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INFLUENCE OF ROAD LONGITUDINAL TERRAIN PROFILE ON VEHICLE KINETIC ENERGY RECOVERY AND MITIGATION OF SELECTED TRANSPORT NEGATIVE ASPECTS

Summary. In recent years, environmental aspects of transport have been at the center of attention for research concerning sustainable development. The most discussed topics comprise vehicle emission production and fuel consumption. These are influenced by many variables and factors. In addition to individual vehicle characteristics and attributes, engine performances, exhaust systems, and their overall construction designs, the terrain and road profile itself have a non-negligible effect on emission production. Road profile parameters can increase or decrease the total vehicle consumption if its potential is utilized correctly. This manuscript discusses the options to reduce road vehicle consumption while accelerating where its velocity is decreased and yet again increased when using the longitudinal terrain profile principle. The physical relations for this subject are presented in the manuscript as well. Based on the data and knowledge achieved, the manuscript then addresses several scenarios in which the fuel consumption of the examined vehicle and an occurrence of certain emission types are examined. Lastly, multiple development trends that can positively affect the specified road vehicle's negative effects on the environment are described. The novel approach of the conducted research consists primarily of the interdisciplinary connection between road transport planning and vehicle traffic study (i.e., negative environmental aspects resulting from road transport can be mitigated not only by assistant devices installed in vehicles, such as catalytic converters, solid particle filters but also by constructing judiciously designed roads).

1. INTRODUCTION

As an integral part of critical infrastructure, road transport is essential for the functioning and stability of society, the economy, and the state. Its disruption could seriously affect national security, public health, citizens' lives, and the economy. Although it is not possible to imagine our lives without effective transport, its negative impacts on the environment and human life are disastrous. Many cities seek ways to mitigate these harmful effects and make urban and suburban logistics more sustainable. The kinetic energy recovery of vehicles using a road longitudinal terrain profile can help municipalities devise a viable strategy.

Vehicle fuel consumption and related environmental aspects preoccupy car manufacturers, public administration, and vehicle operators, severely inhibiting car development and legislation [1].

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All aspects of fuel consumption reflect principles of current physical and chemical knowledge [2]. Vehicle kinetic energy recovery involves the reusing of energy, part of which is standardly released under braking to the environment (like heat in the brakes) [3]. The generated power can be recovered by a system installed in the vehicle (e.g., electric cars) and external conditions (e.g., a longitudinal terrain profile) [4]. This method involves transport corridors designed to minimize the kinetic energy losses of vehicles and maximize recovery [5].

The local transport network is another crucial factor. Kinetic energy recovery may highly reward city centers witnessing heavy traffic and frequent halts but can also be effective on terrains where a vehicle's movement is fast and continuous [6]. Vehicle kinetic energy recovery and a road longitudinal terrain profile have overwhelming advantages, including cuts in fuel consumption and emissions, cleaner air, reductions in car operation costs, and an efficient transport network [7]. On the downside, the technology requires sizeable investments in road infrastructure, calling for careful thinking and the interdisciplinary involvement of problems [8, 9].

Exploiting the full potential of vehicle kinetic energy recovery and the longitudinal terrain profile relies on several factors. On top of efficient road infrastructure, vehicles must be equipped with modern energy recovery systems adapted to specific conditions. For example, cars with regenerative braking can be used, which would recover kinetic energy while slowing down. Car drivers must also be well-informed and trained to use these mechanisms (e.g., taking courses on properly using regenerative brakes and optimizing driving to the full potential of kinetic energy recovery) [10]. This burning issue will become increasingly important since environmental protection is vital for future sustainability. The advantages of vehicle kinetic energy recovery and a road longitudinal terrain profile transcend the drawbacks. Urban and suburban areas must then invest in road infrastructure and teach all transport users to exploit the potential of these technologies.

2. LITERATURE REVIEW

Negative environmental aspects arising from transport and related emission production entail one of the most crucial monitored parameters in the automotive sector. As discussed in [11], plain experiments could be used to determine the effect of acceleration of the vehicle on actual fuel consumption versus laboratory-related fuel consumption and produced pollutants (such as carbon/nitrogen oxides, monoxide, and hydrocarbons). Essentially, their research shows that automobile fuel consumption undergoing inspection is more responsive to a driving velocity compared to acceleration itself, while associated emissions produced are more responsive to the degree of the vehicle's deceleration and acceleration.

Multiple researchers and scientists, including Zarkadoula et al. [14] and Salvi and Subramanian [15], predict that air pollution causes approximately 500,000 premature deaths per year in Europe. The most crucial emissions include nitrogen oxides and particulate matter emitted mostly by road vehicles powered by engines with compression-ignition [16]. While electro-mobility has been gaining momentum, oil products as a propellant medium still prevail in the automotive sector, ensuring approximately 90% of its final energy utilization [17].

Lewicki W. (2017) stated that as far as an investigation in laboratory conditions is concerned, a wide array of variables and factors influencing the actual emissions production while the vehicle is in motion are usually not taken into account [18]. The research findings in relation to vehicles powered by a compression-ignition engine present that temperatures of the surrounding environment under 20 °C can cause insufficient processing and then diminish nitrogen oxide emissions. In that event, it can be caused by the improper functioning of exhaust gas recirculation (EGR) valves and catalytic converters. Rarely, this may even lead to an overall system failure.

The findings by Post et al. (1984) also confirm that actual emissions while the vehicle is in motion in real-world traffic scenarios often vary considerably compared to emissions examined in laboratory conditions when applying standardized procedures [19]. They state that fuel consumption and emission production models by power demand based on chassis dynamometer experiments on a series of vehicles and in real-world traffic in Australia are presented [19].

In line with a key objective of this research, several research works have also been focused on the investigation of negative environmental aspects of traffic in terms of the effect of different longitudinal terrain profiles on vehicle energy recovery. For instance, Da Lio et al. (2019) analyzed four distinct types of neural network models in association with longitudinal vehicle dynamics with gears and two control systems (such as a brake and engine system) [20]. Different road longitudinal slope profiles have been addressed in the literature [21], with the authors focusing on the emission of carbon rules of two distinct passenger car models on multiple road terrain slopes.

The ensuing principles were applied to define the effect of individual road profile parameters on the fuel consumption of vehicles, energy recovery, and carbon emission production: (a) the first law of thermodynamics, (b) the vehicle longitudinal dynamics theory, and (c) the mechanical energy conservation law. The objective of the research [22] was to detect and record specific combustion characteristics of a passenger vehicle propelled by a compression-ignition engine with various blend compositions with diesel while driving on different road height profiles. Lastly, Park et al. (2001) dealt with the design of novel driving modes, including different road gradients concerning their impact on fuel economy and vehicle emission production; several experiments and simulations were performed in real traffic conditions [23].

3. MATERIALS AND METHODS

Physics describes acceleration as the rate of change of velocity of an object in time. If an object's speed is constant, its acceleration equals zero. On the other hand, if its speed changes, the object accelerates. Accelerations are usually marked as 'a' (see Eq. 1) [24].

$$a = \frac{\Delta v}{\Delta t}\,[m/s^2] \quad (1)$$

If acceleration goes against the direction of movement, we call it a slowdown (retardation, deceleration). Physics describes the vehicle as a material point in a uniform straight-line motion unless affected by external forces.

Kinetic energy is the energy of motion observable in an object. Material points, like vehicles, have kinetic energy, which is calculated according to Eq. 2 [24]:

$$E_K = \int mdv\,[J], \quad (2)$$

where kinetic energy is represented by E_k, m is the weight of the vehicle, and v stands for its speed.

This equation involves a square power of the vehicle's velocity, indicating that kinetic energy increases exponentially with rising speed. For ideal vehicle acceleration, physics uses a formula to calculate the kinetic energy given by a driving unit.

If a vehicle weighing 1,300 kg accelerates from 0 to 30 km/h, the resulting energy E_k≈45.139 J. The vehicle consumption can be determined based on the fuel efficiency. Considering petrol fuel at the efficiency of 43.500 J/kg and petrol density of 700 kg/m^3, the resulting volume is V≈1.5 ml.

Since the suggested volume of fuel consumed at the acceleration from 0 to 30 km/h is only a theory supposing 100% efficiency, we did not include the impact of the driving unit and external influences (e.g., wind and tire drag, climate conditions) [25].

Full kinetic energy recovery using a longitudinal terrain profile requires its transformation into potential energy. Potential energy is the energy held by an object because of its relative forces and position. Potential energy is released when the object moves or changes its position.

The formula for potential energy is as follows (Eq. 3) [24]:

$$E_p = m * g * h\,[J], \quad (3)$$

where E_p is potential energy, the object's mass is marked as m, the gravity acceleration is marked as g, and 'h' is the height of an object above the zero level.

This equation uses the acceleration of gravity (usually approximately 9.81 m/s^2) and the object's height above the zero level. The zero level usually means the Earth's surface or another reference level [25]. Fig. 1 suggests a vehicle weighing 1.300 kg is going to a height of 1 m from the reference level, producing a potential energy of E_p=12,753 J for reverse acceleration. The power generated may set the vehicle to a speed of about 17 km/h, ignoring drag [26].

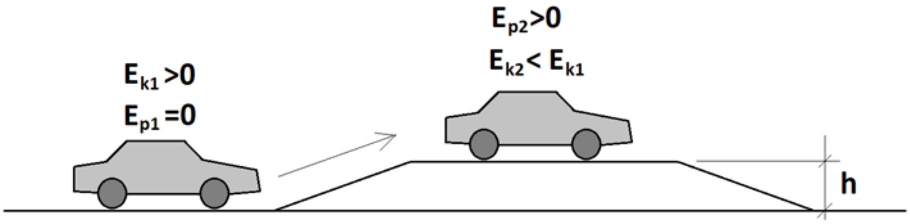

Fig. 1. The relation between potential and kinetic energy

The law of energy conservation says that road vehicles in motion can convert energy, not consume it. The power generated from fuel (or electricity from accumulators in electric cars) only partially transforms to motion because of rolling drags and the vehicle's overall efficiency. The same applies to the efficiency of kinetic energy recovery, depending on whether recovery systems can transform (accumulate) kinetic energy for reuse [26].

4. RESULTS: A CASE STUDY

As part of the research, practical measurements were carried out at the University of Žilina (Slovak Republic), specifically with the Department of Road and Urban Transport, to quantify the chosen operational features of the vehicle under laboratory conditions while accelerating in various height profiles of the road (flat 0.00%, uphill -8.5% and downhill 8.5%). The experiment included five vehicle accelerations on a flat surface, five downhill accelerations, and five uphill accelerations. The vehicle tested in the laboratory was the Kia Ceed (see Fig. 2). Table 1 presents its technical parameters.

Fig. 2. Kia Ceed, the tested vehicle at the University of Žilina

During the tests, the vehicle was equipped with the following technologies:

- Diagnostics of electronic systems Vgate Icar 2, including On-Board Diagnostics (OBD) Fusion program equipment:
  - fuel consumed [ml],
  - velocity [km.h^{-1}],
  - revolutions of the engine [min^{-1}],
  - torque [Nm],
  - position of the throttle valve [%],
  - performance of the engine [kW],
  - intake air amount [g.s^{-1}].

- Exhaust gas analyzer MAHA MGT 5:
  - CO, HC, NO_x, and CO_2 concentrations,
  - production of CO, HC, NO_x, and CO_2 [$g.0.05\ s^{-1}$],
  - CO, HC, NOx, and CO_2 accumulated production [g].

Table 1

Performance data of the tested passenger car

Business name	Kia Ceed	Engine code	G4FC
Displacement	1,591 cm^3	Length	4,265 cm
Type of the fuel	Petrol	Width	1,790 cm
Cylinder number	4	Height	1,480 cm
Max. power (performance)	90 kW (6,200 rotations per min^{-1})	Unladen mass	1,163 kg
Max. torque	154 Nm (4,200 rotations per min^{-1})	Overall mass	1,710 kg
Highest construction velocity	192 $km.h^{-1}$		

Field tests were conducted to measure the accumulated fuel consumption after the vehicle accelerated over 30 m, reaching 30 km/h. Table 2 summarizes the values of the fuel consumption.

Table 2 illustrates how terrain affects vehicle performance and efficiency, showing different fuel consumption data on flat land, uphill, and downhill. The data show how various terrain conditions influence fuel consumption and help us understand the differences. We expected the lowest gas expenditure to be recorded during the downhill acceleration, which the test confirmed, while the uphill speed increase consumed the most gas. Hillsides are an additional obstacle, requiring higher engine performance and more energy to overcome gravitational drag. The resulting higher fuel consumption increases the potential energy the vehicle can use for repeated acceleration.

Table 2

Accumulated fuel consumption after acceleration

Test number	Accumulated fuel consumption [ml]		
	Flat	Uphill	Downhill
1	8.19	11.87	4.73
2	8.35	11.11	6.47
3	9.01	11.03	4.28
4	8.53	10.91	5.50
5	9.19	11.22	6.56

Table 2 displays values regarding fuel consumption when vehicles accelerate under different terrain conditions. When choosing a car, one should consider these factors to meet our needs and preferences for effectively combining performance and fuel consumption.

We also measured CO_2 emissions during the same test (see Table 3).

Table 3

CO_2 emissions

Test number	CO_2 [g]		
	Flat	Uphill	Downhill
1	19.9	28.6	16.2
2	22.1	28.9	16.2
3	21.2	30.2	13.6
4	20.2	30.4	16.3
5	19.9	29.9	14.1

Table 3 shows different vehicle emissions from accelerations on various terrains and related environmental impacts. Understanding these differences allows an accurate assessment of the environmental influences of road transport. Uphill acceleration will probably increase emissions, posing an additional obstacle that involves higher engine performance. The increased exhaust gases may result from higher fuel combustion or gear change frequency to keep the vehicle in motion. Downhill acceleration also presents striking findings. Cars produce lower emissions when moving downhill than when moving over a flat surface, which harms the environment less. Downhill acceleration engages gravitation in relieving the engine of the stress, profoundly reducing emissions. Since cutting on greenhouse gas production is our primary aim, we should focus on road improvements to generate potential energy from the residual kinetic energy by braking.

5. DISCUSSION

The road terrain profile may optimize kinetic energy recovery, offering possibilities for reducing fuel consumption and cutting vehicle emissions. The terrain profile is integral for planning and developing sustainable transport infrastructure. More convenient and environmentally friendly road routes should be the main focus when developing or reconstructing roadways, as this would profoundly reduce fuel consumption and emissions production of CO_2 during acceleration [27].

Good roads need regular maintenance, as bumps, holes, and poor road conditions consume more vehicle energy. Promptly repairing defective segments allows smooth and steady movement without excessive braking and acceleration, significantly reducing fuel consumption and emissions [28]. Information and navigation technologies are also impactful when using an optimized terrain profile. Advanced navigation systems help analyze road topography, informing drivers on optimal speed, gears, or driving techniques to minimize fuel consumption and emissions [27]. Using a road terrain profile may markedly cut fuel losses and exhaust gases from road transport or at least prevent the situation from worsening.

Fig. 3 depicts intersecting Roads 0341 and 14611 in Třebotovice near České Budějovice, South Bohemia, where incoming vehicles on Road 0341 must stop and yield to cars on Road 14611. The figure also suggests ongoing road works and the partial closure of Road 14611, significantly impeding the traffic flow.

Incoming vehicles on Road 0341 must still give way, resulting in breaking downhill (8 m elevation difference) and repeated acceleration from a standstill. The findings of a nationwide survey suggest 800 passing vehicles a day [29]. Measurements of immediate vehicle consumption revealed that approximately 3 ml of fuel is saved per car in total passages by removing slowdowns and halts from the give-way zone (observing all safety rules), leading to a yearly reduction of 870 liters of fuel and related emissions. Thus, similar situations should be examined, and remedial measures (without creating safety hazards) should be adopted [29]. Other solutions may involve either landscaping the existing route and its surroundings or choosing a different trajectory layout. Navigation systems can also suggest a relevant speed when a car goes uphill to avoid sudden violent braking.

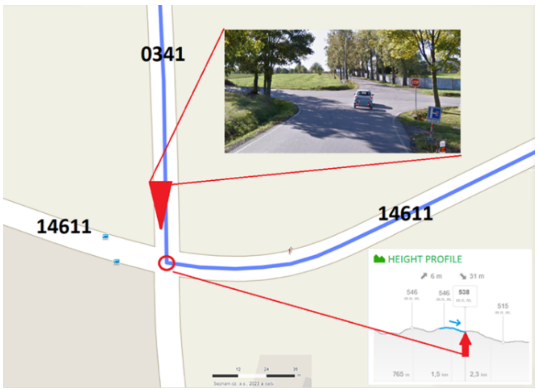

Fig. 3. Transport situation in the experimental profile

6. CONCLUSIONS

If it is necessary for a vehicle (or even a traffic stream) to brake or stop due to a traffic solution (unless this is unavoidable for safety reasons), it is advisable that this happens on elevated terrain as part of the vehicle's kinetic energy would remain available and would be "recovered" as potential energy. In the opposite case, as shown in the example situation, the kinetic energy is converted in the form of braking into heat, which is then freely released into the surrounding environment. For vehicles with the possibility of recuperation, only some kinetic energy can be recuperated, with the amount depending on the efficiency of the given recovery system.

The approach using the longitudinal terrain profile makes it possible to recover part of the kinetic energy without requiring additional technical devices in the vehicles, and its use is universal. However, it must be noted that for this system to work, it must be accepted by road users, which is the purpose of education. The present findings indicate a profound impact of terrain on the production of CO_2 emissions and fuel consumption while accelerating a vehicle. We measured the immediate consumption within 0.05 s, although the study did not require such accuracy. The measurements of cutting fuel consumption and emissions using a road longitudinal terrain profile in the traffic flow depend on various vehicles and drivers. Although a single car consumes very little fuel and produces few emissions when accelerating from rest to around 30 km/h, these are already large numbers in traffic flows. The traffic census indicates what measures to take to improve the situation.

The constantly increasing pressure to reduce emissions leads car manufacturers to support research in this area in an effort to find other possible solutions, as well as in the form of external (i.e., in addition to the car) measures. Similarly, many years ago, the development and construction of noise barriers and similar measures commonly occurred (and still occur) while striving to reduce the noise from road transport. Interest in research such as the present work has been growing perpetually with each publication of sub-findings, mainly because, for instance, in the European Union environment, the described phenomena can save millions of liters of fuel each year and considerably reduce the production of emissions; moreover, the implementation of such solutions does not require any further technological development, only the right application, which is expected to be cost-effective.

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