Application of Multivariate State Estimation Technique for Early Detection of Potential Threats while Driving a Truck

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Abstract—Existing telematic monitoring systems for the state of functioning parameters and characteristics of cars and other mobile equipment make it possible to obtain a large amount of digital data on the state of objects of observation in real time. At the same time, it is possible to evaluate the features and current characteristics of their control parameters by the driver or operator. The paper proposes a fundamental possibility of obtaining predictive information about the features of changes in the characteristics of driving a vehicle by a driver based on the analysis of information received from telematic control of transport information, a block diagram of an information-mathematical system and the principles of mathematical processing of incoming information are proposed. The paper presents some results of the analysis of the time series of the selected vehicle monitoring parameters, which allow applying the Multivariate State Estimation Technique (MSET) method to their assessment in order to obtain the possibility of early detection of a potential emergency situation in driving a car (falling asleep, driver fatigue, stressful situations, inappropriate behavior). The results of the study can become prerequisites for a larger-scale application of MSET methods in monitoring the operation of mobile equipment and assessing the characteristics of its control.

Keywords—trucks; driving quality assessment; predictive control; fault detection; MSET

I. Introduction

The number of fully autonomous vehicles in the world has been growing at a fairly high pace in the last decade, and the expected transition to the use of autonomously driven vehicles, especially in fairly simple algorithmic processes (taxi, intercity freight transportation), is quite expected and understandable. At the same time, this will take quite a long time, and besides, it is rather difficult to convert a number of transport tasks into a fully digital form and replace the driver or operator with a computer [1]. Such transport tasks include the transportation of passengers and goods in particularly difficult road, weather or transport conditions, transportation with a high degree of risk and responsibility, as well as cases where the use of fully autonomous vehicles is unprofitable. In this regard, in order to further reduce transport and social risks, the implementation of the Vision Zero concept requires mechanisms for monitoring the actions and condition of drivers/operators and early detection of potential risks associated with possible unintentional or intentional vehicle control errors. Such systems, as a rule, either based on wearable means of monitoring psychophysiological parameters or / and video recording tools with image analysis complexes, firstly, are quite expensive, and secondly, they cannot only partially perform the functions of predictive detection of the onset of potentially dangerous driver conditions.

The use of the Multivariate State Estimation Technique (MSET) method for early detection of emergencies associated with a disruption in the normal functioning of objects has become a fairly widespread trend in recent years. The method is implemented in conjunction with the use of neural networks and other principles and approaches of machine learning, and as shown by its use in complex and responsible industries, it is quite effective. In [2], the focus is on a harmonic reducer performance prediction algorithm based on the multivariate state estimation (MSET) method and LargeVis dimension reduction, with the error warning threshold set according to the difference between the constructed health state data memory matrix and the actual observed value. In [3], data-driven Kalman filters were used to estimate the distributed state in several domains. The design phase is self-contained and includes simulation of multivariate time series measurements from PMU using linear and non-linear system identification methods. The paper [4] uses a health monitoring method based on the Multivariate Condition Estimation Method (MSET) and Sequential Probability Ratio Test (SPRT) to monitor the state of a lithium-ion battery by comparing the actual residuals of the performance parameters and the healthy residuals obtained from the training data on based on MSET, error detection can be implemented based on SPRT. A similar approach was applied to control the state of the Airbus A320-series aircraft air intake system in [5]. To cope with the deterioration in the accuracy of the MSET model due to different operating conditions of the analyzed object, the authors of [6] proposed an adaptive strategy using samples with a high data quality index (DQI) to control the memory matrix and update the MSET model, thereby improving the fault. The application of the method for estimating the operating parameters of a steam turbine [7] proved that the method can timely and accurately judge the change in the operating mode of the unit, and the

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degree of deviation calculated by the modified information entropy weight method can provide earlier warnings about abnormal operating conditions. The use of the Forward neural network (FNN) based piecewise linear fitting method allowed the authors of [8] to improve the accuracy of the predictive diagnostic model based on the basic MSET method. Works [9-13] also demonstrate the effectiveness and high sensitivity of the method for determining the presence of anomalies in the functioning of multi-parameter physical objects.

At present, we see the potential possibility of applying these approaches to assessing the characteristics of the driving process of vehicles in order to early detect deviations in control parameters in order to prevent the occurrence of transport emergencies.

II. Methods

The object of observation was a KAMAZ truck driven by one driver during one shift (intercity transportation) in the central part of the European territory of Russia, December 2022. The vehicle is equipped with the Wialon telematic surveillance system, which allows real-time transmission to the system server of data on changes in all sensors connected to the system that determine the status and modes of operation of the vehicle's main systems [14, 15]. From there, using reporting, you can upload data in a tabular form for processing and analysis in third-party programs. The operating screen of the system is shown in fig. 1.

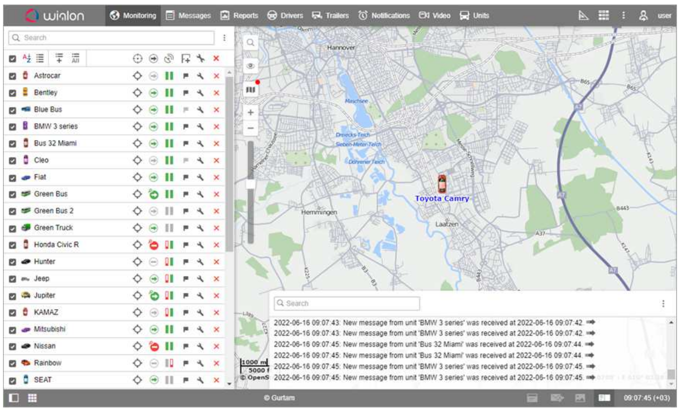

Fig. 1. Working screen of the monitoring system.

As an initial hypothesis, the idea was used that during a long trip as part of intercity transportation of goods, the driver gets tired by the end of the work shift and his psychophysiological parameters change significantly. The above leads to a situation in which a change in the general standing of the driver and his fatigue affects the features and characteristics of control (deterioration of attention, a decrease in the frequency of corrective actions by controls, a decrease in control over other road users, an increase in the occurrence of potentially dangerous situations). Therefore, a comparison of the parameters of the control process at the beginning and end of the work shift can be indicative in terms of studying the potential application of the MSET method for assessing driving performance and early detection of emerging emergencies.

The process of driving a car belongs to complex multi-parameter systems, from the point of view of a telematic monitoring system [16, 17, 18], it is represented as a continuous time series of a large number of parameters continuously formed by sensors of both the system itself and the directly analyzed object. For the purposes of the study, we selected the following indicators: vehicle speed, km/h, engine speed, rpm, lateral acceleration, m/s^2, longitudinal acceleration, m/s^2. The first parameter determines the driving mode of the car, the second - the mode set by the driver, incl. responds to the degree and speed of the driver's manipulation of the control. The third parameter indirectly characterizes the presence or absence of actions by the driver with the steering wheel in the absence of a steering wheel rotation sensor, as well as a possible emergency mode - side skidding of the car. The fourth parameter characterizes the mode of movement of the car - acceleration, uniform movement or braking. The advantage of these indicators is, on the one hand, their sufficient indicativeness and universality of availability on any equipment connected to the transport telematics system, on the other hand, they correlate quite strongly with each other. In this regard, the possibility of their application in the MSET model will be tested in the framework of this study.

A time series view of the vehicle engine speed in revolutions/minute at the beginning of the work shift is shown in fig. 2 and at the end of the work shift on fig. 3.

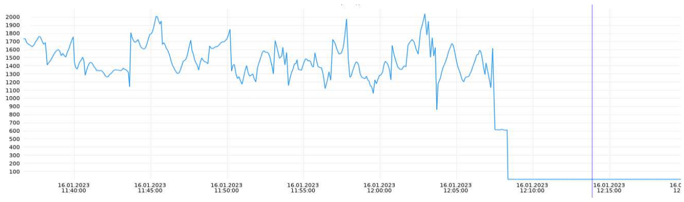

Fig. 2. Time series for the «engine speed» indicator at the beginning of the work shift

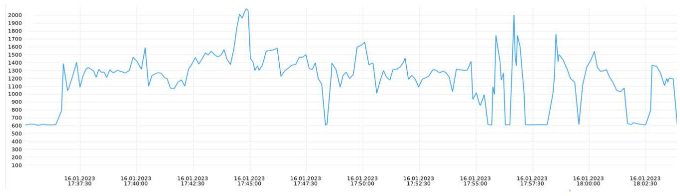

Fig. 3. Time series in terms of «engine speed» at the end of the work shift.

The state of the observed object (car) is characterized by the above and pre-selected parameters at any time, the telematic surveillance system registers them at fairly frequent intervals (up to 1 time per second) and, as a result, forms a multidimensional time series represented as a system $y^1(t)$, $y^2(t)\ldots$, $y^N(t)$. Let us assume that the one-dimensional time series $y^i(t)$, observed at equidistant times t_1, t_2, … ,t_n , *can be represented as a sum of functions*:

$$y^i(t) = f^i(t) + g^i(t) + \psi^i(t) + \varepsilon^i(t) \qquad (1)$$

in this case, the function $f^i(t)$ – non-random (long-term) trend function of the corresponding series; $g^i(t)$ – non-random periodic function - the joint harmonic component of the series, $\psi^i(t)$ – random function with elements of regularity - vector autoregression, $\varepsilon^i(t)$ – irregular component (error).

At the first stage of data processing for all time series, an analysis was made of the presence of a trend component with the selection of the corresponding function $f^i(t)$ and approximation by a polynomial of 2 or 2 degrees. Further, for each series, the stepwise regression method finds significant harmonics and simulates the residuals of a random function, taking into account the elements of regularity of the function $\psi^i(t)$, which is represented in this case as a vector autoregression model.

As a result, for each of the time series *N*, we get a complex analytical model that consists of a regular component (trend, harmonics) and vector autoregression.

The resulting models can be used both to assess the quality of driving and the dynamics of changes in driving style/peculiarities over long periods of time or to establish the individual characteristics of the driver, and to compare control parameters during continuous monitoring of driver actions in order to prevent potential accidents. Since any stable deviation from the existing and constantly corrected automatically models can be interpreted as a signal for possible erroneous or unintentional actions of the driver. An example of the resulting analytical models for one of the selected indicators (2).

$$y_1(t) = -0{,}156t + 1{,}142\sin(2\pi t/23) + \\ +543{,}45\sin(2\pi t/36) + 0{,}567\, y_3(t-1) + \varepsilon_1(t). \quad (2)$$

The obtained analytical models make it possible to predict the parameters with sufficient accuracy (deviations up to 12–14 %) for a period of up to 8-9 seconds when working on time series obtained while the car is moving along the highway.

The traditional method of time series analysis in this case seems to be working, but not the best result for the analysis of existing multi-parameter dependencies, incl. due to low predictive ability (small interval of predictive data with sufficient forecast accuracy), and due to the fact that there is no close relationship between any deviation from the analytical model and the accident rate of the facility. The resulting models, obtained during a uniform movement along a rectilinear trajectory, do not take into account the movements in the turn and incorrectly interpret it as an emergency. In this regard, it is interesting to use the MSET method (the schematic diagram is presented in fig. 4).

The initial data for its implementation are the same as for the previous stage: the values $y^i(t)$ are successive *i* parameters of functioning at time *t*. The specified values form the input observation data matrix for the training sample to train the system. The script developed in Python [11], implementation of Multivariate State Estimation technique; in particular of an "online" approach combined with time-delay embeddings to do anomaly detection with scalar time series.

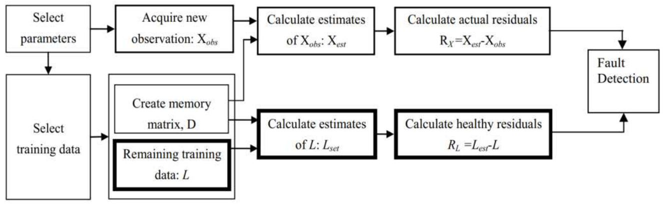

Fig. 4. Block diagram of the MSET method.

With its help, the anomalies present in the time series were analyzed with the issuance of their location within the series and distribution density. An example test run is shown in fig. 5. An indicator was chosen for analysis - engine speed.

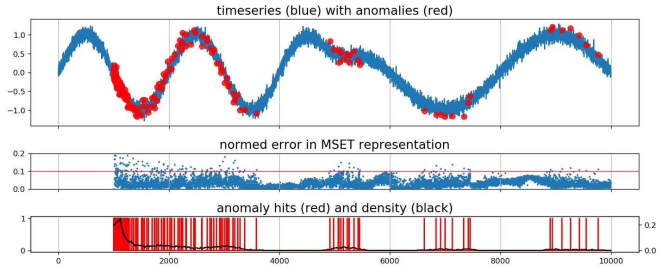

Fig. 5. Test run of the script on the training set.

III. Results

The average value of the coefficients of determination R2 of the constructed models by the MSET method on the training set D1 is 0.97 (standard deviation 0.04), on the set D2 (test) – 0.94 (standard deviation 0.07). The obtained values indicate that the constructed regression models, on average, have a good generalizing ability, i.e. the error probability on the test set is not much different from the error on the training set.

The achieved value of the AUC ROC indicator of the trained regression model on the training set D2 is 0.98, on the test set Dtest - 0.95.

The use of the MSET method, in contrast to traditional methods of analysis and modeling of time series, gives more representative results when applied to the assessment and study of the parameters of control of mobile equipment, in particular, a truck. The use of the models obtained by the first method makes it possible to obtain predictive data for an interval of about 8-9 seconds in the case of movement in the highway mode. However, this method categorically poorly copes with the interpretation of deviations from the simulated behavior of the object in view of the specifics of the motion process and interprets normal situations (smooth turn, deceleration before descent) as emergency. The use of the MSET method in the framework of test runs and the construction of training and test samples for the parameter - engine speed gave encouraging results, the method quite well determines the existing anomalies in the time series of the indicator and is more effective when used in cases where emergency situations are quite rare and difficult to formalize [2, 5, 6, 7].

IV. Discussion

The studies did not analyze complete models describing the process of driving a truck using the MSET method, so the question of the interval for predicting the behavior of the system when using this methodology remains open. Also requiring additional study is the issue of creating a list of indicators of the anomalous functioning of the object when taking into account the multi-parameter model of driving a car. It seems to us that it is possible to apply the proposed principles in the analysis of traffic flows [19, 20].

V. Conclusions

The hypothesis put forward at the beginning of the experimental studies was verified and the calculated data show that the use of the MSET method in the assessment and analysis of vehicle control parameters is more advantageous compared to the use of standard tools for time series analysis due to the fact that emergency situations in transport are not of the same type, are difficult to detect in advance, arise and develop rapidly, as a rule, not allowing to take corrective or preventive actions. In this regard, the application of the MSET method, which has shown itself quite well in the practice of industrial facilities, is possible, although it requires additional research in terms of the formation of initial parameters and criteria for the abnormal functioning of vehicles of various types. The use of telematic monitoring data coming from vehicles in real time to apply the MSET method in order to prevent the occurrence of potential threats seems to us a very promising task. In this regard, the issue of processing big data immediately arises, because each vehicle in the process of telematic monitoring generates a significant amount of information for each day of its work. If we add to this the need not only to collect, but also to constantly monitor key parameters with the processes of pre-processing, analysis, post-processing and output of the resulting data, then the amount of information clearly allows us to attribute this situation to work in the field of "big data". This means the absence of any possibility of using expert methods of analysis involving a human operator. In this regard, one of the most progressive methods of solving can be recognized as the method of data preprocessing using "artificial intelligence" algorithms, for example, neural networks.

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