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RESEARCH ARTICLE

Experimental Analysis of Long-Term Fuel Trim Performance in a Gasoline Engine Under Various Operating Conditions

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ABSTRACT – This paper analyzes the effect of operating conditions on the enrichment of the fuel-air mixture in a car engine due to a decrease in air mass with increasing altitude above sea level. This study focuses on fuel trim, particularly long-term fuel trim, in optimizing the composition of the fuel-air mixture before it enters the engine's combustion chamber. Experimental studies were conducted on the Bishkek–Osh highway in the Kyrgyz Republic, a road characterized by flat, mountainous, and high-altitude sections with complex terrain. Based on the research objectives, experimental results were obtained, and graphs of long-term fuel trim as a percentage of terrain altitude were constructed and analyzed for flat, mountainous, and high-altitude sections of the Bishkek–Osh highway. The study established that fuel trim indicators can be used to analyze changes in the air-fuel mixture's air excess coefficient ($\lambda = 1$, stoichiometric ratio). The reduction in long-term fuel trim was observed in flat, mountainous, and high-altitude sections as air density and pressure decreased with increasing altitude above sea level. The results show that with a reduction in long-term fuel trim to -6.25% to -7.81% at altitudes between 1500 and 3000 meters above sea level, the air excess coefficient (λ) drops to 0.92–0.94. At an altitude of 770 meters (flat terrain), λ was measured at 0.97. The difference in λ (0.03–0.05) indicates that an increase in altitude significantly affects the air-fuel ratio (AFR), impacting mixture formation during vehicle operation in mountainous and high-altitude conditions.

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1. INTRODUCTION

One of the main tasks of modern automobile manufacturing is to improve the fuel-economic and environmental performance of automobiles' internal combustion engines (ICE). Recently, strict requirements for environmental performance have been imposed on automobile manufacturing by introducing environmental standards, which have led automakers to continuously improve the design of manufactured automobiles [1], [2], [3]. Automakers check the compliance of a car with environmental standards on a test bench, the so-called driving cycle, where the car's movement is simulated in various modes in urban and non-urban cycles. However, automobile transport is used in various conditions - in hot climates and low temperatures, in desert-sandy terrain, as well as in flat, mountainous and high-mountainous conditions. Of course, these conditions significantly affect the change in power, dynamic, braking, fuel-economic, environmental and other indicators of the car during operation. Naturally, the environmental standards imposed will change, taking into account the above environmental factors. It is especially important to emphasize the influence of mountain and high-altitude conditions on the deterioration of fuel-economic and environmental performance during vehicle operation. This is explained by the fact that mountain and high-altitude conditions are characterized by complex terrain, variable weather conditions and ambient air parameters – the pressure, density, temperature and humidity of the ambient air change. For example, with an increase in the altitude of the terrain above sea level, the air pressure and density decrease, which leads to a decrease in the mass flow of air (g/s) entering the engine cylinders through the intake manifold. Due to the decrease in air mass with an increase in the altitude of the terrain above sea level, the fuel-air mixture in the engine is enriched. Optimization of fuel-economic and environmental performance, that is, fuel economy and a decrease in harmful substances in the exhaust gases emitted to the environment, when operating a vehicle in the above conditions, depends on the optimal composition of the fuel-air mixture before combustion in the engine cylinders.

Works devoted to fuel-economic and environmental problems and problems of operating cars in mountainous and high-altitude conditions are cited quite a lot in scientific journals of the former Soviet Union and other countries [4] – [8]. However, some works cover research conducted on cars manufactured before the 90s of the 20th century, for example, works [4] and [5]. Work [6] examines the causes of deterioration in the quality of the combustible mixture of a gasoline engine with a carburetor when operating a car in high-altitude conditions. Naturally, such cars were not equipped with modern electronic engine management systems (EEMS). The paper [7] presents the results of research work on determining the consumption rates of liquefied petroleum gas (LPG) for a KIA Optima car when operating in mountainous conditions. The main factors influencing the fuel-economic performance of the car in mountainous conditions are also considered. However, it does not mention the fuel trim processes performed by the engine ECU. Fuel consumption and emissions of harmful substances in the exhaust gases mainly depend on the correct coordination of the engine ECU with other sensors of the systems and mechanisms (fuel trim), regardless of the conditions in which the car is operated.

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The paper [8] considers the issues of providing and burning lean fuel-air mixtures in internal combustion engines in order to improve environmental and fuel-economic performance through the method of stratifying the fuel-air charge in the combustion chamber of the car engine during bench testing. However, the question arises - how will this process occur when operating a car in real mountain and high-altitude conditions? It should be noted that the theoretical composition of the fuel-air mixture for gasoline engines should be when there are 14.7 parts of air per 1 part of gasoline, i.e., AFR (air to fuel ratio) should be 14/1. Then, the excess-air coefficient, which is used to estimate the composition of the fuel-air mixture, should be $\lambda = 1$, and this composition of the mixture is called the stoichiometric composition of the fuel-air mixture [9] – [16]. But, in real operating conditions of the car, it is impossible to constantly maintain the stoichiometric composition of the fuel-air mixture. Therefore, the term is used - the optimal composition of the fuel-air mixture when the excess air ratio is $0.92 < 1 < 1.08$.

Modern cars are equipped with various sensors that have their own functional purposes and are closely related to the operation of the electronic control unit (ECU) of the engine and are also connected to other units and components of the car [17], [18], [19]. In this regard, fuel trim is of particular importance for the formation of the optimal composition of the fuel-air mixture. Fuel trim is performed by the electronic control unit (ECU) of the engine based on information received from sensors of the engine systems and mechanisms and elements of the exhaust system of the car. In simple terms, fuel trim is a combined relationship and interaction of three components: the mass of incoming air (g/s) through the air filter and mass air flow sensor; the amount of residual oxygen (O_2), which is determined by the oxygen sensor located in front of the catalytic converter; and the duration of the injector opening pulse (fuel injection time by the injectors). All these processes are controlled by the engine ECU. As is known, many scanners and software products for diagnosing the engine and exhaust system elements of a car mainly show numerical values of fuel trims in percentages (some scanners show numerical values of fuel trims in coefficients). Therefore, fuel trim is a percentage (coefficient) of change in numerical values of fuel supply depending on the amount of air in the fuel-air mixture over time and in what conditions the car is operated.

It should be noted that there are two types of fuel trim: long-term fuel trim (LTFT) and short-term fuel trim (STFT) [20], [21]. Short-term fuel trim (STFT) is a continuous correction of fuel supply in order to maintain the air-fuel ratio close to the stoichiometric composition of the air-fuel mixture – $\lambda \approx 1$. The voltage (signal) generated by the first oxygen sensor installed before the catalytic converter determines the amount of residual oxygen (O_2) in the exhaust gases, and this signal is transmitted to the engine ECU. Based on the received information (signal), as well as on the information (signal) of other sensors associated with ensuring the optimal composition of the air-fuel mixture, the engine ECU analyzes the mixture composition, the degree of leanness or enrichment in comparison with the stoichiometric air-fuel ratio. The specified discrepancy with the stoichiometric composition of the mixture shows either a decrease in the injected amount of fuel (in the minus if the mixture is rich) or an increase in the injected amount of fuel (in the plus if the mixture is lean) [20], [21]. STFT occurs instantly 2-3 times per second between small positive and negative values depending on vehicle operating conditions. Long-term fuel trim (LTFT) is a cumulative correction of the air-fuel ratio. It is performed over a long period of time to compensate for the continuous deviation of the air-fuel ratio caused by STFT compared to the average value due to changes in engine technical condition, wear due to overhaul, changes in vehicle operating conditions and environmental influences [20], [21]. The term "long-term (extended) period of time" is generally considered to be approximately 10 seconds.

LTFT enters the fuel correction process when the STFT function cannot maintain the optimum fuel-air mixture composition, i.e., $\lambda = 0.92 < 1 < 1.08$ (for example, STFT ≈ 15% - 20% and more). In this case, the correction changes in the basic programming of the fuel supply (in the fuel map) of the engine ECU. This correction is stored in the ECU memory and is therefore called Long Term. In this case, STFT starts functioning from a new starting point, decreasing or increasing the fuel supply by the engine injectors. LTFT and STFT always coexist together, i.e., they are closely interrelated because the LTFT readings are completely dependent and based on the STFT readings. In other words, it is the maintenance of the optimal composition of the fuel-air mixture ($\lambda = 0.92 < 1 < 1.08$) by fuel correction in internal combustion engines that significantly contributes to fuel economy and the reduction of harmful substances (toxic gases - HC, CO, NO and NOx) in the composition of the vehicle's exhaust gases. In this regard, LTFT and STFT fuel corrections are of particular importance for maintaining the optimal composition of the fuel-air mixture. It should be emphasized that these interrelated processes are aimed at improving the fuel-economic and environmental performance of the vehicle and are one of the best achievements of engineering thought and creativity in improving the components of the internal combustion engine design.

During vehicle operation, it can be assumed that with a fuel trim of up to 10%, the engine operates in normal mode; with a greater deviation (for example, 20% or more), the engine may have malfunctions in systems and mechanisms, leading to the "CHECK ENGINE" light (signal) coming on, requiring a check of the engine management system [21]. It should be noted that about 85% of the territory of the Kyrgyz Republic is mountainous and highland areas. Highways connecting settlements within the country and international highways connecting the Republic with neighboring countries pass at an altitude of 1500 m to 4200 m above sea level. Therefore, the author set the goal and objectives of the study – to analyze the influence of operating conditions on fuel trims made by the engine ECU, in particular when operating a car in flat, mountainous and highland conditions. Also, after determining the goal and objectives of this study, as expected, the author examined open scientific and academic sources on this topic, but, unfortunately, sufficiently reliable resources were not found devoted to fuel trims by the engine ECU of a car.

In this paper, due to the continuous change of STFT indicators (several times per second, as well as the voltage signals of the first oxygen sensor), the author considered the changes in LTFT indicators during experimental studies since LTFT is more indicative than STFT. The purpose of this work is an experimental analysis of the change in LTFT indicators during the formation of a fuel-air mixture carried out by the electronic engine control unit depending on the operating conditions of the car, in particular, when operating the car in flat, mountainous and high-mountain sections of the road. To achieve this purpose, the following tasks were set, such as, to study previous works on this topic, to determine and conduct the practical part of the study, and to analyze the factors causing changes in the fuel correction indicators of the engine ECU during vehicle operation in various conditions, which includes the effect of increasing terrain above sea level on the process of mixture formation - air-fuel in the engine during vehicle operation in flat, mountainous and high-mountain sections of the road. The scientific novelty of the work lies in the fact that this work provides an analysis and justification of the dependence of the fuel trim indicators produced by the engine ECU, in particular LTFT, on changes in the altitude of the terrain when operating a car in flat, mountainous and high-mountain sections of the road. Since control over the process of mixture formation – air fuel comes from fuel trims produced by the ECU of the car engine.

2. METHODS AND MATERIAL

The main focus is to analyze how changes in terrain altitude above sea level affect long-term fuel trim values when the engine is idling and when the vehicle is moving at different speeds. To analyze the indicators of long-term fuel trim of the fuel-air mixture in real vehicle operating conditions, a number of experimental studies were carried out on the Toyota Corolla Verso with a 3ZZ-FE engine, Toyota Avensis with a 4A-FE engine, Mitsubishi Space Star with a 4G18 engine in various weather conditions. Car engines are equipped with a distributed fuel injection system; the fuel supply method is phased (synchronous). The vehicles intended for experimental research were in good technical condition. The preparation of the vehicles for experimental research included the following operations: checking the condition of the engine, its mechanisms and units; checking the condition of all engine systems (fuel, ignition, cooling and lubrication systems); checking the condition of the electronic engine management system (EEMS) of the vehicle; checking the condition of all EMS sensors of the vehicle; checking the condition of the chassis units of the vehicle; checking the condition of the brake system of the vehicle; checking the condition of the steering of the vehicle; checking and establishing the norm of air pressure in the tires; checking the serviceability of the speedometer readings. The grades of fuels and lubricants used met the standards. The amount of oil in the units and assemblies met the requirements of the manufacturer's regulatory and technical documentation.

During the experimental studies, the driver's skill was maintained constant. This was achieved by using one driver. At the same time, during preliminary tests, the driver's choice was based on checking the stable skills of economical driving of the car. The latter was assessed by the length of the coasting distance, the number of braking operations, the use of service braking, the exclusion of high-speed engine operating modes, etc. Experimental runs were carried out in the autumn-winter and spring-summer periods of the year. During the experimental study, temperature, air humidity and atmospheric pressure were recorded. Experimental studies were conducted on the Bishkek-Osh highway, which connects the northern regions of the Kyrgyz Republic with the southern regions. The Bishkek – Osh highway is characterized by flat, mountainous and high-mountain conditions for vehicle operation and passes at an altitude of 750 – 3200 m above sea level through the high-mountain passes of Too-Ashuu and Ala-Bel, which are located at an altitude of 3200 m above sea level (Figure 1 and 2) [22].

Figure 1. Too-Ashuu Pass (Northern side of the K. Kolbaev tunnel, altitude 3120 m above sea level)

Complex terrain in mountainous and high-mountain sections of the road has a significant impact on the operating mode of the engine, transmission units and chassis of the vehicle. The large length of sections with maximum longitudinal slopes, and small-radius curves in plan, with turns with zero visibility, impede the movement of vehicles (Figure 3). The maximum slopes of the road when the vehicle is moving uphill towards the pass sections and when descending from the pass section are 12 – 14%. All this ultimately affects the fuel-economic and environmental indicators, as well as the safety of the vehicle.

Figure 2. Ala-Bel Pass (Altitude 3200 m above sea level)

Figure 3. Continuous ascent towards the Too-Ashuu pass

It should be emphasized that in the conditions of the Kyrgyz Republic, the ambient air temperature in flat areas (650 – 1000 m above sea level) in the hot season reaches up to 45 ^{0}C. In mountainous (1500 – 2500 m above sea level) and highland (2500 – 3000 m and more above sea level) conditions, the ambient air temperature in the hot season is 5 – 15 ^{0}C. In the cold season in mountainous and highland areas, the ambient air temperature drops to minus 45 ^{0}C. During the experimental studies, the MotorData software product and the Openport 2.0 Bluetooth adapter were used to connect the computer to the DLC (Data Link Connector) connector of the car, i.e. to the on-board diagnostic system – EOBD (European On Board Diagnostic – European on-board diagnostic system based on the OBD-II specification) of the car (Figure 4), as well as the Bandicam Screen Recorder software for creating screenshots and recording video from the computer screen. The MotorData software product is designed for specialists in the field of diagnostics, repair and maintenance of cars. In particular, this program is necessary for the daily work of professional diagnosticians of automotive electronic and electrical equipment. Also, with the help of this program, you can diagnose the systems, mechanisms, and units of the car, which affect economic and environmental indicators.

2.1 Connecting Bluetooth Adapter

2.1.1 Openport 2.0 to the car DLC connector

Figure 5 shows the experimental study conducted to analyze the parameters of engine systems and mechanisms, as well as exhaust system elements, using the MotorData software product while driving a vehicle in mountainous and high-mountain sections of the Bishkek – Osh highway.

Figure 4. Connecting the Openport 2.0 Bluetooth adapter to the vehicle's DLC connector

Figure 5. Conducting an experimental study

The following parameters were recorded while the engine was idling and while the vehicle was moving on various sections of the Bishkek – Osh highway: vehicle speed; engine crankshaft speed; engine coolant temperature and intake manifold air temperature; mass air flow; injector opening pulse duration; ignition timing; absolute throttle position (in percent); voltages generated by the oxygen sensors before and after the catalytic converter; long term and short term fuel trims, as well as short term fuel trim for the first oxygen sensor (Figure 6).

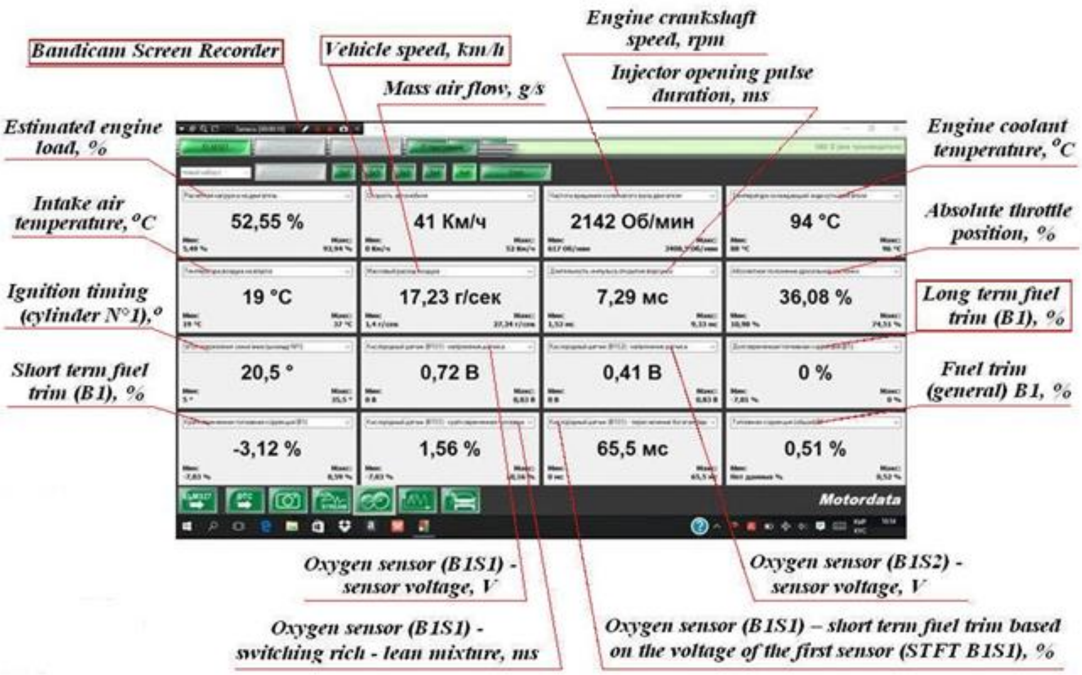

Figure 6. Indicators of the parameters of the engine systems and mechanisms and elements of the exhaust system when driving a car in mountainous and high-mountain sections of the Bishkek – Osh highway

3. RESULTS AND DISCUSSION

According to the stated objective of the study and after statistical processing of the obtained results of experimental studies, graphs (Figures 8, 10 and 12) of the LTFT dependence as a percentage of the terrain height on flat, mountainous and high-mountain sections of the Bishkek-Osh highway were constructed. The essence of the graphs of the LTFT dependence of the vehicle at different speeds on the above-mentioned sections of the road is that the values of the fuel trim indicators are parameters that show how much the excess-air coefficient changes from the stoichiometric composition of the fuel-air mixture (λ = 1). Thus, knowing the fuel trim indicators, it is possible to determine the excess-air coefficient of the fuel-air mixture using the expression [23]:

$$\lambda = 1 + \left(\frac{K_{LTFT}}{100}\right), \tag{1}$$

where K_{LTFT} – is the long-term fuel trim of the fuel-air mixture in %.

Figure 7 shows the longitudinal profile of the terrain of the section – the city of Kara-Balta – the "Sosnovka" post of the Bishkek – Osh highway (61 – 72 km). The terrain is 770 – 960 m above sea level.

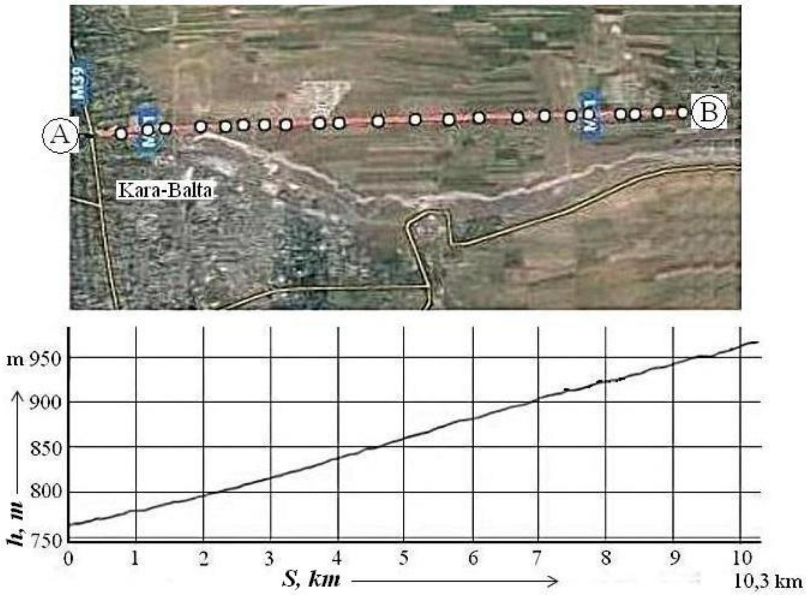

Figure 7. Longitudinal profile of the section Kara-Balta city – «Sosnovka» post highway Bishkek – Osh

The longitudinal profile characteristic of the flat section of the road (Figure 7) is as follows: uphill – 9.9 km (97%); downhill – 0.34 km (3%). The difference in heights is 206 m above sea level. The distance is 10,287 m (10.3 km). The height above sea level is 969 m. Figure 8 shows the graph of the LTFT dependence as a percentage of the terrain height on the flat section – the city of Kara-Balta – the Sosnovka post of the Bishkek – Osh road when the car is moving at different speeds.

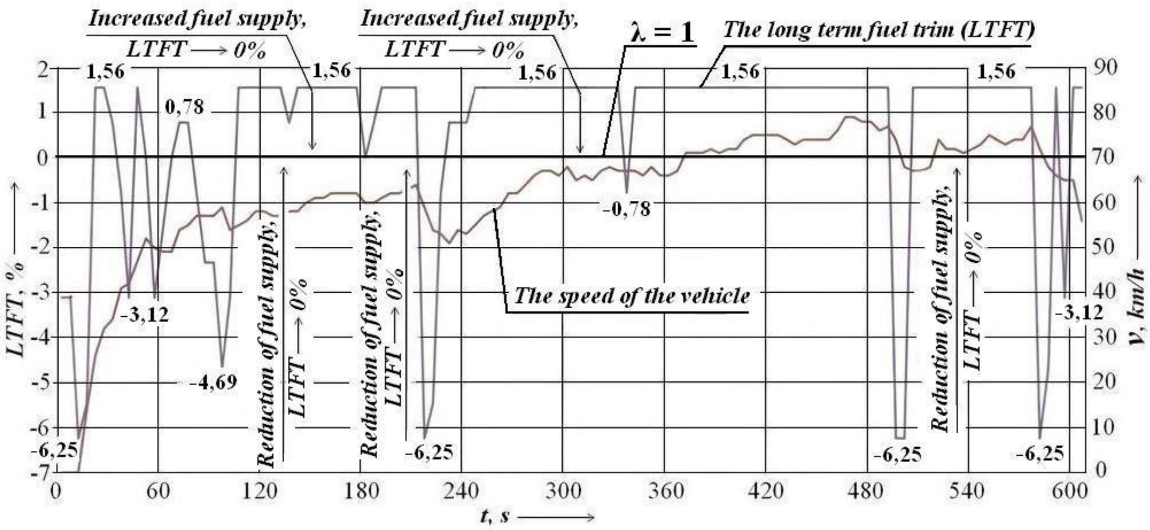

Figure 8. Graph of LTFT (%) relative to terrain height on a flat area (city of Kara-Balta to Sosnovka post on the Bishkek–Osh highway) at different vehicle speeds

As shown in Figure 8, at an altitude of 770 m above sea level, according to the readings of the computer connected to the car's EOBD via the Open port 2.0 Bluetooth adapter, the LTFT of the fuel was minus 3.12% with the engine idling (i.e., engine crankshaft speed is 660-670 rpm, car speed is v = 0 km/h). This means that the fuel-air mixture is enriched by 3.12% of the stoichiometric mixture, i.e., the fuel is supplied more by 3.12% from 0%. The vehicle's engine ECU, based on signals received from various sensors (including the oxygen sensor - the first lambda probe installed before the catalytic converter), seeks to compensate for the enrichment of the fuel-air mixture to 0%, that is, to reduce the fuel supply through the injectors by 3.12% and ensure the optimal composition of the fuel-air mixture. Then, when the clutch pedal is pressed and the first gear of the manual transmission is engaged, the LTFT indicator drops from minus 3.12% to minus 6.25%.

The drop in the LTFT indicator from minus 3.12% to minus 6.25% can be explained by the fact that when the clutch pedal is pressed, the clutch disc is disengaged from the engine (i.e., from the engine flywheel) and there is a slight increase in the engine crankshaft speed and the percentage of throttle opening. During acceleration of the car and during uniform movement (Figure 8), the LTFT indicator reaches 1.56% and remains at this level most of the time. The exception is that when shifting gears from the 1st gear of the transmission to the 2nd, 3rd, 4th and 5th gears, the LTFT indicator drops to minus 3.12%, 4.69% and 6.25%. However, a short period of time is allocated for these processes of gear shifting of the transmission. In tabular form, the graph of the LTFT dependence as a percentage of the terrain height (Figure 8) on the section (Kara-Balta city – “Sosnovka” post), also taking into account the average values of the graph parameters taking into account the absolute position of the throttle valve (in %), can be shown as follows (Table 1).

Table 1. Average parameter values for condition assessment fuel-air mixture

Vehicle travel time in seconds	0 → 60	60 → 120	120 → 180	180 → 240	240 → 300	300 → 360	360 → 420	420 → 480	480 → 540	540 → 600
Average value V, km/h	28.2	55	59.8	58.6	61.3	66.7	71.4	75.4	72	70.3
Average TP value, %	20.2	20.2	22	21.4	23.9	23.1	24.6	24.5	23	21.5
Average LTFT value, %	- 1.63	- 0.72	1.5	- 0.2	1.5	1.4	1.56	1.56	0.26	0.22
Average λ	0.98	0.99	1.02	0.998 ≈ 1	1.02	1.01	1.02	1.02	1.0026 ≈ 1	1.0022 ≈ 1

Note. TP - Absolute Throttle Position, %.

Figures 9 and 10 show the longitudinal profile of the mountain section (98 – 107.1 km) of the Bishkek – Osh highway and the graph of the LTFT dependence as a percentage of the terrain height when the vehicle is moving at different speeds. The terrain is 1550 – 1794 m above sea level.

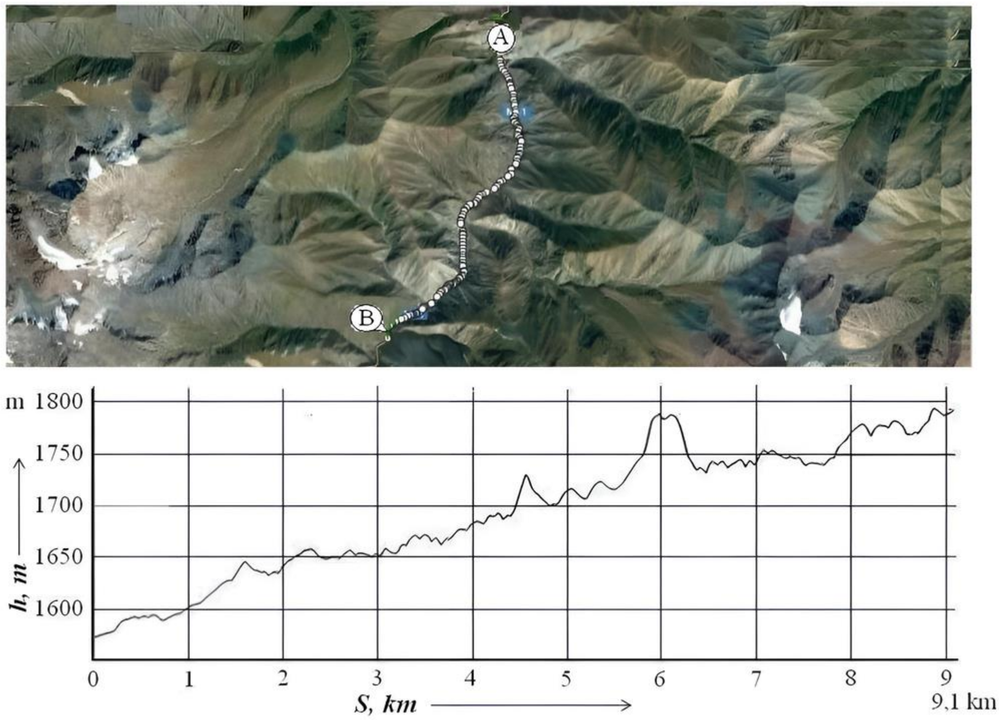

Figure 9. Longitudinal profile of the mountain section of the road Bishkek – Osh (ascent towards the Too-Ashuu pass)

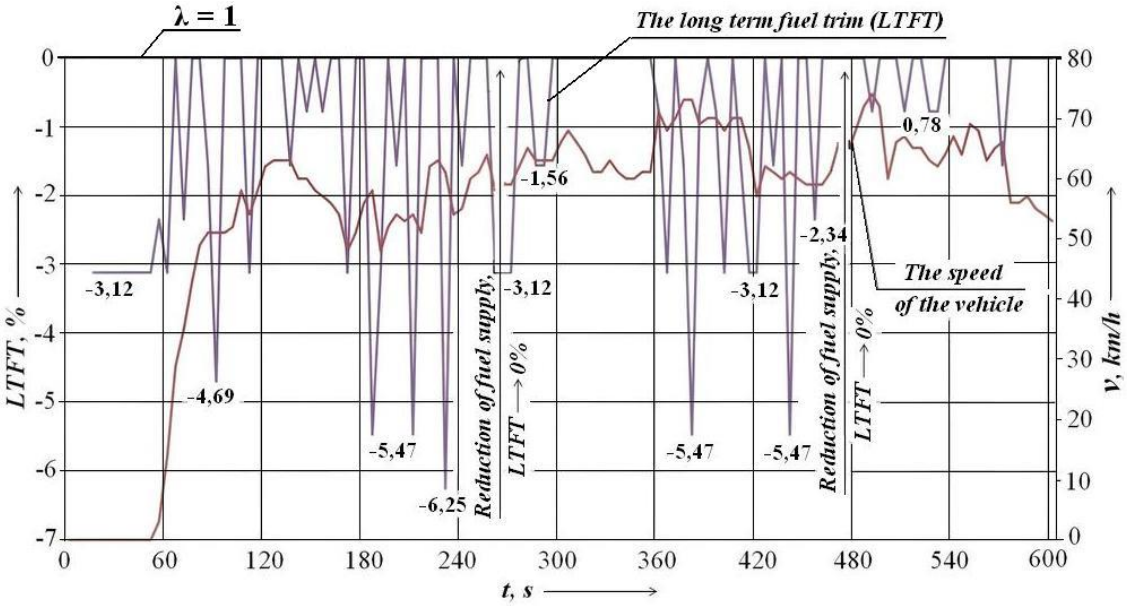

Figure 10. Graph of LTFT (%) relative to terrain height on the mountainous section of the Bishkek–Osh highway (ascent toward Too-Ashuu pass) at various speeds.

The longitudinal profile characteristic of the mountainous section of the road (Figure 9) is as follows: uphill – 5.5 km (60%) and downhill – 3.6 km (40%). The difference in heights is 222 m above sea level. The distance is 9060 m (9.1 km). The height above sea level is 1794 m. When the engine is idling (v = 0 km/h) (Figure 10), the fuel-air mixture is enriched, and LTFT is maintained at minus 3.12%, i.e., the duration of the injector opening pulse slightly increases by 3.12%. On this section of the road, the car moves mainly in 3rd and 4th gears of the transmission. At the same time, the car develops a speed of up to 70 km/h in some sections, and at these speed modes, LTFT remains at 0% most of the time, i.e., the excess-air coefficient λ = 1. However, due to the complexity of the terrain (longitudinal slopes - gradual climbs, curves in the road plan, blind turns - turns with zero visibility) in this section, there is frequent braking and a reduction in vehicle speed. And, in some time intervals of the vehicle's movement, as well as during gear shifting from low to high, and vice versa, the fuel-air mixture is enriched for a short time to minus 5.47 – 6.25%. In tabular form, the graph of the LTFT dependence as a percentage of the terrain height (Figure 10) in this mountainous section (ascent towards the Too-Ashuu Pass), also taking into account the average values of the graph parameters taking into account the absolute position of the throttle valve (in %), can be shown as follows (Table 2).

Table 2. Average parameter values for condition assessment fuel-air mixture

Vehicle travel time in seconds	0 → 60	60 → 120	120 → 180	180 → 240	240 → 300	300 → 360	360 → 420	420 → 480	480 → 540	540 → 600
Average value V, km/h	3	45.4	57.9	55.5	61	62.7	69.75	60.75	66.5	61
Average TP value, %	12.5	27.13	25.6	24	25.1	28.01	23.2	22.09	23.76	27.1
Average LTFT value, %	- 3.03	- 1.12	- 0.52	- 1.82	- 1.17	0	- 1.69	- 1.05	- 0.26	- 0.12
Average λ	0.97	0.99	0.99	0.98	0.988	1	0.98	0.99	0.997 ≈ 1	0.999 ≈ 1

Note. TP - Absolute Throttle Position, %.

Figures 11 and 12 show the longitudinal profile of the high-mountain section of the Bishkek-Osh highway (124 – 130 km) and a graph of the LTFT dependence as a percentage of the terrain height when the vehicle is moving at different speeds.

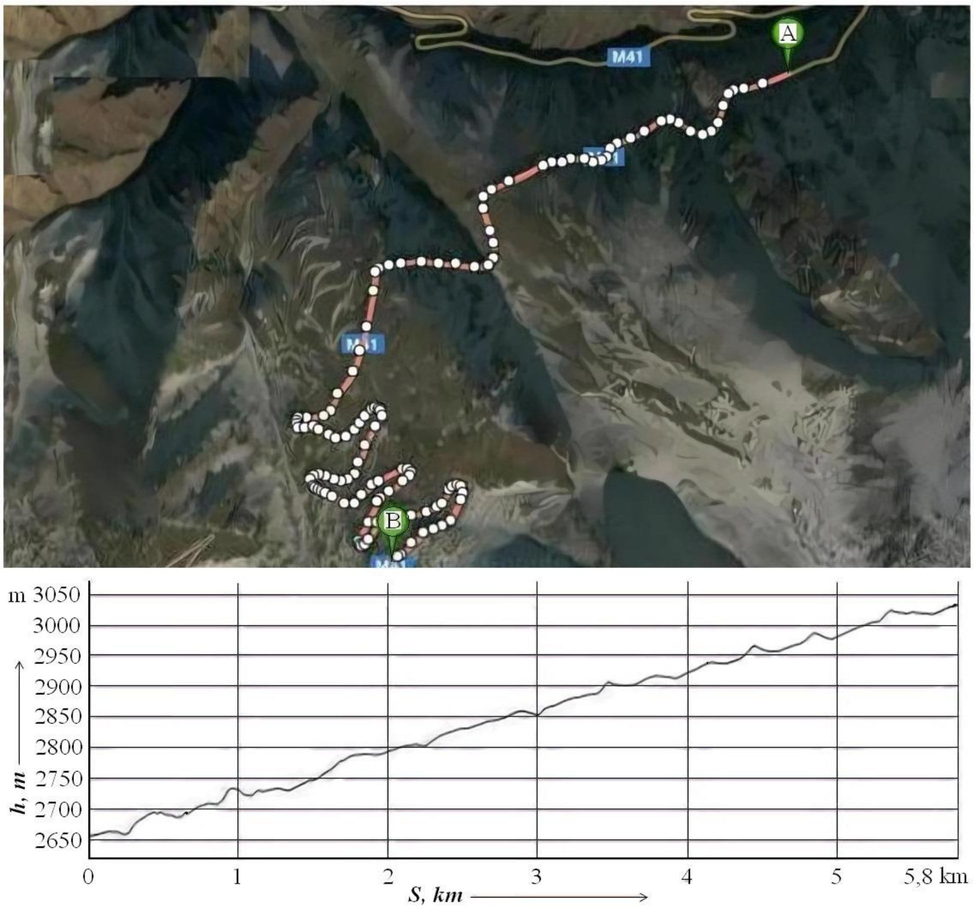

Figure 11. Longitudinal profile of the high-mountain section of the Bishkek – Osh highway (ascent towards the Too-Ashuu pass)

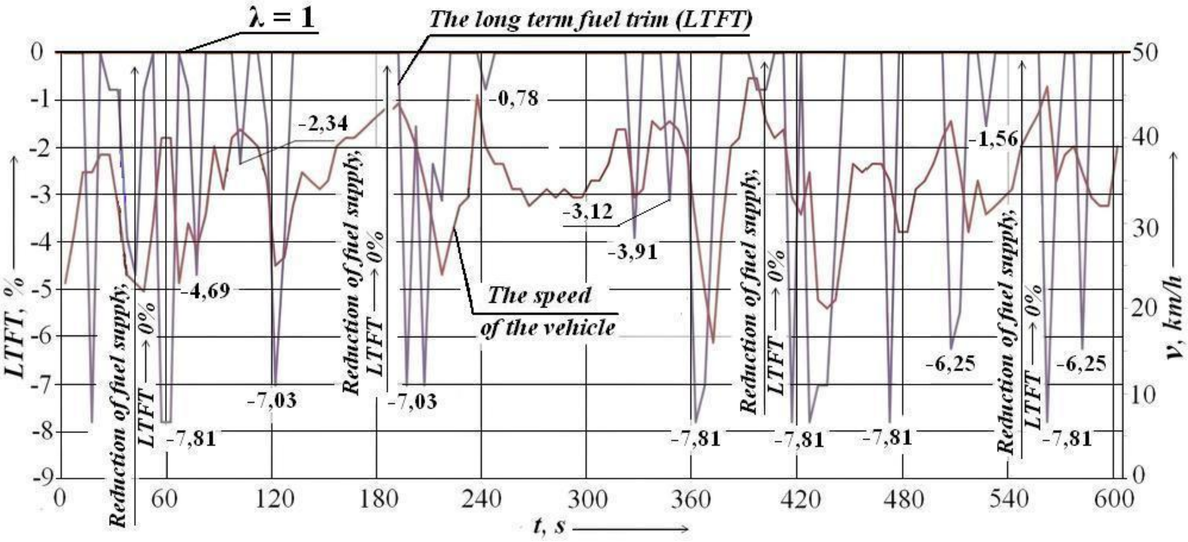

Figure 12. Graph of LTFT (%) relative to terrain height on the high-mountain section of the Bishkek–Osh highway (ascent toward Too-Ashuu pass) at various speeds

The altitude of the terrain is between 2650 and 3033 meters above sea level (Figure 11). At this elevation, the car primarily operates in 3rd gear, reaching speeds of 35-40 km/h. When the engine is idling (v = 0 km/h), the increase in altitude, combined with the decrease in air pressure and density, causes the long-term fuel trim (LTFT) to drop to -7.81% (Figure 12).

When the clutch is depressed during gear shifts—whether from a lower to a higher gear or vice versa in a short period—LTFT similarly drops to -7.81%. However, when the car moves at a steady speed, the engine control unit (ECU), by adjusting the injector pulse duration, continuously attempts to maintain LTFT at 0% (Figure 12).

On this section of the road, the car is constantly moving uphill, where the road slopes reach 14%. The terrain is very complex, often with blind turns (turns with zero visibility) and winding roads. All this leads to a decrease in vehicle speed to 20 km/h. In tabular form, the graph of the LTFT dependence as a percentage of the terrain height (Figure 12) in this high-mountain area, also taking into account the average values of the graph parameters taking into account the absolute position of the throttle valve (in %), can be shown as follows (Table 3).

Table 3. Average parameter values for condition assessment fuel-air mixture

Vehicle travel time in seconds	0 → 60	60 → 120	120 → 180	180 → 240	240 → 300	300 → 360	360 → 420	420 → 480	480 → 540	540 → 600
Average value V, km/h	30.9	34.9	35.4	36.5	34.4	38.3	35.5	30.75	34.4	37.5
Average TP value, %	26.24	27.06	33.14	29.74	33.14	30.62	27.8	24.84	28.99	34.4
Average LTFT value, %	- 2.21	- 1.43	- 0.91	- 1.76	- 0.07	- 0.72	- 2.28	- 2.8	- 1.11	- 1.26
Average λ	0.978	0.986	0.991	0.982	0.999	0.993	0.977	0.972	0.989	0.987

Note. TP - Absolute Throttle Position, %

As stated above, in the descriptions of the previous graphs (Figures 8, 10 and 12), the decrease in LTFT values to a negative value - from minus 3.12% to 6.25% at an altitude of 770 – 960 m above sea level and in mountainous and high-mountain sections of the road – from minus 6.25 to 7.81% can be explained by a decrease in air density with an increase in the altitude of the terrain above sea level (Table 4). Air density decreases with a decrease in air pressure, as well as fluctuations in temperature and humidity depending on weather conditions with an increase in altitude above sea level [24], [25]. If we take into account that with fuel correction up to ± 10%, the engine operates in normal mode, then we can say that in this study, the LTFT readings are within the normal range.

Table 4. Average values of ambient air parameters at various altitudes above sea level from 9.00 to 12.00 local time (data from the Hydrometeorological Service of the Kyrgyz Republic for July 2023)

Altitude above sea level, m	Air temperature, ^{0}C	Air humidity, %	Pressure at altitude, kPa	Air density, kg/m3
Kara-Balta city – “Sosnovka” post, flat section of the road (61 – 72 km)				
770	20	20 – 30	92.62	1.1010
972	20	20 – 30	90.46	1.0760
Mountain section of the road (98 – 107.1 km)				
1550	18	40 – 50	84.45	1.0110
1794	17	40 – 50	82.01	0.9852
High mountain section of the road (124 – 130 km)				
2657	14	60 – 70	73.83	0.8962
3033	13	60 – 70	70.51	0.8589

It should be noted that the mass of air that enters through the air filter and MAF is directly proportional to the density. The lower the density of the air, the lower its mass, i.e.

$$m = \rho \cdot V, \qquad kg \tag{2}$$

where m – is air mass, kg; ρ – air density, kg/m^3; V – air volume, m^3.

The volume of air, in this case, is assumed to be constant, i.e., V = const.

If we follow the data in Table 4, then the decrease in air density (ρ ≈ 0.8589 kg/m3) at an altitude of 3033 m was 22% compared to the air density (ρ ≈ 1.101 kg/m3) at an altitude of 770 m above sea level. It follows that the decrease in air mass (m ≈ 1.48 g/s) at an altitude of more than 3000 m will be 10 – 11% compared to the air mass (m ≈ 1.62 g/s) at an altitude of 770 m above sea level. From the above, we can conclude that when the engine is idling, as well as during the process of gear shifting from a lower gear to a higher one, and vice versa, from a higher gear to a lower one (this process takes a short period of time), LTFT shows negative values and enrichment of the fuel-air mixture. But, at the same time, the car's engine ECU, adjusting the duration of the injector opening pulse, always strives for LTFT to be at 0% (LTFT → 0%).

4. CONCLUSIONS

The following conclusions have been made.

a) Modern car engines are able to quickly adapt to changing conditions thanks to a system of sensors that monitor the composition of the fuel-air mixture, but it also has certain limitations. For example, car manufacturers are unable to change the decrease in atmospheric pressure and air density or the climatic features of the terrain. Therefore, in order to ensure the reliability of their cars, they regulate and compensate for the impact of external adverse factors using modern technologies. During vehicle operation, the following factors affect the change in the fuel trim indicators of the engine ECU:

- Internal factors within the vehicle – These include heating due to temperature load, stress on parts, mechanisms, and units during vehicle operation, wear of the crankshaft and valve train components, wear of the cylinder-piston group, engine units and mechanisms, fuel injection nozzles, and tolerances for fuel quality, among others.
- External factors of vehicle operating conditions – Vehicle operating conditions are variable and change with driving distances, especially over short and long distances in mountainous and high-altitude regions. In these environments, the vehicle passes through different climatic zones, with changes in terrain, and the surrounding air parameters (temperature, pressure, humidity, and density) fluctuate with increasing altitude. Additionally, road parameters such as longitudinal slopes, curves in the road layout and profile, and limited visibility around turns also vary.

b) All the listed factors affect changes in fuel trim parameters and, ultimately, the air-fuel mixture formation process in the engine during vehicle operation. For example, the study results show that when LTFT decreases to minus 6.25–7.81% at a terrain altitude of 1500–3000 m above sea level, the excess-air coefficient decreases to $\lambda = 0.92–0.94$, but, at the same time, when LTFT decreases to minus 3.12% at a terrain altitude of 770 m above sea level (flat terrain), $\lambda = 0.97$. The difference in λ is 0.03–0.05. This indicates that an increase in terrain significantly affects the air-fuel mixture formation process, i.e., the AFR during vehicle operation in mountainous and high-altitude conditions.

It should also be emphasized that as a result of experimental studies, it was established that enrichment of the fuel-air mixture mainly occurs in modes when the engine is idling, as well as when the engine crankshaft speed decreases (for cars with a manual transmission – during gear shifting). At the same time, a decrease in the engine crankshaft speed and, thereby, a decrease in the speed of the car occurs due to the complexity of the terrain (continuous ascent to the pass and a long descent from the pass; frequent turns with insufficient visibility; changeable weather conditions – rain, snow, fog, etc.). Therefore, the author of the work believes that in such modes of car engine operation, in order to ensure the composition of the fuel-air mixture of about one, that is, $\lambda \approx 1$, it is necessary to introduce additional devices (for example, sensors) into the engine design.

These devices should compensate the effects of variable parameters of operating conditions on the fuel-economic and environmental performance of the car during operation. These devices should also facilitate and ensure accurate calculation of fuel injection time depending on the mass of air entering the intake manifold when the engine is idling and when the engine crankshaft speed is reduced. Therefore, at present, solving the above problems is a priority task in improving the design of modern cars in terms of fuel economy and reducing harmful substances in the exhaust gases.

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CONFLICT OF INTEREST

The author declares no conflicts of interest.

AUTHORS CONTRIBUTION

B.U. Akunov: Conceptualisation; Methodology; Experiment conducting; Validation; Data analysis; Resources; Software; Visualisation; Writing - original draft, review & editing, Translating.

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NOMENCLATURE

ICE	Internal combustion engines
AFR	Air to fuel ratio
DLC	Data Link Connector
EOBD	European On Board Diagnostic
OBD-II	On-board diagnostics
MAF	Mass air flow sensor
LTFT	Long term fuel trim
STFT	Short term fuel trim

EEMS	Electronic engine management system
ECU	Electronic control unit
TP	Absolute Throttle Position [%]
λ	Excess-air coefficient
K_{LTFT}	Long Term Fuel Trim [%]
h	Height at sea level [m]
S	Distance [km]
t	Time [s]
v	Speed [km/h]
m	Air mass [kg]
ρ	Air density [kg/m^3]
V	Air volume [m^3]