“Fair” Comparison of Powertrain Configurations for Plug-In Hybrid Operation Using Global Optimization

Dominik Karbowski, Sylvain Pagerit, Jason Kwon, Aymeric Rousseau
Argonne National Laboratory

Karl-Felix Freiherr von Pechmann
Ecole des Mines de Paris/Argonne National Laboratory

ABSTRACT

Plug-in Hybrid Electric Vehicles (PHEVs) use electric energy from the grid rather than fuel energy for most short trips, therefore drastically reducing fuel consumption. Different configurations can be used for PHEVs. In this study, the parallel pre-transmission, series, and power-split configurations were compared by using global optimization. The latter allows a fair comparison among different powertrains. Each vehicle was operated optimally to ensure that the results would not be biased by non-optimally tuned or designed controllers. All vehicles were sized to have a similar all-electric range (AER), performance, and towing capacity. Several driving cycles and distances were used. The advantages of each powertrain are discussed.

INTRODUCTION

Plug-in Hybrid Vehicles (PHEVs) combine an internal combustion engine (ICE) and an electrical energy/power source that is composed of a battery and one or two electric machines. Such vehicles have a great potential to reduce the use of petroleum in personal transportation as most daily trips are short enough to be done by using electric energy only [1]. Similarly to HEVs, several powertrain configurations can be selected. Toyota [2] and Ford [3] favor the power-split configuration; they already use it in current production vehicles such as the Ford Escape Hybrid or the Toyota Prius. General Motors is planning to put in production a series PHEV, the Volt [4]. Daimler has a PHEV version of its Sprinter van [5], which uses a parallel pre-transmission configuration. It is important to compare the three configurations to evaluate their fuel displacement potential in a PHEV context.

An academic study used non-optimized models to compare four hybrid configurations and concluded that the parallel was the best [6]. In another study [7], PHEVs using Argonne National Laboratory’s (Argonne’s) Powertrain System Analysis Toolkit (PSAT) [8, 9] were considered. That approach used rule-based control, and the control was based on an electric operation mode until the battery is fully depleted, followed by a charge-sustaining mode. Results of such a method depend on the proper tuning of each vehicle control: a configuration operating more optimally than another one may appear better. Furthermore, Sharer et al. showed [10] that this control is not optimal in the case of the power-split.

Optimization techniques are numerous in the hybrid control field; however, the global optimization algorithm using Bellman’s principle, also called dynamic programming, is one of the most interesting techniques. It is also very challenging as it requires prior knowledge of the drive cycle and massive computation in order to obtain accurate results. It was implemented for fuel-cell HEVs [11] and for gasoline-electric hybrids [12, 13]. It was eventually used to study PHEV control [14, 15] as well as used as a tool to compare vehicles with different battery sizes [16, 17]. One can also look at the application of the stochastic dynamic programming method to PHEVs [18].
Global optimization, because it takes the control out of the loop, can therefore be used to ensure fair comparison among vehicles. Any vehicle is operated optimally when run by using global optimization.

To compare the three different configurations (series, parallel pre-transmission, and power-split), the first stage of this study addresses an appropriate sizing of the vehicles. The optimization algorithm is then described, and the resulting optimal control analyzed.

**VEHICLE SIZING**

**VEHICLE REQUIREMENTS** - The first step in this study is to define the vehicles. One possible approach is to choose some given components and use the same components in each vehicle. The resulting vehicles would then have various levels of performance and would hardly be comparable for the consumer. Moreover, it is not always possible to use the same components because of the intrinsic differences among configurations. The approach chosen here is to define a common set of requirements that each vehicle of the study has to meet. As a result, the vehicles will be comparable for the end-user. The vehicles used in this study must meet the following requirements:

- Perform the U.S. Environmental Protection Agency (EPA) urban cycle (UDDS) in all-electric (AER) mode.
- Start at 90% of battery state-of-charge (SOC) and reach a SOC of 30% after 10 miles in electric-only mode on the UDDS.
- Sustain a 6% grade at 65 mph (104.6 km/h) indefinitely when loaded with extra cargo mass (about 500 kg). Indefinitely here means using fuel as the unique external energy source and, if applicable, operating any electric machine at or below its maximal continuous torque.
- Reach 60 mph (96.6 km/h) in 9.3 s or less, after the initial vehicle movement.
- Reach a top speed greater than 110 mph.

For each vehicle, there is at least one requirement that is simply met and is not exceeded.

**COMPONENTS** - All three vehicles share a common chassis comparable to the Hyundai Sonata, with a glider mass of 1142 kg. The drag coefficient is 0.28, while the wheel radius is 0.332 m.

The battery model is based on the test data of the Johnson Controls-Saft VL41M cell, which is a 3.6V 41Ah cylindrical lithium-ion cell, currently in use on the Ford Escape PHEV prototypes.

The mechanical components characteristics are summarized in Table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Peak Efficiency</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>36%</td>
<td>Gasoline, spark-ignited</td>
</tr>
<tr>
<td>EM1 (parallel), EM2 (Generator, series)</td>
<td>93.5%</td>
<td>Permanent magnet, top speed 6000 RPM</td>
</tr>
<tr>
<td>EM1 (split), EM1 (series)</td>
<td>93.5%</td>
<td>Permanent magnet, top speed 10000 RPM</td>
</tr>
<tr>
<td>EM2 (split)</td>
<td>95%</td>
<td>Permanent magnet, top speed 14000 RPM</td>
</tr>
</tbody>
</table>

The transmission used in the parallel configuration is a 6-speed automatic (4.2 2.6 1.8 1.4 0.8) with a final drive ratio of 3.32. That same final drive ratio is used in the series and split configuration. In those two configurations, the electric machines are coupled to the final drive with an additional ratio of 1.96. The planetary gearbox used in the power-split configuration has the same teeth number as the one in the Toyota Camry (30 at the sun, 78 at the ring).

There is an additional electric load of 250 W, corresponding to basic electric accessories.

**SIZING ROUTINE** - Vehicles are sized by using an automated sizing routine that employs Argonne’s PSAT, a forward-looking model. In the first step, the battery and electric machine power are sized to perform the UDDS. The number of cells is defined by the desired nominal voltage of the battery (215V) that is within the voltage range of the considered electric machines. The battery capacity is then sized to meet the 10-mi AER requirement on the UDDS. Then, the engine is sized in order to meet the grade requirements. If the vehicle still does not meet the 0-60 mph requirement, the engine power is increased (as well as the motor power in the series and split). There are several iterations of this process because the vehicle mass changes each time a component power (and capacity for the battery) changes.

The scaling involves reshaping the internal resistance or efficiency map of the components described previously. It is done by using a linear scaling.

**SIZING RESULTS** - The outcome of the sizing routine is summarized in Figure 1.
Figure 1: Components Power and Battery Capacity

Engine power is about 73 kW for the series and the parallel configuration, while it is 90 kW for the split. This is due to the 0–60 mph requirements. Because the engine speed is tied to the vehicle speed and the EM2 maximal speed, it reaches its peak power only at high vehicle speed, while it can be reached earlier in speed in the other configurations. The battery size is very similar from one configuration to another. The total mass of each vehicle is 1782 kg for the parallel, 1824 kg for the split, and 1793 kg for the series.

VEHICLE MODEL

The model used in the optimization is backward-looking. The vehicle speed is the cycle trace speed, and the torque, speed, and power are propagated backward from the wheels to the engine and battery.

All three configurations share a common driveline (final drive, wheels, and chassis). The force at the wheels required to follow the vehicle speed trace is defined by Equations 1, 2, and 3.

\[ F_{veh} = m_{veh} \frac{dv_{veh}}{dt} + F^{drag}_{veh} + F^{roll}_{veh} \quad (1) \]

\[ F^{drag}_{veh} = \frac{1}{2} \rho \, a_r \, C_d \, A_f \, \frac{v_{veh}^2}{2} \quad (2) \]

\[ F^{roll}_{veh} = m_{veh} \, g \, (C_{R1} + C_{R2} \, v_{veh}) \quad (3) \]

The final drive is modeled as a constant efficiency torque multiplier. Its input is also the input of the driveline and is connected to either the gearbox (parallel), planetary gearbox (power-split), or motor torque coupling (series).

All three configurations contain the following components:

- Electric machine: the electric power is a function of speed and torque.
- Engine: the fuel rate is a function of speed and torque.
- Battery: the open-circuit voltage as well as the internal resistance are functions of battery SOC. Knowing the output power of the battery, the current can be calculated by using Equation 4:

\[ I_{ess} = \frac{P_{ess}}{V_{oc}} - \frac{R_{int} \, P_{ess}}{V_{oc}^2} \quad (4) \]

Equation 4 is an approximation that avoids the use of the computation-intensive square root operation. The variation of SOC is given by Equation 8.

- Torque couplings: constant efficiency.

Figure 2, Figure 3, and Figure 4 illustrate the models. Arrows represent the flow of power, not the computation path. The physical entities associated with the flows represent the variables that are exchanged between components. Mechanical flows are speed and torque, while electrical flows are power-based.

The parallel pre-transmission configuration also contains a multi-speed gearbox. The torque losses are a function of the gear, the input speed, and the input torque. An actual vehicle includes a clutch between the engine and the gearbox, thus allowing a decoupling of the engine and electric machine speeds when the engine is off. When no torque is requested from the engine, the engine is considered to be off and its speed \( \omega_{ice} \) is null. In the contrary case, its speed is the same as the electric machine and gearbox input speeds \( \omega_{ice} = \omega_{em} \).

![Figure 2: Parallel Configuration Model](image-url)
In the power-split, the planetary gear is used to combine the outputs of the engine and both electric machines. The speeds (resp. torques) are related by Equation 5. (resp. Equation 6):

$$\omega_{eng} = \frac{N_R}{N_s + N_R} \omega_{tc} + \frac{N_s}{N_s + N_R} \omega_{em2}$$  \hspace{1cm} (5)

$$T_{gb} = \eta_{gb} \left( \frac{N_R}{N_s + N_R} T_{eng} + T_{tc} \right)$$  \hspace{1cm} (6)

**GLOBAL OPTIMIZATION ALGORITHM**

**COMMAND AND STATE** - A hybrid system can be considered as having two degrees of freedom: engine speed and torque. For the parallel configuration, the engine speed is defined by the gear ratio and the vehicle speed. In that case, the command is engine torque and gear number. In the case of the series and the power-split configurations, the transmission is continuous; the command should ideally be torque and speed, but doing so would result in too many combinations to consider. Therefore, the command for the series (resp. power-split) is the generator electric power (resp. engine power). The generator set (resp. engine) is assumed to operate along its best efficiency line. For a given generator electric power (resp. engine mechanical power), the engine speed and torque are such that the engine fuel rate is minimal.

For all configurations, the operating points of the other components can be known by using the models described previously.

We define the state of the system as the battery SOC. To keep the computation feasible, no transients are considered, and commands are assumed to be realized instantaneously. The SOC is, therefore, the only state.

**COST FUNCTION AND STATE EQUATION** - The optimization problem aims at finding the command $u$ and the resulting states that minimize the cost function $J$ defined in Equation 7. It is the sum over the cycle of fuel power $P_{fuel}$ and a penalty function $P_{pen}$ used to penalize aggressive changes in the command. In other words, we look for a command that will minimize the fuel use, while resulting in acceptable components behavior.

$$J(SOC, u) = \int_{0}^{t_{end}} (P_{fuel}(SOC, u, t) + P_{pen}(u, t)) dt$$  \hspace{1cm} (7)

The time derivative of the SOC is proportional to the battery current; state and command are linked by the state Equation 8. Further details can be found in [14,16].

$$\frac{dSOC}{dt} = - \frac{l_{ess}(P_{ess}(u, SOC))}{Q_{ess}}$$  \hspace{1cm} (8)

**PENALTY FUNCTION** - The cost function described in Equation 7 contains a penalty factor. Penalty factors are necessary because the output of the global optimization is limited to one set of commands, and any other command that is in the vicinity of the optimum is lost. In other words, among the numerous controls that lead to the minimum or quasi-minimum fuel use, only one is saved. To obtain the one that makes more sense from a real-world controller point of view, a penalty function can help the algorithm to converge toward a solution that
results in quasi-minimal fuel consumption but with different operating points. Because transients are the most sensitive point in hybrid controls, engine starts and gear shifts have to be minimized. The penalty function adds a constant energy to the cost function every time there is a change in the engine or gearbox state. The tuning of the penalty function is done manually on one selected cycle in such a way that the fuel use stays very close to the true optimum, while the number of engine starts is reduced. Those penalties can be interpreted as physical losses that actually occur in the real world. Every time the engine starts, there is an excessive use of fuel to make it start properly, and every time there is a shift, there is a temporary loss of torque transmitted to the wheels, for which the driver may counter-react, leading to unnecessary use of excessive power.

CONSTRANTS - The initial condition is a SOC value between the maximal and minimal limits, respectively, 91% and 25%. Furthermore, the system has to operate under several constraints:

- Vehicle follows cycle vehicle speed;
- Final SOC is 30%;
- Engine and electric machines operate within their speed and torque limits;
- SOC stays between the upper and lower bound defined previously, and
- Battery current stays between the maximal discharge current (>0) and the maximal charge current (<0).

At each time step, all combinations of state and command are looked at. Any combination that results in the component torque, speed, or power being out of bound is removed from the list of possible combinations.

EXECUTION OF THE ALGORITHM - The algorithm, written in Matlab, is based on Bellman’s principle, which states that any sub-trajectory of an optimal trajectory is itself optimal for the optimization problem having that sub-trajectory starting point as the initial condition. The final SOC is set by the user, and it is always 30%. From there, following the cycle backwards, at each time step t, the cost function and the optimal state at time t + 1 are calculated for all possible combinations of states and commands. Only one command per state is saved – the one that minimizes the cost function from t+1 to the end. Once the beginning of the cycle is reached, another calculation, this time forward, is necessary in order to build the optimal control time step by time step, starting from the initial SOC, also defined by the user.

However, because at each time step every possible state (i.e., SOC) is looked at, at time t = 0, the optimal next state is known for each SOC. Therefore, in the forward calculation, not only the path for one selected initial SOC is computed, but the path for all other initial states as well. With little additional computation, the initial SOC, and thus the degree of depletion of the battery, can be used as a parameter of the optimal control, the influence of which can be analyzed. The “charge-sustaining” control is one particular case in which the initial SOC is the same as the final SOC (null electric consumption).

TIME, STATE, AND COMMAND QUANTIZATION - The actual implementation of the algorithm requires the quantization of time, command, and state. Indeed, at each time step all combinations of command and state are investigated. A trade-off between precision and computation intensity has to be made.

Time sampling impacts the calculation of the force required to propel the vehicle at the desired speed because it is calculated by using the derivative of the speed, as given by Equation 1. Figure 5 shows that different time steps can lead to 6% more power required to propel the vehicle and 7% less available braking energy. A time step of 1 s results in up to 5% higher energy consumption in EV mode than a 0.5-s step, and significant differences in operating points.

The optimization results are sensitive to the SOC sampling as well. The variation in SOC, as calculated by Equation 8 has to be rounded to the closest multiple of the SOC step. More precisely, it is the resulting SOC at the following time step that has to be one of the points of the SOC grid, for which the calculation of the optimal path to the end has already been done (as the computation starts from the end). A step that is too low may lead to rounding errors that will impact the final results. Equation 9, deduced from Equation 8 and the assumption that power is the product of the current by the battery nominal voltage, gives the equivalent electric power step.

\[
\Delta P \approx \frac{Q_{es} \cdot \Delta V_{es} \cdot \Delta SOC}{\Delta t}
\]

(9)

A time step of 0.5 s and a SOC step of 0.00005 (.005%) are equivalent to a power step of about 1.5 kW. We believe those values are the lowest in the published literature for such an application.
The sampling of the command (torque for the parallel, power for the series) can also affect the results. A sampling that is too coarse may skip operating points that would bring fuel savings. However, as there is no rounding involved, the results would still be realistic, though possibly not fully optimal.

For each configuration, the final choice of the sampling was done by analyzing the impact of each and by staying within the hardware memory limitations.

**OPTIMAL CONTROL**

The global optimization algorithm was applied to all three configurations on three EPA cycles: urban (UDDS), highway (HWFET), and LA92, which includes urban and highway portions and which is more representative of real-world driving patterns. Figure 6 shows the power split between the battery and the engine during the higher speed portion of the UDDS cycle. The initial SOC was 60%. The engine is ON during accelerations; during the stronger ones, the engine and battery work "together" at comparable power levels, while during milder ones, the engine is the primary source of power. Figure 7 and Figure 8, respectively, compare engine power and battery power for all three configurations. It is interesting to point out that the engine power follows similar patterns, and that most of the starts occur at similar moments, while there are some that are specific to either the parallel or the split configurations.

![Figure 6: Power Split on the 2nd Hill of the UDDS (driven distance = 7.5 mi, initial SOC = 0.6) for Parallel (left), Series (center), and Split (right) Configurations](image6)

![Figure 7: Engine Power during the 1st Hill of the UDDS (driven distance = 7.5 mi, initial SOC = 0.6)](image7)

![Figure 8: Battery Power during the 1st Hill of the UDDS (driven distance = 7.5 mi, initial SOC = 0.6)](image8)
Because the algorithm generates a large amount of data, it is important to use a more macroscopic analysis approach. As previously described, one run of the algorithm outputs results for all possible initial SOC, that is, for all possible electric consumption. It was shown in [16] that the electric consumption is an interesting parameter for analysis to look at macroscopic parameters — meaning one value per simulation (e.g., average engine power, fuel consumption). Since the electric consumption contains both the information of driven distance and battery depletion, it is a convenient parameter for comparison of different vehicles over different cycles and distances. In the following, we analyze the optimal control as output by the algorithm, without any implementation into a real-world controller.

Most rule-based hybrid controllers are designed around two core functions: deciding when the engine is started, and when in hybrid mode, how to split the power between the engine and the battery [19]. Figure 6 shows the power at the wheels above which the engine is ON 95 instances out of 100. Such a parameter can be compared with an engine ON threshold triggering an engine start in a rule-based control. For all three configurations, this parameter follows an increasing trend. At high depletion rates (high electric energy consumption), the engine starts at higher loads. That “engine start triggering” road load is similar for the power split and the parallel, while it is higher for the series configuration: at zero electricity consumption (i.e., charge-sustaining), it is 3.5 kW and 4 kW for the split and parallel, compared with 6.3 kW (50% more). When compared with the Toyota Prius control [19], those values seem low: the “engine ON power threshold” is around 7 kW at target SOC for the Prius. The algorithm, however, chooses to do less charging from the engine than on the Prius and to start the engine more often.

Some noise can be observed at high electric consumptions. This is because the parameters looked at are dependent on “engine is ON” events. As the electric consumption increases, the number of such events tends toward zero, and so does the size of the sample used for the calculation, which leads to noise-like results.

Figure 7 and Figure 8, respectively, illustrate the average engine efficiency and the average engine power when it is ON. Both parameters follow the same trends. In the parallel case, there is a clear increasing trend for both the engine power and efficiency, as higher loads allow the engine to operate in more efficient areas. The engine efficiency in the split configuration is higher and relatively constant, owing to the ability of the planetary gear to make the engine operate in efficient areas. The efficiency is, however, not as high as for the series (35% versus 35.8%) because a potential gain in engine efficiency would have resulted in worse overall system efficiency due to higher recirculation and/or charging rates. In the series configuration, the engine operates very closely to its maximal efficiency, and at a 16-kW level.
The series configuration also tends to have the engine charging the battery, as depicted in Figure 9, which displays the share of the total engine mechanical energy that is used to charge the battery. In charge-sustaining mode, more than 10% of the engine output is directed to the battery, as opposed to 6% for the split and 4% for the parallel. This can be explained by the fact that charging is not as much penalizing for the series as it is for the other two configurations. All the engine output has to be converted through the generator, whether it goes to the wheels or the battery. Directing the engine energy to charge the battery rather than to propel vehicle simply results in battery losses; first due to charging and second due to discharging. In the other configurations, the engine power does not have to be converted into electrical energy first to be used to propel the vehicle, but it does in order to charge the battery. Therefore, the motor losses (both ways) come on top of battery losses; in the best-case scenario, that is, assuming maximum motor/generator efficiency both ways (0.95 for the split using EM2, 0.935 for the parallel), that would add 10 to 15% losses in the generating path, which means additional gains in engine efficiency would not offset the induced conversion losses.

To summarize, in the parallel configuration, the engine power is mostly oriented directly to the driveline, especially when the use of the engine is low (or battery use is high). At higher electric consumption rates, the engine is started at higher road loads, leading to higher engine loads and increased efficiency.

In the series configuration, the engine is always operated at high efficiency and higher engine load. At low electric consumption rates, especially in charge-sustaining mode, it translates into battery charging from the engine and more electric-only operations.

The split configuration also achieves good efficiency, though not as good as the series’, independently from the battery depletion rate. There is, however, less battery charging from the engine.

### ENERGY CONSUMPTION

Figure 10 shows the trade-off between fuel and electricity use for one iteration of the UDDS, which is about 7.5 mi (12 km).

In electric-only mode, the series is the most efficient configuration, with 160 Wh/km — plug-to-wheel, that is, taking into account the charger efficiency. The transmission is only composed of the final drive and the torque coupling, which make it very efficient. In the power-split configuration, the planetary gearbox (98% efficiency) creates additional losses and explains the slightly higher electric energy consumption (169 Wh/km). The parallel configuration consumes more electric energy (195 Wh/km) because of its transmission, the average bidirectional efficiency of which is 88%. It is slightly compensated by a better motor efficiency: 89.2% versus 87.5% for the series and 87% for the power-split.

In charge-sustaining mode, the parallel configuration appears to be the most fuel efficient (4.1 L/100 km). The series configuration is the least efficient (4.5 L/100 km) due to the inherent inefficiency of the hybrid transmission, as the engine output power is first converted into electrical power by the generator before being converted back into mechanical power by the motor. The efficiency of the path between the engine and the input of the final drive is at best $\eta_{em2} \times \eta_{em1} \times \eta_{cc} = 85\%$ — that is, assuming both electric machines work at peak efficiency and there is no battery buffering. It is actually lower than 80%. The power-split configuration’s fuel consumption (4.3 L/100 km) is slightly worse than the parallel one because of the inefficiency induced by the recirculation.

Figure 11 summarizes the fuel and electricity consumption for various cycles and distances driven. Electric-only mode can be achieved only on one UDDS cycle, which is 12 km; the highway cycle indeed requires more energy than the UDDS and is about 10 miles (16 km) long, which is the AER on the UDDS cycle.
while the LA92 cycle is even more energy intensive and contains power demands that cannot be met by the electric system only. The observations made on the UDDS can be extended to other cycles; that is, the series configuration is more efficient when the operation tends to electric-only. In charge-sustaining mode, the difference between the parallel and the split is reduced as well, while the series configuration is consistently less fuel efficient.

CONCLUSION

This paper presents a methodology to fairly compare different PHEV configurations. First, three vehicles, respectively, parallel pre-transmission, one mode power split, and series, were sized with an automated routine that uses PSAT. Each vehicle meets the same requirements in terms of acceleration, grade, and AER range, making them comparable from the end-user point of view. The three configurations were implemented in the form of a backward-looking model into a global optimization algorithm based on the Bellman principle. For a given trip, for a given initial and final battery SOC, such an algorithm outputs the set of commands that minimize the fuel consumption. In other words, each vehicle is operated optimally, thus taking out of the comparison any bias introduced by non-optimal controls.

The analysis of the optimal control showed that in the parallel configuration, engine power goes to the wheels when it is on, even if it means not operating the engine at its peak efficiency. On the other hand, in the series vehicle, the engine operates close to its peak efficiency, and the engine average load is not dependent on the electric consumption, leading to higher rates of charging from the engine. The power-split configuration operations are in between those two configurations. The parallel pre-transmission gets better fuel consumption in charge-sustaining mode than the series and the power-split, although the difference with the latter tends to decrease as the driving cycle is more aggressive. When the vehicle is driven mostly relying on electricity, the series configuration is a better option, closely followed by the power-split, because it is very similar to an electric vehicle. The choice of configuration, therefore, depends on the trips that will be commonly made with the vehicle, and mainly on the distance of those trips. If most of the trips fall close to the designed AER, most of the motion can be produced from the electric energy stored in the battery, and the series configuration is the most efficient configuration. On the contrary, if most of the trips far exceed the AER or are not done with a fully charged battery, the parallel configuration is more suitable. The power-split configuration is a possible trade-off between the two previous configurations. These findings are valid in the global optimization context in which each vehicle is operated optimally; in the real-world, however, it may be harder to achieve such conditions for some configurations than for others.
The study does, however, provide a good theoretical benchmark.

Future research will focus on applications of this theoretical tool in real-world oriented controllers, the ultimate goal being the optimal operation of the vehicle.

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CONTACT
Dominik Karbowski
Center for Transportation Research
Argonne National Laboratory
1-630-252-5362
dkarbowski@anl.gov

Aymeric Rousseau
Center for Transportation Research
Argonne National Laboratory
1-630-252-7261
arousseau@anl.gov

ACRONYMS, ABBREVIATIONS

AER All-Electric-Range
EM Electric Machine
EM1 Electric Machine 1 (also called motor)
EM2 Electric Machine 2 (also called generator)
ESS Energy Storage System (Battery)
HEV Hybrid Electric Vehicle
HWY Highway cycle
ICE Internal Combustion Engine
PHEV Plug-in Hybrid Electric Vehicle
PSAT Powertrain System Analysis Toolkit
SOC State-of-Charge
TC Torque Coupling
UDDS Urban Dynamometer Driving Schedule
ΔP Equivalent electric power step
ΔSOC SOC step
Δt Time step
η_{gb} Planetary gear efficiency
η_{em1} Electric machine 1 efficiency
η_{em2} Electric machine 2 efficiency
η_{tc} Torque coupling efficiency
ρ_{air} Air density
ω_{em} Electric machine speed
ω_{gb} Gearbox output speed
ω_{ice} Engine speed
ω_{tc} Torque coupling output speed
A_{fr} Frontal area

C_d Coefficient of drag
C_{R1}, C_{R2} 1st and 2nd order rolling resistance coefficients
F_{veh} Propelling vehicle force
F_{drag} Aerodynamic drag force
F_{roll} Rolling resistance force
I_{ess} Battery output current
J Cost function
m_{veh} Vehicle mass
N_{s} Number of sun teeth
N_{r} Number of ring teeth
P_{acc} Accessories electric power
P_{elec_{em}} Electric machine electric power
P_{fuel} Engine input (or fuel) power
P_{pen} Penalty function
Q_{ess} Battery capacity
R_{int} Battery internal resistance
t Time
t_{end} Time at end of cycle
T_{em} Electric machine torque
T_{gb} Gearbox output torque
T_{ice} Engine torque
T_{tc} Torque coupling output torque
u Command
V_{oc} Battery open-circuit voltage
V_{nom_{ess}} Battery nominal voltage
v_{veh} Vehicle linear speed