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Thirty Years of Electro-Hybrid Powertrain Simulation

KARI TAMMI¹, (Member, IEEE), TATIANA MINAV¹, (Member, IEEE), AND JUHA KORTELAINEN²

¹School of Engineering, Aalto University, 00076 Aalto, Finland

²VTT Technical Research Centre of Finland Ltd., 02044 Espoo, Finland

Corresponding author: Kari Tammi (kari.tammi@aalto.fi)

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ABSTRACT The continuous demand for improved energy efficiency and reduced pollution has led the car manufacturers to focus on electric propulsion. Due to this, research activities concerning electric and hybrid vehicles have been increasing all over the world. For hybrid vehicle research and development, various modeling and simulation tools have been created as the prerequisites for computational research and development have been developed. This paper explores existing research from the past and presents recent developments in order to predict future trends in powertrain simulation tools. The results of the study indicate that developments in simulation tools have evolved from dedicated modeling and simulation tools for hybrid electric vehicles toward general multi-system simulation tools with increasingly detailed component models and accurate physics. The study results identified that progress in computing technology is steady, the development trend in computational R&D is moving toward large computational studies, and the application of advanced data analytics plays a strong role in hybrid powertrain R&D.

INDEX TERMS Electric vehicle, hybrid electric vehicles (HEV), modeling, simulation, powertrain.

I. INTRODUCTION

Electric cars have existed for more than a hundred years, but broad penetration in the vehicle market has still not been realized. In the early days of automobile manufacturing, the discovery of inexpensive fossil fuels and the development of internal combustion engines led the manufacturers to turn away from electric solutions. However, since the 1990s, manufacturers have turned back to hybrid and electric powertrain solutions due to pollution reduction demands such as the Environment protection act UK [1] and current Tier emission standards (USA) [2]. The first hybrid models came on the market at the end of the 1990s. In contrast to sporadic electric and hybrid vehicle developments in the early 1900s and in the 1970s, hybrid model options have been continuously available on the market since 1997. This growing hybrid and electric vehicle market has also stimulated an increase in research activities. As computer-aided research and development (R&D) has established its role, various modeling and simulation tools have been developed for hybrid vehicles. An overview of existing simulation tools for hybrid vehicle developments was given previously in [3]. However, this paper was written more than 10 years ago; significant changes have since occurred in hybrid vehicles. The current study

analyses previous research from the 1980s until today in order to identify developmental steps, acknowledge earlier work and predict future developments in simulation-based electro-hybrid powertrain.

Research activities are divided into three eras:

- The Pre-commercial era (~1980s–1990s), defined by conceptual electric powertrain design. Different electric vehicle concepts were analyzed and the first analysis tools were developed. Many projects analyzed potential benefits of hybrid powertrains or focused on various electric vehicle concepts. Towards the end of the era, the General Motors EV1 was extensively tested in a leasing program and the Toyota Prius (XW10) went into production in late 1997.
- The Commercialization era (2000–2010) concentrated on analysis of powertrain designs. By 2010, most of the larger car manufacturers had at least one hybrid model to offer. Fully electric vehicles were becoming available under several brands. The era was concluded by the introduction of Tesla vehicles, which finally awakened the last car manufacturers to electrification. Numerous studies on powertrain analysis and energy savings potential were published.

- The Competition era (2010s) is characterized by continuous improvement of powertrain designs. Even with their small market share, it appears that electric vehicles have now established their position in the world vehicle fleet. With some exceptions, the market share of plug-in hybrid or fully electric vehicles varies from 1 to 3 % in the Western world. The number of plug-in hybrid or electric vehicles registered annually has exceeded two million units globally. China has taken the lead in the number of plug-in hybrid or electric vehicles registered [4]–[6].

This paper assesses past developments of electric and hybrid vehicle powertrains in order to predict future trends of simulation tools. The results of the paper point out the significance of powertrain simulation tools and their effect on improvements made in powertrains. The assessment indicates the simulation tools are developing in terms of physical details described, system level coverage, and physical phenomena modelled. The authors believe the current paper is useful to understand the evolution happened in vehicle technology and computer simulation. It is notable that the list of references is not exhaustive, but it describes the features and development of the tools over a long period.

The article is organized as follows: powertrain research and development tools are described in Section 2 in three eras (age categories); Section 3 presents the main findings and discussion; finally, Sections 4 and 5 present a future outlook and concluding remarks.

II. POWERTRAIN RESEARCH AND DEVELOPMENT TOOLS

This section contains an overview of powertrain development and tools in the past and in the present. Subsection 2.1 introduces the Pre-commercial era (~1990s), when early conceptual designs were proposed and the first tools were developed for analyzing electrically driven concept vehicles. Subsection 2.2 presents the Commercialization era (2000–2010), introducing simulation tool developments, new library-based solutions, concentrating on a Modelica modeling language-based approach, and ADVISOR, Autonomie, and other Mathworks-related products, such as Simulink and Simscape. Subsection 2.3 presents the Commercialization era (2000–2010).

A. PRE-COMMERCIAL ERA (~1990S): CONCEPTUAL ELECTRIC POWERTRAIN DESIGN

In this era, researchers started to experiment independently and created in-house software tools for analysis of the various aspects of hybrid or electric vehicle performance.

A personal computer compatible code, SIMPLEV, was introduced in 1991 to analyze the performance of full-electric vehicles under various driving cycles. The code was developed by the Idaho National Engineering Laboratory for the Society of Automotive Engineering (SAE), developing electric vehicle testing and the US Department of Energy, developing urban driving cycles for electric vehicle battery testing. The code had pre-configured and scalable options

for electric motors, batteries, controls and driving cycles. The physics model was based on power balances between driveline components. Hence, the propulsion power was balanced between losses and the power required to propel the vehicle. The limitations of the driveline components were taken into account e.g. by limited torque, current, and voltage. The electric motor efficiencies were given in a lookup table and the battery model was based on energy balance [7].

In 1995, internal combustion engine simulation tools had been used for a long time, but an analysis and optimization tool for hybrid systems needed to be developed. A commercial simulation tool, MATLAB with Simulab and later Simulink, was selected by the developers for the platform. The background motivation was to develop a flexible and configurable tool with a graphical user interface. In addition to SIMPLEV, Braun and Busse [8] mention in their review MARVEL and various commercial vehicle simulation codes as possible alternatives for hybrid powertrain simulation. The code was based on kinematic balance; it included the governing equations of vehicle longitudinal dynamics, powertrain inertia, and gearing balanced with the electric motor torque. The electric motor current and torque were limited as well as the battery voltage; the limits were implemented in the lookup tables. The battery model was energy-based and the state of charge was computed from an integral of the current drawn from the battery. The battery voltage was given as a function of the state of charge and the current drawn. The model configuration presented was for a serial hybrid vehicle. Hence, the internal combustion engine and electric motor power split could be omitted. The authors concluded that the model had still to be validated and tool stability improved. They also showed preliminary studies on a hybrid electric vehicle (HEV) called CSM HEV [8].

CarSim is a tool for analyzing vehicle dynamics, developing active controllers and calculating a vehicle's performance characteristics [9], [10]. The SIMPLEV and CarSim tools were utilized to simulate serial hybrid powertrain vehicles in the Hybrid Electric Vehicle Challenge [11]. The simulation results were compared with experimental results. The comparison with experimental results indicated 5–10 % error of both tools for full-electric vehicles. The article described errors in transients; both tools were based on power balance computation that mainly filters out dynamic phenomena in the powertrain. Furthermore, the time steps of the simulator solvers were of the order of 1 second, rather long compared to today's computer tools. The tools were also applied to the electro-hybrid case, but the accuracy was low, of the order of 50 %, because the power contribution from the internal combustion engine remained unknown. [9]

The Hybrid Vehicle Evaluation Code, HVEC by Lawrence Livermore National Laboratory, was designed to analyze full-electric or serial hybrid vehicles. The HVEC was able to simulate several types of hybrid vehicles. In addition to electro-hybrid vehicles, fuel cell, ultra-capacitor, and flywheel hybrid vehicles could be analyzed. HVEC simulated vehicles on predetermined driving cycles (constant 55 mph,

EPA Federal Urban, and Highway driving cycles are defined in the input files). The electric motor and drive performance were determined by efficiency maps. The error was estimated to be of the order of 10 % in terms of fuel consumption. In addition to fuel consumption, emissions based on consumption were estimated using tabulated data [12].

It is worthy of note that none of the codes described so far, including HVEC, were able to model parallel hybrid vehicles. Although referred to in [13], the codes above are based on vehicle power balance, meaning that they rely on a quasi-static solution without balance between different power sources.

The tool named V-ELPH was built on MATLAB Simulab/Simulink [14] acknowledging SIMPLEV, MARVEL, CarSim, and JANUS [15]. V-ELPH permitted the analysis of parallel hybrid configurations. The simulation tool was used to analyze the torque split between the internal combustion engine and the electric motor. The control schemes for the power sources were developed with the simulator. The analysis required modeling the driveline in more detail using dynamic equations instead of only power balance. For a parallel hybrid configuration, the control was interesting because the internal combustion engine was run at two constant throttle settings (10 % idle, 80 % loaded for speeds over 60 km/h) and the electric drive took care of all the dynamic loads. The tool was developed to analyze the parallel hybrid concept car named ELPH, introduced in 1994 [16].

Senger published a validation of the ADVISOR tool by the National Renewable Energy Laboratory in his Master's thesis (see 2.2.2 for more detailed description). An extensive validation was presented in the thesis: such tools as SIMPLEV, HVEC, SCM HEV, V-ELPH, and ADVISOR were described in detail in Senger's literature review. The simulation results were compared to experimental results on the Federal Urban Driving Cycle (FUDS). The simulation results were in a good agreement with the experimental ones in full-electric mode (the error was of the order of 1 %). Hybrid mode simulation results were not however in agreement; problems related to skewed data and unknown operation logic of the internal combustion engine power plant were mentioned [17].

The tool named SCM HEV was also developed in MATLAB and Simulink, and was based on kinematic equations as well as efficiency maps. It emphasized a modular approach for powertrain simulation [8].

Butler *et al.* in [18] introduced a Simulink library developed for hybrid vehicle simulations. The tool used an induction motor model taking into account losses [19]. The vector control was also mentioned in the hybrid vehicle application, but we assume the induction model used was a torque source (or a torque sink for energy regeneration) including the losses defined in lookup tables. The lead acid battery model was empirically defined [20]. The tool was utilized for hybrid control system development and estimations of fuel efficiency and emissions [21]. The solver accuracy and time-stepping were discussed, and we assume the time step used was of the order of 1 second.

In order to develop more general modeling tools, an approach to describe the sub-systems of a hybrid vehicle as a set of converters or transformers (e.g. the internal combustion engine as a chemical to mechanical converter) was presented. The converters were non-ideal, including losses and saturation (e.g. maximum torque). The interconnection of sub-systems satisfied power balance equations. A scalable engine model using mean effective pressure was presented. This was a new approach for hybrid vehicle simulation, which earlier used fuel efficiency maps or lookup tables. In addition, the electric motor model utilized magnetic pressure producing torque over an air gap. This approach made it possible to scale or develop dimensionless simulation models. Electric motors were modeled using physical parameters possibly for the first time in hybrid powertrain simulation tools. The models of electric drives remained non-physical [22].

As a summary of the Pre-commercial era, it should be noted that kinematic equations were developed. Electric components were still mostly modeled as torque sources or torque sinks and current sources or current drains. For example, the differential-quadrature (dq) formulation commonly used for electric machines was not mentioned, nor switching or any other phenomena for the electric drive. If not constant, the efficiencies were defined in lookup tables as well as battery models, which were mostly lookup tables. A typical battery model contained an internal resistance and state of charge-dependent voltage. The overall vehicle models focused primarily on fuel efficiency and only secondarily on emissions. They did not focus on powertrain as a system, nor on its optimization. It should also be noted that Simulab/Simulink-based tools required a significant effort to model the physics correctly. As Simulink is based on signal flow analysis and is meant for control systems, it does not automatically apply the energy conservation laws or Kirchhoff's law, for example. It is also noteworthy that the cooperation between the internal combustion engine and the electric drive was not solid in the simulation models, and this was mentioned as a major source of errors. Hybrid power control systems were practically non-existent in the numerical studies presented.

B. COMMERCIALIZATION ERA (2000–2010): ANALYSIS OF ELECTRO-HYBRID POWERTRAIN DESIGNS

As hybrid technologies matured, the technological developments and analysis tools became more consolidated, versatile, and multidisciplinary. In the Commercialization era, tools were mostly based on Simulink, some on Modelica, or they were software applications, such as ADVISOR and Autonomie, using libraries from other software. For the Commercialization era, it is notable that vehicle dynamics became available in the simulation tools, first as 1D (dimensional) and later as 3D. However, electric components were still modeled according to empirical models, and typical battery models were mostly based on lookup tables. In this section, the discussion will concentrate on analyzing the simulation

tools and technologies Modelica, Simulink and Simscape, ADVISOR, and Autonomie based on existing literature.

1) MODELICA SIMULATION LANGUAGE IN HEV RESEARCH AND DEVELOPMENT

In the early 1990s, the need for a general system simulation approach for physical systems increased. MATLAB and Simulink had already shown that a general systemic tool for simulation had clear advantages compared to dedicated tools when several subsystems are to be taken into account. The challenge with Simulink was that it did not utilize a convenient process flow approach, i.e. non-causal model notation, for formulating the model, but instead causal model notation, which may cause a physical domain model to become difficult to interpret. In addition, MATLAB and Simulink did not have libraries for many physical domains, such as 2D or 3D mechanics or electrical systems. A relatively new tool, Simscape, filled this lack of non-causal model notation and physical domain libraries. MATLAB and Simulink, as a vendor-specific commercial simulation tool, also introduced an open challenge for third party simulation component and library developers from a continuation and business point of view. Therefore, there was clearly a demand for a general system simulation technology, such as Modelica.

Modelica is a programming language for modeling and simulation of systems. The main focus has been on physical systems, such as electric, multibody and hydraulic systems. The language has object-oriented constructs and a standard library, which support the exchange of models and domain libraries. The development of the Modelica language started in 1996 [23] and has continued actively since that time. The language specification is open and publicly available. The current version of the language specification is 3.4 and is from 2017 [24].

The philosophy of Modelica is to provide a unified programming and modeling language specification together with a standard library [25]. The language specification and the implementations of the specification are separated; thus in principle, models made with the Modelica language can be simulated with any simulation tool that implements the Modelica specification [26], [27]. At the time of writing of this article, there are several commercial and open source tools that either fully or partially implement the language specification, such as Dymola, SimulationX, OpenModelica and JModelica.

While the Modelica language itself has been evolving, the modeling and simulation tools and the simulation domain libraries have also been developing rapidly. The Modelica Standard Library (MSL) contains separate libraries for general components, such as mathematical operations, units and constants, as well as for several physical domains, such as electric, magnetic, mechanical and 1-dimensional fluid flow. The comprehensive coverage of different engineering domains is the primary advantage of Modelica [28]. In addition to the standard library, there are also several engineering domain specific libraries for electric powertrain and HEVs,

such as Vehicle Dynamic Library, Power Train Library, Smart Electric Drives Library and VehicleInterfaces library. The high-level libraries enable efficient modeling of complex systems and improve model exchange and reuse of model components and sub-models. The rapid development indicates how the Modelica community has understood the value of standardization and open specification. The open structure of the language and the standard library are good examples of this. The open source VehicleInterfaces library takes this even further by specifying standards for the interfaces of the vehicle subsystems and thus enabling easy and straightforward exchange of subsystem models. This enables a fluent simulation-based development process in the modern subcontracting ecosystem, in which different parties have their own specific roles [29]–[32].

2) ADVISOR

In 1994 [33], the Advanced Vehicle Simulator (ADVISOR) was created by the National Renewable Energy Laboratory as an advanced vehicle simulator designed to support the U.S. Department of Energy hybrid propulsion system program. This software was written in the MATLAB and Simulink environment and it was freely distributed via the Internet. ADVISOR was developed to use basic kinematic equations to describe the powertrain dynamics. It was probably the first tool accepting efficiency maps for all the powertrain components. In contrast to the efficiency map implementation, earlier studies treated electric drive or transmission either as ideal or including proportional losses only. Similarly to efficiencies, the emissions (hydrocarbons, carbon monoxide, nitrogen oxides) were given as operating point dependent maps. ADVISOR accepted practically all imaginable electro-hybrid powertrain combinations. ADVISOR was explained to operate in “quasi-steady” mode, meaning that transients cannot be arbitrarily fast or disruptive.

According to [33], the software simulates vehicle performance between 1.7 and 8.0 times faster than a comparable benchmark model. Already in 1999, this software provided the opportunity (compared to other available software) to simulate new vehicle configurations (including parallel HEVs and conventional) and to develop vehicle control strategies. In addition, the software allowed the utilization of standard driving cycles and estimation of fuel economy, emissions and maximum-effort acceleration capability via drivetrain component performance.

The ADVISOR software utilized a hybrid backward/forward approach in its stream of calculations. The backward facing stream of calculations handles the component performance limits, in addition to a simple forward-facing stream of calculations. This approach allowed the user to accurately represent vehicle operation under a multitude of operating scenarios without the need to iterate [33].

In ADVISOR, two levels are accessible for user modification, via a graphical user interface and via a block diagram level (Simulink). This allowed ADVISOR’s users

to contribute their own component data to the ADVISOR library [3].

It was mentioned in [3] that ADVISOR was developed as an analysis tool, not a design tool. Its component models are quasi-static, and should not be utilized alone to predict phenomena with time scales less than one tenth of a second. According to [33], ADVISOR, despite its fast computation ability (of the order of 1/75th real time [3]), was unfortunately characterized by inaccuracies in dynamic simulation applications. This software was utilized to evaluate and design control logic by iterative evaluation and various energy management strategies and vehicle system optimization studies. For example, [34] demonstrated parametric studies for high-efficiency vehicles (with a target to achieve threefold the fuel economy of a conventional vehicle) with a combined city/highway fuel economy.

The component models in ADVISOR are empirical and based on test data [3], which allows for linear scaling [34] of components. These component models can be extended and improved by the user. However, creating new models required deep knowledge and familiarity with Simulink [35]. A number of tutorials [35] demonstrated that the limited functionality of ADVISOR can be improved by links to other software and by performing a so-called co-simulation option with the ADAMS, Saber and SIMPLORER software applications. However, only a limited number of papers demonstrated the use and realization of the suggested co-simulations [36], [37]. During this era, the component models, e.g. on battery [38], became physic based, detailed and computationally intensive.

3) AUTONOMIE

Starting from the early 2000s, the System Modeling and Control Group at the Argonne National Laboratory developed integrated tools to evaluate the impact of vehicle topology and technological solutions from the control and energy point of view. The first tool was introduced in 1999 and was called the Powertrain System Analysis Toolkit (PSAT). It was widely utilized in the automotive industry as well as in academic research [39]. A partnership between General Motors and the Argonne National Laboratory resulted in enhancement of the simulation capabilities of PSAT and the creation of a new tool now known as Autonomie.

Autonomie is a MATLAB-based software environment and framework for automotive control system design, simulation and analysis. According to the developers, Autonomie supports flexible adjustment and industrialization of models and is utilized for simulating conventional vehicles, HEVs, plug-in hybrid electric vehicles, and battery-electric vehicles over vehicle drive-cycles to quantify energy use and emissions [40], [41]. Autonomie includes public databases, such as plant models, vehicle level controllers, powertrain configurations, systems and vehicle templates, drive cycles, processing scripts and post-analysis tools.

Autonomie can be linked to other commercial off-the-shelf software applications for further detailed and physics-

based models, including GT-POWER [42], AMESim [43], CarSim [44], and AVL-DRIVE [45].

Autonomie has the reputation of a validated powertrain-modeling tool capable of simulating the advanced hardware and control features of various vehicle powertrains. For example, in [46] two types of powertrains were compared to assess local and highway driving performance with help of the Autonomie software.

The CarSim vehicle dynamics simulation tool has become a part of the Autonomie powertrain software release. A significant number of papers have demonstrated the usability of CarSim [47], [48]. For example, Joshi [49] implemented a real-time version of the path-following lateral controller for automated driving applications and validated it on a powertrain-based longitudinal controlled hardware-in-the-loop (HIL) setup. The authors quantified the real-time behavior and sensitivity of the proposed controller to varying vehicle speeds, payload masses, payload positions, surface types and friction values, rapid acceleration and deceleration, and crosswinds. In [50], a forward-facing powertrain simulation tool named the Powertrain Analysis and Computational Environment (PACE) was introduced. This tool is ready for a High-Performance Computing (HPC) environment and is reusing Autonomie vehicle models.

4) SIMULINK AND SIMSCAPE IN HEV RESEARCH AND DEVELOPMENT

The software tools MATLAB, Simulink and Simscape (since 2007) have been utilized in HEV modeling and simulation throughout the new age of electrical vehicles. Simulink provides analysis capabilities for developing control systems and testing system-level performance. Simscape enables the user to create models of physical systems within the Simulink environment. For example, the user can build physical component models, connect them, and integrate with other physical models or control systems. Basic models, such as electric motors, bridge rectifiers, hydraulic actuators, and refrigeration systems, are available. In addition, the user can create custom component models utilizing MATLAB and combine them with ready-made models from the component library. C-code generation is supported, allowing the user to deploy models in e.g. simulation environments, hardware-in-the-loop (HIL) systems, and controllers. Simscape was utilized for component optimization, such as battery stack [51], supercapacitor [52], and hydrostatic transmission [53]. It was also used to develop control and energy management strategies: dynamic behavior in order to establish appropriate energy management strategies [54], and rule-based supervisory control strategy [55]. In 2016, the Powertrain Blockset for Simscape was introduced, which can also be used for modeling and simulation of electrical and hybrid powertrains [56].

As a summary, the Commercialization era brought the simulation tools to a level almost as sophisticated as hybrid and electric cars were. It was possible to analyze power split devices, arbitrary component efficiency, etc. Furthermore, the computational analysis was fast, faster than real time.

However, high speed transients and sophisticated control systems were still missing from common use.

C. COMPETITION ERA (2010S ONWARDS)

By 2017, over two million fully electric cars had been sold [57]. Hybrids have sold more than 12 million units globally [58] and four million in the USA [59]. Toyota alone has sold more than 10 million hybrid cars [60]. The pace is fast, and the figures given here are likely to be outdated by the time of publication.

Continuous improvement of powertrain designs requires sophisticated tools. Therefore, the Competition era can be characterized by the boom of multi-domain and multi-application software tools for automotive applications. The available software provides easy integration of models with varying levels of detail and with user-friendly graphical user interfaces which can be linked to other commercial off-the-shelf software tools [61], [62].

1) CONCENTRATION OF ENGINEERING SOFTWARE BUSINESS

The consolidation of software vendors has led to the offering of multi-physics modeling and simulation packages. These packages can be used for various purposes from modeling a detail to a full vehicle system. They can also be combined with experimental results acquired from prototypes. The physical prototypes and virtual models have partially been merged. The user interfaces are extending to virtual reality [63], [64].

A model of a modern vehicle includes possibly several power sources, electric systems, controls, mechanics, and exhaust gas after-treatment. The model must represent system level multi-physics in order to cover the relevant phenomena and achieve reasonable results in powertrain topology comparisons. In order to guarantee high-fidelity simulation results e.g. in emissions, a simulation model should describe transient behavior and the actions of various control systems with a sufficient accuracy. System simulation software applications offer a wide selection of components and subsystems, many of them validated and parameterized by software vendors. The user is responsible for identifying or selecting the right parameters for the application in hand [65], [66].

Broad and sufficiently accurate computer models have made it possible to launch such approaches as virtual validation, and recently a digital twin. The automotive and aerospace industries have been considered as forerunners in virtual validation. Advances in computer science have given cost-intensive industrial production an opportunity to minimize the costs associated with prototyping [67]. Recent advances in communication technologies have initiated the concept of a digital twin [68]. The approach may be considered as an extended hardware or software-in-the-loop approach enhanced by modern communication technologies. The approach is still relevant, e.g. one battery state-of-charge estimation development was carried out with a battery-in-the-loop method [69].

Even as existing simulation platforms dominate and consolidate the tools, new simulation tools also appear; these tools aim at faster simulation speed and integration of hardware-in-the-loop [70], [71]. Whereas the design optimization of hybrid vehicles may have transferred to a mature industrial stage, vehicle operation optimization research is booming. Computational power allows the application of sophisticated powertrain control strategies. Today, simulators are extensively used to develop the optimal usage of power sources in hybrid vehicles, e.g. model-predictive control (MPC) [72], [73].

III. FINDINGS AND DISCUSSION

In this study, powertrain development tools are described in three age categories:

- Pre-commercial era (~1980s–1990s)
- Commercialization era (2000–2010)
- Competition era (2010s)

These simulation tools could also be characterized as:

- Based on MATLAB, Simulink and Simscape: library packages for Simscape (2007), V-EHLP, PSAT, ADVISOR, Autonomie.
- Based on Modelica: Dymola, SimulationX, OpenModelica, JModelica.
- Based on their own platform.

In Modelica, the standardization of vehicle subsystem interfaces is an example of the shift towards distributed modeling in a sub-contracting ecosystem. The philosophy of the Modelica language supports the reuse, exchange and switching of components; all this improves the overall efficiency of the modeling and simulation process. In ADVISOR, the component models are quasi-static. The philosophy of ADVISOR supports reuse, exchange and switching of components based on empirical data; all this allows a fast and efficient modeling and simulation process for simple optimization of drivetrains and development of control systems. However, there has been an increasing trend in the development of simulation tools

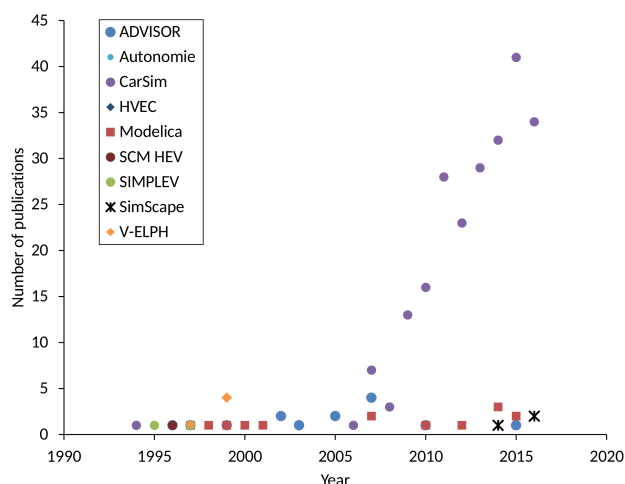


FIGURE 1. The number of publications per year related to powertrain development and utilized simulation tools.

during the past thirty years in order to meet requirements in powertrain designs. This boom can also be observed in publication history. Figure 1 presents the number of publications per year related to powertrain development and the utilized simulation tools based on documents available in the IEEEExplore digital library.

The overall improvements include transition from basic power balance to kinematic models, from kinematic to detailed models. On the component level, the improvements mean moving from electric motor models with limited torque and power levels to detailed models describing the actual physics involved. These improvements allow interplay and interconnection between models.

Figure 2 illustrates simulation tools versus manufactured or released cars on the market. Over the past thirty years, simulation tools went through three eras in development: Pre-commercial (~1980s–1990s), Commercialization (2000–2010) and Competition (2010s). Based on Figure 2, the simulation tool usage since the end of the twentieth century is linked to the development of the electro-hybrid car market. There is room for growth. Electric vehicles in the USA currently represent just 1 % of total new sales. Politicians in the EU are considering a ban on the production of new petrol and diesel cars by 2040 [74], China says that 10 % of the cars it produces by 2019 must be zero-emission vehicles [75]. The world’s largest car makers aim to meet the needs of manufacturing and producing new hybrid and electric vehicle designs. Obviously, this requirement motivates the development of future simulation tools.

IV. FUTURE OUTLOOK

It is obvious that increasingly complex vehicles require increasingly complex simulation tools. Component and sub-system libraries are one way of improving modeling and simulation process efficiency, and increasing reuse of models and components. This seems to be an active trend especially in the case of tools with component-based approaches and supporting user-defined component libraries. Examples of modeling and simulation tools in this category are MATLAB, Simulink and Simscape, and tools based on the Modelica language. In general, simulation is evolving from dedicated single-domain simulation tools towards general tools supporting multi-domain modeling and simulation. There are clear advantages in the multi-domain approach, such as taking all the necessary subsystems into account in simulation, whether they are related to e.g. electric or hybrid powertrains or not. Whereas the models have mainly been based on physics, maps, and lookup-tables, we foresee the emergence of data-driven models in the future. The development is a probable consequence of the machine learning boom.

Computation is becoming more integrated in product development and it is becoming the driver of development. Simulation-based R&D is becoming the dominant approach. There are several motivations for increasing the use of computational approaches, such as the ability to shorten a product’s time to market, the ability to efficiently design complex products and systems, and the continuous pressure on decreasing product development costs. Therefore, the market demands efficient R&D processes with minimal numbers of physical prototypes. Simulation-based product development enables efficient concurrent design and engineering, which is an effective way of shortening the time to market. Multi-domain simulation together with mathematical optimization provides a convenient and efficient way to design complex products. A short development cycle together with computational optimization allows cost efficient product development.

The assortment of simulation tools in R&D is already wide and it is growing. In general, software tools nowadays include several domains, such as mechanics, electrical systems, control systems, and code generation. The role of statistical analysis is decreasing in favor of physical time-domain simulation. Increasing computing power, progress in computing technology (e.g. in parallelization), and especially improving computing cost-efficiency make it possible to shift to massive time-domain analyses.

In the future, we should expect further fusion, which will consist of integrating software with communication possibilities. Internet of Things data and simulation models can be connected in so-called co-simulation: a virtual world implemented as a parallel world digital twin [68], in which data from the outside real world is used for updating the virtual model to achieve better predictions and diagnostics of the real-world counterpart.

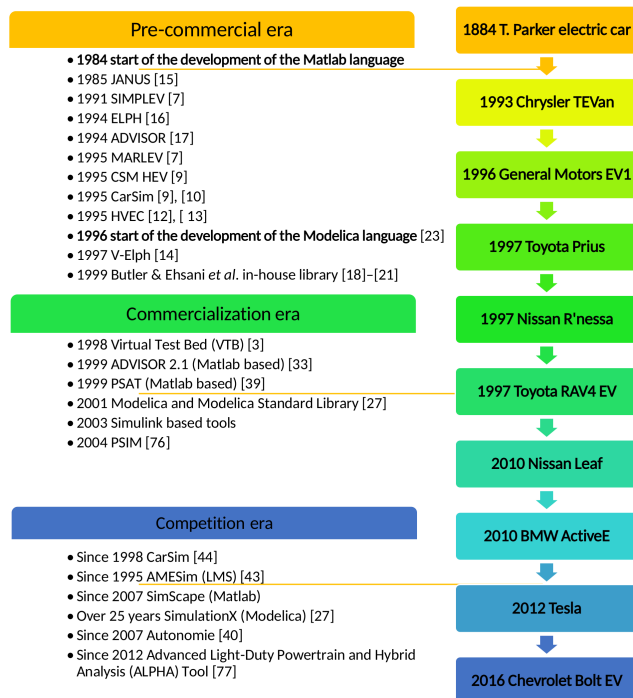


FIGURE 2. The powertrain development and utilized simulation tools versus manufactured or released cars on the market.

In modern vehicles, software has become an important part of the overall product. Software is controlling the engine and its subsystems, power transmission, vehicle dynamics and the controls and entertainment in the passenger compartment. Developing and testing software together with other subsystems has become common practice. Further improvements to this approach will include hardware-in-the-loop, hybrid simulation and overall vehicle virtual prototyping, which are becoming acceptable and sophisticated tools for future powertrain developments. Hardware-in-the-loop will also develop from current laboratory setups, because enhanced connectivity (e.g. 5G mobile data) allows measuring vehicles in use.

In a simulation process, the creation of the simulation model is often the most time-consuming phase. Remarkable improvements in the efficiency of the modeling phase are expected already in the relatively near future. In the long term, design automation will also be increased in modeling and simulation. Automated or at least assisted generation of simulation models will increasingly enable fast virtual prototyping and model modification. The automated features will merge together with artificial intelligence development. Continued and fast progress in computer technology will enable simulation to move from running limited sets of simulation cases and parameter combinations to large computational studies that will produce statistically relevant sets of data. This, on the other hand, will change the simulation post-processing from making conclusions based on data visualization to using data analytics and advanced data analysis methods for gaining relevant new information out the vast data mass.

V. CONCLUSION

Increasing environmental awareness and growing air quality problems in large cities have created demands to develop alternatives for internal combustion engines in vehicles. Hybrid electric and full electric vehicles have become the target for increasingly active research and development, in which it has been shown that the application of simulation in electric vehicle R&D has proved to be an efficient way of working. When comparing the historical developments in simulation tools it was observed that they have evolved from dedicated modeling and simulation tools towards general multi-system simulation tools, with increasingly detailed component models and accurate physics.

The literature review illustrated research activities divided into three eras: the Pre-commercial era (~1980s–1990s), the Commercialization era (2000–2010), and the Competition era (2010s). In the first era, conceptual electric powertrain designs were developed. These designs boosted the development of the tools for analysis and revealed potential benefits of hybrid powertrains, and addressed various electro-hybrid vehicle concepts. Modeling and simulation tools have evolved remarkably since the 1990s.

The second era brought improvements in software applications, computational resources, and in the overall development process. The second era was characterized by the enhanced physical behavior of powertrain components.

The third era was opened by the introduction of Tesla's electric cars and has concentrated on continuous improvement of powertrain design.

In the third era, a simulation-based development approach has become more popular, and the role of simulation in R&D has increased; there has been clear change in the R&D paradigm. Powertrain development has become more integrated first with the vehicle, then with the software. With increasing communication and update possibilities, the development is also more and more connected outside the vehicle.

In the future, system simulation will have an even stronger role in hybrid powertrain R&D. The progress in computing technology is steady and the development in computational R&D is moving towards large computational studies and application of advanced data analytics. All this can accelerate the development of complex systems, such as electric and hybrid vehicles, shorten the time to market and enable more complex systems to be developed efficiently.

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KARI TAMMI (M'15) was born on 1974. He received the M.Sc., Lic.Sc., and D.Sc. degrees from the Helsinki University of Technology in 1999, 2003, and 2007, respectively. He received a Teacher's pedagogical qualification at the Häme University of Applied Sciences in 2017. He was a Researcher with CERN, the European Organization for Nuclear Research, from 1997 to 2000, and a Post-Doctoral Researcher with North Carolina State University, USA, from 2007 to 2008. From 2000 to 2015, he was a Research Professor, a Research Manager, the Team Leader, and other positions at the VTT Technical Research Centre of Finland. He has been an Associate Professor with Aalto University since 2015. He currently serves in the Finnish Administrative Supreme Court as a Chief Engineer Counselor. He has authored over 60 peer-reviewed publications cited in over 1500 other publications. He is a member of the Finnish Academy of Technology. He serves as the Deputy Chair for IFTOMM Finland.



TATIANA MINAV (M'18) received the M.Sc. degree from the Lappeenranta University of Technology (LUT), Finland, in 2008, the M.Sc. degree from Saint-Petersburg State Electrotechnical University LETI in 2008, and the D.Sc. degree from LUT in 2011. She has 10 years of experience working on improving the efficiency of non-road mobile working machines. She is currently with the Department of Mechanical Engineering, Aalto University. Her current interests include zonal hydraulics, position motion control with the help of electric drive, thermal hydraulics simulation, and energy recovery systems in non-road mobile working machines.



JUHA KORTELAINEN received the M.Sc. degree in technology from the Helsinki University of Technology in 1995 and the Ph.D. degree in virtual design from the Lappeenranta University of Technology, with a focus on semantic data model for multibody system modeling, in 2011. He was an Engineering Analyst in a private consulting company. From 1998 to 2001, he was a Researcher with the Helsinki University of Technology, focusing on computational research of internal combustion engines. Since 2002, he has been with VTT Technical Research Centre of Finland Ltd., as a Research Scientist, a Senior Scientist, a Principal Scientist, and the Research Team Leader, where he is currently the Research Team Leader with the Systems Engineering and Simulation Research Team. His background is in mechanical engineering and computational product development, and more specifically in multibody system and multi-technical simulation.

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