Energy conversion efficiency of hybrid electric heavy-duty vehicles operating according to diverse drive cycles

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Abstract

Energy consumption and exhaust emissions of hybrid electric vehicles (HEVs) strongly depend on the HEV topology, power ratios of their components and applied control strategy. Combined analytical and simulation approach was applied to analyze energy conversion efficiency of different HEV topologies. Analytical approach is based on the energy balance equations and considers all energy paths in the HEVs from the energy sources to the wheels and to other energy sinks. Simulation approach is based on a fast forward-facing simulation model for simulating parallel and series HEVs as well as for conventional internal combustion engine vehicles, and considers all components relevant for modeling energy conversion phenomena. Combined approach enables evaluation of energy losses on different energy paths and provides their impact on the fuel economy. It therefore enables identification of most suitable HEV topology and of most suitable power ratios of the components for targeted vehicle application, since it reveals and quantifies the mechanisms that could lead to improved energy conversion efficiency of particular HEV. The paper

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exposes characteristics of the test cycles that lead to improved energy conversion efficiency of HEVs. Mechanisms leading to improved fuel economy of parallel HEVs through drive-away and vehicle propulsion at low powertrain loads by electric motor are also analyzed. It was also shown that control strategies managing energy flow through electric storage devices significantly influence energy conversion efficiency of series HEVs.

**Keywords:** hybrid electric vehicles, energy conversion efficiency, numerical simulation, analytical analysis, transient test cycle

**Nomenclature:**

- $a$: acceleration (m/s$^2$)
- $F$: multiplication factor of the test cycle (-)
- $M$: torque (Nm)
- $m$: mass (kg)
- $n$: engine speed (rpm)
- $P$: power (W)
- $p_{\text{eff}}$: mean effective pressure of the ICE (MPa)
- $Q_{\text{LHV}}$: lower fuel heating value (J/kg)
- $R_v = V_{\text{downsized}}/V_{\text{baseline}}$: swept volume ratio (-)
- $r$: wheel radius (m)
- $t$: time (s)
- $V$: swept volume of the internal combustion engine (m$^3$)
- $v$: velocity (m/s)
- $W$: energy (J)
- $\eta$: efficiency (-)
Subscripts and abbreviations:

- **BR**: brakes, braking
- **eff**: effective
- **EM**: electric machine
- **ES**: electric storage
- **F**: fuel tank
- **f**: fuel
- **G**: electric machine operating in the generator mode
- **I**: internal combustion engine vehicle
- **in**: input
- **L**: load
- **M**: electric machine operating in the motor mode
- **max**: maximum
- **neg**: negative
- **out**: output
- **P**: power converter, parallel HEV
- **PR**: propulsion
- **S**: series HEV
- **TC**: torque coupling
- **tc**: test cycle
- **TR**: transmission
- **V**: vehicle
- **W**: wheel
- **X**: mechanical connection of the brake to the flange
Abbreviations:

CS  control strategy
FR  fuel rack position
HEV  hybrid electric vehicle
HF  hybridization factor
ICE  internal combustion engine
ICEV  vehicle driven by an internal combustion engine
lhs  left hand side of the equation
OEOL  optimum engine operation line
rhs  right hand side of the equation
SOC  state of charge

1. Introduction

Reducing environmental impact of the ground transportation fleet is one of the most urgent issues of modern society. Continuously increasing legislative and market requirements demand new energy efficient low emission powertrain concepts. Among the alternative powertrains being investigated, the HEVs consisting of an internal combustion engine (ICE) and an electric machine (EM) (generally accepted definition of HEV according to Chan [1]) is considered to offer the best promise in the short to mid term due to the use of smaller battery pack and their similarities with the conventional vehicles [2,3].

Improvement of the overall energy efficiency is one of the most important subjects when developing new vehicle technologies. If plug-in option is not considered, improvements in tank-to-wheels efficiency directly correspond to improvements in well-to-wheels efficiency [4]. Well-to-wheels efficiency represents the deciding factor for evaluating environmental
sustainability and also one of the deciding factors for market penetration of different vehicle technologies.

Compared to conventional internal combustion engine vehicles (ICEVs), HEVs incorporate more electrical components featuring many available patterns of combining the power flows to meet load requirements. Due to the multiple power sources, there exist several powertrain topologies and different control strategies to control the power. Dynamic interactions among various components and the multidisciplinary nature make it difficult to predict interactions among various vehicle components and systems. Prototyping and testing each design combination is cumbersome, expensive, and time consuming. Modeling and simulation are therefore indispensable for concept evaluation, prototyping, and analysis of HEVs.

Many commercial and non-commercial vehicle simulation models of different level of details of how each component is modeled and different direction of calculation have so far been developed, e.g. [2,3,5-16]. Characteristics of the cited models are analyzed in Ref. [4]. These simulation models and other hybrid vehicle simulation models are intended for modeling global vehicle parameters, i.e. fuel consumption, exhaust emissions, vehicle performance, or are intended for developing energy management strategy to improve global vehicle parameters, although the simulation models rely on sub-models considering component characteristics. Global vehicle parameters are indeed the deciding factors for evaluating environmental sustainability of the vehicle and also the deciding factors influencing their market penetration and their operating costs. However, in order to achieve the highest energy conversion efficiency, i.e. lowest energy consumption, for particular operating conditions, i.e. test cycle, it is necessary to have profound knowledge on the influences of the hybrid powertrain topology, of the energy flows through their constituting components, their efficiencies etc. on the energy consumption of the particular HEV.
A combined simulation and analytical approach which was introduced in Refs. [15,16] enables analysis of energy flows and energy losses on different energy paths within the hybrid powertrain and evaluation of their influences on energy consumption of the powertrain. The simulation model for parallel hybrid powertrains was proposed in Ref. [15] and upgraded model for series hybrid powertrains was proposed in Ref. [16]. Refs. [15,17] present results of the energy conversion efficiency in parallel hybrid powertrains operating according to engine dynamometer test cycles, whereas Ref. [16] gives comparative study of parallel and series hybrid powertrains operating according to engine dynamometer test cycles. Similar analyses aimed at studying influences of energy flows and energy losses on different energy paths within the hybrid powertrain on global vehicle parameters have not been published by other authors, since, as indicated in the above text, simulation models provide global vehicle parameters, whereas brake-down and analysis of energy losses on different energy paths within the hybrid powertrain were not performed.

Refs. [15-17] analyze energy conversion efficiency of hybrid powertrains operating according to engine dynamometer test cycles. These analyses provide valuable information on powertrain performance. However, it is necessary to simulate the complete vehicle and subsequently analyze the data with analytical framework when realistic on-road tank-to-wheels efficiency of the vehicle and efficiencies of energy paths within the powertrain are concerned. It is due to the fact that vehicle mass, rolling resistance of tires, gearshift strategy, and control strategies during vehicle stops significantly influence energy conversion efficiency.

This paper therefore presents a simulation and analytical analysis of the energy conversion efficiency in parallel and series heavy-duty hybrid vehicles. The analytical approach is based on the analytical framework for analyzing the energy conversion efficiency of different hybrid electric vehicle topologies proposed in Ref. [4]. The simulation approach
is based on the extended version of the simulation model presented in refs. [15,16] that was upgraded with sub-models necessary to model vehicle dynamics, which are presented in section 3. Simulation model provides the input data for subsequent analytical analysis.

Vehicle parameters were analyzed for different test cycles exposing significant influences of the test cycle characteristics on the energy conversion efficiency in different topologies and configuration of HEVs. Applied simulation and analytical approach enables quantification and explanation of the mechanisms influencing energy conversion efficiency through drive-away and vehicle propulsion by electric motor (EM) at low powertrain loads. Influence of start-stop strategy on energy conversion efficiency was also analyzed. Although results are specific for the analyzed vehicle, important generally valid conclusion can be drawn from the results.

The paper is organized as follows: analytical framework is briefly resumed in section 2 to provide specific knowledge for the combined analysis, simulation model is presented in section 3, section 4 gives results on the energy conversion efficiency including analysis, whereas section 5 summarizes significant conclusions.

2. Analytical framework

Analytical framework was fully derived in Ref. [4], therefore only brief resume of equations needed for the presented analysis will be given. The analytical framework considers all energy sources and energy sinks as well as all energy converters including their efficiencies. It thus enables identification of the most energy efficient paths from the on board energy sources to vehicle propulsion considering complex interactions among various components and different control strategies. The advantage of this approach origins from the fact that it considers the complete HEV and therefore enables direct and insightful evaluation of changes of HEV topology, power ratios and efficiencies of the components, control strategies and applied test cycles on the energy conversion efficiency of the HEV. Analytical
framework thus enables structuring of large amount of the data in physical meaningful energy flows and associated energy losses, and therefore provides insightful information for HEV optimization. Input data for the analytical analysis were obtained from the numerical simulations.

It is necessary to divide the HEV, i.e. system, into elements, i.e. subsystems, to investigate energy flows and energy losses and to optimize energy conversion efficiency of the HEV. Elements of investigated parallel and series HEV topologies, and of the ICEV topology are shown in Fig. 1. Brief introduction of HEV topologies is given in Ref. [4], whereas detailed information could be found in the literature, e.g. Refs. [1,18,19]. Energy is added through fuel tank (F) denoted as “energy sources”. Energy is extracted through load (L) and brakes (BR), denoted as “energy sinks”. Energy consumption of all accessories powered by the ICE is considered in the effective efficiency of the ICE and it is therefore not taken into account separately. Energy sources and energy sinks are connected with other elements by only one energy path.

All other elements are denoted as “energy converters”. They are connected to other elements by two or more energy paths. HEVs (Fig. 1) are propelled by an ICE and one or more electric machines (EM) operating in motor and /or generator mode. Mechanical energy is distributed through torque couplers (TC), e.g. gear boxes, pulley or chain assemblies, or different types of power splits. Mechanical energy of the powertrain is transmitted to the load through the transmission (TR) and wheels (W). Electric energy is distributed and converted through power converter (P) that includes voltage source converters, DC/DC converters, controlling electronics etc. Electric energy is stored in the electric storage devices (ES), e.g. batteries, which are the only energy converters with energy accumulation capability.

Elements are linked by electrical, hydraulic and mechanical links. There exist unidirectional and bidirectional energy paths in the hybrid electric vehicle as indicated by the
arrows in Fig. 1. It is assumed that energy can not be accumulated in the links. Analysis of the fuel consumption is commonly performed for a specific test cycle. All energy flows between the elements are therefore integral values over the whole test cycle (tc). It is assumed that all losses that occur in the links between elements are included in the losses of the elements. Energy flows between the elements are denoted with index: “energy source”-“energy sink”. Energy flow of unidirectional energy paths are therefore defined as

\[
W_{A-B} = \int_{0}^{t_c} P(t)_{A-B} \, dt
\]

for the energy flow from A to B (Fig. 2 a)), where A and B represent arbitrary elements.

Energy flows of bidirectional energy paths are calculated separately for directions A-B and B-A (Fig. 2 a)), i.e. energy flow A-B is the energy transferred from A to B and energy flow B-A is the energy transferred from B to A. Let us assume that energy flux has positive sign in the direction from A to B. As depicted in Fig. 2 b), energy flow A-B is thus defined by

\[
W_{A-B} = \int_{0}^{t_c} P^* (t)_{A-B} \, dt ,
\]

where

\[
P^* (t)_{A-B} = \begin{cases} P(t)_{A-B} ; P(t)_{A-B} \geq 0 \\ 0 ; P(t)_{A-B} < 0 \end{cases}
\]

and energy flow B-A is thus defined as

\[
W_{B-A} = \int_{0}^{t_c} P^* (t)_{B-A} \, dt ,
\]

where

\[
P^* (t)_{B-A} = \begin{cases} -P(t)_{A-B} ; P(t)_{A-B} < 0 \\ 0 ; P(t)_{A-B} \geq 0 \end{cases} .
\]
It is assumed that energy flow is positive if energy enters the element and negative if energy leaves the element.

Considering the above sign convention, general energy balance equation of the element B reads

$$W_B = \sum_{i=1}^{n_{\text{inflow}}} W_{i-B} - \sum_{j=1}^{n_{\text{outflow}}} W_{B-j},$$

(6)

where $W_B$ represents energy losses in the element B; energy losses in particular energy converters are denoted $W_{\text{index of the element}}$.

The goal of the analytical analysis is to link together energies added to the energy sources and energies extracted from energy sinks (denoted $W_{\text{index of the element}}$) with the energy flows between the elements and their efficiencies. All values of the $W_{\text{index of the element}}$ are positive, since production and consumption of the energy is considered by the appropriate sign. It is relatively simple to define efficiencies of the elements without energy accumulation capability with two bidirectional energy links as depicted in Fig. 2 c). Eq. (6) is rewritten to

$$W_B = W_{A-B} + W_{C-B} - W_{B-A} - W_{B-C}. $$

(7)

It is possible to separate energy losses in the element B, i.e. $W_B$, into the losses in the element B for the energy flow direction A-C and the losses in the element B for the energy flow direction C-A, e.g. electric machine operating in motor or generator mode.

Considering Fig. 2 c), eqns. (2)-(5) and (7), efficiency of the element B for the energy path A-C is defined by

$$\eta_{B,A-C} = \frac{\int_0^{t_e} P^{*}_{B-C} dt}{\int_0^{t_e} P^{*}_{A-B} dt}$$

(8)

and efficiency of the element B for the energy path C-A is defined by
\[
\eta_{B,C-A} = \frac{\int_0^t P_{B-A} dt}{\int_0^t P_{C-B} dt},
\]

(9)

It follows

\[
W_{B-C} = \eta_{B,A-C} W_{A-B}
\]

(10)

and

\[
W_{B-A} = \eta_{B,C-A} W_{C-B}
\]

(11)

Considering eqns. (7) as well as eqns. (10) and (11) it follows

\[
W_B = W_{B,A-C} + W_{B,C-A} = (1-\eta_{B,A-C})W_{A-B} + (1-\eta_{B,C-A})W_{C-B}.
\]

(12)

It is more complex to define efficiencies of the elements with more than two bidirectional energy links, i.e. TC and P, and elements with energy accumulation capability, i.e. ES; Fig. 1. Energy losses of these elements are split into inlet and outlet losses as shown in Fig. 2 d) to make possible clear derivation of equations. This approach is also suitable to determine energy losses in the elements with energy accumulation capability. In order to perform this analysis, a point inside the element is defined that represents the origin for evaluating the energy balance; more details are given in Ref. [4]. Rewriting eq. (6) according to the above convention thus yields

\[
0 = \sum_{i=1}^{n_{in}} \eta_{B,in,i-B} W_{i-B} - \sum_{j=1}^{n_{out}} \frac{1}{\eta_{B,out,B-j}} W_{B-j},
\]

(13)

where efficiency indexes denote: first index indicated the element, second in or out index indicates losses associated with inflow of the energy to the element B or losses associated with outflow of the energy from the element B respectively, and the third index indicates the energy path.

Notation “element_1”-“element_2”-…-“element_n” is applied in the text to denote different energy conversion chains. Efficiencies of particular elements are not referred to
explicitly in this notation although they are considered in the equations. Energy flow to the element with more than two links could be split into energy flow to two or more subsequent elements; for example energy flow ICE-TC1 in parallel HEV (Fig. 1) could be split into the energy flow ICE-TC1-TR (vehicle propulsion) and to the energy flow ICE-TC1-EM1 (charging the EM by ICE). These energy flows are denoted $W'_{\text{ICE-TC1,TR}}$ for the energy path ICE-TC1-TR and $W'_{\text{ICE-TC1,EM1}}$ for the energy path ICE-TC1-EM1. It follows that

$$W'_{\text{ICE-TC1,TR}} = W_{\text{ICE-TC2}} - W'_{\text{ICE-TC1,EM1}},$$  

where ' indicates that this is only a portion of the energy flow denoted by the first index directed to the element referred to by the second index.

Based on the above definitions, analytical framework for analyzing energy conversion efficiency of vehicle topologies shown in Fig. 1 was derived in Ref. [4].

Energy content of the electric storage devices at the end of the test cycle was equal to the energy content of the electric storage devices at the beginning of the test cycle (denoted non-depleting ES management), and plug-in option was not considered to enable clear and demonstrative comparison of the fuel economy of HEVs and ICEVs over the test cycle. The energy content of the ES at any given time instant during the service is of course variable. In some special operating conditions, e.g. propulsion of the engine dynamometer, power traces of test cycles for different powertrain topologies would be equal, however power traces of test cycles generally differ when different vehicle topologies are driven according to the same vehicle speed trace, since weights of the vehicles are generally different, whereas differences in power traces of the test cycle also consider eventual differences in the drag coefficients of the vehicles. A multiplication factor, i.e. $F$, corresponding to particular vehicle topology is therefore introduced. It is assumed that $F = 1$ for ICEVs, whereas generally $F \neq 1$ for HEVs due to difference in vehicle parameters. Introduction of multiplication factors enables comparison of the energy consumptions of different vehicle topologies, since it makes possible scaling of the propulsion work of the test cycle ($W_{\text{PR}}$ - positive values of the test
cycle power trace) of different HEV topologies to $W_{tc, PR}$ of the ICEV, i.e.

$$[W_{tc, PR}]_P = F_P[W_{tc, PR}]_d$$

and

$$[W_{tc, PR}]_S = F_S[W_{tc, PR}]_d.$$ Index I denotes internal combustion engine vehicle, index P denotes the parallel HEV and index S denotes series HEV.

### 2.1. Parallel HEV

Energy balance equation of parallel HEV (Fig. 1 a)) could be derived based on the definitions given in the above text and algebraic derivation given in Ref. [4]

$$m_{f,tc}Q_{LHV}\eta_{ICE, eff}\eta_{TC1},in,ICE\eta_{TC1}, ICE\eta_{TC1}, out,TC1\eta_{TR, PR}\eta_{W, PR} = F_P[W_{tc, PR}]_d$$

$$- \left(W_{tc, BR} - \frac{W_{BR}}{\eta_{W, BR}} - \frac{W_{TR, ICE}}{\eta_{W, BR}\eta_{TR, BR}} \right)\eta_{W, BR}\eta_{TR, BR}\eta_{TC1}, in,ICE\eta_{TC1},out,TC1\eta_{TR, PR}\eta_{W, PR}$$

$$\times \eta_{ES, in, P, out, ES, P, in, ES, P, P, out, P, EM, P, in, EM, 1, G}\eta_{TC1, in, EM, 1, G}\eta_{TC1, out, EM, 1, G}\eta_{PR, out, P, EM, 1, G}\eta_{PR, out, P, ES}$$

$$\eta_{TR, PR}\eta_{W, PR}$$

$$+ W_{ICE, TC1, EM1}\eta_{TC1, in, ICE, TC1}\left(1 - \eta_{TC1, out, TC1, EM1, G}\eta_{TC1, in, EM1, G}\eta_{TC1, out, EM1, G}\right)\eta_{TC1, out, TC1, TR}\eta_{TR, PR}\eta_{W, PR}$$

$$\times \eta_{P, in, ES, P, out, P, EM, P, in, EM, 1, G}\eta_{TC1, in, EM, 1, G}\eta_{PR, out, P, EM, 1, G}\eta_{PR, out, P, ES}$$

$$\eta_{ES, in, P, out, ES, P, in, ES, P, P, out, P, EM, P, in, EM, 1, G}\eta_{TC1, out, TC1, TR}\eta_{TR, PR}\eta_{W, PR}$$

(14)

Origin for evaluation of the energy conversion efficiency of all topologies is L in the direction W-L. The left hand side (lhs) of eq. (14) represents addition of energy through the energy conversion chain F-ICE-TC1-TR-W-L considering energy added by the fuel ($m_{f, tc}Q_{LHV}$) and efficiencies of all converter elements in the energy conversion chain. The first term of the right hand side (rhs) of eq. (14) represents the major and primary energy sink, since it represents energy needed for vehicle propulsion. It equals to the energy needed for propulsion of the parallel HEV, i.e. $[W_{tc, PR}]_P = F_P[W_{tc, PR}]_d$. All the energy needed for braking the parallel HEV (negative values of the test cycle power trace), i.e. $W_{tc, BR}$, could generally not be recuperated by regenerative braking and thus excessive energy has to be consumed by the brakes and dissipated to heat, i.e. $W_{BR}$, whereas a portion of the excessive energy could also be consumed by the ICE. ICE is generally considered as a power source,
however it can also represent an energy sink when it is motored by the external torque addition, i.e. mechanical friction in the ICE is overcome by the external torque rather than by the fuel addition, as for example during decelerations or hill descending. Portion of the energy flow TR-TC1 directed to the ICE is denoted $W'_{TR\rightarrow TC1,ICE}$. Reduction of the fuel consumption due to motoring ICE by external torque rather by fuel addition is considered by the third term of the rhs of eq. (14). This energy and energy consumed by the brakes ($W_{BR}$) are not available for charging the batteries through regenerative braking $\left(W_{sc,BR} - W_{BR}/\eta_{w,br} - W'_{TR\rightarrow TC1,ICE}/\eta_{w,br}\eta_{TR,br}\right)$ considered by the second term of the rhs of eq. (14). This term clearly indicates that the regenerative braking is always desirable no matter how high the losses are, as this energy would otherwise be dissipated and lost as heat. It is discernable from eq. (14) that recuperating energy by regenerative braking reduces the energy addition through energy sources, i.e. lhs of eq. (14), and thus reduces fuel consumption of the vehicle. The last term of the rhs of eq. (14) considers energy losses due to charging of the ES by operating ICE at higher power output ($W'_{ICE\rightarrow TC1,EM1}$). It is obvious that energy path ICE-TC1-EM1-P-ES-P-EM1-TC1-TR is less energy efficient than energy path ICE-TC1-TR, however, for selected vehicle topologies and test cycles it is necessary to charge the ES by ICE to maintain their energy content above the value that does not restrict performance of the EM1 operating in the motor mode. This term again confirms the statement that regenerative braking is always desirable, since otherwise ES should be charged by the ICE increasing energy consumption of the HEV.

2.2. Series HEV

Energy balance equation of series HEV (Fig. 1 b)) could be derived as given in Ref. [4] in a similar manner than for parallel HEV.
Again, lhs of eq. (15) considers addition of energy through the ICE \( m_{f,sc}Q_{LHV} \) and efficiencies of all converter elements in the energy conversion chain. The first term of the rhs of eq. (15) represents the energy needed for vehicle propulsion. The second term of the rhs of eq. (15) considers charging the batteries through regenerative braking. The last term of the rhs of eq. (15) considers the difference in efficiencies between the energy path EM2-P-EM1 and the energy path EM2-P-ES-P-EM1 multiplied by the portion of the energy flow EM2-P directed to the ES. It thus considers the losses due to charging the ES through the energy produced by the ICE to maintain their energy content above the value that does not limit performance of EM1 operating in the motor mode. It is obvious that charging of ES is associated with energy losses, however, in series HEV operating according to the transient test cycles ES are often charged by the ICE. In the series HEVs, ICE is not mechanically coupled to the load and it does therefore not follow instant load changes, which enables attaining very high effective efficiency of the ICE. ES are therefore used to accumulate or release the excess or deficit energy respectively. In series HEVs, ES are also frequently charged by the ICE after a longer high power output period of the EM1, since maximum power output of the EM1 generally exceeds maximum power output of the ICE, and regenerative braking solely does not provide enough energy to replenish the ES.

### 2.3. ICEV

Considering Fig. 1 and adequately reducing eq. (14), energy balance of ICEV could be derived as proposed in Ref. [4]

\[ m_{f,c}Q_{LHV} \eta_{ICE,eff} \eta_{TR,PR} \eta_{W,PR} = W_{tc,PR} - W_{TR-ICE} \eta_{TR,PR} \eta_{W,PR} \cdot \]  
(16)

Similar to both previous topologies lhs of eq. (16) represents addition of energy through the ICE \( m_{f,c}Q_{LHV} \) and efficiencies of all converter elements in the energy conversion chain.

The first term of the rhs of eq. (16) represents the energy needed for vehicle propulsion. The last term of the rhs of eq. (16) considers motoring ICE by the external torque available through the energy needed for braking the vehicle, which clearly reduces fuel consumption.

2.4. Comparison of different vehicle topologies

ICEVs are the most widespread type of vehicles and therefore they often represent the basis for the evaluation of the energy consumption of other vehicle topologies. Analytical comparisons of the energy conversion efficiency of parallel and series HEV topology to that of the ICEV enable identification and quantification of mechanisms that could lead to improved energy conversion efficiency of particular HEV topology. Multiplying eq. (16) by \( F_p \) and rearranging eqns. (14) and (16) enables derivation of the ratio of the fuel consumptions of parallel HEV and ICEV topology

\[
\left[ \frac{m_{f,c}}{m_{f,c}} \right]_p = \left\{ \left[ \frac{\eta_{ICE,eff} \eta_{TR,PR} \eta_{W,PR}}{\eta_{ICE,eff} \eta_{TC1,in,ICE-TC1} \eta_{TC1,out,TC1-TR} \eta_{TR,PR} \eta_{W,PR}} \right]_d \right\}_{rhs3} \\
\times \left\{ \frac{1}{F_p} \right\}_{rhs2} + \left\{ \frac{1}{m_{f,c}Q_{LHV} \eta_{ICE,eff} \eta_{TR,PR} \eta_{W,PR}} \right\}_d \times \left\{ \frac{F_p \left[ W_{TR-ICE} \eta_{TR,PR} \eta_{W,PR} \right]}{W_{tc,PR} - W_{TR-ICE} \left[ \eta_{BR,PR} \left/ \eta_{TR,PR} \eta_{W,PR} \right] \right]_p} \right\}_{rhs3} \\
\times \eta_{P,out,P} - ES \eta_{P,in,P} - ES \eta_{ES,out,P} - ES \eta_{P,out,P} - EM \eta_{EM,TC1,in,TC1-TR} \eta_{EM1,G} \eta_{P,in,EM1-P} \\
+ \left\{ \eta_{P,out,P} - ES \eta_{ES,in,P} - ES \eta_{ES,out,P} - ES \eta_{P,in,P} - ES \eta_{P,out,P} - EM \eta_{EM,TC1,in,TC1-TR} \eta_{EM1,G} \eta_{P,in,EM1-P} \right\}_{rhs5} \]

(17)
Similar derivation could also be performed for series HEV. Fuel consumption ratio for series HEV and ICEV topology can be derived from eqns. (15) and (16)

\[
\left[ \frac{m_{f,sc}}{m_{f,sc}} \right]_S = \left\{ \left[ \frac{\eta_{ICE,eff}}{\eta_{ ICE - TC2,out,TC2-EM2,g}} \eta_{EM1,M} \eta_{TR,PR} \eta_{W,PR} \right]_S \right\} \times \left\{ \frac{F_S \left[ W_{TR-ICE} \eta_{TR,PR} \eta_{W,PR} \right]}{m_{f,sc} Q_{LVV} \eta_{ICE,eff} \eta_{TR,PR} \eta_{W,PR}} \right\}_{rhs2}
\]

\[
\left\{ \left[ \frac{[W_{tc,br} - W_{br}]_{S}}{m_{f,sc} Q_{LVV} \eta_{ICE,eff} \eta_{TR,PR} \eta_{W,PR}} \right] \left[ \eta_{W,br} \eta_{TR,br} \eta_{EM1,M} \eta_{P,in,EM1-P}\eta_{P,out,P-ES} \eta_{ES,in,P-ES} \eta_{ES,out,ES-P} \right] \right\}_{rhs3}
\]

\[
\times \eta_{P,in,ES-P} \eta_{P,out,P-EM1} \eta_{EM1,M} \eta_{TR,PR} \eta_{W,PR} \right\}_{rhs4}
\]

\[
+ \left\{ \left[ \frac{W'_{EM2-P,ES}}{m_{f,sc} Q_{LVV} \eta_{ICE,eff} \eta_{TR,PR} \eta_{W,PR}} \right] \left[ \eta_{P,in,EM2-P} \left( 1 - \eta_{P,out,P-ES} \eta_{ES,in,P-ES} \eta_{ES,out,ES-P} \eta_{P,in,ES-P} \right) \right] \right\}_{rhs5}
\]

(18)

It can be concluded from eqns. (17) and (18) that both HEVs utilize fuel energy more efficiently than ICEV if

\[
\frac{m_{f,sc}}{m_{f,sc}}_{HEV} < 1,
\]

whereas rhs of both equations reveals and quantifies the mechanisms that could lead to this goal; HEV represents P or S. It can be concluded that rhs1 in both equations represents the inverse ratio of the energy conversion chains from the fuel tank (F) to wheels (W) for particular HEV topology vs. ICEV topology. rhs1 is multiplied by the sum of rhs2-rhs5. rhs2 is equal to the multiplication factor of the test cycle, \( F_p \) or \( F_S \), that is generally larger than unity and thus tends to decrease energy conversion efficiency of both HEV topologies. rhs3 considers the influences of motoring ICE by external torque rather than by fuel addition. rhs3 clearly increases the ratio \( \frac{m_{f,sc}}{m_{f,sc}} \left[ \right]_{HEV} \) in eq. (18), since series HEV topology does not enable motoring of the ICE by external torque. In parallel HEV, rhs3 generally increases ratio \( \frac{m_{f,sc}}{m_{f,sc}} \left[ \right]_{P} \), eq. (17), since parallel HEVs incorporate downsized ICEs with smaller
energy consumption capability. It should be noted that energy consumed by the ICE in ICEV could be used for regenerative braking in both HEV topologies. Additionally, control strategies of the parallel HEV attempt to avoid operation of the ICE at low loads and correspondingly at low efficiency of the ICE thereby reducing the amount of the energy consumed by the ICE through motoring by external torque. In HEVs, negative effects due to the term rhs3 are therefore generally overcompensated by positive effects due to regenerative braking (rhs4), higher $\eta_{ICE,eff}$, and lower losses due to charging ES by the ICE (rhs5). rhs4 considers regenerative braking, which is one of the major mechanisms for increasing energy conversion efficiency of both HEV topologies. It is obvious that increase in the energy conversion efficiency is proportional to the amount of the energy available for regenerative braking, $[W_{bc,BR} - W_{BR}/\eta_{W, BR}]_s$ of the series HEV is generally larger than $[W_{bc,BR} - W_{BR}/\eta_{W, BR} - W'_{TR-TC,ICE}/(\eta_{W, BR}\eta_{TR, BR})]_p$ of the parallel HEV, since EM1 in series HEV needs to be sized for the maximum power output of the HEV and thus enables recuperation of larger amount of the energy through regenerative braking. rhs5 accounts for the losses due to charging the ES by the energy produced by the ICE. It therefore obviously decreases energy conversion efficiency of both HEV topologies.

Additionally, analytical framework for comparing conventional ICEV and ICEV featuring stop/start strategy (denoted I,SS) needs to be developed. Considering eq. (16) for both control strategies it follows

$$\left\{ \frac{m_{f,fc}}{m_{f,fc}} \right\}^{I, SS}_{I} = \left\{ \left[ \frac{\eta_{ICE,eff}}{\eta_{TR,PR} \eta_{W,PR}} \right]_I \right\}^{I, SS}_{rha} \times \left( F_{I, SS} \left[ W_{TR-ICE}/\eta_{TR,PR} \eta_{W,PR} \right]_I \right)^{I, SS}_{rha} - \left[ W_{TR-ICE}/\eta_{TR,PR} \eta_{W,PR} \right]^{I, SS}_{rha} .$$

(20)
Generally mass of the vehicle does not change significantly with the introduction of the stop/start strategy therefore $\text{rhs}_2 \rightarrow 1$. If additionally equal driver model is applied $\text{rhs}_3 \rightarrow 0$. Therefore, introduction of the stop/start strategy influences $\text{rhs}_1$ through $\eta_{\text{ICE, eff}}$ and increases energy conversion efficiency of ICEV featuring stop/start strategy.

3. Simulation model

The scope of the proposed paper is to analyze the energy conversion efficiency of hybrid and conventional powertrains. The simulation model therefore assures accurate evaluation of energy flows and energy losses. A forward-facing model was applied for modeling of ICEV and both HEV topologies. Simulation models for ICE powertrain and both hybrid powertrains were described in detail in Refs. [15,16]. Therefore powertrain models are only briefly summarized subsequently, whereas sub-models of additional components required for modeling vehicle dynamics and corresponding control strategies are addressed in this section.

Analyses are performed for a MAN 8.225 LC 7490 kg gross weight truck equipped with a six gear S6-850 gearbox representing a baseline ICEV. When modeling HEVs, weight increase due to additional batteries, electric machines and other electric accessories is considered, as well as weight decrease due to downsizing ICE in both HEV topologies, and omission of the gear box in the series HEV. However, the latter is much smaller than weight increase due to additional electric components as discernable from the results.

The MAN D0826 LOH 15 turbocharged diesel engine (max. torque 862Nm at 1400rpm, max. power 158kW at 2400 rpm) is applied as the baseline internal combustion engine. Maximum brake mean effective pressure vs. speed characteristics and effective efficiency of the applied baseline ICE, as well as power control strategy (described in the section 3.2) are shown in Fig. 3. The ICEs with $R_v = V_{\text{downsized}}/V_{\text{baseline}}$ equal to 0.8 and 0.5 were analyzed with the parallel HEV, and the ICE with $R_v = 0.5$ was analyzed with the series HEV. The
choice of downsized ICEs in parallel HEV was based on the analyses of powertrain performance presented in Refs. [15,17] and represents a HEVs with small and high hybridization ratio, whereas series HEV configuration represents a good compromise between powertrain performance and vehicle weight. Cyclic fuel delivery is scaled according to the swept volume of the ICE. The simulation model of the ICE is based on the 0-D filling and emptying method, since it was shown in Ref. [20] that transient engine parameters such as ICE power output, boost pressure and turbocharger speed calculated with 0-D and combined 0-D and 1-D model coincide very well and that results of both models agree very well with experimental data. Validation of the 0-D model is presented in Ref. [21].

Battery charging, discharging and determination of SOC was performed according to the model proposed by Kutluay et al [22]. Three control strategies were applied to the number of battery modules in this study, i.e.: 1.) SOC of the battery units must be greater than 0.4, 2.) batteries are of such size that they do not limit the performance of the electric motor and 3.) charge-discharge efficiency of the batteries is approximately 65%; details are presented in Ref. [15]. The charge-discharge efficiency value is in a good agreement with the data published in Refs. [23,24,25]. The Genesis 12V, 28 Ah VRLA battery is considered as the module of the storage system. Basic storage module used in the simulation consists of 25 batteries connected in series, whereas the number of modules is selected upon the previous criteria.

Model of the electric motor evaluates torque output, electric energy consumption and efficiency estimation based on measured input data of the electric machine and input signals from other sub-models of the simulation model. Similarly, electric energy production, required torque input and efficiency estimation are determined in the model of the electric generator. A prototype electric motor-generator produced and tested by ISKRA Avtoelektrika d.d. (max. torque 80Nm, max. efficiency 89.7%; details are presented in Ref. [15]) was
applied in the parallel hybrid powertrain and as electric motor in the series one. The electric machine was scaled according to the constraints given in the next paragraph in order to ensure required torque output of the powertrain, whereas its efficiency characteristics were also modified simultaneously according to the data provided by the manufacturer.

Characteristics of the STAMFORD UCM 274F (max. input power 94.6kW, max. efficiency 93%) were used to simulate electric generator in the series hybrid powertrain.

Components of analyzed HEVs were sized according to the following constraint

\[
\left( M_{ICE,h} + M_{EM} \right) \mid_{n\left(M_{ICE,h,max}\right)} = M_{ICE,h} \mid_{n\left(M_{ICE,h,max}\right)} 
\]

for the parallel HEV, and

\[
M_{EM} \mid_{n\left(M_{ICE,h,max}\right)} = M_{ICE,h} \mid_{n\left(M_{ICE,h,max}\right)} 
\]

for the series one, where \( n\left(M_{ICE,h,max}\right) \) represents engine speed that corresponds to the maximum torque of the baseline ICE engine. Baseline ICE powertrain and both hybrid powertrains thus feature the same maximum torque at \( n\left(M_{ICE,h,max}\right) \). Hybridization factor (HF’) [2,7,14] can be evaluated when parallel hybrid powertrain is considered

\[
HF' = \frac{P_{EM}}{P_{EM} + P_{ICE,h} \mid_{n\left(P_{ICE,h,max}\right)}} , \quad (21)
\]

where \( n\left(P_{ICE,h,max}\right) \) represents engine speed that corresponds to the maximum power output of the baseline MAN engine. However, considering the above definition it is more convenient to define alternative hybridization factor (HF), as proposed in [15]

\[
HF = \frac{M_{EM}}{M_{EM} + M_{ICE,h} = const.} \mid_{n\left(M_{ICE,h,max}\right)} . \quad (22)
\]

Hybridization factors of particular parallel hybrid powertrains are: HF=0.203 and HF’=0.17 for \( R_v = 0.8 \), and HF=0.531 and HF’=0.464 for \( R_v = 0.5 \).

In proposed analysis both HEV topologies do not incorporate torque couplers (TC). In the series HEV, ICE is directly mechanically connected to the EM2, therefore TC2 is not considered and its efficiency equals unity as analyzed in Ref. [4]. In parallel HEV, EM1
operates in the same speed range as ICE and it could therefore be directly mechanically coupled to the shaft. Again, TC1 is not considered and its efficiency equals unity.

3.1. Driveline models

Models of wheels (W), brakes (BR) and transmission (TR) are introduced in this section. Longitudinal vehicle dynamics corresponding to vehicle dynamometer test cycle specification is considered in the proposed energy conversion efficiency analysis.

Energy losses and thus efficiencies of the tire are evaluated by the rolling resistance momentum model of the tire. Rolling resistance momentum of the tire was modeled according to the model proposed in Ref. [26]. The model considers free rolling resistance moment and momentum due to rolling radius radial deflection resulting from the power balance of the wheel. The wheel is subjected to a propulsion torque and drag force acting backward on the wheel in its center. The model thus also considers influences of a forward speed and normal force including interaction of overall stiffness and growth function. The model applied in this study does not include arctan multiplier that was added to the free rolling resistance moment term in Ref. [26] to take care of a possible sign change of a rolling speed, which significantly improved low speed values of the rolling resistance momentum.

Brakes were modeled as an energy sink. It was assumed that brakes could always consume braking power, since standardized test cycles feature moderate braking and driving forces. Braking power was determined by the driver model being presented in the next section.

Transmission losses were split into gear box losses and differential losses. Both energy losses apply for parallel HEVs, whereas only differential losses apply for series HEVs, since they do not incorporate a gear box. Constant efficiencies determined according to the manufacturer’s instructions for vehicles with one driven axle were applied to model energy
losses in the transmission. Losses due to the clutch slip were also considered in the transmission losses. Clutch slip losses are applicable only for parallel HEVs. Additionally, clutch slip losses are significant only for parallel HEVs without drive-away by electric motor, whereas for parallel HEVs with drive-away by electric motor clutch slip losses are insignificant.

3.2. Control strategies

Control strategy (CS) has significant effect on the performance and on the fuel economy of a vehicle. It should be noted that minimum fuel consumption of particular hybrid powertrain running under particular operating conditions can only be assessed by global optimization, which can not be used for the real-time control [27]. Therefore, the CS used in this study has to be flexible enough to provide equivalence for all topologies and configurations. A relatively simple control strategy was applied in order to assure credible comparisons of different hybrid vehicle configurations running under different operating conditions.

Two control strategies were applied to ICEVs: 1) normal operation of the ICEV, and 2) ICEV with stop/start control strategy (denoted SS).

All parallel HEVs apply SS control strategy. Additionally, two different regimes of vehicle propulsion during drive-away and at low powertrain loads were analyzed: 1) ICE solely provides the torque for vehicle propulsion up to maximum torque output of the ICE (Fig. 4 - ICE), and 2) EM solely provides the torque up to a specified limit (Fig. 4 - EM) and afterwards ICE solely provides the torque for vehicle propulsion up to maximum torque output of the ICE (denoted EM_START). For both strategies EM assists ICE if torque demand of the test cycle is higher than the maximum torque output of the ICE (Fig. 4 – ICE+EM). Control strategy of the parallel HEV allows for: 1) drive-away and vehicle
propulsion at low powertrain loads by EM if EM\_START operating regime is enabled (denoted CS\_P\_1; Fig. 4 - EM), 2) ICE and EM deliver power in parallel if ICE is not able to provide required power (denoted CS\_P\_2; Fig. 4 – ICE+EM), 3) replenishing the batteries by operating the ICE at higher torque output (denoted CS\_P\_3), 4) regenerative braking (denoted CS\_P\_4), 5) simultaneous operation of the ICE and the EM in order to prevent charging of the batteries above the specified limit (denoted CS\_P\_5), and 6) normal operation of the ICE (denoted CS\_P\_6 ; Fig. 4 – ICE). Control strategy algorithm executes particular control modes as listed above.

Basic data on particular control strategy are briefly addressed subsequently. The vehicle is driven by EM (CS\_P\_1) if EM\_START operating regime is enabled, and \( P_{\text{IC}} < P_{\text{CS\_P\_1\_max}} \) where \( P_{\text{CS\_P\_1\_max}} = \min \{ P_{\text{EM\_P\_max}}, P_{\text{EM\_assist\_max}} \} \). Driving mode CS\_P\_1 is entered if \( P_{\text{IC}} < P_{\text{CS\_P\_1\_max}} / 2 \) to prevent unstable alternation between different control strategies.

\( P_{\text{EM\_P\_max}} \) is defined by the characteristic of EM and \( P_{\text{EM\_assist\_max}} \) was set to 30 kW, since higher values of \( P_{\text{EM\_assist\_max}} \) lead to decreasing energy conversion efficiency due to large amount of electric energy needed to replenish the ES after the EM propulsion. Vehicle is driven in CS\_P\_2 if \( P_{\text{IC}} > P_{\text{ICE\_P\_max}} \), and SOC>SOC\_min. In this analysis SOC\_min =0.4. CS\_P\_3 features two different operating modes based on the SOC of ES. If SOC is low, i.e. SOC<SOC\_ch2, and \( p_{\text{ICE\_P}} < p_{\text{ch2}} \), ICE is operated at high load, i.e. \( p_{\text{ch2}} \), to amply charge the ES.

CS\_P\_3\_LOW operating mode is entered if \( p_{\text{ICE\_P}} < p_{\text{ch2}} - \Delta p_{\text{CS\_P\_3\_LOW}} \) to prevent unstable alternation between different control strategies. In this analysis SOC\_ch2 =0.6, \( p_{\text{ch2}} \) is shown in Fig. 3, and \( \Delta p_{\text{CS\_P\_3\_LOW}} \) =0.2 MPa. If SOC is higher, however still below SOC\_ch1 and \( p_{\text{ICE\_P}} < p_{\text{ch1}} \), then ICE is operated at \( p_{\text{ch1}} \) to avoid area of low effective efficiency (Fig. 3). CS\_P\_3\_HIGH operating mode is entered if \( p_{\text{ICE\_P}} < p_{\text{ch1}} - \Delta p_{\text{CS\_P\_3\_HIGH}} \) to
prevent unstable alternation between different control strategies. In this analysis SOC_{ch1} = 0.7, \( P_{\text{eff, ch1}} = 0.68 \text{ MPa} \), and \( \Delta p_{CS_{P_3}}^{HIGH} = 0.38 \text{ MPa} \). Vehicle is driven in CS_{P_4} if SOC < 1 and \( P_{tc} < P_{\text{neg, max, ICE}, p} \), since regenerative braking is always desirable as indicated in section 2.

Vehicle is driven in CS_{P_5} if SOC > SOC_{dch}, \( P_{tc} > 0 \) and \( P_{\text{eff, ICE}, p} > P_{\text{eff, dch}} \) to prevent overcharging of the ES. In CS_{P_5} mode \( P_{\text{ICE}, p} = aP_{tc} \) and \( P_{\text{EM1, out}} = (1-a)P_{tc} \), where value of parameter \( a \) is dependent on SOC of the ES and is limited by \( 0 < a < 1 \). CS_{P_5} mode is entered if \( P_{\text{eff, ICE}, p} > P_{\text{eff, dch}} + \Delta p_{CS_{P_4}} \) to prevent unstable alternation between different control strategies. In this analysis SOC_{dch} = 0.75, \( P_{\text{eff, dch}} = 0.1 \text{ MPa} \) and \( \Delta p_{CS_{P_4}} = 0.4 \text{ MPa} \). In CS_{P_6} mode ICE power the vehicle. Mean effective pressure and engine power were applied as the parameters determining engine load, since they could easily be evaluated by the ECU.

The ICEs of the series HEVs were operated according to the optimum engine operation line (OEOL), Ref. [19], shown in Fig. 3. OEOL is constituted of engine speed and torque points where engine speed \( (n) \) increases with increasing fuel rack position (FR). In the presented analysis the power output of the ICE operating according to OEOL was based on the battery SOC, i.e. FR \( \propto \) SOC, and \( n \propto \) FR as indicated in Fig. 3. ICE is turned off if power output of the ICE falls below the specified threshold (in this study \( n = 1000 \text{ rpm} \) corresponding to FR=0.8 as indicated in Fig. 3 to prevent low power input of the EM2, which reduces efficiency of the EM2 and thus energy conversion efficiency of the series HEV. Corresponding to the OEOL two control strategies were applied to series HEVs: 1) ICE is turned on and off according to the SOC (denoted CS_{S_SOC}; fig. 5), and 2) ICE is turned on and off according to the characteristics of the test cycle (denoted CS_{S_tc}; fig. 5). These two control strategies were introduced to analyze influences of the energy flow \( W'_{EM2-P, ES} \), i.e. charging the ES by the ICE, on the energy conversion efficiency of the series HEV.
CS_S_SOC strategy enables ICE operation during vehicle stops and during regenerative braking, as well as propulsion of the vehicle by delivering all energy solely by the ES, since ICE might be turned off at that instant. This strategy generally increases energy flow through the batteries, since ICE might not be turned on during vehicle propulsion, and also decreases charging efficiency of ES, since ES might be charged by regenerative braking and by ICE increasing charging currents. The latter implies larger number of battery modules to maintain required charge-discharge efficiency of ES, imposing vehicle weight penalty. CS_S_tc suppresses these deficiencies, since ICE is turned on during vehicle propulsion period and it is turned off during vehicle stops and during regenerative braking decreasing energy flow through the batteries and increasing charge-discharge efficiency of the ES. However, CS_S_tc decreases maximum sustained power compared to CS_S_SOC, since CS_S_SOC enables continuous operation of the ICE throughout the complete test cycle. Improved SC of series HEV would feature characteristics of both CSs to combine high energy conversion efficiency and high maximum sustained power, however both CSs are analyzed separately to expose their influence on the energy conversion efficiency.

3.3. Test cycles

Three different test cycles were analyzed to investigate influences of test cycle characteristics on energy conversion efficiency of different HEV topologies and configurations [28]: 2.65-km bus route with 28 stops (BUSRTE), Fig. 6 a), Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles (UDDSHDV), Fig. 6 b), and ECE+EUDC (NEDC) for low-powered vehicles (ECE_EUDC_LOW), Fig. 6 c). UDDSHDV is a highly transient cycle featuring frequent accelerations/decelerations including high velocity segments. Average velocity of the ECE_EUDC_LOW is similar to that of the UDDSHDV, however significantly less acceleration magnitude changes are characteristic for
ECE_EUDC_LOW. BUSRTE features significantly lower average velocity than both previous cycles and frequent decelerations to stand-still. BUSRTE thus enables significant recuperation of the energy by regenerative braking. It can be concluded that applied test cycles differ significantly in terms of relative amount of the energy available for regenerative braking, average velocity, and magnitude of the segments featuring steady-state operation of the powertrains. All test cycles are performed on a flat road.

3.4. Driver model

Driver model uses the test cycle velocity and the actual vehicle velocity to develop the appropriate acceleration, brake, gear, and clutch commands. Driver commands the acceleration pedal during vehicle propulsion, whereas most suitable vehicle drive power is selected by the control strategy introduced in section 3.2. In the proposed analysis different topologies and configurations of vehicles are analyzed. A stable and robust driver model capable of following velocity trace given by the test cycles with high fidelity is thus needed to enable credible analysis of the energy conversion efficiency.

The driver model is aimed for analysis of the energy conversion phenomena, therefore powertrain and vehicle parameters might be applied to follow the speeds trace given by the test cycle with high fidelity. Variation of the acceleration pedal was modeled by over-damped second order differential equation

\[ a x^{n+1} + b x^{n+1} + c x^{n+1} = x^n + \Delta x^n, \]  

(23)

where \( x \) represents acceleration pedal position, \( n \) represents time level,

\[ \Delta x \propto -(M_{\text{powertrain}} - M_{L+WR} - m_v r_{\text{ giriş}} a_v) \]  

(24)

and

\[ a_v \propto \frac{v_v(t + \Delta t) - v_v(t)}{\Delta t}. \]  

(25)
\( \Delta x \) is evaluated upstream of the TR of particular vehicle topology. \( M_{L+WT} \) therefore includes vehicle load and losses of wheels and transmission. \( r_{\text{eff}} \) represents wheel radius corrected by the differential gear ratio and eventually by gear box gear ratio, and \( a_v \) represents acceleration corrected to upstream of the TR. \( a_v \) includes a forward looking approach and thus makes possible very good agreement between the velocity trace given by the test cycle and the vehicle velocity trace.

Gear shift strategy represents an important mechanism influencing energy conversion efficiency of ICEVs and HEVs. Gear shift strategy is applied to ICEV and parallel HEV. Gear shift strategy has to be general to provide equivalence for all topologies and configurations. Input parameters of the gear shift strategy are therefore powertrain speed and acceleration pedal. Gear shift strategy for vehicle propulsion by ICE, and ICE and EM is shown in Fig. 7. Up- and down-shift limits are determined considering high fuel economy and high performance of the vehicle, as well as operating speed range of the components and gear ratios of particular gears. It can be concluded considering Fig. 3 and Fig. 7 that the gear shift strategy enables operation of the ICE in the high efficiency region, whereas it also allows reaching maximum power output of the ICE.

Stability and robustness of the driver model have been confirmed by the great accuracy in terms of following the vehicle velocity trace given by the test cycle for all powertrain topologies and all test cycles. Example of very good agreement between velocity imposed by the test cycle and vehicle velocity trace for a segment of the UDDS HDV cycle is shown in Fig. 8. It can therefore be concluded that the proposed driver model is highly applicable for analysis of the energy conversion phenomena.
4. Results

Results for three analyzed test cycles and different powertrain topologies and configurations are shown in this section. Only results of powertrain configurations that are able to comply with non-depleting ES management are shown to enable credible comparison of energy conversion efficiencies.

Following parameters are introduced based on the eqns. (17), (18) and (20) to enable clear and demonstrative analysis. Relative change in the fuel consumption, \( \Delta m_{f,X} \), could also be written as the product of rhs\(_i^*\) terms considering influences of particular mechanisms (mogoce upostevaj iz SAE)

\[
\Delta m_{f,X} = \frac{[m_{f,X}]_X}{[m_{f,X}]_I} - 1 = \left[ (\text{rhs1} \times \text{rhs} 2 - 1) + \sum_{i=3}^{n} \text{rhs1} \times \text{rhs}_{i,^*} \right]_X,
\]

where \( X \) represents P or S or I,SS, and \( n \) equals the number of rhs terms in eqns. (17), (18) and (20). rhs\(_i^*\) terms clearly indicate influence of particular mechanisms on \( \Delta m_{f,X} \), since terms larger than 0 indicate increase of the \( \Delta m_{f,X} \), and terms smaller that 0 indicate decrease in \( \Delta m_{f,X} \). On the other hand, it is also instructive to analyze rhs1 term, representing ratio of the energy conversion chains from fuel tank (F) to wheels (W) for particular topology vs. ICEV topology, and \( \sum_{i=2}^{n} \text{rhs}_{i} \) term, representing all other mechanisms influencing energy conversion efficiency

\[
\frac{[m_{f,X}]_X}{[m_{f,X}]_I} = \left[ \text{rhs1} \times \left( \sum_{i=2}^{n} \text{rhs}_i \right) \right]_X.
\]

If terms rhs1 and \( \sum_{i=2}^{n} \text{rhs}_i \) are larger than 1 they indicate increase of the \( \frac{[m_{f,X}]_X}{[m_{f,X}]_I} \) ratio, and if the terms are smaller than 1, they indicate decrease of the \( \frac{[m_{f,X}]_X}{[m_{f,X}]_I} \) ratio.

Additionally, the ratio
\[ \Delta m_{v,x} = \frac{m_{v,x}}{m_{v,f}} \]  

(28)

is introduced to reflect change in vehicle mass relative to the mass of the ICEV. In the subsequent text indexes are not written with the parameters introduced in eqns. (26)-(28), since it is discernable from the accompanying text and figures which topology and configuration is analyzed.

Following notation is adopted in this section: ICEV – internal combustion engine vehicle, ICEV_SS – internal combustion engine vehicle with stop/start (SS) strategy, PHEV_Rv=0.8_EM=0 – parallel HEV incorporating ICE with \( R_v = 0.8 \) without EM_START strategy, PHEV_Rv=0.8_EM=1 - parallel HEV incorporating ICE with \( R_v = 0.8 \) with EM_START strategy, PHEV_Rv=0.5_EM=0 – parallel HEV incorporating ICE with \( R_v = 0.5 \) without EM_START strategy, PHEV_Rv=0.5_EM=1 - parallel HEV incorporating ICE with \( R_v = 0.5 \) with EM_START strategy, SHEV_SOC – series HEV with CS_S_SOC, and SHEV_tc – series HEV with CS_S_tc.

4.1. BUSRTE test cycle

The following parameters are presented in Fig. 9: a) \( \Delta m_f \) and \( \eta_{ICE,eff} \), b) rhs, c) rhs1, 

\[ \sum_{i=2}^{n} rhs_i \]  

and \( \Delta m_{v,x} \), and d) \( W_{ic,PR} \), \( W_{ic,BR} \) and \( W_{BR} \). It is discernable from Fig. 9 a) that \( \Delta m_f \) values are significantly influenced by the vehicle topology, configuration and applied control strategy. Comparing \( \Delta m_f \) and \( \eta_{ICE,eff} \) values (Fig. 9 a)) it can be concluded that \( \Delta m_f \) values do not correlate with the increases in \( \eta_{ICE,eff} \). It is therefore necessary to analyze particular terms of eqns. (26) and (27) to explain energy conversion phenomena influencing the fuel consumptions of particular vehicle topology.
Fig. 9 d) reveals that $W_{tc,BR}$ approaches $W_{tc,PR}$, being the consequence of very low average velocity of the test cycle. It is shown in Fig. 9 d) that $W_{BR}$ is large compared to $W_{tc,BR}$ for ICEV and ICEV_SS indicating that large amount of the energy is dissipated to heat.

It is discernable from Fig. 9 c) that ICEV_SS features equal vehicle weight ($\Delta m_v$) than ICEV resulting in equal values of $W_{tc,PR}$, $W_{tc,BR}$ and $W_{BR}$ (Fig. 9 d) and $\sum_{i=2}^{n} rhs_i$ (Fig. 9 c)). Improved fuel economy of ICEV_SS is therefore the consequence of improved $\eta_{ICE,eff}$ (Fig. 9 a)) resulting from application of the stop/start strategy during vehicle stops. Influence of $\eta_{ICE,eff}$ of ICEV_SS is reflected in rhs1 (Fig. 9 c)) and $\Delta m_f$ (Fig. 9 a)).

Fig. 9 reveals that PHEV_Rv=0.8_EM=0 and PHEV_Rv=0.8_EM=1 feature improved fuel economy ($\Delta m_f$) over ICEV due to increased $\eta_{ICE,eff}$ and thus rhs1, and due to regenerative braking (rhs4*). Both vehicles feature increased vehicle mass ($\Delta m_v$), however higher $\eta_{ICE,eff}$ largely overcompensates this deficiency resulting in rhs2*<0. It is discernable from Fig. 9 d) that $W_{tc,PR}$ and $W_{tc,BR}$ of PHEV_Rv=0.8_EM=0 and PHEV_Rv=0.8_EM=1 are larger compared to those of ICEV due to larger vehicle mass, however $W_{BR}$ is much smaller indicating once again that large amount of the energy is recuperated by regenerative braking.

It is discernable from fig. 9 c) that $\sum_{i=2}^{n} rhs_i <1$ for PHEV_Rv=0.8_EM=0 and PHEV_Rv=0.8_EM=1 indicating that, besides higher efficiency of energy conversion chains from F to W (rhs1), all other mechanisms incorporated in the parallel HEV also contribute to improved energy conversion. Parameter rhs1 also indicates that PHEV_Rv=0.8_EM=1 features improved fuel economy over PHEV_Rv=0.8_EM=0 due to higher $\eta_{ICE,eff}$, whereas $\sum_{i=2}^{n} rhs_i$ values are similar for both powertrains.
It is discernable from Fig. 9 that PHEV_Rv=0.5_EM=1 does not feature improved fuel economy (\(\Delta m_j\)) over PHEV_Rv=0.5_EM=0 despite higher \(\eta_{ICE,eff}\) and that both configurations consume more fuel than PHEV_Rv=0.8_EM=1 in spite of higher \(\eta_{ICE,eff}\). It is discernable from Fig. 9 c) that rhs1 values of PHEV_Rv=0.5_EM=1 and PHEV_Rv=0.5_EM=0 are indeed lower than rhs1 value of PHEV_Rv=0.8_EM=1 indicating higher efficiency of the energy conversion chain from F to W. However, \(\sum_{i=2}^{n} rhs_i\) values representing other mechanisms influencing energy conversion efficiency are higher, overcompensating positive effect of rhs1. Comparing \(\Delta m_j\) values of PHEV_Rv=0.5_EM=1 and PHEV_Rv=0.5_EM=0, it can be concluded that \(\Delta m_j\) of the PHEV_Rv=0.5_EM=1 is larger despite higher efficiency of the energy conversion chain from F to W (rhs1), since \(\sum_{i=2}^{n} rhs_i\) value of the PHEV_Rv=0.5_EM=1 is significantly larger. \(\Delta m_j\) of PHEV_Rv=0.5_EM=1 is thus larger due to charging ES by ICE (rhs5*) and due to larger value of rhs3*. rhs3* of both PHEV_Rv=0.5_EM=0 and PHEV_Rv=0.5_EM=1 are larger than 0, since they incorporate downsized ICEs with smaller energy consumption capability. Additionally, rhs3* value of the PHEV_Rv=0.5_EM=1 is larger than rhs3* value of the PHEV_Rv=0.5_EM=0, since PHEV_Rv=0.5_EM=1 has to recharge the ES by ICE (rhs5*>0) and thus operates in CS_P_3 for longer periods.

Conclusion on suitability of operation in CS_P_1 mode (drive-away and vehicle propulsion at low powertrain loads by EM) could be drawn by comparing results of PHEV_Rv=0.8_EM=0 and PHEV_Rv=0.8_EM=1, and PHEV_Rv=0.5_EM=0 and PHEV_Rv=0.5_EM=1. CS_P_1 is always desirable if energy consumed by EM could be recuperated by regenerative braking and not by operating the ICE at higher power output (rhs5*=0), since it increases \(\eta_{ICE,eff}\). On the other hand, if ES are charged by the ICE
(CS\_P\_3, rhs5*>0) to enable CS\_P\_1 operation, CS\_P\_1 is desirable if higher $\eta_{ICE,eff}$ overcompensates negative influences due to charging the ES by ICE (rhs5*) and eventual negative influences due to rhs3* and rhs4*.

Analyzing parameters of series HEVs it can be concluded that SHEV\_tc features much better fuel economy than SHEV\_SOC ($\Delta m_f$), whereas the latter also consumes more fuel than ICEV despite the largest amount of the energy recuperated by regenerative braking (rhs4*) and high $\eta_{ICE,eff}$. Fig. 9 d) indicates that SHEV\_SOC features the largest values of $W_{tc,PR}$ and $W_{tc,BR}$ due to the largest number of battery modules, whereas $W_{BR}$ is very small indicating again that it is capable of recuperating large amount of the energy by regenerative braking. It is discernable that $\eta_{ICE,eff}$ of SHEV\_SOC and SHEV\_tc are significantly higher than $\eta_{ICE,eff}$ of other topologies, since they operate according to OEOL (Fig. 3). However, rhs1 values of SHEV\_SOC and SHEV\_tc are not the smallest, since series HEVs incorporate longer energy conversion chain from F to W that unavoidably includes EM2, P and EM1. This is clearly discernable from the rhs1, eq. (18), of the series HEV. The main reason for low fuel economy of SHEV\_SOC is very large value of $\sum_{i=2}^{n} rhs_i$, where losses due to charging the ES by ICE (rhs5*) clearly represents the mechanism deteriorating fuel economy. It can also be seen that rhs3* terms increase $\Delta m_f$ of both series HEVs, since series HEVs do not incorporate the mechanism of energy consumption by the ICE as indicated in section 2. This analysis indicates that improvement in $\eta_{ICE,eff}$ and regenerative braking represent the major mechanisms to improve fuel economy of series HEVs, whereas it is necessary to reduce losses associated with charging ES by ICE and achieve the lowest possible vehicle mass to increase energy conversion efficiency of series HEVs.
4.2. UDDSHDV cycle

Fig. 10 shows vehicle parameters for UDDSHDV cycle equal to those shown in Fig. 9. It is discernable from Fig. 10 d) that UDDSHDV cycle features much larger values of $W_{tc,PR}$, and larger difference between $W_{tc,PR}$ and $W_{tc,BR}$ than BUSRTE cycle, indicating that average velocity of the UDDSHDV cycle is much higher. Consequently, smaller ratio of $W_{tc,BR}$ to $W_{tc,PR}$ indicates that relatively less energy is available for regenerative braking imposing lower maximum values of rhs4 terms in eqns. (17) and (18)) for UDDSHDV cycle.

PHEV_Rv=0.5_EM=0, PHEV_Rv=0.5_EM=1 and SHEV_tc were not able to comply with non-depleting ES management, since ICE could not provide enough energy to replenish the ES in the period when it is turned on. These results are therefore not shown.

Similar to BUSRTE cycle, it can be concluded that stop/start strategy increases $\eta_{ICE,eff}$ and therefore improves fuel economy of the ICEV_SS, since other vehicle parameters are equal for ICEV_SS and ICEV as discernable from Fig. 10 and addressed in the previous section.

Opposite to BUSRTE cycle, it is discernable that PHEV_Rv=0.8_EM=0 and PHEV_Rv=0.8_EM=1 consume more fuel than ICEV_SS, however, they still feature slightly improved fuel economy compared to ICEV. Significant factor influencing small improvement in $\Delta m_f$ is small improvement in $\eta_{ICE,eff}$ of PHEV_Rv=0.8_EM=0 and PHEV_Rv=0.8_EM=1 compared to $\eta_{ICE,eff}$ of ICEV, resulting in rhs1 value slightly less than unity. This phenomenon is the consequence of high $\eta_{ICE,eff}$ of the ICEV ($\eta_{ICE,eff} = 35\%$), allowing only limited $\eta_{ICE,eff}$ improvement through powertrain hybridization as discernable from Fig. 3. It should also be noted that $\eta_{ICE,eff,max}$ of downsized engines is just slightly lower than $\eta_{ICE,eff,max}$ of the baseline engine as addressed in Ref. [15]. $\sum_{i=2}^{n} rhs_i$ values larger than

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unity represent additional factor influencing small improvement in $\Delta m_f$ of

PHEV_Rv=0.8_EM=0 and PHEV_Rv=0.8_EM=1. This is to a large extent the consequence of limited relative amount of the energy available for regenerative braking as addressed previously in this section, resulting in smaller values of rhs4*. Moreover, larger vehicle mass ($\Delta m_v$), smaller capability of energy consumption by the ICE (rhs3*), and charging the ES by ICE (rhs5*) determine the value of $\sum_{i=2}^{n} rhs_i$. Comparison of PHEV_Rv=0.8_EM=0 and PHEV_Rv=0.8_EM=1 results reveals that PHEV_Rv=0.8_EM=1 features better fuel economy despite negative influences due to charging the ES by ICE (rhs5*), since higher $\eta_{ICE,eff}$ of the PHEV_Rv=0.8_EM=1 overcompensates deficiencies in rhs3* and rhs5*.

It is discernable that $\Delta m_f$ of SHEV_SOC is significantly larger than 1 indicating very low fuel economy. Low fuel economy of SHEV_SOC is the result of both rhs1>1 and $\sum_{i=2}^{n} rhs_i>1$. It is discernable from Fig. 10 that rhs1>1 despite the fact that $\eta_{ICE,eff}$ of the SHEV_SOC is higher than $\eta_{ICE,eff}$ of the ICEV. However, compared to the BUSRTE cycle increase in $\eta_{ICE,eff}$ of the SHEV_SOC is not so significant that it would be able to overcompensate drawbacks of the longer energy conversion chain incorporating EM2, P and EM1 (rhs1 eq. (18)). Additionally, $\sum_{i=2}^{n} rhs_i>1$ due to limited relative amount of the energy available for regenerative braking (rhs4*), due to larger vehicle mass ($\Delta m_v$) resulting in high rhs2* value, due to rhs3*>0, since series HEVs do not incorporate the mechanism of energy consumption by the ICE, and due to losses associated with charging of ES by ICE (rhs5*).

Larger vehicle mass of the SHEV_SOC is related to large number of battery modules necessary to maintain charge-discharge efficiency due to large energy flows through the ES.
4.3. ECE_EUDC_LOW cycle

It is discernable from Fig. 11 d) that ECE_EUDC_LOW cycle features similar ratios of $W_{tc,PR}$, $W_{tc,BR}$ and $W_{BR}$ than UDDSHDV cycle (Fig. 10 d)) despite different test cycle velocity trace featuring significantly less acceleration magnitude changes (Fig. 6). Analyzing values of $W_{tc,PR}$, $W_{tc,BR}$ and $W_{BR}$ and test cycle duration for both cycles, it can be concluded that average power values over the cycle are lower for the ECE_EUDC_LOW cycle. Therefore, PHEV_Rv=0.5_EM=0 and SHEV_tc are able to comply with non-depleting ES management for the ECE_EUDC_LOW cycle. Despite small differences in average power and significant differences in the acceleration magnitude changes, $\Delta m_f$ values of both test cycles feature similar trends.

Again, stop/start strategy increases $\eta_{ICE,eff}$ resulting in highest fuel economy of the ICEV_SS.

Mechanisms for lower fuel economy of PHEV_Rv=0.8_EM=0 and PHEV_Rv=0.8_EM=1 compared to ICEV_SS are equivalent to those of the UDDSHDV cycle. However, for ECE_EUDC_LOW cycle PHEV_Rv=0.8_EM=1 consumes more fuel than PHEV_Rv=0.8_EM=0. Similar as in the case of the BUSRTE cycle, negative influence due to charging the ES by the ICE (rhs5*) and to a lesser extent influences due to rhs3* and rhs4* overcompensate increased $\eta_{ICE,eff}$ resulting in lower fuel economy of the PHEV_Rv=0.8_EM=1.

It is discernable that fuel consumption of PHEV_Rv=0.5_EM=0 is larger than fuel consumption of ICEV. This is on one hand the consequence of larger vehicle mass ($\Delta m_v$) that overcompensates positive effects due to higher effective efficiency ($\eta_{ICE,eff}$) resulting in rhs2*>0. On the other hand, low energy conversion efficiency of the PHEV_Rv=0.5_EM=0 is also the consequence of losses associated with charging the ES by ICE (rhs5*) and to a
lesser extent the consequence of smaller capability of energy consumption by the downsized ICE (rhs3*).

It is discernable from Fig. 11 that both series HEVs feature very low fuel economy. Again, higher $\eta_{\text{ICE, eff}}$ could not overcompensate negative influences due to longer energy conversion chain resulting in rhs1>1, similar as for UDDS HDV cycle. Additionally, $\sum_{i=2}^{n} \text{rhs}_i > 1$, since regenerative braking could no overcompensate energy losses due to larger vehicle mass ($\Delta m_v$), losses due to charging the ES by ICE (rhs5*) and losses due to rhs3*. It is discernable from Fig. 11 that SHEV_tc consumes less fuel than SHEV_SOC due to smaller vehicle mass ($\Delta m_v$ and rhs2*) and due to lower losses associated with charging ES by the ICE (rhs5*).

5. Conclusion

Energy conversion efficiency of different HEV topologies, configurations and control strategies was analyzed by simulation and analytical analysis. Both analyses consider the complete HEV including all energy paths. Combined approach enables deep insight into energy conversion phenomena in the HEVs. It enables analysis of energy flows and energy losses on different energy paths within the hybrid powertrain, and evaluation of their influences on energy consumption of the powertrain. Combined approach clearly interprets influences of different test cycles, HEV topologies, configurations and control strategies on energy consumption of the HEVs, and therefore represents an efficient tool for optimizing HEVs based on their target application.

Despite the fact that heavy-duty vehicles were analyzed in the paper, the following general conclusions can be drawn. It is discernible from the analysis that HEV make possible significant fuel economy improvement for test cycles where ICEVs feature low effective efficiency of the ICE, and for test cycles enabling significant recuperation of the energy by
regenerative braking. It was also shown in the paper that HEVs feature very limited fuel economy enhancement or ever feature worse fuel economy in comparison to ICEVs, if effective efficiency of the ICE in ICEV is already relatively high for particular test cycle. It is discernable from the results that with increased average power of the test cycle and with decreased possibility of recuperating energy by regenerative braking parallel HEV topology could clearly be favored over series HEV topology. It is evident from the results that control strategy significantly influences fuel economy of series HEVs, since losses due to charging ES by ICE might be considerable. It was shown in the paper that drive-away and vehicle propulsion at low powertrain loads by EM is always desirable for parallel HEVs if energy consumed by EM could be recuperated by regenerative braking and not by operating ICE at higher output. Otherwise, a detailed analysis revealing improvement in effective efficiency of the ICE and negative effects due to charging ES by ICE and other minor effects addressed in section 4 is necessary to justify this operation mode. It is also evident from the results that stop/start strategy always leads to improved fuel economy of the ICEV.

Results also indicate that reduction of HEVs weight and improvement of the ES efficiency leads to enhanced fuel economy of HEVs.

References


**Fig. 1** a) Parallel and b) series HEV topology, and c) ICEV topology with indicated energy paths

**Fig. 2** a) Elements A and B linked with the energy path, b) energy flow pattern between elements A and B, c) element B without energy accumulation capability linked with two bidirectional energy paths, and d) split of the energy losses of the element B into inlet and outlet losses; B represents origin for evaluation of the energy balance

**Fig. 3** Effective efficiency of the MAN turbocharged diesel engine with indicated $p_{\text{eff}, ch2}$, and OEOL control strategy (section 3.2)

**Fig. 4** Schematic torque outputs of different parallel HEV propulsion regimes

**Fig. 5** Operation of the ICE for CS_S_SOC and CS_S_tc control strategies applied to the series HEV

**Fig. 6** Velocity profile of: a) BUSRTE, b) UDDS, and c) ECE_EUDC_LOW test cycles

**Fig. 7** Gear shift strategy

**Fig. 8** Agreement between velocity imposed by the test cycle and vehicle velocity trace for a segment of the UDDS cycle
Fig. 9 a) $\Delta m_f$ and $\eta_{ICE, eff}$, b) rhs$_i^*$, c) rhs1, $\sum_{i=2}^{n} \text{rhs}_i$ and $\Delta m_V$, and d) $W_{tc,PR}$, $W_{tc,BR}$ and $W_{BR}$ for different powertrain topologies and configurations evaluated for BUSRTE test cycle

Fig. 10 a) $\Delta m_f$ and $\eta_{ICE, eff}$, b) rhs$_i^*$, c) rhs1, $\sum_{i=2}^{n} \text{rhs}_i$ and $\Delta m_V$, and d) $W_{tc,PR}$, $W_{tc,BR}$ and $W_{BR}$ for different powertrain topologies and configurations evaluated for UDDS HDV test cycle

Fig. 11 a) $\Delta m_f$ and $\eta_{ICE, eff}$, b) rhs$_i^*$, c) rhs1, $\sum_{i=2}^{n} \text{rhs}_i$ and $\Delta m_V$, and d) $W_{tc,PR}$, $W_{tc,BR}$ and $W_{BR}$ for different powertrain topologies and configurations evaluated for ECE_EUDC_LOW test cycle
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Fig. 10 a) $\Delta m_f$ and $\eta_{ICE,eff}$, b) rhs$_{i,*}$, c) rhs$_1$, $\sum_{i=2}^{n}$ rhs$_i$ and $\Delta m_v$, and d) $W_{tc,PR}$, $W_{tc,BR}$ and $W_{BR}$ for different powertrain topologies and configurations evaluated for UDDS HDV test cycle.
Fig. 11 a) $\Delta m_f$ and $\eta_{ICE, eff}$, b) rhs$_i$, c) rhs$_1$, $\sum_{i=2}^n$ rhs$_i$ and $\Delta m_V$, and d) $W_{ic,PR}$, $W_{ic, BR}$ and $W_{BR}$ for different powertrain topologies and configurations evaluated for ECE_EUDC_LOW test cycle.