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Integral Evaluation of Implementation Efficiency of Automated Hardware Complex for Vehicle Traffic Control

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ABSTRACT

Reducing the speed of the vehicle can reduce the risk and severity of the collision. Automatic means of vehicle traffic operation control, such as automatic speed cameras, is one of the main methods to solve traffic violations such as speeding. This study takes the actual operation of the automated hardware complex for vehicle traffic control in the Russian Federation as the research objective, and discusses the impact of the application of automated hardware complex for vehicle traffic control on traffic safety. In the process of building the automated traffic flow monitoring system of urban agglomeration, it is necessary to form a set of methodology to evaluate the hardware complex of traffic infrastructure. According to the research results of the influence of vehicle traffic automation and control system on road safety, a model, method and algorithm were developed to evaluate the efficiency of automated hardware complex for vehicle traffic control. The relevant factors introduced into the intelligent transportation system for the overall evaluation of the application efficiency of the vehicle traffic operation control automation hardware complex were determined. A life cycle model of automated hardware complex for vehicle traffic operation control was established to evaluate its operation efficiency in the development stage of intelligent transportation system, and on this basis, the maneuverability standard of urban agglomeration traffic monitoring system management is determined. The results show that the number of hardware complexes used in vehicle traffic operation control has a positive impact on the road traffic accident rate. It is suggested that the standard of one hardware complex for every 6.5 thousand registered vehicles in this area should be used as an indicator of the equipment level of the integrated automated system for vehicle traffic control in this area.

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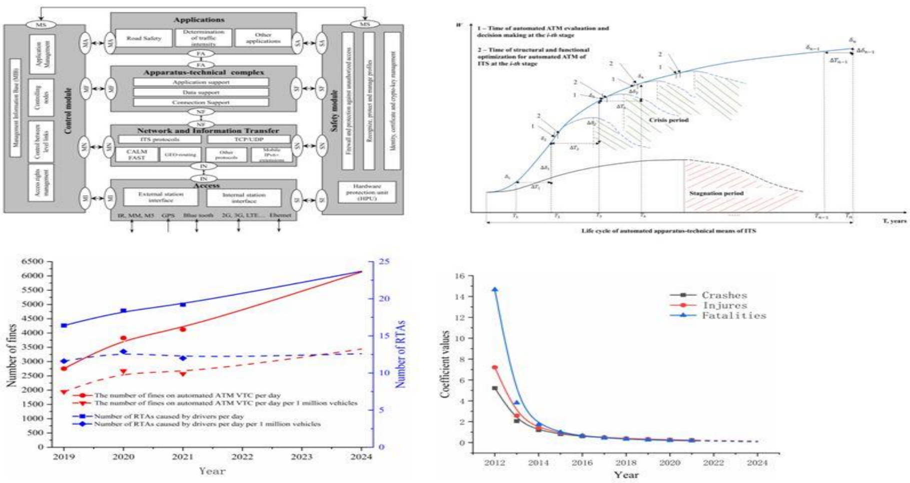
Graphical Abstract[1]



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LIST OF ABBREVIATIONS

ITS: Intelligent transportation system
ATM VTC: Apparatus-technical means for vehicle traffic control
AHC VTC: Automated hardware complex for vehicle traffic control
RTAs: Road traffic accidents
RTOI: Road traffic operational indicators

1. INTRODUCTION

The problem of establishing intelligent transportation system (ITS) is closely related to the introduction of automated hardware complex for vehicle traffic control (AHC VTC) into the transportation system, which is based on the development of digital technology in this field, which will significantly improve the socio-economic and environmental performance of the transportation process by improving road capacity, saving labor and reducing the number of road traffic accidents (RTAs) (1-3). The improvement of regulatory means and effective systems in the field of transport, including automated means and information systems for remote supervision, will greatly improve road traffic safety and management efficiency (4-6). The developed ITS construction model (Figure 1) shows the key role of the apparatus-technical complex among the existing functional modules, united in a telecommunication unit, various interfaces used for communication within the system, as well as communication with other ITS objects (7-9).

The traffic accident rate is an important evaluation index to evaluate the degree of traffic safety, and speeding is one of the important causes of RTAs. Related studies show that the average speed increases by 1 km per hour, traffic accident injuries increase by 3%, and deaths increase by 4 to 5%. As one of the important measures of road traffic management, speed limit plays a positive role in improving traffic efficiency, ensuring traffic safety and reducing energy consumption. Speed limit laws are

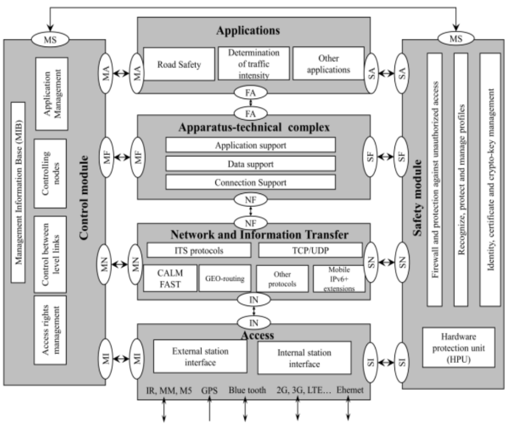

Figure 1. Generalized model for building intelligent transportation systems

generally enforced by police officers driving police cars and rely almost entirely on technologically assisted observation. In recent decades, many countries have adopted automatic and automated systems for traffic monitoring and traffic enforcement. The application of these technologies and systems can have a positive impact on drivers' safe driving in accordance with the law, thus improving traffic management and road safety (10-15).

The automated traffic-speed enforcement system has three basic components: (1) vehicle speed subsystem, (2) vehicle/driver photo subsystem, and (3) speeding violation subsystem. radio detection and ranging (RADAR) or light detection and ranging (LIDAR) sensors are often used as fixed or portable installations in the vehicle speed subsystem to determine the speed of the vehicle. In a recent study Yasar et al. (16) compared the effectiveness of RADAR speedometer тrameras and LIDAR tachometer cameras as automated traffic law enforcement systems. The study found that these two techniques are effective in improving the overall safety, but there are some differences in technology and operation. Specifically, the LIDAR speed camera is more accurate in measuring vehicle speed, while the RADAR speed camera is more reliable in bad weather conditions. In addition to the integrated hardware of automation for the purpose of ensuring traffic safety and improving the level of traffic operation and management of traffic control departments, and the urban intelligent transportation subsystem taking automated traffic monitoring and law enforcement system as an example, due to labor-intensive and technological progress, in order to adapt to different traffic and transport scenarios, alleviate and solve traffic problems (traffic congestion, parking, cargo / passenger transportation). More urban intelligent transportation subsystems have been developed, including: adaptive traffic control system, intelligent parking system, commercial vehicle law enforcement system, etc (17-21).

Currently, many areas of research on the application of ITS technologies have moved from the conceptual and experimental stage to the stage of large-scale implementation. Therefore, in the process of developing the ITS subsystem and realizing the modernization of road infrastructure, it is necessary to evaluate the application of automated apparatus-technical means for vehicle traffic control (ATM VTC) that supports its operation.

Høye (22) used META analysis to estimate the crashes were reduced by 15%, 20%, and 25% after using automatic cameras. Studies by Thomas et al. (23) also concluded that on roads where cameras were installed, injured crashes were reduced by 20 to 25%. The traditional radar tachometer can be divided into fixed and mobile types (24-26). The report by Erke et al. (27) showed that on roads where fixed tachometers are installed, injuries were reduced by 35%; while on roads with mobile tachometers, injuries were reduced by only 14%, which seems to mean that fixed tachometers are more effective than mobile tachometers. However, other studies have shown that the safety effect of fixed tachometer is lower than that of hidden mobile tachometer (28-30). In a research by Jeong-Gyu (31) pointed out that on certain roads (especially those near intersections or schools), using fixed tachometers with warning signs (visible) is more effective than hidden tachometers. On the other hand, the use of a hidden mobile tachometer may have a wider impact and greater preventive effect, because the driver does not know the location and time of installation of the tachometer, so it is impossible to predict (32-35).

Taking into account the impact on vehicle road safety, the evaluation of automated ATM VTC applications will determine the potential or actual development of ITS projects and their hardware in the transportation system at each stage of the life cycle (including construction, operation and decommissioning). In the construction of ITS, it is necessary to control the maintainability, technical and technological conditions of the hardware complex of ITS (AHC VTC) and the establishment of local automatic vehicle monitoring system (36-40).

However, the analysis of results showed that there is not a set of key indicators to evaluate automated ATM VTC application effect in ITS technical control system at present, and there are few researches related to the implementation, creation and selection of vehicle traffic control hardware complex in Russian Federation. In addition, there are no general criteria to assess the effectiveness of AHC VTC on road safety on highways. In order to solve this scientific problem, it is necessary to establish the relationship between AHC VTC operation efficiency performance index and accident rate index (41-48). To this end, we consider the elements of AHC VTC, its capabilities, and the characteristics of the following complexes and modules, such as:

- The LBX-RSU-59 type receiving and transmitting stationary module, which is a roadside device through which to provide DSRC 5.9 GHz communication for the ITSs between transport infrastructure and vehicles, as well as other mobile devices;
- The video recording measuring complex “CORDON-CROSS”;
- The mobile system "PARKON-A";
- The smart video recorder “GROM-1”;
- The system for measuring the average speed of vehicles “DUET";
- The multipurpose complex for the automatic photo-fixations of traffic violations "SKAT", etc.

The authors of the present study attempted to to create a model of the life cycle of AHC VTC operation, which will be able to assess the effectiveness of operation by the coefficient of influence on the road safety indicator. Also, the authors have developed an algorithm for assessing the efficiency of AHC VTC operation and obtained an empirical dependence for determining road safety indicators taking into account all parameters of AHC VTC influence. The results of this study can help road traffic authorities of Russia and the region of the study to make appropriate decisions on installation of AHC VTC.

2. METHODS AND RESULTS

It is impossible to form the life cycle of AHC VTC without their techno-economic assessment. At the moment, AHC VTC is characterized by a low number of integral efficiency parameters, in this connection there are no methodological approaches to subsequent modernization of ITS taking into account changes in the current transport situation, scientific and methodological substantiation of the choice of technologies and placement of AHC VTC. In case when the maximum efficiency of AHC VTC functioning is not reached, the ITS enters the stage of stagnation, and further use of this ITS is inexpedient (49-51).

As a result of the study, a life cycle model of AHC VTC was developed (Figure 2), which reflects the tendency of change in time of the influence of ATM VTC application on the considered road traffic operational indicators (RTOI) in accordance with the development of modern ITS technologies. On the basis of which the main indicator of AHC VTC operation efficiency was established: the coefficient of technical efficiency of AHC VTC utilization (the ratio of the number of optimal adaptation processes to the total number of all intelligent control levels). A methodological approach is formed for assessing the efficiency of AHC VTC utilization, based on the determination of the effects and their influence on the RTOI at the considered stage of ITS development (52-55). The cause-effect relationship between the

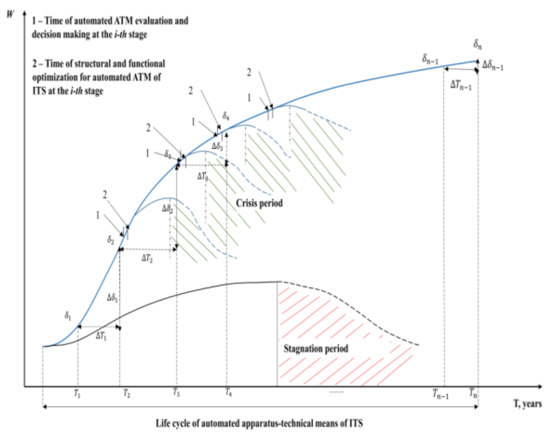

Figure 2. An AHC VTC application efficiency assessment model based on the life cycle concept (operational phase)

indicators of AHC VTC efficiency is determined by a generalized mathematical model:

$$W = F[\delta_1, \delta_2, \delta_3, \ldots \delta_n], \quad (1)$$

where W is the criterion for evaluating AHC VTC application effectiveness, which ought to have the highest value ($W \rightarrow$ max); $\delta_1, \delta_2, \delta_3, \ldots \delta_n$ are the values of the coefficient of influence for ATM VTC on the RTOI at the stage under consideration, provided that $\delta_1 < \delta_2 < \delta_3 < \ldots < \delta_n$.

According to Newton–Leibniz formula, the definite integral of a continuous function on the interval [a, b] is equal to the increment of any of its functions on the interval [a, b]. In combination with the developed model, we can obtain the value of the change in the coefficient of influence of AHC VTC on RTOI in the period t_{n-1}, t_n, which can be expressed by the following equation:

$$\Delta\delta = \int_{t_{n-1}}^{t_n} W(t)dt = F(t_n) - F(t_{n-1}) = F(t)\Big|_{t_{n-1}}^{t_n}, n > 1, \quad (2)$$

where $\Delta\delta$ is the value of the change in the coefficient of influence for AHC VTC on RTOI, which, in an ideal case, should always be greater than 0.

$$W(T) = \begin{cases} \delta_1 T_1 + \Delta\delta_1(T_1 + \Delta T_1) \\ \delta_1 T_1 + \Delta\delta_1(T_1 + \Delta T_1) + \Delta\delta_2(T_1 + \Delta T_1 + \Delta T_2) \\ \delta_1 T_1 + \Delta\delta_1(T_1 + \Delta T_1) + \Delta\delta_2(T_1 + \Delta T_1 + \Delta T_2) + \Delta\delta_3(T_1 + \Delta T_1 + \Delta T_2 + \Delta T_3) \\ \ldots\ldots \\ \delta_1 T_1 + \Delta\delta_1(T_1 + \Delta T_1) + \Delta\delta_2(T_1 + \Delta T_1 + \Delta T_2) + \cdots + \Delta\delta_{n-1}(T_1 + \Delta T_1 + \Delta T_2 + \cdots + \Delta T_{n-1}) \end{cases}, n \geq 2 \; and n \in Z. \quad (3)$$

Thus, the general formula for expressing the effectiveness of the AHC VTC used during the ITS development life cycle over time can be expressed by Equation 4:

$$W(T_n) = \delta_1 T_1 + \Delta\delta_1(T_1 + \Delta T_1) + \Delta\delta_2(T_1 + \Delta T_1 + \Delta T_2) + \cdots + \Delta\delta_{n-1}(T_1 + \Delta T_1 + \Delta T_2 + \cdots + \Delta T_{n-1}), n \geq 2 \; and n \in Z. \quad (4)$$

where $W(T_n)$ are indicators, that, over time, describe the efficiency of the use of AHC VTC, which should have a maximum value, i.e., $W_T \rightarrow$ max.

The main criterion for assessing the effectiveness of the use of AHC VTC was defined as the criterion of operational control $W(T_n)$. The concept is introduced: control is operative if the time spent on carrying out measures to control vehicles will not exceed the critical time dictated by the conditions of the current situation and is achieved by accelerating the process of data collection and processing, decision-making, planning, extensive use of software and information support, systems and means of automated control (56). The dependences Equations 3 and 4 allow, on the basis of the set coefficient (δ) (which takes into account the impact of the functioning of AHC VTC on RTOI), to assess the effectiveness of the road traffic accident rate, i.e., the number of crashes, injuries, and fatalities (57-59).

A multiple regression analysis was performed to analyze the impact of the functioning of AHC VTC in various conditions on the traffic safety of transport systems (number of crashes) in the analyzed regions. It was found that the accident rate was significantly influenced by the specific indicator characterizing the ratio of the number of vehicles to the number of fines for offenses in the field of road safety (TC/unit). To determine the relationship between the performance indicators of AHC VTC and the accident rate, a correlation analysis was carried out to analyze the statistical data (60-63).

The establishment of the correlation between the indicators of RTAs and the indicators of efficiency for AHC VTC would indicate that the work of AHC VTC lead to a decrease in the indicators of RTAs—which is one of the most significant criteria for the effectiveness of AHC VTC. The correlation between the two arrays of indicators and those that identify their mutual influence allows the use of the method of mathematical statistics correlation analysis (64-67).

The correlations between the indicators of the following two blocks were examined beforehand in order to determine the relationship between the indicators of AHC VTC work and road safety.

The block characterizing the work of AHC VTC:

- The total number of fines during the reporting period;
- The number of fines per day on average over the reporting period;
- The specific number of fines per day per million registered vehicles ($N_{F/V}$).

The block that characterizes the road safety:

- The total number of crashes during the reporting period;
- The number of crashes during the reporting period through the fault of the drivers;
- The number of crashes caused by drivers on average per day;
- The specific number of crashes caused by drivers per day per million registered vehicles ($N_{A/V}$).

The findings of the investigation into the effects of AHC VTC on traffic safety (Fig. 3, Table 1) made it possible to establish a significant correlation between the specific indicators $N_{F/V}$ and $N_{A/V}$.

The specific performance indicator of AHC VTC (Formula 5):

TABLE 1. The results of the analysis of the effects of AHC VTC on road safety

Objective	2019	2020	2021	Correlation coefficient
Number of fines on ATC VTC during the reporting period	1005212	1396919	1504126	0.989421
Number of crashes during the reporting period	7550	8288	8341	
Number of fines on ATC VTC per day	2754	3827	4121	0.997167
Number of crashes caused by drivers per day	16.4	18.4	19.2	
Number of fines on ATC VTCper day per 1 million vehicles	1945,7	2675.3	2574.2	0.999998
Number of crashes caused by drivers per day per 1 million vehicles	11.6	12.9	12	

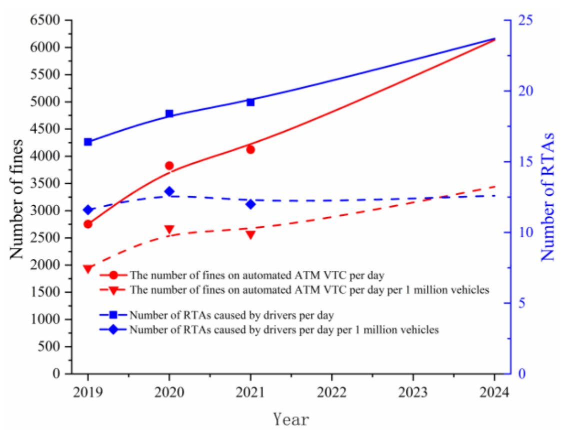

Figure 3. Comparative assessment of the impact of AHC VTC on road safety indicators

$$N_{F/V} = \frac{N_{offenses}}{D_{operation} \cdot N_{RV} \cdot 10^{-6}} \tag{5}$$

where $N_{offenses}$ is the number of offenses detected by the AHC VTC in a year;

$D_{operation}$ is the number of calendar days of AHC VTC operation in the year under consideration;

N_{RV} is the number of registered vehicle.

This indicator is independent of the number of vehicles, and it has a correct sensitivity to changes and allows you to average the performance of the AHC VTC, which are characterized by the uneven distribution of fines during the calendar year.

To establish the specific number of crashes caused by drivers in 1 day per 1 million registered vehicles we use the following formula (Equation 6):

$$N_{A/V} = \frac{N_{A.Driver}}{D_{calendar} \cdot N_{RV} \cdot 10^{-6}} \tag{6}$$

where $N_{A.Driver}$ is the number of crashes caused by the drivers of vehicles per year;

$D_{calendar}$ is the number of calendar days in the year under consideration.

It should be noted that the application of the correlation analysis of the total number of crashes has the disadvantage of taking into account the types of crashes, which are not affected by the work of AHC VTC (for example, due to the technical condition of vehicles). In this regard, only crashes caused by the drivers of vehicles were used for further consideration. As in the case of $N_{F/V}$, in order to average fluctuations of the indicator by calendar year, as well as to ensure the correct sensitivity to changes and independence from the natural dynamics of changes in the number of registered vehicles, the number of crashes caused by the drivers was recalculated to the specific indicator. In the course of assessing the effectiveness of an AHC VTC, the extent to which the correlation between the dependencies of the specified indicators on the year of operation of the control system was assessed.

When conducting a correlation analysis based on the Pearson correlation coefficient (68), as the simplest option, two arrays of numerical values, which allows us to determine the closeness of the linear relationship between the two values (Formula (7):

$$r = \frac{\sum(N_{F/V_i} - \overline{N_{F/V}}) \cdot (N_{A/V_i} - \overline{N_{A/V}})}{\sqrt{\sum(N_{F/V_i} - \overline{N_{F/V}})^2 \cdot \sum(N_{A/V_i} - \overline{N_{A/V}})^2}} \tag{7}$$

The Spearman correlation coefficient was chosen as an additional indicator to confirm the results of the Pearson correlation analysis. Spearman correlation is rank correlation, i.e., numerical values are not used, but their corresponding ranks are used instead in order to assess the strength of the relationship. The coefficient is invariant with respect to any monotonic transformation of the measurement scale, which provides an additional advantage in revealing the relationship between the quantities of heterogeneous dimensionality (Formula 8):

$$\rho = 1 - \frac{6}{n(n-1)(n+1)} \sum_{i=1}^{n} (R_{F/V_i} - R_{A/V_i})^2, \tag{8}$$

where n is the number of values in the data arrays;

R_{F/V_i}, R_{A/V_i} are the ranks of the i values in the data arrays of specific AHC VTC performance indicators and specific accident rate indicators, respectively.

The range of values for the Spearman correlation coefficient and Pearson correlation coefficient is from minus 1 to 1. Positive numbers denote a direct association between the variables, whilst negative values denote an inverse relationship. The closer the modulus of the criterion is to unity, the closer the relationship between the values is (44). In this particular case, the more intensively AHC VTC work (i.e., a higher value of $\boldsymbol{N_{F/V}}$), the greater reduction in accident rate should take place (a lower value of $\boldsymbol{N_{A/V}}$). Thus, the more pronounced positive correlation between the work of AHC VTC and the reduction in crashes, the more the correlation coefficient is close to minus 1. That is, the correlation coefficient value that is closest to minus 1 will indicate the effectiveness of the AHC VTC.

The above calculation sequence can be the basis of the algorithm for assessing the performance of AHC VTC in terms of their impact on the RTAs. Figure 4 displays the algorithm's block diagram.

A comparative analysis of the data obtained from the research on ensuring the stable operation and maintenance of the ATM VTC and the supervision of its operation shows that the AHC VTC has a systematic impact on road safety in the study area. Therefore, it is necessary to adopt a unified method to evaluate the effectiveness of the AHC VTC in the Russian Federation. In order to evaluate the use efficiency of expressway AHC VTCs under operating conditions, a method is developed, which, combined with life cycle cost analysis, can be based on the determined mode and index. Select the best variety of control technical means to meet the requirements of traffic organization and ensure traffic

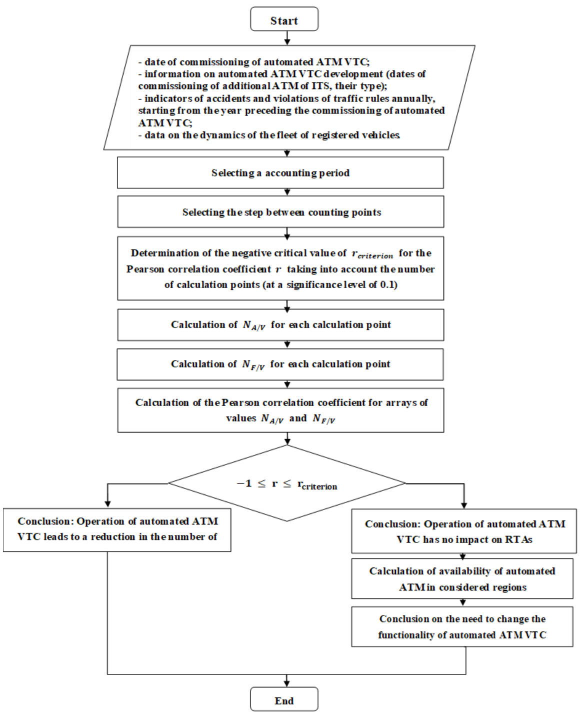

Figure 4. Algorithm for evaluating the performance of automated apparatus-technical means for vehicle traffic control in the context of ensuring road safety

safety on expressways. The established sequence for assessing the efficacy of the application of AHC VTC can be used to evaluate the influence of AHC VTC on RTAs. This method has a multi-stage process for determining the effectiveness of AHC VTC.

The first stage:

1. Initial data on the functioning of AHC VTCs, such as the cost of one AHC VTC; the number of used AHC VTCs; the loan rate (in %); the service life of AHC VTCs; the deductions for the maintenance and repair of AHC VTCs; the assembly of AHC VTCs, as well as their installation and adjustment; the wages of technicians, operators, and drivers;

2. The cost of installation and the cost of maintaining the performance of the AHC VTCs throughout their service life are taken into account when calculating the annual maintenance cost in accordance with the technical, operational, and economic performance of the AHC VTC ITS:

$$\mathrm{C}_{tech.} = \frac{\mathrm{C}_{AHC\,VTC} \cdot \eta_{MR}}{100}, \tag{9}$$

where C_{AHCVTC} is cost of one AHC VTC in rubles;

η_{MR} is the norm of deductions for the maintenance and repair of AHC VTCs per year in %.

3. Calculation of costs during the installation of AHC VTCs on the control line:

$$\mathrm{C}_{dur.install} = \mathrm{C}_{allins.} + \mathrm{C}_{op} + \mathrm{C}_{tech.} + \mathrm{C}_{driv.} \tag{10}$$

where $\mathrm{C}_{allins.}$ is the cost of the AHC VTCs assembly, installation, and adjustment;

C_{op} is the operator'' salaries in rubles;

$\mathrm{C}_{tech.}$ is the technicians' salaries in rubles;

$\mathrm{C}_{driv.}$ is the drivers' salaries in rubles.

4. Calculation of costs for the maintenance of technical means operability:

$$C_{VU} = [(C_{AHC\,VTC} * N_{AHC\,VTC}) + C_1]\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] + nC_M, \tag{11}$$

where N_{ATM} is the number of AHC VTC ITS;

C_1 is the turnkey installation cost in rubles;

C_M is the annual maintenance cost in rubles per year;

i is the credit rate in %; n is the service life in a year.

5. Determination and selection of alternative options for AHC VTCs, taking into account the necessary requirements on the following criteria: specific capital investment in building projects; specific capital investment in the installation of AHC VTCs; wages of operators, technicians, and drivers of vehicles; the number of automated ATMs; the coefficient of the increase in the cost of AHC VTCs; the cost of installation for road signs; the required number of road signs; the number of crashes on the examined segments of the road network before the installation of automated ATMs; and the annual number of crashes on the examined segments of the road network after the installation of an AHC VTC.

6. Calculation of capital investments for the implementation of AHC VTCs according to the considered parameters:

$$I = (I_{construction} + I_{installation}) * N_{ATM} * k_2 + (\mathrm{C_{RS}} + \mathrm{C_{ins.\ RS}}) * N_{RS}\ ; \quad (12)$$

where $I_{construction}$ is the specific capital investment for the construction of the traffic control lines in rubles;

$I_{installation}$ is the specific capital investments for the installation of AHC VTCs in rubles;

k_2 is the coefficient of increase in the costs for AHC VTCs;

$\mathrm{C_{RS}}$ is the cost of road signs in rubles;

$\mathrm{C_{ins.\ RS}}$ is the costs for the installation of road signs in rubles;

$N_{RS}$is the number of road signs.

The presented calculation of the first stage allows one to determine the cost of maintenance and installation, as well as the capital expenditures for maintaining the performance of AHC VTCs on the basis of which to determine their alternatives and to form the requirements for AHC VTCs.

Second stage:

1. Assessment of the impact of AHC VTCs on the TOI of the road. Determination of the impact of AHC VTCs on road safety by indicators (based on the generalized criterion for assessing the parameters of AHC VTCs functioning δ):

- By the indicator "number of crashes ":

$$\delta = A_2 / \left[A_1 (\frac{N_{F/V_1}}{N_{F/V_2}})^2\right], \quad (13)$$

- By the indicator "number of injures":

$$\delta = B_2 / \left[B_1 (\frac{N_{F/V_1}}{N_{F/V_2}})^3\right], \quad (14)$$

- By the indicator "number of fatal

$$\delta = D_2 / \left[D_1 (\frac{N_{F/V_1}}{N_{F/V_2}})^4\right], \quad (15)$$

where N_{F/V_1} is the specific number of fines per day per 1 million registered vehicles issued in the previous period (for example, 2018); N_{F/V_2} is the specific number of fines per day per 1 million registered vehicles issued in the subsequent period (for example, 2019); A_1, B_1, D_1 are the number of RTAs (crashes, injuries, and fatalities, respectively) committed in the previous period (for example, 2018); A_2, B_2, D_2 are the number of RTAs (crashes, injuries, and fatalities, respectively) committed in the subsequent period (for example, 2019).

2. Calculation of the quantitative indicators of losses from one road accident before the start of AHC VTCs:

$$\varphi_{\mathrm{RTAs}_1} = \frac{D_{\mathrm{RTAs}_1}}{N_{\mathrm{RTAs}_1}}, \quad (16)$$

where $D_{\mathrm{RTAs}_1}$is the damage from RTAs in the base case, in rubles;

$N_{\mathrm{RTAs}_1}$is the annual number of RTAs in the base case.

3. Calculation of quantitative indicators of losses from one road accident after the beginning of an AHC VTC ITS functioning:

$$\varphi_{\mathrm{RTAs}_2} = \frac{D_{\mathrm{RTAs}_2}}{N_{\mathrm{RTAs}_2}}, \quad (17)$$

where D_{RTAs_2} is the damage from RTAs in the projected option, in rubles;

$N_{\mathrm{RTAs}_2}$is the annual number of RTAs in the projected option.

4. Calculation of the cost estimates of losses from one accident before and after the start of an AHC VTC ITS:

$$\Delta\varphi = \varphi_{\mathrm{RTAs}_1} - \varphi_{\mathrm{RTAs}_2}, \quad (18)$$

5. Calculation of the index of the reduction of the total losses from RTAs (reduction in damage) after the implementation of an AHC VTC ITS:

$$\Delta = \Delta\varphi * (N_{\mathrm{RTAs}_1} - N_{\mathrm{RTAs}_2}), \quad (19)$$

The results of the calculation in the second stage allowed us to determine the functional efficiency of an AHC VTC on the social characteristics before and after the beginning of the AHC VTC's functioning; namely, the assessments of the impact of AHC VTC functioning parameters on road safety relative to the previous year; the quantitative indicators of losses from RTAs; and the index of reduction in total losses from one road accident.

Thus, the developed method, based on the assessment of the functional efficiency indicators of an AHC VTC and the TOI of the road, for evaluating the effectiveness of AHC VTCs on the road enables the selection of an optimal AHC VTC option for meeting the requirements for vehicle traffic management organizations on the road.

Table 3 displays the modeling findings for the effect of AHC VTC use on the changes in the territory accident indicator from 2019 to 2022 (by years).

In certain regions, there is a significant change in the RTAs depending on the indicators of an AHC VTC ITS functioning. This change is determined by regression relationships (Table 3): the impact of AHC VTCs on the drivers of vehicles leads to a gradual reduction in the indicators of RTAs, with a corresponding decrease in the number of fines.

TABLE 3. Mathematical models on the impact of AHC VTCs on the indicator of RTAs

Considered period	**Regression dependence**
Number of RTAs	
2019	$y = -0{,}5134x^2 + 39{,}808x + 1934{,}6$
2020	$y = -0{,}3079x^2 + 23{,}872x + 1160{,}2$
2021	$y = -0{,}1385x^2 + 10{,}737x + 521{,}8$
2022	$y = -1{,}308\ x^2 + 26{,}2x + 745$

The established generalized criterion is the coefficient that considers the influence of the functioning of AHC VTCs on RTAs; it is a comprehensive indicator that realizes the dependence of the number of RTAs on the activities of organizations on the use of AHC VTCs and their equipment with technical means.

The empirical dependences were created to evaluate the effects of AHC VTCs on the primary accident indicators, while taking into account the generalized criteria for measuring the parameters of AHC VTC ITS operations, which considers their impact on road safety (i.e., the number of crashes, injuries, and fatalities). The following is the model that was created for determining the accident indicators (i.e., the number of RTAs) in the territories of the Russian Federation:

$$A_2 = \delta * A_1 (\frac{N_{F/V_1}}{N_{F/V_2}})^2, \tag{20}$$

where N_{F/V_1} is the number of fines per day per 1 million registered vehicles issued in the previous period (e.g., 2018); N_{F/V_2} is the number of fines per day per 1 million registered vehicles issued in the subsequent period (e.g., 2019); A_1 is the number of RTAs committed in the previous period (e.g., 2018); and δ is the coefficient taking into account the impact of the operation of the AHC VTCs in the region under consideration.

Thus, the established influence of the functioning of AHC VTCs on the RTAs in the examined regions is proposed to be determined by the generalized coefficient - δ_i, which takes into account the impact of AHC VTCs on the indicator of RTAs. The values of the coefficient δ_i are presented in Table 4.

The graphical representation of changes in the values of the coefficient that considers the effect of the operation of automated ATM VTCs on the indicator of RTAs is shown in Figure 5.

Taking into account the impact of the operation of the AHC VTC on the accident rate and its schedule, we can determine the regression dependence. Table 5 summarized the mathematical model that takes into account the impact of the vehicle traffic control automation hardware integrated system (AHC VTC) on the accident rate to determine the predicted value of the coefficient. In addition, the degree of the polynomial determines the number of extremes of the function considered during the analysis interval.

The analysis of the graphs shows that the coefficient that takes into account the impact of the functioning of AHC VTC on RTAs is decreasing, i.e., the obtained data on the impact of the application of automated ATM VTC for the period until 2022 indicate a decrease in the impact of these complexes on the safety of road traffic in the regions of the Russian Federation.

In order to quantitatively assess the potential for the development of AHC VTC, it is necessary to forecast the prospects of its formation in order to maximize the level of road safety. The dependence of the influence of the equipment of AHC VTC in the studied regions on the relative indicators of change in the number of issued resolutions is linear in nature. The trend line (y = 3.8876 ln(x) + 0.9748), presented in Figure 6, indicates a significant impact of AHC VTC equipment on the indicator of RTAs.

The data on the values of the coefficient, which considers the effect of the functioning of AHC VTC on the crashes and its schedule, allowed us to determine the

TABLE 4. Calculated coefficient values that account for the effect of automated ATM VTC performances on the accident indicator

δ_i	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8	δ_9	δ_{10}
Crashes	5,218	2,055	1,192	0,809	0,600	0,469	0,381	0,319	0,272	0,236
Injures	7,2131	2,5750	1,4096	0,9193	0,6598	0,5032	0,4	0,328	0,275	0,235
Fatalities	14,654	3,811	1,733	0,991	0,642	0,4508	0,3341	0,2577	0,205	0,167

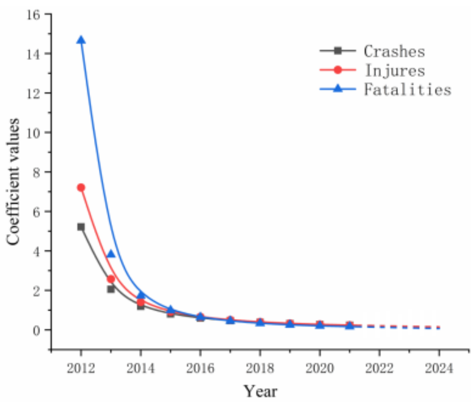

Figure 5. Coefficient values that take into account the impact of AHC VTC on the indicator of RTAs

TABLE 5. Results of the mathematical modeling on the impact of AHC VTC on RTAs

The accident indicators	Regression dependence
Number of crashes	$y = 5{,}2189x^{-1{,}344}$
Number of injured	$y = 7{,}2131x^{-1{,}486}$
Number of fatalities	$y = 14{,}654x^{-1{,}943}$

regression relationships. Mathematical models, determining the predicted values of the coefficient, which considers the impact of the functioning of AHC VTC on RTAs.

This is due to various reasons of technical, informational and managerial nature. Thus, the number of AHC VTCs has a positive impact on RTAs. The criterion Y_{ATMs}- one AHC VTC per 6.5 thousand vehicles registered in the region - is proposed as an indicator of the level of equipment of the region with AHC VTC:

$$Y_{AHC\ VTCs} = \frac{1}{6500}, \tag{21}$$

Due to the use of a certain number of AHC VTCs, it is possible to achieve a reduction in RTAs to a certain level. At the same time, it is necessary to take complex measures affecting all spheres of people's life activity (social, demographic, cultural, public, legal).

The hypothesis of the influence of the number of resolutions for traffic violations on the indicator of RTAs indicates the existence of a relationship between the number of RTAs and the performance of AHC VTC. In this regard, the forecast of the prospects for the formation of a system that maximizes road safety can be based on the forecast of changes in the number of vehicles for the region and the calculation of the necessary number of AHC VTC on its basis, according to the following formulas:

$$\sum N_{\text{AHC VTCs}} = \frac{N_{vehicle_i}^{forecast}}{\rho_{vehicle/\text{AHC VTCs}}}, \tag{22}$$

where $\sum N_{AHC\ \text{VTCs}}$ is the forecast total number of ATM VTCs in the region for the *i-th* period; $N_{vehicle_i}^{forecast}$ is the forecast number of registered vehicles in the region during the *i-th* period; $\rho_{vehicle/\text{AHC VTCs}}$ is a relative indicator showing for how many vehicles how many AHC VTCs is needed.

The assumption in performing these calculations is the constancy of the characteristics of the street and road network, it is not possible to take into account the development prospects of which for all regions within the framework of this study.

3. DISCUSSION

The combination of information and control plays a pivotal role in shaping a positive attitude toward traffic safety among a majority of vehicle owners. Additionally, it fosters a critical perspective regarding the conduct of individuals who jeopardize the safety of both themselves and others through risky behaviors. The existence of a substantial portion of the population, often referred to as the "critical mass," advocating for safety further contributes to the establishment of a social milieu in which safety-conscious behavior becomes the prevailing norm. Research has conclusively shown that the absence of any single component, whether it be experience, knowledge, awareness, consciousness, external feedback, or regulatory enforcement, impedes the transformation of a driver's behavioral model (68-70). As such, there arises a compelling need to effectively harness AHC VTC. On the basis of the conducted research the methodological bases and proposals on rational application and improvement of AHC VTC to improve road traffic safety of motor transport are developed. These recommendations contain the developed methods, algorithms of actions for the selection and rational functioning of AHC VTC, provide specific measures for their improvement. The lack of standardized requirements and protocols for the utilization of these tools and systems has precipitated a state of conceptual confusion, leading to the proliferation of equipment and, in tandem, software of questionable caliber and functionality. Frequently, cameras are positioned not at accident-prone epicenters, but rather in locations with minimal accident probabilities. This disparity has resulted in the inability to comprehensively process and dispatch appropriate administrative proceedings to offenders, as well as to expeditiously address grievances from road users pertaining to administrative sanctions. Throughout our study, we leveraged mathematical and statistical techniques, including regression analysis and correlation analysis. To gauge the impact of AHC VTC on road safety metrics, the volume of statistical sampling of data on the functioning of AHC VTC in 56 regions of the Russian Federation was carried out.

A comparative analysis of the data obtained in the course of the research on the provision of the stable operation and maintenance of AHC VTC, as well as regulatory aspects of their functioning, indicates a systemic impact of AHC VTC on road traffic safety in the regions under study. However, on the other hand, the analysis of the calculated values of the coefficient that accounts for the influence of the AHC VTC on accident indicator ($\delta_1 > \delta_2 > \delta_3 > \cdots > \delta_{10}$) shows that the impact of AHC VTC on road safety decreases every year—which is contrary to our initial assumptions. This implies that there is still room for improvement in the AHC VTC and vehicle traffic control systems in place to guarantee road safety. In order to modernize the existing monitoring system and to ensure that the AHC VTC have a further positive effect on the target RTOI of the road, it is necessary to assess the effectiveness of the existing AHC VTC and, if necessary, introduce new technical means of control. Formation of the methodological basis and improvement of the technology of operation of AHC VTC of different levels will allow to justify the conceptual approach and form a single basic platform, based on which it will be possible to build an effective control system.

In the process of conducting research the positive results were analyzed and options for solving the identified problems were proposed. The issues related to the development of criteria for evaluating the management of structures and organizations that ensure the functioning of AHC VTC on the basis of basic principles and provisions of the theory of decision-making are of particular relevance.

A concise examination of the existing literature aimed at enhancing road safety in the realm of road transportation has exposed a distinct void in research pertaining to the integration of automated advanced traffic management vehicle technologies within the transportation framework. Equally underexplored are the matters surrounding the introduction of AHC VTC into the transport infrastructure, as well as the evaluation of their efficacy and the subsequent influence on road safety outcomes. The contemporary landscape of road safety management is characterized by a substantial surge in the scope of responsibilities tied to constructing ITSs. Given the incorporation of cutting-edge technologies, achieving this construct solely through administrative and organizational approaches is unattainable without the inclusion of scientific expertise and input.

Separately, the methodological levels of activities to improve road safety were considered and a review of studies in the field of choosing evaluation criteria for the quality of road traffic, which is devoted to a number of investigations by Vrubel et al. (56), Petrov et al. (58) and Caroles et al. (71). It has been established that the existing methods are unsuitable for the assessment of modern ITS ATM functioning at the stage of decision-making, due to the continuous development of ITS subsystems ensuring the sustainability of ITS projects.

In this regard, the primary criterion for evaluating the efficacy of utilizing AHC VTC has been established as the operational control criterion $W(T_n)$. To elaborate, the notion of operative control is introduced, signifying that the time dedicated to executing vehicle control measures remains within the critical time frame prescribed by prevailing conditions. This attainment is realized through expediting the data collection and processing process, hastening decision-making and planning, and leveraging extensive software and information support, as well as automated control systems and tools. Equations 3 and 4 allow, on the basis of the set coefficient (δ) (which takes into account the impact of the functioning of automated ATM on RTOI), to assess the effectiveness of AHC VTCs on road safety indicators, i.e., the number of crashes, injuries, and fatalities.

In order to enhance the road transportation management system, models, methods and algorithms to support managerial decision-making on the formation of a local telematic automated traffic control system have been developed. The conducted research of the relationship between the performance indicators of automated vehicle traffic control system and the performance indicators of road transportation efficiency has established a significant impact on road traffic safety when implementing AHC VTC.

Further research will be focused on the automation of the method by developing application software (72) to assess AHC VTCs efficiency based on the described method. Moreover, the research could be included in the wide studies on complex systems (73, 74), identifying the interrelationships between various automated traffic control information technology tools and the traffic environment (RTOI), for example, the study of the dependence of automated weighing station deployments on the average speed of vehicles and the capacity of the roadway, which contributes to the formation of an automated telematics control system, which is a promising line of research.

4. CONCLUSIONS

In the course of the study, it is found that there is not a method to evaluate the operation effect of AHC VTC equipment and technical means, in order to determine the quantitative and qualitative characteristics of its impact on highway accident rate. According to the research results of the operation of vehicle traffic safety automatic control hardware and technical means in Russian Union State, it can be concluded that automated ATM VTC have a significant impact on the accident rate at the initial stage of operation, and then determine the reduction in its number. Therefore, considering these conclusions and the experimental data, we propose a life cycle model and a mathematical model to evaluate the running effect of AHC VTC. This model reflects the trend that the impact of its application on the accident rate changes with time with the development of modern ITS technology. In view of this, the main indicator of the functional efficiency of AHC VTC is determined: the technical efficiency coefficient used by AHC VTC (the ratio of the number of optimal adaptive processes to the total number of all intelligent control levels), which will make it possible to quantitatively and qualitatively determine the impact of AHC VTC on the accident rate of highway sections where the system is installed. Therefore, we put forward a methodology, which can model and equip the AHC VTC of expressways reasonably, so as to reduce the accident rate of different levels of ITS design, because one of the standards for the development of vehicles and their use technology to a new level is the extensive adoption of continuous monitoring and its operating conditions. Therefore, as an indicator of the level of AHC VTC equipment in this area, the AHC VTC standard is proposed-one hardware complex for every 6.5000 registered vehicles in the area. The developed methodological approach for assessing the effectiveness of the AHC VTC can serve as a methodological support for the modernization of the system of automation and control of vehicle traffic and the development of ITS on the highway.

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Persian Abstract

چکیده

کاهش سرعت خودرو می تواند خطر و شدت برخورد را کاهش دهد. ابزارهای کنترل خودکار عملیات تردد خودروها مانند دوربین های کنترل سرعت اتوماتیک یکی از روش های اصلی رفع تخلفات رانندگی مانند سرعت غیرمجاز است. این مطالعه عملکرد واقعی مجتمع سخت افزاری خودکار برای کنترل ترافیک وسایل نقلیه در فدراسیون روسیه را به عنوان هدف تحقیق در نظر می گیرد و تأثیر کاربرد مجموعه سخت افزاری خودکار برای کنترل ترافیک خودرو را بر ایمنی ترافیک مورد بحث قرار می دهد. در فرآیند ساخت سیستم نظارت خودکار جریان ترافیک تراکم شهری، لازم است مجموعه ای از روش شناسی برای ارزیابی مجموعه سخت افزاری زیرساخت ترافیک تشکیل شود. با توجه به نتایج تحقیق تاثیر اتوماسیون و سیستم کنترل ترافیک خودرو بر ایمنی راه، مدل، روش و الگوریتمی برای ارزیابی کارایی مجموعه سخت‌افزاری خودکار برای کنترل ترافیک وسایل نقلیه توسعه داده شد. عوامل مرتبط وارد شده به سیستم حمل و نقل هوشمند برای ارزیابی کلی کارایی کاربرد مجموعه سخت افزاری اتوماسیون کنترل عملیات ترافیک خودرو تعیین شد. یک مدل چرخه عمر مجتمع سخت افزاری خودکار برای کنترل عملیات تردد وسایل نقلیه به منظور ارزیابی کارایی عملکرد آن در مرحله توسعه سیستم حمل و نقل هوشمند ایجاد شد و بر این اساس استاندارد مانورپذیری مدیریت سیستم نظارت بر ترافیک تراکم شهری تعیین می شود. نتایج نشان می‌دهد که تعداد مجتمع‌های سخت‌افزاری مورد استفاده در کنترل عملیات ترافیک خودرو تأثیر مثبتی بر میزان تصادفات جاده‌ای دارد. پیشنهاد می شود استاندارد یک مجتمع سخت افزاری به ازای هر ۶/۵ هزار خودروی ثبت نام شده در این منطقه به عنوان شاخص سطح تجهیزات سیستم یکپارچه خودکار کنترل تردد خودروها در این منطقه مورد استفاده قرار گیرد.