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THEORY OF ASSESSING ACCIDENT PROBABILITY IN INTELLIGENT TRANSPORT AND LOGISTICS SYSTEMS

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Abstract: The article justifies the necessity to develop Russia's national road transport network and integrate it into the world economic space in order to realize its transit potential in the system of Euro-Asian international transport corridors more effectively as well as to increase the volume of transport service exports. Introducing an intelligent transport and logistics system (ITLS) it is possible to ensure road safety which will increase economic efficiency and integrated safety of transport corridors because traffic accidents (TA) have a detrimental effect on the social and economic development of any country. Drivers of vehicles (Vs) can be informed as a group or individually about the risk of an accident and the need to change the speed or location of the vehicle on the road. It is suggested that the problem can be solved online by using the parametric identification of the ITLS elements and the neural network management of the classification and regulation process. The process of training the neural network and the principles of its operation are presented.

1. Introduction

The modern transport system created in Russia in recent years is an integral part of its production and social infrastructures to ensure stability and a steady development of the national economy, its territorial integrity and national security. Improving its transport system Russia is able to remain a great power influencing the entire Euro-Asian space, ensuring its economic unity, a free movement of people, goods and services, developing competition and freedom of enterprise, improving the conditions and living standards of the population despite the imposed sanctions [1].

Russia's transport strategy for the period up to 2030 is aimed at the development of a national and international transport corridors (ITC) system ensuring road safety as a priority task. This will make it possible to more effectively realize the transit potential of Russia in the Euro-Asian ITC system and increase the volume of export of transport services. In addition, the obligations undertaken by Russia upon the WTO entry must be fulfilled. The development of the Common Economic Space is among them.

Russia's transport network is not as dense as that of the developed countries in Europe and Asia, some countries of the former USSR, China and a number of other developing countries. The density of China's road network is 3.6 times greater than that in Russia, Ukraine’s - 5.3 times, Belarus’s - 7.8 times, Finland’s - 18 times, Germany’s - 34 times, Japan’s - 60 times [2].

Economic globalization requires the development of existing and the creation of new geostrategic communications connecting the main centres of the Eurasian continent, stimulating the development of the national transport and logistics infrastructure (TLI) [3]. Increased integration of national transport networks will contribute to regional mutually beneficial cooperation between neighbouring countries. At the same time, all TLI transformations must focus on transport safety and, first of all, on road safety. Drivers’, pedestrians’, other transport process participants’ behaviour, as well as the assessment of road infrastructure vehicles (operational safety checks) and traffic control systems condition must be of paramount importance. In this area it is necessary to use the most modern technologies to monitor, transmit and process information about the road infrastructure and the parameters of transport and passenger flows (density, speed, composition) [4].

2. Problem statement

Traffic accidents have a detrimental effect on the social and economic development of most countries of the world. Highway accidents continue to cause enormous material and moral damage both to society as a whole and to individual citizens. Road traffic injuries that accompany most road accidents lead to the exclusion of people of working age from the sphere of production. Children, who are the strategic potential of society, die or become disabled. Moreover, the country's economy suffers both direct and indirect losses. The annual economic damage to Russia as a result of TAs is about 2% of gross domestic product (GDP) [5]. The situation is aggravated by the high growth rate of the country's car fleet.

The introduction of ITLS will increase the economic efficiency and integrated security of transport corridors [6]. The intelligence of the transport systems responsible for traffic safety is manifested in the possibility of continuous monitoring information from sensors installed in controlled areas, data on vehicles, its uploading for operational analysis, forecasting the situation and informing traffic participants in real time within which an ordinary person is unable to work out a solution. Moreover, the tasks solved by the system can be complex in nature, the level of complexity of which exceeds the ability of the human mind. The system has the opportunity not only to find new solutions, but also to gain experience in the form of precedents entered in the knowledge base [14].

ITS or its elements are available in many developed foreign countries and international organizations (for example, the European Union). ITS of the USA, Japan, Korea, Singapore, the European Union have the most finished look. Their integration with developed logistics networks must draw extraordinary attention. ITS development programs should have state status, since they are based on standards, conceptual documents of the strategic and applied levels. Significant financial resources are allocated for their financing. The fragmentation of countries, for example, the European Union, has a negative impact on the implementation of ITS [4].

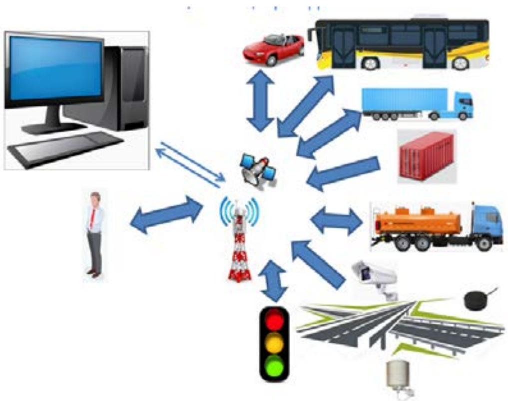


Figure 1: The direction of information flows in ITLS, assessing the risk of accidents in ITC.

ITS subsystems, whose task is to support road safety systems implemented in many countries, show that it is possible to significantly reduce the number of accidents, the number of fatalities in road incidents and at the same time increase the efficiency of the transportation process. One of the main projects is the Intelligent Motorway. In this case, the collection of information, its processing and its transmission to the driver, is carried out by the situational center using sensors that equip the infrastructure created along the roads using information about loading the vehicle in a warehouse or terminal. In this case, at least one-way communication with the vehicle is required, for example, using RDS-TMC. If the processing of the received data does not allow issuing recommendations for each car, then informative displays installed on the highway are used [7].

3. Methods and approaches to assess the risk of accidents

The methodology for creating ITLS provides, as one of the tasks, monitoring the main system parameters that affect the formation of an accident, predicting its possible occurrence and informing the driver about it. Users of ITLS services often replace the probability of an accident concept by the risk concept [8].

Literature analysis allows us to conclude that most experts in the field of road safety define risk as the probability of an event called an accident, which is a dimensionless quantity lying in the range from 0 to 1 [9].

Risk assessments are increasingly used in the field of road safety. This is carried out in the course of a safety audit of existing roads, in car insurance, in planning road works aimed at reducing the number of accidents and the severity of their consequences. However, in our opinion, it is necessary to more accurately assess the risk in ITLS in relation to a specific section of the road, a specific car, taking into account its individual characteristics (speed, load, type of cargo, placement of cargo in the body), a specific environment.

Modern approaches to risk assessment by various automated systems in automobile transport are based on the processing of statistical information on road accidents, performing the function of a low-probability forecast based on data on a “static” transport situation in comparison with baseline indicators. They make it possible to predict the result of adverse road traffic outcomes on the estimated road section, but they are not able to quickly recognize and timely prevent the formation of transport and logistic conflicts using the existing program-algorithm and technological complexes.

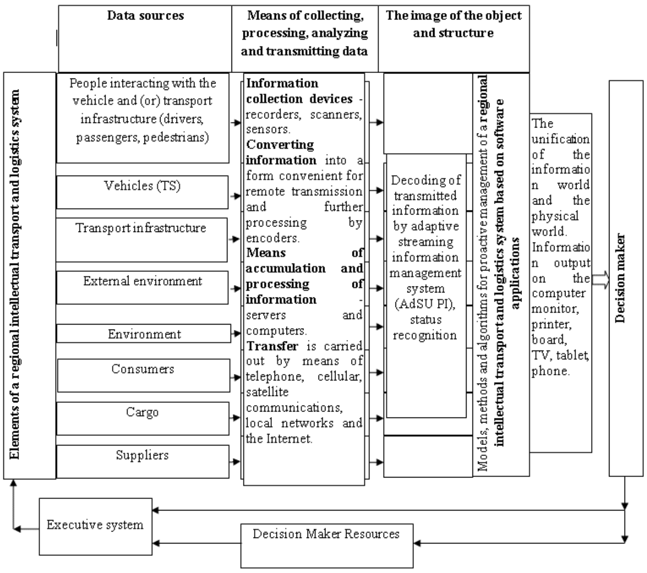


Figure 2: The decision-making flowchart in regional ITLS for road safety management.

Accident risk assessment on road sections during the audit of transport infrastructure facilities can be carried out using relative accident rates, also called accident rates [10], measured by the number of accidents per 1 million automobile kilometers (accident / 1 million automobile km), referred to the size of the traffic flow passing through the site:

$$K_R = \frac{10^6 z}{365LN}, \tag{1}$$

where z - the number of accidents per year per 1 million kilometers; L - length of road section, km; N - average annual daily traffic intensity in both directions, taken according to traffic accounting data, auto / day.

From the point of view of statistical analysis, since these coefficients are the ratio of cars that got into an accident at a site to the total number of cars that drove through a site during this time (for a year), in fact, this is the probability of an accident at a given site, related to the length of the site, expressed in millions (10^6) km.

In [8], the general probability of occurrence of incidents in a section of length is proposed to determine by

$$P_k = C_r^k p^k (l - p)^{r-k}, \tag{2}$$

where $C_r^k = \frac{r!}{k!(r-k)!}$ number of combinations of r by k; $p = k\Delta l / L$ - the probability that on a segment of length Δl the entire length of the site L one incident will happen; r - number of elementary lengths Δl on a length of land l on which is fixed k incidents; $r = l / \Delta l$, where Δl - minimum distance between adjacent incidents.

Value definition P_k using location data k accident spots on a length l does not allow the researcher to decide on the accident or non-accident of what happened in order to classify the site as an emergency. To do this, define the class boundary $\hat{P}_k$ the transition of which transfers the site to the category of emergency. Often, it would seem, on very dangerous sections of the road for a number of years there are no accidents that happen on clearly less dangerous.

The main disadvantage of methods based on mathematical statistics is the impossibility of using them to assess the danger of sections of newly constructed roads, since this requires the collection of a large amount of information, the receipt of which takes a considerable period of time, according to scientists, not less than three years.

In some papers, for example, [15], the probable number of accidents in various sections of roads is determined using the multivariate correlation analysis method. At the same time, researchers are trying to take into account as many significant factors as possible, which, in their opinion, affect the occurrence of accidents. Relative accident rate K_R, calculated here by the formula:

$$K_R = 2935{,}18 \cdot N^{-0{,}9819} \cdot \varphi^{0{,}4512} \cdot p^{0{,}4806} \cdot R^{-0{,}0707} \cdot L^{-0{,}0329} \cdot S^{0{,}1015} \quad (3)$$

where N - average annual daily traffic intensity, aut./day; L - the length of the study area, km; φ - adhesion coefficient; p - roadway width, m; R - the radius of the curve in the horizontal plane, m; L - visibility distance, m, %; S - evenness of the coating, which is estimated by the readings of the push-button, cm/km.

When analyzing the impact of individual characteristics of the elements of the transport infrastructure on the risk of an accident, the coefficients of their relative influence (private accident rates) can be used [12-13]. The generalized accident rate on the site is a product of partial coefficients.

$$K_{acc} = \prod_{i=1}^{n} K_i \,. \quad (4)$$

It is easy to notice that the partial accident rates are the relative probabilities of an accident in the estimated area, due to the deterioration of road conditions for one reason that is independent of other influencing factors. Moreover, their combined influence can be estimated, in accordance with the provisions of probability theory, on the probability of an event under the action of several factors independent of each other, by the product of partial coefficients. Their values are determined empirically from domestic and foreign statistics. The list of coefficients currently established is not exhaustive, but their values are final. With the further accumulation of statistical data, the list of influencing factors and the values of the coefficients should be clarified. Since not all of the above factors equally affect traffic safety, in the process of further research it is necessary to establish the relative weight of each of the coefficients and their interdependence [16-17].

ITLS subsystems providing real-time road safety should have the ability to monitor and intelligently analyze transport and logistics processes within the regional sections of the Euro-Asian transport corridors and to prevent the occurrence of accidents by giving information along the TC [18].

To quickly solve the problems of assessing the risk of accidents, the approach described above and associated with the assessment of road conditions, but supplemented by environmental impact assessment coefficients, data on a moving vehicle and the nature and location of cargo or passengers with weights corrected using a neural network, can be applied programming. For this, ITLS will be described by the equation

$$W(t) = W(z_{k1}, z_{k2}, ..., z_{kn}, z_1, z_2, ..., z_{1m}, t)\,, \quad (5)$$

where $z_{k1}, z_{k2}, ..., z_{kn} = \mathbf{z}_k$ - ITLS parameters that can be changed as a result of management; $z_1, z_2, ..., z_m = \mathbf{z}$ - ITLS parameters that cannot be changed as a result of management.

We assume that the state of the system is completely described by vectors $\mathbf{z}_k, \mathbf{z}$. Then it is obvious that in $(n+m)$- dimensional space, there are two, adjacent to each other, in one of which ITLS with many vectors $[\mathbf{z}_k\ \mathbf{z}]$, corresponds to a system in which the probability of an accident is zero, in another region, with many vectors $[\mathbf{z}_k\ \mathbf{z}]$, the state of the system will be characterized by the probability of an accident equal to 1. For the formulated clustering problem, it is necessary to justify the criterion for assigning the state of ITLS to one or another class. In [19], a criterion is proposed for solving problems of this type, which takes into account the probabilistic model of the control object and is widely used in solving problems of decision support (PPR) in the process of managing complex technical systems.

$$P\left(C_C(t_{k_i}), f(\tau)\right) = \begin{cases} 1, & C_C(t_{k_i}) \notin \mathbf{C}_\mathbf{C}(t) \\ \int_t^{\infty} f(\tau)d\tau, & C_C(t_{k_i}) \in \mathbf{C}_\mathbf{C}(t) \\ 0, & C_C(t_{k_i}) \in \mathbf{C}_\mathbf{C}(t) \text{ и } t = t_{k_i} \end{cases}, \tag{6}$$

where $\mathbf{C}_\mathbf{C}(t)$ - area of permissible states of ITLS elements; $f(\tau)$ - accident density probability distribution over time ; $C_C(t_{k_i})$ - state of the ITLS element at the time of control t_{k_i} .

Thus, the task of testing ITLS elements based on monitoring results is reduced to the problem of parametric identification

$$C_C(t_{k_i}) = \left[\mathbf{z}_k\ \mathbf{z}\right]_н = F(\mathbf{y}) \tag{7}$$

$\mathbf{y}$ - vector of observed system output parameters; $\left[\mathbf{z}_k\ \mathbf{z}\right]_i$ - vector of parameters of the function describing the observed system; F - parametric identification operator.

For the diagnosis of ITLS, an analysis of the causes that led to a change in the vector of function parameters W .

$$\begin{aligned} \Delta\left[\mathbf{z}_k\ \mathbf{z}\right] &= \left[\mathbf{z}_k\ \mathbf{z}\right]_н - \left[\mathbf{z}_k\ \mathbf{z}\right]_э \\ \mathbf{R}_д &= f(\Delta\left[\mathbf{z}_k\ \mathbf{z}\right]) \end{aligned} \tag{8}$$

$\Delta\left[\mathbf{z}_k\ \mathbf{z}\right]$ - changing the vector of function parameters W , describing the observed system, relative to the vector of parameters of the function of the reference system.

$\mathbf{R}_д$ - vector of diagnostic results of ITLS elements.

4. The Results Discussion

The process of driving a vehicle after warning the driver by the ITLS subsystem about the accident risk increase can have four reaction options:

- change in vehicle speed;
- change in vehicle position on the road;
- change in vehicle speed and its position on the road;
- lack of driver's response.

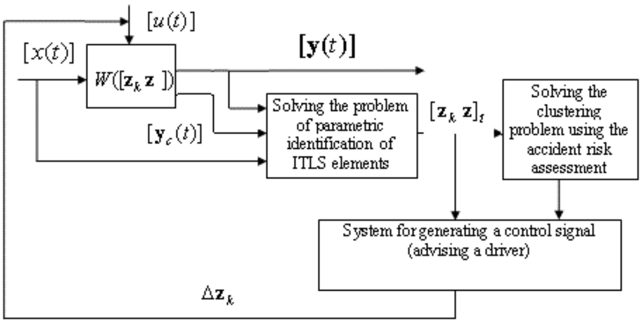


Figure 3: Structural diagram of a model for identifying ITLS parameters to reduce the risk of accidents.

Note that the change in speed can be either positive or negative acceleration. Maneuvering can also be different in complexity.

$$\begin{aligned} V_k &= V_{k-1} + \Delta V(N_{k,k-1} k_{\text{飋}}) \\ V_k &= V_{k-1} + \Delta V(N_{k,k-1} k_m) \end{aligned} . \tag{9}$$

ΔV - vehicle speed change; $N_{k,k-1}$ - the number of pulses affecting the fuel or brake pedal; k_{n-m}, k_m - coefficients characterizing the depth of the fuel pedal and brake pedal, respectively. The first equation characterizes the change in speed by impulse action on the fuel pedal, the second – the change in speed by impulse action on the brake pedal [20].

A change in the position of the car on the road is characterized by a change in the coordinates of its center of gravity x_i, y_i and the angle of rotation of the longitudinal axis β_a relatively motionless coordinate system.

$$\begin{aligned} \bar{V}(t) &= \int_0^t V'(t)dt + \bar{V}_0 \\ x &= \int_0^t V_{i}(t)dt + x_{0} \\ y &= \int_0^t V_{i}(t)dt + y_{0} \\ \beta_a &= \int_0^t \omega_a(t)dt + \beta_{a0} \end{aligned} \qquad (10)$$

V_{x_i}, V_{y_i} - projection of the velocity of the center of gravity of the vehicle on the axis X and Y respectively; $\bar{V}_0, x_{i0}, y_{i0}, \beta_{a0}$ - initial values of the velocity of coordinates of the center of gravity and the angle of rotation of the longitudinal axis of the vehicle relative to the fixed coordinate system; ω_a - angular velocity of rotation of the longitudinal axis of the vehicle relative to the fixed coordinate system.

Minimizing the error will be achieved if the nominal and actual parameters match

$$\Delta L \approx \frac{\partial L}{\partial V}\Delta\bar{V} + \frac{\partial L}{\partial x_a}\Delta x + \frac{\partial L}{\partial y}\Delta y + \frac{\partial L}{\partial \beta}\Delta\beta + \frac{\partial L}{\partial t}\Delta t \qquad (11)$$

To address the issues of risk assessment of accidents in transport corridors of ITLS using proactive control, due to the limited prior information about the elements of the system, the absence of functional dependencies of their influence on each other when the technological characteristics change in the conditions of functioning, the presence of acting uncontrolled disturbances, a long reaction delay time on control impact, it is proposed to use control methods with predictive models – Model Predictive Control (MPC) in conjunction with simulation models, parametric identification of elements of ITLS.

The MPC approach is applied to vehicles driving to a section of a TC controlled by a regional ITLS, based on a control panel for information boards and recommendations given to drivers of specific vehicles about the accident risk increase with the recommended speed and direction of movement.

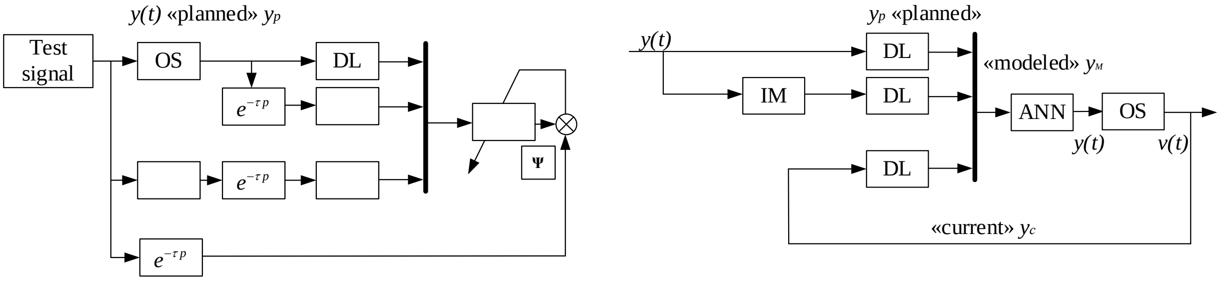
Using predictive inverse models with a small forecast horizon directly as classifier-regulators in practice is quite feasible for real traffic control systems. This class of control systems can include predictive inverse neurocontrol (PIN), in which the optimization procedure is performed using a simulation model implemented in the AnyLogic environment, and the construction of a neuroclassifier-regulator is carried out using parametric classification directly from the experimental input-output data of the object. This eliminates the need for a prior knowledge of the mathematical model of the object.

A predictive inverse model of parametric classification integrated with a simulation model is used as a classifier-regulator in PIN systems. The synthesis of such models is performed using the apparatus of artificial neural networks (ANN) in accordance with the scheme presented in Fig. 4.

In accordance with this scheme, arbitrary control actions $u(t)$, applied to the control object of the OS and the simulation model IM, are considered as examples of targeted controls seeking to translate the OS and IM in the assigned time τ into some new state $y(t+\tau)$. In this case, the input vector of the neural network $\mathbf{P}$ contains information about the three states of the system, which are interpreted as "current" within the framework of the methodology $\mathbf{y}_c$, "planned " $\mathbf{y}_p$, ccorresponding to the reference parameters, and «simulated» $\mathbf{y}_м$. The formation of these states is carried out using blocks LZ (delay line with taps) in the form of regression vectors:

$$\mathbf{y}_c = [y(t-\tau), y(t-\tau-\Delta t), ..., y(t-\tau-d\Delta t)]$$
$$\mathbf{y}_м = [y_м(t-\tau), y_м(t-\tau-\Delta t), ..., y_м(t-\tau-d\Delta t)] \quad (12)$$
$$\mathbf{y}_p = [y(t), y(t-\Delta t), ..., y(t-d\Delta t)]$$

where Δt - sampling period; τ - the time interval by which these states are separated by the time delay element (determines the forecast horizon of the synthesized model); $e^{-\tau p}$ - the number of delayed values in the formed vectors. In accordance with the strategy of MPC, which uses the principle of a receding horizon, neural network training begins with the use of the first value of a discrete sequence of control actions, which is formed in the time interval between the "planned" and "current" state (target value $\psi = u(t-\tau)$).



(a) (b)

Figure 4. Neural network training scheme (a) and the regulator-classifier scheme (b)

The training sample is formed by combining the sets of input vectors $\mathbf{P}$ obtained in the current "run" and the corresponding target values $\boldsymbol{\psi}$. A neural network that has been trained on the basis of these data acquires the ability to generate such a control action that must be applied to the input of an object in the current control interval in order to transfer it from the current state $\mathbf{y}_c$ to the planned state $\mathbf{y}_p$ during the forecast horizon « τ » [21].

5. Conclusion

Increasing the level of systemic traffic flow safety in the ITC is one of the main tasks, the solution of which will allow obtaining a social and economic effect both at the regional level and at the level of the whole country. The use of ITLS subsystems, whose task is to support road safety systems implemented in many countries, shows that it is possible to significantly reduce the number of accidents, the number of fatalities in road incidents and at the same time increase the efficiency of the transportation process. ITLS subsystems providing real-time road safety should have the ability to monitor and intelligently analyze transport and logistics processes within the regional sections of the Euro-Asian transport corridors and to prevent the occurrence of accidents by giving information along the TC.

Road accident risk assessment should be increasingly used in the field of road safety. This should be carried out in a safety audit of existing roads, in car insurance, when planning road works aimed at reducing the number of accidents and the severity of their consequences.

To quickly solve the problems of assessing the risk of accidents, an approach based on the parametric identification of ITLS elements can be applied, which must include the parameters estimation of the environment of the moving vehicle, characterizing the type of cargo and its location in the car body with weight coefficients, adjusted using neural network programming.

The developed theoretical framework for assessing the likelihood of accidents, using the parametric identification of ITLS elements that can act as control objects, suggest the development of algorithms for analyzing real-time video information that, along with other sources of information, is the basis for assessing the risk of accidents in transport corridor in the places of their installation. As a mathematical apparatus for transmitting and processing information from cameras and sensors, it is possible to use recurrent neural networks with a carrier information flow that solves the problem of a damped gradient and increases the efficiency of the network, and convolutional neural networks that are well established in image recognition problems.

Acknowledgements

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