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DEVELOPMENT AND VERIFICATION OF AN ENERGY-EFFICIENT CONTROL SYSTEM FOR CONNECTED, HIGHLY AUTOMATED VEHICLES IN VARYING TRAFFIC DENSITIES.

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Abstract— One of the world's greatest challenges is the effort to reduce greenhouse gas emissions. One of the major sources of these emissions is road transport. The government is introducing a number of restrictions on the operation of internal combustion engine vehicles, such as a ban on warming up the engine. At the same time, car manufacturers are developing start-stop systems. All this is aimed at reducing fuel combustion and atmospheric emissions. Despite the complete phase-out of internal combustion engines by 2050, such vehicles will still form a significant part of the European car fleet. On the other hand, one of the reasons for the slow distribution of electric vehicles is their limited range. Both of these problems can be mitigated by energy efficient driving. The paper presents a mathematical model for energy efficient control of connected highly automated vehicles in the conditions of the modern metropolis. The mathematical model incorporates terrain, speed modes, and traffic light schedules. Field tests of the developed energy efficient control system were carried out. A car of the 3rd automation level with a petrol power plant was selected as a test object. The test route included highway and urban roads, with permitted speed limits ranging from 40 to 80 km/h, and 5 intersections with traffic lights and 3 ramps along the way. The tests were conducted with different traffic densities. The results of experimental runs are presented and the impact of traffic on the energy efficiency of an autonomous vehicle is analysed.
Keywords— road vehicle, energy efficiency, verification, autonomous transport, fuel consumption.

I. INTRODUCTION

Generally, the factors affecting fuel consumption include many aspects such as vehicle characteristics (e.g., weight, load, engine type, and power consumption of on-board devices), road conditions (e.g., road surface roughness, road gradient, and geometry), and environment (e.g., weather, temperature, and traffic conditions). In addition to these factors, optimizing the driving behavior of human-driven vehicles is considered by many researchers as the main measure used to reduce fuel consumption, this measure has been called "eco-driving". Fuel consumption (l/100 km) varies significantly depending on the speed range.

Juergen Hauenstein et al. [1] devoted their paper to vehicle energy efficiency, in their paper the authors investigated the effect of terrain on fuel consumption of heavy-duty vehicles. Many truck manufacturers offer on-board systems, which are also called GPS cruise control and are offered by most European manufacturers under brand names, e.g. EfficientCruise from MAN, Predictive Powertrain Control from Daimler, Opticruise from Scania. With topology information via a digital map and current position, energy-efficient rolling maneuvers can be performed. Such driver cues can save up to 7% fuel, but there is a nuance. A study by Samaras et al. found that at very high traffic densities, eco-driving leads to increased fuel consumption rather than fuel savings. Also, eco-driving cars may interfere with other road users, but it is not clear when this happens and how it can be formalized. Thus, the authors tried to address the problem of energy efficiency in mixed traffic flow.

Collision avoidance takes place using the calculated trajectories of the autonomous vehicle and the planned and desired trajectories of other road users. Due to inaccuracies, e.g. in the collection of measurement data or in the determination of the position or trajectory, a multi-stage collision check is performed. Trajectories are assigned tolerances. At any point in the trajectory, the position may deviate by a previously defined amount. If the selected trajectory is likely to lead to a collision, it is immediately discarded. The trajectories are then evaluated in terms of potential energy costs.

To test the developed system, a route with an uphill gradient of 2% and a downhill gradient of 6% was created. It is assumed that on a 2% gradient a 40 t truck is still able to maintain the maximum allowed speed, in the experiment this speed was 80 km/h. Scenario 1 simulates vehicles other than V2X that are not driven in an energy efficient manner. Scenario 2 represents vehicles other than V2X that are driven in an energy efficient manner, unlike scenario 1. Scenarios 3 and 4 represent V2X vehicles that use joint prediction but do not coordinate maneuvers among themselves. Scenario 3, unlike scenario 4, does not use an energy efficient driving strategy. Scenario 5 presents v2x vehicles that interact with each other and are also equipped with an energy-efficient driving system.
For the two trucks, there was no strong difference between scenarios 2,4 and 5 in terms of fuel economy, with an average fuel economy of 6.56%. In terms of average speed, as expected, scenario 3 took the lead, the other scenarios were between 0.25 and 0.49 meters per second. Scenario 5 was the most energy efficient scenario for the three trucks, with an average fuel saving of 5.61% over the 1500 meter distance. At the same time, the difference in average speed between Scenario 3 and 5 was reduced from 0.26 to 0.2 m/s.
As noted by the authors of the previous paper, the development of 5G technologies will significantly increase the data exchange between vehicles and the surrounding infrastructure. Yasutaka Okada et al [2] developed a system to reduce the fuel consumption of a hybrid vehicle.
In the case of two vehicles, it was found that it is efficient in terms of fuel economy to maintain a driving speed equivalent to the vehicle ahead. At the moment when the driving speed is approaching the speed limit or the distance to the nearest traffic light is short, then it is more efficient to use a different behavior model.
If the vehicle ahead of you starts to slow down or plans to stop before a red traffic signal, it will be ineffective to reduce your speed in the same way as the vehicle ahead. In this case, it is necessary to be able to predict the behavior of the road user ahead. This will allow you to start slowing down in advance and avoid sudden braking.
In the case when the vehicle in front is moving at the maximum permitted speed, the authors propose to introduce a correction in the form of 0.36 km/h to avoid violation. Reducing the maximum permitted speed by this amount will avoid the violation and avoid unnecessary corrections in acceleration/deceleration.
According to the experimental results, it was found that the developed system allows the powertrain to be driven in high efficiency areas and efficiently recover energy. Thus, compared to a transmission with a constant torque ratio, the difference in fuel economy was about 30%.
Another area for improving the energy efficiency of a vehicle is the management of power distribution to the drive wheels [3,4]. This work examines the factors affecting the efficiency of a multi-purpose wheeled vehicle, focusing on the maximum and average technical speeds. It explains how power-to-weight ratios and suspension parameters determine these speeds and how increasing power-to-weight and mass ratios can result in lower speed gains. The author also discusses various ways of distributing power to the driving wheels of a vehicle, such as disconnecting drive axles and locking differentials. Ways of upgrading the drivetrain of multi-purpose wheeled vehicles to improve efficiency are suggested, including the introduction of four-wheel drive and tyre pressure adjustment.
Bin Zhao et al [5] examined the effect of different scenarios of higher density mixed traffic flow on vehicle fuel consumption. The mixed traffic flow was modeled on 3 separate road sections: a straight road with one of the lanes reduced, a freeway with gradients, an exit and abutment, and a regulated intersection.
Having analyzed the simulation results, it turned out that in the case with the reduction of one of the lanes, the dependence of fuel economy on the percentage of connected vehicles is approximately linear and at 100% automation of traffic flow reaches 13.7%. In the case of highway traffic it was possible to achieve a significant increase in fuel economy only at 100% automation of the traffic flow, the value was 7.2%. In the scenario with a controlled intersection, approximately the same dependence as in the first scenario was observed, but the effect of the introduction of connected vehicles was more significant - at the level of traffic flow automation of 50% the fuel economy was 19.3%, and at full automation - 40.9%.
The utilization of sound source arrival direction estimation technology has the potential to enhance a vehicle's energy efficiency by optimizing its capacity to perceive and navigate its surrounding environment [6]. By accurately estimating the direction of sound sources, an autonomous driving system can enhance its comprehension of the surrounding environment, thereby enabling more informed decision-making about its driving. This may result in a reduction of unnecessary accelerations and decelerations, which are a source of energy wastage. Furthermore, the incorporation of auditory information into the vehicle's sensory systems enables more efficient operation in complex urban environments, facilitating the avoidance of obstacles and the optimization of routes to reduce fuel consumption.
Viranjan Bhattacharyya and others studied the effect of traffic flow on energy efficiency and came to the following conclusions: Stop-and-go driving is one of the primary causes of high fuel consumption and reduced energy efficiency [7]. Frequent acceleration and deceleration lead to increased engine power usage, resulting in greater fuel consumption. Vehicles idling at red lights consume fuel without any productive movement, leading to wasted energy. The proposed control strategy helps minimize red-light idling by adjusting vehicle speeds so that they reach intersections during green lights. By reducing the time spent idling, the framework lowers overall fuel

consumption, leading to better energy efficiency. This effect is more pronounced in urban areas with frequent traffic signals. Abrupt acceleration and heavy braking consume more fuel than gradual, smooth driving. The control framework improves traffic flow by providing velocity suggestions that help human-driven vehicles (HDVs) anticipate changes in speed and adjust more gradually. The smoother driving patterns reduce the amount of energy needed for acceleration, enhancing the fuel efficiency of both CAVs and HDVs in the traffic network. Traffic congestion and high traffic density lead to increased energy consumption due to more frequent braking, idling, and slow speeds.

Ozan Yazar and others have found that technologies such as V2X can increase vehicle energy efficiency even in dense traffic [8]. CACC (Cooperative Adaptive Cruise Control) systems utilize information from surrounding vehicles to maintain optimal distances and speeds, reducing unnecessary acceleration and braking. This coordination leads to smoother traffic flow, which can significantly lower energy consumption compared to traditional driving methods. In a platoon of HEVs, vehicles can closely follow one another, reducing aerodynamic drag and improving overall fuel efficiency. Studies have shown that energy optimization in a platoon can lead to substantial fuel savings, as vehicles can share information about their speed and acceleration, allowing for more efficient driving strategies. The overall traffic conditions, such as congestion and stop-and-go scenarios, can lead to increased energy consumption. In contrast, steady traffic flow allows for more consistent speeds, which is generally more energy-efficient for HEVs. The integration of V2X communication technologies allows vehicles to receive real-time information about traffic conditions, enabling them to adjust their driving strategies accordingly. This can lead to reduced energy consumption by avoiding unnecessary stops and optimizing speed profiles based on traffic flow.

The article is organized as described below. In the Energy efficiency system, we introduce an approach for fuel (energy) saving on hilly roads, including traffic lights and in the field of fuel consumption analysis and optimization. In the Verification of the developed system, we describe the experimental conditions. In the Results, we describe the results of the experimental runs. In the Impact of traffic flow on vehicle energy efficiency, we provide comparative graphs and analysis of the empty road and traffic runs.

II. ENERGY EFFICIENCY SYSTEM

The analysis of scientific solutions for energy efficiency of highly automated vehicles found that:

- Existing scientific studies address disparate energy efficiency problems. Different works consider the energy efficiency of a certain vehicle with a certain type of power plant in certain driving modes.
- Most of the published studies are theoretical in nature, unsupported by experimentation, and need to be proven in the real world.
- Work is needed to develop a comprehensive approach to the energy efficiency of connected, highly automated vehicles regardless of their powertrain, modes and operating conditions. In addition to the scientific novelty justified in the article, the development of such a system has obvious practical significance due to the economic potential of reducing the costs of transport and logistics companies for passenger and freight transportation by road, and will also reduce the volume of exhaust emissions from highly automated vehicles.

This paper proposes a system adapted for internal combustion engines, taking into account traffic lights and road topography. It will be further developed to meet the above criteria.

A. Fuel consumption model

In the present work, the main equation, which is used for calculation of fuel consumption and optimization of control actions, is formula (1) [9].

$$G_t = \frac{\int \frac{3600 \cdot \rho_k \cdot \eta_v}{p_e \cdot \alpha \cdot l_0} \cdot \mathrm{v} \cdot (P_r + P_a + P_i + \mathrm{Br}) \cdot \frac{1}{\eta_T} \cdot dt}{\int 755 \cdot \mathrm{v} \cdot \mathrm{dt}}, (1)$$

where: $\boldsymbol{G_t}$ – fuel consumption per unit of traveled distance, $\boldsymbol{\rho_k}$ – charge density, η – transmission efficiency, $\boldsymbol{\eta_v}$ – fill factor, $\mathbf{p_e}$ – average effective pressure, $\boldsymbol{\alpha}$ – excess air factor, $\mathbf{l_0}$ – theoretically required amount of air for combustion of 1 kg of fuel, υ – vehicle speed, Br – braking resistance, t – time, $\boldsymbol{P_a}$ – air resistance, $\boldsymbol{P_i}$ – inertia forces.

The model that takes into account the physics of the car and engine, tested in the article [10], was taken as a basis. The proposed model, in comparison with the previous one, additionally takes into account the following factors (2 - 4) [11]:

$$\rho_k = \frac{\rho_0 \cdot 10^6}{R \cdot T_0}, (2)$$

where: R – specific gas constant, $\boldsymbol{\rho_0}$ – ambient pressure, $\mathbf{T_0}$ – ambient temperature.

$$p_e = p_i - \left(0{,}089 + 0{,}0118 \cdot \frac{s * n}{30}\right), (3)$$

where: S – piston stroke, n – crankshaft revolutions, $\mathbf{p_i}$ – average indicator pressure.

$$\boldsymbol{P_r = sin\alpha \cdot g \cdot G + G \cdot g \cdot cos\alpha \cdot \frac{k}{1000} \cdot \left(5{,}1 + \frac{550000+90 \cdot G_k}{P_{TP}} + \frac{1100+0{,}0388 \cdot G_k}{P_{TP}} V^2\right)}, \quad (4)$$

where: k – coefficient accounting for tire structure; Gk – vertical wheel load; $\boldsymbol{P_{TP}}$ – tire pressure; V – vehicle speed, g – free fall acceleration, α – longitudinal slope of roadway profile, G – vehicle weight

Specific fuel consumption (5 - 6) was calculated according to the following formula [12]:

$$\mathbf{g_e = 1000\frac{G_t}{N_e}}, (5)$$

where: $\mathbf{G_t}$ **– fuel mass flow,** $\mathbf{N_e}$ **– effective power.**

$$\mathbf{G_t = G_{tc} \cdot 60 \cdot \frac{2n}{t}}, (6)$$

where: $\mathbf{G_{tc}}$ **– cycle fuel rate, n – engine speed, t – coefficient of stroke (4 for 4 stroke engines)**

The general view of the implementation of the mathematical model in Matlab Simulink environment is shown in Fig. 1.

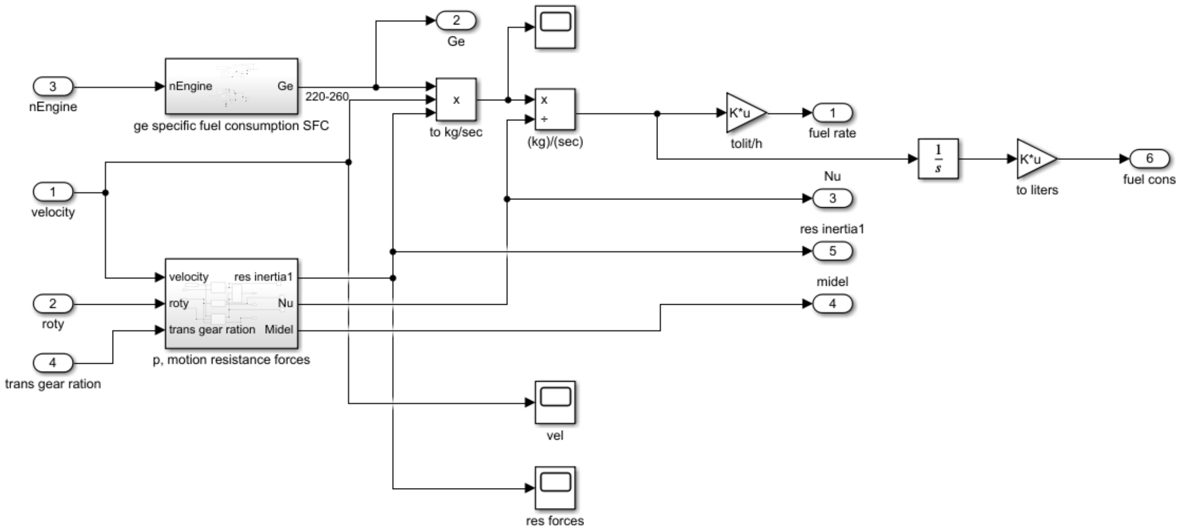

Fig 1 General view of realization of the mathematical model of car fuel consumption in Matlab Simulink environment.

B. Energy efficiency algorithms

The output value at the accelerator pedal depends on the following factors: the mode of the nearest traffic light, the predicted road slope, the vehicle acceleration error, the vehicle speed error, the distance to the nearest traffic light, the time to change the speed limit, and the difference between the current speed limit and the future speed limit. Schematic of the proposed method in the Fig. 2.

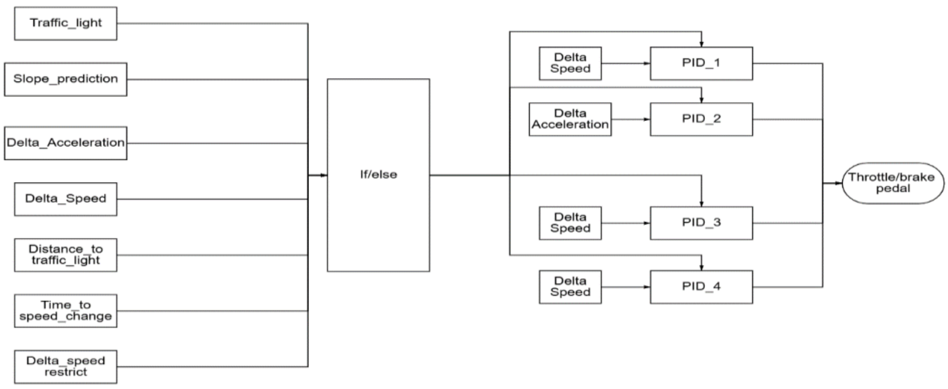

Fig 2 Schematic of the proposed method

Then, depending on the driving conditions, one of the 4 PID controllers is activated. PID_1 - responsible for driving the vehicle on a horizontal road with small deviations from the nominal speed. PID_2 - Responsible for rolling before a speed change and/or traffic light. PID_3 - Responsible for controlling vehicle speed on uphill and downhill slopes. PID_4 - Involved in the driving process if none of the above conditions are met.

There are essentially 2 ways to implement V2X: via cellular links or ad hoc networks. Ad hoc networks, such as ITS-G5 or IEEE 802.11p, do not require any other infrastructure and send messages via broadcast to all surrounding participants. In cellular networks, such as V2X-LTE or 5G NR mode 1, messages are sent through a cell tower. Cellular networks have the advantage of theoretically infinite range and can handle more data traffic, but only where there is network coverage. In addition to packet loss, there is a delay in receiving messages. On average, this delay is between 90 and 125 ms for IEEE 802.11p and typically more than 2500 ms for V2X-LTE. However, the introduction of 5G in cellular networks is expected to bring significant improvements over LTE technology and reduce latency from 4 to 1 ms. [13].

C. Computer simulation

Computer simulation was carried out on a digital twin of the real road, Figure 3, taking into account the elevation difference and traffic light regulation. The characteristics of the route are given in Table 1. The route includes highway and urban roads, with permitted speed limits ranging from 40 to 80 km/h, and 5 intersections with traffic lights and 3 ramps along the way. To create the most accurate virtual copy of the test route, a multi-band RTK GNSS module was used for accurate navigation and mapping [14]. The digital twin was created with mapping requirements in mind [15].

The information about the operation mode of the traffic light was received by the automobile instantly. Each traffic light had its own GPS coordinates. The automobile was oriented to the operation of the nearest traffic light. The operation of the traffic light in the Simulink is shown in the fig. 3.

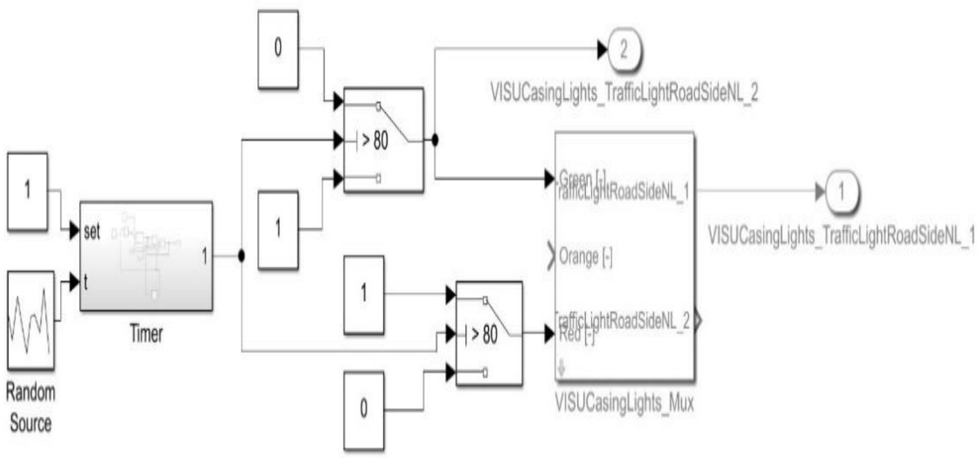

Fig. 3 Implementation of traffic light in Matlab Simulink

There are 5 traffic lights along the route. Each of the traffic lights has its own operating schedule. The time of red and green light switching on is determined randomly within a specified range. The range of green or red light activation is set via Random source and Switch block.

The following assumptions were used during simulation:

- the reduction of vehicle speed during maneuvering is not taken into account;
- the traction properties of the wheels and the road surface are unchanged;
- weather conditions (temperature, humidity, air pressure, wind speed) are set to be stable.

The experiment lasted 13.5 kilometers on the entire route and we compared two driving modes: 1) driving with intelligent speed control with a speed regulation algorithm at a nominal value of speed limit ± 10 km/h, depending on whether the route has an upward or downward slope and taking into account traffic lights; 2) driving with a constant velocity as the average velocity in the first case (and therefore the same time of driving). The results of the experimental run are shown in fig. 4.

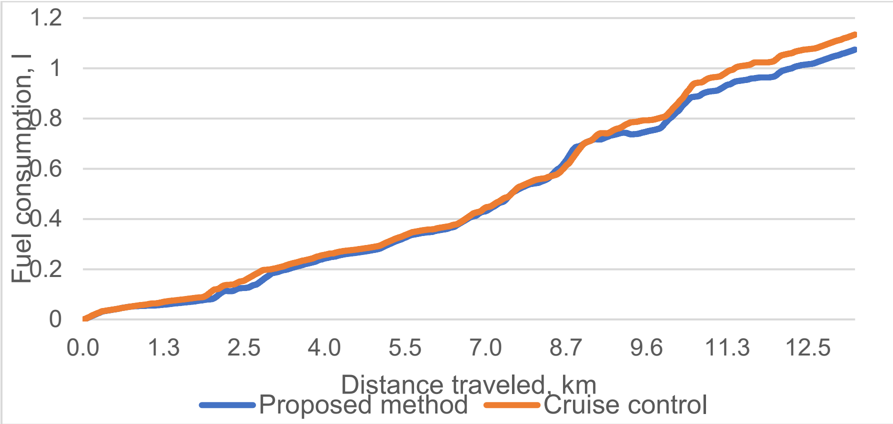

Fig. 4 Comparison of fuel consumption with the proposed method and cruise control.

For a vehicle weight of 1650 kg and an average speed of 50 km/h. To draw conclusions from this experiment we will use Figures 5 and 6 for convenience.

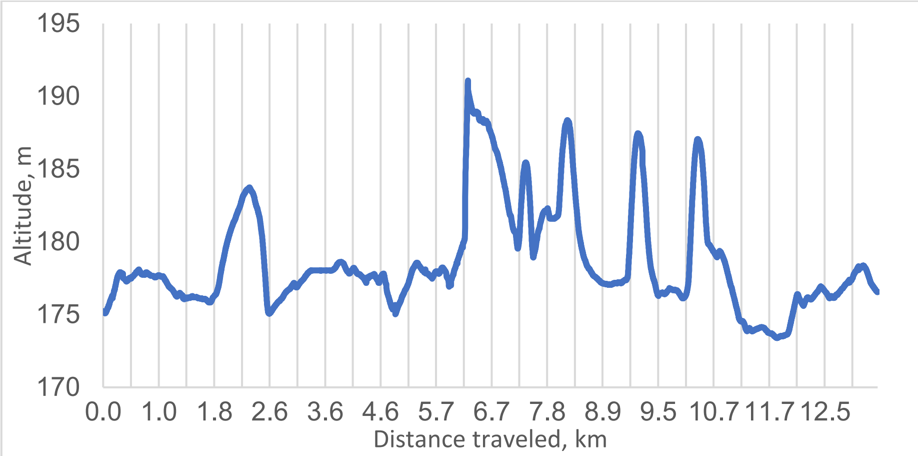

Fig. 5 Federal highway altitudes (Leningradsky Prospekt - Volokolamskoye Highway)

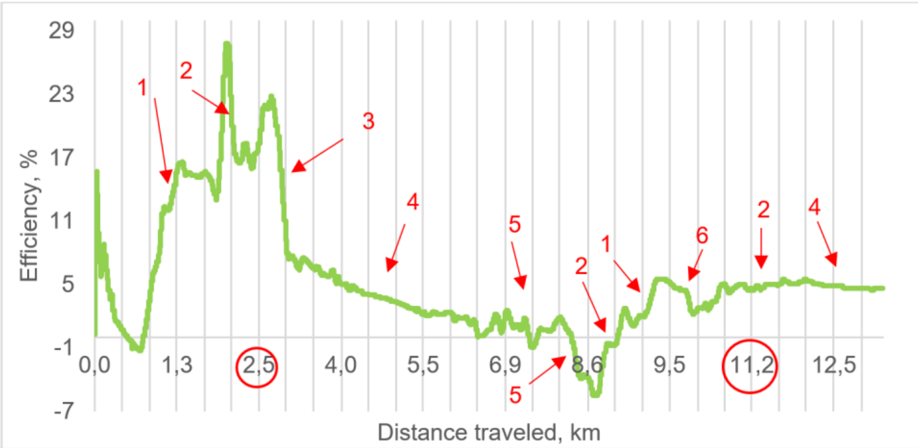

Fig. 6 Federal highway altitudes (Leningradsky Prospekt - Volokolamskoye Highway)

D. Impact of road infrastructure on energy efficiency

The following conclusions can be drawn as a result of the conducted experiment:

1) Energy efficiency improvement due to topography. Improving energy efficiency by controlling vehicle inertia on hilly terrain is not new. This approach has been successfully used by professional drivers, and it has also been proven to work in highly automated transport studies [16,17].

The proposed method also demonstrates energy efficiency in hilly terrain. This can be seen under figures 2. On the first flyover, the efficiency gain was 15%, while on the second and third flyovers 10% and 2% respectively.

2) Energy efficiency improvement due to V2I. Unlike the terrain, it is more difficult for the driver to predict the mode of operation of traffic lights and plan his maneuver. But this approach also demonstrates high energy efficiency in the reviewed studies [18,19]. The performance of the traffic light interaction of the proposed method can be observed at 2 locations under numbers 1, +15% and + 4%.
3) Negative energy efficiency on flat terrain. The basis of controlling the inertia of the vehicle on hilly terrain is to control the speed in a certain range (in this experiment around 10 km/h) depending on the angle of ascent/descent. This leads to the fact that on overpasses, the average speed of a car equipped with intelligent speed control will be higher than a car with cruise control. In order for both cars to cover the same distance in the same amount of time, it is necessary to set the cruise control to a slightly lower speed than the smart controller. This leads to the fact that on flat terrain (around 1% in this experiment), the fuel consumption of the cruise control car will in any case be lower than the smart controller, which can be observed under numbers 4 in graph 6. In the first case at a distance of 3 km the energy efficiency was minus 5%, in the second case at a distance of 1 km it was minus 1.7%.
Comparing the graph of terrain and energy efficiency, it can be found that in some places after overpasses (3,5) or traffic lights (6), energy efficiency is not so significant or even negative. Here we can draw another conclusion:
4) Road infrastructure can have a significant impact on vehicle energy efficiency. Vehicle inertia control on hilly terrain is designed to drive up a hill at high speed and then accelerate down the hill. It is easier for the car to move downhill under the influence of gravity than uphill, so the fuel consumption per unit of traveled distance will be less. It is at these moments that the speed of the car is controlled (increasing the speed on the downhill and decreasing it on the uphill). Thus, ideally, nothing should prevent the car from going uphill or downhill. But in reality, this is not always the case. The number 3 on the energy efficiency graph symbolizes the overpass exit shown in Fig. 7. The red line in Fig. 7 represents the vehicle's trajectory. Ideally, the car should accelerate to 80 km/h from the ramp and save fuel. In reality, it turns out that the car accelerates to about 60, after which it is forced to brake, otherwise it simply will not fit into the realignment across 2 lanes (one of which is a bus lane) at a distance of 100 meters. In medium or dense traffic in this place cars may even stop to make such a maneuver. In the described experiment, by performing this maneuver the energy efficiency was reduced from 23% to 7%.

Fig. 7 Exit ramp near Dynamo

The ideal situation for controlling the vehicle's inertia on hilly terrain is when one uphill/downhill section immediately alternates with another, bypassing the flat terrain sections we described in point 3. The road section from kilometer 6 to kilometer 9 is exactly like this. There are 3 overpasses in this distance. But the whole effect of the energy efficient management is offset by the speed limits (number 5 in figure 6). This is especially visible at a distance of 8.5 kilometers. The car accelerates to a speed of 100 km/h when descending from the previous overpass and must reduce its speed to 40 km/h over a distance of 150 meters when entering the next ramp. This is quite intensive braking and all the energy saved goes into heat. As a result, this maneuver resulted in an energy efficiency loss of 7%. Under number 6 is an example of another failed infrastructure solution in terms of vehicle energy efficiency. At a distance of 9.5 kilometers there is a traffic light, which in the presented scenario was red when the car reached it. Figure 5 shows that this traffic light is located directly after the downhill exit from the ramp. In this case we have 2 energy efficiency models overlaid at the same time in the same location. We need to pick up speed while descending from the ramp and we need to roll (which in this case will not give a visible advantage, because the car is moving from the downhill slope and we will have to use brakes anyway) before the traffic light. In the end, neither approach saves fuel and as a result we get an energy efficiency of -2%. Negative energy efficiency is taken from the point of view that we should have been moving faster on that stretch than we actually did. All our energy has gone into the heat of braking. The car with cruise control also braked on this section, but it was traveling at a slower average speed on the previous section, hence the -2% difference. This overpass exit is also unfortunate because of its location. We have previously described how a car should ideally behave when descending an overpass. If the green traffic signal was on, the car would accelerate to 60 km/h when going down the overpass, after which it would have to brake to 30 km/h to fit into a turn of more than 90 degrees, fig. 8.

Fig. 8 Exit ramp near Streshnevo

III. VERIFICATION OF THE DEVELOPED SYSTEM

Within the framework of field tests 2 series of runs of 10 laps were carried out, and the total amounted to 270 kilometres. The 1st series of races was conducted with the energy efficiency system on. During the 2nd series of runs, the car was driven on cruise control at a speed equal to the average speed of the car in the 1st series of runs. After each series of runs, the car was refuelled to a full tank. The difference between the petrol burned after the first and second series of runs was the energy efficiency.

The fuel consumption calculation model was calibrated before the test runs. The correction factor was determined during the separate experimental run. The fuel tank was filled up. After that the car travelled 140 km and returned to the same gasoline station. The ratio of fuel consumption from the diagnostic scanner and the specially calibrated for this purposes fuel column was 0.96.

A. Route

The route includes highway and urban roads, with permitted speed limits ranging from 40 to 80 km/h, and 5 intersections with traffic lights and 3 ramps along the way. The characteristics of the route are given in Table 1. A general view of the route is shown in fig. 9.

TABLE 1. TRAVEL ROUTE CHARACTERISTICS

Characteristics	**Value**
Length, km	13,5
Route type	Closed
Average gradient, %	+- 1
Maximum ascent, %	~ 14
Maximum descent, %	~ 17
Type of pavement	Asphalt concrete
Surface condition	Clean

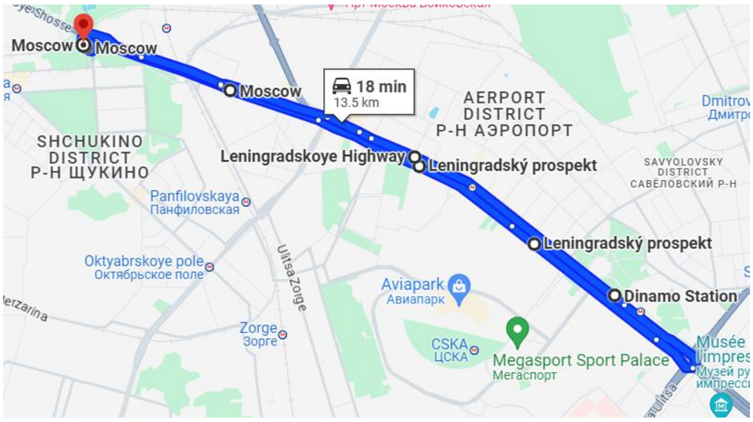

Fig. 9 The plot of a real road from which was made the digital terrain model

B. Vehicle

The tests were conducted on a Chevrolet Orlando automation level 4 vehicle, Fig. 10. The vehicle utilizes a hybrid navigation system that includes satellite navigation, inertial reporting systems, and computational-analytical calculations. The vehicle is equipped with a radar placed in the front of the vehicle, two side cameras, two cameras on the windshield, a GPS receiver and lidar.

Fig. 10 The general view of the test vehicle

C. Experiment results

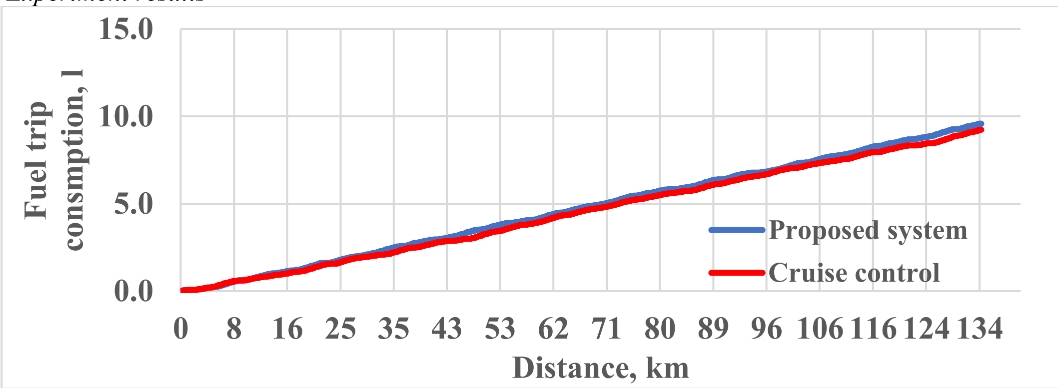

Fig. 11 Results of the field experiment

The field experiment was conducted on the same road section as in the computer simulation. The 1st series of runs was conducted with the energy efficient control system, in the evening time of day, under low traffic density conditions. The average speed on the route was 47.7 km/h. The car consumed 9.59 litres of fuel. The 2nd series of races was conducted with the car with cruise control on, set at a speed of 48 km/h. The race was held at night, with minimal traffic. Also, the traffic lights schedule were changed so that the red light was on much less and the green light much longer, compared to the evening run. The average speed over the 134 kilometer distance was 53.5 km/h. The car consumed 9.23 litres of fuel, fig. 11.

D. Impact of traffic on energy efficiency

The relationship between energy efficiency and driving performance is characterized by a trade-off, often referred to as conflict correlation in eco-driving management. Optimizing energy efficiency typically involves minimizing vehicle speed fluctuations through smooth acceleration and deceleration, which reduces kinetic energy losses. Conversely, improving driving efficiency often requires rapid changes in speed to reduce travel time, resulting in increased energy consumption due to frequent acceleration and deceleration. This dichotomy is particularly pronounced in mixed-vehicle platoons, where the diverse dynamics of connected and automated vehicles (CAVs) and human-driven vehicles (HDVs) further complicate the optimization of both efficiencies [20]. In fig.12, the blue arrow indicates that the car is stopped in front of a traffic light. The red arrows show a vehicle suddenly reducing speed due to an obstruction in the road (unpredictable behavior of other road users). In the fig. 12, the arrows indicate only a few situations where other road users have an impact on energy efficiency. The green arrow indicates a section of road where the car was descending from an overpass at a permissible maximum speed of 95 km/h. The car equipped with the energy efficiency system was not only unable to accelerate to the allowed speed, it also started to slow down while on the overpass due to traffic. Such a maneuver has a very negative impact on the energy efficiency of the vehicle. Also, comparing the red and blue lines, we can see that in the first series of runs, the car was almost nowhere able to accelerate to the permissible speed. The higher the speed, the higher the inertia of the car and the higher the energy efficiency. On average, the difference in fuel consumption per lap in traffic and without it was 5%.

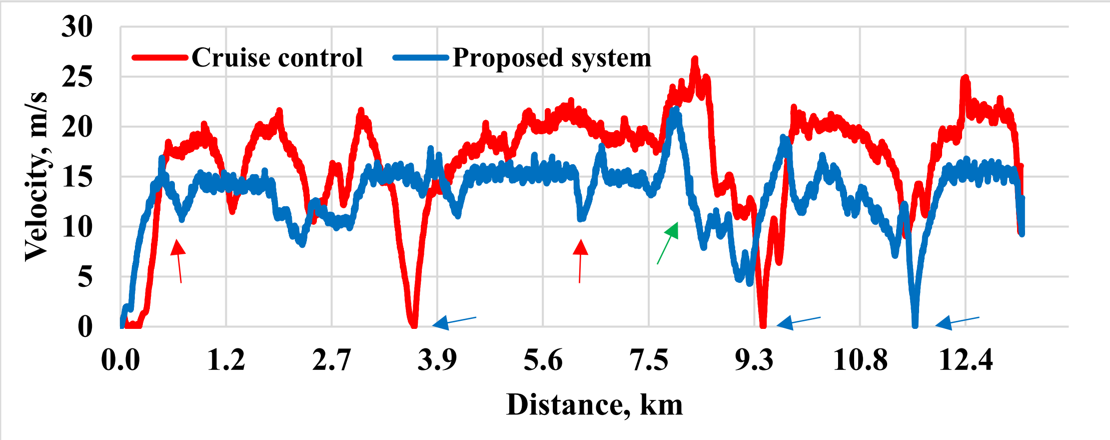

Fig. 12 Comparative diagram of vehicle speed in traffic and without traffic

IV. CONCLUSIONS

This paper presents a study on the development of a mathematical model and control algorithms to improve the energy efficiency of connected automated vehicles. The conducted field tests and laboratory tests on the third level of automation vehicle demonstrated the significant impact of road infrastructure and traffic density on fuel consumption. The results of virtual experiments showed that the use of intelligent speed control that adapts to changing route conditions can achieve improved energy efficiency, especially in sections with changing terrain.
During the tests, a comparative evaluation of two driving modes was carried out: with intelligent speed control and with constant average speed. In the full-scale experiment, the system worked reliably, and all speed limits were met. Due to the different road conditions, the effectiveness of this method cannot be confirmed. In addition, the obtained difference in fuel consumption is within the limits of measurement error. The next step will be to refine the system to improve its performance and conduct additional field tests to demonstrate energy efficiency in equal road conditions with cruise control.
Further research will focus on adapting the proposed algorithms for hybrid and electric vehicles, and conducting comparative tests to evaluate their energy efficiency. An important aspect of future research is the improvement of V2I systems, which can significantly improve the efficiency of traffic management and reduce greenhouse gas emissions.
Plans for further research:
1. Conduct a field experiment for the developed energy efficiency system and system and standard cruise control under the same conditions.
2. Adapt the proposed algorithms to hybrid propulsion and electric traction vehicles.
3. Conduct comparative tests of energy efficiency and cruise control algorithms for hybrid and electric propulsion system.

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