vehicle very economical. The overall component sizing calculations of the DC and AC systems indicate some advantage of cost and efficiency of the AC system.

3.3. Energy Storage Systems

In the last decade, the use of nickel metal hydride (NiMH) or lithium ion (Li-Ion) battery technologies (Walters, 2001) was generally considered as energy storage system in hybrid vehicles. These technologies are preferred to traditional lead acid (PbA) technology and to nickel cadmium technology for reasons of energy density, power density, and power output at low state of charge. Clearly, Li-Ion and NiMH have much higher specific power than PbA technology, meaning that they will result in a much lighter battery pack for a given set of specifications. Higher specific power also means that NiMH and Li-Ion are much able to accept the high peak power levels associated with regenerative braking. Often this factor drives a lead acid battery pack to increased size and weight. At present, NiMH is four to five times more expensive than lead acid batteries. Li-Ion batteries, while being expensive at the time being, are viewed as having the potential to become cost competitive in high volumes over time. Li-Ion batteries require more monitoring than NiMH due to undesirable overcharge and over-temperature characteristics. NiMH batteries are more suitable from this standpoint due to its inherent internal charge balancing, although there are still thermal runaway characteristics that require a cooling system. NiMH batteries also demonstrate severe output power degradation at low temperatures.

The battery pack design is extremely important and requires careful system analysis to determine the proper strategy. In sizing battery packs for hybrid vehicles, the required peak power becomes a dominant concern. Power flow from regenerative braking and to motor demand sets the power rating that the battery pack must meet. The power requirement is further defined by the expected performance in low temperature. This is in contrast to electric vehicles where the energy capability drives the battery pack design due to the desire to maximize the vehicle autonomy. Voltage is also important to consider since for a fixed power requirement, a higher voltage system will decrease the current requirements, which can reduce losses, diminish the required battery volume and save cost in connectors and wires. Since NiMH battery performance is poor at low temperature, a NiMH pack would have to be made significantly larger to meet the cold-cranking requirements of the engine. By using a 12 V lead acid battery and a cranking motor, this cost is avoided. In terms of dual-machine vehicles, significantly more power and energy are required. Vehicle launch requires substantially more torque than engine cranking. Both also need extra capacity for assisting the engine during an extended hill climbing.

Recent studies demonstrate that for small or medium vehicles, Li-Ion systems are more suitable for mild hybridization level, while NiMH systems have better overall performance in medium-high hybridization levels (Balch, 2001). For the near future, in general, a NiMH system is preferred while lithium ion technology is considered for long lead future (Walters, 2001 and Koehler, 1996). Both systems are liquid-cooled and require significant vehicle space. With NiMH technologies, the challenge of cold performance is clearly seen in terms of having an over-designed battery pack or of having a separate starting system. Lithium ion packs offer the possibility to reduce battery size by alleviating the cold power performance issue at the expense of a more careful battery management (Walters, 2001).

The battery pack for future vehicles would ideally have a high power-to-weight ratio, be inexpensive, thermally robust and have a high coulombic efficiency to allow maximum reuse of regeneration. Lithium ion technology has most of these characteristics with the exception of the battery management. This however is being worked on by industry and assuming no material regulation issues arise it promises to be an attractive technology (Walters, 2001 and Koehler, 1996).

It is important to point out that ultra-capacitors have also being considered for powering hybrid vehicles. Simulations in several vehicles indicate that such systems could be used replacing batteries packs in hybrid/electric vehicles. Projections for energy density based on materials and dimensional characteristics combination indicate the possibility to reach energy densities similar to those available in batteries with the continuity of development in ultra-capacitors materials (Burke, 1996). However, they were not exhaustively tested in real conditions regarding to durability and reliability, so an immediate application in a mass production HEV is highly unlikely (Yamagushi, 2001).

3.4. Internal Combustion Engine

The ICE choice for HEVs requires a careful study of its operation characteristics along with the EM to be used. Required characteristics for torque and power are a direct result of the class and level of hybridization to be adopted. In consequence, a light hybrid using an integrated starter/generator should have an engine with characteristics close to that used in a conventional vehicle. In the other extreme, in a parallel energy-hybrid the ICE will be much smaller and based on propulsion EMs and battery capacity.

Due to HEVs extra weight, the future engine strategy must provide a very efficient, low mass, high-output engine. Presently, turbocharged compression-ignition diesel-injected (CIDI) engines with common rail fuel injection look attractive as long as they are not excluded by emissions regulations in the target market. Challenges still exist in reducing NO_x and particulate matter. A gasoline direct-injected engine, perhaps turbocharged, may also be competitive by allowing leaner operation and higher performance without the challenges of NO_x and particulate matter removal (Walters, 2001).

4. Case Study

In this section, a new hybrid powertrain is proposed and evaluated. Some economical aspects are next pointed out to set a line guide to the case study.

According to the Brazilian Institute of Public Opinion and Statistics (IBOPE), in 2000, 99% of the C class and 94% of D class population in Brazil owned, at least, one television set in their homes, however, car ownership were rare in that population classes (FECAP, 2001). Moreover, in Brazil, federal taxes over vehicle ownership are subject of complicated policy that recently reduced and revised taxes rates several times, creating no conditions for strategic planning. In addition, there is no tax incentive in Brazil for fuel consumption reduction that could create advantages for HEVs over other vehicles.

In environmental aspects, the National Environmental Council (CONAMA) created the Program for Control of Atmospheric Pollution from Vehicles (PROCONVE), which was considered one of the best-elaborated programs for mobile sources emission's control. The Environmental Sanitation Technology Company of São Paulo (CETESB), the technical company responsible for PROCONVE implementation and operationalization, fitted international methodologies to Brazilian requirements and developed the technical base to reduce the atmospheric pollution generated by motorized vehicles. This served as basis for the CONAMA's program. The conclusion of program implementation is schedule to 2011, when a drastic reduction of pollution is foreseen (CETESB, 2004).

4.1. Propulsion System Design

While designing a vehicle propulsion system, the constraints commonly imposed on sizing the components are: the initial acceleration, maximum speed and road grades. HEV performance depends on the rate of hybridization, which is defined as the ratio between electric power and the total propulsion power expressed in percentage. Hybridization of the powertrain increases total vehicle weight and, therefore, increases the acceleration time.

A comparative study between parallel hybrid control concepts indicates that hybrids with higher hybridization rates have better fuel economy and reduction in hydrocarbons (HC) and NO_x emissions even though the weight increases. Additionally, the use of an electrically assisted control strategy leads to lower carbon monoxide (CO) emission. This strategy uses the ICE as main power source in high efficiency operation points and the EMs only in cases where the ICE works inefficiently or additional power is required (Rahman, 2000).

4.2. Proposed Architecture

Medium passenger vehicles are the higher sales volume in world market. In this category, sedans models are more appropriate for hybridization since the extra volume required by additional hybrid systems could use part of the luggage compartment, minimizing adverse effect on payload. Among models available in Brazilian market, Chevrolet Vectra was chosen for a hybridization study because of its technical characteristics, time in market and technical data availability.

The definition of a special configuration demands a deep analysis of existing architectures, restraining it to commonly adopted solutions, which favorably limits both analysis effort and possible combinations. Table 1 shows major configurations, its effects and main features.

Table 1 – Hybrid systems features and effects (Toyota, 2003a and Husted, 2003).

	Fuel Economy Improvement				Overall Vehicle Performance Effect			
Configuration	Idling Stop-Start	Regenerative Breaking	High Efficiency Operation Control	Electric Propulsion	Engine Vibration Damping	Vehicle Launch	Continuous High Output Power	Additional Power
Series Hybrid	Superior	Excellent	Superior	Excellent	-	Somewhat unfavorable	Somewhat unfavorable	-
Mild Hybrid (belt-driven)	Superior	Reduced	Somewhat unfavorable	-	-	Superior	Somewhat unfavorable	-
Mild Hybrid (ISG)	Superior	Superior	Somewhat unfavorable	-	Excellent	Superior	Somewhat unfavorable	Reduced
Power Hybrid (Series/Parallel)	Excellent	Excellent	Excellent	Excellent	-	Superior	Superior	Superior

From Tab. 1 analysis, it can be observed that power hybrid is superior or excellent in most of the listed features. Only in engine vibration damping it is not favorable. Power hybrids with series/parallel configuration are also commonly used in latest power hybrid vehicles launched recently (Ford, 2004 and Toyota, 2003a). ICE capacity to drive the vehicle and charge the batteries or drive the propulsion EMs, through the generator, gives to this configuration good efficiency in high speed cruising conditions or low speeds transients situations. A reasonable selection is thus the Toyota Prius architecture.

Toyota Prius, the selected template for the vehicle model, uses a distributed control approach. In this approach, each component has it owns individual control, managed by a central hybrid control and communication is performed through a Controlled Area Network (CAN). The hybrid control system for the proposed vehicle will determine, coordinate and control the following events (Kosowski, 2000):

- Traction control in EMs and ICE in both forward and reverse speed selections;
- Breaking torque distribution between EM regenerative and hydraulic breaking systems;
- Starting and stopping of the ICE to reduce emission and fuel consumption;
- Traction torque distribution between EM and ICE, according to acceleration and speed required by the driver.

5. Simulations and Results

To validate and evaluate results from the proposed model, the software ADVISOR 2002 (ADVISOR, 2002) was used. It allows simulation of different configurations and architectures of electric, hybrids or even conventional vehicles. This system – based on an empirical approach – uses powertrain components performance to estimate the vehicle's fuel consumption and emissions in a given traffic cycle as well as vehicle acceleration capacity in maximum effort.

Analyzing the software, recent studies demonstrate that results precision differs only 0.8% for acceleration time and 1.9% for energy use (Wipke, 1998), when compared to real vehicles tests. However, other study, using the software ADVISOR version 3.1, specifically for the Toyota Prius 1997, demonstrates that some considerations on the empirical model must be revised to ensure better model results (Weihua, 2002). This study still indicates that the cited software version does not accomplish cold start conditions, causing major results divergences in some traffic cycles, demanding cold start.

Through simulation results analysis for Toyota Prius, it can be realized that ADVISOR is not precise in atmospheric emissions results as well (DOE - USA, 2001). Even so, these problems do not invalidate the software use to compare new constructive solutions.

5.1. Toyota Prius Review and Modifications

Simulation results presented next were obtained using a modified model of the Toyota Prius available in ADVISOR 2002. The original model in ADVISOR was first submitted to a critical evaluation regarding its accuracy. This leaded to a number of changes based on new technical data available in references for Prius models launched up to 2004 (Sasaki, 1998; Chang, 2002; ADVISOR, 2002; Toyota, 2003a and 2003b). Still, the traffic model was the New European Driving Cycle (NEDC), used to demonstrate the significantly improved results. The first change was performed in the maximum speed parameter in which the Prius ICE remains off. It was redefined to 45km/h according to ADVISOR 2002 descriptions. In addition, the regenerative breaking model was revised with new parameters to match the 90% application as in Toyota, 2003b. Results are listed in Tab. 2.

Table 2 – Mathematical model emissions and fuel consumption reductions due to changes performed.

Model Change	Fuel Consumption (km/l)	Battery Final State-of-Charge (SOC)	Emissions (g/km)			Reductions compared to Initial Review (%)				
			HC	CO	NO_x	Fuel	SOC	HC	CO	NO_x
Initial Review	17.2	0.58	0.164	0.195	0.106	-	-	-	-	-
Breaking/ Max. Speed	18.9	0.60	0.156	0.203	0.106	-9.4	3.4	-4.9	4.1	0.0
Power	19.6	0.58	0.154	0.199	0.103	-13.7	0.0	-6.1	2.1	-2.8
Feedback	24.4	0.56	0.137	0.167	0.079	-29.3	-3.4	-12.2	-17.7	-25.5

Another parameter checked and modified was the of overall car power limit which defines the starting point beyond that the ICE must apply its maximum torque. This parameter was set around 15kW, forcing the engine to work in full load even when not necessary. This was also modified to make the ICE to work in full load only when the engine acceleration exceeds a minimum established value.

In further investigations on the ICE original model simulation, a system feedback for engine load was revealed. This feedback uses the average speed between the previous and current instants to predict what will be the engine load in the next instant, adding extra inertial load and, consequently, allowing the engine to have additional torque to improve its general performance. It is clear that this method creates additional load that does not really exist, producing excessive torque available in the output engine shaft. Results are oscillation in system outputs. Removing the feedback, it causes a significant reduction in ICE load, emissions and fuel consumption.

The result for all proposed improvements is 29% in fuel consumption for the analyzed cycle. Emissions can be potentially reduced up to 12% for hydrocarbons, 18% for carbon monoxide and 26% for nitrogen oxides. Final state-of-charge in the battery has a reduction around 3%.

5.2. Model application in Chevrolet Vectra

In this study, the goal is that the acceleration performance defined for the designed vehicle be equal or greater than the standard vehicle to be hybridized. The Vectra 2.0 holds 11s to accelerate from 0 to 100km/h, maximum speed of 193km/h in flat, urban fuel consumption of 10.2km/l, road fuel consumption of 14,5km/l and average fuel consumption of 12.1km/l. Payload capacity is 530kg, summing a total mass of 1,800kg for the vehicle.

Due to absence of a specific model in ADVISOR for the proposed Vectra with hybrid systems, the Toyota Prius mathematical model was used instead, with some proposed improvements analyzed previously already included. As much as possible, some parameters were changed in order to make the existing model compatible to the proposed one. Major changed characteristics were the vehicle total mass and its distribution, aerodynamics aspects, final axle ratio and tires diameter. The U. S. Federal Test Procedure (FTP) was used since it is also adopted by CONAMA in Brazil as the standard procedure in PROCONVE (CETESB, 2004).

A closer analysis of the model reveals that the 1:5 axle ratio is near to the optimal ratio in the proposed model. This relation was then employed in the case study.

Available ICEs were simulated and results compared against the original model, as shown in Tab. 3. An overall analysis demonstrates that the proposed architecture with e-CVT showed problems with acceleration (up to 46% slower) and gradeability (up to 63% lower). These results can be explained by the fact that axle ratio in lower speeds is smaller than in the original manual transmission from Vectra 2.0. In opposite, hybrids fuel consumption is, at least, 24% lower and 80 to 120km/h flexibility is, at least, 16% higher than original model. ICEs indicated with “ME 49kW” in Tab. 3 have an alternative EM with higher power installed instead of the original EM with 30kW.

Table 3 – Simulations results of different engines applied in Vectra model.

Vectra Engine Simulated	Power (kW)	Payload (kg)	Engine volume (cm^3)	Axle Ratio	Fuel economy (km/l)	Maximum Speed (km/h)	Acceleration (s) 0-100 km/h	Acceleration (s) 80-120 km/h	Gradeability (%)
Original ICE 2.0	81	530	1,998	4.17	12.1	193.0	11.0	14.6	N/A
Prius ICE 1.5	41	470	1,500	5	22.2	137.7	16.1	12.1	11.9
ICE 1.9	63	400	1,900	5	17.5	137.2	14.0	9.4	15.7
ICE 1.5 (EM 49kW)	41	470	1,500	5	21.7	176.7	15.8	11.8	12.3
ICE 1.9 (EM 49kW)	63	400	1,900	5	17.2	195.1	13.3	9.1	16.2

Final simulation results are much higher than those obtained originally and rank the last solution as the most appropriate for the proposed model. Compared to original Vectra 2.0, disadvantages are a reduction of 25% in payload capacity and an increase of 21% in time for 0 to 100km/h acceleration. Advantages include final speed 1% higher, reduction of 38% in flexibility time and 42% in fuel consumption. All those benefits are associated to an ICE 22% less powerful than the original.

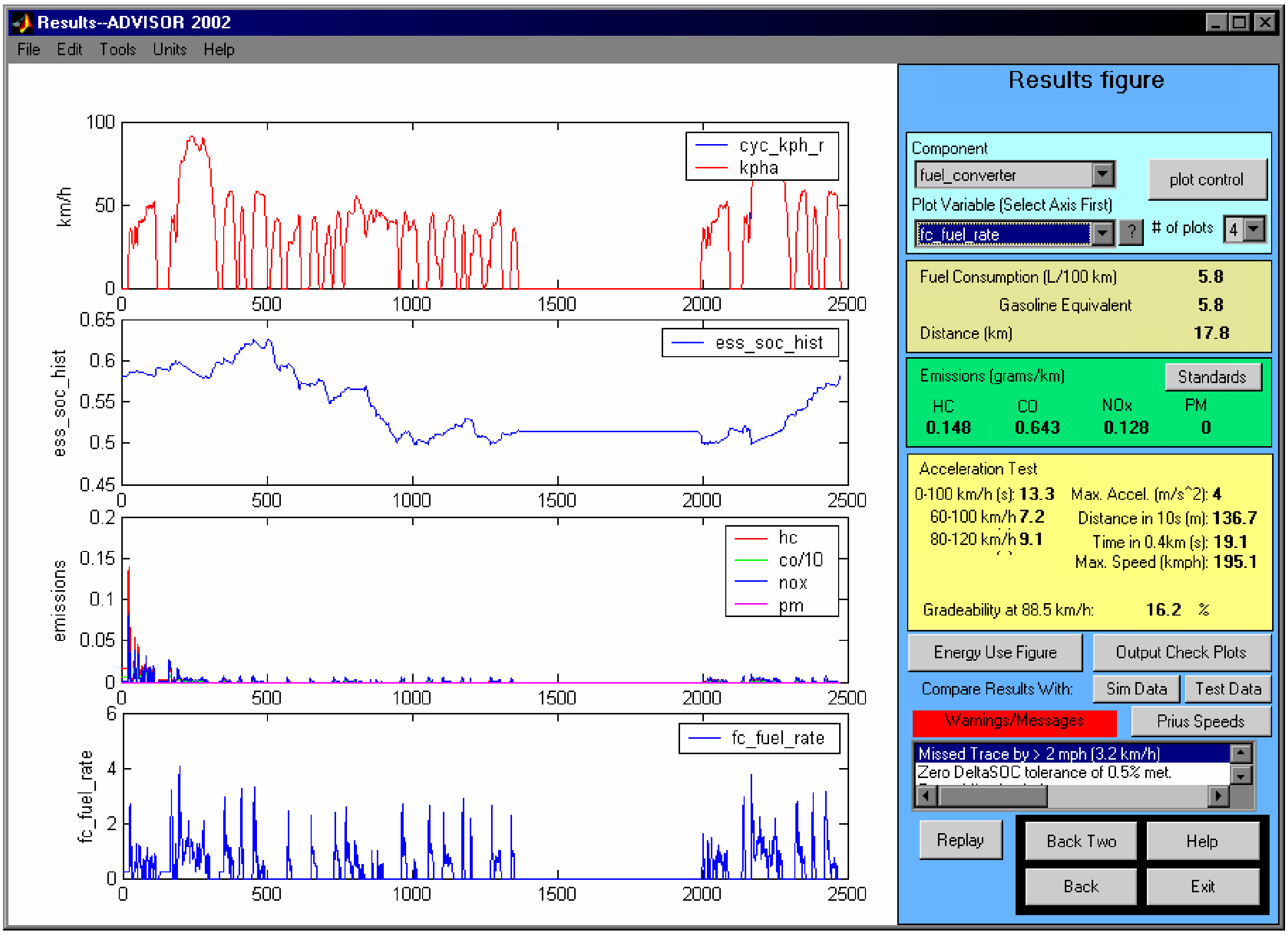

Figure 1. Results from ADVISOR for simulation of Vectra Hybrid with ICE 1.9 and EM with 49kW. Graphics curves represent model speed against cycle demand, SOC of battery pack, emissions produced over driving cycle and fuel consumption rate by ICE. Data in right side shows final values for the simulation.

This validates the initial proposal for model hybridization, affected only by the lack of more precise data regarding engines to match the hybrid model. A lighter ICE would improve payload capacity and would possibly reduce the total acceleration time.

6. Conclusion

Hybrid vehicles and associated systems demonstrate its maturity level and capacity to an immediate application and consequent benefits for existing vehicles.

Simulations performed confirm beneficial foreseen in conventional models hybridization and validate the proposed solution, although difficulties to get some actual test data. Hybridization proposal resulted in superior performance when compared to the conventional model. The hybrid model has an ICE 22% less powerful, a drawback of 25% in payload reduction and 21% in higher time for 0 to 100km/h acceleration. Advantages are final speed 1% higher, flexibility time 38% lower from 80 to 120km/h and fuel consumption 42% lower.

Further improvements could be achieved focusing on the replacement of powertrain components such as ICE, EMs, battery pack, or changing vehicle dynamics characteristics.

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8. Responsibility notice

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