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Original Articles

Influence of a CVT on the fuel consumption of a parallel medium-duty electric hybrid truck

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Abstract

Hybrid electric vehicles are being developed to reduce the pollutant emissions and the fossil-fuel consumption of transportation. Innovative technologies are inserted to improve the performance of hybrid vehicles, including trucks and buses. Thereby, trends towards gear shifting automation motivate the research on replacing a discrete conventional Automated Manual Transmission (AMT) with a Continuously Variable Transmission (CVT). Theoretically, such a transmission enables better operation points of the thermal engine, and therefore a reduction of its fuel consumption and emissions. However, the conventional (hydraulic actuated) CVT efficiency during quasi-stationary operation is typically lower than the efficiency of a classical discrete gearbox, which leads to higher fuel consumption. This paper is focused on the study of the interests of a CVT for a medium-duty Hybrid Electric Truck (HET). The complete model and control of CVT-based and AMT-based HET are described in a unified way using Energetic Macroscopic Representation (EMR). These models are transformed to backward-models to be computed by the Dynamic Programming Method (DPM). Such a method leads to define the (off-line) optimal energy management strategies for a fair comparison of both hybrid trucks. For the studied driving cycle, the hybridization allows a fuel saving of 10% with an AMT and 3% with a CVT. The fuel consumption is higher for the CVT-based HET in comparison with the AMT-based HET due to the lowest efficiency of the CVT (85%) compared to the AMT (around 92%). However, future (on-demand) CVTs with an increased efficiency could be a solution of interest to reduce the fuel consumption of such applications. The developed method can be used to test these new CVTs, other vehicles or other driving cycles.

Keywords: Hybrid electric truck; Continuous variable transmission; Energetic macroscopic representation; Dynamic programming method

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1. Introduction

Energy saving, GreenHouse Gases (GHGs) and fossil fuels depletion are critical issues for the next decade. According to the International Energy Agency and the US Environmental Protection Agency, transportation is an important cause of the global CO_2 emissions (22% of the world emissions in 2010 and 31% of the US GHGs emissions in 2013) [38]. Within transportation, heavy-duty vehicles contribute about 80% of the total CO_2 emissions of commercial vehicles. New transportation systems such as Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs) or Fuel Cell Vehicles (FCVs) should thus increase mobility while limiting environmental impacts [12,4,29]. However, EVs have the drawback of low autonomy and long charging time due to the battery. FCVs are still too expensive and with a low reliability for the automotive sector. HEVs can thus be considered as the more realistic intermediary step towards CO_2 neutral vehicles.

Multiple energy sources in HEVs (fuel tank, battery, supercapacitors, etc.) combine the advantages of each source allowing reduction of the fuel consumption and GHGs emissions and improvement of the component's life time [27,3]. Furthermore, different configurations and transmission systems can be used to link the ICE (Internal Combustion Engine), the electric drive, and the wheels. In conventional HEVs, Automatic Manual Transmission (AMT) is generally used with five/six discrete gear ratios [14,26,2]. New innovative transmissions are currently developed such as Continuous Variable Transmission (CVT) [30,37,24,15,31,25,35], Electric Variable Transmission (EVT) [35,5,6,36] or Double Planetary Gear (DPG) [39,19] to improve the drive agreement and reduce the fuel consumption. These new transmission systems introduce a new degree of freedom in the system, which can be used to develop more efficient Energy Management Strategy (EMS). The operating point of the ICE can thus be imposed in the best consumption area in the torque-speed plan. However, the development of efficient EMS is a sensitive issue for these kinds of vehicles [20,28,34].

Some commercial HEVs use already innovative transmission systems such as CVT [33,9,8]. However, they are not yet used in medium and heavy-duty Hybrid Electric Trucks (HETs). Indeed, the technology is not yet mature and the actual efficiency of CVT is still too low compare to conventional AMTs for high torque demand vehicles. A first paper [23] demonstrates that the actual CVT technology is not mature enough to have a positive impact on the fuel consumption for such hybrid trucks. However, the considered EMS was based on rules that do not lead to optimal results. No direct comparison has therefore been provided between CVT-based HET and AMT-based HET. An off-line optimal EMS is thus required to provide a fair comparison. For the studied driving cycle, an optimal EMS will guarantee the optimal consumption for each vehicle. It should in particular lead to a final state-of-charge of the battery equal to its initial value to compare the fuel consumption as the unique energy consumption.

The objective of this paper is to compare the CVT-based hybrid truck with an AMT-based hybrid truck using an optimal EMS. The studied HET is a medium-duty parallel hybrid truck. Energetic Macroscopic Representation (EMR) [1,11] is used to organize the models and the controls of both vehicles in a forward-approach. By this way, the outputs of the EMS are clearly defined. Moreover, the EMR of the vehicle is transformed in backward simplified models to be computed by the Dynamic Programming Method (DPM). This method is an off-line optimization method which can be used to study non-linear systems [32,10]. DPM will thus define optimal EMSs of both vehicles for a considered driving cycle. The deduced EMSs are then applied to the forward detailed models for a fair comparison.

Section 2 presents the studied vehicle and its forward-based model using the EMR to highlight the optimization variables (distribution of energy, gear ratio, etc.) to be defined by the DPM. Section 3 converts the forward-based into backward-based model to be applied in the DPM. In Section 4, a comparison of both vehicles is performed using the DPM results applied to the complete simulation.

2. Forward-based model of the medium-duty parallel HET

The studied system is a CVT-based mild-duty parallel HET. A P2 configuration has been considered in this paper due to the specific design of the Electric Drive (e-drive), but other configuration could also be studied with the methodology proposed in this paper. The P2 configuration integrates the e-drive through a belt between the ICE and the transmission (Fig. 1). The e-drive is thus decoupled from the ICE and has the same speed (or multiple of it). The main advantage of this configuration is the increase of the energy recuperation potential and the availability of additional hybrid control functions such as electric creep/drive or energy recovery during coasting. Furthermore, the benefits of P2 configuration are to have lower e-drive specifications and currents, while P3 configuration benefits from higher transmission efficiency at the cost of a larger e-drive system. The studied parallel HET therefore consists in an ICE

Table 1
Data of both studied medium-duty parallel HETs.

ICE power	P_{ice}	205 kW	Total HET mass	M_{het}	7.5 t
e-drive power	P_{ed}	58 kW	Frontal area	A_f	6.9 m^2
Battery Li-ion pack capacity	C_{bat}	41.3 Ah	Air drag coef.	c_{d}	0.67
Belt ratio	K_{belt}	1	Rolling resistance	c_r	0.8%
Final drive ratio	K_{fd}	8.4	Air density	ρ	1.2 kg/m^3
CVT ratio	K_{cvt}	[0.8, 7.1]	Wheel-base length	L	4.8 m
AMT ratio	K_{amt}	{0.8;1.0;1.6;2.5;4.2;7.1}			

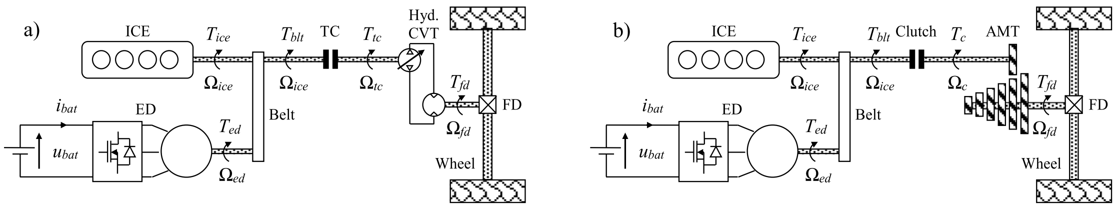

Fig. 1. Studied HETs: (a) CVT-based HET, (b) AMT-based HET.

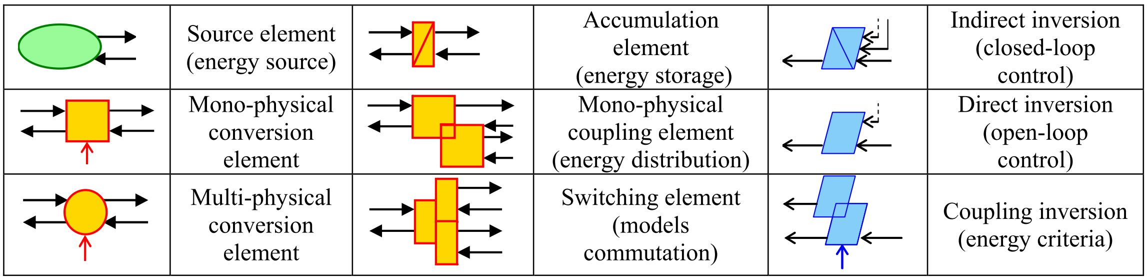

Fig. 2. EMR elements.

which is coupled to an e-drive using a belt (Fig. 1.a). The belt acts as a torque and power addition, which is connected via a shaft to the Torque Converter (TC). The torque converter couples the ICE and e-drive to the Continuously Variable Transmission (CVT). A hydraulic (oil pump) CVT technology is considered. Finally, the output shaft of the CVT is coupled to a final drive (FD), which is included in the differential of the front axle. For the AMT-based parallel HET, a clutch replaces the torque converter and the AMT replaces the CVT (Fig. 1.b). The main parameters are given in Table 1. Both HETs are represented using the EMR.

2.1. EMR of the studied HET

EMR is a graphical description for interconnection of subsystem models of a system [1]. EMR organizes the system into basic functions (Fig. 2) [11]: source of energy (green oval), accumulation of energy (orange crossed rectangle), conversion of energy (orange square or circle), distribution of energy (orange double square) and switching elements. The connected elements respect the interaction principle: the exchanged power is the product of the action and reaction variables. Furthermore, all the components respect the physical integral causality [17,13]. The EMR methodology has already been successfully used for simulation and control of various EVs and HEVs.

The common EMR of both HETs is presented (Fig. 3). The ICE is depicted by an energy source (green oval). Its output is the actual ICE torque T_{ice}, assumed equal to the reference torque $T_{ice\text{-}ref}$ with respect to its limitations. The reaction variable is the rotation speed Ω_{ice}, which is used to determine its operating point and subsequently its instantaneous brake specific fuel consumption. The Li-ion battery pack is depicted by an energy source (green oval). The action variable is the voltage u_{bat} applied to the e-drive. The reaction variable is the battery current i_{bat}. The battery voltage depends on the open-circuit voltage, internal resistance and battery current. Both open-circuit

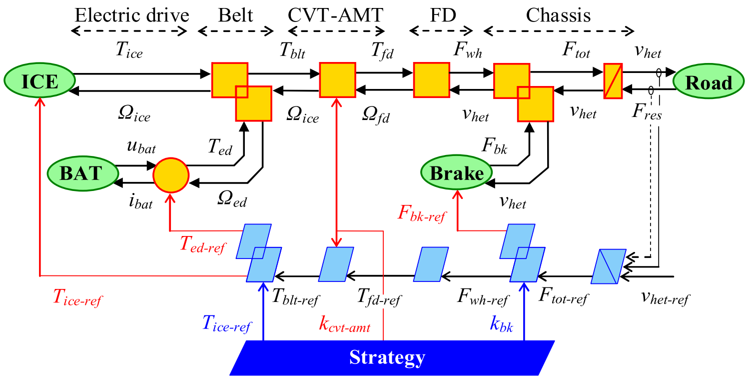

Fig. 3. Common EMR of the studied AMT-based or CVT-based HETs.

voltage and internal resistance are dependent on the battery temperature and state of charge *SoC* related to the battery current. The e-drive is composed of a Voltage-Source-Inverter and a Permanent Magnet Synchronous Machine. A static model of the e-drive is depicted by an orange circle (multi-domain conversion element) [22]. An equivalent constant efficiency η_{ed} is used. It means that the average losses during the drive cycle are reflected by this equivalent efficiency. The e-drive torque T_{ed} is assumed equal to its reference $T_{ed\text{-}ref}$ and the torque limitations are considered. The belt is a mono-physical coupling element (orange double square). Accordingly to the studied HET, a clutch-AMT association or a TC–CVT association is then used. They are both depicted by controlled mono-conversion elements (orange squares). The AMT ratio k_{amt} can take 6 discrete values between 0.8 and 7.1 (see Table 1), whereas the CVT ratio k_{cvt} can take all values between 0.8 and 7.1. Losses in the CVT come from the absorbed torque by the oil pump and mechanical torque. Both torque losses are obtained via look-up tables as a function of torque, rotational speed, and CVT ratio. These losses have been determined by experimental tests on a conventional mechanical hydraulic actuated CVT. Input torques and speeds have been scaled accommodating the operation ranges of the CVT model to effectively scale the efficiency of the CVT model to the operation range of interest for the medium duty truck. The final drive is a mono-physical conversion element (orange square) which converts rotational variables into linear variables. The mechanical brake imposes a force F_{bk} to the chassis. As an ideal brake is considered, its force is equal to the reference force $F_{bk\text{-}ref}$. The chassis describes the dynamical relation between the forces and the velocity v_{het} according to the second law of Newton. Finally, the road applies a resistive force F_{res} on the chassis and is represented as a source element (green circle). More information and equations can be found in [23].

2.2. Control and EMS of the studied HET

Specific rules have been defined to deduce control schemes from EMR [1,11] (light blue elements in Fig. 3). The objective is to impose a specified speed profile (drive cycle). The Urban Dynamometer Driving Schedule (UDDS), which is developed by the United States Environmental Protection Agency (EPA), is considered [14]. A tuning path is thus defined to derive the tuning variables $F_{bk\text{-}ref}$, $T_{ed\text{-}ref}$ and $T_{ice\text{-}ref}$ by means of inverting the EMR elements step-by-step. Conversion elements are directly inverted (light blue parallelograms), and accumulation elements require closed loop controls (light blue crossed parallelograms). Moreover, coupling elements are inverted using distribution coefficients (light blue double parallelograms), which allocate the energy distribution within the system. More information on the control is in [23].

The deduced inversion-based control provides a local control of the system. It highlights the variables, to be defined by the energy management strategy: $T_{ice\text{-}ref}$, k_{cv} or k_{amt}, and k_{bk}. These variables can be used to optimize the fuel consumption. In traction mode, the energy can be provided by the ICE and/or the e-drive. The EMS defines thus the reference ICE torque $T_{ice\text{-}ref}$ (distribution between the ICE and the electric drive) but also the CVT or AMT ratio. Regarding the CVT ratio, the objective is to track an optimal operating line to promote the best efficient area. In addition, the limitations (torque, power, speed) of the ICE and e-drive must be respected. In braking mode, the energy can be recovered on the battery while the SoC is lower than its maximal value respecting the e-drive limitations.

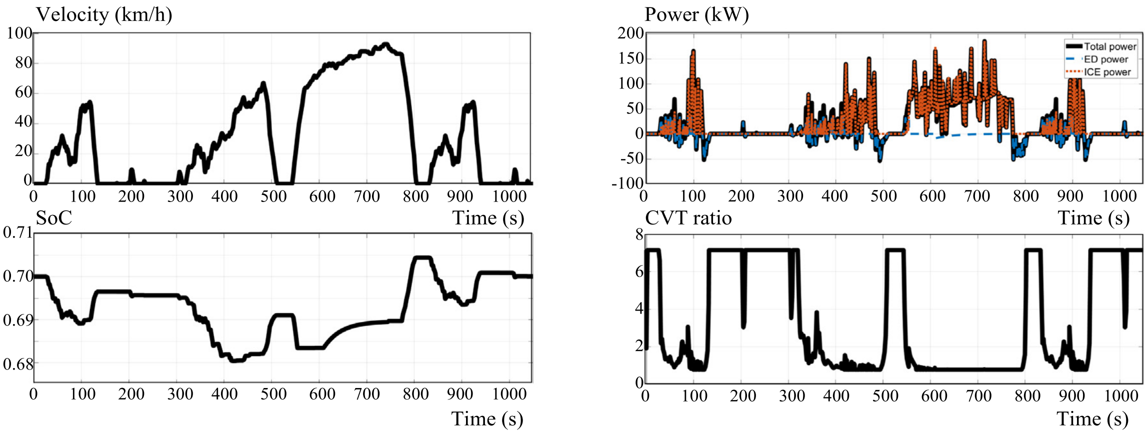

Fig. 4. Initial result of the CVT-based HET model (efficiency map for the CVT).

Furthermore, only the front wheels can recover energy because there is no e-drive in the rear wheel. Considering mass transfer, a braking balance of 60% on the front wheels and 40% on the rear wheels is assumed. The EMS defines the distribution coefficient k_{bk} (distribution between the mechanical brake and the e-drive). A first non-optimal rules-based has been defined in [23].

2.3. Model simplifications

To study the influence of the CVT efficiency in Section 4, the CVT model of is simplified. The efficiency map is replaced by a constant equivalent efficiency. A parametrized study is performed to define the appropriate average value of the equivalent CVT efficiency. The initial results of the HET with the CVT efficiency map are taken as reference (Fig. 4) [23]. Then comparisons are performed between the reference model and the model with the equivalent constant CVT efficiency (Fig. 5). An average equivalent constant efficiency of 85% is selected for the CVT to correspond with the results of the initial model with the efficiency map (18.2 L/100 km) [23]. This value is only valid for this studied case (drive cycle, studied vehicle, etc.) and is based on the CVT technology (oil pump) considered in the model of losses (see Section 2.1). Furthermore, newest technologies can be more efficient. Indeed, future CVT systems contain on-demand functionality with efficient compact hydraulic actuator designs that eliminate the relatively high initial actuation losses, making them more competitive compared to other (discrete step) powershift systems. More specifically, advanced and novel CVT systems, e.g., hydraulic-actuated [21] or electro-mechanical actuated CVTs [18], have proven to have average power losses in the order of 40 W on the WLTP or FTP-72, respectively.

3. Backward-based model of the medium-duty parallel HET

In [23], a non-optimal rules-based EMS has been developed. But in order to obtain a fair comparison, an optimal EMS is required. DPM-based optimal strategies are used in this section to perform fairest comparisons between both vehicles. As the DPM requires backward-based model, the forward-based initial model is thus turned into backward calculation.

3.1. Backward-based model of the studied HET

The EMR and control are merged to obtain an equivalent backward-based model (Fig. 6) [16]. The model organization is conserved but the inputs and outputs are changed. Moreover, the control is assumed perfect and the EMS provides only the control inputs. For the needs of the DPM, this model is implemented in Matlab© code [32]. The objective of the DPM is then to determine the optimal control inputs.

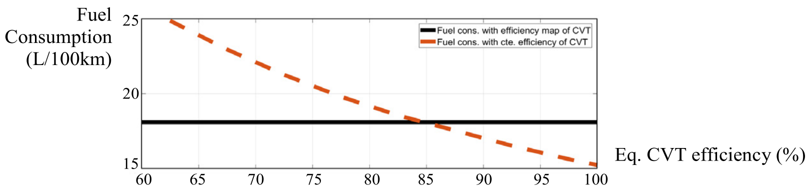

Fig. 5. Comparison of equivalent constant efficiency with a variable efficiency of the CVT.

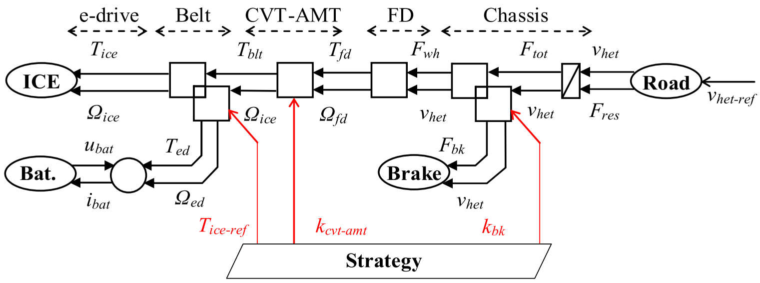

Fig. 6. Common backward representation of AMT-based or CVT-based HETs.

3.2. DPM-based optimization of the studied HET

The DPM is used to solve the optimal HET control problem [32,10]. In the studied case, it is a non-linear problem with final state constraints. When using the DPM, the solution space is discretized and interpolation is used to estimate the cost-to-go function between the grid points. Furthermore, when the final state constraints are imposed, any solution trajectory is bound to lie inside the backward reachable space. The DPM is thus used to solve the following optimization problem where J^* is the minimization of the cost function J, which is the sum of states transfer costs L (cost between two steps).

$$J^* = \min(J) = \min\left(\sum_{k=0}^{N-1} [\min\left(L\left(x\left(k\right), u\left(k\right), k\right)\right)]\right) \tag{1}$$

In this case L is the fuel consumption to minimize, and depends on the combination of the distribution vector noted $u_j(k)$, which is composed of the ICE reference torque $T_{ice\text{-}ref}$, the braking ratio distribution k_{bk} and the CVT or AMT ratio $k_{cvt\text{-}amt}$ depending on the studied vehicle.

$$L\left(x\left(k\right), u\left(k\right), k\right) = qm_{fuel}\left(x\left(k\right), u\left(k\right), k\right) \quad \text{with} \quad u\left(k\right) = \left[T_{ice-ref} \quad k_{bk} \quad k_{cvt-amt}\right]^t \tag{2}$$

The battery SoC is defined as state variable $x(k)$. Two constraints are imposed to the SoC: its initial and final values are targeted to be equal (fair fuel comparison); the SoC is limited for the battery lifetime.

$$x\left(k\right) = SoC\left(k\right) \quad \text{with} \quad \begin{cases} x\left(k_{final}\right) = x\left(k_{initial}\right) \\ SoC_{\min} \leq x\left(k\right) \leq SoC_{\max} \end{cases} \tag{3}$$

The limitations and discretization of the state variable and the distribution vector are given in Table 2. A time step of 1 s is chosen. The drive cycle duration is 1060 s. The SoC is limited between 40% and 90%. The ICE torque is limited according to its limitation (variable limitation with maximum of 1300 Nm). The braking distribution is limited to 60% due to the transfer balance between rear and front wheels [23]. The CVT ratio k_{cvt} is directly discretized and imposed by the DPM for the CVT-based HET. However, it can be noted that the selected gear G_{amt} is chosen for the AMT-based HET because it is by nature discrete, which allows keeping more realistic ratio value corresponding to the selected gear. On another hand, the internal variables can also be limited such as the e-drive torque and power limitations for example.

Table 2
Limitation and discretization of the DPM variables.

DPM variable	Variable name	Discretization	Minimal value	Maximal value
Time	k	1 s	0 s	1060 s
SoC	$x(k)$	1%	40%	90%
ICE torque	$T_{ice\text{-}ref}(k)$	10 Nm	0 Nm	1300 Nm
Braking distribution	$k_{Dbk}(k)$	1%	0%	60%
CVT ratio	$k_{cvt}(k)$	0.1	0.8	7.1
AMT gear	$G_{amt}(k)$	1	1	6

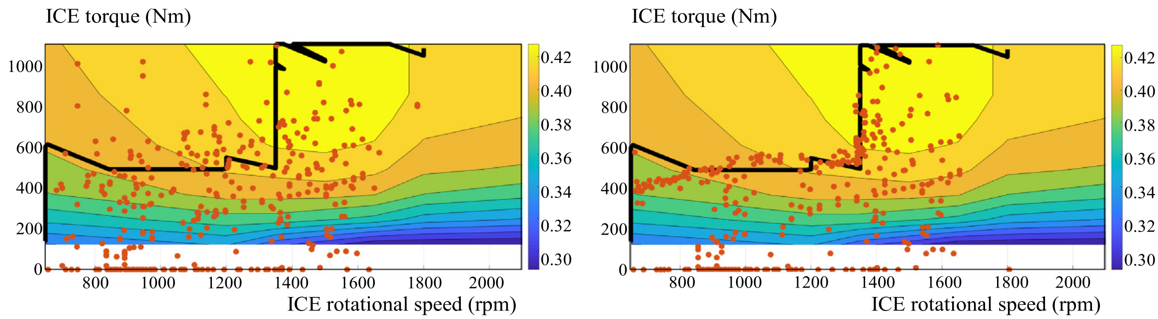

Fig. 7. ICE operation points of the studied HETs on the ICE efficiency map: (a) AMT-based HET, (b) CVT-based HET.

4. Comparisons of the studied HETs

The DPM is used to perform a fair comparison between the AMT-based and CVT-based HETs. As the DPM is an offline optimization method able to determine the theoretical optimal solution of a non-linear and complex problem, it can be used to obtain a benchmark in terms of fuel consumption. The different optimal solutions for different topologies, configurations and technologies can therefore be compared in a fair way on the same driving cycle. Furthermore, the DPM leads to EMSs which deliver the control inputs for the vehicle controls. If the optimal EMSs are calculated off-line from a backward-model, they are then imposed to the forward-based simulation in Matlab-Simulink© based on the EMR organization. In addition, the DPM imposes the energy balance in the battery, which is necessary to perform fair comparisons of fuel and energy consumption.

4.1. Actual CVT efficiency

Both vehicles are thus simulated and the actual efficiency of the CVT is considered. The ICE operation points of both HETs (Fig. 7) (ICE efficiency map) and the simulation results (Fig. 8) are presented. The black line (Fig. 7) is the ICE optimal operating line. With the CVT flexibility the system is more able to follow this line compared to the AMT. The ICE losses are thus reduced by approximately 2%. On another hand, the e-drive is mainly used at low speed whereas the ICE is used at high and medium speed. Unfortunately, the energy gains due to the improvement of the ICE operating are lower than the CVT losses. The results of the studied are summarized in Table 3. However, more detailed studies would be needed to better identify the different energy losses and gains within the different components and subsystems of the vehicle.

Table 3.a gives the fuel consumption for the AMT-based and CVT-based HETs. Furthermore, the results are also given for a non-hybrid conventional truck (AMT-based) as a reference. This most conventional truck is used as reference to compare the fuel consumption of the different HETs. Despite the interest to also compare a CVT-based diesel truck, it has not been included in this paper. However, a first comparison between a AMT-based gasoline car and a CVT-based one have already been proposed in [7]. The hybridization allows a fuel saving of approximately 10% with an AMT and only 3% with a CVT. The fuel consumption is higher (+7.8%) for the CVT-based HET (17.9 L/100 km) in comparison with the AMT-based HET (16.6 L/100 km) due to the lowest efficiency of the CVT (85%) compared to the AMT (around 92%) (Table 3). As a conclusion, the conventional hydraulic actuated CVT technology is not yet

Table 3
Simulation results: (a) Fuel consumption of the different HETs, (b) Comparisons between the different HETs.

(a)	DPM-based (L/100 km)	(b)	Conventional truck	AMT-based HET	CVT-based HET
Conventional truck	18.4	Conventional truck	0%	**−9.8%**	−2.7%
AMT-based HET	16.6	AMT-based HET	+10.8%	0%	**+7.8%**
CVT-based HET	17.9				

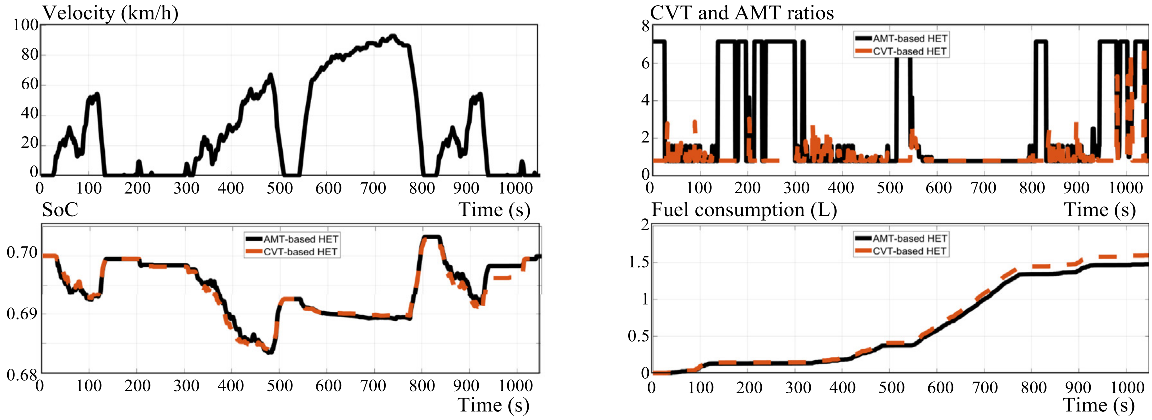

Fig. 8. Simulation results of AMT-based and CVT-based HETs with DPM-based EMS.

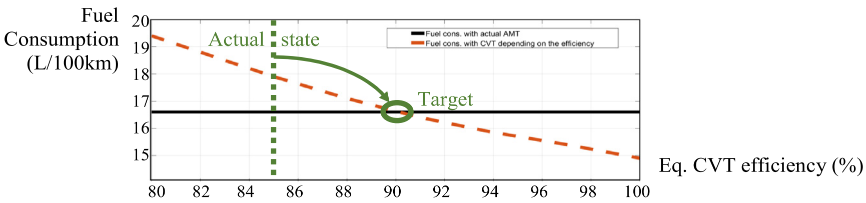

Fig. 9. Influence of the equivalent constant CVT efficiency on the fuel consumption.

competitive due to its relative lower efficiency than the one of an AMT for this medium-duty parallel-HET. The initial rule-based EMS developed in [23] lead to globally the same results but with more important fuel consumptions due to a non-optimal strategy. Moreover, in this previous study, the final SoC was not equal to the initial SoC that lead to a difficulty for the analysis.

4.2. *Influence of the CVT efficiency*

To conclude this study, the influence of the CVT efficiency on the fuel consumption of this medium-duty parallel HET is highlighted (Fig. 9). It could be a benchmark in terms of efficiency for the future generation of CVT. The DPM is used with different equivalent CVT efficiencies to calculate the fuel consumption. The current CVT efficiency of 85% leads to a fuel consumption of 17.9 L/100 km. The efficiency should be 90% to have comparable fuel consumption to an AMT-based HET (16.6 L/100 km). An important effort of at least 5% is required to make the CVT competitive with the AMT in terms of efficiency and fuel consumption.

5. Conclusion

The influence of a Continuous Variable Transmission (CVT) on the fuel consumption of a medium-duty parallel Hybrid Electric Truck (HET) has been studied. In that aim, a comparison with an HET using an Automatic Manual Transmission (AMT) has been achieved. Energetic Macroscopic Representation (EMR) has been used to organize the models of both HETs and highlight their control inputs. A backward-based model has been deduced from the EMR. Then, the Dynamic Programming Method (DPM) has been used to perform a fair comparison between AMT-based and CVT-based HETs. DPM leads to optimal control inputs in terms of fuel consumption, and thus optimal fuel consumption for both studied HETs. One of the perspectives of this work is to assess these results using Hardware-In-the-Loop simulation. However, this study gave first results on the impact of CVT on the fuel consumption of a parallel HET. It can be also noted that the ICE and CVT have been modeled using static efficiency of losses maps. More detail studies are to be conducted by using dynamical models of such sensitive elements to confirm the results.

Contrary to the expected results, the fuel consumption is higher for a CVT-based HET in comparison with an AMT-based HET for the studied vehicle and driving cycle. These results highlight that the optimal EMS will distribute the energy between the ICE and the e-drive in order to position the ICE in the best consumption area. The added value of a CVT is then lower for hybrid vehicle than for thermal vehicle. The use of CVT globally allows an improvement of 2% on the ICE efficiency by improving its operation points. Unfortunately, the efficiency of the studied CVT is about 7% lower than the efficiency of a classical AMT, which result in higher fuel consumption.

The main efforts should focus on the CVT efficiency to improve the next generation of CVT and make it competitive with the AMT, e.g. by on-demand technology enabling significantly energy actuation savings during time instants when no shifting is required. An improvement of 5% to reach 90% at least should be done on the CVT efficiency to be used in medium-duty parallel HETs. Other configurations, technologies, and transmission systems could also be considered and studied using the same method, such as Electric Variable Transmission (EVT) and Double Planetary Gear (DPG), as future innovative transmission for medium-duty parallel HETs.

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