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Energy efficiency of a car driving with regenerative braking

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Currently offered satellite navigation systems for cars are primarily focused on selecting the route with the shortest travel time. These systems also feature relatively simple models that allow the selection of the route with regard to minimizing fuel or electricity consumption, usually called the most ecological. Their effective use requires users to define basic vehicle data, such as drive type, maximum speed, etc. The paper presents an analysis of the impact of selected parameters characterizing vehicle properties and traffic conditions on energy consumption. The focus is mainly on parameters that can be technically used in car navigation systems to plan energy-saving routes. The analysis uses routes recorded in real traffic. The results of these analyses allowed the development of several guidelines for planning routes taking into account the EEC minimization criterion. One of the observations is that for roads with large changes in road height (> 20 m per km), a flat route with a length increased by 50% may be more energy-efficient than the original one. This is due to the efficiency of the regenerative braking system being significantly lower than 100%.

Key words: *electric vehicle, urban conditions, regenerative braking, energetic efficiency, route planning*

1. Introduction

As the global transition toward sustainable transportation accelerates, improving the energy efficiency of Internal Combustion Engine Vehicle (ICEV) [1, 7]. Especially electric vehicles (EVs) and hybrid electric vehicles (HEVs) have become a central research focus [6, 13]. Two major strategies for reducing vehicular energy consumption are the use of regenerative braking systems (RBS) and energy-aware route optimization algorithms [3, 4]. Together, these strategies enable smarter driving that aligns with the goals of energy efficiency, reduced emissions, and longer driving range [8]. Regenerative braking systems allow electric and hybrid vehicles to recapture kinetic energy during deceleration, converting it into electrical energy that is stored in the battery [11, 16]. Unlike conventional friction braking, which dissipates kinetic energy as heat, RBS contributes to energy reuse, thus improving overall vehicle efficiency. RBS can recuperate between 10% and 30% of the total energy consumed during urban driving, depending on various parameters such as driving patterns, traffic conditions, and terrain [9]. Urban driving, characterized by frequent acceleration and deceleration, offers ideal conditions for effective energy regeneration. The amount of recoverable energy depends on several dynamic factors: a) vehicle speed and deceleration rates: higher deceleration rates typically allow more energy to be harvested, though limitations exist based on battery charge rates and vehicle safety; b) battery state-of-charge (SOC): high SOC can limit energy recovery as the battery cannot accept more charge, potentially leading to reduced efficiency or increased use of mechanical brakes. Brake blending strategies: effective integration of regenerative and friction braking ensures driver safety while optimizing energy recovery. Adaptive control systems dynamically allocate braking torque between electric motors and hydraulic brakes to maximize regeneration without compromising stability [12]. Modern regenerative systems also incorporate predictive algorithms that estimate optimal braking force distribution in real time, accounting for the road slope, vehicle load, and traffic.

Traditional navigation systems prioritize time or distance minimization, but such objectives do not always align with energy efficiency. Energy-aware routing considers additional parameters, such as: a) elevation profiles (gradient): uphill roads increase energy consumption, while downhill roads offer potential for regenerative braking; b) traffic congestion: frequent stopping and idling increase energy usage and reduce regenerative opportunities; c) speed limits and driving behaviour: energy-efficient routes may involve smoother acceleration profiles and fewer stops. Researchers have proposed multiple routing algorithms focused on minimizing energy usage [2, 5]. Machine learning techniques have emerged as powerful tools in this domain. Although RBS and energy-aware routing have individually shown strong potential in reducing energy consumption, their combined use results in even greater efficiencies. Integrating regenerative braking potential into route planning allows vehicles to exploit downhill segments and frequent deceleration zones, which can be strategically selected to increase energy recovery. For example, a route that includes gentle downhill slopes with traffic lights can enhance energy regeneration without significant speed loss. These scenarios have inspired research into "eco-routing" or "green routing," where algorithms analyse the entire road profile for energy-optimal paths. The inclusion of regenerative braking factors into eco-routing decisions improved energy savings by an additional 7–10% over standard energy-optimized routing [10]. Moreover, vehicle-to-infrastructure (V2I) and vehicle-to-everything (V2X) communication technologies enhance this synergy by allowing real-time traffic signal prediction and adaptive speed control. The author [5] demonstrated a V2I-based cooperative control strategy that synchronized vehicle movement with signal phasing to avoid unnecessary stops and maximize regenerative braking potential.

Despite promising results, several challenges hinder the widespread adoption of integrated regenerative-route optimization systems. Real-time energy-optimal routing under uncertain traffic and environmental conditions requires high computational resources. Accurate road gradient, traffic, and SOC data are crucial but not always available. Aggressive driving can undermine energy savings, even on optimized routes. Energy recovery is constrained by battery acceptance rates, particularly in cold weather or near-full SOC levels [14]. Looking ahead, advancements in artificial intelligence, edge computing, and battery technologies are expected to mitigate these limitations [15]. Predictive analytics, cloud-based routing services, and real-time data integration will allow future EVs to self-optimize their routes and braking strategies based on continuous feedback from the environment and the vehicle's internal state.

This work presents an analysis of the impact of selected parameters characterizing vehicle properties and traffic conditions on energy consumption. The focus is mainly on parameters that can be technically used in car navigation systems to plan energy-saving routes. The analysis uses routes recorded in real traffic. The analysis included the impact of vehicle mass on electric energy consumption (EEC) and changes in the road gradient, by modifying the original height at which the vehicle is located, on EEC.

2. Traffic conditions

The main parameters characterizing the traffic conditions are defined below. The amount of energy expended to drive the vehicle will depend on the maximum speeds achieved, the number of acceleration cycles, their intensity, but also the vehicle mass and the distance travelled. In order to use the data in the analysis of the operation of drive systems of various vehicles, with different masses and covering different distances, it was decided to use specific energy consumption (SEC), in which the amount of energy expended is related to the vehicle mass and the distance travelled [9]:

$$\mathrm{SEC} = \frac{\mathrm{E}}{\mathrm{m} \cdot \mathrm{L}} \tag{1}$$

where: E – mechanical energy delivered to the wheels: L – distance covered, m –vehicle mass.

Mechanical energy delivered to the wheels can be calculated based on the following relationship:

$$\mathrm{E} = \int_{t=0}^{t=t_c} \left(k_p \cdot M \cdot \omega \cdot \eta_t\right) dt \tag{2}$$

where: M – engine torque, t_c – time of the cycle, ω – engine angular velocity, η_t –transmission system efficiency, k_p – positive tractive force factor:

$$k_p = \begin{cases} 1 & \text{for powered wheels} \\ 0 & \text{for idlling or braking} \end{cases} \tag{3}$$

Alternatively, the mechanical energy delivered to the wheels can be calculated as follows:

$$\mathrm{E} = \int_{t=0}^{t=t_c} \left(k_p \cdot P\right) dt \tag{4}$$

where: P – mechanical power,

$$P = F_t \cdot V \tag{5}$$

F_t – tractive force, V – vehicle velocity.

There are four types of driving resistances, which must be covered by the tractive force: aerodynamic drag, rolling resistance, gradient resistance, and acceleration resistance. With a constant time, step for measuring vehicle motion parameters, the following relationship can be used:

$$\mathrm{E} = \Delta t \cdot \sum_{i=1}^{N} \left(k_{p_i} \cdot P_i\right) \tag{6}$$

where: Δt – constant time step.

For the regeneration process, the regenerative braking energy can be calculated:

$$E_{reg} = \Delta t \cdot \sum_{i=1}^{N} \left(k_{reg_i} \cdot P_i\right) \tag{7}$$

where: k_{reg} – negative tractive force factor:

$$k_{reg} = \begin{cases} -1 & \text{for idlling or braking} \\ 0 & \text{for powered wheels} \end{cases} \tag{8}$$

Using negative tractive force factor when calculating regenerative braking energy, which is available for recovery system may cause some ambiguity in the research results, because the amount of available energy from the regeneration process depends not only on the speed profile and changes in height but also on the degree of aerodynamic perfection and quality of the driving wheels capable of generating lower or higher rolling resistance. In other words, a vehicle with low rolling and air resistance will have more energy available for the regeneration process than a vehicle of the same mass that generates higher rolling and air resistance.

Regenerative braking specific energy (RBSE) has been defined as follows:

$$\mathrm{RBSE} = \frac{E_{reg}}{m \cdot L} \tag{9}$$

Absolute electric energy delivered by the battery can be calculated as follows:

$$E_{battery} = m \cdot L \cdot \left(\mathrm{SEC} \cdot \frac{1}{\eta_{el}} - \mathrm{RBSE} \cdot \eta_{reg}\right) + P_{aux} \cdot t_c \tag{10}$$

where: η_{el} – efficiency of electric drive system (including: battery, inverter, motor and transmission), η_{reg} – efficiency of regenerative braking system (including: transmission, generator, inverter, battery), P_{aux} – auxiliary devices power consumption.

Electric energy consumption can be calculated as follows:

$$\mathrm{EEC} = m \cdot \left(\mathrm{SEC} \cdot \frac{1}{\eta_{el}} - \mathrm{RBSE} \cdot \eta_{reg}\right) + \frac{P_{aux} \cdot t_c}{L} \tag{11}$$

3. Specification of the testing conditions

The traffic conditions identification studies were carried out in the city of Gdynia (approx. 250,000 inhabitants), in regular city traffic, using a vehicle whose technical specifications are presented in Table 1. The vehicle was equipped with a GPS position recording system, which enabled both the determination of the vehicle's horizontal position and changes in height.

Table 1. Drive system parameters of the tested vehicle

Vehicle	Mass (driver inc.) [kg]	Power [kW]	Battery capacity [kWh]	η_{el} [%]	η_{reg} [%]	P_{aux} [W]
Mazda MX-30	1795	107	35	78	61	200

Figures 1 to 4 illustrate test routes with average driving speeds for 100-meter sections. The routes run through the city center, but due to the use of modern road infrastructure, some of them allow for a relatively high average speed (a small number of intersections with traffic lights, increased permissible driving speed). The routes were diversified in terms of the cross profile of the road so that the impact of the road gradient on the energy consumption to drive the vehicle could be taken into account in the tests.

Fig. 1. Average speed distribution on route 1 over 100 m sections

Fig. 2. Average speed distribution on route 2 over 100 m sections

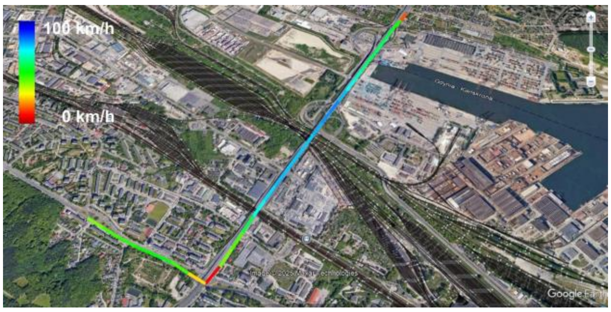

Fig. 3. Average speed distribution on route 3 over 100 m sections

Table 2 presents the specification of the routes used in the tests. Their length is close to 3 km. The specification includes the highest and lowest height (Height max and Height min) at which the vehicle will be located and the relative change in height for the end and beginning of the route (Height difference). The parameter "Height difference" indicates the possibility of reducing or increasing the energy consumption for the drive due to gradient resistance. The routes were selected to ensure the widest possible variation in traffic conditions resulting from the hills overcome and traffic difficulties resulting in different average driving speeds.

Fig. 4. Average speed distribution on route 4 over 100 m sections

Table 2. Routes specification

Route No.	Length [m]	Av. speed km/h	SEC [kWh/(t·100 km)]	RBSE [kWh/(t·100 km)]	Height min [m]	Height max [m]	Height difference [m]
1	2762	16	10.7	5.3	41	88	20
2	2931	26	8.5	4.5	40	67	0
3	3117	35	6.6	1.9	45	57	–2
4	2891	45	6.2	3.6	33	59	–21

4. The influence analysis of vehicle properties and traffic conditions on energy consumption

The effect of vehicle mass, road gradient change, and traffic conditions on the amount of mechanical power required to drive the vehicle is presented below. This power was determined based on vehicle speeds and changes in height recorded during regular traffic for 4 selected routes, the specification of which was presented in the previous section. The power required to drive the vehicle (positive), the specification of which was included in Table 1, was calculated based on the vehicle motion resistance model that takes into account rolling resistance, air resistance, gradient resistance, and acceleration resistance. Similarly, the power that can be recovered in the energy recuperation system (negative) was calculated based on this model.

Figure 5 shows the speed and height at which the vehicle moves for route 1. This is the route with the lowest average speed of 16 km/h, but there are large changes in height; the difference between the highest and lowest height is 47 m, and the vehicle ends the route at a height 20 meters higher than it started. Figure 6 shows the profile of mechanical power supplied by the drive system or that can be delivered to the recuperation system (negative value) for a vehicle mass of 100%, 125% and 150% of the original vehicle mass, respectively. Figure 7 shows the effect of changing the road gradient, by modifying the original height at which the vehicle is located, on the mechanical power supplied or received by the drive system. Three levels of interference with height were considered: flat road (0%), original height (100%), and double height (200%).

Figures 8 to 10 show the results for route 2, which has a relatively low average driving speed of 26 km/h, while the height between the start and end of the route remains practically unchanged.

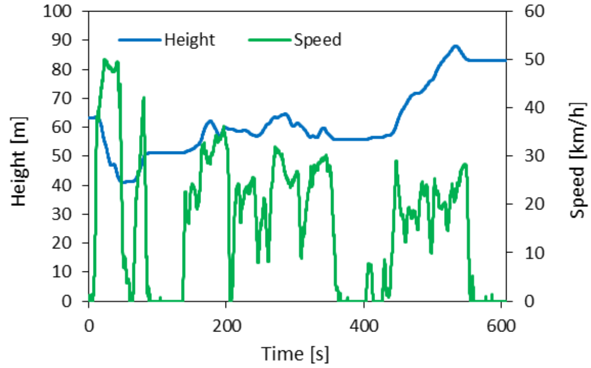

Fig. 5. Vehicle speed and height above sea level for route 1

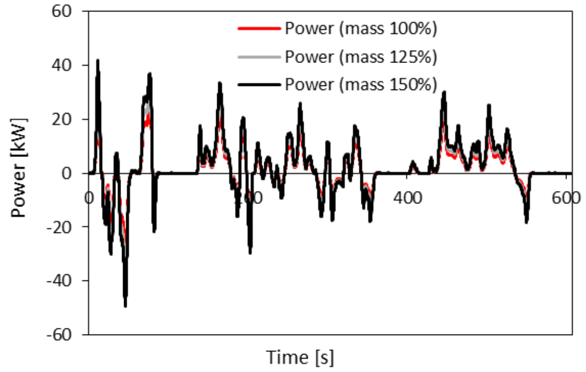

Fig. 6. Influence of vehicle mass on mechanical power supplied/received by the drive system for route 1

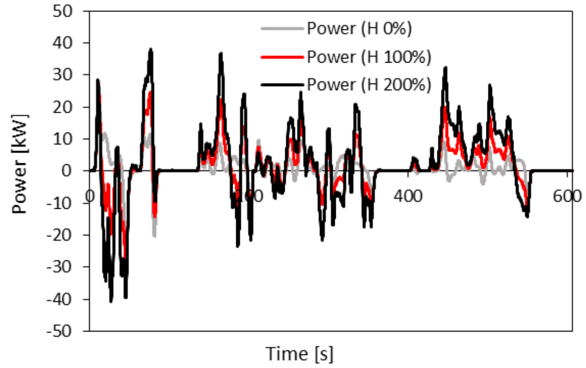

Fig. 7. Influence of road gradient (height multiplication) on mechanical power supplied/received by the drive system for route 1

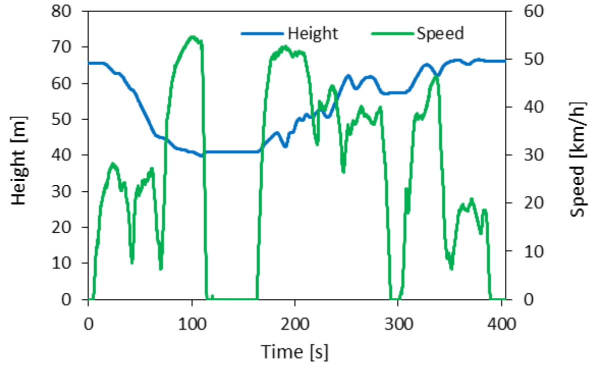

Fig. 8. Vehicle speed and height above sea level for route 2

Figures 11 to 13 show the results for route 3 (average speed 35 km/h), which has relatively few acceleration and braking cycles and is practically flat.

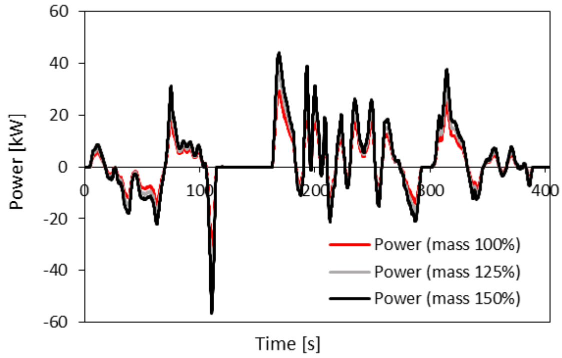

Fig. 9. Influence of vehicle mass on mechanical power supplied/received by the drive system for route 2

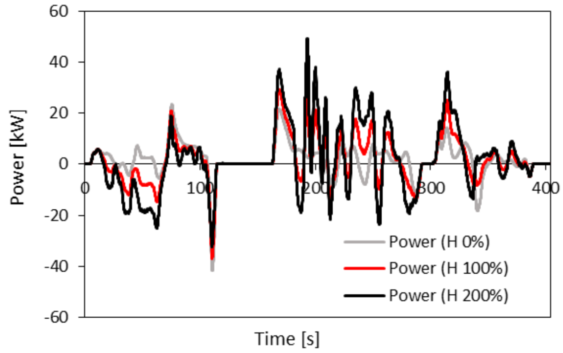

Fig. 10. Influence of road gradient (height multiplication) on mechanical power supplied/received by the drive system for route 2

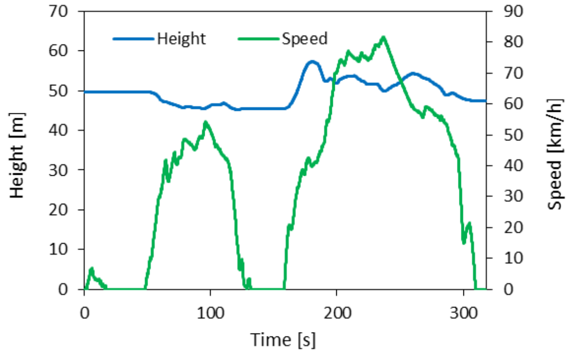

Fig. 11. Vehicle speed and height over the sea level for route 3

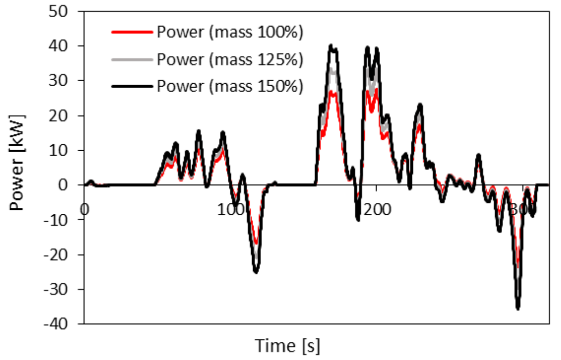

Fig. 12. Influence of vehicle mass on mechanical power supplied/received by the drive system for route 3

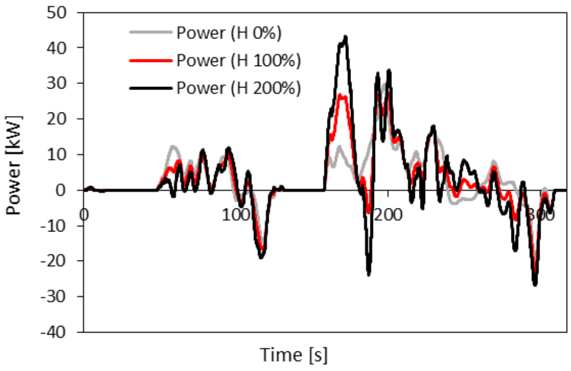

Fig. 13. Influence of road gradient (height multiplication) on mechanical power supplied/received by the drive system for route 3

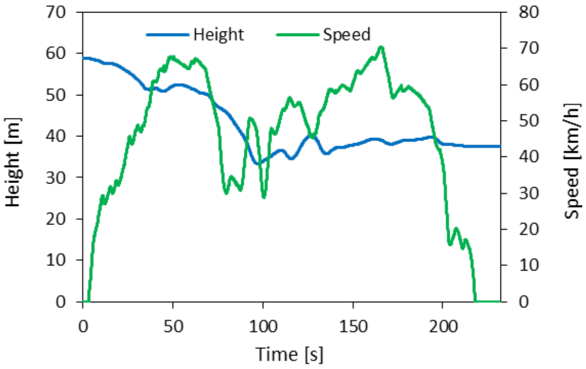

Fig. 14. Vehicle speed and height over the sea level for route 4

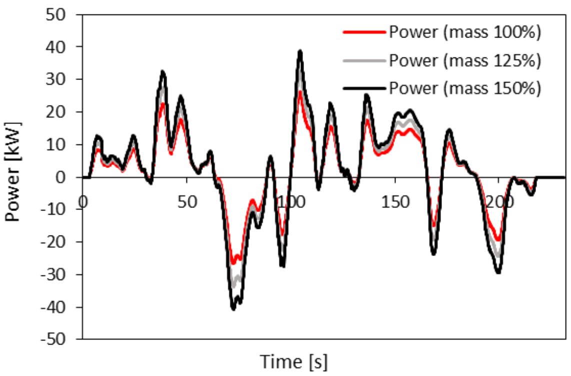

Fig. 15. Influence of vehicle mass on mechanical power supplied/received by the drive system for route 4

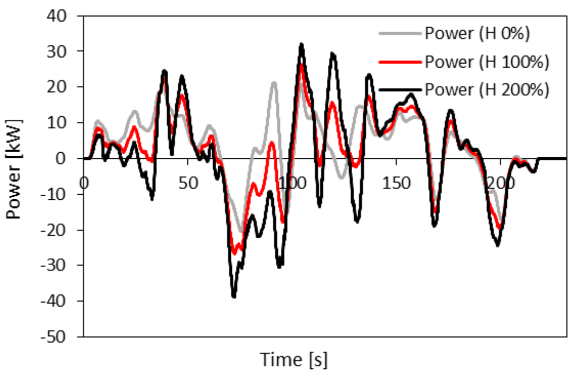

Fig. 16. Influence of road gradient (height multiplication) on mechanical power supplied/received by the drive system for route 4

Figures 14–16 show the results for route 4, which has the highest speed (45 km/h) and the fewest stops. At the same time, the road is sloping downwards; the end of the route is 21 m lower than the beginning.

Using the results presented in Fig. 5 to 16 and equations (1) to (11), the electric energy consumption (EEC) was determined for the analysed cases. While, based on findings from studies [10], this auxiliary power consumption was assumed to be constant at 200 W. The results of the effect of vehicle mass on EEC are presented in Fig. 17.

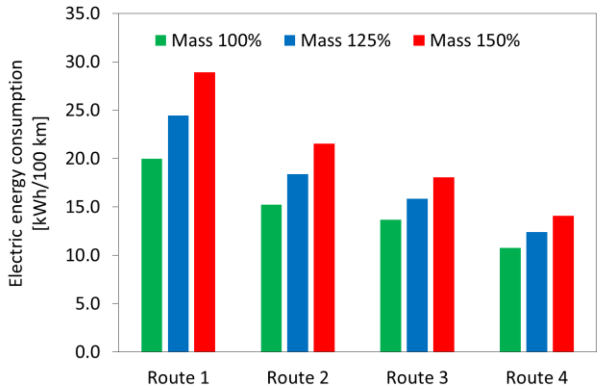

Fig. 17. Influence of vehicle mass on electric energy consumption

Based on the results obtained, it can be stated that route 1 is characterized by the highest EEC, despite the lowest average driving speed. The decisive factor in this situation turned out to be the necessity to overcome the difference in height of 20 m between the beginning and the end of the route. Similarly, the lowest EEC was recorded for route 4, where the speed variability is the lowest, and at the same time, the route leads downhill by 21 m. The influence of the vehicle mass on EEC is clearly visible for all routes, but it is not proportional to the increase in mass for all routes. For route 1, the increase in mass by 25% and 50% gives an increase in EEC by 22% and 45%, respectively, so it is almost proportional. For route 2, the EEC increases are 21% and 41%, respectively. For route 3, the EEC increases are 16% and 32%, respectively. For route 4, the EEC increases are 16% and 31%, respectively. It can therefore be concluded that for routes with a greater number of acceleration processes and their intensity, the impact of the mass increase on the EEC is greater. The regenerative braking process is therefore unable to compensate for the increased energy consumption resulting from the numerous acceleration processes and the increased mass. This is due to the efficiency of the regenerative braking system being significantly lower than 100%; usually, it is well below 80% [9].

Figure 18 shows the influence of road gradient (height multiplication) on the electric energy consumption.

Based on the obtained results, it can be stated that on flat roads (height 0%), the factor determining the EEC is the average driving speed; the lower it is, the lower the EEC. However, these differences are not large due to the occurrence of numerous acceleration processes at low average driving speeds and only their partial compensation during regenerative braking. On routes leading uphill, the increase in energy consumption is not proportional to the increase in gradient. For example, for route 1, doubling the gradient of the road causes an increase in EEC by 49%. It should be remembered that the resistance to the climb is only a part of the resistance to the vehicle's motion, which either does not depend on the road gradient (air resistance) or can decrease (rolling resistance). In the analysed cases, for a difference between maximum and minimum height of 27 m (route 2) with a route length of 2.9 km, the increase in energy consumption compared to a flat road is 16%, and with doubled elevation differences, 47%. This means that in the first analysed case, the flat route with a length greater by 16% (0.47 km) will require the same amount of energy as the original. For route 2, with double the height, the flat route can be as much as 47% (1.39 km) longer, giving the same energy consumption.

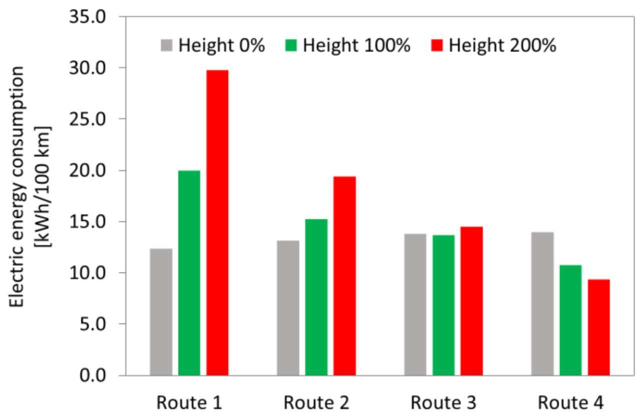

Fig. 18. influence of road gradient (height multiplication) on the electric energy consumption

5. Conclusions

Energy efficiency in vehicles is no longer confined to the powertrain design alone but extends to intelligent systems for energy regeneration and route optimization. Regenerative braking offers substantial energy savings by recapturing kinetic energy during braking, while energy-aware route optimization ensures that vehicle paths are aligned with energy conservation goals. Together, they provide a robust framework for enhancing vehicular efficiency, especially in EVs and HEVs. As energy efficiency becomes a competitive differentiator and environmental imperative, integrating regenerative braking and optimal routing will be key to the next generation of intelligent transportation systems.

This work presents an analysis of the impact of selected parameters characterizing vehicle properties and traffic conditions on energy consumption. The main focus was on parameters that can be technically used in car navigation systems to plan energy-efficient routes. The analysis used routes recorded in real traffic in the city of Gdynia. Four routes of similar length but different average speed and different cross-sectional road profiles were selected for testing. The analysis included the impact of vehicle mass on electric energy consumption (EEC) and changes in the road gradient, by modifying the original height at which the vehicle is located, on EEC. The results of these analyses allowed the development of several guidelines for planning routes taking into account the EEC minimization criterion:

– Vehicles should avoid routes with large changes in road height, as the increase in height causes an almost proportional increase in energy consumption, which is only slightly compensated by regenerative braking. This is due to the efficiency of the regenerative braking system being significantly lower than 100%; usually, it is well below 80%. On flat routes with an increase in mass, the increase in ECC is much smaller and can be almost twice as small as on routes with large changes in road height.
– Driving in a traffic jam gives a smaller EEC, due to the lower driving speed as long as the cross profile of the road is flat. A significant number of changes in road height causes an increase in EEC. Statistically, driving in traffic jams in terrain with changes in road height should therefore be avoided.
– Driving down and up to the same height causes additional energy consumption; the greater the changes in road height, the greater the increase in energy consumption. A road with a flat cross profile is therefore more energy-efficient.
– Driving a longer flat road can be more energy-efficient, especially with significant changes in road height (driving up–down–up). For roads with large changes in road height (over 20 m/1 km of route), a flat route with a length increased by 50% may be more energy-efficient than the original one.

Nomenclature

EEC	electric energy consumption
EV	electric vehicle
HEV	hybrid electric vehicles
ICEV	internal combustion engine vehicle
RBS	regenerative braking systems
RBSE	regenerative braking specific energy
SEC	specific energy consumption
SOC	state-of-charge

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