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Advisor Based Modelling of Regenerative Braking Performance of Electric Vehicles at Different Road Slopes

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Abstract

In this study, an electric vehicle model, which has 75kW AC asynchronous engine and 25kW Nickel-metal hydride (Nimh) batteries, has been composed by means of (ADVISOR-Advanced Vehicle Simulator) program. During the driving cycle formed for the designed electric vehicle, charging state of batteries, braking losses, battery temperatures and fuel consumption have been analyzed at different road slopes. The study has shown that power to batteries is provided by regenerative braking at all slopes and if the slope is downhill, more energy is stored into batteries due to regenerative braking. In simulation of the modelled device, maximum brake power loss of 4.43 kW has decreased at road slope of $\propto = -\%1.5$ by means of regenerative recovery. At road slope of $\alpha = -4.5$, the highest charging level has been obtained as 99.1%. With regenerated recovery, $\alpha = -4.5$, $\alpha = 0$, $\alpha = 4.5$ on road slopes % 57, % 5, % 2 fuel savings have been achieved respectively.

Keywords: ADVISOR, battery charge, electric vehicle, regenerative braking, road slope

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1. Introduction

Need for renewable energy sources increased day by day in the world, in order to struggle with climate change and enhance power safety [1]. When we look into new generation vehicles manufactured today, it is seen that weight of vehicles and fuel consumption are decreased constantly and more saving vehicles are manufactured [2]. Electric vehicle is the name given to vehicles that provide motional energy by electrical energy. By generalizing such vehicles, it is planned to decrease emission oscillation, caused by engine vehicles running with fossil origin fuels. Studies on manufacture of electric vehicles in economic terms besides their environmental benefits continue [3]. Basic operation principle of electric vehicles is based on usage of power stored in the battery for activating the electric engines. Today, both electric and
hybrid usages are available. As of 2016, many automotive manufacturer produce electric vehicles. The problem with electric vehicles is the high cost despite their short range distance when compared to fossil fuel vehicles [4]. Although electric vehicles have many advantages, reasons such as short distance of range and long term of charging create serious disadvantages. In internal combustion engines, the kinetic energy generated during braking is transformed into heat energy by means of mechanical friction and it is consumed; and such situation sometimes composes 50% of all effective traction energy on average. The kinetic energy consumed for nothing is transformed into electric energy thanks to regenerative braking system and stored in batteries; and the obtained beneficial energy is used for increased range in electric vehicles. In this way, an effective improvement is made for solving range problem of the vehicle and total energy efficiency of the vehicle increases. Recovery of energy of electric engines used in electric and hybrid electric vehicles, resourcing from opposite electromotor force during braking results in higher system efficiency and

increase of battery charge and range. Regenerative braking system decreases fuel cost and emissions and increases vehicle range distance [5]. ADVISOR vehicle simulation program is used in modelling of vehicles by means of different configurations and in analyzing their performance in different driving cycles. There are many studies related to analysis of performance of electric and hybrid electric vehicles by means of such program [6-11]. Kinetic energy recovery systems have been used firstly in race cars. Researches have been made in locomotives [12], tracks [13], buses [14] and automobiles [15] aiming at enhancing recovery from braking energy. Studies related to recovery of kinetic energy in electric and hybrid vehicles continue [16]. Yang et al., in their study on electric scooter, have stated that regenerative energy recovery is more suitable for current systems included in electric vehicles [17]. In a simulation of electric vehicles, made for recovery of energy lost during braking, it has been foreseen that an energy saving of 25% can be made by KERS for intra-city usage [18]. The road slope is very important for electric vehicles in terms of vehicle control and fuel economy. Road slope also has an effect on establishing more effective control strategies for regenerative braking system [19]. Many parameters must be considered to improve energy recovery in electric vehicles. The most important of these parameters are the mass of the vehicle, the road slope, and the type of road [20]. Although there are models defining the traffic of electric vehicles [21-27], there are not many studies investigating the effects of the slope of the road determining the performance of these vehicles. In real driving conditions, each road has a certain slope and the road slope has an effect on the driver's behavior [28-31]. The effect of regenerative braking performance on downhill situations in electric vehicles is not a subject of much research due to the lack of observational data and difficulty in meeting experimental conditions [32]. During daily vehicle use, especially on urban roads, short-term downhill ups and downs up to α=0-4.5° slope are frequently observed. It is therefore important to investigate regenerative gains in short-term road slopes of electric vehicles.

2. Modelling of the Vehicle

2.1 Forces Affecting the Movement of the Vehicle

Forces affecting the movement of the vehicle can be classified into two groups as resistance forces that resist movement of the vehicle and affected by environmental factors and as moving (traction) forces that enable transmission of the power generated by the engine to the wheels [33]. Resistance forces consist of rolling resistance on vehicles as shown in equation 1 (F_r), aerodynamic (wind) friction (F_w), inertial resistance that the vehicle should exceed (F_a) and inclination resistance (F_{st}) [34]. In figure 1, forces affecting the vehicle are shown [35]. In Table 1, force parameters from which the vehicle is affected are shown.

$$F_t = F_r + F_w + F_a + F_{st} \quad (1)$$

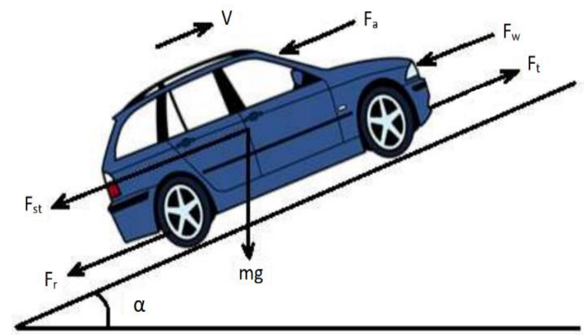


Fig. 1. Forces acting on the vehicle

$$F_r = c_{r,ro} mg + c_{r,r1} mgV \quad (2)$$

Equation (2), $c_{r,ro}$, $c_{r,r1}$ indicate 1st and 2nd Rolling resistance coefficients, m- indicates the vehicle mass, g- indicates gravity acceleration and V- indicates vehicle speed.

$$F_w = \frac{1}{2}\rho \; C_d A_f V^2 \quad (3)$$

Equation (3), ρ- indicates air density, C_d- indicates aerodynamic friction coefficient, A_f- indicates frontal cross-sectional area.

$$F_a = m \; M_i \frac{dV}{dT} \quad (4)$$

Equation (4), M_i- indicates inertial mass factor, $\frac{dV}{dT}$- indicates vehicle acceleration.

$$F_{st} = mg \;\; \sin\alpha \quad (5)$$

Equation (5), α- indicates the slope of the road [34].

2.2 Regenerative Braking Equations

The energy emerging during braking (W_b) is equal to the total moving power ($\int_0^t -P_v(t)dt$) from the start of braking until the moment stop of the vehicle which is assumed to be lack of rolling resistance of the wheels and air resistance (aerodynamic) occurring during the movement of the vehicle for ideal position.

$$W_b = \; -W_d = \int_0^t -P_v(t) \;\; dt \quad (6)$$

Under real conditions, it is not possible for such state to realize. As the speed of the vehicle decreases, some of the energy is spent for frictions. The amount of net brake energy to be stored in KERS after losses is related to modelling of moving and power transmission organs of the vehicle. Besides the energy, which is not gained during braking by means of KERS ($\boldsymbol{P_{br,loss}}$), a part of the obtained energy is lost due to reasons such as loss occurring as a result of aerodynamic factors ($\boldsymbol{P_{a,loss}}$), transformation of re-cycled energy into electric energy, losses occurring during its transmission and regulation ($\boldsymbol{P_{tr,loss}}$), losses of electric engine, losses of mechanical parts ($\boldsymbol{P_{mek,loss}}$), losses occurring during charging and de-charging transactions ($\boldsymbol{P_{bat}}$), depending upon the type of battery used in storing unit (lead, acid, lithium-ion, nickel-cadmium, ultra-capacitor,etc.). Net energy ($\boldsymbol{W_{KERS}}$) re-gained by means of KERS after suchlosses in orderto be stored in the battery can be shown as follows [4].

$$W_{KERS} = \int_0^t \big(-P_v(t) + P_{br,loss}(t) + P_{a,loss}(t) + P_{tr,loss} + P_{em,loss} + P_{mek,loss} + P_{bat,loss}\big)dt \qquad (7)$$

2.3Vehicle Design and Analysis by Means of Advisor

ADVISOR-Advanced Vehicle Simulator is a system vehicle formed for vehicle modelling in MATLAB/Simulink environment by NREL-National Renewable Energy Laboratory located in USA. It offers a flexible and sound model, data and instruction file used to measure fuel saving, performance and emission in various driving cycles of vehicles included in different classes. In Figure 2, Advisor program's introductory screen of the vehicle in shown. After entering the parameters required for vehicle definition, the second stage is followed, in which options for driving cycles for testing the electric vehicle are offered. In Table 1, the characteristics of the defined vehicle for the simulation are given in "drive cycle" part, driving cycle has been chosen as 'CYC_IM240' and number of cycle has been chosen as 1.

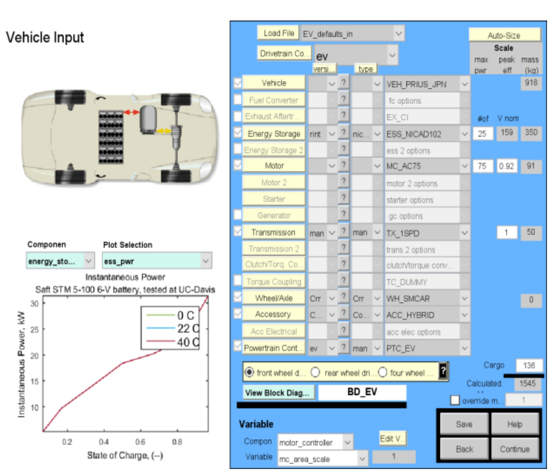


Fig. 2. Introductory screen of Advisor program

Table 1. Technical parameters of simulation

Parameter	Unit	Data
Vehicle weight	kg	1429
Tyre type		SAE J2452, P205/60R15
Wind resistance coefficient		0.3
Rolling resistance coefficient		0.009
Vehicle center of gravity height	m	0.57
Air density	kg/m^3	1.2
Motor type		AC cont. ind.
Motor power	kW	75
Battery type		Nimh
Total number of battery modules		65
Nominal voltage (for 1 module)		6.9
Total battery mass	kg	234
Gearbox		One shift automatic
Energy consumed by hardware (fixed)	W	700

IM240 test is the ones carried out for exhaust emission inspection and maintenance. Total test duration is 240 seconds and total cycle distance is 3.15 km (1.96 miles). Average speed is 47.08 km/h (29.4 mile/h) and maximum speed is 91.25 km/h (57 mile/h. In line with the parameters determined for such stage in Advisor program, when simulation of the electric vehicle during active mode of regenerative brake is on, results shown in Figure 3 are obtained.

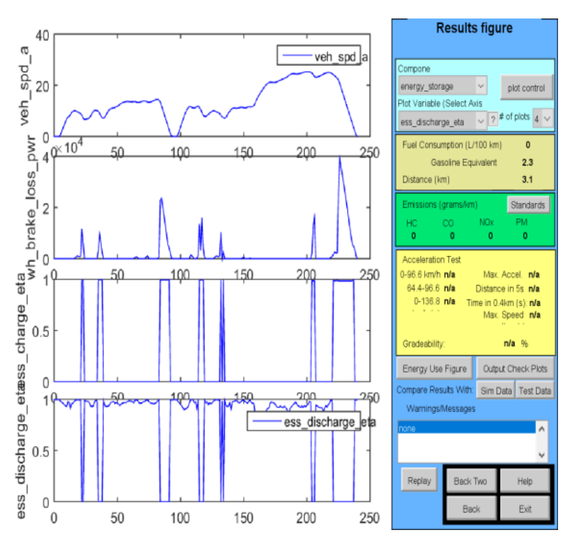


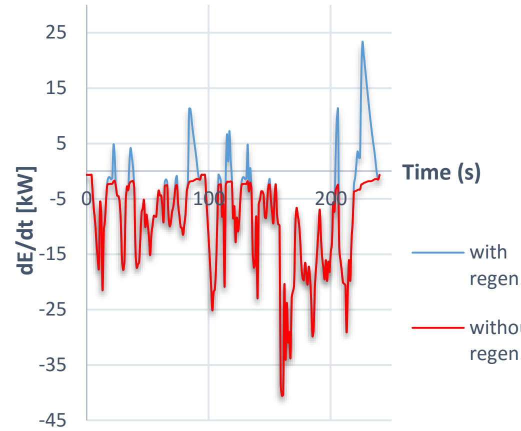
Fig. 3. Result screen for Advisor program

3. Analysis of Regenerative Braking State

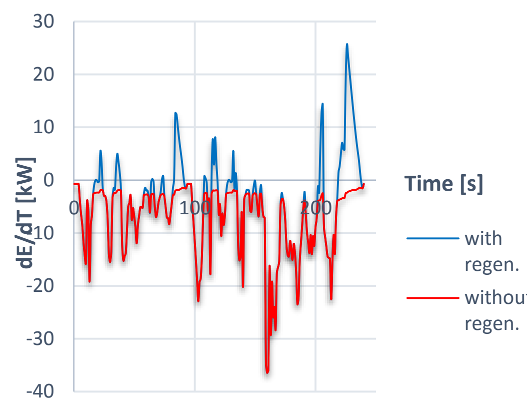
In Figure 4, energy change occurring in batter group pf vehicle as per IM240 driving cycle under $\propto= 0$, $\propto= 1.5$ (uphill) and $\propto= -1.5$ (downhill) conditions is shown. Traction value should be negative in order to obtain regenerative braking power and energy. In the case when traction is negative, entry of power, obtained from regenerative braking and measured, occurs. Such state is shown as the place between curves in Figure 5. During time intervals of 19-25 s, 37-40 s, 66-68 s, 75-76 s, 85-95 s, 116-121 s, 129-136 s, 151-152 s, 206-209 s and 221-242 seconds in which slowing is in question according to driving cycle, regenerative braking is enhanced. The area between the curves shows the power obtained by means of regeneration. According to the driving cycle, 2.09 kW, 2.17 kW and 1.28 kW recovery has been achieved for $\propto= 0$, $\propto= -1.5$ (downhill) and $\propto= 1.5$ (uphill) road slopes, respectively. There has been obtained a 4% regenerative gain difference for a cycle of 240 seconds between $\propto= 0$ and the $\propto= -1.5$ (downhill) slope.

In Figure 5, the change in brake power loss is shown according to IM240 driving cycle under $\propto= 0$, $\propto= 1.5$ (uphill) and $\propto= -1.5$ (downhill) conditions. During time intervals of 19-25 s, 37-40 s, 66-68 s, 75-76 s, 85-95 s, 116-121 s, 129-136 s, 151-152 s, 206-209 s and 221-242 seconds in which slowing is in question according to driving cycle, brake pads are worn less thanks to regenerative braking. During the driving cycle, braking energy loss has occurred maximum in 221-242 seconds. In such time interval, less braking loss has occurred due to regenerative braking. During downside inclination, acceleration due to downhill increases the braking load. The biggest braking power loss in different road slopes has occurred on $\propto= -1.5$ road slope. In Table 2, braking power loss according to road slope is shown.

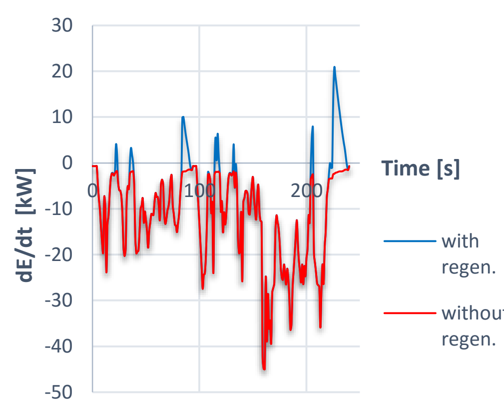
In Figure 6, the change in consumed fuel amount is shown according to cycle 1 in IM240 driving cycle on different road slopes. On downhill roads, while 0.9 l gasoline equivalent fuel is consumed at $\propto= -4.5$ slope during regenerative driving, 1.1 l gasoline equivalent fuel is consumed during non-regenerative driving. When road slope changes as uphill incline, fuel consumption increases in both situations due to the increase in rolling resistance. While 4.8 l gasoline equivalent fuel is consumed at $\propto= 4.5$ slope during regenerative driving, 4.9 l gasoline equivalent fuel is consumed during non-regenerative driving.



(a) $\propto= 0$ road slope

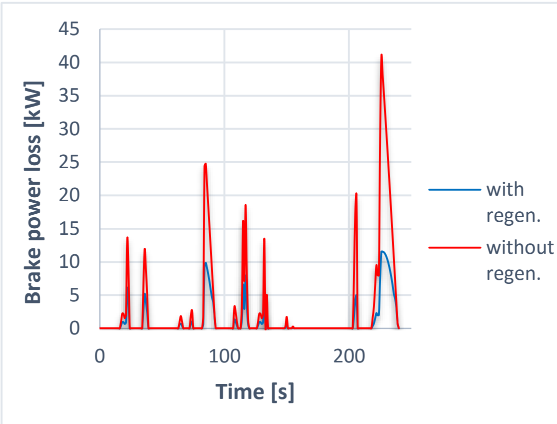


(b) $\propto= -1.5$ (downhill) road slope

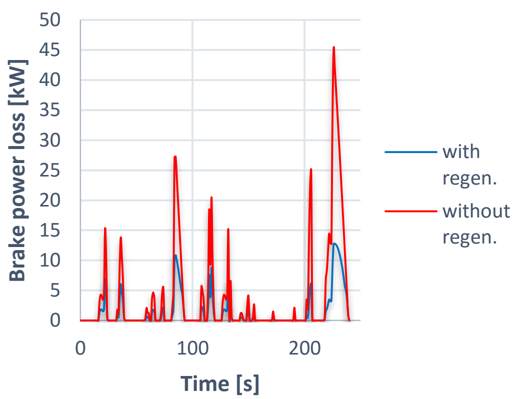


(c) $\propto= 1.5$ (uphill) road slope

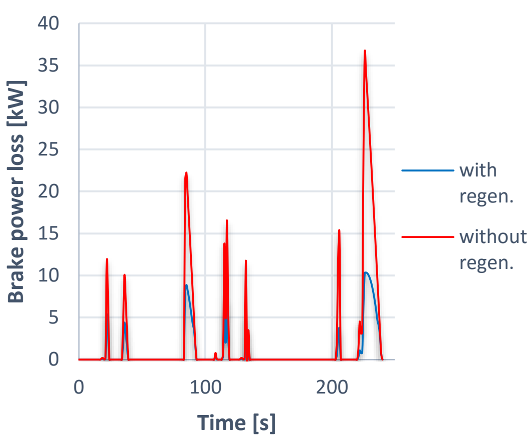
Fig. 4. Graphic showing the energy change in battery for unit if time during driving cycle



(a) $\propto=0$ road slope



(b) $\propto=-1.5$ (downhill) road slope



(c) $\propto=1.5$ (uphill) road slope

Fig. 5. Braking energy loss depending on time in driving

Table 2. Braking power loss according to different road slopes

	Road slopes		
	$\propto=1.5$	$\propto=0$	$\propto=-1.5$
with regen. (kW)	11.98	13.98	16.13
without regen. (kW)	16.02	18.12	20.56
Recovery (kW)	4.04	4.14	4.43

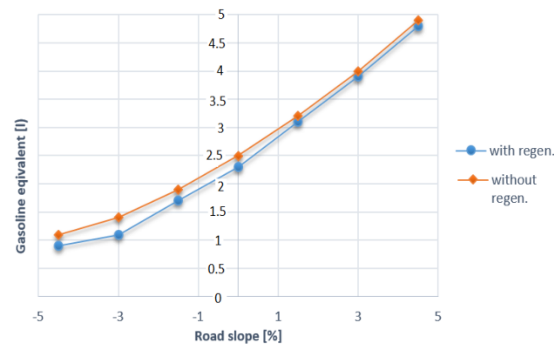


Fig. 6. Amount of fuel consumed according to road slope

In Figure 7, the state of charge (SOC) change depending on time is shown for different road slopes. During downhill driving, as the road slope accelerates the vehicle, battery charge decreases at minimum rate. On the contrary, during uphill driving, as the incline resistance increases, battery charge decreases at maximum rate. During the simulation carried out, the lowest charge level at the end of driving cycle is 93% at road slope of $\alpha=4.5$, and the highest charge level is 99.1% at road slope of $\alpha=-4.5$. With regenerated recovery, $\alpha=-4.5$, $\alpha=-3$, $\alpha=-1.5$, $\alpha=0$, $\alpha=1.5$, $\alpha=3$, $\alpha=4.5$ on road slopes % 57, % 18, % 11, % 5, % 4.7, % 4, % 2 fuel savings have been achieved respectively.

In Figure 8, shows the battery temperature change with regeneration state according to 5 driving cycle. Temperature of selected Nimh battery is 20 °C during the beginning of the cycle. When driving cycle is run for 1 driving cycle, a negligible temperature increase has occurred, when compared to the beginning temperature of the battery. At the end of 5 cycles, the lowest battery temperature increased by 5% (20.9°C) on the -4.5% road slope and by 30% on the 4.5% (26.05°C) road slope. When batteries are subjected to a large number of charges and discharges with regeneration effect, undesirable chemical reactions have increased, resulting in a greater increase in the battery temperature. The charge-discharge status of the battery affects the battery temperature [36].

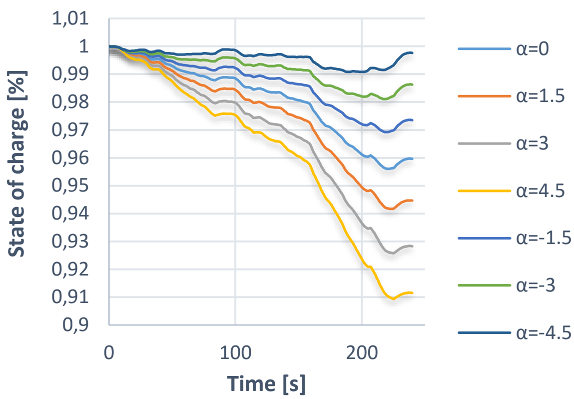


Fig. 7. The state of charge (SOC) change depending on time at different road slopes

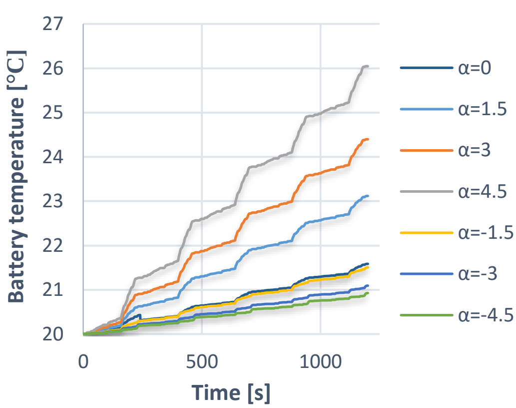


Fig. 8. The battery temperature and the vehicle speed change depending on time at different road slopes (with regen.)

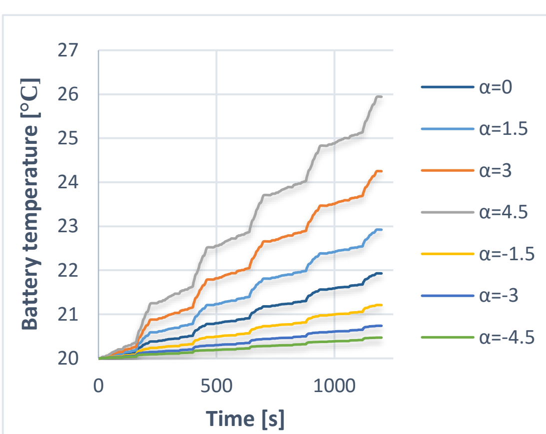


Fig. 9. The battery temperature and the vehicle speed change depending on time at different road slopes (without regen.)

In Figure 9, shows the battery temperature change without regeneration state according to 5 driving cycle. For all road slopes, time-dependent battery temperatures have increased. However, in the without regeneration state, the lack of battery charge resulted in lower battery temperature compared to the regenerated state. At the end of 5 cycles, the lowest battery temperature increased by 3% (20.5°C) on the -4.5% road slope and by 29% on the 4.5% (25.8°C) road slope. Reduced road slope caused the battery to heat up less.

3. Conclusions

The fact that the slope of the road is in the direction of uphill reduces the regenerative gain. However, regenerative gain can be achieved on slopes up to 4.5% slope. The road slope, increasing uphill during the operation of driving cycle of the related electric vehicle model, helps slowing and results in less brake power loss during braking. However, in such situation, recovery by regenerative braking has occurred less. The road slope increasing downhill has decreased fuel consumption and battery discharge, and resulted in highest value of the state of charge (SOC). During driving cycle in which battery charge-discharge number is high, higher battery temperature has occurred. In this study, stabile cargo load has been taken into consideration and in following studies effect of Cargo load on recovery shall be examined at different road slopes. Selecting lower road slope routes by pre-detecting the road slope with the GPS system will increase the range of electric vehicles.

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