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Hybrid drivetrain systems 48 V in rally cars

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This article deals with the issue of using a 48 V hybrid drive system in rallying. Conclusions regarding the selection of elements of the above-mentioned system for further reasearch were presented. An analysis and calculations of the energy recoverable from regenerative braking using the BISG on a given section of the rally were carried out. Conclusions were also drawn regarding further work that will be carried out to successfully implement the above-mentioned systems for rally cars.

Key words: *hybrid drivetrain, mHEV, 48 V, regenerative braking, car rallies*

1. Introduction

The popularity of 48 V hybrid drivetrain systems is systematically increasing in modern cars. This is not without reason, given the very ambitious legal targets to reduce the emissions of CO_2 and other pollutants, their use is increasingly justified. Fuel consumption can be reduced by up to 20% compared to a car without this system [1–3]. The components of 48 V technologies are diverse and are constantly evolving, which allows them to implement the above-mentioned tasks in various ways. These are, for example a Belt Integrated Starter Generator (BISG), Crankshaft Integrated Starter Generator (CISG), which can both drive the internal combustion engine (ICE) and recover part of the braking energy, or electrically driven compressors (eBooster® [4]) supporting the work of the ICE turbocharger. An important advantage of the 48 V technologies is a very favorable relation between the costs of their implementation and the results obtained, compared to drive systems with a higher supply voltage or purely electric cars. Attention should be paid to the fact that 48 V is a safe voltage, which is not without significance when it comes to handling or using cars equipped with this technology.

In rallying, the competition takes place with the use of cars, the vast majority of which are to a lesser or greater extent based on mass-produced cars. For this reason, they are related to the current technological trends of the automotive sector. The consequence of this relationship are the activities of the International Automobile Federation (FIA), which realizes the strategy of implementing hybrid and electric propulsion systems for cars taking part in rallies. The first representation of this direction from the next 2022 season will be the Rally1 group [5]. These cars will be equipped with a 100 kW rear-axle mounted electric motor and a 3.9 kWh battery. The first presented Rally1 car was the Ford Puma Rally1, built by M-Sport, so the official Ford Motor Company rally team [6]. At the same time, it is planned to hybridize lower groups of rally cars. Therefore, consequently, subsequent groups, i.e. Rally2, Rally3 and Rally4, are also to be equipped with alternative drive systems. Due to the limited level of car modifications and much more cost-oriented thinking in these groups compared to Rally1 cars, they cannot be equipped with the same hybrid system. It must meet such conditions as: a significantly reduced level of costs, the possibility of retrofitting existing rally cars, ensuring operational safety with relatively easy to implement procedures.

The current work is based on discussions between the FIA and car manufacturers interested in participating in rallies. M-Sport takes part in the above-mentioned discussions and conducts internal research of possible solutions in their rally cars. One of the most important findings so far is the supply voltage of these hybrid systems, i.e. it was defined at 48 V. The final cost limit and the selection of components in the 48 V technologies still remain to be determined. Aspects such as the development of the system operation strategy are also important issues and, consequently, the determination of the battery capacity. In motorsport, it is also necessary to pay attention to the increase in weight of the car, as it directly affects the decrease in the performance. At the present stage of works, it is assumed that the applied system will increase the car's performance and reduce the emission of harmful substances. Following functions of the 48 V components are discussed:
- Recovery of braking energy,
- ICE support in transient states by means of an electric motor or electrically driven compressor.

2. Hybrid drivetrains 48 V

The possibilities offered by the 48 V technology include partial recovery of previously irretrievably lost braking energy, or ICE support, especially in transient states. Although the approach differs, the goal is one – to implement a technology that will reduce fuel consumption and improve ICE performance at a reasonable cost level.

48 V hybrid drivetrain systems are implemented in many different forms. Possible variants of integration of these systems with the car are presented in Fig. 1. It shows four currently known combinations of connecting the electric motor with the car propulsion system [1]:
- P0 – to the internal combustion engine through the accessories belt,
- P1 – to the internal combustion engine through the crankshaft,

– P2 – to the gear input (disconnection from the combustion engine possible),
– P3 – to the gear output through gears (disconnection from the combustion engine possible),
– P4 – to the rear axle drive system (no connection to the internal combustion engine).

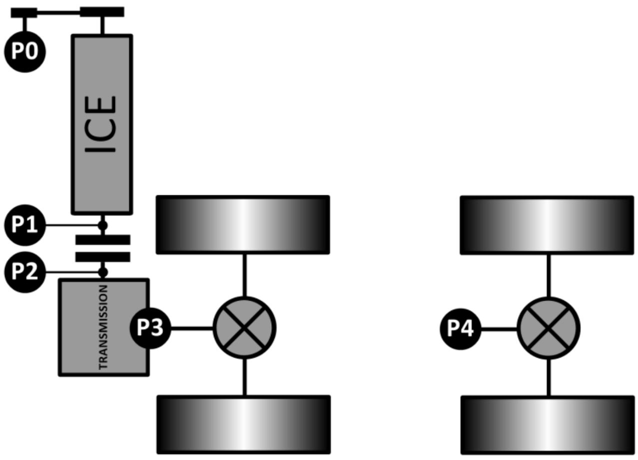

Fig. 1. Possible variants of the 48 V hybrid drivetrains in the car

The P0 configuration, the main element of which is BISG, was adopted as the first choice for a broader analysis.

2.1. BISG

The choice of the P0 configuration is not accidental. An important argument when implementing 48 V technologies is, above all, the ease of its integration with both new and existing rally cars. When choosing BISG, it is not necessary to redesign the driveline and all the integration work will focus on the ICE accessory drive. It should be added that in the case of configurations other than P0, the problem would be to find parts from series production that are universal enough to be able to integrate them without significant interference with other car systems. Another advantage of BISG is their relatively good availability on the market, which is the reason for their more and more frequent use in mass-produced cars. It should be noted here that both the FIA and other manufacturers participating in the discussions about hybrid rally cars prefer to use as many parts from series production as possible. To sum up, the lack of flexibility with possible integration with the car, higher costs and currently low popularity of configurations other than P0 in mass-production mean that they will not be analyzed at the moment. This is aimed at reducing implementation costs by using existing components, as well as increasing R&D and marketing potential by using serial parts under extreme rally conditions. In the Rally1 car, a dedicated hybrid system in the P3 configuration was used, however, in this group, the cost of building the car and its operation is at a much higher level. BISG can perform the following functions [1]: engine starting, generating electricity, supporting the ICE in various situations, and as a result, it also allows extending the operation of start-stop systems through the so-called sailing [3]. BISG with a power of up to 13 kW of maximum motor power and up to 7 kW of continuous motor power is assumed o use and such systems are now available on the market [2].

2.2. Electrically driven compressor

To further increase the benefit of a 48 V installation, an electrically driven compressor is contemplated. One such solution is eBooster® [4]. Its operation is based on a complementary action in relation to the ICE turbocharger, thanks to which in states of high demand for torque, it significantly reduces the ICE response time. In addition, it was confirmed in tests that eBooster® improves acceleration time by about 18% compared to the car without it and by 3% compared to the version with BSIG while consuming less than half of the electricity [4]. Rally cars use internal combustion engines with relatively small displacements, i.e. between 998 cm^3 and 1620 cm^3. It is required by the FIA regulations, which at the same time reflect the current trends of the automotive sector. With the assumption of obtaining high output parameters of these engines, it is necessary to use turbochargers with high efficiency. This causes a delay in the operation of the turbocharger, especially at low and medium ICE speeds. To prevent this, the Anti Lag System (ALS) is used, which ensure a quick response of the turbocharger in transient states, but also increase fuel consumption and can increase the engine operating temperature and reduce the durability of the turbocharger. An electrically driven compressor can potentially replace the ALS system and thus its disadvantages will be eliminated. Taking into account the above benefits, the ease of integration with the car and the complementary operation of the above-mentioned system with a 48 V system, its use will be further analyzed for use in a rally car.

2.3. Diagram of the analyzed 48 V hybrid system

The configuration of the 48 V hybrid drive system intended for further analysis for use in the Rally2, Rally3 and Rally4 rally cars is shown in Fig. 2. Similar solutions have already been tested with good results for use in production cars [4, 7]. This system consists of the following 48 V powered components:
– BISG,
– Electrically driven compressor.

Additionally, components of the 48 V system (not shown in the diagram) are:
– 48 V battery,
– DC-DC converter.

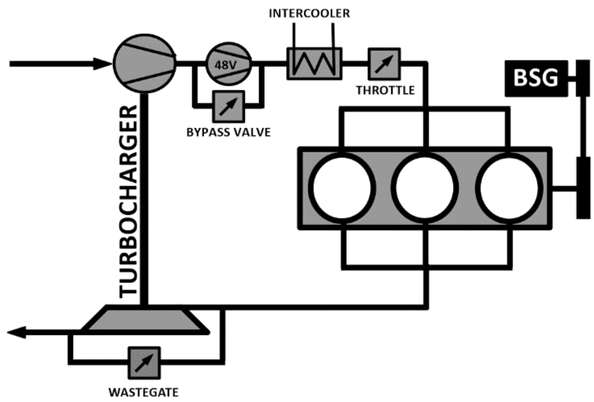

Fig. 2. Diagram of the analyzed 48 V hybrid system

3. Characteristics of the car

The Ford Fiesta ST Rally3 is a rally car that is being analyzed for the use of 48 V hybrid drivetrain. The car is presented in Fig. 3.

Fig. 3. M-Sport Poland Ford Fiesta ST Rally3

It is a rally car designed and manufactured by the M-Sport Poland company. Table 1. presents the basic technical data of the above-mentioned car.

Table 1. Basic technical data of the Ford Fiesta ST Rally3

Parameter	Unit	Value
Weight of the car	kg	1210
Engine type	–	turbocharged, petrol
Number of cylinders	–	3
Displacement	cm^3	1496
Maximum power	kW	158 (FIA 30 mm restrictor)
Maximum torque	Nm	400
Drivetrain	–	constant four wheel drive
Transmission	–	five speed sequential gearbox

5. Analysis of the car rally section in terms of energy that can be recovered by BISG

A rally consists of both Special Stages (SS), which, as defined by the FIA, are timed speed test on roads colsed to the public for the rally and Road Sections, which are the parts of an itinerary which are not used for SS [8]. From the point of view of the analyzes carried out, the most important are the SS, because there the actual sports competition takes place and the system analyzed will be used.

The first stage of further work was to calculate the energy that can be obtained by regenerative braking using BISG, analyzing for this purpose a section of the FIA ERC (FIA European Rally Championship). The rally section was analyzed, as it is assumed that between sections it will be possible to charge the 48 V battery of the hybrid system. This stage of the analysis is very important as further decisions regarding the capacity of the 48 V battery or the operating strategy of the systems depend on it. The rally section schedule is shown in Table 2.

Taking into account the above, the analysis of the possibility of energy obtained from regenerative braking on the SS was carried out. The calculation of the braking power and energy was performed using the data on the instantaneous value of pressures in the front and rear brake circuits stored in the car's data logging system. A rally with a gravel surface with high average speeds was selected to verify the worst case, i.e. with the lowest possible braking energy of the car.

Table 2. Rally section characteristic

Length of	Unit	Value
SS1	km	18
SS2	km	17
SS3	km	29

The calculations were performed by determining the pressure force of the pistons in the brake calipers, knowing their surface based on the measured value of the instantaneous pressure in the front and rear brake circuits. Then, the circumferential force on the active circumference of the brake discs was calculated taking into account the coefficient of sliding friction in the disc brake. The last step to calculate the total braking force F_B was to calculate the braking force on the dynamic radius of the tire, taking into account the active radius of the brake disc and the dynamic radius of the tire. The pressure in the brake circuits was measured with a constant sampling frequency, which allowed to record the instantaneous value of pressure every $\Delta t = 0.1$ s. For the road in the analyzed case, for the section where braking occurred, the braking work W_B was determined according to the relationship (1) (taking into account that $\Delta x \to 0$):

$$W_B = \int_0^1 F_B \, dx \tag{1}$$

The braking power was determined subsequently as below in (2) (taking into account that $\Delta t \to 0$):

$$\Delta P_B = \frac{\Delta W_B}{\Delta t} \tag{2}$$

where in (1) and (2): Δx – road increment, W_B – work of braking force, Δt – time increment, ΔP_B – instantaneous braking power.

The work W_B performed during braking is treated as the energy E_B needed to brake the car, which theoretically can be used for the BISG drive. The Figures 4–6 shows the braking power and vehicle speed from SS1, then on the next SS2 and SS3.

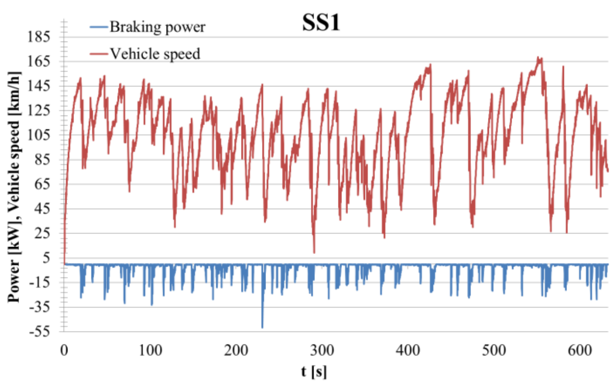

Fig. 4. Braking energy and vehicle speed during SS1

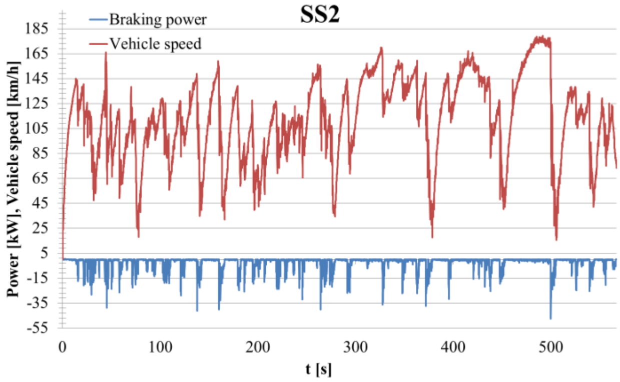

Fig. 5. Braking energy and vehicle speed during SS2

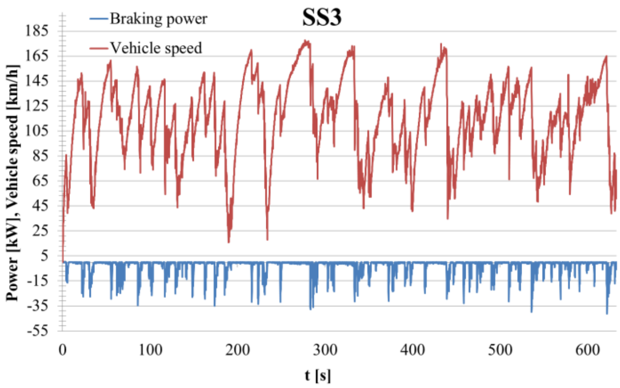

Fig. 6. Braking energy and vehicle speed during SS3

The maximum values of the braking power for each SS are presented in the Table 3.

Table 3. Maximum braking power in SS1, SS2 and SS3

Maximum braking power in	Unit	Value
SS1	kW	52
SS2	kW	48
SS3	kW	41

It can be assumed that when using BSIG, in which the maximum power of generating electricity is up to a maximum of 14 kW and in continuous mode up to 10 kW, the recovered energy will be much lower, because the calculated values of the maximum values of the braking power significantly exceed them. Another significant limitation when analyzing the ability to regenerate braking energy is the design of the 48 V battery itself and the maximum electric current that can be charged by the BISG. As it was researched the currents within the 48 V MHEV (Mild Hybrid Electric Vehicle) battery are significantly higher than in the BEV (Battery Electric Vehicle) with voltage usually around 400 V [9]. These high currents in the 48 V applications are serious challenge in terms of battery design.

Using data form the same SS, the braking energy was calculated, which is theoretically available for the application of regeneration braking, driving the BISG and thus charging the 48 V battery. The results are presented in Figs 7–9 for each of analyzed SS.

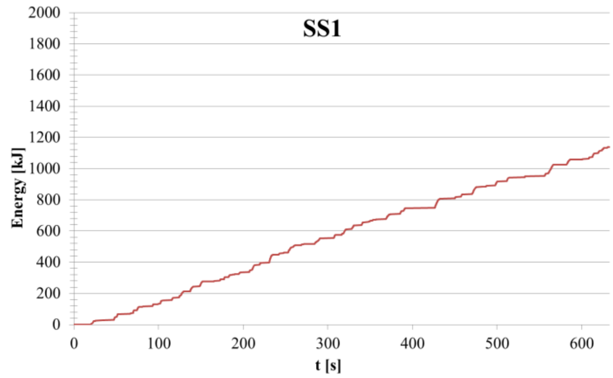

Fig. 7. Braking energy in SS1

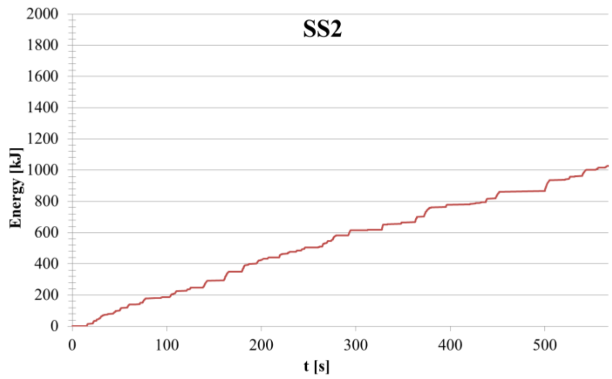

Fig. 8. Braking energy in SS2

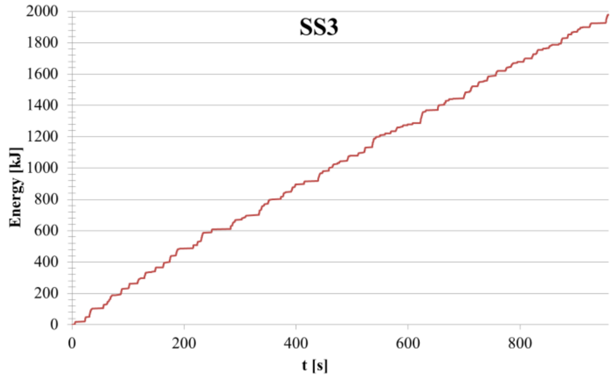

Fig. 9. Braking energy in SS3

In the above figures of the braking energy, only cases where the driver's foot was off the accelerator pedal were taken into account, i.e. at these moments the BISG system could perform regenerative braking.

Note that these are theoretical values as the following was not considered in this analysis:

– the resistance in the drive train while driving the BISG,
– the maximum possible power generated by BISG,
– the maximum electric current that the BISG can charge the battery with.

When analyzing the curves of these graphs, it can be noticed that there is a constant and continuous increase in energy generated as a result of braking. At the same time, it is good phenomenon considering the possibility of using regenerative braking in the rally, which can be a significant part of the energy possible for use in the 48 V hybrid drive system.

An attempt to answer what part of the determined theoretical braking energy is possible to recover was made on the basis of the previously conducted researches [2]. On their basis, it can be concluded that about 62% of the braking energy is recoverable and about 36% of this energy was recovered during these tests using BISG with parameters similar to the assumed ones. The conclusion from this is that a total of 1493 kJ would be recovered when driving the analyzed SS. This amount of energy would allow the BISG to be powered for 115 seconds in maximum power mode and 213 seconds in continuous power mode. Comparing this to the times obtained from all stages, the driver would be able to use the additional power generated by the BISG as shown in the Table 4.

Table 4. SS time percentage at which BISG or eBooster® can be used

Parameter	Unit	Value
BISG maximum power 13 kW	%	5.3
BISG continuous power 7 kW	%	9.8
eBooster® maximum power 5 kW	%	13

It should be noted here that the maximum power of BISG support, i.e. 13 kW, can only be generated for 5 seconds [2], so finally the percentage of the BISG support that can be used will fall between the two values listed in the Table. By analyzing the possibilities of using the recovered energy for eBooster®, the maximum power is 5 kW, its use would be possible for 295 s, and consequently the percentage of the eBooster® support in relation to the all SS distance is presented in the Table 4.

This discussion does not take into account the SOC (State of Charge) of the battery, showing only the potential for using the energy from regenerative braking. It can be concluded that the above-mentioned the results, assuming the use of a 48 V battery with a capacity properly matched to the characteristics of rallies, along with the possibility of charging them between sections, will be much better. Moreover in order to achieve even better parameters of the analyzed system possibility of use supercapacitors should be recognize to reduce peak battery current and handle with the high power during acceleration and capture more regenerative braking energy than with the battery itself [10].

6. Operation modes and equal competition

The use of a 48 V hybrid drivetrain system combined with regenerative braking creates completely new challenges in rallies as to the way they are used. The FIA is currently discussing this on the Rally1 group. Looking at FIA series such as Formula 1, WEC and Formula E, it can be concluded that planning kinetic energy recovery and its subsequent use during a race is an increasingly large part of the racing strategy. As an example of the importance of energy planning in motorsports where regenerative braking is used, the Formula E principle is that cars enter the race with 70% of the battery charge and the missing 30% must be recovered by regenerative braking during the race [11].

In the case of the 48 V hybrid drive system in the Rally2, Rally3, Rally4 groups, it is important to understand the following issues:

– a method of aligning systems coming from different manufacturers,
– regenerative braking mode or modes,
– BISG ICE support mode or modes,
– the operating strategy of an electrically powered compressor.

It should be assumed that each of the manufacturers involved in the creation of Rally2, Rally3, Rally4 cars with a 48 V hybrid drivetrain system will want to use components from their series-produced car models. For this reason, BISG, DC-DC converters and potentially electrically driven compressors will vary from one rally car to another. Taking this into account, the most advantageous element of the system, in order to equalize parameters between systems, is to develop a battery with specific, identical parameters for all. Determining battery parameters such as maximum voltage, capacity, charging/discharging powers (these parameters should be determined in relation to the capabilities of the BISG with the lowest power) will potentially allow limiting and, as a result, equalizing performance between systems from different manufacturers. Standardized battery parameters between different systems would create a real limitation in the use of BISG.

Regenerative braking modes must strive for maximum energy recovery, but also take into account the different conditions of the car's grip on the road and the driver's preferences. A more sophisticated brake-by-wire system can be used, where the braking signal given by the driver will then be processed and as a result will automatically decide whether to use traditional or regenerative braking and to what extent. When the brake-by-wire solution turns out to be too complicated and thus expensive, it is also possible to adopt a strategy that regenerative braking takes place with a constant predefined intensity and the braking force needed by the driver above it is obtained by activating traditional braking. In this case, it is necessary to define the number of predefined strategies and their intensity levels in order to cover as many variants of the car's grip on the road as possible.

The ICE assist mode of the BISG depends primarily on the decision to use an electrically driven compressor in the system. If used, then according to the research carried out and the logic of the ALS system, which must operate along the entire length of the SS, the electrically driven compressor would have priority in operation over the BISG. In other studies it was proved that the influence of an electrically driven compressor on the improvement of ICE characteristics in transients is more favorable than BISG, and this with lower energy consumption. In the event that the electrically driven compressor would not be finally applied, then the support of the ICE by the BISG would take on a much greater role. In such a case, it is necessary to define the method of turning on this support and define the limits of its use (e.g. the limit of energy during a single activation). The aim is that the use of this support should be evenly distributed over the entire length of the SS as far as possible.

The electrically driven compressor, intended to replace the current ALS system, would have to operate along the entire length of the SS, in line with the ICE's transient needs. The 48 V hybrid drive system must be configured so that it is possible to use an electrically driven compressor on all SS in the section between battery charges.

7. Conclusions for further work

The next steps to draw conclusions for discussion with the FIA regarding the implementation of 48 V hybrid propulsion systems should be to analyze the different operating strategies of the BISG and the electrically driven compressor and simulate the energy consumption by them in sections of different rallies. The pool of rallies analyzed should be as large as possible so that the conclusions drawn are consistent with the actual use of the system. Then, having the specified electric energy consumption and energy recoverable during regenerative braking, the parameters of a battery that meets the assumptions regarding the capacity and charging/discharging power should be determined. Then it will be possible to create a prototype of the system and start testing in conditions similar to real ones, which will allow validating numerical simulations as well as checking the durability of components in the extreme rally use.

Acknowledgements

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Nomenclature

ALS	turbocharger anti lag system
BEV	battery electric vehicle
BISG	belt integrated starter generator
CISG	crankshaft integrated starter generator
ERC	European Rally Championship
FIA	International Automobile Federation
ICE	internal combustion engine
MHEV	mild hybrid electric vehicle
SOC	state of charge
SS	special stage
Δx	road increment, [m]
W_B	work of braking force, [kJ]
Δt	time increment, [s]
ΔP_B	instantaneous braking power, [kW]

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