EVS25
Shenzhen, China, Nov 5-9, 2010

Optimization of Propulsion Systems for Series-Hybrid City Busses through Experimental Analysis.

Thierry Coosemans[1], RicardoBarrero[2], Jean-Marc Timmermans[3] and Joeri Van Mierlo[4]

[1,2,3,4] *Vrije Universiteit Brussel, IR-ETEC, Pleinlaan 2, B-1050 Brussel, Belgium*
Tel: +32 2 629 2800, +32 2 629 2803. FAX: +32 2 629 3620
thierry.coosemans@vub.ac.be

Abstract

This article describes a methodology for the optimization of hybrid propulsion systems combining an on-road measurement campaign with the development of a simulation tool. This methodology has been applied in particular on a series-hybrid city bus. The experimental set-up and the software tool are presented. The measurement setup is based on a National Instruments-cDAQ data acquisition system, containing a real-time programmable embedded processor. The software model is mainly based on the 'backwards-looking' or 'effect-cause' method which calculates the energy consumed by a vehicle following a predefined driving cycle by going upstream the vehicle components. Experimental as well as simulated results are presented. The developed simulation tool is assessed and refined by means of the experimental data obtained during the thorough on-road measurement campaign. Suggestions for an improved and more efficient power flow control strategy for series-hybrid city busses are given. - *Copyright Form of EVS25*.sz

Keywords— Efficiency, Series Hybrid Vehicles, Power Flow Control Strategy

1 Introduction

The future shortage of fossil energy resources as well as the daily increasing evidence of global climate changes, urge many to decrease energy consumption. The automotive industry forms no exception: hybrid and electric cars are slowly but surely making part of the street scene. On short term, hybrid vehicles seem to be most adequate alternative technology for the classical combustion-based vehicles, at least when somewhat larger distances need to be covered [1, 2]. They have proved their validity when it comes to improve the vehicle efficiency and reduce their consumption and exhaust emissions [3]. Several hybrid topologies, parallel, series and combined, have been developed in order to improve the vehicle's overall efficiency and, in some cases, the driving performances. No topology is superior to all others in all circumstances, hence the drive train configuration has to be chosen in function of the type of vehicle as well as its use [4]. Once the topology is chosen, an adequate power flow control strategy has to be applied in order to optimize for efficiency and performance [5]. The developement of such a strategy requires an accurate simulation tool that mimics the power flow within the propulsion system of a moving vehicle. In order to fine-tune such a tool, power measurements on an on-road vehicle are indispensable: they show the behaviour of the propulsion system under real circumstances and hence allow one to fully characterize the drivetrain components. This article describes a methodology for the optimization of hybrid propulsion systems combining an on-road measurement campaign

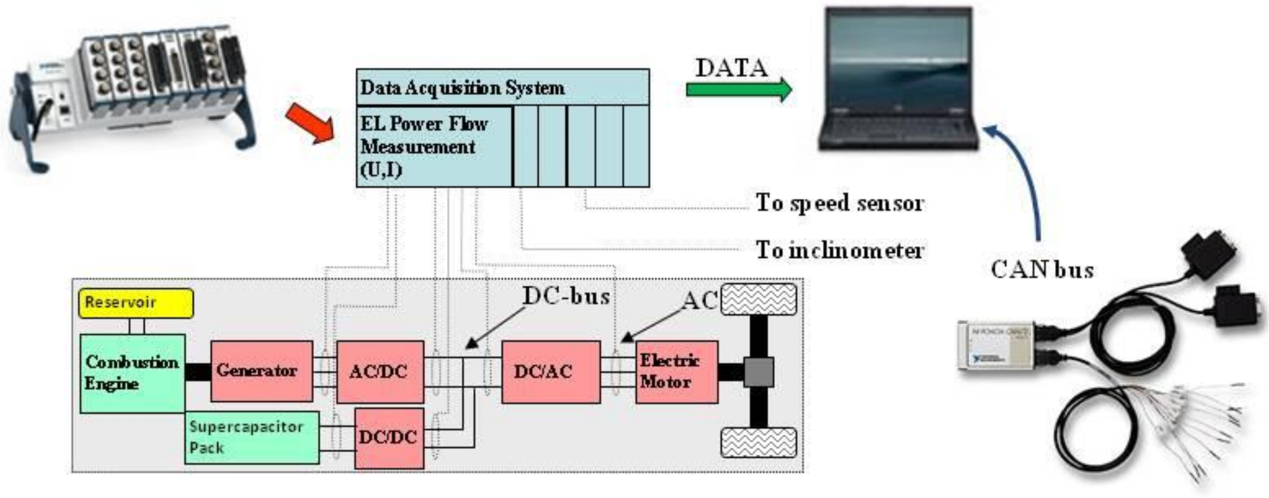

Figure 1: series hybrid structure using supercaps and scheme of the measurement

with the development of a simulation tool. This methodology has been applied in particular on a series-hybrid city bus. The experimental set-up and the software tool are presented, as well as experimental and simulated results.

2 Experimental setup

A typical topology for a series-hybrid vehicle can be found in figure 1. The wheels are directly driven by the electric motor. The motor is fed by the generator or by a Rechargable Electrical Storage System. In the particular case of the studied city bus, the RESS consists of a supercapacitor package that serves as a peak power unit catering for the breaking and acceleration peaks.

Table 1: overview of analog sensors

Parameter	Sensor	Range	Accuracy
AC and DC Voltage	LEM Transducer	-1500V to 1500V	± 0.2%
AC and DC current	LEM Transducer	-300A to 300A	± 0.05%
Inclination	Mems-based	-60° to 60°	± 0.05%
Speed	Optical	0-400km/h	± 0.5%

The Internal Combustion Engine runs on diesel. For monitoring the power flow within the drive train, the electric power flow between the different components has to be measured (DC and AC, see figure 1). In addition, mechanical parameters such as the speed and inclination of the vehicle and the r.p.m. of the combustion engine need to be recorded during on-road measurement campaigns.

The heart of the setup consists of a National Instruments-cDAQ data acquisition system, containing a real-time programmable embedded processor. The modular build-up of the NI-cDAQ allows one to connect it to a multitude of sensors and interfaces, both analog and digital. In parallel, the Controller Area Network (CAN) bus of the vehicle is monitored via a PCMCIA module. The data retreived by the NI-CDAQ and the PCMCIA are synchronyzed and stored simultaneously on PC. The AC and DC voltages and currents in the propulsion system are measured by means of LEM transducers at a maximal sample of rate 100Ks/s. The speed of the vehicle is measured with an optical sensor while the inclination (pitch) is sensed by a MEMS-based device. An overview of the used analog sensors for the concerned measurement campaign is given in table1. The relative high sampling rate and the good synchronisation of the sampling channels allows one to monitor PWM signals and phase-related parameters such as the power factor of an AC current.

3 Software tool

The software model is mainly based on the 'backwards-looking' or 'effect-cause' method [6,7], which calculates the energy consumed by a vehicle following a predefined driving cycle by going upstream the vehicle components and accounting for their losses depending on the working point (figure 2). However for certain drive cycles, or under some circumstances, the power (or another quantity such as current, torque, etc.)

requested to a vehicle component, is higher than the component rating, and the vehicle is not able to satisfy the drive cycle. To overcome this problem, a 'forward-looking' module is implemented in the model. This module calculates the power stream forwards as soon as any of the vehicle components is requested a

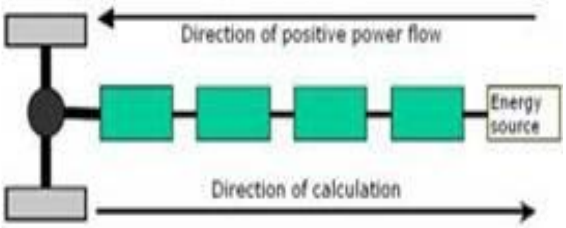

Figure 2: direction of the calculation for the effect-cause method

power (or another magnitude) level out of its working region. It will eventually calculate the actual speed and fuel consumption of the vehicle. Different power flow control strategies are implemented and compared.

4 Experimental results

An extensive measurement campaign has been carried out on a 12 meter hybrid city bus, for different drive cycles. The obtained results are used to refine the model of the propulsion system and to evaluate its global working and the interaction between its components. The monitoring of the power flow at several points in the propulsion system allows one to obtain a clear view on the efficiencies of the drive components in real conditions. These efficiencies are implemented as look-up tables in the software model. Also one can assess whether the propulsion system acts following the implemented power flow algorithm. An example of a measurement can be seen in figure 3, where the power of the electric motor and the speed of the vehicle are shown.

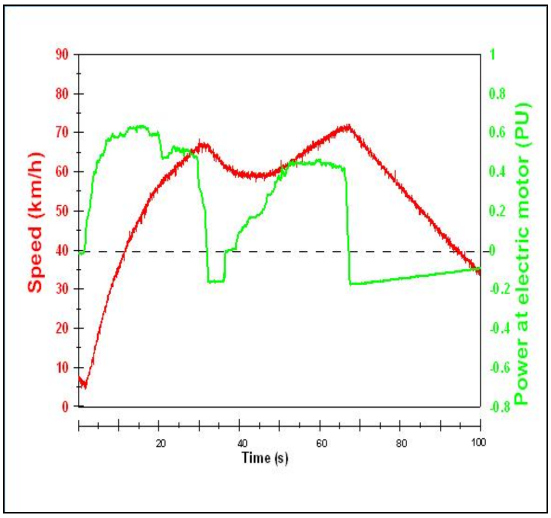

Figure 3: Normalized power at the electric motor, as well as the speed profile of the bus. It can clearly be seen that with increasing speed, the motor is delivering power to the wheels (positive). While slowing down, the motor delivers power back to the propulsion system (negative).

5 Simulation results

After the refinement of the characteristics of the propulsion components, different power flow strategies are investigated. The energy consumption efficiciency for a typical drive cycle of a bus in the city of Brussels is used as a test case. This includes frequent stop-and-go behaviour as well as several gentle slopes. The speed cycle,

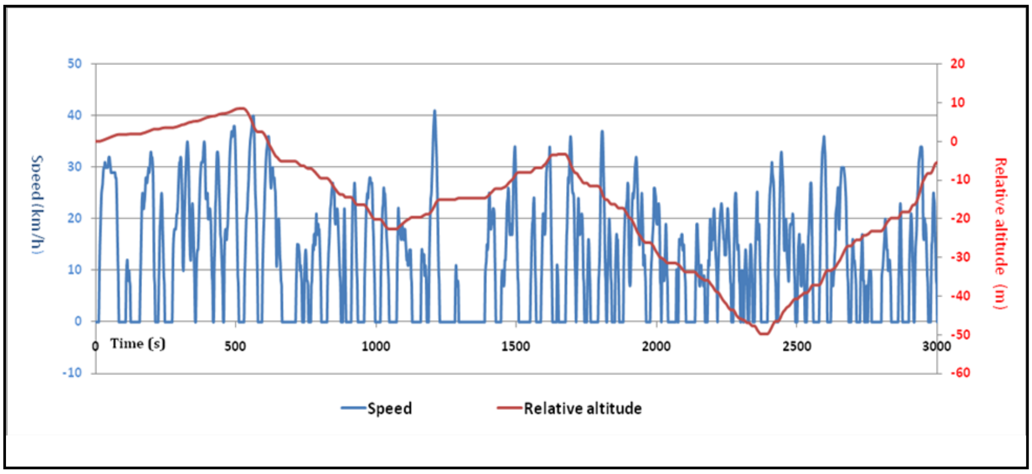

Fig 4: Part of the drive cycle under investigation

as well as the change in altitude, is partially depicted in figure 4.
Two power flow strategies which can be applied are discussed. Their effect on the power flow distribution is shown in figures 5a and 5b. In figure 5a, the so-called 'Kinetic Strategy' is explained. The aim of this strategy is mainly to recover the braking energy of the vehicle to improve its energy consumption. The supercaps energy is handled in function of the speed. This means that the energy that can be recovered by braking, should be able to charge the supercaps fully again. Hence the energy stored in the supercapacitors, between their allowed minimal and maximal State-of-Charge (SoC), should at least equal the maximal kinetic energy of the bus, reduced with a factor due to the losses during the recovery of the braking energy. The braking energy stored in the supercaps can be used to 'shave' the ICE power peaks during the acceleration. However the ICE will still follow the vehicle load, and will certainly not continuously function at its most efficient working point, and hence the ICE efficiency is not significantly improved. The strategy illustrated in figure 5b tackles this problem. During the 'ICE on-off strategy' the combustion engine only runs when the state of charge of the supercaps is below a certain limit and moreover the ICE is run at its most efficient working point. In order to assess and compare the energy efficiency of both strategies, the energy consumption was simulated for different sizes of supercap packages, for both strategies. For the smallest supercap package the used energy capacity of the caps equales the maximal kinetic energy of the city bus, or:

$$\frac{1}{2}C(V_{\max}^2 - V_{\min}^2) = E_{\max}^{kin} \qquad (1)$$

With C the totale capacitance, Vmax and Vmin, the maximal and minimal used voltages of the supercaps. Two other configurations are taken into account: a supercap package storing twice the maximal kinetic energy of the bus, and a supercap package storing four times the kinetic energy of the bus. The results in terms of consumption reduction with respect to a comparable, classical, ICE-based diesel bus, can be seen in tables 2 and 3. For the calculations in table 2 we ignored the slopes and considered the road to be flat. Here it is seen that for the smallest package the reductions are similar. However, for increasing size of the caps package, the energy consumption is further reduced in case of the ICE on–off strategy while it slightly increases for the kinetic strategy. This is due to the fact that for the on-off strategy the excess of power produced while the ICE is running at its ideal working point, is stored in the supercaps. The larger supercaps assure the necessary storage capacity. For the kinetic strategy no more than the maximal kinetic energy needs to be stored, and further upsizing of the supercaps only increases the weight and the power consumption of the bus. In case of a more hilly road we can see that the divergence between both strategies becomes even larger. This is due to the fact that the kinetic strategy does not account for the gain of potential energy while ascending a slope, since it only considers the speed of the vehicle. In fact, the ICE on-off strategy neither does take this gain of potential energy into account, but the gain in energy while descending the slopes is stored in the increased supercap packages. The ICE on-off strategy is clearly more adequate for a more hilly track.

Table 2: Consumption reduction for different strategies taking for a drive cyle without slopes.

Strategy	**1X E_{kin}**	**2X E_{kin}**	**4X E_{kin}**
Kinetic	24%	23.5%	23%
ICE on-off	25%	30%	32%

Table 3: Consumption reduction for different strategies taking for a drive cyle including slopes.

Strategy	**1X E_{kin}**	**2X E_{kin}**	**4X E_{kin}**
Kinetic	17%	16%	14%
ICE on-off	25%	33%	35%

6 Conclusions

An adequate methodology for the optimization of hybrid drivelines has been developed. The developed simulation tool has been refined by means of experimental data obtained during a thorough on-road measurement campaign. The influence of an adequate power flow strategy on the energy consumption of a diesel series-hybrid bus is assessed , while taking into account the topology of the road during a typical drive cycle for a city bus.

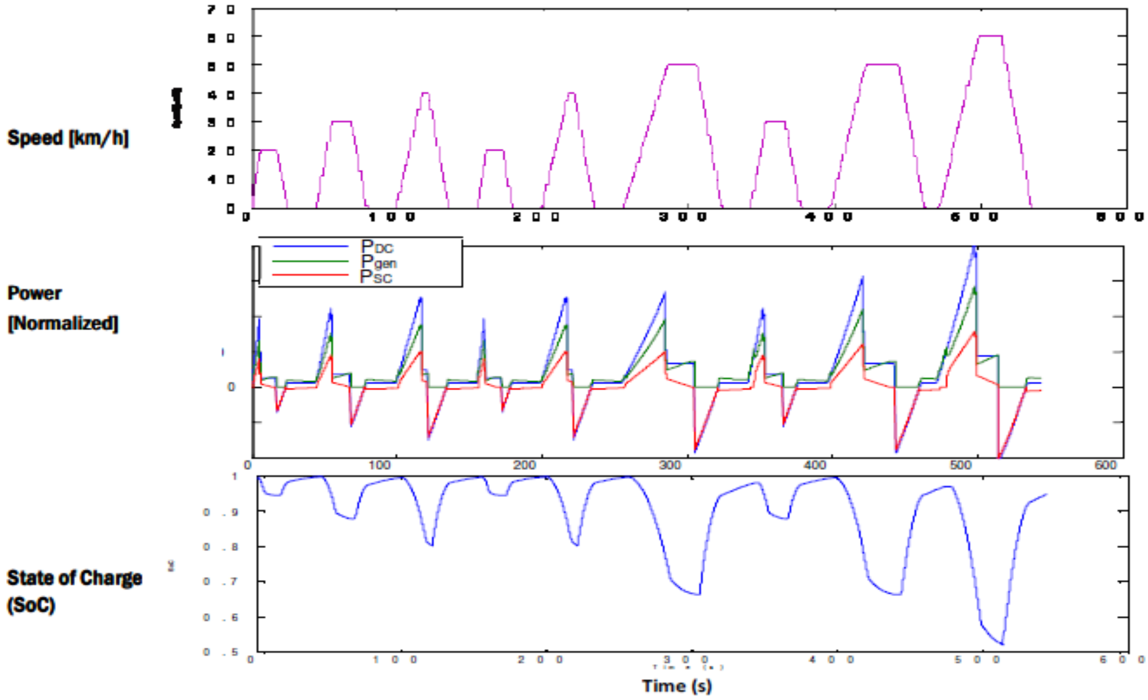

Figure 5a: power flow when kinetic strategy is applied

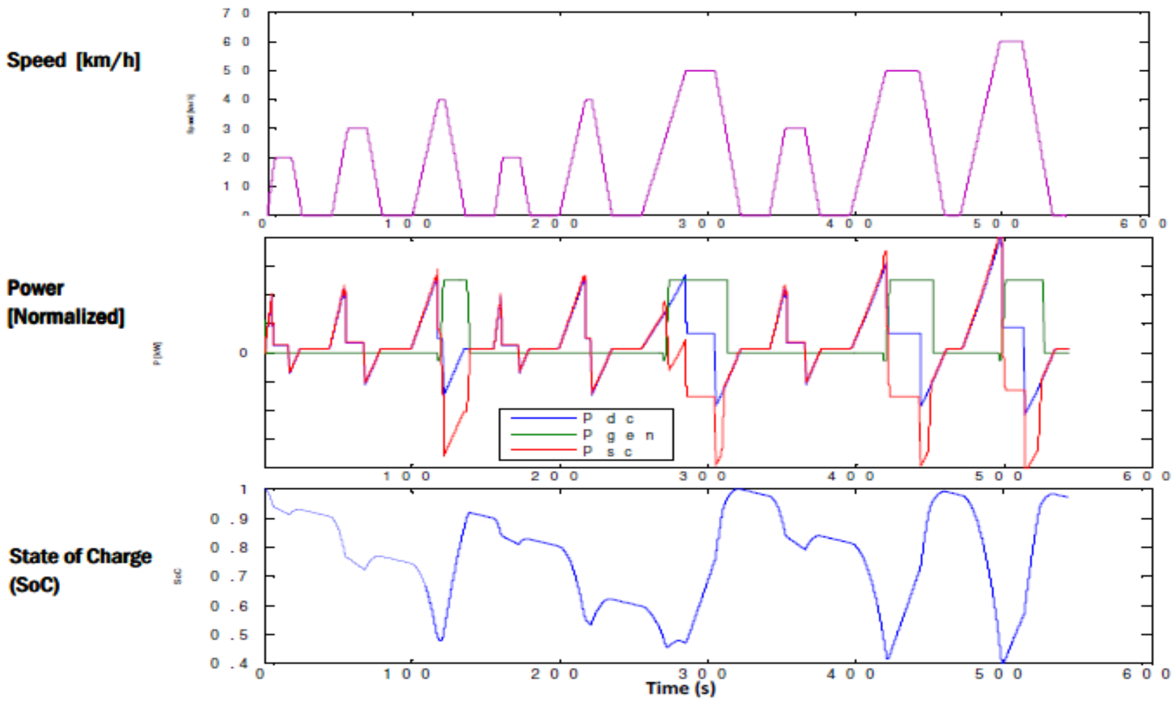

Figure 5b: power flow when ICE on-off strategy is applied

References

[1] Van Mierlo J, Maggetto G, et al., "Which energy source for road transport in the future? A comparison of battery, hybrid and fuel cell vehicles.", Energy Conversion and Management, Vol 47, Issue 1, Pg 2748-2760, Octobre 2006

[2] Chan C.C., 'The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles', Proceedings of the IEEE, Volume 95, Issue 4, April 2007, Page(s):704 – 71

[3] Van Mierlo J, Maggetto G, et al., "How to Define Clean Vehicles? Environmental Impact Rating of Vehicles", International Journal of Automotive Technology (IJAT), KSAE,SAE, isbn 1229-9138, Vol 4, Nr 2, Pg 77-86, 2003

[4] Emadi, A.; Rajashekara, K.; Williamson, S.S.; Lukic, S.M., 'Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations', IEEE Transactions on Vehicular technology, Volume 54, Issue 3, May 2005 Page(s): 763 – 770

[5] Chau K.T, Wong Y.S., 'Overview of power management in hybrid electric vehicles', Energy Conversion and Management, Volume 43, Number 15, October 2002 , pp. 1953-1968(16). Elsevier

[6] Barrero R, Coosemans T, Tackoen X, Van Mierlo J, 'Hybrid buses: defining the power flow management strategy and energy storage system needs', EVS24, Stavanger, Norway, 2009.

[7] Van Mierlo J, Maggeto G, 'Innovative iteration algorithm for a vehicle simulation program', IEEE transactions on vehicular technology. vol 53 (2). pg 401-412. MAR 2004

Authors

Dr. Thierry Coosemans
Vrije Universiteit Brussel
Email: thierry.coosemans@vub.ac.be
Tel: +3226292800 Fax: +3226293620

Thierry Coosemans obtained his PhD in Engineering Sciences from Ghent University in 2006. After several years in the industry, he now became a member of the ETEC research team on transport technology at the VUB. His research topics include the assessment of HEV propulsion systems.

Dr. ir. Jean-Marc Timmermans
Vrije Universiteit Brussel
Email: jptimmer@vub.ac.be
Tel: +3226293804 Fax: +3226293620

Jean-Marc Timmermans graduated in 2003 as an Electromechanical Engineer at the Vrije Universiteit Brussel. As an academic assistant, he was involved in several projects related to the evaluation of the environmental impact of both conventional and alternative vehicles and was involved in the development and evaluation of electric bicycles for postal delivery use. In 2010 he obtained a PhD at the Vrije Universiteit Brussel.

Ricardo Barrero
Vrije Universiteit Brussel
Email: ricardo.barrero@vub.ac.be
Tel: +3226292839 Fax: +3226293620

Ricardo Barrero obtained the M.S. degree in electronics and industrial automation engineering from the Universidad Pública de Navarra, Spain in 2004. He is currently pursuing the Ph.D. degree in the department of electrical engineering and energy technology (ETEC), at the Vrije .Universiteit Brussel, Belgium. His research interests include applications of super capacitors in HEVs and public transportation.

Prof Dr. ir. Joeri Van Mierlo
Vrije Universiteit Brussel
Email: thierry.coosemans@vub.ac.be
Tel: +3226292803 Fax: +3226293620

Joeri Van Mierlo obtained his PhD in Engineering Sciences from the Vrije Universiteit Brussel. Joeri is now a full-time lecturer at this university, leads the MOBI - Mobility and automotive technology research group.mHis research interests include vehicle and drive train simulation, as well as the environmental impact of transportation.