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Development of an Algorithm that Represents a Logical Model of Interoperability with The Element of Road Infrastructure by Testing The “Intelligent Start-Stop System” in The Conditions of Auto Polygon and Urban Conditions

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ABSTRACT: This paper analyzed the “vehicle-to-infrastructure” part of the intelligent transport system on the example of the “Intelligent start-stop system” in auto polygon and urban driving modes. There are different aspects in the coverage of this research. Turning off the vehicle engine at the traffic light through ISSS in the limited time of traffic red light (if the red light is more than t_r>10 s, otherwise the engine will not turn off) and after a particular time during the engine restarting process in yellow light (t_y = 1 ... 3 s) or green light (t_{gr} = 1 ... 30 s) the effect on engine parts, to the battery, to the starter, to the alternator resources is not studied. Because of the high degree of quality and reliability of the technology used in the manufacturing of mechanical and electrical parts of modern vehicles ensures that they do not break down during vehicle operation. Many kinds of research have shown that the start-stop system saves an average of 5-10% of fuel in an urban condition and it is consistent with the values that we obtained from the experimental results.

KEY WORDS: intelligent transport system, intelligent start-stop system, infrastructure, traffic light, mode, synergetic, order and flexible parameters.

I. INTRODUCTION

Increasing the number of vehicles in the world, the transmission of dynamically changing information to drivers on existing highways is one of the most pressing problems. In order to solve this problem, taking into account the traffic intensity of vehicles in other countries of the world, such as the United States of America, Canada, Germany, Italy, Japan, South Korea and China, these countries are improving their performance through the effective use of intelligent transport systems (ITS). Scientific and practical researches are being conducted by experts in the field to improve the energy efficiency of road transport in the world, receiving real-time data from the elements of road infrastructure, ensuring traffic safety through the interaction of vehicles with elements of ITS, increasing fuel economy, and improving environmental performance. In this direction, special attention is given to the development of software to ensure the interoperability of road infrastructure elements with the vehicle design based on new mathematical models in changing dynamic conditions.

The disproportionate level of development of road infrastructure in our country with the construction of cars leads to lost time on the roads, increased fuel consumption, and high emissions of toxic gases into the environment. Today, “Daily consumption of global demand for petroleum products was about 91 million barrels in 2020 and 96,5 million barrels in 2021 per day” [1]. Motor transport accounts for 15.9% of the carbon dioxide (CO_2) emissions released into the environment as a result of the use of these petroleum products [2]. This indicator does not constitute the largest share compared to other sectors, but it is important to reduce them. For this, one of the important issues of theoretical and practical research is the selection of order and flexibility parameters in real-time based on the principles of synergetics, developing of justification methods, ensuring the interoperability of vehicle design with road infrastructure in exploitation conditions. Emissions in Uzbekistan in 2020-2021 amounted to 2.2-4.0 million tons, 58 % of them were vehicles [3]. The main factors mentioned were the intersections of traffic and pedestrian crossings, fuel quality and increased loading of highways. Among the priorities for the implementation of the New Uzbekistan Development Strategy for 2022-2026, including "... Increase energy efficiency of the economy by 20 percent until 2026 and reduce emissions of harmful gases into the atmosphere by 20 percent through actively introducing "Green economy" technologies in all spheres" taskes has been defined [4]. In the implementation of this task, it is important to technical and technological improvement of vehicle modes control methods in the "vehicle-driver-infrastructure" environment with the transmission and reception of real-time data in the vehicle and road infrastructure through ITS technologies.

II. METHODOLOGY

The main innovations in vehicle design in recent years have been related to mechatronic systems, and ITS are being formed on this platform. As a result, vehicles can be operated in accordance with external infrastructure conditions, and there are "Intelligent Transport Systems" regarding technological and methodological foundations that aim to save resources in operational functions. ITS and Intelligent Technologies (IT) are based on specialized software that allows vehicle mechatron systems to collect data, automated analysis, modeling real-time processes, minimize the "human factor" and propose (or to receive) specific management decisions. Modernization of transport sectors in the country is not up to modern standards, and advanced ICT and ITS have not been effectively implemented in the field. It is also necessary to take use of available opportunities and resources to improve the country's road transport services, export, and transit capacities [5-6].

The occurrence of problems of the vehicle with other objects in different exploitation conditions is due to unsufisient of accurate data in a real-time and the lack of synergistic parameters that coordinate the systems. The main parts of the ITS aimed at overcoming these problems are shown in Figure 1 [7].

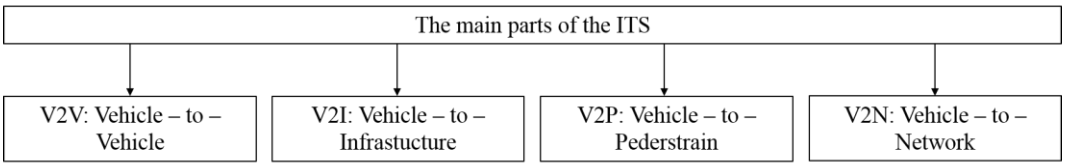

Fig.1. The main parts of the ITS

ITS is divided into subsystems consisting of vehicle and road infrastructure elements. The intelligent elements of a vehicle form a fast-changing is a dynamic group, while the elements of intelligent road infrastructure form a relatively slow-changing is a static group. The infrastructure information system is the order parameter, and vehicles are the subordinate system. The Automobilization rate of the country and forecast are shown in Figure 2 [8].

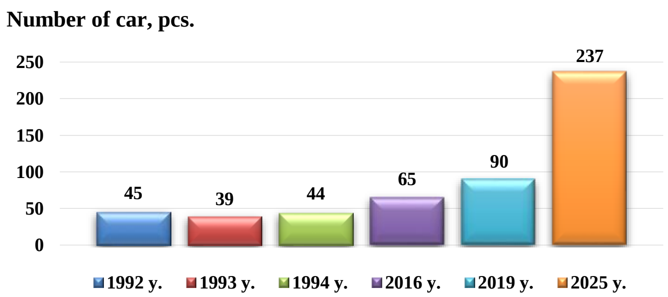

Fig.2. Dynamics of the vehicles per 1,000 people in the Republic of Uzbekistan

ITS consists of many components, it is important to have a scientific approaching in the organization of their interoperability. ITS is a complex system, the dynamic state of which depends on many external and internal factors.
Due to the large-scale use of ITS in the motor transport sector, it is planned to conduct research on the interaction of vehicles with road infrastructure in the country on the example of "Intelligent start-stop system" (ISSS) as a single

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element of ITS. Other elements of the ITS will also be represented like this system. The efficiency of the ISSS was determined by turning off the vehicle engine at the red light of traffic lights for a certain period of time, saving fuel consumed during that time [9]. During the research, a Wi-Fi device was installed on the traffic light and the ISSS in the vehicle, which were taken as an element of infrastructure. The traffic light's Wi-Fi module works as a "server". It determines the frequency of operation of the lights and sends it every second to the second traffic light, which works as a "client" in parallel with it, as well as to the ISSS Wi-Fi modules in the vehicle. The distance of wireless information exchange is up to 300 meters (Fig.3) [10].

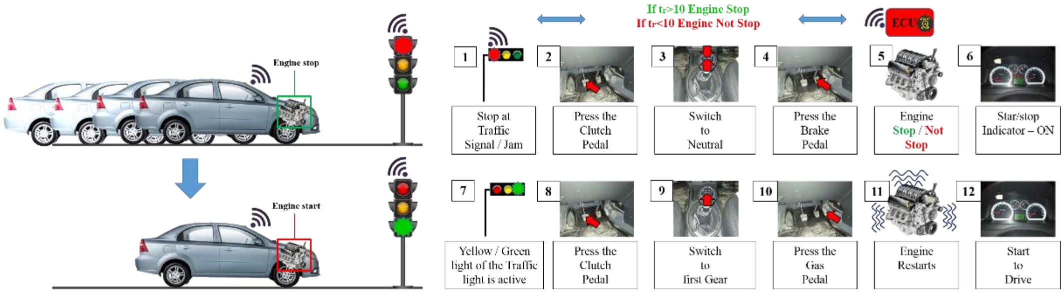

Fig.3. The mode of operation of the "Intelligent start-stop system" in V2I

According to the analysis, it was found that it is effective to turn off the engine for at least 10 seconds before using the start-stop mode at traffic lights. This system allows the vehicle's mechatronic systems to work in harmony with the infrastructure on the principles of synergetics. The basic principle of synergetics is the principle of subordination to the order parameter. External objects are integrated with the vehicle's mechatronic systems in ITS, and the system is described by an open, dynamically unbalanced, and nonlinear connection between parts based on synergetic requirements. We known that, the vehicle moves in different drive cycles throughout exploitation, such as "city", "highway" and "mixed". The most complex is the "urban" drive cycle. At the same time, the vehicle's speed is extremely variable, and the idle time of the engine increases as a result of regular stopping at traffic lights and traffic jams. In addition, the constant speed is limited, and acceleration and deceleration movements are often observed. Such a situation leads to an increase in fuel consumption. This means that the level of development of road infrastructure is important in traffic regulation, congestion elimination, and other processes. When the engine is running in idle mode, the amount of emission gases released into the environment is higher than in other modes. Because in this mode the engine runs on an enriched mixture ($\alpha<1$) so that it does not shut down [11]. We consider that it is necessary to increase the vehicle's fuel economy and improve environmental performance in this mode. There are several methods to save fuel. One of these methods is to use the ISSS in the component of "vehicle-to-infrastructure" of the ITS in the idling mode of the vehicle. Because saving fuel in this mode has not been researched in our country. Theoretically, it is possible to ensure the fuel economy of the engine in the idle mode of the driving modes. That is,

$$\text{If, } V_a=0;\ \omega_e=\omega_{i.m}>0;\ S=0;\ t>0 \text{ is } Q_f=0 \quad (1)$$

The start-stop system has been divided into two groups as a result of research and analysis. They are constructive and synergistic approaches. *In a constructive approach*, when the driver stops at a red traffic light, in congestion, or anywhere else, the engine automatically shuts off within 2-3 seconds under system requirements. After a certain time, it is automatically restarted when the driver performs several operations. *In the synergistic approach*, however, the car stops because of the above situations. ISSS activates in the designated area. According to the system requirements, several parameters are received and controlled by the vehicle and the infrastructure elements (traffic lights) to decide whether the engine should be shut down or not and the engine restarted after a certain time. The components that make up the ISSS are shown in Figure 4 [12-13].

During the test, the main parameters of movement of the car in the specified direction in urban conditions by using a Scanmatic diagnostic device to receive about 90 exploitation parameters were obtained through OBD-II CAN on board the electronic control unit of the engine. These include vehicle speed, engine speed, torque, load engine (in, percent), temperature, ignition timing (in, grades), detonation (in, voltage), fuel injection pulse duration, fuel tank reserve (in *l*, %

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position), λ-zond sensor voltage, such as the discharge and charge voltage of the battery when starting the engine on the electrical supply, as well as the voltage generated by the alternator and so on (Fig.5).

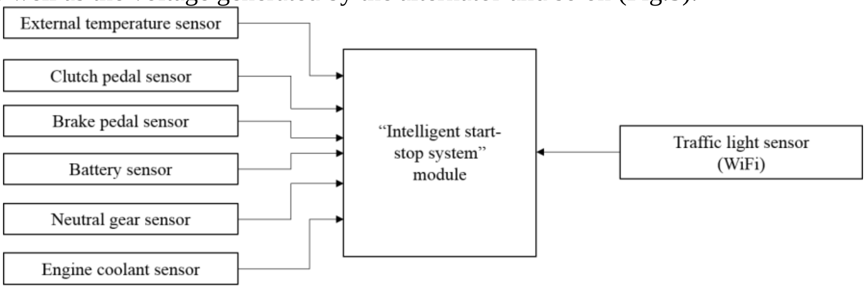

Fig. 4. Electronic control module of the "Intelligent start-stop system"

Fig.5. Recording the parameters of the vehicle in the driving mode through the scanmatic diagnostic device

The test was conducted in two steps in the autopoligon and in the city driving cycles. ***The first step*** of the test was carried out in a part of the normal driving cycles, ie 200 seconds because the horizontal part of the road was 2 km in the conditions of the auto polygon in Piskent. The fuel economy and environmental performance of vehicles produced in our country will be tested in accordance with the European Standard in New European Driving Cycle. In addition, under the leadership of Prof. A.A. Mukhitdinov was created driving cycle of Tashkent. A autopolygon test was held on both driving cycles. The main reason for testing ISSS in NEDC and Tashkent drive cycle is that the stop phase during cycles is more efficient than the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) drive cycle (Figure 6) [14-15].

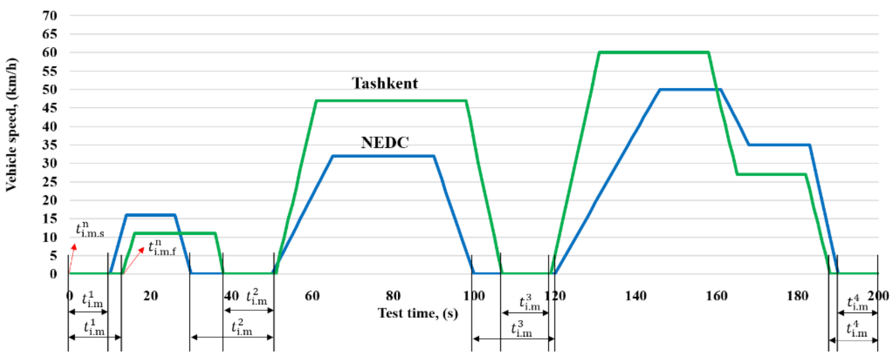

Fig. 6. Drive cycles for vehicle test

where: t_c^1,..., t_c^4 are stopping phases of vehicle (engine idle mode), (s).
The time in engine idle mode is calculated for a one-stop phase of the drive cycle by using the following equation:

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$$t_{i.m}^{n} = t_{i.m.f}^{n} - t_{i.m.b}^{n}, \text{(s)} \tag{2}$$

where: $t_{i.m.b}^{n}$ – the starting time of the idle mode in n-period, s; $t_{i.m.f}^{n}$ – the ending time of idle mode in n-period, s.

The idle times of the engine during the stop phases of the drive cycles are calculated as follows:

$$T_{i.m} = t_{i.m}^{1} + t_{i.m}^{2} + \cdots + t_{i.m}^{n}, (s) \tag{3}$$

Fuel consumption in idle times of the engine during the stop phases of the drive cycles are calculated as follows:

$$Q_{f\_dc.i.m} = \sum_{i=1}^{n} \Delta Q_{f\_dc.i.m}^{n}, (s) \tag{4}$$

where: $\Delta Q_{f\_dc.i.m}^{n}$ – the theoretically calculated amount of fuel consumption in the idle mode of the engine for each stop phase of the drive cycle, (*l/s*).

During the test process, the fuel consumption of the vehicle's on-board computer and more than 90 other parameters are recorded in the program of the Scanmatic device through special connection OBD-II CAN from the engine ECU. The required parameters were checked at the beginning and end of the test. Fuel consumption per each drive cycle - $Q_{\text{d.c}\_n}$ was determined as follows.

$$Q_{\text{d.c}\_n} = Q_{\text{d.c}\_n}^{t.b} - Q_{\text{d.c}\_n}^{t.e}, (l) \tag{5}$$

where: $Q_{\text{d.c}\_n}^{t.b}$ – measured amount of fuel at the beginning of the test, (*l*); $Q_{\text{d.c}\_n}^{t.e}$ – measured amount of fuel at the end of the test, (*l*).

For standard and ISSS vehicles, the average fuel consumption in the driving cycle (Q and Q_{ISSS}) were determined as follows:

$$Q = \frac{Q_{d.c\_1} + Q_{d.c\_2} + \cdots + Q_{\text{d.c}\_n}}{n} = \frac{\sum_{i=1}^{n} Q_m^{n(b-e)}}{n}, \ (l) \tag{6}$$

where: $Q_m^{n(b-e)}$ and ($Q_{ISSS\_n}^{n(b-e)}$) – measured amount of fuel at the beginning and end of the test, (*l*); *n* - the number of movements per cycle.

The hourly fuel consumption of the engine in idle mode is usually determined experimentally using special equipment. Fuel savings for a vehicle with ISSS in the drive cycle $Q_{f.s\_ISSS}$ is determined as follows:

$$Q_{f.s\_ISSS} = (Q - Q * \Delta_{f.s}) - (Q_{ISSS} - Q_{ISSS} * \Delta_{f.s}), (L/km) \tag{7}$$

In the calculation of equation (10), taking into account the fuel consumption during the restart of the engine, the total amount of fuel saved during the drive cycle $Q_{fuel\ cumulative}$ was determined as follows [16]:

$$Q_{fuel\ cumulative} = Q_{f.s\_ISSS} - Q_{fuel/restart} * N_{restart}, (L/km) \tag{8}$$

where: $Q_{fuel/restart}$ – fuel consumption at engine restart in, (*g/s*); $N_{restart}$ – number of engine restarts in, (*per 100 km*).

III. RESULT AND DISCUSSION

According to the results of experimental research conducted for the first 200 s of the drive cycles, the fuel consumption of the engine in the idle mode is calculated and the results are shown in Table 1.

Table 1.

Parameters	Unit	Theory		Experimental		Difference (+/-), (Degree of adequacy, %)
		Stan-dard	With ISSS	Stan-dard	With ISSS	
Fuel consumption of the engine in idle mode time	*l/s*	**NEDC drive cycle**				
		0,021	-	0,015	-	+ 0,006 (71 %)
		Tashkent city drive cycle				
		0,017	-	0,012	-	+ 0,005 (70,6 %)

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The polynomial equations of the fuel consumed were determined using Newton's first interpolation equation on the example of the NEDC drive cycle for a standard and a vehicle with ISSS in the autopolygon conditions.

$$P_n(x) = y_0 + \frac{\Delta y_0}{1!h}(x - x_0) + \frac{\Delta^2 y_0}{2!h^2}(x - x_0)(x - x_1) + \ldots + \frac{\Delta^n y}{n!h^n}(x - x_0)(x - x_1)\cdots(x - x_{n-1}) \quad (9)$$

The polynomial equation of fuel consumption in a standard vehicle:

$$P_f(x) = P_{t.b}(x) - P_{t.e}(x) \quad (10)$$

$$P_f(x) = 1{,}5x^4 - 200{,}8x^3 + 1657x^2 - 31716{,}8x + 1031377{,}3$$

The polynomial equation of fuel consumption in a vehicle with ISSS:

$$P_{ISSS\_f}(x) = P_{ISSS\_t.b}(x) - P_{ISSS\_t.e}(x) \quad (11)$$

$$P_{ISSS\_f}(x) = 1{,}01x^4 - 135{,}9x^3 + 1138{,}4x^2 - 20788{,}2x + 655006$$

Using the polynomial equations determined by Newton's first interpolation formula, the spatial representation of the volume of fuel consumed in the tank during the experiment on the X, Y and Z axes was expressed (Figure 7).

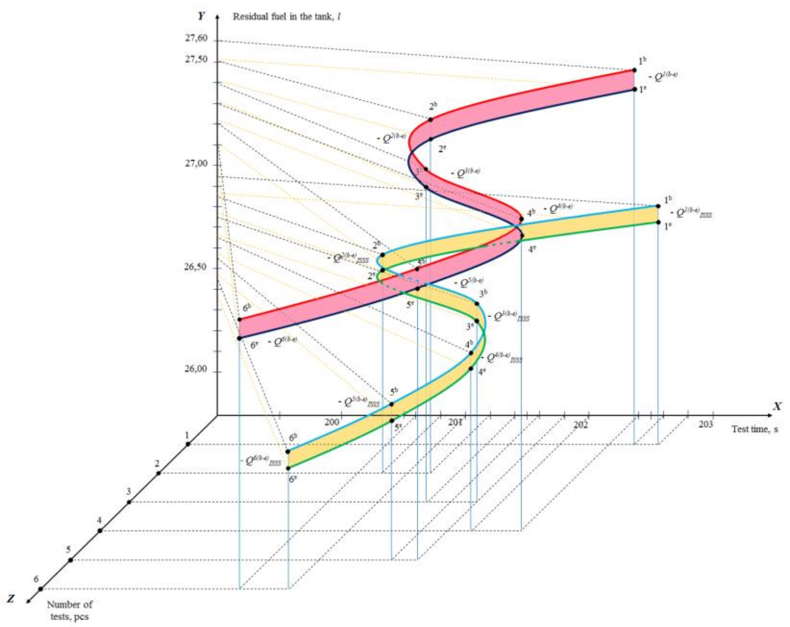

Fig. 7. Graph of dependence of fuel consumption in the tank on the test procedure and during the experiment time

According to the results of experiments conducted at the autopolygon, in the example of the NEDC drive cycle, the graph of the time dependence of the vehicle speed $V_a = f(t_{d.c})$ was constructed for a vehicle with ISST (Figure 8, a). Also, in this drive cycle, the number of crankshaft rotations in different modes of the engine was analyzed according to the graphs of the time-dependent function n = f (t) and its idle mode (Figure 8, b).

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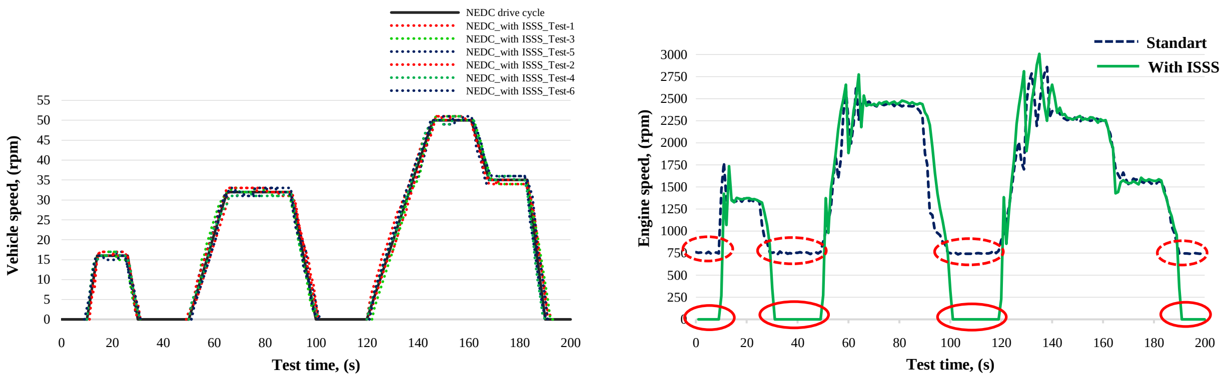

a) b)

a) ISSS drive cycle, b) engine speed.

Fig. 8. Graph of the New European drive cycle

The calculated fuel consumption in drive cycles is shown in Table 2.

Table 2.

Vehicle model	Time, *s*	According to technical description, *l/100 km*	The fuel consumption in the drive cycle: Theoretical in *ml*, Standard	The fuel consumption in the drive cycle: Theoretical in *ml*, With ISSS	The fuel consumption in the drive cycle: Experimentalin *l/100 km*, Standard	The fuel consumption in the drive cycle: Experimentalin *l/100 km*, With ISSS	Difference, +/-, *l/100 km*, Standard	Difference, +/-, *l/100 km*, With ISSS	Percentage of fuel saved, % *(l/100 km)*
NEDC да харакат циклида									
Chevrolet Nexia	200	8	0,084	0,078	7,96	7,40	- 0,04	- 0,56	7
Тошкент шахри харакат циклида									
Chevrolet Nexia	200	8	0,116	0,106	7,94	7,56	- 0,06	- 0,38	4,78

The second step of the test was conducted in the Tashkent city condition. According to the test requirements, the traffic on the inner central streets of the small ring road in Tashkent was determined as the direction of traffic, which includes 45-50 traffic lights at a distance of 25-30 km. The test planed to drive on a standard and an ISSS vehicle in the direction indicated during peak hours of the day (morning, lunch, and evening). At the same time, the time of stopping the vehicle at the red light of a random traffic light was measured. During the restart of the vehicle engine with ISSS at the yellow or green lights of the traffic light, it was accepted to measure the discharge voltage $U_{d.ch}$ of the battery through a voltmeter device. Analyzing the conditions of exploitation of vehicles, and taking into account the density of traffic, the city of Tashkent was selected as the object of research. On the Drive cycle of the Tashkent city we used a Chevrolet Nexia. The statistics data were collected using the experimental method in a small ring road with a high traffic intensity on the central streets of the city at the tight time, which is a distance of 25-30 km long and passing 45-50 traffic lights (Fig.9). Given that the operation of the system depends on a microcontroller setted on the traffic light, during the test, when the vehicle stopped at the red light, by using simulation its engine was stopped and started.

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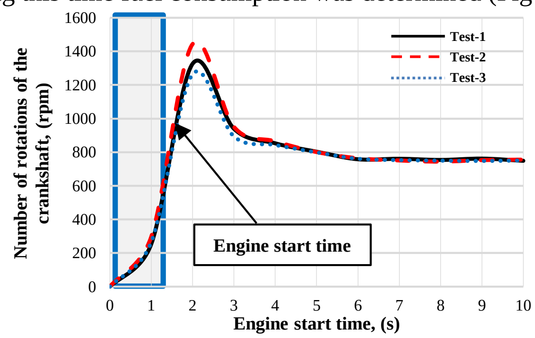
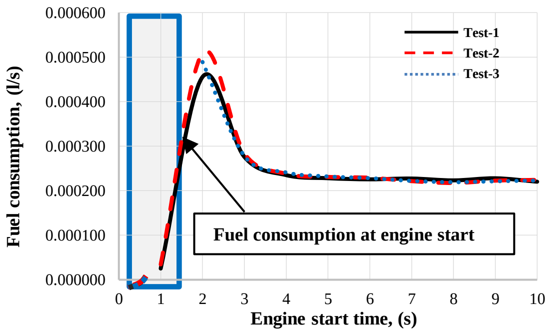
Fig.9. Research processes by using "Intelligent start-stop system" at the traffic lights to determine the lost times

According to the experimental results, it was accepted the average number of crankshaft rotations in the idle mode of the engine at temperatures of 75... 100 ° C is $n_{i.m} = 750$ rpm. In addition, the engine restart time was 0.9 ... 1.8 seconds, during this time fuel consumption was determined (Figure 10).



a)



b)

a) engine restart time, b) fuel consumption at restart.

Fig. 10. Graph of the engine restart time dependence on fuel consumption (Chevrolet Nexia B15D2)

Fuel consumption of a vehicle with ISSS was calculated in *l/km* and the results are given in Table 3.

Table 3.

Vehicle model	According to technical description, *l/100 km*	Experimental fuel consumption, *l/75 km*		According to the description of the experiment, *l/100 km*		Difference, +/-, *l/100 km*		Percentage of fuel saved, % (*in l/100 km*)
		Stan-dard	With ISSS	Standard	With ISSS	Stan-dard	With ISSS	
Chevrolet Nexia	8	5,99	5,52	7,98	7,32	-0,02	-0,658	8,25

The test vehicle meets the requirements of Euro 3 in accordance with European environmental standards. Additionally, based on the testing results, the following toxic gases were reduced in according to the European standard and normative requirements for exhaust gas concentrations: (Table 4).

Table 4.

Compliance of European standards and norms of toxic gases used in the test process on the example of Chevrolet Nexia

Concentration of toxic gases	Unit	Chevrolet Nexia, MT, Euro 3		Difference (Δ), +/-, g/km
		Standard	With ISSS	
Carbon Monoxide (CO)	g/km	2,3	1,897	- 0,403

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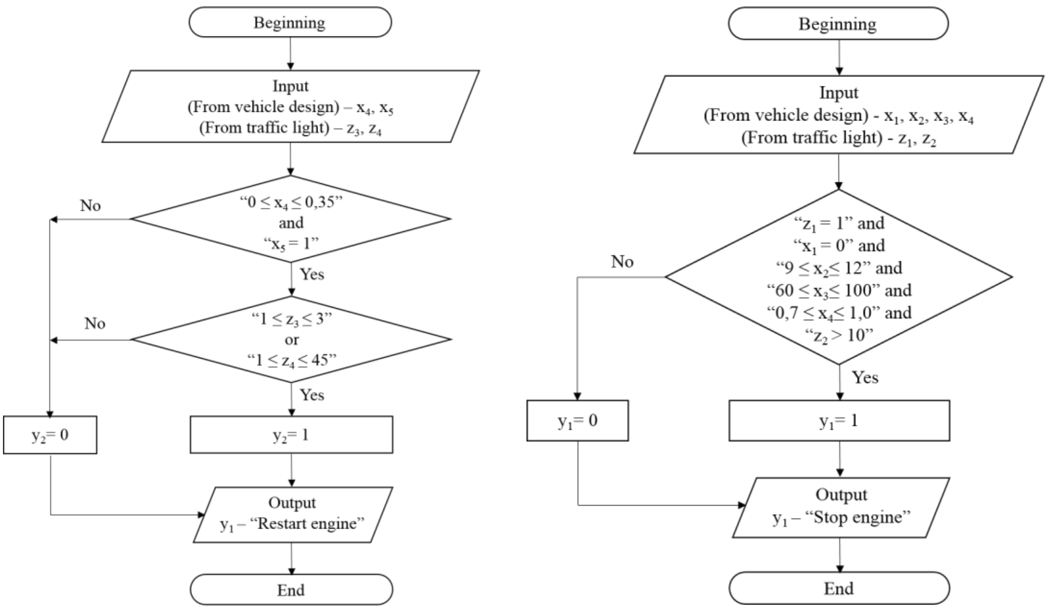
Hydrocarbons and Oxide of Nitrogen ($HC + NO_x$)	g/km	-	-	-
Hydrocarbons (HC)	g/km	0,20	0,165	- 0,035
Oxide of Nitrogen (NO_x)	g/km	0,15	0,124	- 0,026
Particulate matter (PM)	g/km	-	-	-

Based on the information model of ISSS, 13 input parameters of vehicle design and 4 input parameters of infrastructure elements were determined during the experiment. The interdependence of the parameters determined during the experiment was analyzed with correlation values. Five input parameters with a strong correlation were selected to the system from the vehicle design. To develop the logical function of the ISSS were determined their boundary-values. That is, x_1 – is speed sensor of vehicle, $(0 \leq X_1 \leq 1)$ km/h, x_2 – is charge level of the battery, $(75 \leq x_2 \leq 100)$ % or $(9 \leq x_2 \leq 12)$ V, x_3 – is the engine temperature, $(60 \leq x_3 \leq 100)$ °C, x_4 – is throttle valve position of engine, $(0{,}7 \leq x_4 \leq 1{,}0)$ V, x_5 – is clutch pedal sensor (for MT), $(0 \leq x_5 \leq 1)$ (if clutch pedal is not depressed, $x_5=0$ or "No", if depressed, $x_5=1$ or "Yes" logical action was determined). The control algorithm was developed through the Boolean function for the ISSS in the part of the "vehicle-to-infrastructure" of ITS (Figure 11).

The test was determined by the ability to save time, resources, and relative costs of technical systems on the basis of the vehicle (Table 5).

Table 5.
Technical and economic indicators of justification of synergy of innovative ITS in local conditions on the example of "Intelligent start-stop system"

№	Parameters	Unit	Quantity		Difference, +/-
			Standard vehicle	ISSS vehicle	
1.	Coefficient of ISSS use in the test (Order parameter)	-	0	0,69 (0,31)	- 0,69 (0,31)
2.	Comparison fuel consumption	l/100 km	7,98	7,32	+ 0,68
		l/20000 km	1 596	1 464	+ 132
3.	Exploitation costs	sum/year	375 850	763 719	- 387 869
4.	Annual cost-effectiveness for a single vehicle	sum/year	$((1596 - 1464) \cdot 9000) - 763719 = 424281$		



a) b)

a) for engine stop, b) for engine start (restart).

Fig. 11. Algorithm representing the ISSS`s logical model working in combination with infrastructure

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IV. CONCLUSION

The following general conclusions were reached based on the scientific research:

1. Today, the issues of synergetics of driving modes of vehicles with the road infrastructure using the capabilities of intelligent transport systems have not been sufficiently studied. It was also observed that the level of implementation of these technologies in our conditions is still low, that there are resources in the field to solve problems, and that the methodologies and present condition of vehicle-intelligent transport system interaction were analyzed.

2. On the basis of the analysis of intelligent transport systems, the practical aspects of the application of the interaction of infrastructure with the vehicle in the local condition on the example of the “Intelligent start-stop system” were studied. Its input and output parameters were analyzed theoretically and practically, and based on its information model, a control algorithm using the Gantt model and the Boolean function was developed. Also, the concepts of order and flexibility parameters were established according to the synergetic concept of the use of ITS in the exploitation condition. The infrastructure information system is the order parameter, and cars are the subordinate system, which created an opportunity to save energy resources by providing information transfer between them.

3. The capabilities of mechatronics systems and internal intelligent systems of the vehicle were used in conducted to analyze the vehicle with the “Intelligent start-stop system” interaction with the infrastructure. For the experiment, modern methods and the necessary diagnostic equipment based on the principles of synergetics were selected.

4. Based on the following results, experimental research was conducted on a vehicle with the “Intelligent start-stop system”:

- The use of the "Intelligent start-stop system" allowed the vehicle saved by 7% of fuel in the NEDC for 100 km and by 4.78 % in the Tashkent driving cycle, according to an experiment conducted at the Piskent autopolygon;

- The time of stopping at a red traffic light of a vehicle with the “Intelligent start-stop system” was calculated in Tashkent city condition. According to theoretical and practical analysis, the time limit before the red traffic light turns off in the engine start-stop mode was fixed at least 10 seconds. In order to ensure the resource of components', it was determined that if the time is less than the limited time, the engine will not be switched off or otherwise switched off;

- In the experimental conditions, the polynomial equations of fuel consumption for a vehicle with a standard and “Intelligent start-stop system” were determined using Newton's first interpolation method;

- the vehicle with the “Intelligent start-stop system” saved 8.25 % of fuel per 100 km in urban conditions. By using practical and analytical methods, it was determined that one vehicle saved an average of 132 liters of fuel per year when traveling 20,000 km, and minimizes CO emissions by 8060 g, HC emissions by 700 g, and NO_x emissions by 520 g.

5. Using the “Intelligent start-stop system” as an example of justification of the synergy of innovative intelligent transport system in local conditions with vehicle engine`s capacity in 1,5 liter taking into account exploitation costs, the annual economic efficiency has 424,281 soums (per vehicle).

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