MOBILITY & VEHICLE MECHANICS

https://doi.org/10.24874/mvm.2024.50.04.03
UDC: 629.3.072.2

DEVELOPMENT OF AN ENERGY-EFFICIENT CONTROL SYSTEM FOR CONNECTED, HIGHLY AUTOMATED VEHICLES

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Received in August 2024 *Revised in September* *Accepted in October 2024*

RESEARCH ARTICLE

ABSTRACT: One of the world's most significant challenges is the effort to reduce greenhouse gas emissions. One of the primary sources of these emissions is road transport. On the other hand, road freight transport, which represents a huge portion of freight transportation, accounts for a considerable portion of the company's expenditures on fuel. Reducing fuel consumption and, therefore, greenhouse gas emissions, reducing fuel costs and increasing driving range can be achieved by increasing the energy efficiency of the vehicle. The paper presents a mathematical model for the energy-efficient control of connected, highly automated vehicles. The mathematical model incorporates terrain, speed modes, and traffic light schedules. Laboratory tests of the developed mathematical model are carried out on a digital twin of a test road section recreated on the basis of high-precision navigation data and a passenger vehicle with an internal combustion engine. In the laboratory tests, the proposed system is compared with a vehicle being driven on cruise control. The average speed of both vehicles on the selected route is identical. The results of the experimental runs indicate that the proposed mathematical model is 4.5% more efficient than the vehicle operating on cruise control. Further research is planned to adapt the developed model for hybrid and electric propulsion systems and to conduct field tests on unmanned vehicles with internal combustion engine and electric power plant.

KEY WORDS: *Road vehicle, Digital twin, Simulation, Digital terrain model, Fuel consumption, Mathematical model verification, Automobile, Highly automated transport, Autonomous transport, Energy efficiency, Fuel economy, Energy saving, v2x.*

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RAZVOJ ENERGETSKI EFIKASNOG UPRAVLJAČKOG SISTEMA ZA UMREŽENA, VISOKO AUTOMATIZOVANA VOZILA

REZIME: Jedan od najznačajnijih svetskih izazova je nastojanje da se smanje emisije gasova staklene bašte. Jedan od primarnih izvora ovih emisija je drumski transport. S druge strane, drumski teretni transport, koji predstavlja veliki deo transporta tereta, čini značajan deo troškova kompanije za gorivo. Smanjenje potrošnje goriva, a samim tim i emisije gasova staklene bašte, smanjenje troškova goriva i povećanje dometa mogu se postići povećanjem energetske efikasnosti vozila. U radu je prikazan matematički model za energetski efikasnu kontrolu povezanih, visoko automatizovanih vozila. Matematički model uključuje teren, režime brzine i raspored semafora. Laboratorijska ispitivanja razvijenog matematičkog modela vrše se na digitalnom dvojniku probne deonice puta rekonstruisanom na osnovu visoko preciznih navigacionih podataka i putničkom vozilu sa motorom sa unutrašnjim sagorevanjem. U laboratorijskim ispitivanjima, predloženi sistem se upoređuje sa vozilom koje se vozi na tempomat. Prosečna brzina oba vozila na izabranoj trasi je identična. Rezultati eksperimentalnih vožnji pokazuju da je predloženi matematički model za 4,5% efikasniji od vozila koje radi na tempomatu. Planirana su dalja istraživanja radi prilagođavanja razvijenog modela za hibridne i električne pogonske sisteme i izvođenje terenskih ispitivanja na bespilotnim vozilima sa motorom sa unutrašnjim sagorevanjem i elektroenergetskom postrojenjem.

KLJUČNE REČI: *Drumsko vozilo, Digitalni blizanac, Simulacija, Digitalni model terena, Potrošnja goriva, Verifikacija matematičkog modela, Automobil, Visoko automatizovan transport, Autonomni transport, Energetska efikasnost, Ušteda goriva, Ušteda energije, v2k.*

DEVELOPMENT OF AN ENERGY-EFFICIENT CONTROL SYSTEM FOR CONNECTED, HIGHLY AUTOMATED VEHICLES

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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. Licheng Zhang et al. [1] developed a new computational approach to accurately estimate the fuel consumption of heavy-duty vehicles. The researchers derived an equation that confirms the proportionality of fuel consumption to speed fluctuations. The greater the oscillation, the more fuel is required to overcome wind resistance, and the more likely it is to decelerate to ensure safe driving - hence there will be more energy lost due to friction as more additional energy is converted to heat energy. The more instances of deceleration, the more noticeable the stop-and-go factor is when driving the same kilometer, which is why frequent acceleration and braking entail more frictional energy loss

Experimental validation included computer simulations and a road experiment. The simulation was conducted using data recorded from the vehicle. The data was collected using an on-board diagnostic port reader. Parameters such as: speed, instantaneous fuel consumption, crankshaft speed, time, mileage and others were recorded on a laptop. Field experiments were conducted with the autonomous vehicle in two driving modes: autonomous and human driven. The test route covered several road scenarios: urban infrastructure, expressways and rural road. The total length of the route was 160 km. The speed range varied from 0 to 130 km/h

The tests showed that speed fluctuations have a significant effect on fuel consumption. When the vehicle is in deceleration mode, fuel consumption is negligible. During the trip, fuel consumption is mainly in cruising mode and during acceleration. The fuel consumption in acceleration mode is about 2 times higher than in cruising mode.

The experiment with the autonomous vehicle took place in a closed area. The vehicle was equipped with lidar, cameras, DGPS, radars and could operate in both autonomous and manual modes. The test vehicle belongs to automation level 3. The experiment was conducted in manual and autonomous mode at two speeds of 20 and 40 km/h. In the test driver control mode, fuel consumption (l/100 km) increased by 5.6%

Juergen Hauenstein et al. [2] also 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 [3] 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%.

Bin Zhao et al [4] 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%.

Another area for improving the energy efficiency of a vehicle is the management of power distribution to the drive wheels [5,6]. 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.

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 [7]. 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.

The article is organized as described below. In Approach, we introduce an approach for fuel (energy) saving on hilly roads, including traffic lights and in the field of fuel consumption analysis and optimisation. In Simulation and results, we provide a description of the computer simulation represents results of fuel values for gasoline vehicles with and without use of the proposed algorithm of intelligent speed adjustment.

1 APPROACH

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.

1.1 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) [5].

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

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

The model that takes into account the physics of the car and engine, tested in the article [6], was taken as a basis. The proposed model, in comparison with the previous one, additionally takes into account the following factors (2, 3, 4) [5, 7]:

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

where: R – specific gas constant, ρ_0 – ambient pressure, $\mathrm{T_0}$ – ambient temperature.

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

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

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

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

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

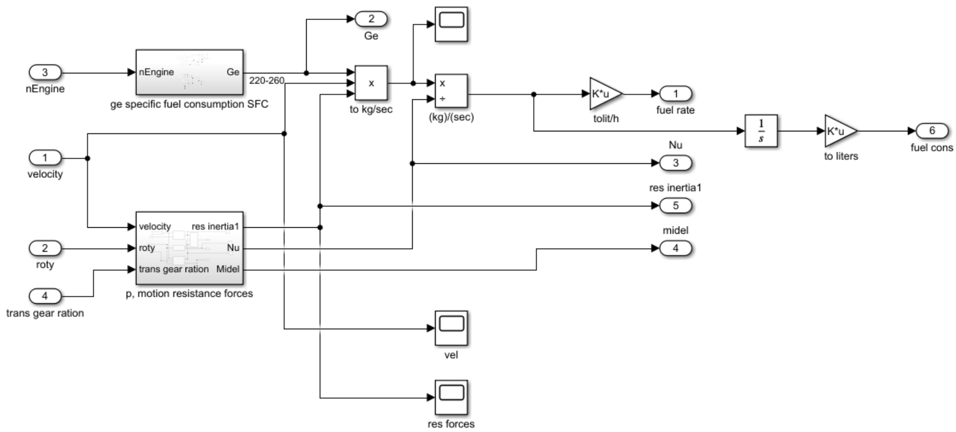

Figure 1 General view of realization of the mathematical model of car fuel consumption in Matlab Simulink environment.

1.2 Method

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 Figure 2.

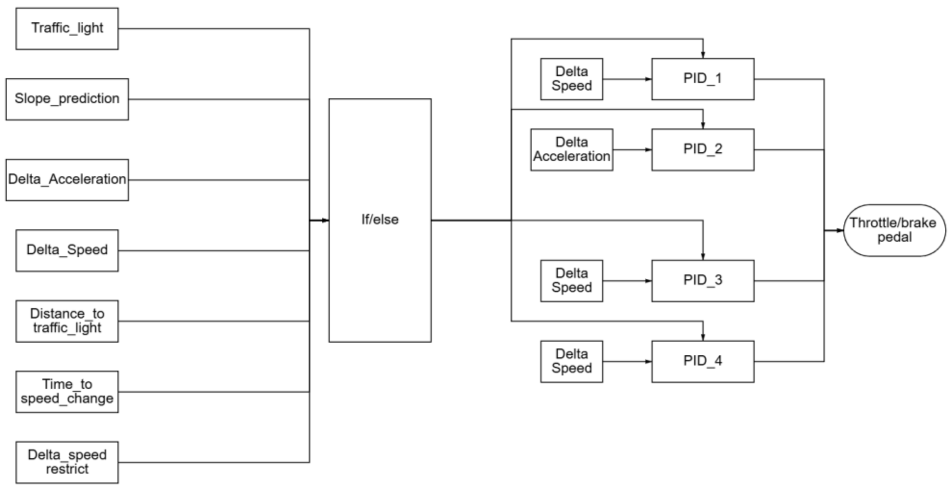

Figure 2 Schematic of the proposed method

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. [8].

Within the present work, wireless information exchange between cars and traffic lights was not implemented. 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 figure 3.

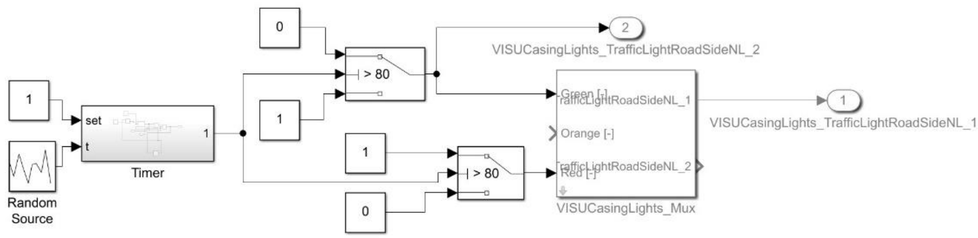

Figure 3 Implementation of traffic light in Matlab Simulink

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.

2 SIMULATION AND RESULTS

To achieve the objectives, computer simulation and full-scale experiment were carried out.

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 [9]. The digital twin was created with mapping requirements in mind [10].

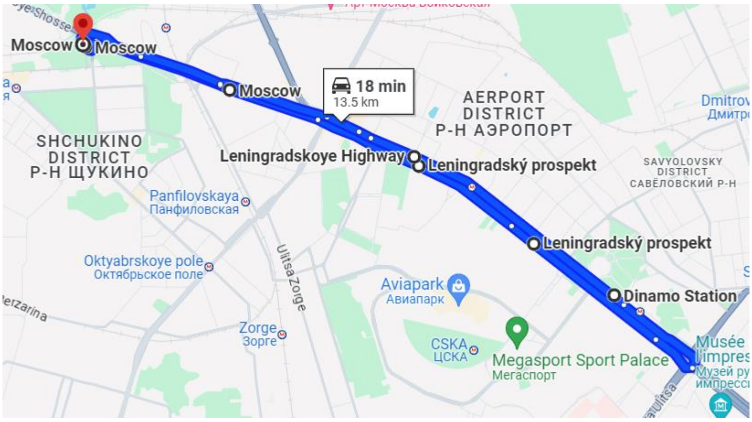

Figure 3 The plot of a real road from which was made the digital terrain model

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

The test object was a car of category M1 - Chevrolet Orlando I, technical characteristics of which are given in Table 1 [11].

Table 1 Technical characteristics of the experimental car Chevrolet Orlando I

Parameter	**Value**
Engine	
Engine type	Petrol
Arrangement	Front, lateral
Number of valves per cylinder	4
Cylinder diameter, mm	80.5
Piston stroke, mm	88.2
Compression ratio	10.5
Toxicity standard	Euro 5
Fuel tank capacity, l	64
Powertrain	
Transmission	Automatic
Wheel Drive	Front

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 Figure 4.

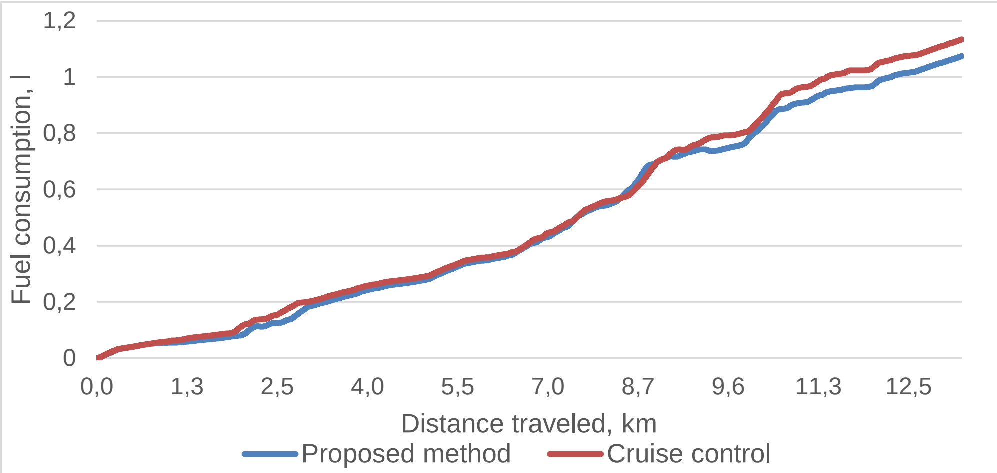

Figure 4 Comparison of fuel consumption with the proposed method and cruise control.

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.

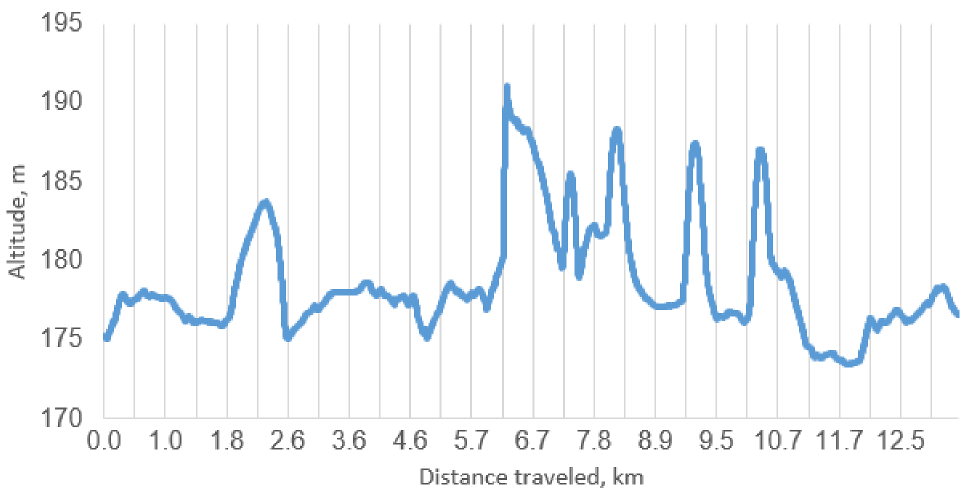

Figure 5 Federal highway altitudes (Leningradsky Prospekt - Volokolamskoye Highway)

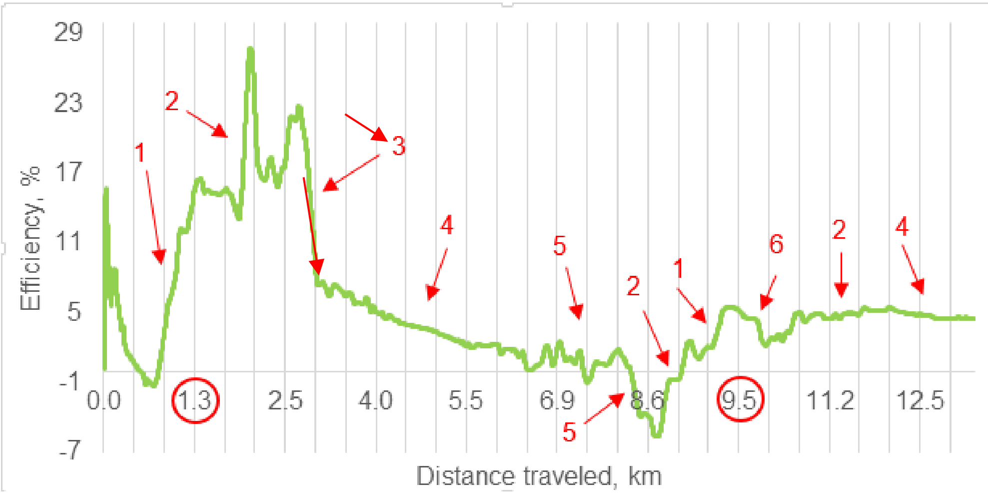

Figure 6 Federal highway altitudes (Leningradsky Prospekt - Volokolamskoye Highway)

The initial velocity of the car was equal to 5 m/s. The operation modes of the traffic lights were regulated randomly by the algorithm described above. In the presented experiment, in the course of the car movement, the red traffic signal was turned on at 2 traffic lights out of 5. The distance at which these traffic lights are located is circled in red in Figure 6. 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 [12,13].

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 [14,15]. 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 that was not touched upon in the energy efficiency studies that I was able to study:

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 Figure 7. The red line in Figure 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%.

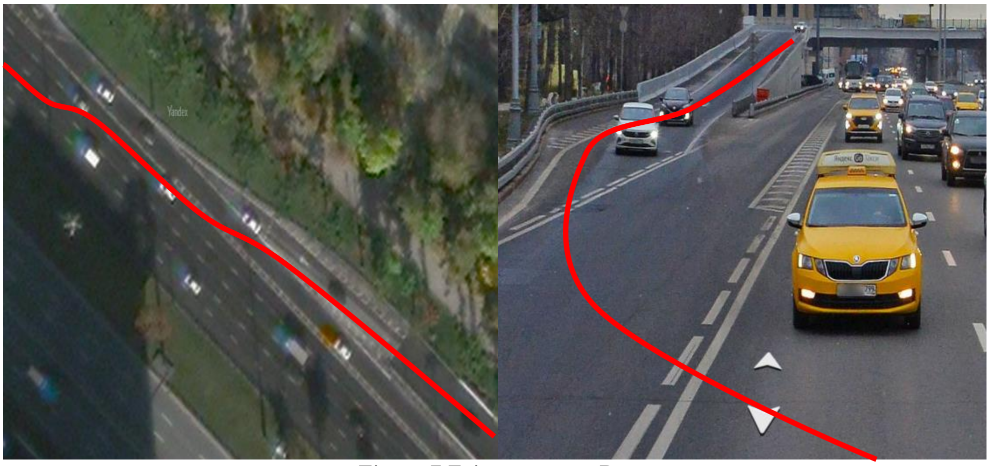

Figure 7 Exit ramp near Dynamo

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. Yes, 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, figure 8.

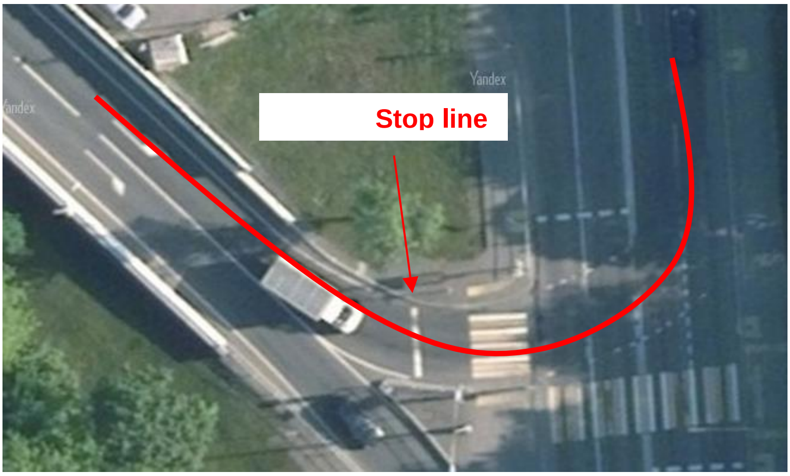

Figure 8 Exit ramp near Streshnevo

Of course, all the infrastructure solutions discussed above are made with safety in mind. In this article, these solutions have only been evaluated from the point of view of energy efficiency. Despite the negative factors, the proposed system demonstrates an energy efficiency of 4.5% in mixed conditions.

3 CONCLUSIONS

The developed method demonstrates energy efficiency both on a highway and in an urban area. The algorithms have an integrated approach to energy efficiency: they take into account the terrain of the road and interact with the road infrastructure.

The main results and conclusions of this study are as follows:

- 1. A mathematical model that improves the energy efficiency of connected, highly automated vehicles with internal combustion engines is proposed.
- 2. Virtual tests of the developed algorithms were carried out on a digitized section of a real road, taking into account the height difference, intersections and traffic light regulation.
- 3. Comparison of the results of car fuel consumption modelling with the proposed algorithms and cruise control was carried out. The proposed algorithms showed an efficiency of 4.5 % on a passenger car with internal combustion engine.

Plans for further research:

- 1. Integrate the developed energy efficiency algorithms into a real highly automated vehicle.
- 2. Conduct field tests of the developed algorithms on the road considering elevation

difference, intersections and traffic light regulation.
- 3. Adapt the proposed algorithms to hybrid propulsion and electric traction vehicles.
- 4. Conduct comparative tests of energy efficiency and cruise control algorithms for hybrid and electric propulsion system

FUNDING

The research was carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation within the framework of the project “Development of a mathematical model of chassis operation (transmission, chassis and control mechanisms) in static and dynamic states and creation of a digital twin of a passenger car platform on its basis” (code: FZRR-2023-0007).

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