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The Design and Evaluation of a Telematic Automated System of Weight Control for Heavy Vehicles

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Abstract: In this article, the authors reviewed the existing system of weight control of heavy vehicles in the Russian Federation. In this research, the main shortcomings of the system, which prevent its effective functioning in relation to the use of road infrastructure, were determined. To solve these problems, we developed a model of the functionality of a telematic automated system of weight control of heavy vehicles, as well as defining the optimization tasks of the transportation process. Mathematical modeling of the operational factors that influence the system of weight control of heavy vehicles on roads was carried out. As a result of the research, the most significant parameters that have the greatest impact on the efficiency of the road were determined. By means of these parameters, it is feasible to choose suitable hardware and equipment for a weight control system. The methodology of developing automatic points for the weight control of heavy loads during road transportation was formulated. As a result of the study, it was concluded that the introduction of a telematic automated system of weight control of heavy vehicles would increase the efficiency of road transport on the highway by positively affecting its basic transport and performance indicators.

Keywords: telematic systems; weighing in motion; overloaded vehicle; heavy vehicle; road capacity

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1. Introduction

The development of an intelligent transport system (ITS) involves the use of information and communication technologies and, as a consequence, an increase in the number of different technical solutions.

The main goal of the digital transformation of the transport industry is to improve its efficiency as a whole. Since this study focuses on road transport, we can note that digital transformation concerns, among other things, the efficiency of road transport, road safety, and the comfort of road users.

Due to increased demand for road freight transport, shippers of goods, seeking to optimize the cost of transportation, load cargo in excess of the official established value. The consequences of regularly overweight cargo are manifested both in reduced road safety and in the negative impact on road surfaces. The present study found that up to 30% of road transport is carried out in violation of weight and dimension limits, with an average overweight of about 50%.

Statistics on freight traffic in the Russian Federation are presented in Table 1, which shows that during the pandemic year of 2020, the volume of freight traffic decreased, but for the first nine months of 2021, we can see an upward trend.

The trend towards the introduction of ITS is represented in many official documents, both international official documents (1. Official website of the European Union: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021SC0475&qid=1645789857701 (accessed on 19 January 2022) 2. Official website of the United Nations Economic Commission for Europe: https://unece.org/sites/default/files/2021-01/ECE-TRANS-2021-15r.pdf (accessed on 19 January 2022)) and official acts of the Russian Federation:

Decree of the Government of the Russian Federation of 27.11.2021 Russian Federation Government Order No. 3363-r "On Approval of the Transport Strategy of the Russian Federation until 2030, with a forecast for the Period 2035" (Official website of Ministry of Transport of the Russian Federation // https://mintrans.gov.ru/documents/2/11577 (accessed on 19 January 2022)).

Table 1. Statistical data on freight transportation by road in the Russian Federation [1].

	Name	2019	2020	January–September 2021	In % to January–September 2020	Unit of Measurement
1	Cargo transportation in Russia	5735	5405	3986	98.7	mtn
2	Length of roads	1706	1717	-	-	thou. km
3	Road accidents involving HGV	10.8	9.6	6.6	61	thousand cases

[1] Official website of the Federal State Statistics Service of the Russian Federation: https://rosstat.gov.ru/folder/23455 (accessed on 21 February 2022).

Intelligent transport systems are considered to assist in solving current and future transport problems. They are widely recognized as one of the effective tools for ensuring efficient, safe, and sustainable mobility [1–4].

In this regard, the further development of unified ITS involves the creation of theoretical science-based principles for building ITS subsystems at each level of their functionality.

The subject of the study is a subsystem of ITS weight control of heavy vehicles, which is designed to improve the efficiency of the transportation process of heavy goods, as well as increase traffic safety on the roads. Building the architecture of the subsystem of weight control requires a scientific analysis of ways to improve the efficiency of transportation of heavy goods by road.

Currently, there are studies devoted to elements of the weight control subsystem, such as weight-in-motion stations. Weight-in-motion stations are mainly considered to be a tool for collecting data on traffic flow parameters, including weight parameters for calculations in the design and operation of bridges and roads [5–9]. These studies also provide new ways of measuring the weight parameters of heavy vehicles [10,11]. The objectives of the above studies are to calculate the carrying capacity of bridge crossings and roadbeds on the basis of the data on the weight parameters of traffic flow obtained by weight-in-motion stations, as well as analyze the relevance of the problem of overloaded vehicles and damage to road infrastructure in different regions of the world [10–13].

Many studies have analyzed existing problems related to congestion and damage to road infrastructure in various regions, which emphasizes the relevance of this research [14–16].

Another area of research is the direct planning of freight transportation and, among other things, planning the distribution of traffic congestion on roads by one mode of transport or another during certain time periods [17–20].

Analysis of the existing system of weight control in the Russian Federation revealed the lack of a number of tools necessary to create an effective system of weight control:

- There is no methodology for building an integrated system of weight control for transportation by heavy vehicles [21,22];
- There is no methodology for assessing the measuring tools of a telematic automated control system of weight control for freight vehicles;
- No methodology for evaluating the effectiveness of the implementation of a telematic automated system of weight control for the transportation process of heavy vehicles has been formulated [23–25].

The objectives and goals of the present study are:

- The development of an architecture of telematic automated control system for the weight control of heavy vehicles, based on the analysis of functional capabilities and the main influencing factors on the transportation process;

- The development of a methodology for assessing the means of measuring a telematic automated control system for the weight control of heavy vehicles [26–30].

The novelty of this research lies in the fact that the study develops the architecture of building a telematic automated control system for the weight control of heavy vehicle traffic at the regional or state level, as well as an algorithm for the rational equipment of automated complexes of telematic control system for weight control.

2. Methods

The efficiency of the heavy cargo transportation process is affected by many factors, both internal factors related to the organization of transport work by the road transport enterprise [31–33], and external factors related to traffic conditions, the condition and categories of roads on the chosen route, obtaining permits for transportation, and the state of the transport infrastructure in general [34,35].

In the framework of this study, the relationship of "Vehicle–Road–Weight Control" was considered. The following relationship was established: Improving the quality of the road affects the efficiency of the transportation process as a whole, and the standard state of the road (transport and operational performance of the road) depends on the performance of the system of weight control.

As a result of the analysis of the existing system of weight control of trucks on highways, the composition of the system, types of weight control, structure, and functionality of the system were evaluated, and the advantages and disadvantages of the system were identified.

Having analyzed the subsystem of ITS weight control, a model of an integrated **telematic automated system of weight control of heavy vehicles** (hereinafter TASWC HGV) on the road was formed (Figure 1).

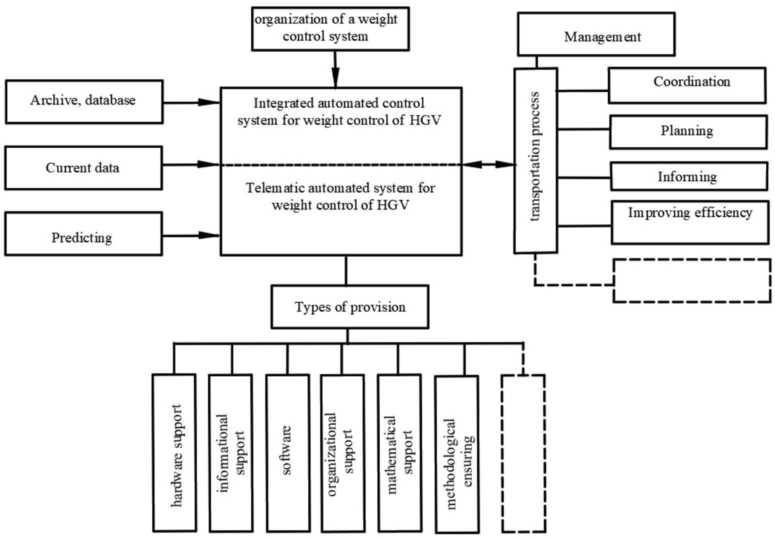

Figure 1. Model of an integrated telematic automated control system of weight control of HGVs on the road (TASWC HGV).

When building the TASWC HGV, it is necessary to provide the following: hardware, information, software, and organizational, mathematical, and methodological information [19].

During the selection of hardware and the technical specification of the automated control system of weight control, it is necessary to take into account the functions performed by the system. The model of the functional scheme of the TASWC HGV is shown in Figure 2.

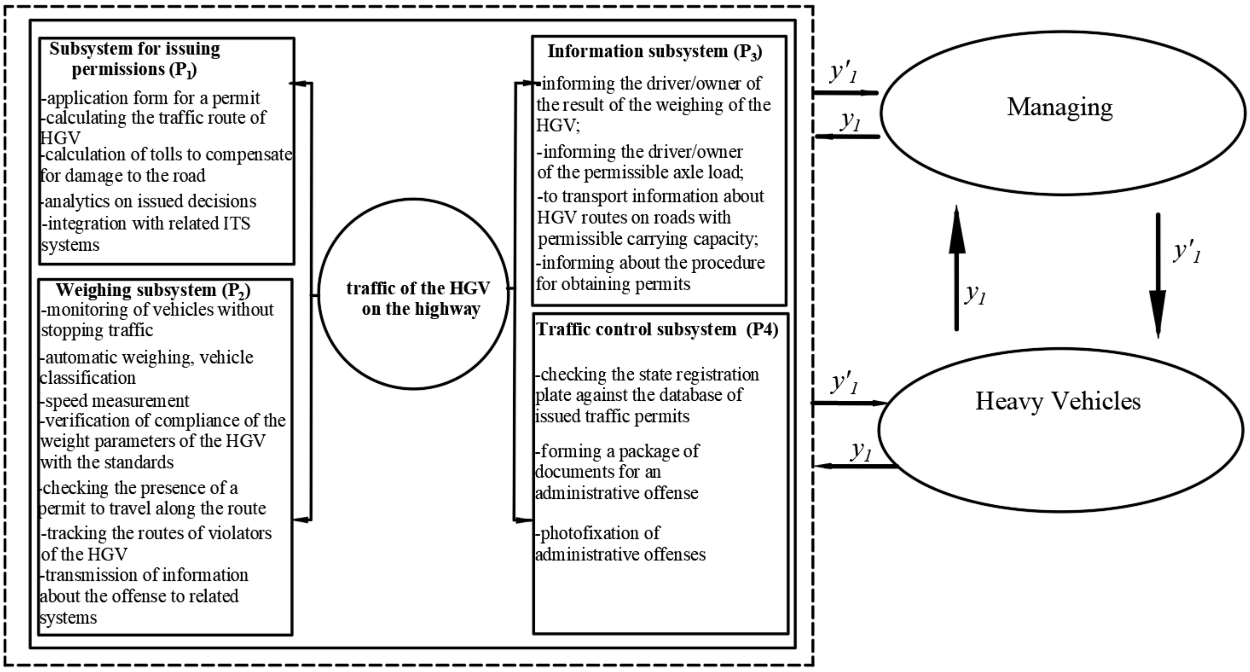

Figure 2. Model of the functional subsystems of the TASWC HGV.

The figure shows the model in which the data exchange between subsystems of the automated system of weight control is provided, which allows the problem of optimizing the movement of heavy vehicles on the road to be solved.

Some of these functions entail stopping or slowing down trucks, which affects travel time. Weighing a truck at a stationary or mobile weighing station can take 15–30 min. If overweight is detected, or if it is necessary to reload the cargo or take the vehicle to the impound lot, the delivery of the cargo may be extended for a period of 1 h to 1 day. Verification of travel documents may take 5–10 min. Given the length of the HGV route and the number of checks, the delay for the HGV en route will increase, lowering the efficiency of transportation [14]. In addition, the time spent on performing the functions of the traffic control system affects the main operational indicators of the road, such as the average speed of vehicles (km/h) and the capacity of the road (thousand vehicles/day).

Increasing the transport and operational indicators of the road increases the efficiency of road transportation and can be made possible by increasing the efficiency of the control system functions. Thus, F is the efficiency of TASWC HGV, which is composed of the functions of subsystems. On this basis, the optimization problems were formulated:

$$W = (y_1 y'_1 + y_2 y'_2 + y_n y'_n), \tag{1}$$

where W—the task of the traffic control system; y_n—execution of the n-th control function

$$F = \sum P_n(\mathrm{T}_n),\ \mathrm{T}_n \to min, \tag{2}$$

where F—the task of the traffic management system on the road, P_n—system functions; T_n—speed of execution n-th functions.

The efficiency of one or another subsystem of the TASWC HGV consists of the functions of the subsystems. Figure 3 shows the functional diagram of the weighing subsystem.

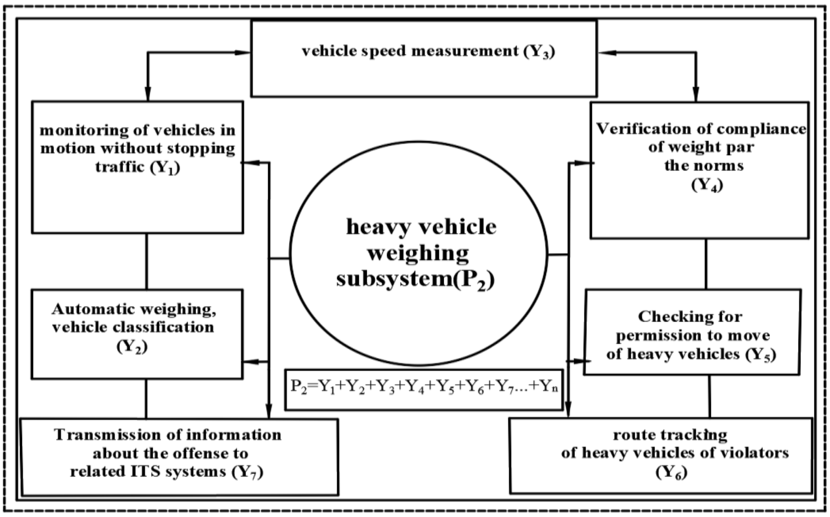

Figure 3. Functional diagram of the weighing subsystem.

Thus, the generalized scheme of TASWC HGV can be characterized as a set of subsystems and their main functions, the implementation of which renders the system optimal.

Thus, the system of weight control allows the combination of the functions of both the control and management of heavyweight transport traffic and the diagnostic assessment of the technical characteristics and condition of the vehicles. In the future, combining these functions will allow us to move from an automated to an automatic mode of traffic control.

In order to justify and clarify the structure and order of construction of the telematic automated control system of weight control, as well as establish the impact on the operational performance of the road, a model of its construction was developed (Figure 4).

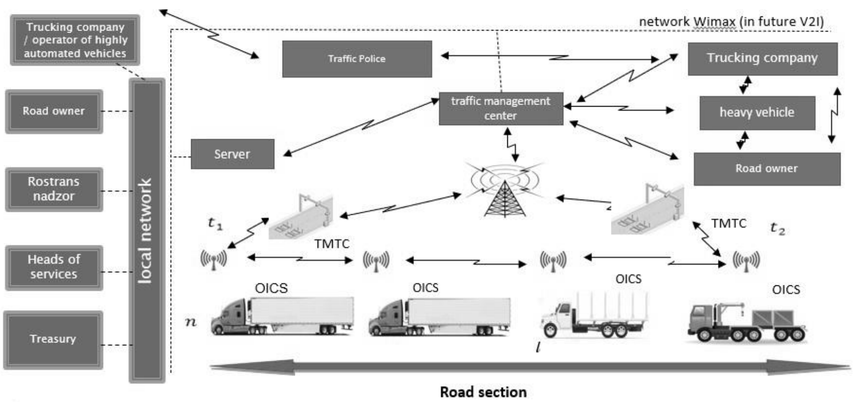

Figure 4. Model for the construction of the TASWC HGV.

To achieve this purpose, technical means of traffic control (hereinafter TMTC) were placed on the route of a heavy-duty vehicle. TMTC perform identification of a heavy-duty vehicle at the control points and transmit the received information via communication channels, through the station of differential correction of high-frequency navigation, in a form convenient for its analysis and decision-making. The received information is accumulated and delivered via the server to the officials involved in the organization of the transportation process of heavy loads.

As a result of experimental studies, the following indicators of the choice of measurement tools were determined: recognition characteristics, accuracy, ease of installation, performance, cost, and type of data (Figure 5).

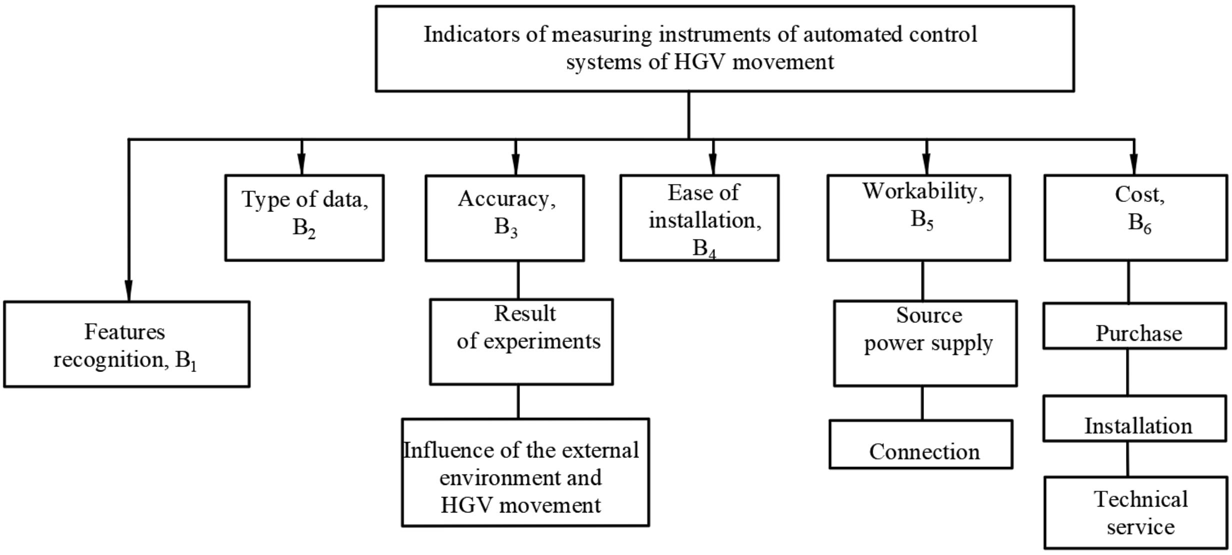

Figure 5. Indicators of means of measurement of the telematic automated system for the weight control system of HGVs (TASWC HGV).

Thus, the search for the optimal solution for the choice and evaluation of the means of measurement of the weight control system is carried out according to the following criteria: recognition efficiency and cost of the means of measurement.

The generalized criterion for selecting the means of measurement of the weight control system is the degree of efficiency of identification of a heavy vehicle (P_i) and is a set of probabilities of solving **k**-th identification problem in the degree of correspondence of the obtained probability estimate (P_k) and the required one ($P^{\text{э}}{}_k$): if

$$\begin{gathered} P_i = P^{\text{э}}{}_k - P_k,\ \text{if}\ P^{\text{э}}{}_k \geq P_k, \\ P_i = 0,\ \text{if}\ P^{\text{э}}{}_k < P_k, \end{gathered} \tag{3}$$

where,

$$P_i = \frac{1}{\sum_{k=1}^{P} n_k},\ \text{if}\ \sum_{k=1}^{P} n_k \neq 0, \tag{4}$$

Thus, the evaluation of the effectiveness of the task of recognition of heavy vehicles will be characterized by the coefficient P_i = 0...1 and will depend on the degree of compliance of the probability of each recognition task with the task specified in the technical specifications.

Figure 6 presents an algorithm for the rational choice of means of measurement of automatic TMTC of heavy vehicle traffic, based on the Pareto optimal.

This approach is implemented in the design of automated TMTC, which allows the integration into its composition additional measuring modules, complexes, cameras, or devices that determine the parameters related to road safety (for example, measuring vehicle speed, establishing the fact of an administrative offense, measuring the temperature of the ambient air or road pavement, determination of coordinates by GLONASS/GPS satellite system, and synchronization of the internal time scale from signals of coordinates and so on). The software performs the functions of collecting, processing, and further transmitting information from all measuring and technical devices of TASWC HGV. All software is divided into two parts. The part of the software installed in the microprocessor unit of the analog–digital converter is designed for processing the legally controlled parameters (axle loads, wheel loads, interaxle distances, overall dimensions, speed, and total weight of the vehicle). It is built in. The second part of the software, which is installed on the computer with the operating system, is not responsible for the processing of legally controlled parameters. The basis of the automated TMTC consists of such elements as sensors embedded in the road surface and mounted on a support over the road, as well as photo–video fixation means:

- Strain gauge sensors—determining the weight parameters of the vehicle without reducing the speed;
- 3D laser sensors—detection of vehicle dimensions;
- Photo and video cameras—acquisition of vehicle images and recognition of license plate number plates;
- Computer equipment (protected controller)—recognition of license plate numbers, control of peripheral equipment;
- Communication equipment—data transmission via 3G, fiber-optic channel or satellite communication, data encryption;
- Inductive sensors—determining the fact of passing vehicles and wheel configuration, as well as determining the speed of vehicles. These sensors are not fully capable of measuring the weight and dimensions of vehicles without reducing the speed, so to increase the efficiency of TASWC HGV, it is proposed to implement an algorithm for the rational choice of measuring tools based on criteria approaches.

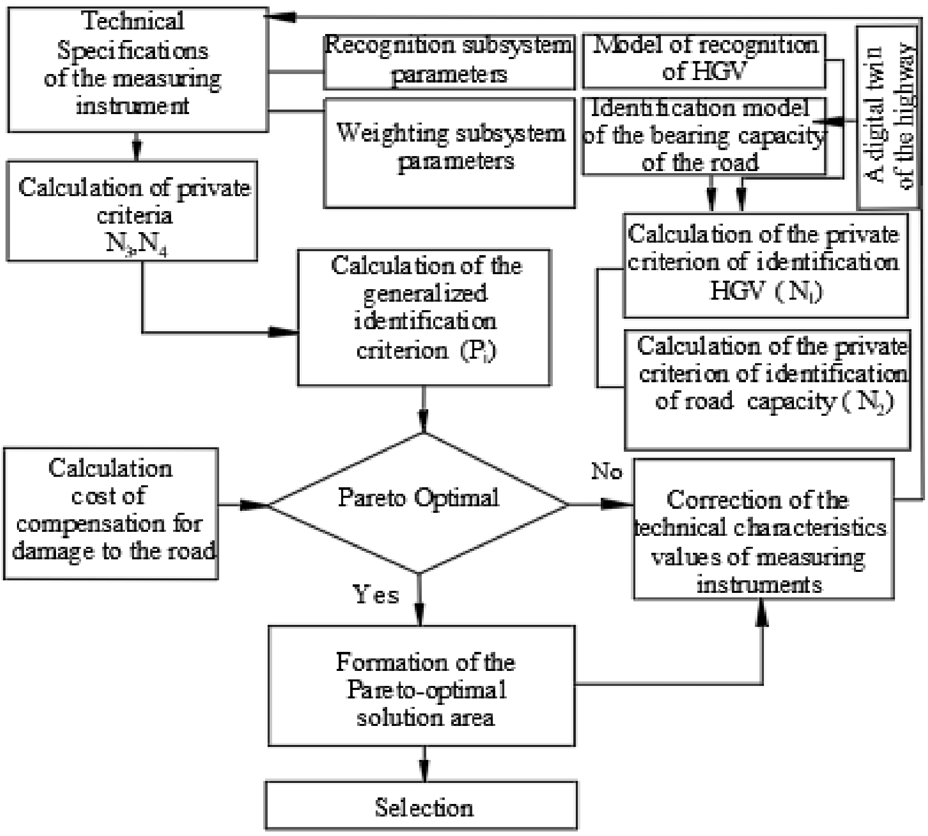

Figure 6. Algorithm of rational choice of measuring instruments of automatic TMTC on the basis of the Pareto method.

3. Discussion

The purpose of the study was to determine a system architecture that could be called optimal. When analyzing the current components of the weight control system, subsystems and functions were identified, taking into account all the minimum necessary functions to ensure the non-stop transportation process of heavy goods on the road. Non-stop weight control can significantly reduce the delivery time of goods, thereby improving the efficiency of the transportation process.

At the same time, weight control will help to reduce the tendency of premature deterioration of the quality of the road surface by reducing the load during the movement of HS exceeding the standard weight, as well as timely restoration of the road surface at the expense of funds collected from overloaded HGVs as compensation for damage. The road condition is also one of the most significant operational indicators of the road, affecting the efficiency of the transportation process.

In this study, the main components of the TASWC HGV are the automatic weight control points, which, when organized by the integration platform of weight control management, allow for prompt interaction with the HGV.

In the available studies devoted to the elements of a weight control system, such as automatic weight control stations, attention is focused on the analysis of HGV weighing equipment and procedures. In the literature, mobile weighing stations are mainly considered to be tools for collecting data on traffic flow parameters, including weight parameters for calculations in the design and operation of bridges and roadbeds [6,7,9,12]. The objectives of the above studies are to calculate the carrying capacity of bridge crossings and roadbeds on the basis of the data on the weight parameters of traffic flow obtained by mobile weighing stations as well as analyze the relevance of the problem of overloaded vehicles and damage to road infrastructure in various regions. [8,17]. The methodological basis for the construction of a comprehensive TASWC HGV in the available publications has not been formulated.

In the process of forming the architecture of TASWC HGV, the functions of subsystems, equipment, and software necessary for the proper execution of the allocated functions were considered. The equipment, in addition to the means of weighing and data transmission, includes TSCs, which carry out the identification of HGVs in motion. Since this equipment is of no less importance for the construction of TASWC HGV than the weighing equipment, to which not a few studies are devoted, the authors have developed a method of rational equipment of TMTC control boundaries, presented in Figures 4 and 5.

4. Results

In the process of forming the model of the TASWC HGV, in particular, its component software part, the software was developed as follows for the computer: "Methods of justification of technical means necessary for automated vehicle weight control on the highways" (Certificate RU2021614874 of 31 March 2021).

Identification of heavy vehicles is carried out through on-board information management systems (hereinafter OIMS) installed directly on the truck. On-board equipment is a hardware and software complex based on an information and measuring system controlled by a microcomputer with basic and technological software. Each OICS includes data exchange facilities.

In this case, the output data will be reports on the location of the vehicle, its technical condition, the composition of cargo, etc., and the input data—the operator's instructions.

During the formation of the hardware and software of the TASWC HGV, the structure of the onboard information and management system (hereinafter OIMS) has been specified, which includes the automated system for monitoring the environmental parameters of the HGV internal combustion engine developed by the author (Patent for Invention No. RU 2739652 of 28 December 2021).

The architecture of the TASWC HGV on the road, which is based on the developed proposals and technical solutions for its formation allows the functionality of the system to be increased due to the speed of information transfer between its elements (Figure 7).

Thus, the represented architecture of the telematic automated system of weight control management can be applied in the formation of the ITS subsystem for weight control at the level of state structural units responsible for road maintenance, such as the Federal road agency «Rosavtodor» and regional operators of public roads related to the subjects of the Russian Federation.

So, calculations according to the established dependencies showed a significant improvement in the main operational indicators of the road with the implementation of the TASWC HGV (Table 2).

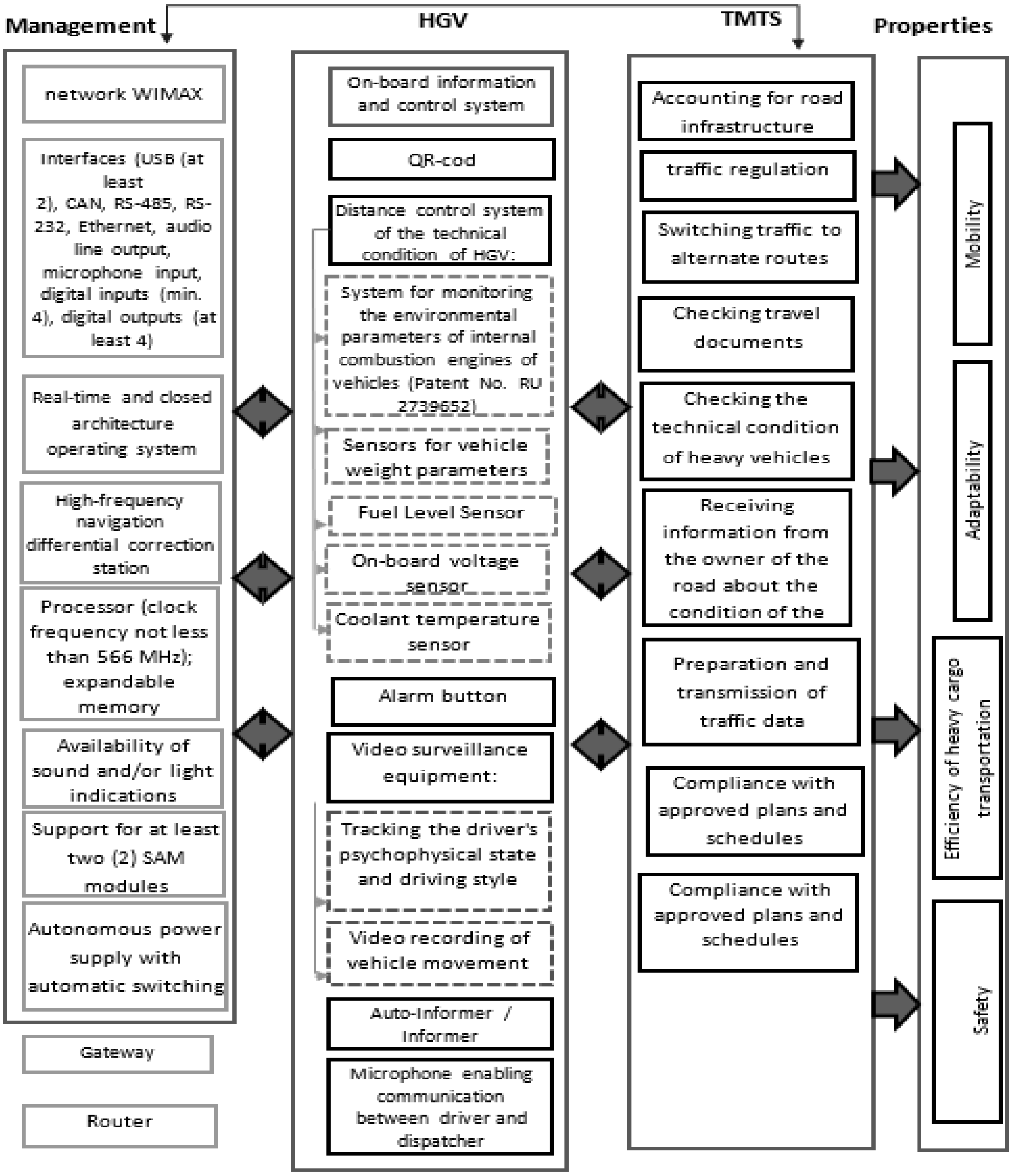

Figure 7. The architecture of the TASWC HGV.

Table 2. Estimated operational indicators of the road with the implementation of TASWC HGV.

		Motor Road		
	Transport and Operational Road Parameters	**Normative Indicators**	**Values of Transport and Operational Indicators of the a/Road after the Application of TASWC HGV**	**Efficiency of Application of TASWC HGV, %**
1	Average speed of traffic on the road, km/h	40	50.8	25% (+10.8 km/h)
2	Traffic volume, 4.5 thousand cars/day	4.5	5.1563	15% (+0.6563 thousand. cars/day)

The nature of the impact of the TASWC HGV on the operational performance of the highway on the value of the coefficient κ_n, which considers this impact, which shows an increase in traffic volume by 15% and the average speed by 25% (Figure 8), has been established.

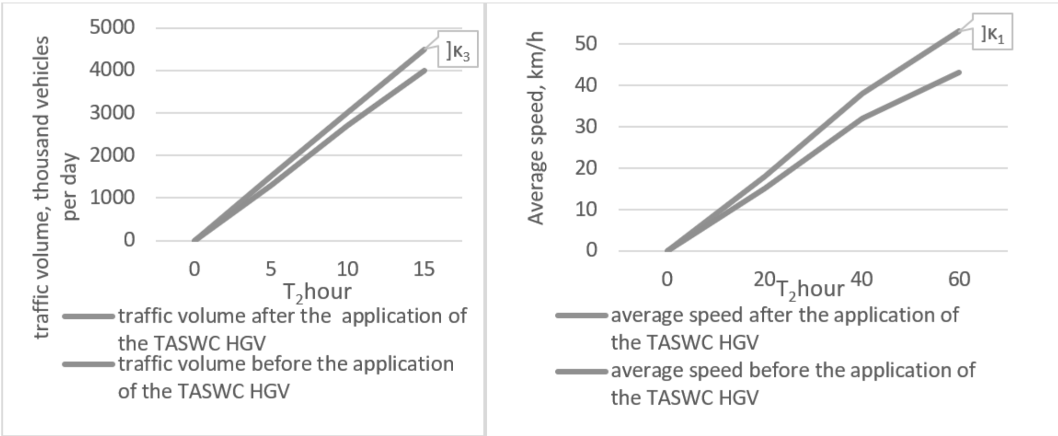

Figure 8. Effect of TASWC HGV on the performance of the road.

Based on the results of the study, the effectiveness of the implementation of TASWC HGV has been assessed. (Figure 9)

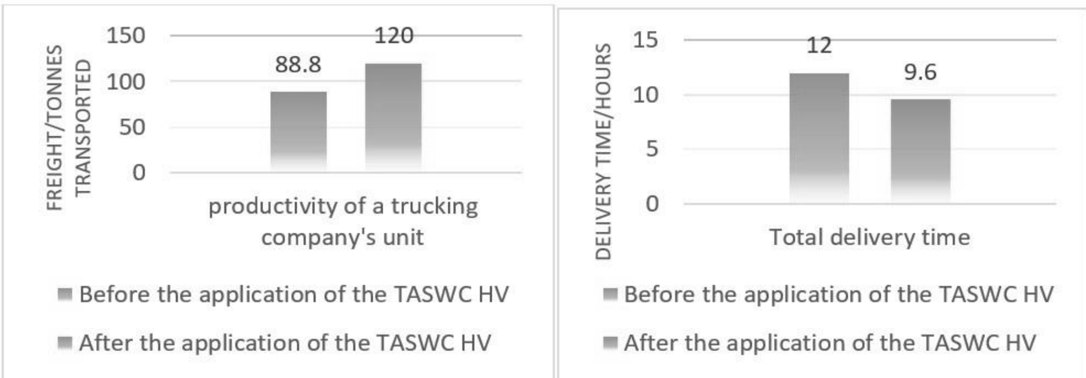

Figure 9. Evaluating the effectiveness of implementation TASWC HGV.

Final calculations demonstrated that the total time of delivery of heavy cargo is reduced by 20%, and the productivity of the road transport company units is increased by 26%.

5. Conclusions

1. In this study, the authors conclude that, given the introduction of modern intelligent advanced technologies in the creation of hardware, software and information supply, as well as organizational and methodological supply necessary for an integrated automated system to control the movement of HGV on the road, the ability to implement weight control of heavy vehicles on the road will lead to improved traffic management.
2. Some kind of dependence has been established, in which the increase in performance indicators of the road, such as road capacity and average speed of traffic, increases the efficiency of road transport, by increasing the speed of execution of the control system functions. Consequently, the introduction of automated complexes of a telematic management system of weight control increases the efficiency of road transportation of heavy goods in general.

3. Based on the mathematical modeling, the authors concluded that the most significant parameters affecting the efficiency of the road are the state of the road, the average speed of traffic, and the efficiency of management of heavy vehicles. The choice and evaluation of hardware and equipment for the TASWC HGV based on these parameters.
4. A methodology of rational equipping of automatic points of weight control of heavy vehicles during transportation by automobile transport is established, which includes a certain algorithm of rational choice of means of weighing with the use of experimentally determined generalized criterion: the degree of efficiency of identification of weight parameters of automobile equipment (P_i).

Author Contributions: R.N.S.—substantiation of the research concept; research planning. D.D.B.—generalization of research results; comparative analysis; formulation of conclusions; interpretation of research results; analysis and systematization of experimental data; design of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are openly available in Official website of the Federal State Statistics Service of the Russian Federation: https://rosstat.gov.ru/folder/23455; Official website of the European Union: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021SC0475&qid=2 (accessed on 5 May 2022). Official website of the United Nations Economic Commission for Europe: https://unece.org/sites/default/files/2021-01/ECE-TRANS-2021-15r.pdf (accessed on 5 May 2022); Official website of Ministry of Transport of the Russian Federation // https://mintrans.gov.ru/documents/2/11577 (accessed on 5 May 2022).

Conflicts of Interest: The authors declare no conflict of interest.

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