ORCA PROJECT: OPTIMISATION FRAMEWORK FOR NEXT GENERATION HEAVY DUTY HYBRIDS

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1. Introduction

The ORCA (Optimised Real-world Cost-Competitive Modular Hybrid Architecture for Heavy Duty Vehicles) project has the ambitious goal to develop a powertrain for hybrid bus and truck, which consume 40% less fuel compared to conventional vehicles on the market, while costing no more than a conventional diesel powered truck or bus. The penetration of current hybrid heavy-duty vehicles is not only hampered due to the high cost but also due to the limited driving range. Currently, these vehicles have a full electric power range of around 10km and ORCA has as a goal to increase this to 30km. This increased range will allow them for operation in urban low emission zones.

ORCA aims to achieve these challenging objectives through an innovative redesign and optimization of the powertrain and battery technologies. A smaller yet high-performance combustion engine will reduce both cost and fuel consumption. An optimised modular battery pack will be developed to fit a variety of heavy-duty vehicle models. An integrated energy management will cover and optimize power flows among the powertrain components and allow to improve the overall efficiency of these hybrid heavy-duty vehicles.

The technologies being developed will leave the lab as actual prototypes and will be delivered at the end of the project. It is foreseen that the powertrain technology for heavy-duty vehicles will be ready for its first market introduction between 2021 and 2022.

This paper presents the project overview, as well as the optimization design framework being developed within the project.

Keywords: Hybridisation, Total Cost of Ownership, Emission Zones, Plug-in Hybrid Electric Vehicles

2. Context and Background

The role of heavy duty vehicles in both urban and regional environments places increasingly demanding functional and operational demands on the vehicles, in terms of zero emission capabilities, combined with interfacing with charging infrastructure. Moreover, heavy duty vehicles are often attractive to run outside of usual business hours, where vehicle noise becomes a higher priority.

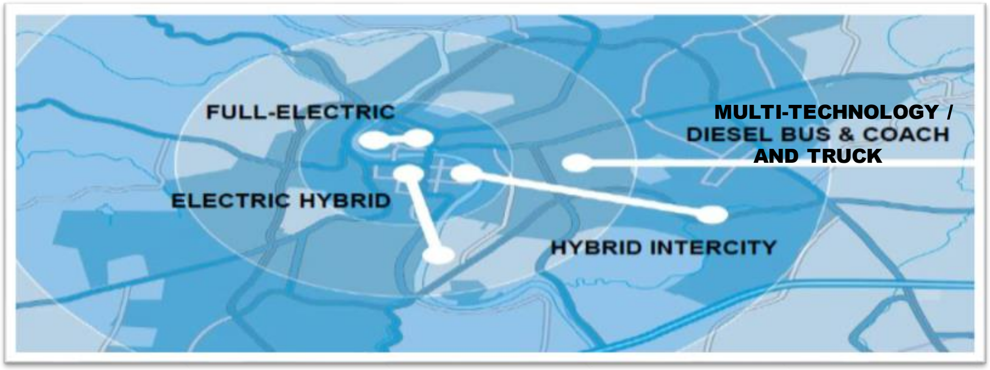

Figure 1: City of the Future, *(adapted from City Mobility from Volvo, Adrian Felton, Cenex LCV, September 2016)*

Hybrid vehicles offer an attractive option to allow for both extended range, whilst being able to satisfy emerging city zonal operating constraints (Figure 1). However, developing vehicles with compelling Total Cost of Ownership remains a challenging development topic. Fundamentally, understanding the wide range of transport assignments (Figure 2) becomes key to exploring standardised, modular and simplified powertrain design, as well as adaptive energy management strategies. Such approaches can significantly contribute to both the initial cost premium, as well as the operational cost and lifetime of the vehicle in use.

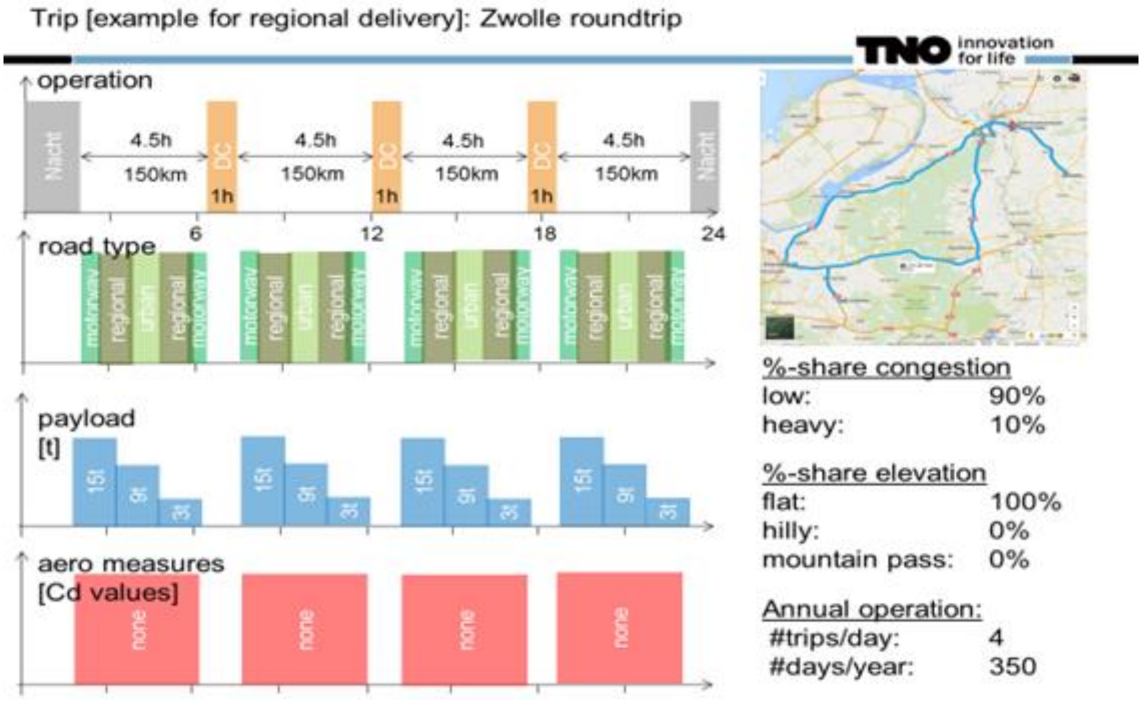

Figure 2: Example Regional Distribution Use-Case

In order to optimise both the design of the vehicle powertrain hardware (e.g. engine, electric machine, battery), as well as the energy management strategy; an integrated optimal design approach is required.

Project Overview and Goals

The activity proposed will be conducted by a 11-members consortium from 7 different European Members States representing all requested competencies in the field of powertrain optimization for Heavy Duty vehicles. The consortium comprises OEMs with IVECO-ALTRA, CRF and VOLVO (also members of EUCAR, suppliers VALEO, BOSCH, JOHNSON MATTHEY and JSR MICRO (CLEPA), leading Engineering and Technology Companies/organizations and Universities with TNO, FRAUNHOFER, and VUB (EARPA). The majority of the consortium are also active members of ERTRAC and EGVIA. The project is supported by EGVIA and EUCAR.

The overall objectives of the ORCA project are:

- Reduce the TCO up to the same diesel vehicle TCO level, targeting over 10% system cost premium reduction compared to actual IVECO hybrid bus and VOLVO conventional truck with the same performances, same functionalities and operative cost, and also targeting up to 10% rechargeable energy storage (RES) lifetime/energy throughput improvement.
- Improve the hybrid powertrain efficiency up to 5% compared to actual IVECO hybrid bus and conventional truck through optimized RES selection & sizing and by improving the energy and ICE management.
- Reduce the fuel consumption by 40% compared to an equivalent conventional HD vehicle (bus & truck).
- Downsize the ICE by at least 50% compared to actual IVECO hybrid bus and VOLVO conventional truck.
- Improve the electric range from 10km to 30km by adding the PHEV capabilities and optimising the RES capacity.
- Case study assessment to replace a diesel engine by a CNG engine for future heavy-duty vehicles.

Achieving these key innovations at affordable cost will significantly strengthen the European technical and technological leadership in the value chain of heavy-duty vehicles, enabling a leading position in this crucial field of hybridised vehicles and increasing the competitiveness of European heavy-duty road vehicle manufacturers and suppliers. The Optimised Real-world Cost-Competitive Modular Hybrid Architecture will be ready for its first market introduction between 2021 and 2022. More importantly, the technology devised will have a strong impact on hybridised vehicles (HEVs, PHEVs) with respect to being cost competitive, with reduced TCO, and featuring downsized ICE, environmental performance and energy efficient rechargeable energy storage (RES) technologies (including range and related RES lifetime and reliability).

3. Research Approach

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. Moreover, 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 [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].

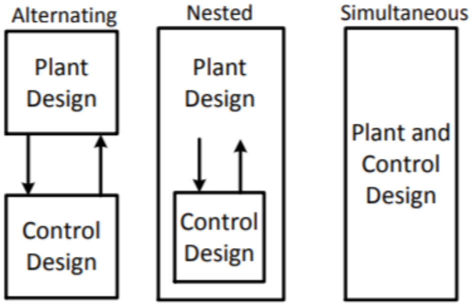

Figure 3. Coordination Architecture for System-level co-design in HEVs [9]

The general framework for system co-design is denoted in Figure 4 and described in more details as follow. The optimization layer, system co-design framework for TCO minimization, aims at optimizing the hybrid powertrain topology and component size to achieve a minimal TCO.

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 energy management strategy are iteratively evaluated in the co-design block until a stopping condition is satisfied, e.g. component size converges to a specific value, or maximum number of iteration is reached. The iterative process is elaborated in Figure 4. An initial design is performed to make the design space smaller. That is done by using a developed forward facing vehicle model to check the predefined performance requirements such as acceleration, gradeability. The minimum powertrain component sizes satisfying performance requirements are then sent to component size optimisation as its design space for the alternating (iterative) co-design. The component size optimisation can be done using two approaches namely, exhausted search in whole design space and artificial intelligent with genetic algorithm. Besides, the optimal energy management strategy optimizes the power flows, engine on/off of the vehicle powertrain to minimize operational cost (fuel + electricity cost from grid charging).

The optimal topology and component size, resulted from the optimisation 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

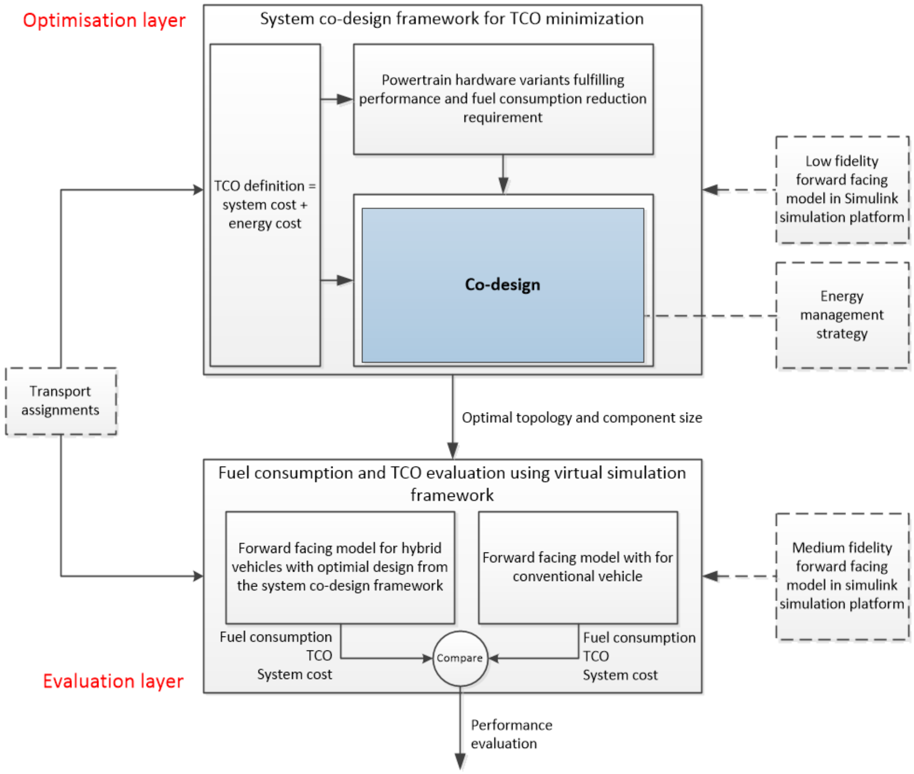

Figure 4. System co-design and evaluation framework for TCO minimization

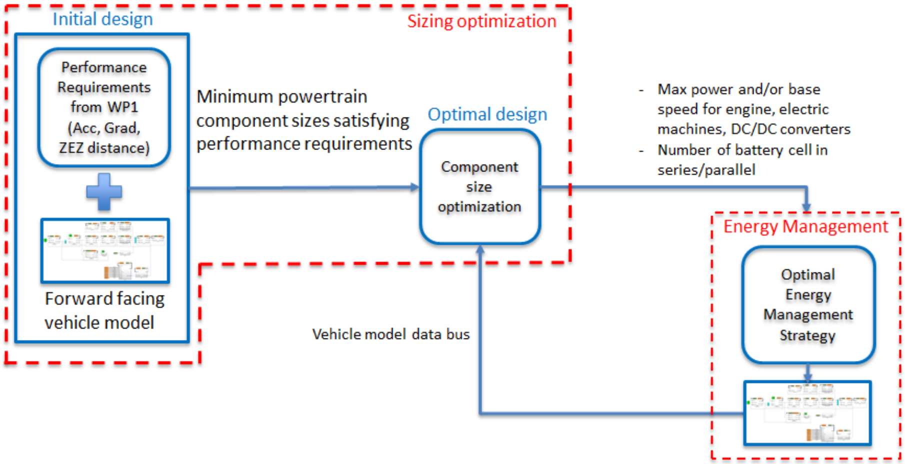

Figure 5. System co-design with alternating approach

3. Preliminary and Expected Results

This section presents some preliminary simulation results for the considered hybrid truck and bus. Moreover, expected results are also discussed when using the developed co-design optimization framework.

3.1. Approach and Preliminary Results

Hybrid Truck

For the hybrid truck, the hybrid powertrain is simplified through the inclusion of an electric axle, where torque is combined through-the-road. Due to clutches on the transmission of both the conventional and electrical axles, mode selection is possible beyond the hybrid torque split configuration. The focus of the solution is in terms of modularity, whilst supporting gradeability and drive-off performance improvements. Figure 6 illustrates the powertrain schematic.

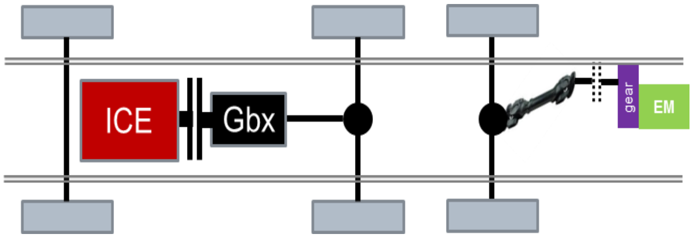

Figure 6. Schematic powertrain topology for hybrid truck

The hybrid truck model is developed by attaching the electric path to the conventional powertrain. It is noted that the conventional truck model is validated with measured data with good accuracy in fuel consumption estimation, engine and gear shift operation. The simulated daily transport assignment for the hybrid truck in this paper is a three shift mission for a distribution truck, shown in Figure 7.

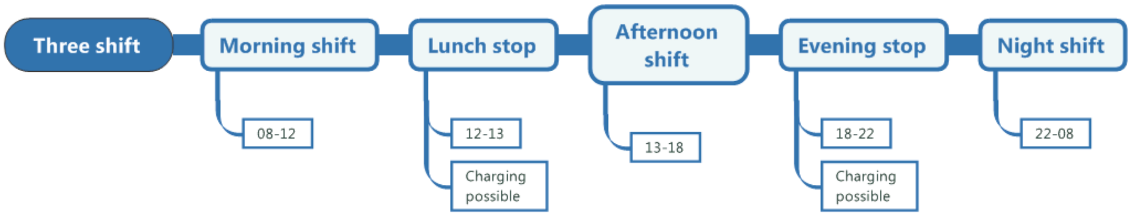

Figure 7. A possible use-case for a distribution truck

During the stop, there will be possibility for plug-in charging functionality with charging power capability and allowable charging time. There is also a predefined zero emission driving zone in the truck transport assignment/mission. The transport assignment is denoted in Figure 8.

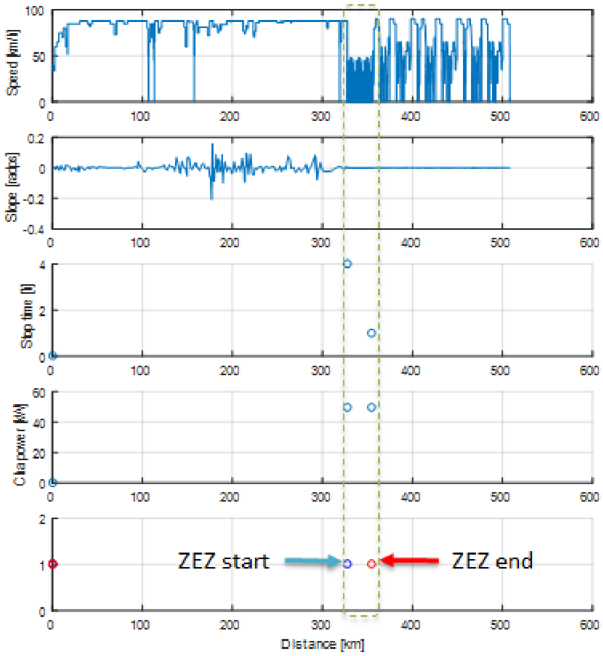

Figure 8. Three shift transport assignment with three shift use-case, plug-in charging capability and zero emission driving zone (ZEZ)

An energy management strategy is developed to make sure that the vehicle can complete the transport assignment while reducing the fuel consumption from utilizing regenerative braking energy and electric energy from grid charging. The simulation results are shown in Figure 9 with an estimated fuel consumption of about 23 [l/100km], which is around/ 30% smaller than the conventional one.

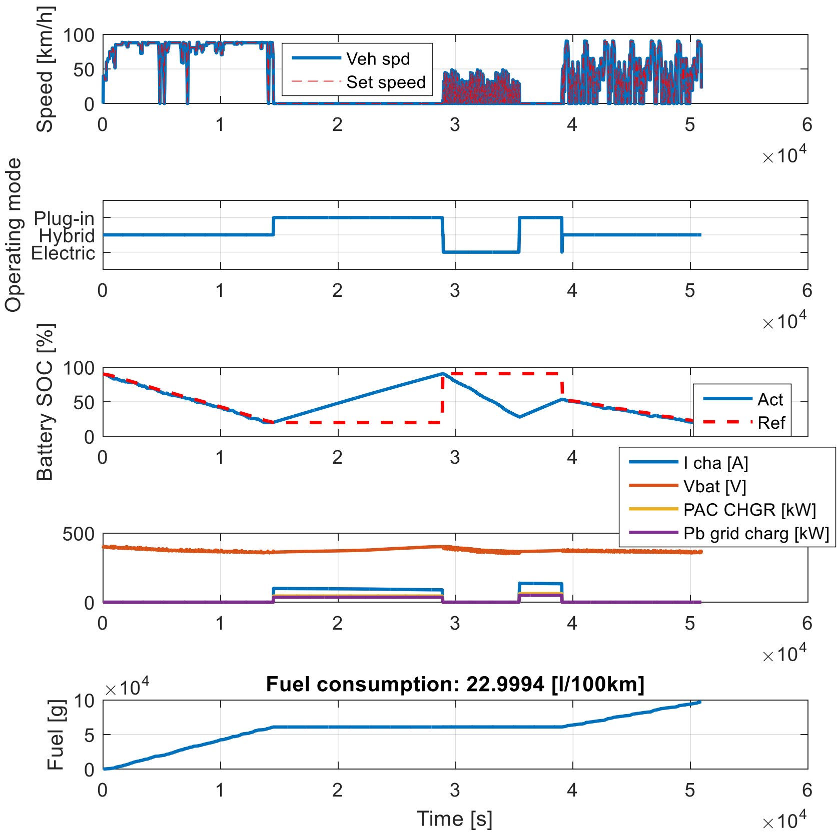

Figure 9. Powertrain operation for complete transport assignment

Hybrid Bus

The hybrid bus comprises a multi-modal transfer box, able to switch the hybridisation topology on demand given the operating regime. This technology allows for optimal mode-based switching based on the required functionality and operation of the vehicle. Figure 10 shows a schematic for this topology.

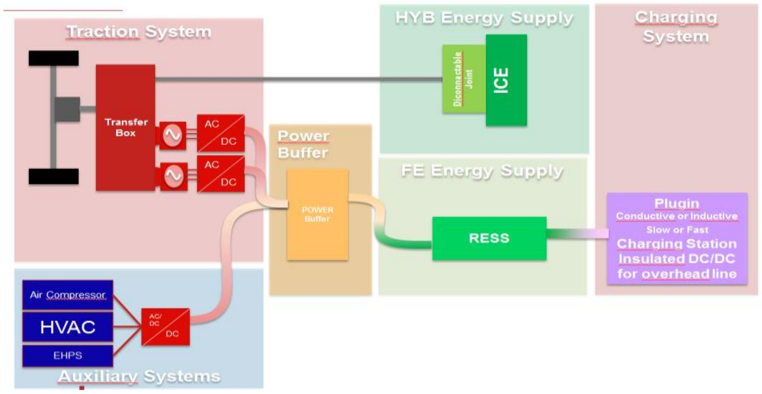

Figure 10. Schematic for Hybrid Bus Powertrain

Figure 11 shows the simulation results of the hybrid multimodal bus on pure electric mode following a SORT cycle. In this case, the difference comes from the configuration of the RESS. 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.

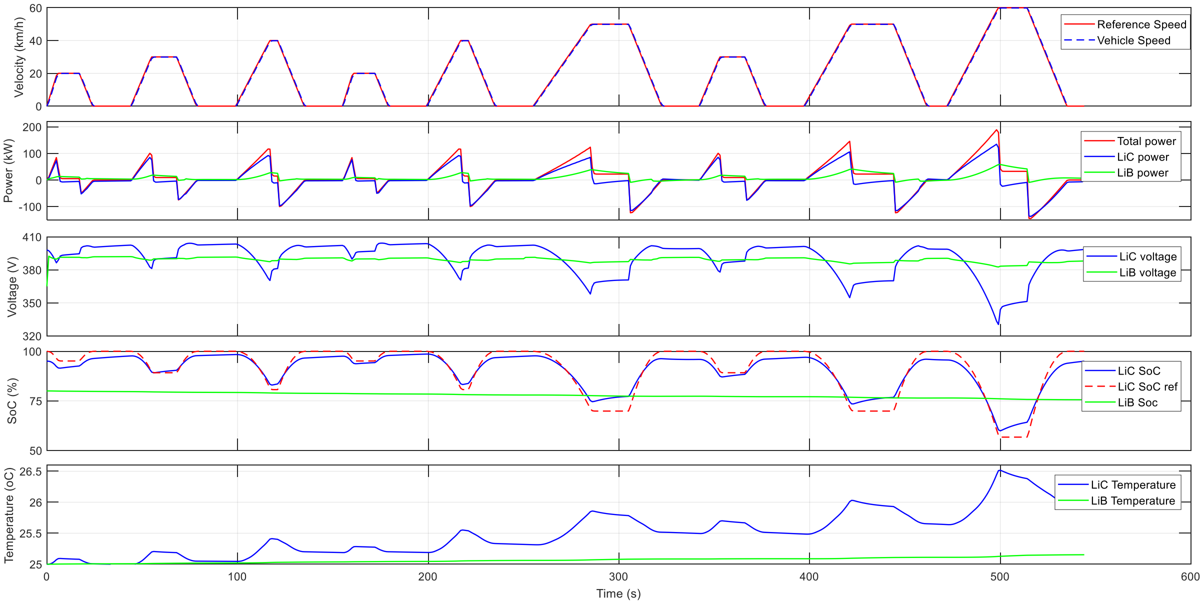

Figure 10. Simulation results of multi-modal bus in pure electric mode with hybrid RESS

3.2. Expected Results

Using the developed hybrid truck/bus model, energy management strategy and the smart component sizing optimisation, it is expected to have a general co-design optimization framework which being able to find the optimal component size with minimal TCO for both truck and bus application on their daily transport assignment. It is noted that, component size optimization takes into account the dependence of the component mass, cost when their sizes are varied as well as the battery life and replacement. The co-design optimization framework also aims at reasonable computational effort.

4. Conclusions and Discussion

For many years, design tools have been used for the modelling of vehicle hybrid powertrains [10][11]. Hybrids offer a wide spectrum of possible topologies, combined with component sizing and control development [12]. The codesign approach towards full optimisation of these vehicle types remains a challenging area; both from a theoretical and pragmatic viewpoint.

This article presented the European Project ORCA objectives, use cases and the methodology being followed to attain them. An exhausted search and genetic algorithm optimization 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.

Preliminary simulation results show the potential in reducing fuel consumption significantly when using plug-in hybrid truck compared to conventional one. Moreover, operations of hybrid truck and bus are also simulated for a daily transport assignment which facilitate the development of the system co-design framework.

In the next steps, the Energy Management Strategy of the vehicle will be further improved to enhance the fuel economy and take into account the battery life degradation. Several techniques are suitable for the optimisation of such a controller [13]. Regarding the hybrid RESS of the hybrid bus, the EMS will also be improved with additional functionality to divide the battery and Li-Caps aiming to extend the RESS lifetime while keeping a high system efficiency. Simulation results for optimal component sizing will be also presented and discussed in details to show the effectiveness of the developed system co-design framework.

The approach will be validated through the construction and testing of the two vehicle demonstrators in later stages of the project; considered against the various key performance indicators defined within the project.

Finally, the assessment of such vehicles in tools such as VECTO will require careful redefinition of the utility factor (the fraction of charge-depleting operation), through combinations of the vehicle topology, mission profile, and in relation to the availability of charging infrastructure.

Acknowledgements

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