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Progress in Maximizing Electrified Powertrain Efficiency

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Abstract

Previous research mainly concentrated on minimizing energy consumption of electrified powertrains in either design or control respect. Furthermore, thermal domain, which plays a crucial role in determining the energy usage, has not been fully investigated yet. Therefore, this paper aims to provide a comprehensive analysis of the state of the art of approaches for improving electrified powertrain efficiency. Two case studies are carried out based on the opportunities found. It is concluded that, to maximize electrified powertrain efficiency, an integrated approach including energy and thermal aspects, taking into account of topology, technology, size and control optimization, is recommended.

Keywords: BEV (battery electric vehicle), PHEV (plug in hybrid electric vehicle), efficiency, optimization, transmission.

1 Introduction

Electrified powertrains which probe opportunities of reducing energy consumption are emerging to meet unprecedented emissions regulations and energy shortage. Enormous effort has been made to improve electrified powertrain efficiency. Earlier studies were mainly concerned with a facet of electrified powertrains, such as proposing an architecture, adopting a technology or developing a control algorithm [1, 2, 3]. An optimal system design, however, demands concurrent plant and control optimization, considering the coupling between the physical system and the control algorithm [4].

Furthermore, in literature, in order to improve energy efficiency of electrified powertrains, the optimization problem is often solved, taking into consideration of chemical, mechanical and electrical energy flows [5, 6]. Thermal domain, which is also an integral part of the energy flow of an electrified powertrain, has yet to be explored.

Energy-efficient electrified powertrains, on the other hand, require a holistic and integrated approach to synthesize design and control with respect to both energy and thermal aspects. In view of the drawbacks of previous research, this study aims at providing a comprehensive overview of the state-of-the-art methods for maximizing electrified powertrain efficiency and identifying opportunities. The energy saving techniques found are justified by two case studies on hybrid electric vehicles (HEVs) and electric vehicles (EVs), respectively. The rest of this paper is organized as follows. In Section 2, an overview of progress in improving electrified powertrain efficiency is given. Section 3 presents an integrated energy and thermal management system (IETMS) with applications to plug-in HEVs (PHEVs). In Section 4, continuous variable transmission (CVT) technologies for EVs are investigated. The main results in the form of conclusions and future suggestions are provided in Section 5.

2 Overview of energy conservation techniques

In order to gain qualitative insights into areas where most of the energy efficiency improvements could be achieved, a numerical simulation was performed to analyze energy losses of a CVT-based plug-in HEV (PHEV) on the New European Driving Cycle (NEDC), as shown in Figure 1. The simulation result indicated that equal attention should be paid to reducing rolling resistance and air drag as vehicle hybridization, e.g., through mass reduction [7]. Moreover, a variety of electrified powertrain architectures exist, as illustrated in Figure 2. For definitions of these driving modes, interested readers are referred to [8]. Each architecture has its merits and demerits. The choice is often dependent on the applications and the trade-off between performance and cost [4]. Serial architectures are common in buses and heavy-duty vehicles, while parallel topologies are dominant in passenger cars. Eliminating the engine path, an EV architecture is visible, which can have different variants, for example, different transmission technologies used.

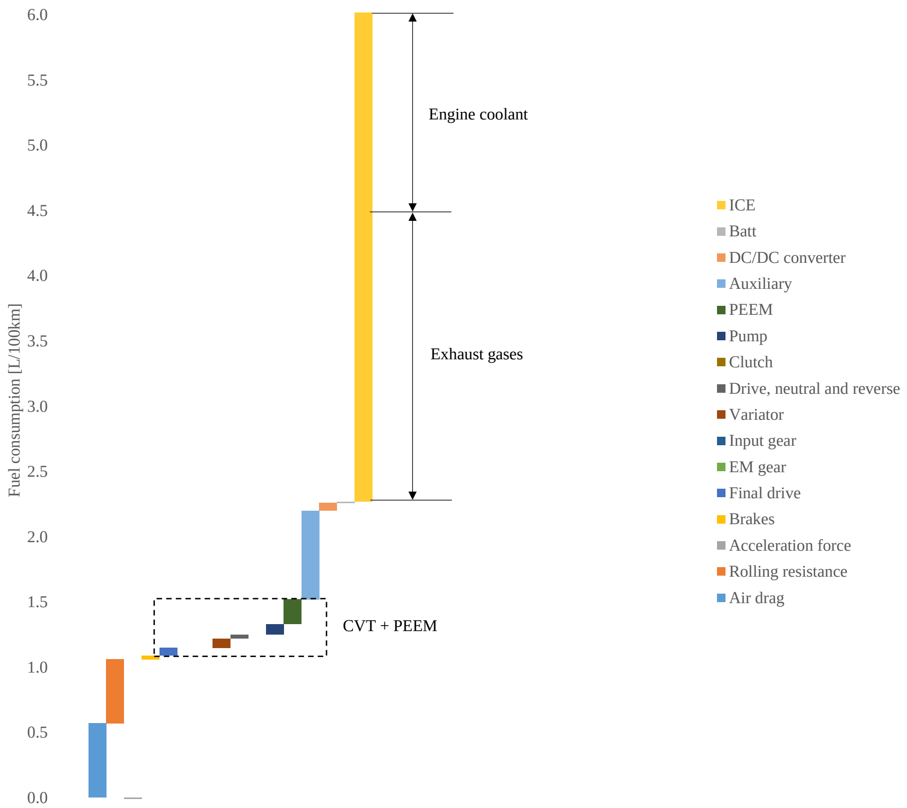

Figure 1: Energy losses of a CVT-based PHEV on the NEDC. ICE is the internal combustion engine, Batt the battery and PEEM the power electronics (PE) and electric machine (EM).

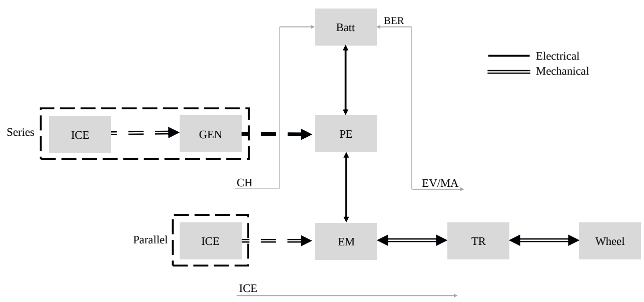

Figure 2: Electrified powertrain architecture. Series denotes the series HEV, GEN the generator, parallel the parallel HEV, ICE the engine only mode, CH the charging mode, EV the electric vehicle mode, MA the motor assist mode and BER the brake energy recuperation mode.

For a given topology, earlier works mainly focused on energy management systems (EMSs), which have shown that optimization-based algorithms, such as dynamic programming (DP), Pontryagin's minimum principle (PMP), equivalent consumption minimization strategy (ECMS), and model predictive control (MPC), outperform conventional rule-based ones [9, 10, 11, 12, 13]. Advantages and disadvantages of each method can be found in [8, 14, 15]. Optimization-based approaches minimize a cost functional, by finding an optimal control law, subject to various constraints. Rule-based methods make decisions, by using a set of rules, e.g., if-then conditions, derived from engineering intuition. Furthermore, a combined dimensioning and control optimization was presented to reduce energy consumption and cost of ownership simultaneously in [16]. The optimal solution can be found on a representative driving pattern even under constraints of performance requirements by evaluating

$$J = \frac{\rho_f}{H_{lhv}} \sum_{k=k_0}^{k_{n-1}} P_f(k)\Delta t + \frac{\rho_e}{1000 \cdot 3600} \sum_{k=k_0}^{k_{n-1}} P_c(k)\Delta t + \sum_j \rho_{c_j} n_{c_j}. \tag{1}$$

where the fuel power P_f and charger power P_c are converted to costs using energy prices ρ_f for gasoline and ρ_e for electricity. H_{lhv} is the lower heating value of gasoline, ρ_c the price of the battery cell, and n_c the number of battery cells. In addition, since most optimization strategies are not online implementable, predictive EMSs using external information provided by intelligent transportation system, were investigated in [17].

From Figure 1, it can be seen that a large portion of the fuel energy is dissipated into the surroundings in the form of exhaust gases, and recovering a part of that energy would be an effective way to improve powertrain efficiency. Two categories of waste heat recovery (WHR) technologies may be distinguished, namely Rankine cycle-based WHR systems and thermoelectric generators (TEGs). A Rankine cycle-based electrical WHR (REWHR) system recuperates waste energy from exhaust gases and the power harvested is stored into the battery, as illustrated in Figure 3 [18, 19], where the expander is coupled with a generator. A TEG generates electricity as long as there is a thermal gradient based on the Seebeck effect

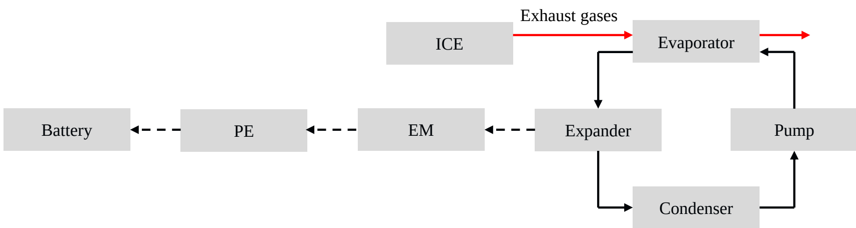

Figure 3: Schematic of a Rankine cycle-based electrical WHR system.

[20]. It can also be observed that the auxiliary load, for example, heating, ventilation and air conditioning (HVAC) and engine cooling system, consumes a significant amount of energy. It is thus imperative to develop energy-saving thermal management systems (TMSs). Solar-reflective glazing, thermal storage using phase change materials and component encapsulation were reported as viable means to reduce energy consumption [21]. TMS architectures featuring efficient heat exchange through proper arrangement of cooling circuits, e.g., distributing the engine coolant to heat up the cabin, lubrication oils and battery, have revealed substantial powertrain efficiency improvement, as demonstrated in Figure 4.

It is apparent that the amount of waste heat from PEEM is significant as well, and recuperating a certain percentage of that power, which would otherwise be wasted into the ambient, is a promising way to promote energy efficiency. A heat pump, because of higher coefficient of performance, is proved to be an alternative to an electric heater [23]. It can be adopted for extracting waste heat from PEEM, resulting in increased heating capacity and heating performance for cabin heating, which contributes to a decrease in the battery load [24, 25], as shown in Figure 5.

The results in [26] presented remarkable energy consumption reduction via upgrading traditional mechanical actuators to their electrified counterparts, enabling cooling on demand by using optimal controllers. More importantly, an integrated energy and battery TMS, as depicted in Figure 6, was proposed in [27]. Note that, for simplicity, only cooling part is considered. Specifically, the battery can be cooled down with a radiator (u_r) and chilled down with the air conditioning (AC) system (u_{ac}), as demonstrated in Figure 7. The objective of this system is to minimize the overall fuel consumption, while maintaining the battery temperature within its suitable range. The control vector u is found by minimizing the following Hamiltonian

$$H(E_s, T_b, \lambda_1, \lambda_2, u) = \dot{m}_f(t) + \lambda_1 \cdot \dot{E}_s + \lambda_2 \cdot \dot{T}_b. \tag{2}$$

where $\dot{E}_s$ and λ_1 represent the battery energy dynamics and the associated costate, respectively. $\dot{T}_b$ and λ_2 represent the battery temperature dynamics and the accompanying costate, respectively. The temperature dynamics relate to the corresponding cooling power consumption. The proposed integrated system demonstrated superior performance to its separated equivalence.

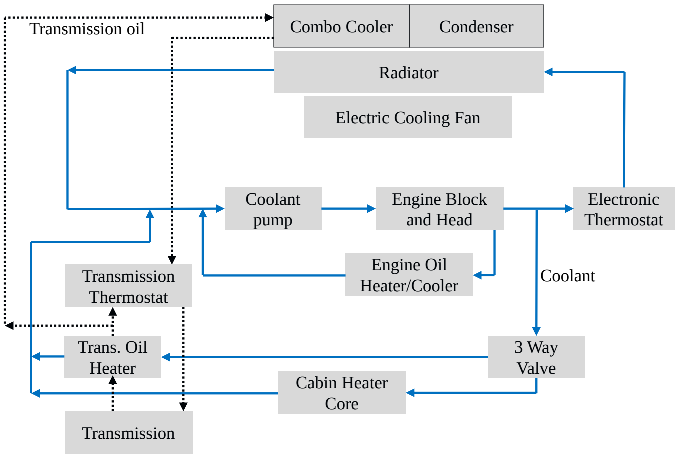

Figure 4: Thermal management system architecture [22].

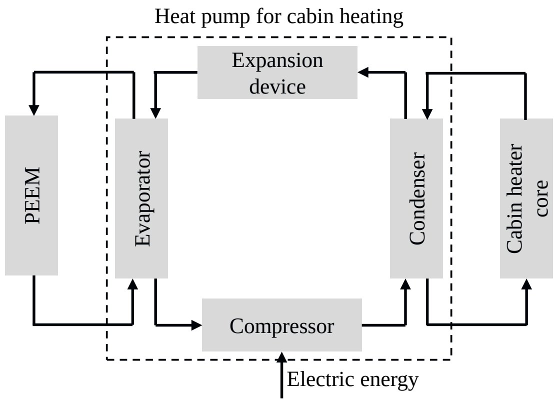

Figure 5: Electric path waste heat recovery in electrified powertrains.

In general, electrified powertrains comprise HEVs and EVs. From design perspective, these two types of vehicles have different requirements. Therefore, to verify the energy saving of implementing some methods and technologies as aforementioned, they are investigated individually.

3 IETMS for HEVs

Considering conversion efficiency, technical readiness and cost, REWHR systems are preferred to TEGs. Moreover, observing the temperature levels of main components of a CVT-based electrified powertrain, it is feasible to group CVT and PEEM, sharing the same housing and coolant loop, for example, with oil cooling. This further increases the amount of waste heat that could be harvested. Harvesting waste heat from PEEM and CVT is termed electric path WHR (EPWHR). A REWHR system, which is mostly used in internal combustion engine vehicles (ICEVs), and a heat pump, which is mainly adopted for EVs, are employed in a PHEV context. As a result, an IETMS is originally proposed to quantify the benefit of using these WHR technologies on the fuel saving of the PHEV, as illustrated in Figure 8. The PHEV with cabin heating demand from the battery, is subject to a cold-start, for example, the car has been parked for a long time, which is common in reality. A backward-facing model is developed, consisting of energy dynamics (black lines) and thermodynamics (red lines). Let γ_v be the CVT variator ratio and u_t be the torque split factor, which represents the torque split between the ICE and the EM. Given the demanded torque T_d based on the vehicle speed v_v and vehicle acceleration a_v, which are prescribed by a driving

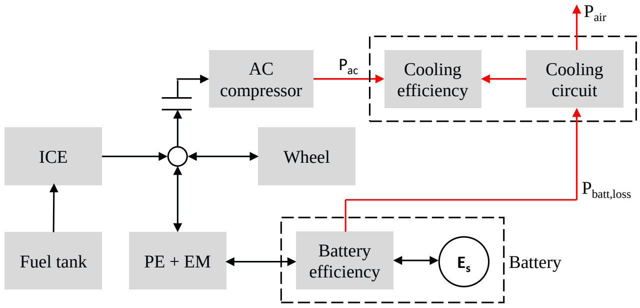

Figure 6: Integrated energy and battery thermal management system. $P_{batt,loss}$ is the heat generation of the battery, P_{air} the radiator's air cooling power, and P_{ac} the cooling power provided by the AC system.

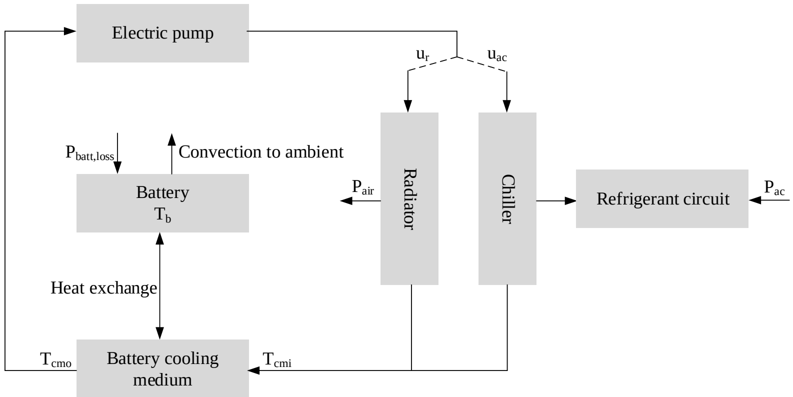

Figure 7: Battery thermal management system. T_{cmi} and T_{cmo} are the cooling medium inlet temperature and outlet temperature, respectively.

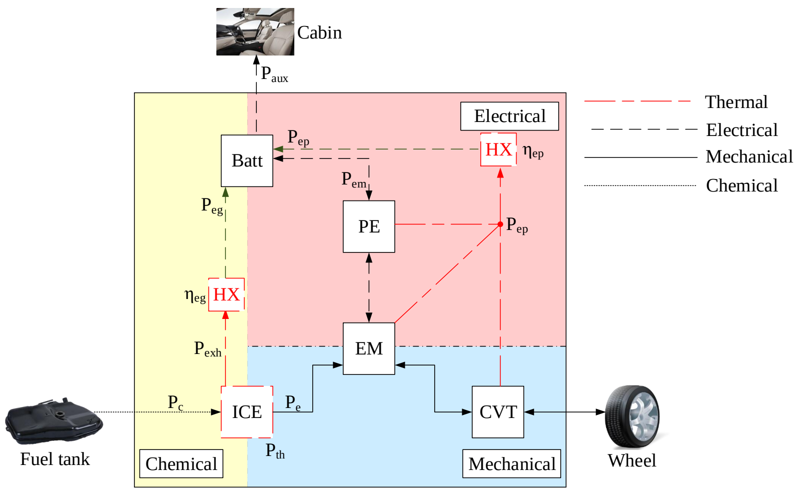

Figure 8: Integrated energy and thermal management system for a CVT-based PHEV.

cycle, the torque provided by the ICE and EM are expressed as

$$T_e(k) = (1 - u_t(k)) \cdot T_d(k), \quad \text{if } T_d(k) > 0, \tag{3}$$

$$T_{em}(k) = u_t(k) \cdot T_d(k), \quad \text{if } T_d(k) > 0 \vee T_d(k) \leq 0 \wedge w_p(k) \geq \frac{1000 \cdot \pi}{30}. \tag{4}$$

where k represents the time index and w_p is the speed of the primary pulley of the CVT. In this configuration, the ICE and EM speeds (w_e and w_{em}) are equal to w_p. The fuel consumption represented by the injected fuel mass flow $\Delta m_f(k)$, under warm-start conditions, meaning the engine is already at its efficient operating temperature, is described by a look-up table, i.e.,

$$\Delta m_f(k) = \Delta m_f(T_e(k), w_e(k)). \tag{5}$$

With cold-start conditions, however, the fuel consumption is higher due to higher oil viscosity effects and frictional losses. This cold effect is reflected by introducing a correction factor, which is given by [28]

$$c(\theta_e(k)) = \begin{cases} 1 + c_{e,1} \cdot (\theta_{e,max} - \theta_e(k)) \cdot e^{c_{e,2} \cdot (\theta_{e,max} - \theta_e(k))}, & \text{if } \theta_e(k) < \theta_{e,max}, \\ 1, & \text{if } \theta_e(k) = \theta_{e,max}. \end{cases} \tag{6}$$

where $c_{e,1}$ and $c_{e,2}$ are constant coefficients. $\theta_{e,max}$ is the engine operating temperature. Therefore, the temperature-dependent fuel power is calculated by

$$P_c(k) = c(\theta_e(k)) \cdot \Delta m_f(k) \cdot H_{lhv}. \tag{7}$$

A large portion of the fuel power is converted into mechanical power $P_e(k) = w_e(k) \cdot T_e(k)$ to propel the wheels. Another significant part is dissipated to the exhaust gases $P_{exh}(k) = (c_{exh,1} - c_{exh,2} \cdot w_e(k)) \cdot P_c(k)$, where $c_{exh,1}$ and $c_{exh,2}$ are constant coefficients. The power lost to the ambient air due to convection is computed by $P_a(k) = c_a \cdot A_e \cdot (\theta_e(k) - \theta_a)$, where c_a is the heat transfer coefficient, A_e the heat exchange area and θ_a the ambient temperature. Hence, the heat production in the engine is obtained by

$$P_{th}(k) = P_c(k) - P_e(k) - P_{exh}(k) - P_a(k). \tag{8}$$

As a result, the engine temperature can be described as follows:

$$\dot{\theta}_e(k) = \begin{cases} \frac{P_{th}(k)}{c_h \cdot c_e \cdot m_e}, & \text{if } \theta_e(k) < \theta_{e,max}, \\ 0, & \text{if } \theta_e(k) = \theta_{e,max}. \end{cases} \tag{9}$$

where c_h is a heating coefficient, which balances the faster heating of the lubrication oil and the slower heating of metal parts. c_e is the engine specific heat and m_e its mass. The REWHR system is employed to recuperate a certain amount of the exhaust gas heat $P_{exh}(k)$, and the recovered energy is ultimately stored into the battery. For the sake of simplicity, a lumped recovery efficiency $\eta_{eg} \in [0, 10\%]$ is used to gain qualitative insights, and the power harvested is given by

$$P_{eg}(k) = \eta_{eg} \cdot P_{exh}(k). \tag{10}$$

Similarly, the EPWHR system is adopted to recover a certain percentage of the waste heat from the PEEM and CVT with a lumped harvesting efficiency $\eta_{ep} \in [0, 20\%]$ to reduce the load on the battery, and the recovered power is calculated by

$$P_{ep}(k) = \eta_{ep} \cdot (P_{peem,loss}(k) + P_{cvt,loss}(k)). \tag{11}$$

where $P_{peem,loss}(k)$ is the power loss of the EM including PE and $P_{cvt,loss}(k)$ is the power loss of the CVT. Detailed loss maps of the EM and CVT are used for the calculation. Taking into account of the electrical power of the EM, $P_{em,el}(k) = w_{em}(k) \cdot T_{em}(k) + P_{peem,loss}(T_{em}(k), w_{em}(k))$, and the cabin heating request, P_{aux}, which constitute the electric power supplied by the battery, the battery current is computed by

$$I_b(k) = \frac{V_{oc}(k) - \sqrt{V_{oc}^2(k) - 4 \cdot (P_{em,el}(k) + P_{aux}) \cdot R_{int}(k)}}{2R_{int}(k)}. \tag{12}$$

where V_{oc} is the open circuit voltage of the battery and R_{int} its internal resistance. Consequently, the SOC of the battery evolves according to

$$\xi(k+1) = -\frac{I_b(k) \cdot \eta_b(I_b(k))}{Q_b \cdot 3600} \Delta k + \xi(k). \tag{13}$$

where η_b is the battery charging efficiency and Q_b is the battery capacity. Therefore, the overall system can be summarized as follows. The state variables are $\xi(k)$, which represents the energy dynamics, and

$\theta_e(k)$, which reflects the thermodynamics. The control inputs are $\gamma_v(k)$ and $u_t(k)$. The disturbance vector contains $v_v(k)$ and $a_v(k)$. A trade-off exists between the cost of the engine warm-up, increasing the engine temperature to its operating temperature, and the benefit of adopting WHR technologies. Among the control strategies introduced earlier, DP [29, 30], which uses Bellman's principle of optimality and finds the global optimal solution, is applied to obtain an optimal control law by minimizing the following cost function

$$J = \sum_{k=k_0}^{k_{n-1}} \left[1 + c_{e,1} \cdot (\theta_{e,max} - \theta_e(k)) \cdot e^{c_{e,2} \cdot (\theta_{e,max} - \theta_e(k))}\right] \cdot \Delta m_f(k). \tag{14}$$

Constraints imposing on the system are given by

$$w_e(k) \in [w_{e,min}, w_{e,max}], \tag{15a}$$
$$T_e(k) \in [T_{e,min}(w_e(k)), T_{e,max}(w_e(k))], \tag{15b}$$
$$w_{em}(k) \in [w_{em,min}, w_{em,max}], \tag{15c}$$
$$T_{em}(k) \in [T_{em,min}(w_{em}(k)), T_{em,max}(w_{em}(k)], \tag{15d}$$
$$I_b(k) \in [I_{b,min}, I_{b,max}], \tag{15e}$$
$$\gamma_v(k) \in [\gamma_{v,min}, \gamma_{v,max}], \tag{15f}$$
$$u_t(k) \in [u_{t,min}, u_{t,max}], \tag{15g}$$
$$\xi(1) = \xi(N), \tag{15h}$$
$$\xi(k) \in [\xi_{min}, \xi_{max}], \tag{15i}$$
$$\theta_e(k) \in [\theta_{e,min}, \theta_{e,max}]. \tag{15j}$$

The simulation result is shown in Figure 9. It should be noted that due to resolution, the SOC trace appears to be a straight line. It can be observed that the recuperated power from the exhaust gases is temporarily stored into the battery and retrieved efficiently at high power demand. Furthermore, the recovered energy from the PEEM and CVT reduces the load on the battery directly, as the charging power in S_1 is much less than that in S_0. Compared with the baseline S_0, remarkable fuel efficiency improvement can be achieved, up to 13.1%. Altering the efficiencies of the WHR systems, different fuel savings can be obtained, which provide insights into design of WHR technologies and dimensioning of electrified powertrain components. For example, the recovered power can downsize the battery pack.

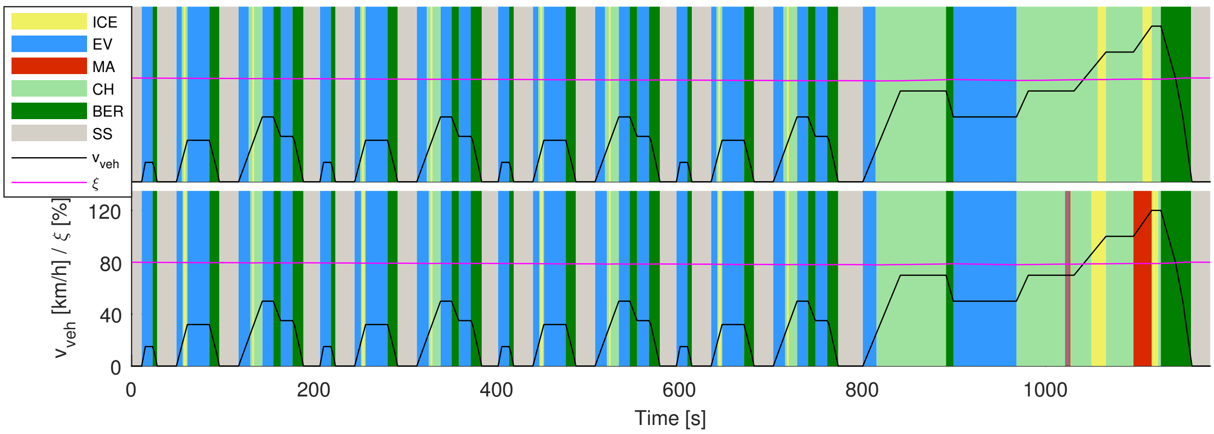

Figure 9: Hybrid mode visualization for the PHEV in charge sustaining mode on the NEDC. The upper subplot S_0 represents a simulation setting without WHR technologies, while the lower subplot S_1 represents a simulation setting with WHR technologies.

4 CVT for EVs

Currently, the emerging EV market is dominated by the single-speed transmission due to its system simplicity. The potential benefits of multi-speed transmissions, e.g., CVTs, for improved energy efficiency and drivability, are under discussion. To evaluate the benefit of a CVT, a compact class EV is used in this study, where system integration, especially the dependency between EM and CVT, plays a pivotal role. This case study is based on the work presented in [31]. Main vehicle parameters and vehicle performance requirements are listed in Table 1. Despite its simplicity, a single-speed transmission poses conflicting requirements for EMs. At low speeds, EMs have to offer a good drive-off performance, leading to large dimensions and magnetic forces, which have a negative impact on their ability, at high speeds, to achieve top vehicle speed, resulting in a reference EM as shown in Figure 10. The CVT, however, can solve this trade-off due to ratio variation between the Low ratio and the overdrive (OD) ratio, resulting in a downsized EM, which has similar peak power and peak efficiency as the reference one, as evidenced in Figure 11. Through analyzing several variator options, belt, chain, toroidal, and variable planetary, the pushbelt type variator stands out, taking into consideration of efficiency, power density and NVH (noise, vibration and harshness). In order to achieve the performance of the considered EV, two spur gear stages are added to the variator to provide the demanded ratio coverage. The variator helps find the most efficient regions of the driveline, owing to its continuous adjustment. The wider power availability of the EM, in turn, requires a smaller ratio coverage, resulting in, e.g., improved variator efficiency, decreased actuation power, and reduced NVH. In order to investigate the benefit of a ratio change, three systems, as

Table 1: Main vehicle parameters and vehicle performance requirements

Parameter	Value	Unit
Mass	1415	kg
Payload	400	kg
Trailer mass	2715	kg
Aerodynamic coefficient	0.24	-
Frontal area	2.13	m^2
Dynamic wheel radius	0.3065	m
Maximum range	400	km
Maximum speed	170	km/h
Maximum acceleration 0-100 [km/h]	9.2	s
Drive-off slope	35	%
Climb sidewalk step	10	cm

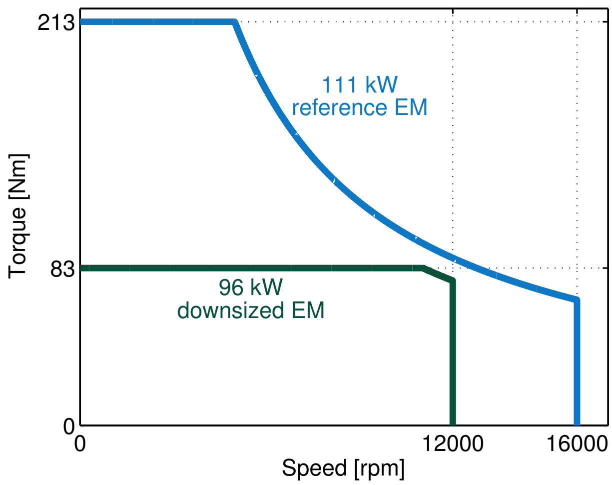

Figure 10: Performance characteristics of the reference EM and the downsized EM.

depicted in Figure 12, are compared on Worldwide Harmonized Light Vehicles Test Cycles (WLTC) in terms of energy consumption and vehicle performance, by using a backward-facing model with optimal control. These three systems are the single-speed transmission with the reference EM, the CVT with the reference EM, and the CVT with the downsized EM. Compared to the single-speed transmission, transmission technologies with variable speeds reduce energy consumption by 3-4% [31]. The integration of CVT with the downsized EM demonstrates a competitive energy consumption. Furthermore, in terms of key performance indicators, CVTs are compared with two-speed transmissions, as shown in Figure 13. Reducing speed and torque requirements on the EM specification contributes to reduced size, weight and cost. When it comes to vehicle performance, as listed in Table 2, the maximum vehicle speed is

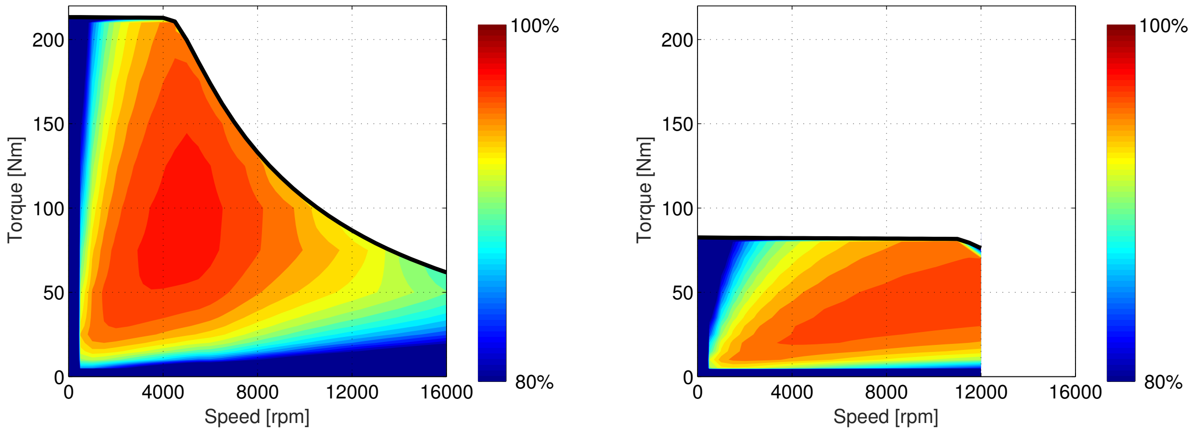

Figure 11: Efficiency maps of the reference EM and the downsized EM.

not met by the single-speed transmission. In Table 2, std EM represents the reference EM and opt EM represents the downsized EM. The difference in acceleration performance between the CVT with the reference and downsized EM can be explained by the lower maximum power of the downsized EM. It can be envisioned that, due to the addition of a CVT, the battery pack and the cooling system can also be downsized, contributing to further energy saving, which is subject to ongoing research.

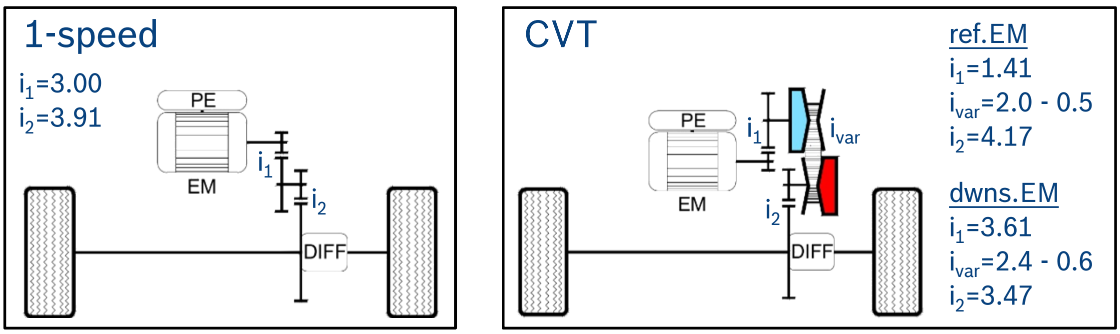

Figure 12: EV topologies with different transmission types. 1-speed denotes the single-speed transmission, ref.EM the reference EM and dwns.EM the downsized EM.

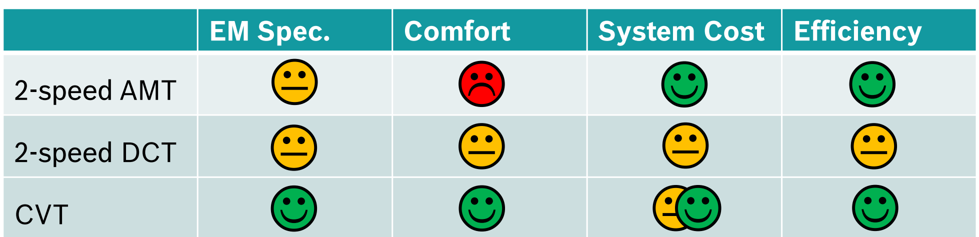

Figure 13: Comparison of key performance indicators. AMT represents the automated manual transmission and DCT represents the dual clutch transmission.

Table 2: Simulation results of vehicle performance

Parameter	1-speed std EM	CVT std EM	CVT opt EM
Top speed	158	>170	>170
Acceleration	6.9	7.4	8.0
Gradeability	35	35	35

5 Conclusions

Powertrain electrification is a logical solution to tackle energy and environmental issues. A numerical simulation is conducted to analyze energy losses of a PHEV so as to identify components and systems where most of the energy efficiency improvements could be obtained. The state of the art of approaches for improving electrified powertrain efficiency are thoroughly reviewed. To verify the energy saving potential of the opportunities found, two case studies are performed. An IETMS is proposed for a PHEV with cabin heating request, subject to cold-start conditions, where up to 13.1% fuel efficiency improvement can be achieved, by using REWHR and EPWHR systems. Compared with commonly used single-speed transmissions, EVs equipped with CVTs, which provide opportunities of downsizing the electric machine, battery pack and TMSs, demonstrate significant energy consumption reduction, 3-4%. Based on the research findings, a combined strategy containing both energy and thermal aspects, in consideration of topology, technology, size and control optimization, is recommended to maximize energy efficiency of electrified powertrains.

References

[1] J. An and A. Binder, *Operation strategy with thermal management of e-machines in pure electric driving mode for twin-drive-transmission (DE-REX)*, 2017 IEEE Vehicle Power and Propulsion Conference (VPPC), 2017, 1-6.

[2] C. Capasso and O. Veneri, *Integration between super-capacitors and ZEBRA batteries as high performance hybrid storage system for electric vehicles*, Energy Procedia, ISSN 1876-6102, 105(2017), 2539-2544.

[3] H. Borhan, A. Vahidi, A. M. Phillips, M. L. Kuang, I. V. Kolmanovsky and S. Di Cairano, *MPC-based energy management of a power-split hybrid electric vehicle*, IEEE Transactions on Control Systems Technology, ISSN 1063-6536, 20(2012), 593-603.

[4] E. Silvas, T. Hofman, N. Murgovski, L. F. P. Etman and M. Steinbuch, *Review of optimization strategies for system-level design in hybrid electric vehicles*, IEEE Transactions on Vehicular Technology, ISSN 0018-9545, 66(2017), 57-70.

[5] S. Stockar, V. Marano, G. Rizzoni and L. Guzzella, *Optimal control for plug-in hybrid electric vehicle applications*, 2010 American Control Conference, ISSN 2378-5861, 2010, 5024-5030.

[6] N. Murgovski, L. Johannesson, X. Hu, B. Egardt and J. Sjöberg, *Convex relaxations in the optimal control of electrified vehicles*, 2015 American Control Conference, ISSN 0743-1619, 2015, 2292-2298.

[7] S. Pagerit, P. Sharer and A. Rousseau, *Fuel economy sensitivity to vehicle mass for advanced vehicle powertrains*, SAE 2006 World Congress & Exhibition, ISSN 0148-7191, 2006.

[8] T. Hofman, M. Steinbuch, R. van Druten, and A. Serrarens, *Rule-based energy management strategies for hybrid vehicles*, International Journal of Electric and Hybrid Vehicles, 1(2007), 71-94.

[9] C. Lin, H. Peng, J. Grizzle and J. Kang, *Power management strategy for a parallel hybrid electric truck*, IEEE Transactions on Control Systems Technology, ISSN 1063-6536, 11(2003), 839–849.

[10] N. Kim, S. Cha, and H. Peng, *Optimal control of hybrid electric vehicles based on Pontryagin's minimum principle*, IEEE Transactions on Control Systems Technology, ISSN 1063-6536, 19(2011), 1279-1287.

[11] L. Serrao, S. Onori and G. Rizzoni, *ECMS as a realization of Pontryagin's minimum principle for HEV control*, 2009 American Control Conference, ISSN 0743-1619, 2009, 3964-3969.

[12] B. Sampathnarayanan, L. Serrao, S. Onori, G. Rizzoni and S. Yurkovich, *Model predictive control as an energy management strategy for hybrid electric vehicles*, 2009 ASME Dynamic Systems and Control Conference, 2009, 249-256.

[13] D. Bianchi, L. Rolando, L. Serrao, S. Onori, G. Rizzoni, N. Al-Khayat, T-M. Hsieh and P. Kang, *A rule-based strategy for a series/parallel hybrid electric vehicle: An approach based on dynamic programming*, 2010 ASME Dynamic Systems and Control Conference, 2010, 507-514.

[14] A. Sciarretta and L. Guzzella, *Control of hybrid electric vehicles*, IEEE Control Systems Magazine, ISSN 1066-033X, 27(2007), 60-70.

[15] W. Enang and C. Bannister, *Modelling and control of hybrid electric vehicles (a comprehensive review)*, Renewable and Sustainable Energy Reviews, ISSN 1364-0321, 74(2017), 1210-1239.

[16] N. Murgovski, L. Johannesson, J. Sjöberg and B. Egardt, *Component sizing of a plug-in hybrid electric powertrain via convex optimization*, Mechatronics, ISSN 0957-4158, 22(2012), 106-120.

[17] T.J. Böhme and B. Frank. *Hybrid systems, optimal control and hybrid vehicles*, ISBN 978-3319513157, Cham, Switzerland, Springer, 2017.

[18] G. Latz, *Waste heat recovery from combustion engines based on the rankine cycle*, Ph.D. dissertation, Chalmers University of Technology, 2016.

[19] K. Upendra and A. Grauers, *Synergy and conflicts between waste heat recovery system and hybrid electric vehicle*, Technical Report, Chalmers University of Technology, 2015.

[20] B. Orr, A. Akbarzadeh, M. Mochizuki, and R. Singh, *A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes*, Applied Thermal Engineering, ISSN 1359-4311, 101(2016), 490–495.

[21] S. Osborne, J. Kopinsky, S. Norton, A. Sutherland, D. Lancaster, E. Nielsen, A. Isenstadt and J. German, *Automotive thermal management technology*, Technical report, The International Council on Clean Transportation, 2016, 1-16.

[22] K. Laboe and M. Canova, *Powertrain waste heat recovery: A systems approach to maximize drivetrain efficiency*, 2012 ASME Internal Combustion Engine Division Spring Technical Conference, 2012, 985-992.

[23] Z. Qi, *Advances on air conditioning and heat pump system in electric vehicles – a review*, Renewable and Sustainable Energy Reviews, ISSN 1364-0321, 38(2014), 754–764.

[24] C. Cho, H. Lee, J. Won, and M. Lee, *Measurement and evaluation of heating performance of heat pump systems using wasted heat from electric devices for an electric bus*, Energies, 5(2012), 658–669.

[25] J. H. Ahn, H. Kang, H. S. Lee, H. W. Jung, C. Baek and Y. Kim, *Heating performance characteristics of a dual source heat pump using air and waste heat in electric vehicles*, Applied Energy, ISSN 0306-2619, 119(2014), 1-9.

[26] X. Tao, K. Zhou, A. Ivanco, J. R. Wagner, H. Hofmann and Z. Filipi, *A hybrid electric vehicle thermal management system - nonlinear controller design*, SAE 2015 World Congress & Exhibition, ISSN 0148-7191, 2015.

[27] T. H. Pham, J. T. B. A. Kessels, P. P. J. van den Bosch, R. G. M. Huisman and R. M. P. A. Nevels, *Online energy and battery thermal management for hybrid electric heavy-duty truck*, 2013 American Control Conference, ISSN 0743-1619, 2013, 710-715.

[28] K. van Berkel, *Control of a mechanical hybrid powertrain*, Ph.D. dissertation, Eindhoven University of Technology, 2013.

[29] D. P. Bertsekas. *Dynamic Programming and Optimal Control*, 3rd ed., ISBN 978-1886529267, Belmont, MA, USA, Athena Scientific, 2005.

[30] O. Sundström and L. Guzzella, *A generic dynamic programming matlab function*, 2009 IEEE Control Applications, (CCA) Intelligent Control, (ISIC), ISSN 1085-1992, 2009, 1625-1630.

[31] G. van Spijk, I. Hupkes, L. Römers, F. van der Sluis and R. van Iperen, *CVT: Extending possibilities for powertrain electrification*, 13th International CTI Symposium "Automotive Drivetrains, Intelligent, Electrified", 2019 CTI Symposium US Automotive Drivetrains.

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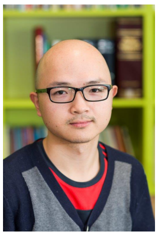

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