Next generation HEV powertrain design tools: roadmap and challenges

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Abstract

Hybrid electric vehicles (HEVs) represent a fundamental step in the global evolution towards transportation electrification. Nevertheless, they exhibit a remarkably complex design environment with respect to both traditional internal combustion engine vehicles and battery electric vehicles. Innovative and advanced design tools are therefore crucially required to effectively handle the increased complexity of HEV development processes. This paper aims at providing a comprehensive overview of past and current advancements in HEV powertrain design methodologies. Subsequently, major simplifications and limits of current HEV design methodologies are detailed. The final part of this paper defines research challenges that need accomplishment to develop the next generation HEV architecture design tools. These particularly include the application of multi-fidelity modeling approaches, the embedded design of powertrain architecture and on-board control logic and the endorsement of multi-disciplinary optimization procedures. Resolving these issues may indeed remarkably foster the widespread adoption of HEVs in the global vehicle market.

Introduction

Among the deep transformations currently undertaken by the automotive industry, electrification of powertrains represents a central problem [1]. Electrification indeed does not affect the propulsion source solely, yet it entails a revolution both in the overall vehicle architecture [2] and in the users' habits [3][4]. In this framework, the automotive industry requires innovative research and development (R&D) tools to face these profound and unresolved, yet stimulating, challenges.

Hybrid electric vehicles (HEVs) currently represent a profitable technology to simultaneously comply with the stringent CO_2 emission regulations and satisfy customer requirements [5]. They are particularly effective at addressing the so-called "charge-anxiety", which is currently a major issue for the widespread use of battery electric vehicles (BEVs) [6][7]. HEVs therefore represent a fundamental step in the progressive global paradigm shift towards transportation electrification [8]. Nevertheless, the development of HEVs demonstrates remarkably complex with respect to both traditional internal combustion engine (ICE) vehicles and BEVs. In fact, the simultaneous presence of different power sources (i.e. ICE and one or multiple electric motors (EMs)) consistently complicates the implementation of an effective energy management strategy to reduce the fuel consumption of these vehicles. Further examples of complications to the HEV development relate to the problematic packaging and the increase of the vehicular overall mass.

The HEV R&D problems illustrated above have mobilized researchers worldwide over the past thirty years. The first published design tool for electrified powertrains indeed dates back in 1991. This code, named SIMPLEV, was developed as cooperation between the Idaho National Engineering Laboratory, the Society of Automotive Engineers and the US Department of Energy [9]. It allowed to size the power components of a BEV (i.e. EMs and batteries) for different pre-selected drive cycles. SIMPLEV was then gradually improved and it laid the foundations for the first HEV powertrain design tools presented in 1996 [10][11]. From that time, R&D tools for HEVs have been consistently improving over the years. Tammi et al. [12] particularly propose a categorization of the research activities related to HEV design into three historical periods:

- The "Pre-commercial" era (1990-2000), characterized by early conceptual BEV powertrains design.
- The "Commercialization" era (2001-2010), dedicated to the exploration of HEV powertrain designs and the development of complex control strategies.
- The "Competition" era (2011-2020), defined by a constant advancement in HEV powertrain designs.

Despite the actual crucial role of electric hybridization of powertrains, little work has been done providing high-level analysis of past and current design and simulation tools for these systems. Moreover, capturing high-level evolution trends for these tools in both near and remote future currently represents a major knowledge gap. This paper consequently assesses past and current HEV R&D tools, highlighting their features and limitations. From this analysis, specific research challenges are then identified that need to be presently undertaken by researchers and engineers. Some potential methods to merge the illustrated research gaps are also suggested. In general, this paper also aims at providing guidance for developing the next generation of HEV design tools. The rest of this paper is organized as follows: a brief outlook of the evolution of HEV R&D tools is firstly presented. Then, limits for the current HEV design methodologies are stated. Questions that need resolution in the next generation of HEV design tools are subsequently established. Finally, conclusions are provided.

Evolution of the HEV powertrain development tools

In this section, the historical evolution of HEV powertrain R&D tools is briefly discussed. This overview follows the categorization of the HEV research periods proposed in [12]. Figure 1 and Figure 2 illustrate the evolution over time of the amount of published work concerning HEV powertrain designs considering respectively the industrial state-of-art (i.e. patents) and research materials (i.e. conference and journal papers). Orbit Intelligence©, SAE Mobilus© and IEEExplore© particularly represent consulted digital libraries in this case.

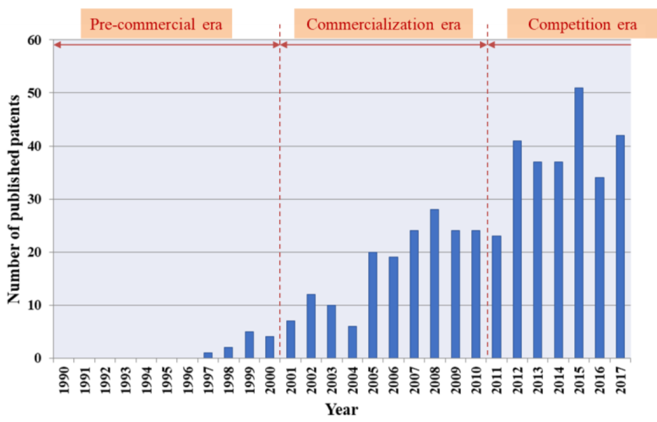

Figure 1. Evolution over time of the number of published patents related to HEV powertrains

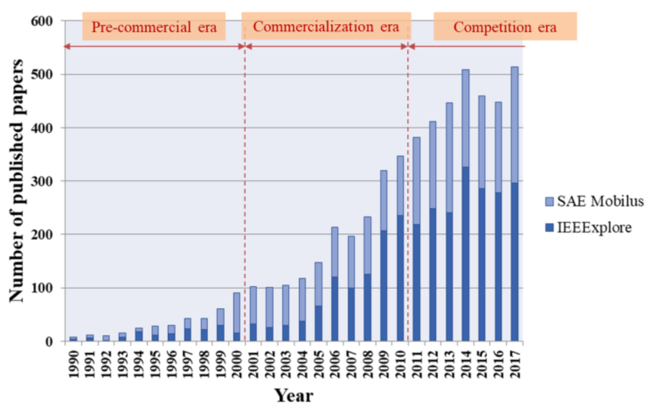

Figure 2. Evolution over time of the number of published papers related to HEV powertrain design.

1. *The "Pre-commercial" era (1990-2000)*

Meanwhile the use of SIMPLEV was extended to HEVs, MATLAB/Simulink© was firstly selected as commercial simulation tool for developing a platform dedicated to HEV analysis and optimization. A series HEV architecture was retained as first example, due to its modelling simplicity (i.e. power split between ICE and EM did not need determination), however designers declared that the tool still needed validation and stability improvement [11].

Other examples of HEV powertrain R&D tools developed in this period include the Hybrid Vehicle Evaluation Code (HVEC) for series HEVs [13], V-ELPH for parallel HEVs [14] and lately a draft version of the well-known ADVISOR [15]. Some general observations can overall be made for this period [12]:

- Kinematic equations for HEVs were developed adopting a quasi-static approach;
- Power balance methods were employed to estimate the HEV fuel consumption values, however the cooperation between ICE and EMs was not well assessed in the simulation models;
- Efficiency values for EMs and batteries were already modeled as lookup tables;
- Series and parallel HEV architectures were simulated, yet optimization and sizing of powertrain components was not considered;
- HEV control strategies were fundamentally absent at that time.

These initial uncertainties and difficulties in HEV modeling reflect in the limited number of papers and patents published over the considered period in Figure 1 and Figure 2. However, a generally increasing trend can be observed in the final phase of the era. Moreover, Toyota launched the first mass production HEV on the market in conjunction in 1997.

2. *The "Commercialization" era (2001-2010)*

This period mainly features the consolidation of the HEV R&D tools developed in the previous era. The increased knowledge concerning hybrid technologies particularly encouraged development and diffusion of commercial HEV analysis tools. Examples of HEV simulation tools which acquired popularity in this period relate to Modelica©[16][17], Autonomie(formerly PSAT)©[18][19], and ADVISOR©[20]. This era can be summarized as well through general remarks:

- The simulation of power split HEV architectures was made possible;
- HEV R&D tools consistently improved the overall sophistication level;
- Computational efficiency remarkably increased;
- Transients and dynamic phenomena were still not considered in HEV powertrain models;
- Advanced HEV controllers still did not find common use.

This era witnessed the early development of complex HEV control strategies. Notable examples are the equivalent consumption minimization strategy (ECMS) and dynamic programming (DP). ECMS was introduced by Paganelli in 2002 and represents a real-time implementation of the Pontryagin's minimum principle (PMP) [21]. As regards DP, an early example of its application to HEVs dates back in late 70s [22], however this technique did not draw much attention at that time due to the excessive computational effort required. Later, in early 2000s, the remarkable advances in computational power available stimulated researchers and designers worldwide to increasingly apply DP to HEV control and design [23][24][25].

Significant improvements achieved in this era in the field of HEV R&D tools led to an exponential increase both in the amount of technical discoveries (Figure 1) and in the volume of published literature (Figure 2). As examples, the number of patents related to HEV powertrains published in year 2008 increase the corresponding value for year 2000 by seven times. Similarly, the amount of yearly published papers about HEV powertrain design gradually increased from 90 in year 2000 to 347 in year 2010. Furthermore, the final phase of this period witnessed the introduction of the BEV Tesla Roadster, which made the remaining car manufacturers alert regarding powertrain electrification.

3. *The "Competition" era (2011-2020)*

In this period, considerable improvements can be observed for the HEV design and component sizing methodologies. Analysis and simulation of all the possible HEV architectures has nowadays in fact become possible, including the complex multimode power split configuration with multiple planetary gears [26][27]. Moreover, consistent advances can be identified for commercial HEV R&D tools:

- They have started including multi-domain and multi-application features [28] [29];
- User interfaces are becoming more and more friendly [30][31];
- High-fidelity simulations have become possible that include transient behaviors and detailed component models [32].

Furthermore, a certain number of experimental validation activities have been carried out in order to merge physical prototypes and production HEVs with corresponding virtual models [33]-[39]. Concerning energy management strategies, these have experienced remarkable improvements as well in this period. HEV control can indeed be divided in off-line and on-line control depending whether the future driving conditions are known a priori beforehand or not. As regards on-line control, major evolutions can be classified into three aspects:

- The enhanced calibration of rule-based strategies (both heuristic and fuzzy-logic based) based on off-line optimization processes [40]-[43];
- The development of battery state-of-charge-adaptive control strategies, usually ECMS-based [44]-[46];
- The first adoptions of machine learning techniques to optimally control HEVs [47]-[54].

As far as off-line control is concerned, research activities have mainly focused on the development of rapid near-optimal control strategies. These procedures aim at predicting near-optimal fuel economy results comparable to the globally optimal DP benchmark, yet by consistently reducing the corresponding computational cost. These strategies can consequently be implemented in advanced HEV design methodologies where a large pool of candidate designs need evaluation. Examples of such techniques include the power-weighted efficiency analysis for rapid sizing (PEARS) [55][56], and the slope-weighted energy-based rapid control analysis (SERCA)[57].

All the above-mentioned progresses reflect in the consistently broad number of published patents and papers on HEV powertrains related to this period (see Figure 1 and Figure 2). Overall, the historical trends of the published material concerning HEV powertrains is reflected in the US HEV market evolution displayed in Figure 3 [58]. In fact, the steepest slope in the HEV market penetration rate to date can be observed for the "Commercialization" era of HEV R&D tools. Nevertheless, the HEV market has been demonstrating an uncertain and fluctuating trend over the past ten years. This does not correlate well with the consistent amount of research conducted on HEVs for the same period. Examples of motivations for the current quiescence in the HEV market after the initial boom relate to the overall cost of an HEV (still consistently greater than a traditional ICE vehicle) and the lack of significant fiscal incentives to promote the widespread adoption of electrified vehicles [59][60].

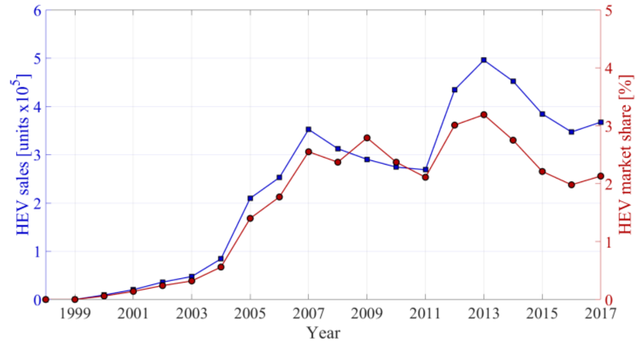

Figure 3. Evolution over time of the HEV market in the US.

In this framework, from an R&D perspective, there is an urgent need to furtherly improve HEV design tools in order to remarkably diminish both development, production and operative HEV costs. The following sections therefore highlight the major limits of current HEV design methodologies and set the research challenges that need accomplishment to develop the next generation of HEV powertrain design tools.

Limits of current HEV design methodologies

Focusing on design and component sizing methodologies for HEVs, despite remarkable achievements and continuous improvements have been highlighted in the previous section, some major current limitations can be identified and divided into five categories:

- Modelling approach
- Driving requirements
- Control strategy
- Design space
- Design disciplines

The follow-up of this section will detail these elements separately.

Modelling approach

In the previous section, it has been mentioned that detailed approaches are currently available to model each component of an HEV. However, the quasi-static approach (QSA) still represents the standard and most employed modelling method in HEV design procedures [61]. QSA is characterized by three main features:

- Speed and torque values for the powertrain are evaluated in a backward approach, i.e. their actual values exactly match target values imposed by the driving profile constraints. No deviations can therefore be observed between target and actual values of the vehicle speed as in feed-forward approaches.
- The vehicle is modelled as a single rigid body with 1 longitudinal degree of freedom (DoF) only. Rotating inertias of single power components are taken into account through equivalent contributions in the overall vehicle inertia, however supplemental DoFs to evaluate the dynamic behavior of single powertrain components are not included.
- The simulation time step is fixed and set to 1 second.

The primary advantages of the QSA are represented by the remarkable computational efficiency and the modeling simplicity compared to more detailed approaches. The considered HEV design space can be explored more effectively in this way. Furthermore, the development of systematic design approaches for complex HEVs as well has been eased by the adoption of the QSA [62]. Nevertheless, this approach might reveal simplistic and deceiving compared to the amount of different physical phenomena involved in HEVs. Moreover, it has been demonstrated how fuel economy predictions for the same HEV architecture may diverge significantly depending on the considered plant model in forward simulations [63]. As regards single power components, these are still generally modelled through empirical steady-state lookup tables (e.g. fuel and efficiency maps). This approach is compliant with the QSA, however it may reveal simplistic as well when considering transient powertrain phenomena and actual operating conditions (e.g. temperature, current status of components degradation).

Driving requirements

As common industrial practice, standard homologation drive cycles are usually considered as driving requirements for designing and sizing HEV powertrains. The worldwide harmonized light vehicle test procedure (WLTP) has recently been introduced to tighten the performance constraints for homologated vehicles compared to previously adopted cycles such as the new European drive cycle (NEDC) and the federal test procedure (FTP) [64]. However, driving profiles for these cycles are generally not representative of real-world driving conditions. The presence of road slopes and the consistently higher peak values of accelerations/decelerations represent typical divergence factors in this case [65]-[67]. As consequence, fuel economy performance may degrade when the vehicle is operated by consumers in real-world driving conditions. Figure 4 reports an example of comparison between driving requirements for the NEDC, the WLTP and a real-world driving mission for a crossover vehicle. An extensive operating region at higher torque values can be identified for the real-world driving case that is not considered in the retained standard drive cycles. This suggests the need of considering real-world driving scenarios to properly design and size HEVs, as it can be seen in [68]-[73].

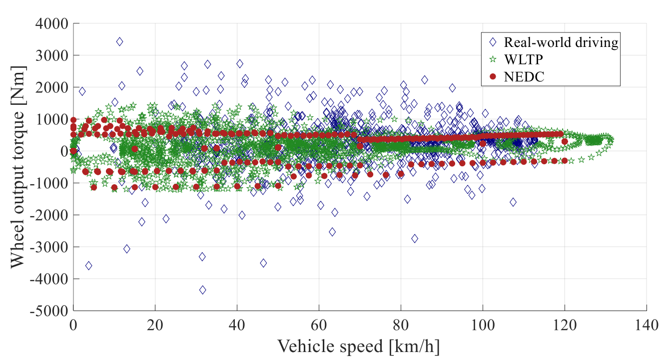

Figure 4. Driving requirements for NEDC, WLTP and real-world driving.

Control strategy

Currently two main opposite approaches can be adopted in the overall industrial development process of HEVs: “architecture-based” and “control logic-based”. These are distinguished by the relationship between HEV architecture design and control strategy implementation, as it can be seen in Figure 5 [74].

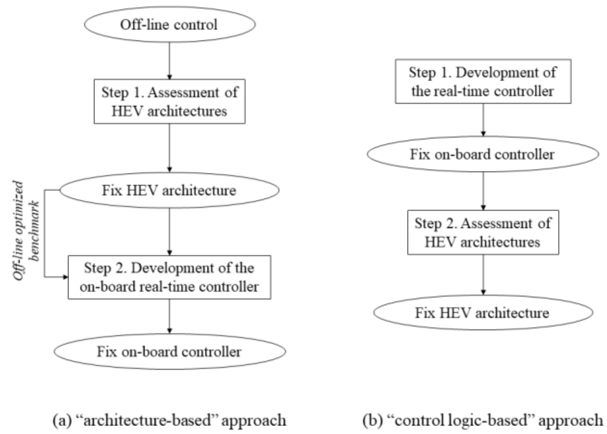

Figure 5. Workflow of the HEV development processes.

In the “architecture-based” approach, an assessment of the fuel economy potential for the considered vehicle type and size is carried out based on off-line optimized control for different HEV architectures. DP, PEARS and SERCA particularly represent examples of suitable control strategies at this stage. Optimal solutions for both the HEV architecture type (e.g. series, parallel, power split) and the corresponding size of power components can thus be selected for the retained vehicle. Later, the actual on-board real-time controller for the HEV is developed aiming at reproducing the benchmark provided by the off-line optimized vehicle operation. Rule-based on-line control policies are generally implemented and calibrated as result of this development procedure [40][43]. Main advantages of this approach relate to the capability of exhaustively exploring the HEV design space and the potential of thoroughly assessing HEV fuel economy capabilities. Nevertheless, the late development of the on-board real-time controller generally entails demanding and tedious calibration processes. Moreover, accomplishing the off-line optimized benchmark performance represents a hard task that is rarely achieved for all the possible driving missions of the vehicle type. The HEV architecture that has been previously selected as optimal solution according to off-line control solely might therefore not represent the best option anymore when considering actual real-time control. In other words, if the calibration process for the on-board HEV real-time controller was considered as well in the HEV design procedure, the outcome of the optimization process might be represented by a different HEV layout or by different component sizes with respect to the HEV design procedure that considers only off-line control.

On the other hand, in the “control logic-based” workflow, the real-time controller is developed first without involving off-line control. ECMS may be retained as real-time control strategy in this case. Subsequently, candidate architectures and component sizing are evaluated on HEV plant models with high level of fidelity according to the developed control logic. The HEV configuration realizing the best performance according to the implemented control strategy will thus be selected as the final one [80][83]. This method allows to accelerate the HEV development process given the early advancement for the actual on-board real-time controller. However, the HEV architecture selected according to this procedure cannot be defined as the globally optimal one (i.e. it represents a sub-optimal solution) due to the constraint imposed by the former selection of the control logic.

It should be noticed that, for both the illustrated development processes, HEV design stage (i.e. the selection of the powertrain architecture) and on-board controller implementation phase are considered in a sequential order. As consequence, design choices made in Step 2 of Figure 5 are deeply affected and constrained by the decisions previously accomplished in Step 1 for both processes, thus preventing the achievement of a globally optimal solution. The finally selected HEV powertrain architecture considerably depends on preferences of the retained off-line energy management strategy and the developed on-board control logic for the "architecture-based" approach and the "control logic-based" approach, respectively.

Design space

In general, most research works published to date on HEV design consider a limited portion of the overall design space associated to these vehicles. The complete HEV design space can indeed be categorized according to the architecture and the electrification level.

As regards HEV architecture, different studies have proposed component sizing for series [75], parallel [76]-[78], power-split [79] and multimode layouts [26][55] alone. Some work has been done examining different HEV architectures [80]-[89], nevertheless considering few possibilities out of the entire HEV design options. Furthermore, when dealing with component sizing, different alternatives are usually retained by linearly scaling the operating maps of actual specific power components (i.e. ICE, EMs, battery). Despite this approach improves the computational efficiency, it might produce incomplete results as distinctive shapes may be realized in power and efficiency characteristics of the powertrain components [90]. Concerning the powertrain electrification level, research analysis and design methodologies generally focus on micro [96], mild [97][98], full [83] or plug-in [99]-[101] HEVs alone.

As a matter of fact, to the best of the authors' knowledge, a unified framework for assessing all the different HEV architectures, the different grades of electrification and component sizing at the same time still needs extensive development.

Design disciplines

Typically, in the development process of conventional ICE vehicles, design considerations for the propulsion source present limited interaction with other vehicular sub-systems (e.g. thermal management, crashworthiness, battery management, brake systems). This is due to the consolidated capability and the effectiveness of OEM workflows in handling the complete vehicle development by partitioning design responsibilities into different specialized departments with limited interaction between them [91]-[95]. On the other hand, from a physical perspective, interactions between different vehicular systems extremely broaden in HEVs. As example, optimal sizing of HEV hydraulic brake systems is heavily affected by the selection of HEV architecture and electrification level [102], which in turn impacts on the battery management [105]. Moreover, HEVs typically demonstrate packaging issues due to the amount of different power components embedded and the resulting increase in the vehicle overall mass. Furthermore, the total cost of ownership of an HEV is no more simply proportional to the initial purchasing costs (associated with the HEV complexity level), but it may encounter significant shifts according to the operative costs over its lifetime (e.g. related to fuel consumption and CO_2 emissions)[81][106]. Effectively answering all these needs at the same time consistently complicates the development of HEVs.

Some studies have been conducted considering interactions between different vehicle sub-systems, for example:

- Incorporating battery state-of-health consideration in the HEV control [103]-[107];
- Incorporating noise vibration harshness (NVH) considerations in the HEV control [82][108];
- Considering impacts of thermal management strategies in HEV simulations [109]-[115]
- Including autonomous driving features in the optimal control of HEVs [116]-[120].

Nevertheless, a very limited number of different design disciplines is simultaneously involved in each study analyzed from literature. Moreover, a single specific HEV configuration is considered at each time in these studies, therefore the potential impact of the interaction between design disciplines on high-level HEV design methodologies and sizing procedures still needs comprehensive evaluation.

Research challenges

This section aims at highlighting research challenges that currently need resolution to implement the next generation HEV R&D tools. Typically, vehicle development processes in the automotive industry follow the well-know "V-Model" illustrated in Figure 6 [121][122]. Particularly, overall objective and subjective vehicle level requirements are established at the very beginning of the vehicle development project. Subsequently, defined targets are broken down to the sub-systems level first and then to the components level. The primary objective of this procedure consists of efficiently handling work split and responsibilities between different departments of OEMs and suppliers [123].

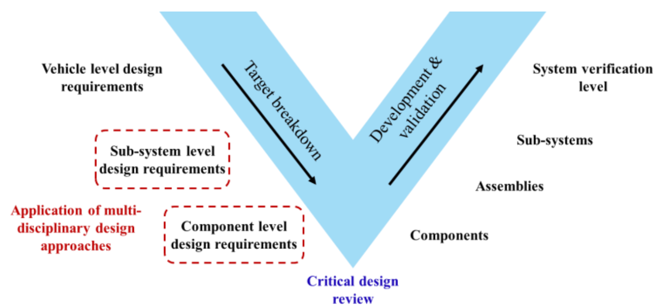

Figure 6. The V-model.

As common practice, the V-Model has recently found application for HEV powertrains as well [124][125]. Nevertheless, the complex and multi-disciplinary nature of HEVs with respect to traditional ICE vehicles may imply adaptations of the established processes. Particularly, the main drawback of the V-Model is associated with its lack of flexibility: once specific targets are set, apply eventual modifications in the following development steps becomes problematic. This contrasts with rethink and rework required by the significant diversities of an HEV compared to a traditional vehicle. Moreover, current HEV powertrain design methodologies reviewed above may reveal simplistic when faced with the intricate design environment of HEVs. These considerations thus set new challenges for the HEV R&D tools under development. Current limits highlighted in the previous section need particularly resolution in this framework.

Vehicle and powertrain modelling approach

As regards the modeling approach, ongoing research activities intend to integrate high fidelity and detailed, yet computational consuming, HEV simulation models (see [126] as example) into effective and computational efficient sizing procedures and design methodologies. Achieving this target may be eased by the consistent and exceptional advancements in computational power available on CPUs at reasonable costs. Moreover, multi-fidelity approaches could find application in this framework. Low-fidelity (e.g. QSA-based) models may particularly be used to exhaustively explore the design space, while high-fidelity models could be called as a supplement in the procedure to refine the calculation of objective functions for the optimization procedure (e.g. fuel economy, drivability performance) [127]. However, mixing the usage of low-fidelity or high-fidelity models in a proper way (i.e. achieving optimal results while limiting the course of dimensionality) may represent a major challenge in this framework.

HEV design space exploration

Effective algorithms and optimization procedures are core elements to exhaustively explore the entire HEV design space. Nevertheless, discrete optimization variables are often encountered in HEV powertrain design procedures. As example, when considering multimode power split HEVs, changing the set of clutch connections represents a discrete variable. The number of gears for parallel HEV transmissions and the number of cells in the battery are further examples in this case. A brute-force optimization approach might reveal simplistic and time-consuming in this framework. Nevertheless, brute-force currently represents the only algorithm that can effectively and exhaustively compare different HEV architectures and component sizes at the same time [26]. As example, in Amesim© software a Hybrid Optimization Tool (HOT) has recently been introduced that is capable of assessing several HEV powertrain architectures (e.g. parallel, dual parallel, series, input split, output split) while intuitively modifying design parameters and component sizes in a brute force approach [128].

Future research should aim at developing innovative HEV design and optimization algorithms that combine exhaustiveness of the design space exploration with computational efficiency. In this framework, dedicated mixed-integer nonlinear optimization algorithms might reveal promising in dealing with different kinds of design variables [129]. Nevertheless, ensuring that algorithms implemented to explore the HEV design space effectively return the globally optimal powertrain solution (i.e. not a local optimum) represents one of the major challenges in this case.

HEV control in design methodologies

In this paragraph, control strategies typically employed in HEV design methodologies will be analyzed first. Subsequently, related on-going research activities will be reviewed and directions for future work will be provided.

Control strategies implemented in current HEV design methodologies

Figure 7 displays a comparison between powertrain-level control strategies commonly adopted in HEV design methodologies. Normalized evaluation metrics include optimality for the fuel economy prediction, computational efficiency, ease of use in HEV design methodologies, and ease of on-board implementation. Computational efficiency and fuel economy optimality metrics are particularly based on the averaged and normalized results presented in [57] for a power split HEV layout. DP is generally known to achieve global optimal fuel economy prediction values, nevertheless it exhibits the highest computational cost. This optimization process examines the driving mission backwardly from its final time step back to the first one, exhaustively evaluating the cost function for each discretized control value at each discretized state value. The control decisions are hence selected to minimize the cumulative sum of the retained cost function [130]. The embedment of DP in automated HEV design methodologies is usually quite eased, nevertheless this algorithm requires accurate tuning of its parameters (e.g. number of discretized elements for the state variables, number of discretized elements for the control variables, size of the analyzed SoC window) depending on the specific HEV application under study [131][132]. As regards the on-board implementation as real-time controller, two main drawbacks indicate DP as the less convenient approach: the excessive computational cost and the required exact knowledge of long-term future driving conditions. As far as ECMS is concerned, this algorithm operates in on-line control by solving a local optimization problem. The best operating condition for the HEV is particularly determined by minimizing a cost function constituted by the sum of two terms: the instantaneous rate of fuel consumption and the correspondingly required battery power [21]. A parameter, named equivalence factor, is responsible for weighting these two cost contributions. Accurate tuning of this parameter is needed in order to achieve charge sustained HEV operation over the analyzed driving missions. The major strength of ECMS relates to the potentially straightforward implementation in the on-board vehicular control unit. This correlates well with its considerable computational efficiency in Figure 7. Moreover, it has been demonstrated in literature how ECMS can achieve near-optimal fuel economy results compared to DP [131][133]. Nevertheless, this strategy exhibits considerable weakness when considering its implementation in HEV design methodologies. Indeed, the fuel economy optimality of ECMS strongly depends on the tuning of the equivalence factor between fuel power and battery electrical power according to the PMP [134][135]. The calibration process for the equivalence factor must be repeated not only for each driving mission considered, but also for each set of HEV design parameters under study, thus reducing the overall flexibility of the ECMS algorithm in HEV design processes.

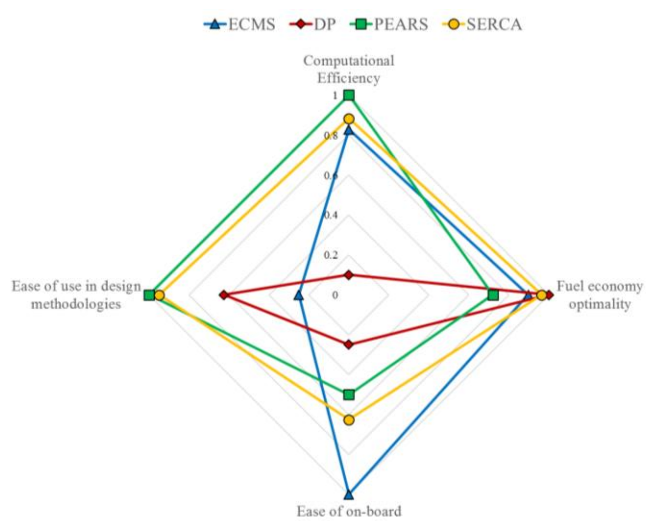

Figure 7. Comparison between common HEV control strategies.

In this framework, the PEARS algorithm was developed specifically for being implemented in HEV design methodologies in order to overcome both the course of dimensionality of DP and the lack of flexibility of ECMS. Zhang et al. particularly introduced this offline near-optimal HEV control strategy in 2013 and applied it to the design problem of multimode power-split HEVs [136]. In the PEARS algorithm, mode overall efficiency values are retained as the weighting factor for selecting hybrid or electric powertrain operation. Beforehand, speed and torque of power components are swept to determine the optimal combination in terms of mode efficiency at each driving cycle point. Once the entire driving cycle is analyzed to extract the optimal power split for each operating mode at each time step, the powertrain is initially set to operate in electric modes only (the most efficient one according to speed and torque required output). Subsequently, a recursive process starts that aims at replacing electric with hybrid operation in the drive cycle points where the smallest ranges between hybrid and electric mode efficiencies are observed. This iterative procedure is conducted until charge-balance is realized and the battery SoC exhibits equal values at the beginning and at the end of the drive cycle. The mode-shifting schedule and the resulting fuel consumption can be evaluated in this way. A comparison between values of fuel economy predicted by DP and by PEARS for an HEV design was performed, and the latter algorithm was shown to achieve similar results while remarkably minimizing the computational cost [55]. In order to avoid excessive mode-shifting occurrence, two different improved versions of the algorithm were developed. In the first one, introduced by the developers of PEARS, a small DP problem for determining the mode shifting solely is combined with the traditional algorithm [137]. In the second version, proposed by the authors of this paper, an heuristic approach is adopted to minimize mode-shifting occurrence while maintaining the computational efficiency of PEARS [56]. With reference to Figure 7, the strengths of PEARS refer to the highest computational rapidity and its ease of implementation in automated HEV design methodologies. Indeed, the objective achievement of charge-sustained operation in PEARS does not require either an accurate selection of the mesh size for the state variables (as in DP) or the calibration of the equivalence factor (as in ECMS). Nevertheless, the PEARS algorithm currently represents an off-line solely HEV control strategy. A version of this algorithm being potentially straightforwardly implemented in the vehicular control unit still needs development. Moreover, when first introduced, the PEARS near-optimality was validated only for power-split HEVs with several operating modes. Recently, the authors of this paper studied the operation of a two-mode power-split HEV coming from the industrial state-of-the-art being controlled by ECMS, DP and SERCA [57]. Curiously, the PEARS algorithm was demonstrated under-performing for the retained HEV layout. The main reason for the PEARS ineffectiveness in this case apparently related to its operating principle. Exclusively optimizing the overall mode efficiencies may particularly bring to near-optimal fuel economy solutions when multiple HEV operating modes are available, nevertheless it may lack of flexibility when few HEV operating modes are applicable in the powertrain layout. To overcome this draft, in the same work the authors of this paper introduced a new approach to the rapid HEV off-line control problem named SERCA. This algorithm combines elements of DP, ECMS and PEARS to achieve values of estimated fuel consumption close to the global optimum, while exhibiting computational efficiency close to the PEARS benchmark. The objective realization of charge-sustained operation, inherited by PEARS, allows the flexible implementation of SERCA in automated HEV design methodologies. Concerning the on-board execution as real-time controller, the SERCA algorithm currently reveals only suitable for HEV off-line control as for PEARS. Nevertheless, since both SERCA and ECMS operate by minimizing the value of an equivalent fuel consumption, the development of a real-time version of the SERCA controller according to an ECMS-type logic might be eased with respect to PEARS. The reader interested in more details about the SERCA algorithm can consult [57].

This analysis does not include rule-based and machine learning HEV control strategies, since they are not commonly implemented in HEV design and sizing procedures.

On-going research activities and related challenges

The above-presented analysis of controllers for HEV design methodologies highlights how a globally optimal option is currently not available, rather a trade-off choice is needed. Overall, three examples of current research activities in this domain include further development of recently introduced controllers, the integration of real-world driving data, and the development of nested design approaches for both the HEV powertrain layout and the corresponding on-board controller.

Advancing the employment of recently developed HEV controllers (e.g. PEARS, SERCA) in design methodologies particularly implicates two main activities: extending the applicability of these control strategies to various HEV layouts, and developing on-line controllers based on the off-line counterparts. Both PEARS and SERCA, when introduced, have indeed been applied to multimode and dual-mode power split HEVs only, respectively. On the other hand, DP and ECMS have been successfully applied to control a large variety of HEV architectures. This demands for further studies aiming at extensively applying PEARS and SERCA controllers to different HEV layout (e.g. series, parallel, series-parallel) and validating their performance compared to the global optimal benchmark. Moreover, the development of vehicle real-time controllers based on PEARS and SERCA may be enhanced by the computational efficiency of these algorithms. As example, these rapid off-line near-optimal algorithms may remarkably accelerate the optimal HEV calibration processes for the corresponding real-time controllers. Related examples of recent activities can be found in [40][43][50]. Alternatively, the rapidness of PEARS and SERCA approaches could be combined with accurate predictions of future driving conditions, fostered by recent advances in intelligent transportation systems and advances in vehicle connectivity, to develop effective on-board controllers for connected HEVs.

Another current research direction in this framework relates to the consideration of real-world driving scenarios when simulating the behavior of analyzed HEVs. This is consistent with the recent development of Real Driving Emissions test procedures (RDE) [138][139]. Increased availability of public real-world driving and emissions data provides support in this direction [140]-[143].

Finally, more effective HEV design approaches may be developed to overcome the limitation of current processes illustrated in Figure 5 and previously detailed. Particularly, presently open research topics include the development and implementation of effective nested procedures to simultaneously design both the HEV powertrain architecture and the related control logic in early design phases. This requires the advancement of on-line HEV control logics which can achieve near-optimal fuel economy performance and simultaneously be adapted to different HEV architectures and hybridization levels in a smooth manner. Example of related initial studies can be found in

[144][145], however these novel methodologies still need exhaustive validation. Furthermore, choosing and tuning the on-line HEV controller represents an additional design variable which consistently increments the computational burden associated to the overall design process.

HEV design disciplines

Much effort should be done to increase the potential amount of different design disciplines (i.e. related to different vehicle sub-systems) which could be effectively and simultaneously involved in the HEV development process at early phases. Indeed, this may represent the most promising research direction to overcome the excessive rigidity encountered when directly applying the V-Model to HEVs. Multi-disciplinary (MD) approaches are supposed to find integration in specific steps of the development process which are highlighted in red in Figure 6. Particularly, designers may set more experienced and perceptive design targets during higher-level vehicle analysis by combining detailed considerations from different design disciplines at once. In the previous section it has been highlighted how some studies implementing MD considerations can be found in current literature about HEVs. Due to the effectiveness of such approaches in the HEV design, the integration of further design disciplines is expected to find implementation over the next years. As example, the power components may no more be modeled through their operational map solely, but their actual dimension and mass values may be considered to simultaneously optimize packaging and evaluate their relationship with the overall vehicle body. In this framework, multi-disciplinary optimization (MDO) approaches may find effective application [146]. MDO procedures are particularly powerful when applied to design environments with multiple disciplines. They decompose a large design problem into smaller discipline-related sub-problems [147]. These can be subsequently solved by adopting dedicated algorithms and numerical tools. The ultimate goal of MDO is to simultaneously gain design knowledge and retain design freedom into the development process. This concept finds illustration in Figure 8, where the knowledge/freedom design paradox is illustrated in solid line for the traditional V-Model development approach. Particularly, the freedom in making design decisions gradually shrinks when advancing in the development process due to the design targets fixed earlier. On the contrary, design knowledge and awareness improve over the vehicle development process thanks to a better understanding of the involved phenomena. Cumulated expertise in late development phases could thus be useful to make more attentive design choices, which are unfortunately no more editable at these stages of product advancement. In this framework, the introduction of MDO approaches aims at acquiring improved design knowledge during early development phases, in order to preserve and prolong freedom in design choices over the complete product development process (see the dashed lines in Figure 8).

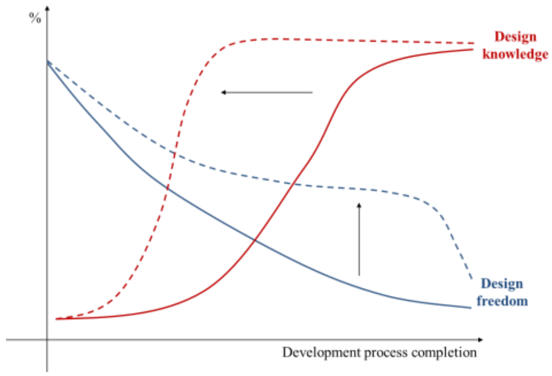

Figure 8. Benefits of adopting MDO approaches in the product development process.

Traditionally, MDO procedures have found widespread application in the aerospace industry, where consistently increased complexity can be observed both for the considered physical systems and the corresponding requirements [127][148]. Nevertheless, some recent applications of MDO have covered the field of electric vehicles as well [149]-[151]. As consequence, it is in the authors' opinion that the use of MDO procedures will need expansion to consistently ameliorate current HEV development processes. In this framework, MDO could represent the leading path in the development of HEV powertrain design tools of the next decade (2020s).

Conclusions

This paper aims at providing a comprehensive review of the current state-of-the-art concerning HEV powertrain design tools while identifying major limits that need overtaking in future developments.

To date, research activities related to HEV design have been divided into three periods corresponding to the pre-commercial, the commercialization and the competition eras. These are distinguished by an overall increasing quality level with respect to the level of modeling details and the amount of HEV architectures examined. Nevertheless, the current lack of widespread adoption of HEVs in the market, associated with their significant development and production costs, claims further advancement of R&D tools to assist the designers of the next generation HEVs.

In this framework, primary restrictions have been highlighted for current HEV powertrain design methodologies that relate to the modeling approach, the driving requirements, the adoption of proper control strategies, the exploration of the design space and the inclusion of different design disciplines. Subsequently, research challenges to overcome these drafts are proposed. These include the use of HEV models with different grades of fidelity, the simultaneous design of HEV architecture and on-board control logic, and the adoption of MDO approaches. Focusing on the illustrated challenges is particularly identified as a core element to advance future development processes of HEVs.

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