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Technical Assessment of Hybrid Powertrains for Energy-efficient Heavy-Duty Vehicles

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Abstract

This article presents the approach used for the design optimization of heavy vehicles such as urban buses and delivery trucks as a part or the ORCA European Project. A methodology to find the optimal combination of hardware components and energy management strategy is presented and the use cases where it will be applied are described.

To achieve the optimal results, the vehicles need to be modeled with an appropriated methodology that allows for both performance evaluation and energy consumption assessment in short times. To achieve both objectives, the "forward" vehicle modeling, together with static or "low fidelity" models is proposed. Several simulation examples in both electric and conventional mode are given. These models will be used to assess several potential vehicles design, assess their performance, consumption and eventually estimate the total cost of ownership.

Keywords: Heavy Duty Vehicles, Hybrid Technology, Design Optimization, Modeling and Simulation, Hybrid Energy Storage System.

1. Introduction

Transportation sector is, according to the International Energy Agency (IEA), responsible for 22% of the global CO_2 emissions [1]. In Europe, Heavy-Duty (HD) vehicles contribute about 26% of the total CO_2 emissions within the road transport sector [2].

In this context, the ORCA project [3] aims to improve the hybrid architecture of heavy duty vehicles in the following aspects: reduce the Total Cost of Ownership (TCO) to the same level of a conventional non-hybrid heavy duty vehicle; Improve the powertrain efficiency up to 5% compared to current hybrid generation; reduce the fuel consumption by 40% compared to conventional non-hybrid vehicles; and Increase the electric range from 10 to 30km. This latter objective will allow the vehicles drive in Zero Emissions Zones.

This will be done thanks to the cooperation of 11 partners (TNO, VOLVO, IVECO, VRIJE UNIVERSITEIT

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BRUSSEL, VALEO, JOHNSON MATTHEY, JSR MICRO, BOSCH, CENTRO RICERCHE FIAT, ALTRA AND FRAUNHOFER) that came together to form the ORCA project, thanks to the EU H2020 funding. The project, that includes partners from industry (both OEMs & Tier 1 suppliers), research centres and universities, started in September 2016 and has a duration of 4 years.

To achieve the mentioned objectives, the project will work on different fields: Software-Hardware Co-design methodology, design of modular scalable Rechargeable Energy Storage Systems (RESS) [4], [5], development of prediction algorithms to extend the RESS lifetime, development of optimal Energy Management Strategies and recycling the system waste heat.

Traditional design methodologies of hybrid vehicles do not optimize the hardware components in function of EMS algorithm, which is typically optimized once the hardware components have been selected. During the ORCA project, a co-design methodology will be developed to find the optimal combination of software (Energy Management System algorithms) and sizing of hardware components to satisfy the transport assignment and the performance requirements. This will be further explained in section 2.

The vehicles RESS [6], [7], will be enhanced by developing a modular scalable system that will reduce the TCO of the RES by 10%. Moreover, the use of innovative lifetime models and state functions will allow the Battery Management System (BMS) and the EMS extend the battery lifetime by optimizing the power profile requested from the RESS and the thermal management.

The optimization of the EMS and the vehicle design will be tested in a vehicle simulation platform that will be developed during the project. The model will follow the “forward” approach and is further described at section 4.

The article is structured as follows: Section 2 describes the vehicle co-design approach while section 3 presents the specific project use cases. Section 4 shows the modeling and simulation results will be shown at Section 5. Finally, section 6 highlights the conclusions

2. Hardware-Software Co-Design Methodology

Optimal design of HEVs involves the sizing of the ICE and the electrical components on the one hand and the design of an Energy Management Strategy that controls the power flow split between the ICE and the electric motor on the other hand. That is because the achievable performance by the Energy Management Strategy is limited by the physical limitations of the HEVs’ powertrain [8]. As a result, design of the plant and its controller need to be addressed simultaneously in the design phase with an integrated manner to obtain an optimal system design. The aforementioned integrated manner is referred as hardware-software co-design methodology

The co-design attempts to find the optimal sizing of the PHEV powertrain components in relation to the development of an optimal energy management system algorithm to minimize the vehicle total cost of ownership. Morover, the PHEV design should satisfy also specified performance requirements such as acceleration, gradeability, autonomy in electric mode, etc. To achieve this goal, several architectures, e.g. alternating, nested and simultaneous, have been investigated in literature as summarised in Figure 1 [9].

Within ORCA, the co-design methodology exploits the alternating plant and control design architecture since it may provide computational advantages compared to the nested and simultaneous schemes [9]. The system co-design is described in more details as below.

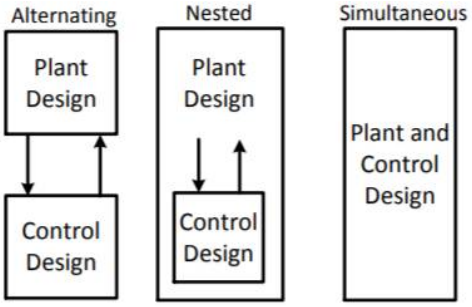

Figure 1. Coordination Architecture for System-level co-design in HEVs [9]

Figure 2 shows a possible design method for plugin hybrid distribution trucks. The first set of powertrain hardware variants might be extensive, including tens of engines and battery sizes. Due to performance requirements, some of these variants can be filtered out. A variant with for example a small engine and a battery with low power capability may not handle top speed /gradeability/acceleration performance requirements.

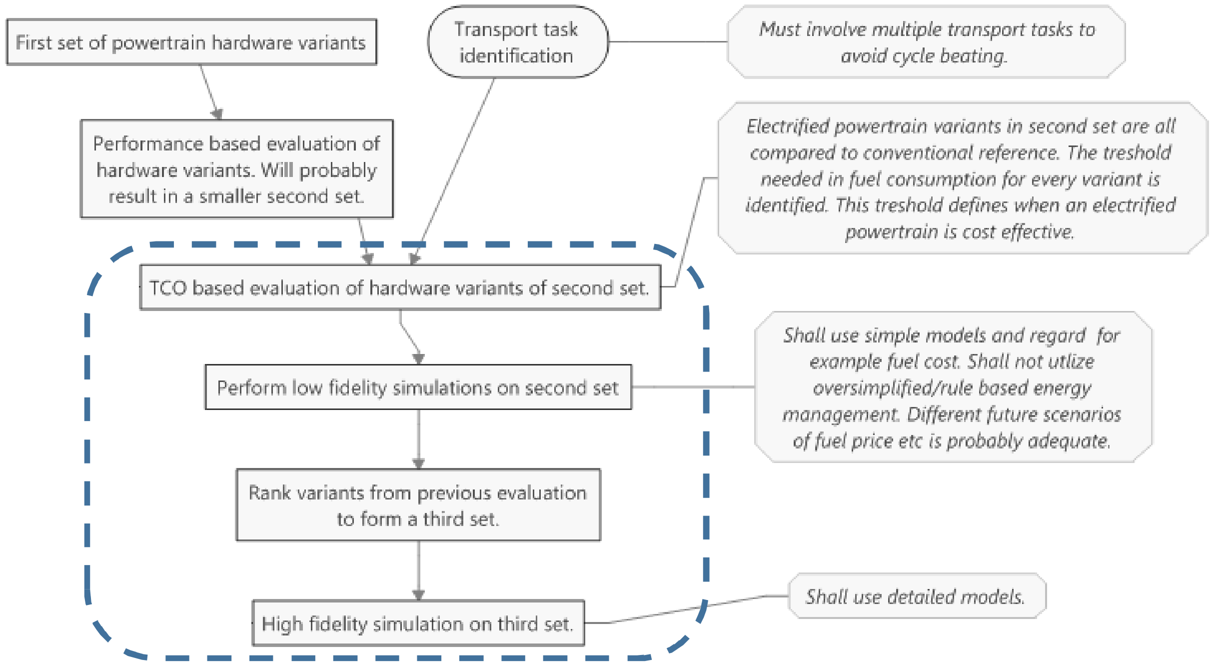

Figure 2. Design method.

The resulting smaller set is fed into a TCO analysis. This analysis uses following equations

(1) $c_{own\ conv} = c_{hw\mathrm{conv}} + c_{fuelconv}$ [€/year]

(2) $c_{own\ phev} = c_{hwphev} + c_{fuelphev} + c_{elecphev} + c_{batt} = c_{hwphev} + c_{operphev}$ [€/year]

With $c_{own\ conv}$ being the TCO of conventional truck; c_{hwconv}, the hardware cost of a conventional truck; $c_{fuelconv}$, the fuel cost of a conventional truck; c_{own_phev}, the TCO of the PHEV truck; c_{hwphev}, the hardware cost of the PHEV; $c_{fuelphev}$, the fuel cost of a PHEV; $c_{elecphev}$ the electricity energy cost and c_{batt}, the battery replacement cost (the initial battery cost is included in c_{hwphev}).

By setting $c_{own\ conv} = c_{own\ hev}$ a threshold on the needed operation cost reduction of the PHEV is derived. PHEV operation cost $c_{operphev}$ is defined in (2). The threshold, here named roc, is defined by

(3) $roc = \frac{c_{fuelconv} - c_{operphev}}{c_{fuelconv}} = \frac{c_{hwphev} - c_{hwconv}}{c_{fuelconv}}$

Figure 3 shows a possible result from this type of analysis. The vertical axis shows the necessary operating cost reduction so that the PHEV exhibited the same TCO as a conventional vehicle. Every line represents a hardware variant and a scenario (horizontal axis) a specific transport mission (and/or setup of for example fuel price). One reflection from the plot is that the variants represented by the two upper plots probably can be sorted out. The reason is that they for some scenarios needs a non-feasible reduction, above 100%.

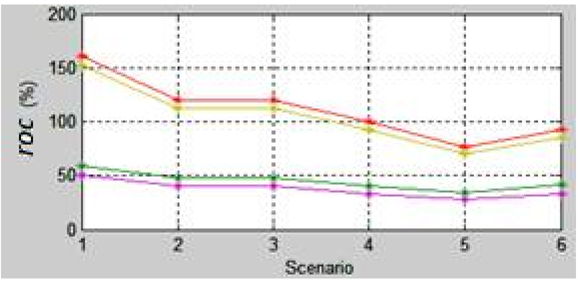

Figure 3. Possible TCO analysis results.

The next step is simulation of the second set. This set fulfils performance requirements and has adequate fuel consumption reduction need. A very important issue in the design process now is the fact that the simulation analyzing the hardware variants needs to be based on sophisticated energy management algorithms. As mentioned earlier, PHEV algorithms needs, for example, to take into account the planning of the battery energy content with respect to future grid charging.

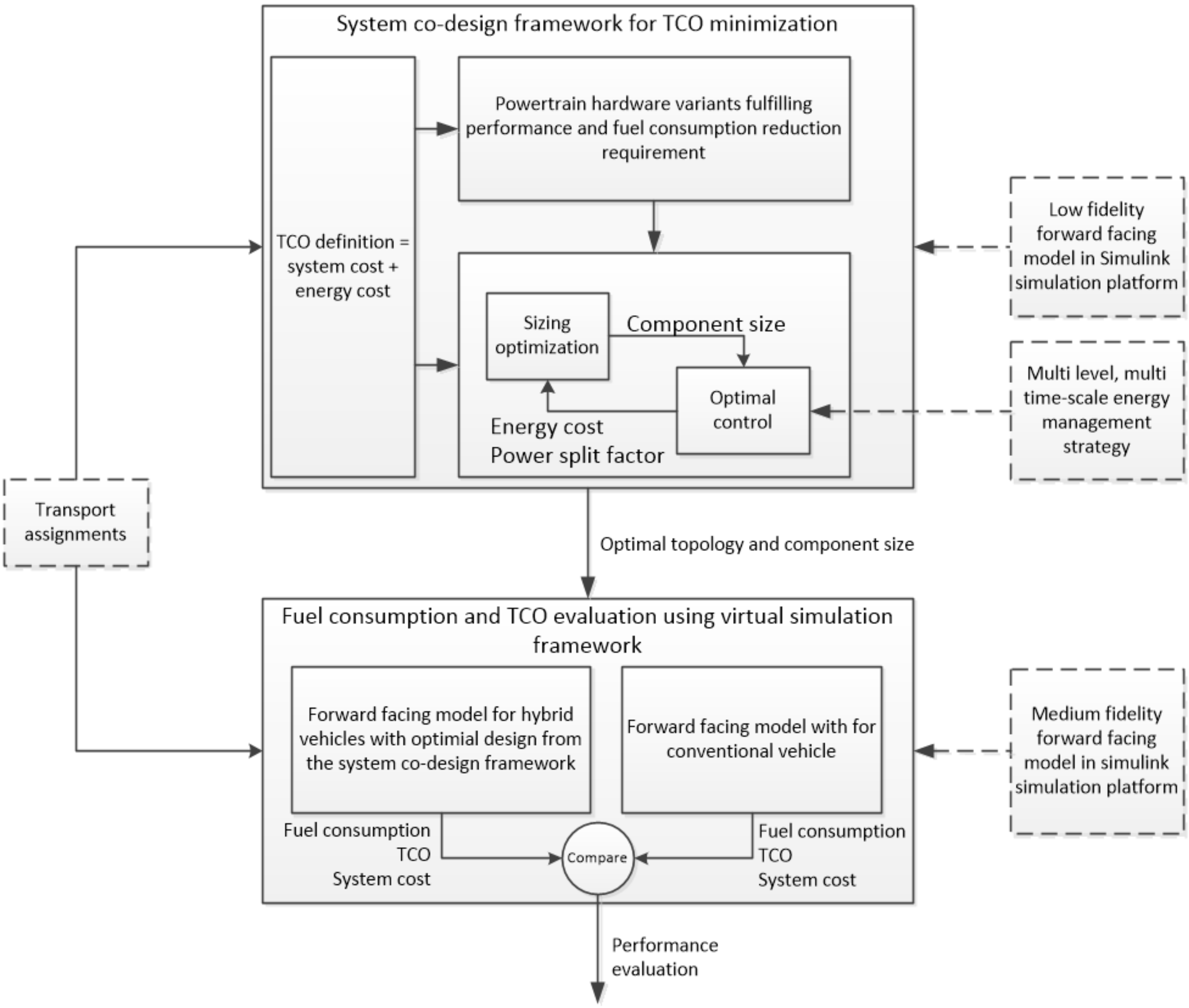

Figure 4. System co-design and evaluation framework for TCO minimization

The design steps inside the dash blue area in Figure 2 are elaborated in Figure 4. The upper layer, system co-design framework for TCO minimization, aims at optimizing the hybrid powertrain topology and component size to achieve a minimal TCO which is defined in equations (1) and (2). A predefined transport assignment is required for the design process. Moreover, a low fidelity forward facing model and a sophisticated energy management strategy (EMS) are exploited in the design process to optimize the hardware components in function of EMS algorithm. The sizing optimization and optimal control are iteratively evaluated until a stopping condition is satisfied, e.g. component size converges to a specific value, or maximum number of iteration is reached.

The optimal topology and component size, resulted from the co-design framework layer, are fed to the lower layer for fuel consumption and TCO evaluation. Within this layer, a medium fidelity forward facing model will be used to evaluate the fuel consumption, TCO and system cost of the hybrid powertrain. Comparison with an equivalent best-in-class conventional vehicle will be conducted to justify the performance of the optimized hybrid powertrain. It is noted that, the predefined transport assignment used in the upper layer (co-design framework) will be re-used for the evaluation and verification process.

3. ORCA Use-Cases

The outcome of the co-design and the TCO analysis heavily depends on the choice of the transport task that is considered. This section describes the use-cases applied to the Volvo distribution truck and IVECO bus.

3.1. Plug-in Hybrid Electric Distribution Truck (Volvo)

A plug-in hybrid electric vehicle (PHEV) is a hybrid electric vehicle that uses rechargeable batteries. The batteries can be recharged by plugging it in to an external source of electric power. A PHEV shares the characteristics both of a hybrid electric vehicle (HEV), having an electric motor and an internal combustion engine (ICE), and of an all-electric vehicle, having a plug to connect to the electrical grid. A major advantage of PHEVs is the possibility to harvest grid energy, which is normally cheaper compared to fossil fuels. Another advantage for PHEVS compared to HEV, is the possibility of running longer distances in full electric mode. This feature opens up the possibility for distribution truck to operate in emission free and silent zones.

In ORCA Volvo will consider a plug-in hybrid truck with a separate electrical axle. The combustion engine will be downsized and the loss of engine power will be compensated by power from the electrical axle. The truck will be a 6x2 regional distribution truck which will become 6x4 when running in hybrid mode. Figure 5 shows a schematic of the Volvo HD truck topology. The rear axle is propelled by an electric motor while the second axle is powered by the ICE. This is known as a parallel *through-the-road* configuration.

The capabilities of powertrain components are not yet defined. Instead the ICE, the electrical motor and the battery storage will be sized by the co-design and evaluated in the TCO analysis. This means also that the choice of use-case, or transport task, will affect the optimal sizing of powertrain components. The output of the co-design should be an appropriate powertrain design that fits the operator in terms of electric range, product cost, operating cost and driving performance.

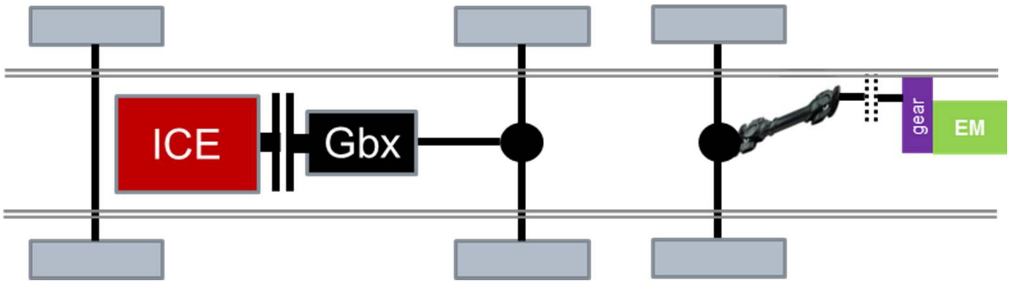

Figure 5. Volvo distribution truck topology

Two challenges for PHEV distribution trucks are:

- An efficient interaction with the charge infrastructure. To maximize the amount of energy harvested from the grid, charging stations need to communicate their availability and charging power capability.
- An efficient energy management algorithm. Hybrid electric vehicles, that do not use grid energy, needs a sophisticated algorithm managing the power slit between the engine and the electric drive system. On top of that, a PHEV needs an algorithm that takes into account the planning of the battery energy content with respect to future grid charging.

This means that use-cases for PHEV must include charging stations, it positions in the cycle, charging capabilities and charging time.

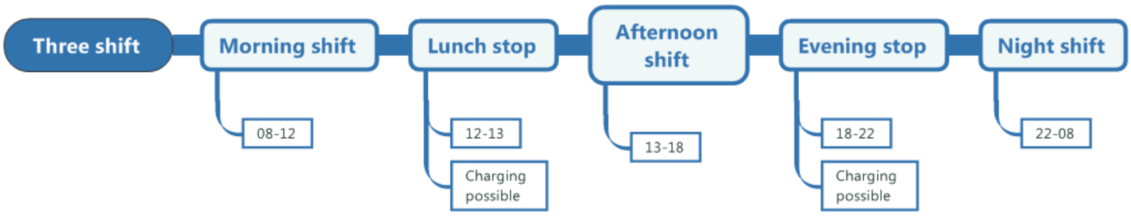

Figure 6: A possible use-case for a distribution truck.

The proposed use-cases should reflect relevant transport tasks for regional distribution truck that can operate in zero emission zones. However, it is complex to define the operation of the vehicle in terms of statistically representative driving cycles, especially when it comes to distribution operations that are less consistent compared to long haul. To address this problem the proposed framework is to initially combine existing cycles and add aspects as charging stations in-between. Aspects of this cycle will be changed in the course of the project to address real life characteristics and problems. The cycles will test features such as the energy content of the batteries, battery degradation, charging time, electric driving range and highway performance along with many other aspects.

Figure 6 illustrates a possible transport mission for a distribution truck. In between the driving shifts, battery charging is possible.

3.2. Plug-in Hybrid Multimodal Bus (Iveco)

The multimodal bus by IVECO, based on standard 12 meters bus, is designed for performing the most efficient hybrid electric mode depending on mission profile. Zero Emissions Vehicle (ZEV) mode is provided as well. The complete vehicle architecture is shown at Figure 7.

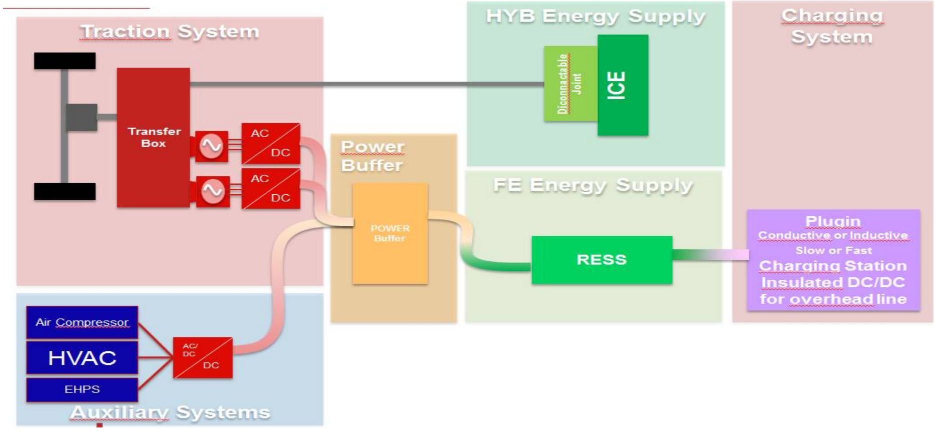

Figure 7. Multi-Modal Bus Architecture

Mode selection is made possible by using a specifically designed and developed transfer box couples to two electric motors and internal combustion engine, able to be configured in several traction modes:

1. ZEV, by shutting-down and disconnecting the internal combustion engine
2. Series Hybrid, by using one electric motor for generation, the other for traction
3. Parallel Hybrid, by using both internal combustion engine and electric motors – use of one single possible – for traction
4. Thermal mode: only internal combustion engine used for traction. Mainly for limp-home mode and high speed for considerable time.

The goal of the bus is to perform urban mission. To define a real urban mission representative of all possible use cases – strictly depending on Customers' needs, cities altimetry, traffic and several other parameters – is not possible, therefore Standardized On-Road Test Cycles – SORT are the best option for benchmarking purposes. As a further step, SORT cycles can be virtually combined and repeated so to build a complete daily mission and analyze vehicle, components, energy throughput and then related costs.

One important element for fulfilling the requirements is the RESS. Three are the main drivers in terms of performances expected by the RESS:

- Power: especially to guarantee vehicle performances in ZEV mode
- Energy: to guarantee ZEV mode according to mission requirements
- Cost: to fulfill Customers' expectation in terms of business case

In order to fulfil power and energy requirements and for lifetime increasing, the RESS is designed with two subsystems working in parallel:

- Lithium capacitors to provide high peak powers and release the batteries from damaging current levels
- Lithium-Ion batteries providing the desired autonomy in pure electric mode.

Being the multimodal bus a plug-in vehicle, a dedicated 11kW battery charger will be installed on-board, with overnight charge purposes, as depicted at Figure 7. The installation of the RESS, battery charger and converters will be done in the vehicle roof.

4. Modeling Methodology

The development of a reliable vehicle model is a key aspect of the project since it will help the authors evaluate the best vehicle configuration regarding the performance requirements, fuel economy, components ageing and eventually, the vehicle TCO. The models will be used in the hardware/software co-design optimization process depicted by Figure 4.

Vehicle models can be divided in several groups depending on classification criteria such as the direction of calculation [10], [11], consideration of transients, causality, etc. A good overview of this classification is given by [12], [13].

In this project, the vehicles will be modelled using the “cause-effect” or “forward-looking” methodology. In this methodology, the direction of calculation follows the direction of the positive power flow in the vehicle, i.e. from the energy sources, to the wheel. The advantage of this methodology is that it respects the limits of the vehicles components and it can be used to evaluate the performance of the vehicle when different rated components are used. The disadvantages, is that a driver model is necessary and simulation times are generally longer.

This methodology can be used with both dynamic and “quasi-static” models of the vehicles’ components. The use of “quasi-static” models, ignores the fast dynamics of the vehicle and allows for faster simulations oriented to energy consumption assessments. In addition to this, any component can be modelled using a higher level of detail considering the fast dynamics. Thus, the model can also be used for design and control purposes.

In the framework of the ORCA project, the model will be used to optimize the vehicle design in an attempt to reduce the TCO, as depicted by Figure 4, while satisfying the performance requirements (acceleration, gradeability, electric range, etc.). This performance requirements’ assessment demands the use of the “forward” approach, while the co-design optimization task would benefit from fast simulation times. To satisfy the latter, the vehicle component models will be developed using static, quasi-static or “low fidelity” models, focusing on the components efficiency, by means of look-up tables and ignoring the fast dynamics inside each component. Thus, the effect of reducing the engine or motor power rating are accounted for and studied, but fast dynamics such as motor current variations ignored. When necessary, this “low fidelity” components models can be replaced by detailed dynamic or “high-fidelity” models representing the physical phenomena inside each block.

An example of the calculation direction of the parallel-through-the-road truck is given below by Figure 8.

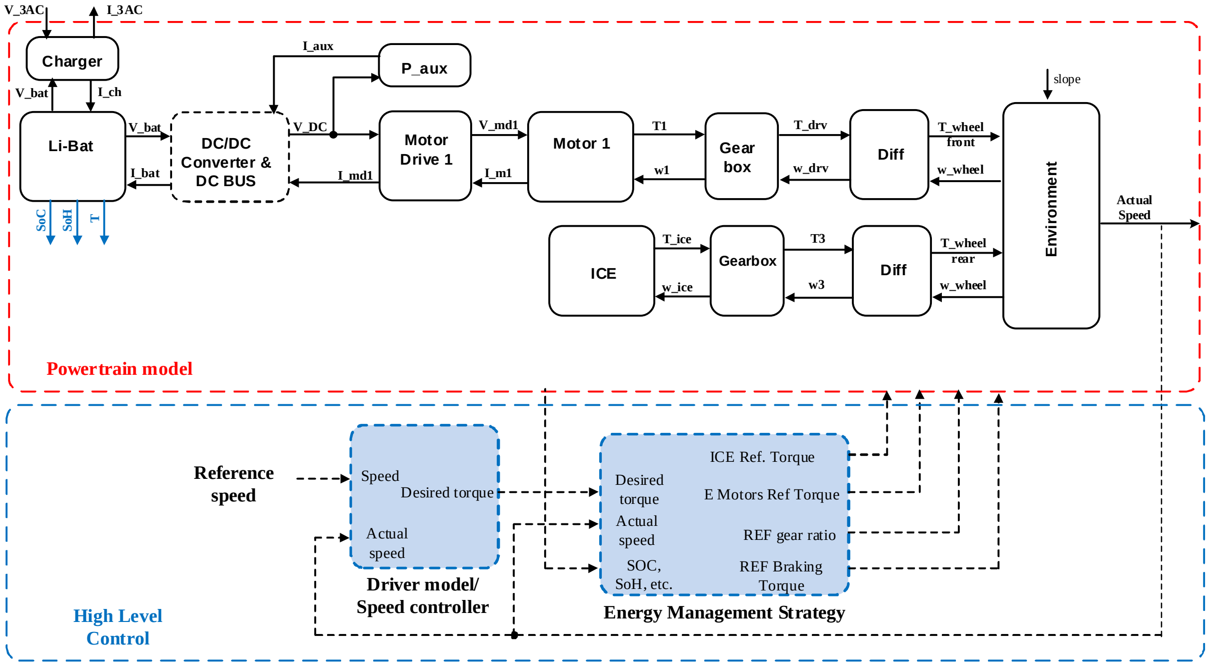

Figure 8. Cause-effect model of parallel through-the-road truck

In some applications, for example early stages of TCO analysis, a “backward-looking” methodology for modelling the vehicle is useful. In such applications the focus is to perform preliminary screening and optimization of vehicle topologies. With thousands of possible combinations of topologies, a “backward-looking” offering faster simulation times is handy. This is at the expense of accuracy as “backward-looking” models are usually calculation models where it is assumed that the vehicle can follow a given drive cycle. One common methodology to implement a “backward-looking” is to use set vehicle speed to calculate engine torque required to achieve that speed and then to calculate fuel consumption based on fuel maps. By doing such calculation over an entire drive cycle it is possible to compare different topologies on the basis of fuel efficiency.

5. Simulation results

Figure 9 and Figure 10 show simulation results of the truck in pure electric mode and conventional mode respectively. In electric mode, the motor peak power is limited to 250 kW and at some points, the vehicle cannot follow the reference. Higher peak power rating would allow for higher accelerations. At time t=1800s, the vehicle is slowly recharging through the onboard charging at 11 kw. It can be observed how the SoC slowly increases after that moment (Figure 9). The battery temperature increases during the cycle and it slowly decreases while charging, due to the low charging power and the reduced losses generated with the small current rate.
In conventional mode, the vehicle can follow the cycle thanks to the higher power rating of the ICE. The distance travelled is 20km and the fuel economy obtained is around 35l/100 km for the 29 tons truck. Vehicle speed, Gear number, ICE speed, ICE power and driver input are shown by Figure 10.

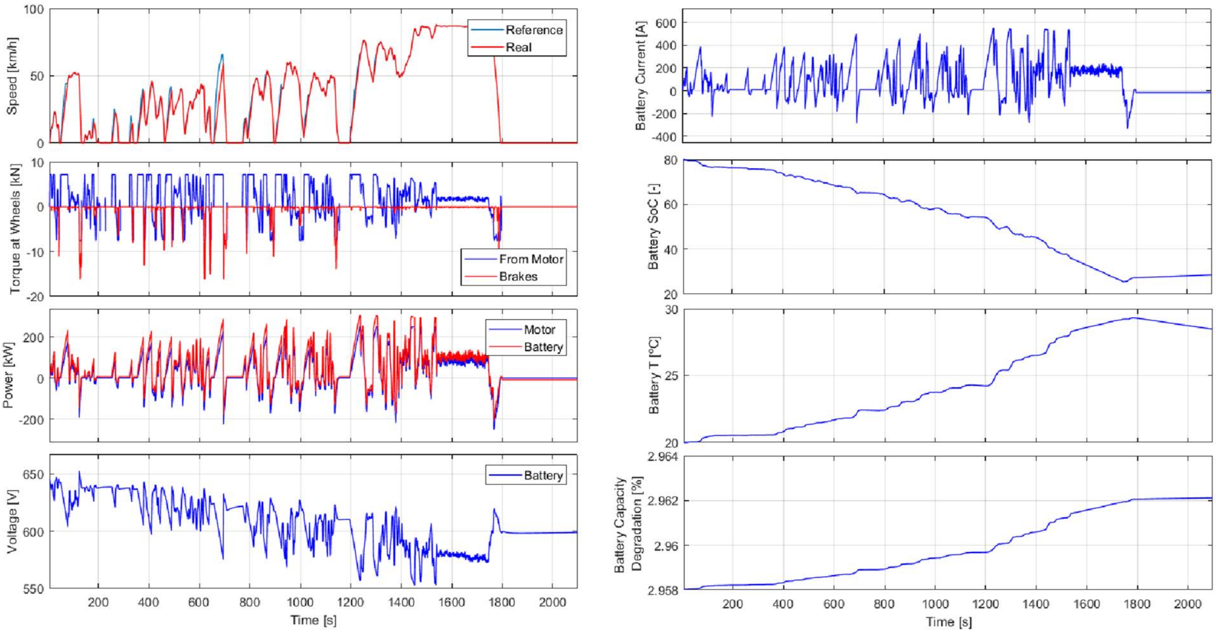

Figure 9. Simulation results of truck use case in pure electric mode (ICE off)

Similarly, Figure 11 shows the simulation results of the Iveco multimodal bus on pure electric mode following a SORT cycle. In this case, the difference comes from the configuration of the RESS. In this case, it is formed by high energy system, Lithium Batteries and a high power system, Lithium Capacitors. The high peak powers are absorbed by the LiC, limiting thus, the power and current given by the batteries. This can be especially interesting during the braking events, because batteries are more sensitive to high recharge currents.

The second graph of Figure 11 shows this particular control strategy where the battery provides the average moving power while the LiC provides peak power and stores the braking energy. Since the energy content of the LiC is lower compared to batteries, their SoC has to be controlled so that it is ready to provide or store the traction energy when necessary.

This section has shown the vehicles working in either conventional mode or electric mode (Figure 9 to Figure 11), but can also operate in hybrid mode engaging both the ICE and the motor. Since one of the aims of the project is to optimize their behaviour in hybrid mode, high level energy management strategies (EMS) based on advanced optimization techniques will be developed and will set the reference working point of each power source. Besides, in the case of the hybrid RESS, the EMS will divide the battery and Li-Caps aiming to extend the RESS lifetime while keeping a high system efficiency.

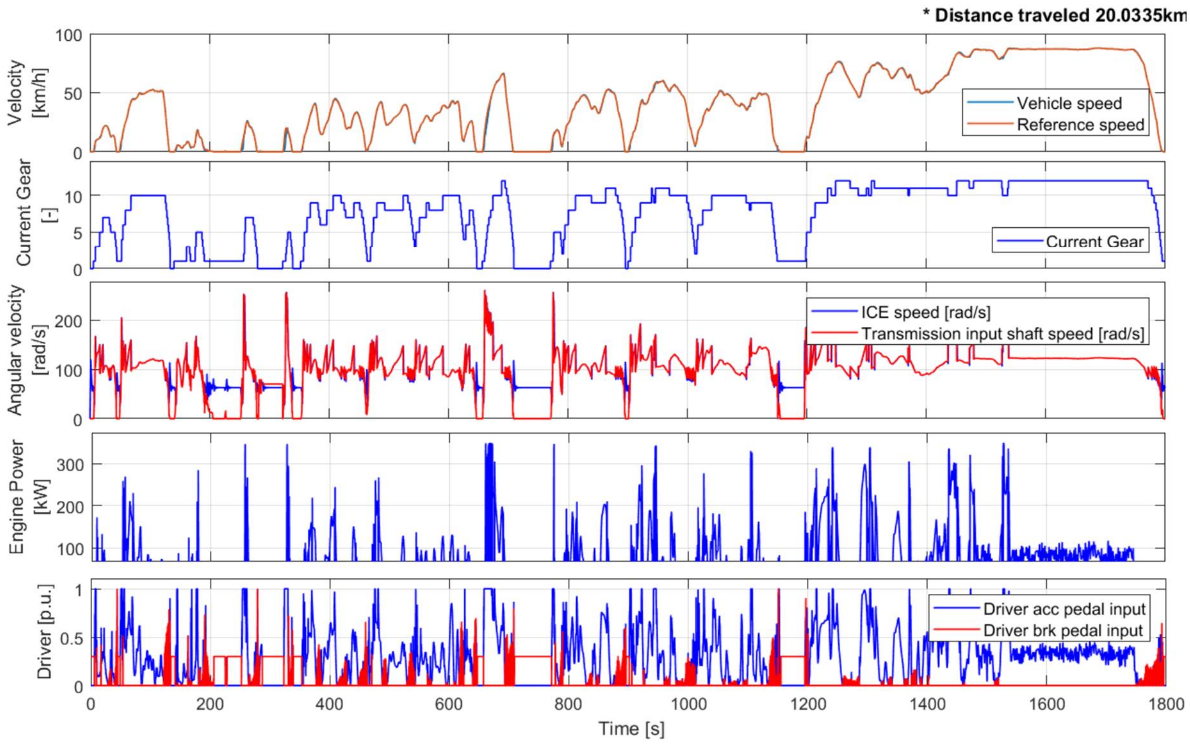

Figure 10. Simulation results of truck use case in conventional mode (only ICE on)

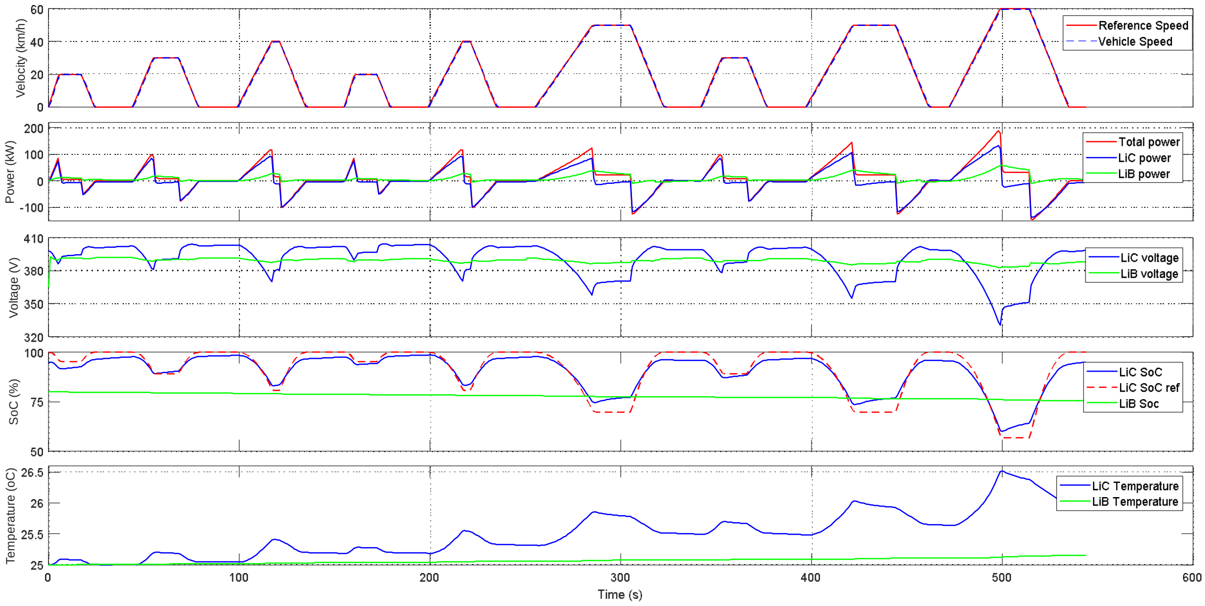

Figure 11. Simulation results of multi-modal bus in pure electric mode with hybrid RESS

6. Conclusions and Further Work

This article presented the European Project ORCA objectives, use cases and the methodology being followed to attain them. An iterative optimization methodology to size the vehicles' components and to optimize the energy management strategy simultaneously has been proposed with the aim of reducing the total cost of ownership of both use-cases.

Furthermore, the modelling methodology that best suits the project objective is the "forward" or "cause-effect" methodology using static or "low-fidelity" models to reduce simulation times. However, in certain cases,

"backwards" or "effect-cause" methodology can be useful for faster preliminary evaluations of multiple configurations.
In the next steps, an optimal Energy Management Strategy of the vehicle will be developed and simulation results in hybrid mode will be shown. This will also be integrated in the co-design methodology.

Acknowledgements

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