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EFFICIENCY OF AN OFF-ROAD HEAVY-DUTY SERIES HYBRID DRIVE BASED ON A MODIFIED WORLD HARMONIZED TRANSIENT CYCLE

Summary. As electric drives slowly replace passenger cars and light special vehicles, electric drives in the heavy-duty road sector have started to emerge. As for off-road vehicles, there is some effort to reduce the amount of fossil fuel used. In this study, the series hybrid application for a heavy-duty tractor is investigated. Work conditions are described using modified worldwide transient vehicle cycle to evaluate the efficiency of an energy management system applied, as well as the overall vehicle performance and efficiency. As a result, in some test scenarios, smaller-than-expected energy outputs were identified and new ways to improve energy management were found.

1. INTRODUCTION

Although emissions certification started in the past century, humans are still fighting against air pollution. In the past decade, electric and hybrid vehicles have played a growing role in transportation fleets—not only regarding road vehicles but also marine and airborne vehicles [1]. As a result, off-road and special vehicles have also been improved to cause less environmental damage [2].

A similar technique as in passenger car testing can be applied to do research on the performance and emissions of a hybrid heavy-duty vehicle. As New European Driving Cycle or The Worldwide harmonized Light vehicles Test Procedure can be used for light vehicles, similar speed and time dependant cycles can be used on heavy vehicles. For example, research on energy management of a plug-in electric bus was based on a city cycle [3]. Public transportation also can be studied using schedules and routes [4]. Heavy-duty trucks and tractors are also tested using city or highway cycles, including the worldwide transient vehicle cycle (WHVC) [2, 5].

The worldwide harmonized transient cycle (WHTC) was developed in 2001 when the growth of transportation by heavy-duty road vehicles required more defined and universal means to control emissions [6]. A cycle was formed based on a statistical analysis of driving behavior and the use of heavy-duty vehicles worldwide. This cycle is called the WHVC and is time resistant compared to WHTC due to constantly evolving engine technology. However, since testing heavy-duty vehicles are more complicated than testing passenger cars, WHVC was modified into the WHTC cycle [7].

Since off-road tractors have different work properties than highway trucks, a default WHVC cycle does not show the real efficiency of off-road hybrid vehicles. In WHVC, there is a low-speed city part that consists of many stops and a highway part that consists of speeds too high for a tractor to reach. Usually, a tractor works at low speeds with some speed changes and stops for turns and backward driving. For this purpose, a modified WHVC cycle is proposed in this research.

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2. METHODOLOGY

A tool like WHVC should be used to evaluate off-road heavy-duty vehicles [5, 8]. As WHVC is based on recurring travel speed templates, fieldwork can also be described as a series of recurring speeds. The WHVC cycle was recalculated using acceleration that is specific to off-road high-load conditions to create the Low Speed I work cycle [9]. The result of this modification is shown in Fig. 1.

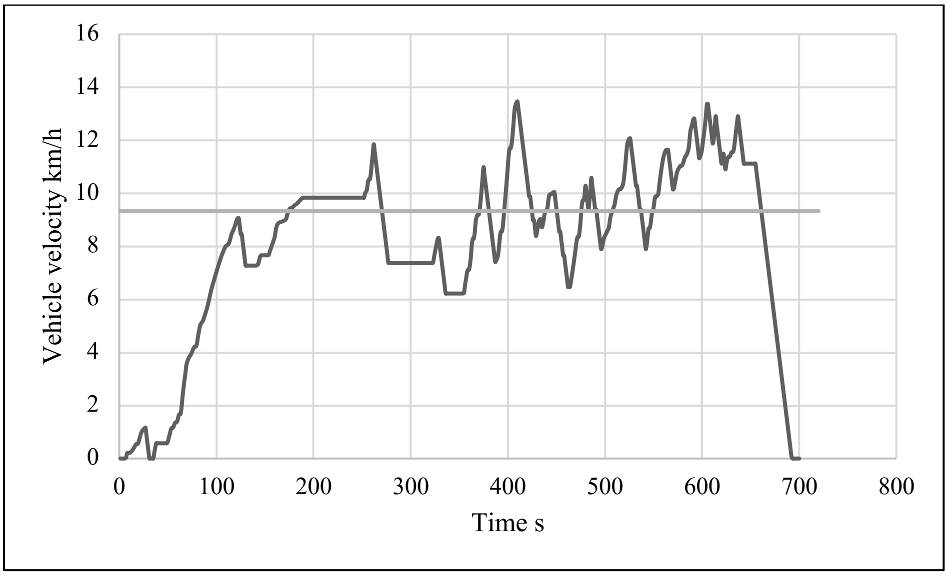


Fig. 1. Low Speed I work cycle

The course depicted in Fig. 1 describes 720 s of fieldwork with an average speed of 9.3 km/h and a maximum speed of 13 km/h as maximum speed. There are speeds of continuous work at 9.8 km/h, 7.4 km/h, and 6.2 km/h.

For this vehicle model, a series hybrid vehicle is used. In a series hybrid vehicle, an ICE and alternator are coupled into a single power unit that provides energy to run the transmission. In this case, this power unit supplies electricity to two separate electric motors (EMs) to run the axles independently. This application of the EM allows the gearbox to be dismissed and might help reduce vehicle weight and improve overall efficiency. In this study, vehicle models were developed using AVL Cruise software.

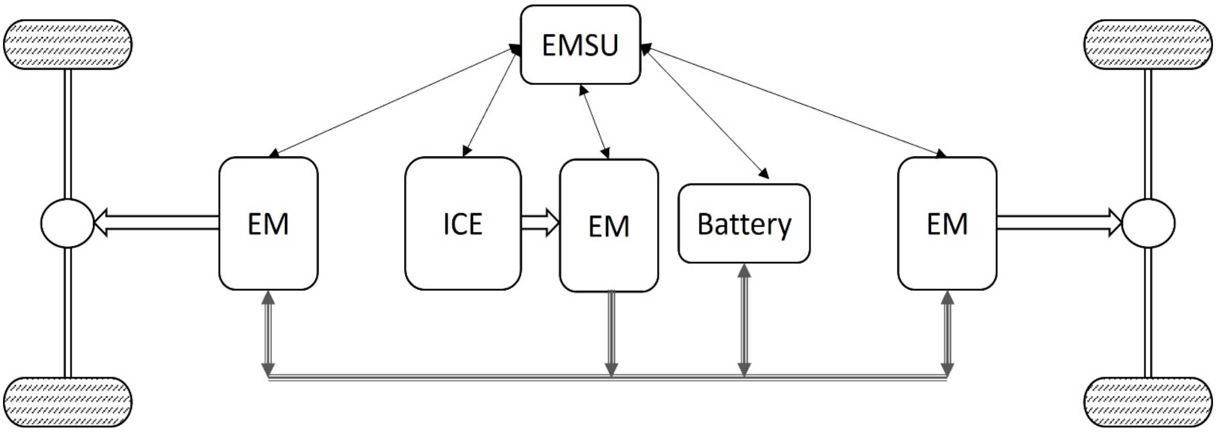


Fig. 2. Series-hybrid scheme

As shown in Fig. 2, there are mechanical connections only between the ICE and alternator and EM and differentials. All electrical energy provided by the power unit is either used by Ems or stored in the battery. EMs can also regenerate electrical energy by braking. Regeneration and supply modes are controlled by an energy management system unit (EMSU). Energy management systems are usually based on energy savings or emission reduction [10, 11], such that a hybrid model provides control with a smaller impact on performance. The EMSU considered in the present study was made using MATLAB Simulink. The characteristics of the power units used in this hybrid model are presented in Table 1.

Table 1

Main characteristics of power units

Cat 9 Acert ICE	
Displacement, l	8.82, Turbocharged
Power, kW / rated speed, rpm	254 / 2200
Torque, Nm / rated speed, rpm	1485 / 1400
Danfoss EM-PMI540-T1100-1200 Alternator	
Voltage, V	500
Current, A	242
Power, kW / rated speed, rpm	177 / 2400
Torque, Nm / rated speed, rpm	1410 / 1400
Danfoss EM-PMI375-T800-1300 Motor	
Voltage, V	500
Current, A	145
Power, kW / rated speed, rpm	122 / 2600
Torque, Nm / rated speed, rpm	828 / 1300

A coupled internal combustion engine and alternator power unit features similar power and torque at rated speeds to maximize compatibility and efficiency. When an EMSU is used, the working properties of the ICE and alternator are adjusted to each other by keeping the alternator torque low to keep the engine at low speeds and maximize the power output at high speeds. Joint torque is shown in Fig. 3.

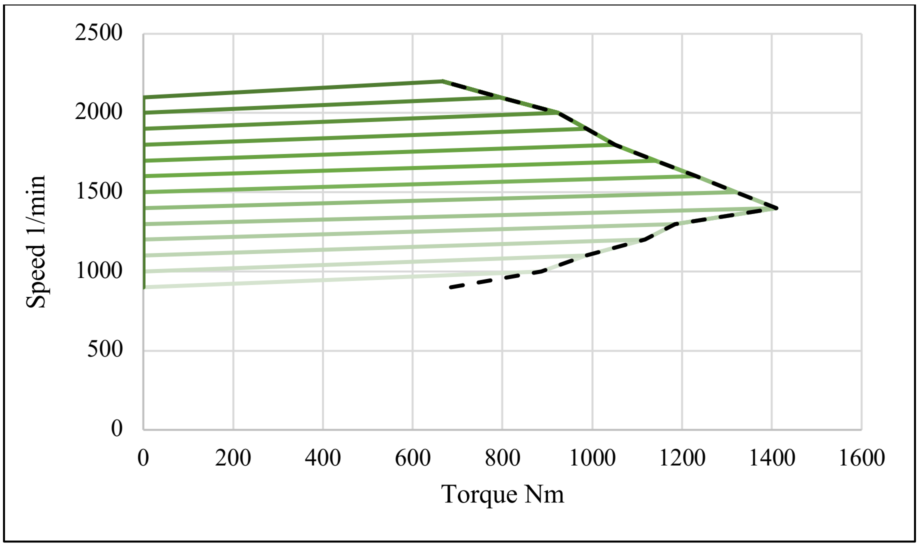
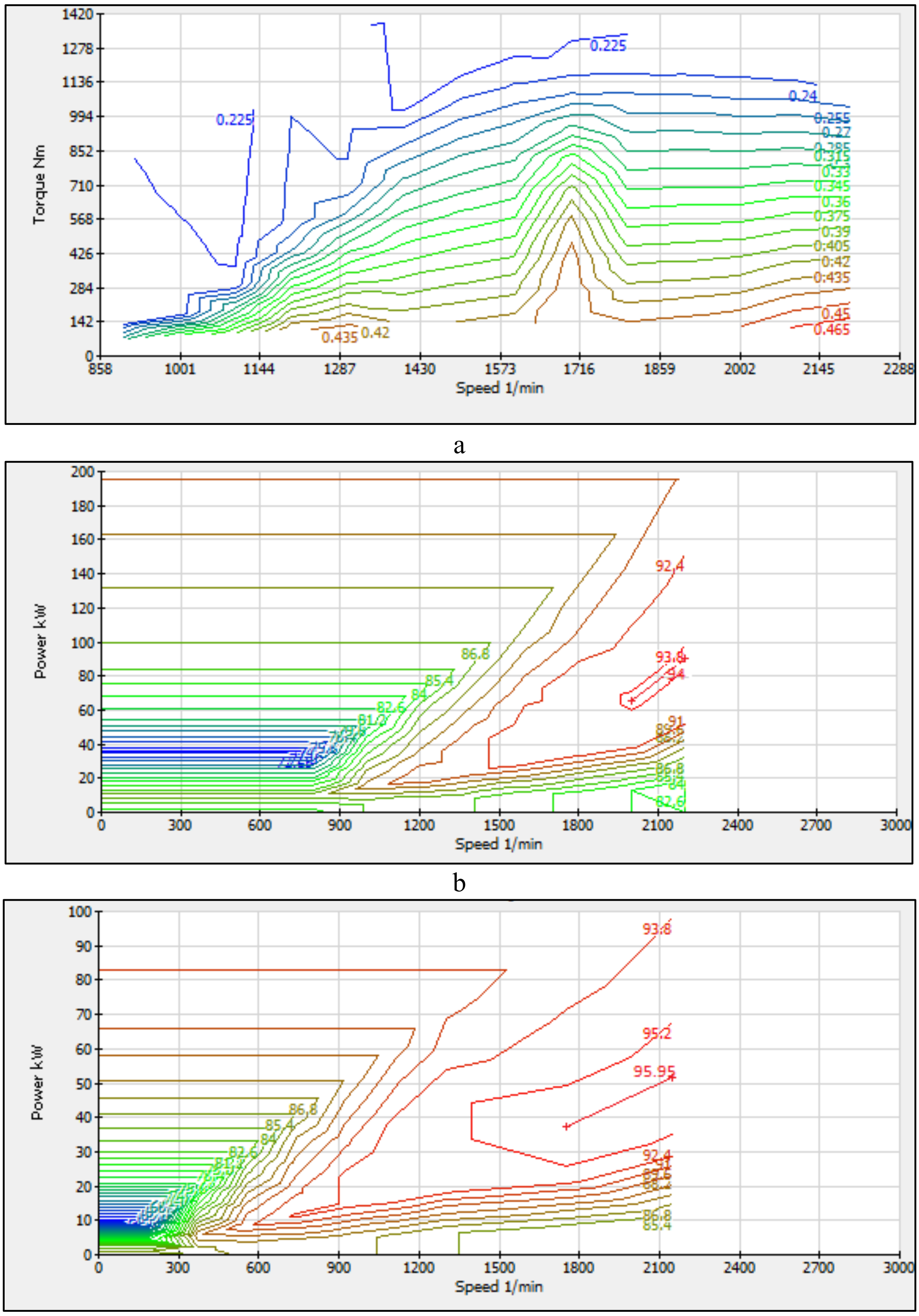


Fig. 3. Joint power unit torque

The dotted curve in Fig. 3 is the allowed torque of the ICE at a maximum load, which is 686 Nm at the lowest speed point, 1410 Nm at the midpoint, and 667 Nm at the maximum speed point. The optimal torque of the power unit was determined using an ICE break-specific fuel consumption (BSFC) map and an efficiency map of the alternator, which are presented in Fig. 4.

An ICE has the best fuel efficiency (Fig. 4 a) at low speeds (up to 1100 rpm) when working with higher loads and in the range of 1400 rpm to 1800 rpm under the same conditions. An alternator's maximum efficiency (Fig. 4 b) is slightly lower than that of a motor (Fig. 4 c), with a peak efficiency of 94% and 96%, accordingly. However, because an EM also works at significantly lower speeds than an alternator, the overall efficiency of a motor might be lower.



a

b

c

Fig. 4. a – BSFC map, b – alternator efficiency map, c – motor efficiency map

The efficiency of a hybrid drive under off-road work conditions is determined by evaluating the performance of a heavy-duty vehicle under relative work conditions, such as workload and the state of the track. Vehicle parameters are described in Table 2.

Three workloads are considered, with an added weight of 1400 kg, making the overall load on the tires 140 kN and 3400 kg to 160 kN and 5400 kg to reach the maximum load allowed (i.e., 180 kN). The state of the track is described using the friction coefficient and rolling resistance coefficient (RR), which are specific to certain types of terrain [12]. The variables used in model test runs are described in Table 3.

Table 2

Vehicle parameters

Mass (empty), kg	12600
Mass (full load), kg	18000
Maximum speed, km/h	40
Final gear ratio, -	28
Tires	900/60 R38

Table 3

Test variables

Workload			
#		Load, kN	
1		140	
2		160	
3		180	
Terrain			
#	Type	Friction Coeff.	Rolling Resistance Coeff.
A	Grassland	0.75	0.04
B	Seedbed	0.60	0.09
C	Tilled Loam	0.60	0.15

Nine test runs were made using AVL Cruise software with the Matlab interface; every workload was run on every type of terrain.

3. RESULTS

For each test, an EM must overcome different loads while maintaining the same rotating speed. This condition leads to multiple work zones in the efficiency map (Fig. 4 c). The efficiency of an EM during the course is shown in Fig. 5.

The efficiency of an EM correlates with rolling resistance and the workload (Fig. 5). The results are presented in order and then compared by load, starting from A to C. However, while the efficiency of a motor has a strongly expressed congruence to workload, it diminishes compared to rolling resistance. There is a noticeable difference of 7% between the highest and lowest RR while maintaining the same maximum wheel load; however, it merges at the lowest workload. The 7% difference in EM efficiency translates to about a 5.5-kW difference in power loss, as shown in Fig. 6.

The correlation between power loss and a workload appears only on terrain with high rolling resistance (Fig. 6). The load on wheels does not seem to affect the work of an EM at lower RR, but the correlation between power loss and RR is direct.

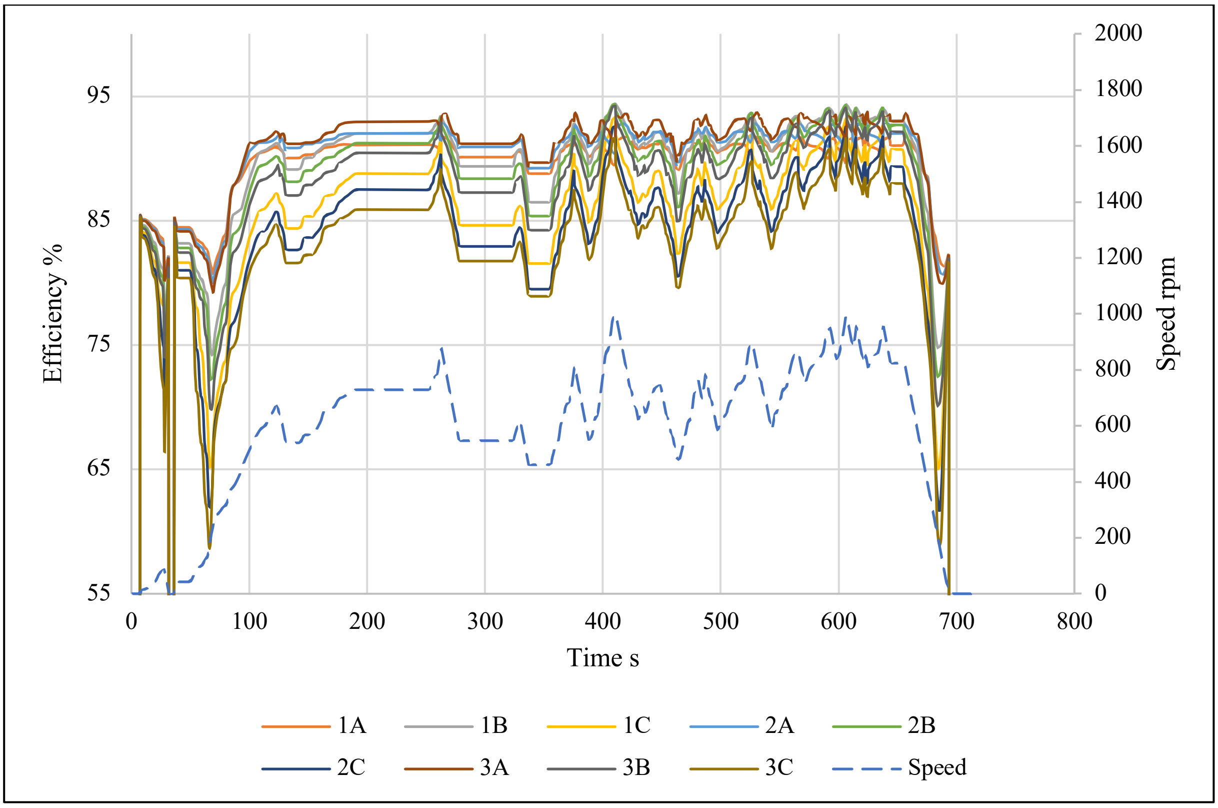


Fig. 5. Efficiency of an electric motor during the test course

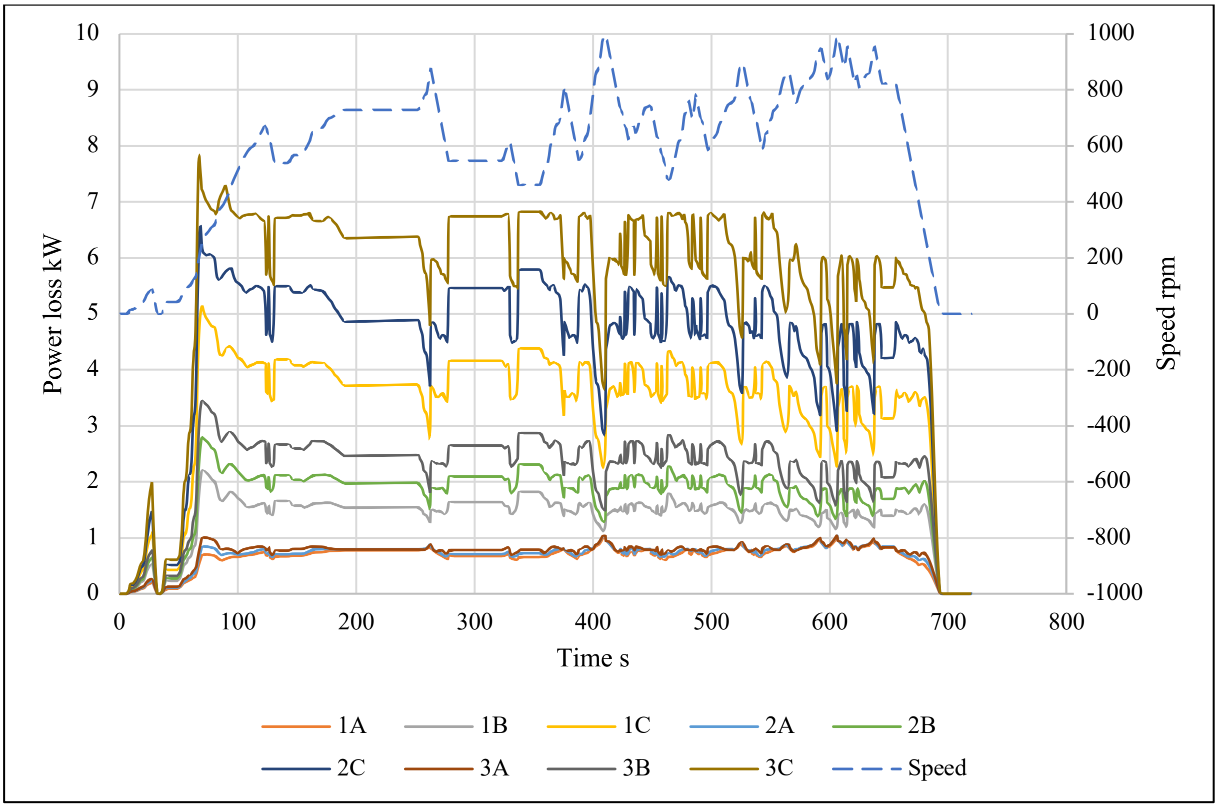


Fig. 6. Power loss of an electric motor during the test course

During a complete course, the power loss of a battery slightly decreases, as shown in Fig. 7. It is higher than the power loss of an electric motor on a smooth terrain independent of workload but seems to be steady compared to EM, for which power loss drastically increases.

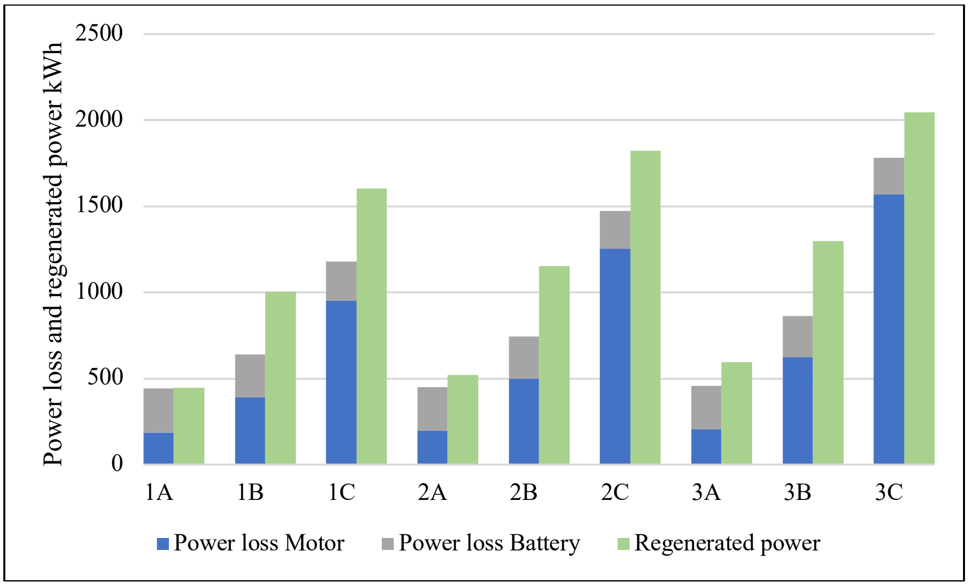


Fig. 7. Power loss and regeneration

Brake regeneration compensates for power losses in the electric drive in all test runs. The highest percentage of regeneration was reported for test B (this percentage was over 50% greater than power loss), followed by tests 1C (36%) and 3A (30%). Regenerated power increased compared both by workload and terrain. The higher resistance, the more energy recovered. The amount of power regenerated during the course was over 30% of the power output of EMs in three of four test runs (Fig. 8). In test run 3C, 2.84 kWh of energy was recovered from the 10.68 kWh of energy consumed (about 29%).

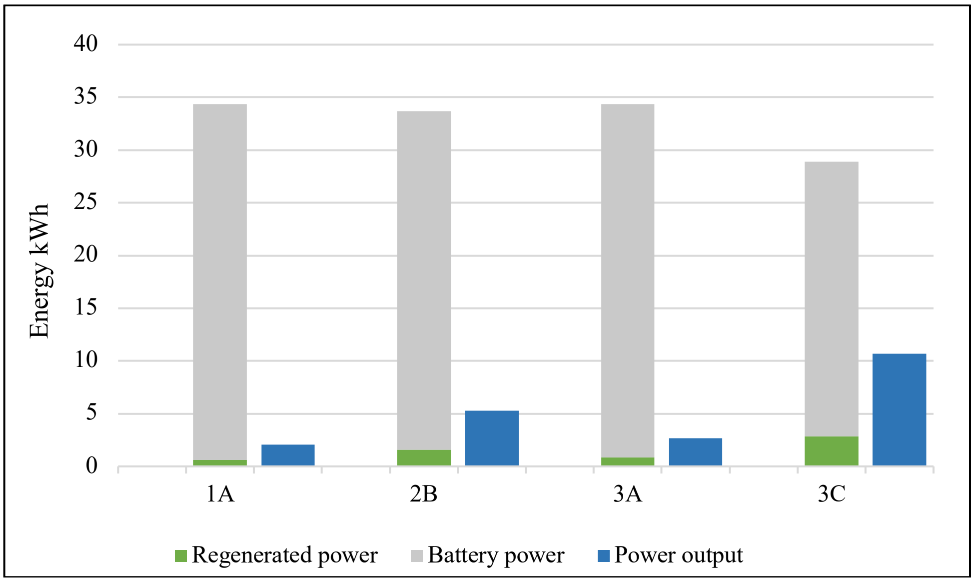


Fig. 8. Energy generation, output, and regeneration

As depicted in Fig. 8, the power unit generates more power than EMs consume during the course. As a result, battery stored energy can be used to run the same cycle at least two times without a working power unit in test 3C. In test run 2B, there was six times more stored energy than required for the run. In scenario A, the power unit could be turned on course loop 10 or even less frequently. However, since test runs require little power, and energy waste can occur at the end of a run due to battery overcharge (Fig. 9).

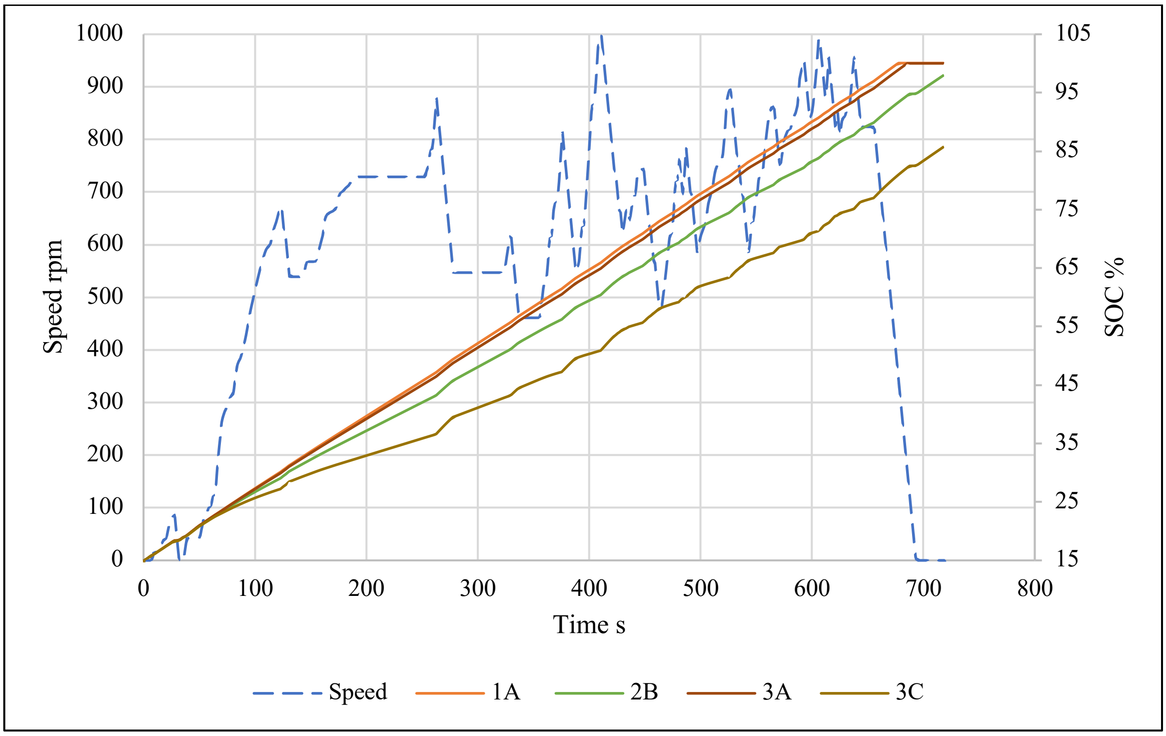


Fig. 9. Battery state of charge

With an initial state of charge (SOC) of 15% in test runs 1A and 3A, a full charge is reached before the vehicle fully stops and the cycle ends (Fig. 9). As a result, not all regenerative braking energy is stored. In these scenarios, regeneration is not apparent since a small amount of energy is recovered compared to production (Fig. 8). The opposite condition of test run A is test run 3C, in which the surge of the SOC is visibly affected by regeneration.

4. DISCUSSION AND CONCLUSIONS

Since an alternator is operated by an ICE, its efficiency stayed at about 84% during the complete test. As a result, the efficiency of an electric drive during steady-state work conditions was 63–65% for the course with the highest efficiency (3A) and 55–60% for the course with the lowest efficiency (3C).

The efficiency of electric motors cannot be changed; however, the efficiency of an alternator can be improved by reducing the power of an ICE, especially in low-load courses, in which case the battery charge is full. In this case, even if less energy is generated, a similar amount of energy might be stored due to the higher generator efficiency.

Also, using a series hybrid drive brings the benefit of brake regeneration, which, in this study, completely compensated for the power losses of power users. It can be stated that brake regeneration can be most useful on rough terrain by relying less on workload.

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