# Energetic macroscopic representation and inversion- based control of a CVT-based HEV

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# Energetic Macroscopic Representation and Inversion-Based control of a CVT-based HEV

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**Abstract**

A Continuous Variable Transmission (CVT) is introduced in the simulation model of a Hybrid Electric Vehicle (HEV). The CVT-based vehicle simulation and its control are deduced from the Energetic Macroscopic Representation (EMR). Simulations are provided to show the interest of the CVT in term of fuel consumption.

*Keywords: energetic macroscopic representation, hybrid electric vehicle, control.*

## 1 Introduction

Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) are developed in order to face the automotive challenges [1] [2]. EVs have the limitation of a low range and long charging time. HEVs can thus be considered as an alternative solution. But the benefits of HEVs have to be increased in order to attract more users.

A lot of new components have been developed in order to reduce the fuel consumption and C02 emissions of HEV. In particular CVT (Continuous Variable Transmission) technologies [3]-[5] are used in parallel HEVs. This mechanical subsystem enables a continuous speed ratio between the wheels and the ICE (Internal Combustion Engine). By this way, the operation point of the ICE can be chosen closed to the optimal efficiency operation points in order to reduce the fuel consumption. But the efficiency of a CVT is slightly lower than the efficiency of a classical gearbox. Comparative studies have to be proposed to highlight the benefits of this mechanical device. Some automakers are already integrating CVT in their vehicle [6]-[8].

Simulation is a key step in comparison of different HEV topologies [9]. Different simulation methods have been intensively used [10]. Energetic Macroscopic Representation (EMR) [11] is a graphical description to organize simulation model and control scheme of complex energetic systems. It has been successfully used for series, parallel, series-parallel and other kinds of HEVs [12][13].

This paper aims to develop the EMR and the Inversion-based control of a CVT-based HEV. A Matlab-Simulink simulation is derived from the EMR of the studied vehicle and first comparison are achieved using a NEDC profile.

## 2 Studied HEV

### 2.1 Structural description of the vehicle

The studied vehicle is a parallel HEV. The ICE is connected to a CVT. Using the position of the two pulleys, the speed ratio can be continuously changed (Figure 1). Hydraulic actuators are used to move the pulleys.

In this paper, the topology of the Honda Insight is considered (Figure 2). The electric drive is composed of a battery, a Voltage-Source-Inverter (VSI) and a Permanent Magnet Synchronous Machine (PMSM). The torque of the Internal Combustion Engine (ICE) and the electrical machine are coupled on the same shaft using a belt. A torque converter (TC) is used to couple the ICE shaft to the CVT, which is connected with the wheels.

The ICE is a in-line 4-Cylinder engine of 1339 cc. The PMSM has a maximum power of 9.56 kW @ 1500 rpm and a maximum torque of 80 Nm @ 1000 rpm. The NiMH battery imposes a 100.8 V with a capacity of 5.74 Ah. The CVT is a metal V-belt type with a gear ratio range of 0.425-2.25. The vehicle mass is 1700 kg including passengers and load.

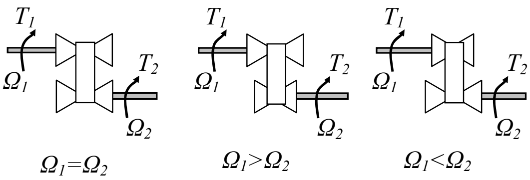


Figure 1: CVT subsystem principle

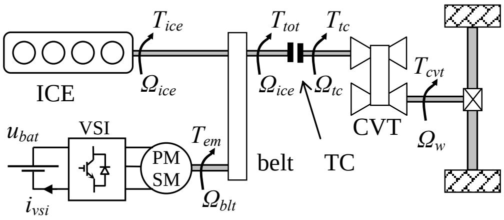


Figure 2: Parallel HEV with CVT and TC

## 2.2 Modelling of the vehicle

***Internal Combustion Engine*** — The ICE is modelled using an iso-consumption static map (Figure 3).

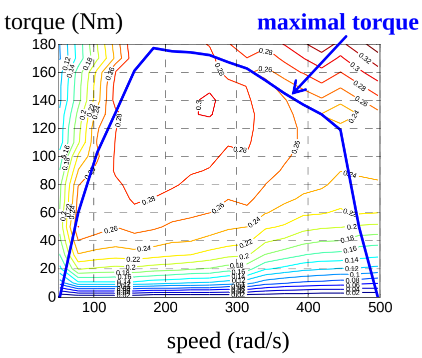


Figure 3: iso-efficiency map of the ICE

***Battery*** — A simple model of the battery is considered with an OCV (Open Circuit Voltage) and an internal resistance, in order to compute the battery voltage $u_{bat}$ from the load current $i_{vsi}$:

$$u_{bat} = OCV + Ri_{vsi} \tag{1}$$

The OCV and the resistance are dependant of the battery temperature and the SoC (State of Charge):

$$SoC = 100\left[1 - \frac{\frac{Q_n}{1-SoC_0} + \frac{1}{3600}\int i_{vsi}dt}{Q_n}\right] \tag{2}$$

Where $Q_n$ is the rated capacity of the battery and $SoC_o$ the initial SoC.

***Electric drive*** — A static model is considered for the PMSM, the VSI and their control [13], with a constant efficiency of $\eta_{ed}$=0.91 %:

$$\begin{cases} T_{em} = k_{cvt}T_{em-ref} \\ i_{vsi} = \eta_{cvt}^{j}\dfrac{T_{em}\Omega_{blt}}{u_{bat}} \end{cases}$$
$$\text{with} \begin{cases} j=1 \text{ if } P_{em}>0 \\ j=-1 \text{ if } P_{em}<0 \end{cases} \text{ and } P_{em} = T_{em}\Omega_{blt} \tag{3}$$

***Belt and torque converter*** — The belt ensures a torque coupling through the belt ration $k_{blt}$ with its own efficiency $\eta_{blt}$=0.95 %:

$$\begin{cases} T_{tot} = (k_{blt}T_{em} + T_{ice})\eta_{blt}^{j} \\ \Omega_{blt} = k_{blt}\Omega_{tc} \end{cases}$$
$$\text{with} \begin{cases} j=1 \text{ if } P_{blt}>0 \\ j=-1 \text{ if } P_{blt}<0 \end{cases} \text{ and } P_{blt} = T_{tot}\Omega_{blt} \tag{4}$$

In this paper, the torque converter is considered as a binary ideal clutch with a ratio $k_{tc}$ equal to 1 or 0:

$$\begin{cases} T_{tc} = k_{tc}T_{tot} \\ \Omega_{tc} = k_{tc}\Omega_{cvt} \end{cases} \tag{5}$$

A more advanced model of the torque converter [14] can be considered in further steps.

***CVT*** — The CVT is modelled using a first order model, capturing the dynamics of the CVT and including the efficiency $\eta_{cvt}$ and the CVT input $k_{cvt}$:

$$\begin{cases} T_{cvt} = k_{cvt}\eta_{cvt}^{j} T_{tc} \\ \Omega_{cvt} = k_{cvt}\Omega_{w} \end{cases} \tag{6}$$

with $\begin{cases} j = 1 \text{ if } P_{cvt} > 0 \\ j = -1 \text{ if } P_{cvt} < 0 \end{cases}$ and $P_{cvt} = T_{cvt}\Omega_{w}$

$$\frac{d}{dt}k_{cvt} = u_{cvt}\Omega_{tc}(F_{p1} - F_{p2}) \tag{7}$$

With $F_{p1}$ and $F_{p2}$ are the equilibrium forces on the pulley (Figure 4), and $u_{cvt}$ denoted as a constant which depends on the pulley ratio.

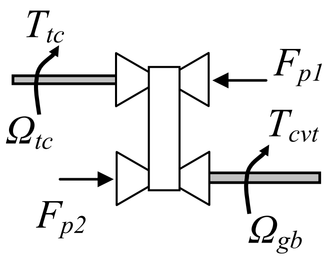


Figure 4: CVT and balance forces

The CVT efficiency is dependant of different losses due to the torque converter, the actuators to move the pulleys and friction phenomenon. In this paper, a constant efficiency is considered as a first step, $\eta_{cvt}$=87 %. An efficiency map or a more complete model of losses can be used in further steps [16].

***The wheels*** — An equivalent wheel is considered (curve and contact law are not considered). The mechanical transmission converts the rotational motion into a linear motion:

$$\begin{cases} F_{w} = \dfrac{1}{R_{mt}} T_{cvt} \\ \Omega_{w} = \dfrac{1}{R_{mt}} v_{hev} \end{cases} \tag{8}$$

***The chassis*** — The mechanical brake imposes a supplementary mechanical force $F_{mb}$ to the chassis:

$$F_{tot} = F_{mt} + F_{mb} \tag{9}$$

The dynamical equation expresses the vehicle velocity in function of the total force and the resistive force:

$$M_{eq}\frac{d}{dt}v_{hev} = F_{tot} - F_{res} \tag{10}$$

With $M_{eq}$ the equivalent mass of the vehicle including the mass of the rotating parts.

***The environment*** — The resistive force depends on the vehicle characteristics and the environment (slope, etc);

$$F_{res} = F_{0} + Av_{hev} + Av_{hev}^{2} \tag{11}$$

# 3 EMR of the studied HEV

## 3.1 EMR bases

EMR is a graphical description for the organisation of simulation and control of energetic systems. Different pictograms are used (see Appendix): source elements (green ovals, source of energy), accumulation elements (orange crossed rectangles, energy storage), mono-physical (orange squares) or multi-physical (orange circles) conversion elements (conversion without energy storage) and coupling elements (orange overlapped pictograms, energy distribution). All elements are connected according to the action/reaction principle (the product of the action and reaction variables yields the exchange power). Moreover; the accumulation elements are defined according to the integral causality (i.e. physical causality), and they thus define input and output of other elements.

## 3.2 EMR of the vehicle

The ICE is an energy source, which imposes the ICE torque $T_{ice}$ from its reference. The battery is an energy source, which imposes the battery voltage $u_{bat}$, in function of the reaction current of the system (1) (2). The mechanical brake is an energy source, which imposes the brake force $F_{mb}$ from its reference. The vehicle environment is an energy source, which imposes the resistive force $F_{res}$ in function of the vehicle velocity $v_{hev}$ (11). All these sources are described by green oval pictograms in the EMR of the vehicle (Figure 5).

The electrical machine is a multi-physical converter (orange circle), which imposes the machine torque $T_{ice}$ from its reference (3) defined by the control scheme.

The belt is a mono-physical coupling element which defines the total torque $T_{tot}$ from the ICE and machine torques (4). The chassis includes another coupling element, which define the total force $F_{tot}$ from the traction and brake forces (9). All these coupling elements (distribution of energy) are described by overlapped orange squares in EMR.

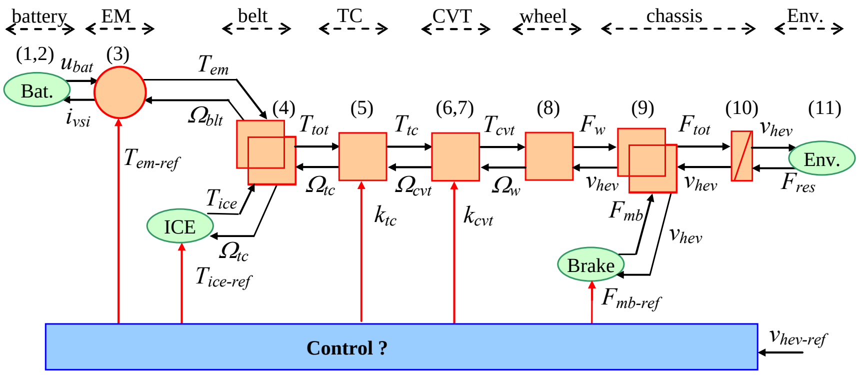


Figure 5: EMR of the CVT-based HEV

The torque converter is a mono-physical converter, which enables a torque transmission (5) in function of $k_{tc}$ defined by the control. The CVT is a mono-physical converter, which enables a torque and speed adaptation (6), (7) in function of CVT input $u_{cvt}$ defined by the control. The wheels are a mono- physical converter, which impose the traction force $F_w$ (8). All these mono-physical converters are described by orange squares.

The mass of the vehicle is an accumulation elements (crossed orange rectangle), which imposes the vehicle velocity $v_{hev}$ from the total and resistive forces (10).

In order to achieve the driver objective (reference of vehicle velocity), the control has to defined 5 tuning inputs on the system.

# 4 Inversion-based control of the studied HEV

## 4.1 Inversion-based control bases

Specific rules have been defined in order to deduce control schemes from the EMR of the system. Accumulation elements are inverted by closed-loop controls (blue crossed parallelograms). Conversion elements are directly inverted without closed-loop (blue parallelograms). Coupling elements are inverted using distribution criteria (blue double parallelograms). The different distribution criteria are defined by a strategy level in order to decide how to distribute energy in the system.

## 4.2 Inversion-based control of the vehicle

The objective of the control is to achieve the requested velocity by reducing the fuel consumption. Five tuning variables can be used to that aim: the ICE torque, the machine torque, the CVT ratio, the TC input and the braking force (during deceleration). A tuning path is deduced from that objective (Figure 6).

The control structure is deduced by an step-by-step inversion of the EMR all along this tuning path.

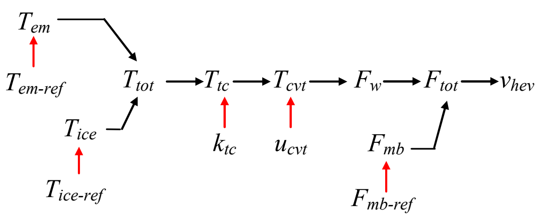


Figure 6: Tuning path of the CVT-based HEV

The first element to be inverted is the chassis (10). A closed-loop control of the velocity imposes the total force reference from the velocity reference and measurement, using an explicit compensation of the resistive force:

$$F_{tot-ref} = C_v(t)(v_{hev-ref} - v_{hev-meas}) + F_{res-meas} \quad (12)$$

With $C_v(t)$ a controller, which can be P, PI or other kind.

The second part of the chassis (9) is inverted using a distribution input $k_{d1}$ in order to define the brake and traction force references from the total force reference:

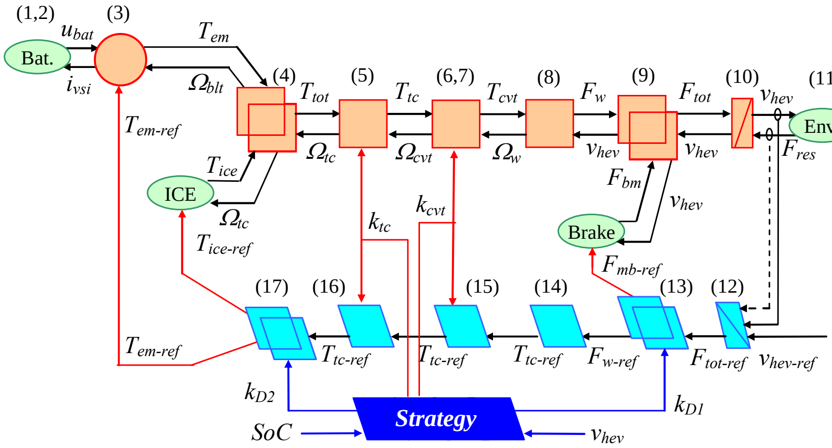


Figure 7: Inversion-based control of the CVT-based HEV

$$\begin{cases} F_{w-ref} = k_{D1} F_{tot-ref} \\ F_{mb-ref} = (1-k_{D1}) F_{tot-ref} \end{cases} \tag{13}$$

The wheel (8) is directly inverted in order to define the CVT torque reference from the traction force reference:

$$T_{cvt-ref} = R_w F_{w-ref} \tag{14}$$

The CVT is directly inverted. The CVT ratio $k_{cvt}$ is firstly estimated from the CVT ratio $k_{cvt}$ by an inversion of (7), which is defined by the strategy level

$$T_{tc-ref} = \frac{1}{k_{cvt-ref}} T_{cvt-ref} \tag{15}$$

The total torque reference is deduced from the TC torque reference by an inversion of (5) and using the TC input defined by the strategy:

$$\begin{cases} T_{tot-ref} = T_{tc-ref} \quad \text{if} \quad k_{tc} = 1 \\ T_{tot-ref} = 0 \quad \text{if} \quad k_{tc} = 0 \end{cases} \tag{16}$$

The belt (4) is inverted using a distribution input $k_{d2}$ in order to define the ICE and machine torque references from the total torque reference:

$$\begin{cases} T_{ice-ref} = k_{D2} T_{tot-ref} \\ T_{em-ref} = (1-k_{D2}) T_{tot-ref} \end{cases} \tag{17}$$

## 4.3 Energy management strategy

The energy management strategy has to define the different distribution inputs, $k_{D1}$, and $k_{D2}$. The first distribution input has to define the part of mechanical and electrical braking. The second distribution input has to define the part of thermal and electrical traction. Both criteria are classically used in HEV [13].

The strategy has to define the CVT ratio $k_{cvt}$ in order to reduce the fuel consumption of the ICE. As the torque converter is used as a clutch, the strategy defines the TC input in order to open or close such a coupling element.

The main aide of the strategy of a CVT-based EVT is to act on the CVT ratio $k_{cvt}$ in order to impose the optimal ICE rotation speed from the wheel rotation speed (Figure 8). At the same time, the torque distribution input $k_{D2}$ imposes the optimal ICE torque in function of the requested traction torque.

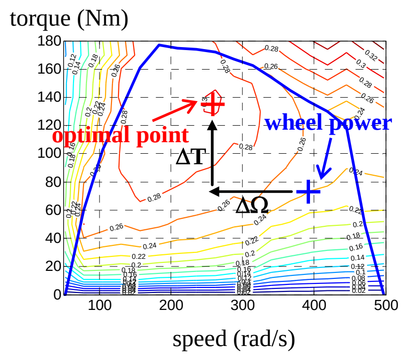


Figure 8: ICE map and strategy

# 5 Simulation results

## 5.1 Thermal vehicle with discrete-ratio gearbox

A first simulation is realized for a classical thermal vehicle for a NEDC (New European Drive Cycle (Figure 9.a). The control is well achieved because the velocity is closed to its reference (Figure 9.b). The discrete ratio $k_{gb}$ is imposed by the NEDC with 5 gear values: 3.73, 2.05, 1.32, 0.97 and 0.76 (Figure 9.c). The gearbox efficiency is assumed to be constant $\eta_{gb}$=93% [15]. The total energy consumption is 5.036 l/100 km (Figure 9.d). The consumption of the real vehicle (automaker data) is 5.4 l/100 km.

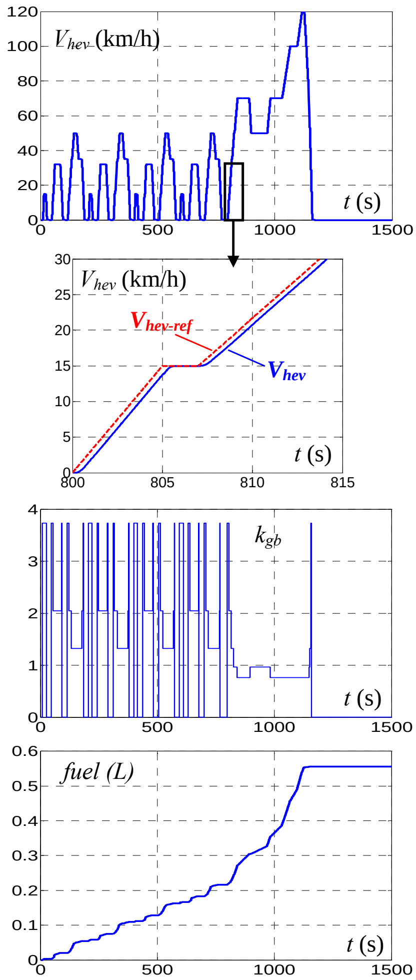


Figure 9: Simulation for a thermal vehicle using a classical gearbox: a) velocity, b) zoom on the velocities c) gear ratio d) fuel consumption,

## 5.2 Thermal vehicle with CVT

A CVT is then introduced in the vehicle. The gear ratio is deduced from inversion-based control. The CVT efficiency is assumed to be constant $\eta_{cvt}$=87% due to its ancillaries [16]. We have a unique tuning input (the CVT ratio) in order to impose the optimal rotation speed and torque for the ICE in order to reduce the fuel consumption (OP22 in Figure 8). There is not enough degree of freedom to achieve this goal. A very simple strategy is chosen: the CVT ratio is calculated to impose the optimal rotation speed of the ICE. The CVT ratio is defined in order to impose the optimal ICE speeds from the wheel speeds using (6):

$$k_{cvt} = \frac{\Omega_{ice-opt}}{\Omega_{w-meas}} \tag{18}$$

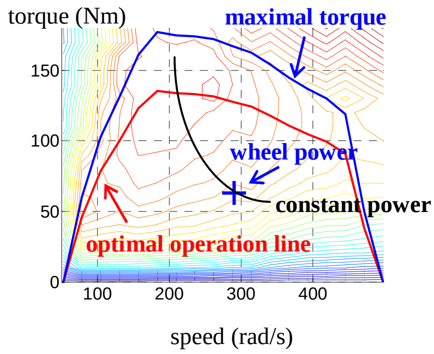


Figure 10: ICE map and strategy of the CVT-based thermal vehicle

The optimal rotation speed is defined by the optimal power, which is equal to the requested power. If this strategy is not optimal, it will show the possible improvement using a CVT.

The same NEDC is used (Figure 11.a). The CVT ratio is smoothly adapted in function of the vehicle velocity and limited to its minimum and maximum value (Figure 11.b). The torque converter is open when the velocity is zero. Even when limitations are activated, the reference velocity is well achieved. The fuel consumption is 4.32 l/100 km (Figure 11.c). That means that event if the CVT has a lower efficiency than a classical gearbox, it enables a consumption reduction by choosing more efficient operation points of the ICE. Moreover, this strategy is very simple and can be optimized using advanced control and optimization methods.

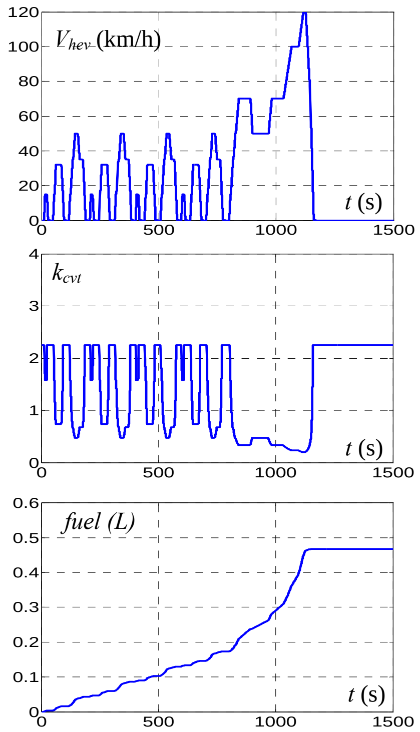


Figure 11: Simulation for a thermal vehicle using a CVT: a) velocity b) CVT ratio c) fuel consumption

## 5.3 HEV with CVT

In that case, there are two degrees of freedom in order to impose the optimal operation point of the ICE: the CVT ratio and $k_{D2}$, which distributes the torque of the ICE and the electrical machine. The CVT ratio is defined in order to impose the optimal ICE speeds from the wheel speeds, as in the previous case (18).

The distribution coefficient is the used to define the optimal torque of the ICE from the total torque reference using (17):

$$k_{D2} = \frac{T_{ice-opt}}{T_{tot-ref}} \quad (19)$$

This very simple strategy can be achieved only if no torque and speed limits are reached.

The velocity is well achieved by using both fuel and battery (Figure 12.a). The pure electric mode (i.e. $k_{d2}=0$) is imposed until 40 km/h. A hybrid mode is used in other cases: the distribution ratio $k_{d2}$ is imposed using (19) and the CVT ratio is imposed using (18).

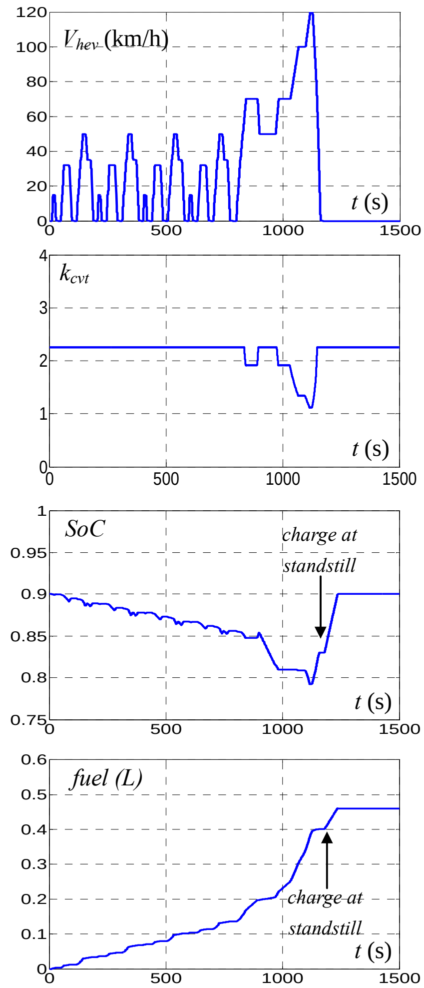


Figure 12: Simulation for a CVT-based HEV: a) velocity b) CVT ratio c) battery SoC, d) fuel consumption

The CVT ratio is thus smoothly adapted in function of the vehicle velocity (upper 40 km/h) and limited to its minimum and maximum value (Figure 12.b). The initial battery SoC is imposed to 90% (Figure 12.c). The SoC decreases when the electrical machine is activated and increases when the vehicle decelerates because of regenerative braking. At t=1180s, the vehicle is at standstill and the ICE is used to recharge the battery to reach its initial SoC of 90%. By this way a fair comparison of the fuel consumption is possible. This battery charge is realized using the optimal torque and speed of the ICE. Thus, for the CVT-based HEV using such as simple strategy, the fuel consumption is 4.018 l/100 km (Figure 12.d). Obviously, a more advanced strategy can enable a more important reduction of the fuel consumption.

# 6 Conclusion

A CVT-based HEV has been studied in simulation thanks to Energetic Macroscopic Representation. An inversion-based control has been derived from the EMR of the vehicle. A very simple strategy has been developed for the choice of the CVT ratio in order to reduce the fuel consumption.

Using a CVT instead a discrete gearbox can enable a reduction of the fuel consumption because the CVT ratio is adapted to keep close to the optimal ICE operation points. Moreover, a CVT-based HEV can also increase the reduction of fuel consumption, by using the electrical part.

Using more advanced strategies the fuel consumption could be more significantly reduced. Moreover, new technologies of CVT are developing in order to increase their efficiency. These developments will also reduce the fuel consumption.

Appendix: Synoptic of Energetic Macroscopic Representation (EMR)

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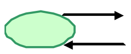
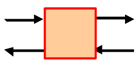
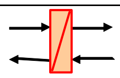
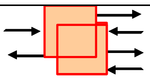
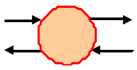
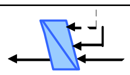
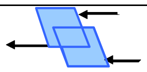
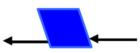
|---|---|---|
|  |  |  |
| Source element (energy source) | Mono-physical conversion (without energy storage) | Accumulation element (energy storage) |
|  |  |  |
| Coupling element (energy distribution) | Multi-physical conversion (without energy storage) | Control block with a controller (close-loop) |
|  |  |  |
| Inversion of coupling element | Control block without controller | Strategy level |

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