ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2023-21-5-13

World of Transport and Transportation, 2023, Vol. 21, Iss. 5 (108), pp. 272–281

Technological Basis for Data Interoperability of Highway Structural Health Monitoring Systems and Intelligent Transport Systems

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ABSTRACT

The study is devoted to description of technological basis for data interoperability of structural health monitoring system for highway artificial structures with intelligent transport systems as well as to developed physical and functional architectures for data interoperability of these systems.

The study also highlights possibilities of using monitoring data to automatically launch scenarios for emergency situational road traffic control and offers a developed mathematical model describing the features of switching between road traffic control modes and steps to implement relevant digital device.

The paper suggests also a simple algorithm developed for diagnosing and activating a scenario in case of a dangerous state of the monitored object.

The results of the work may be advised for consideration when developing intelligent transport systems in the road industry to improve the level of road traffic safety.

Keywords: *intelligent transport system; structural health monitoring; data interoperability of systems; automatic situational control; using monitoring data to run scenario.*

For citation: *Efanov, D. V., Mikhailyuta, E. M., Pashukov, A. V. Technological Basis for Data Interoperability of Highway Structural Health Monitoring Systems and Intelligent Transport Systems. World of Transport and Transportation, 2023, Vol. 21, Iss. 5 (108), pp. 272–281. DOI: https://doi.org/10.30932/1992-3252-2023-21-5-13.*

The text of the article originally written in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

INTRODUCTION

The development of regions and cities follows the path of intellectualisation of processes and creation of «smart» systems and subsystems capable of self-adaptation and providing users with an expanded set of services [1; 2]. All this fully refers to the transport systems of regions and cities as well.

The use of intelligent transport systems (ITS) in road transport allows us to improve the principles of traffic control and, importantly, increase the safety of the transportation process. ITS are being implemented all over the world, including on highways of the Russian Federation [3; 4].

ITS are implemented using a variety of technical means that make it possible to provide traffic participants (within commercial, corporate, and social segments) with various information and communication services: from automatic toll collection and parking management to optimisation of traffic flows depending on road congestion [5]. The role of ITS in the traffic system on the road arteries of large cities is, in general, irreplaceable, since it is the use of the services, they provide, that allows users to significantly save time resources.

ITS includes hardware and software components, including devices for monitoring vehicles, traffic flows and infrastructure facilities. Requirements for functional and physical architectures of ITS are given in GOST R [Russian state standard] 56294–2014 «Intelligent transport systems. Requirements for functional and physical architectures of intelligent transport systems». To achieve ITS management goals, scenarios are used that allow the implementation of normal and emergency control modes. The normal control mode allows controlling traffic in accordance with the planned work, the emergency mode allows doing that depending on the current situation. Emergency control can be operational and situational: the first refers to control that requires planned intervention (for example, assigning priority to certain modes of transport), and the second refers to control that requires unplanned intervention in operation of the system (for example, control in case of a traffic accident).

Highways that comprise complex and unique engineering structures, often require implementation of structural health monitoring systems (SHMS) or more functional structured structural health monitoring and control systems (SHMCS) the structure of which as a rule integrates SHMS [6], allowing real-time analysis of their technical condition.

The regulatory document GOST R [Russian state standard] 59200–2021 «Automobile roads of general use. Bridges and culverts. Capital repair, repair and maintenance. Technical regulations» in its clause 7.2.9 stipulates that control of the condition of bridge structures, inter alia, is carried out with a system for monitoring the technical condition of engineering structures, considering the requirements of GOST R 22.1.12 «Safety in emergencies. Structured system for monitoring and control of building / construction engineering equipment. General requirements», while the clause 7.2.10 indicates that subject to monitoring are bridges:

– with large spans (more than 100 m long);

– high height (height of piers more than 40 m);

– with complex design solutions and features (suspension, cable-stayed, swing, road-rail bridges, drawbridges);

– operated under difficult engineering-geological, seismic or climatic conditions;

– operated after construction, reconstruction, modernisation or repairs carried out using new technologies, structures and materials;

– operated under emergency conditions caused by emergency circumstances during the period of liquidation of emergencies.

Many facilities around the world, most often bridge structures, are equipped with automated monitoring systems [7–9]. In Russia, for example, automated monitoring systems are installed on the transport crossing across the Kerch Strait [10], the bridge crossing to Russky Island across the Eastern Bosphorus Strait [11], the bridge crossing over the Pur River in Yamalo-Nenets Autonomous District [12] and many other objects. The use of these systems makes it possible to identify the development of critical situations related to operation of monitoring objects and the corresponding operational intervention in traffic management.

The use of SHMS could have prevented many major accidents and disasters, for example, the famous disaster of the Morandi Bridge in Italy, which occurred on August 14, 2018, when one of the bridge spans collapsed with dozens of cars on it causing victims[1]. ITS could implement

[1] A road bridge collapsed in Genoa, Italy, killing dozens of people. [Electronic resource]: https://lenta.ru/news/2018/08/14/bridge/. Last accessed 01.06.2023.

emergency situational management considering the SHMS operating on highways. However, such interoperability has not yet been fully implemented: the results of structural health monitoring are analysed by dispatch personnel and are not automatically used when implementing scenarios for road traffic control. Moreover, at the regulatory level in the road sector, the interoperability itself is not regulated (neither interstate or national standards, nor road industry's methodological documents have been validated).

This article is devoted to the presentation of the technological features of data interoperability of SHMS and ITS, which allow, in the near future, to automatically run scenarios of emergency situational control on highways during critical changes in the state of monitored objects.

RESULTS

Data Interoperability of Monitoring and Control systems

First, it is necessary to note several important aspects regarding the operation of SHMS.

Firstly, these systems are not certified to safety integrity levels and often provide results with low reliability, and that should be undoubtedly taken into account when using monitoring data for management and control of any critical technological processes. Therefore, SHMS must necessarily be subject to requirements for reliability of recording so-called diagnostic events – events that occur during operation of the monitored object. In the road industry, it is necessary at the regulatory level to regulate the procedure for implementing SHMS with the required level of safety integrity.

Secondly, the ITS itself must contain SHMS data analytics tools (or the data must be considered in some external analytics platforms before transferring them to the ITS hardware and software systems): for example, data received from, respectively, SHMS and tools of road load monitoring are not jointly processed in any way, which does not make it possible to record the exact cause of the load on the monitored object and, accordingly, does not make it possible to consider monitoring data when implementing additional traffic control scenarios.

Thirdly, it is necessary to establish a list of critical diagnostic situations that cause changes in road traffic control modes and causing transition of the transport system to a dangerous state. For example, it is necessary to identify at least one diagnostic situation that is associated with the transition of a monitored object to a dangerous state that does not guarantee its safe operation.

Considering these aspects, let us move on to a description of the architecture of data interoperability of monitoring and control systems, as well as of its technological foundations.

First, let us note that this problem has been raised more than once in related sectors of transport – on railways there is still no data interoperability of SHMS (and of other stationary automated monitoring systems) with automated train traffic control systems [13]. However, attempts to establish such interoperability are being made at JSC Russian Railways, that is described, for example, in [14]. Let us note that the data interoperability between SHMS and the train traffic control system described in that work cannot be safe, since the reliability of the monitoring results has not been determined by industry's regulations. However, the management of JSC Russian Railways is currently pondering over developing regulatory documentation regarding the use and operation of SHMS, as well as the interpretation of monitoring results.

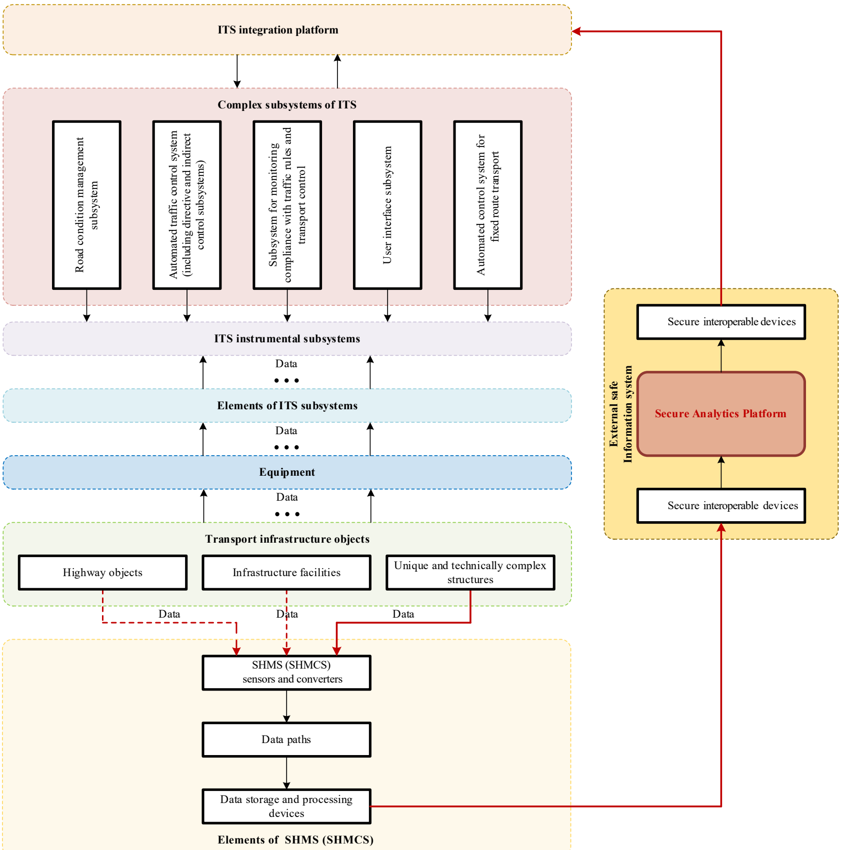
The paper [15] described the basics of creating safe train traffic control systems providing for data interoperability with measuring systems. Consideration of developments in railway industry, where train traffic control systems are certified to the highest level of safety integrity (SIL 4), is extremely important for the road industry.

Architectures of Interoperability of Monitoring and Control Systems

Let us define some important functional requirements for data interoperability of SHMS and ITS:

– SHMS data enter an external secure analytics platform, which generates data messages with a predetermined level of reliability (it must be regulated) and then transmits to the ITS only a signal about the alarm level for the monitored object (for this example, we will limit ourselves to only such a signal, in reality, it is possible to make a much deeper gradation of diagnostics situations).

– SHMS and ITS must have compatible protocols for integration.



Pic. 1. Hardware architecture [developed by the authors].

– SHMS data should have high reliability for subsequent analysis, and this indicator must be standardised.

– SHMS and an external secure analytics platform should process data in real time for rapid launching of ITS scenarios.

– Data interoperability should comply with cyber security requirements.

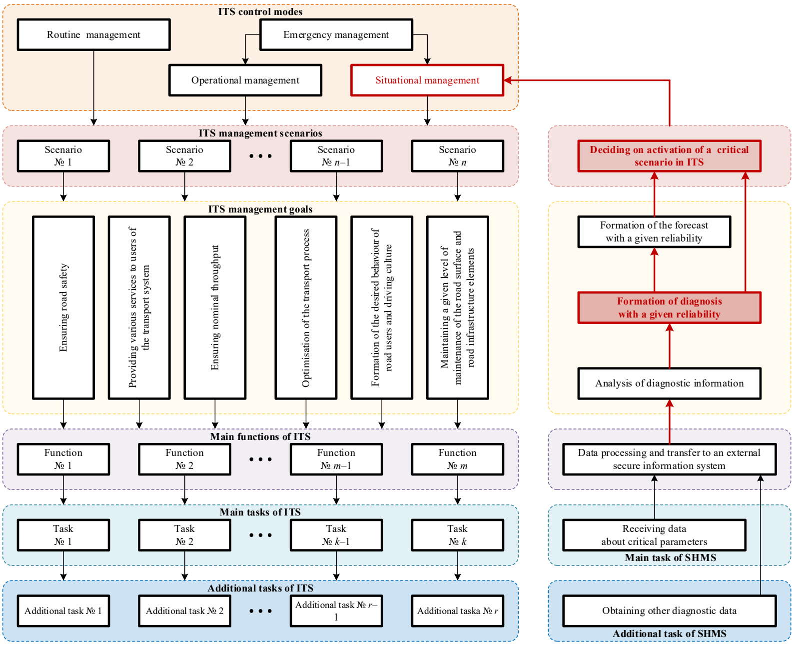
– Integration of SHMS and ITS, as well as interaction between systems should comply with security and data integrity standards.

The hardware and functional architectures of ITS, which had data interoperability with the SHMS tools, is shown in Pics. 1 and 2. They have been developed by the authors of the article considering the ITS architecture provided for in GOST R [Russian State standard] 56294–2014 «Intelligent transport systems. Requirements for functional and physical architectures of intelligent transport systems» and the SHMS architecture provided for in GOST R [Russian State standard] 59943–2021 «Automobile roads of general use. Systems of monitoring bridges. Design rules».

Let us note that monitoring systems do not cover all highway infrastructure facilities, but only some of them, as shown in Pic. 1 by a solid arrow; dotted arrows indicate objects that may not necessarily be equipped with stationary monitoring equipment. Data interoperability is carried out through an «add-on» – a secure platform for analysing monitoring results. Thus, ITS hardware elements actually include SHMS elements and the safe platform intended for analytics and decision-making on the activation of critical scenarios corresponding to the non-standard state of transport infrastructure objects.

Synthesis of Hardware for Data Interoperability of Monitoring and Control Systems

To synthesise hardware for data interoperability of monitoring and control systems, it is necessary to determine a set of states in which the system can be. Let us state the problem as follows. There are two main (generalised) modes of ITS operation: 1) operation when the monitored object is operational; 2) functioning when recording a dangerous state of the monitored object. It is required to synthesise a scenario switching device for road traffic control.

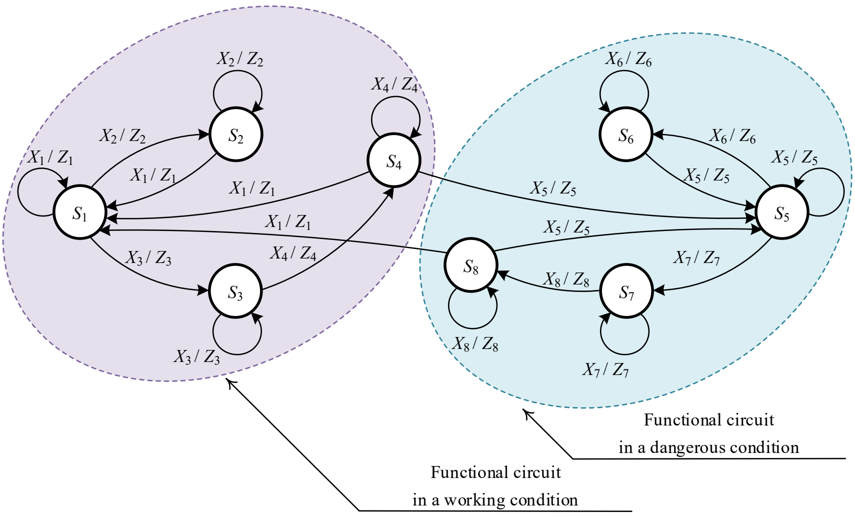


Pic. 2. Functional architecture [developed by the authors].

Let us use the mathematical model of a finite-state automation (finite-state machine) [16].

Pic. 3 shows the transition graph of the ITS finite-state machine, which has SHMS of some object (for example, of a bridge) as a subsystem. In the graph, each vertex corresponds to the state of the system, and the arcs indicate possible transitions between states. On the arcs, the values of the input vectors $<X> = <x_1 x_2 \dots x_t>$ and output vectors $<Z> = <z_1 z_2 \dots z_m>$ are signed separated by a slash. Moreover, in each specific state, the values of the digit of the input and output vectors are uniquely defined, therefore, on the arcs of the input and output vectors, the indices of the states in which the arcs enter are labelled.

The initial state S_1 is the state in which the normal control mode is implemented, and the monitored object is in an operational state. The process of functioning in this mode continues, and in parallel with predetermined measurement periods τ_i, the SHMS collects data from the *i*-th number of diagnostic sensors (data acquisition periods are usually different). In other words, after a given period of time there is a transition to the S_2 state and back to the S_1 state. As data is accumulated, at specified time intervals τ_A,



Pic. 3. ITS transition graph for two modes of operation of the monitored object [developed by the authors].

Table 1

Finite-state machine transition and output table

S	$x_1 x_2 x_3 x_4$															
	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
S_1	(S_1), 0	~	~	~	S_3, 0	~	~	~	S_2, 0	~	~	~	~	~	~	~
S_2	S_1, 0	~	~	~	~	~	~	~	(S_2), 0	~	~	~	~	~	~	~
S_3	~	~	S_4,0	~	(S_3), 0	~	~	~	~	~	~	~	~	~	~	~
S_4	S_1, 0	S_5,1	(S_4),0	~	~	~	~	~	~	~	~	~	~	~	~	~
S_5	~	(S_5),1	~	~	~	S_7,1	~	~	~	S_6,1	~	~	~	~	~	~
S_6	~	S_5,1	~	~	~	~	~	~	~	(S_6),1	~	~	~	~	~	~
S_7	~	~	S_8,1	~	~	(S_7),1	~	~	~	~	~	~	~	~	~	~
S_8	S_1,0	~	(S_8),1	~	~	~	~	~	~	~	~	~	~	~	~	~

Table 2

Minimised finite-state machine transition table

S	$x_1 x_2 x_3 x_4$															
	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
S_1, S_2, S_3, S_4	(S_1), 0	S_5,1	(S_4),0	~	(S_3), 0	~	~	~	(S_2), 0	~	~	~	~	~	~	~
S_5, S_6, S_7, S_8	S_1,0	(S_5),1	(S_8),1	~	~	(S_7)1	~	~	~	(S_6),1	~	~	~	~	~	~

a comprehensive analysis is carried out with the shaping of a diagnosis, prognosis, calculation of reliability indicators, and assessment of the risks of road traffic safety violations. That is, a transition occurs from state S_1 to state S_2, and then a control mode is selected – transition to state S_4. The system is in this state for a short time. Exit from it is possible by moving to state S_1, or to state S_5 – this is a state in which a critical state is recorded for the monitored object according to the SHMS data (for example, limitedly operable or completely inoperable). Let us call this condition «dangerous» for traffic. At this moment, an emergency situational control scenario is launched related to restraints on traffic through the monitored object. Diagnostics procedures are ongoing. The system within a given period transitions to state S_6, and then back to S_5. Then, as data accumulates, a comprehensive analysis is carried out – a transition from state S_1 to state S_7. In this case, the period of complex analysis can be reduced $\tau_{A*} \leq \tau_A$. Next, the ITS operating mode is selected – transition to state S_8. Similar to the S_4 state, the control mode is selected and the transition to the S_5 state or to the S_1 state is carried out. The system itself records this. But in the physical part, the maintenance personnel perform the necessary procedures for checking the technical condition of the monitored object and maintenance work, after which the ITS, having made sure that there is no danger, launches a safe operation scenario when the monitored object is operational. The data interoperability algorithm is presented in Pic. 4.

Pic. 5 shows one of the options for encoding input and output vectors: x_1 – enabling measurement, x_2 – enabling analysis, x_3 – selecting control mode, x_4 – activating control mode, z – signalling about the used control mode.

Using the well-known technique for synthesising a finite-state machine [16], we implement a digital device that operates according to the mathematical model presented in Pic. 5. To do this, we will compile a table of transitions and outputs of the finite-state machine (Table 1). Then we minimise and encode the transition table (Tables 2 and 3).

After encoding the table of transitions and outputs, we will calculate the values of the functions for switching on memory elements. We use an implementation based on standard *RS* flip-flops, the operating logic of which is given in Table 4 [16].

In Table 4, the previous moment in time is designated as t – 1, and the current moment is designated as t.

Table 3

Encoded finite-state machine transition table

y	$x_1 x_2 x_3 x_4$															
	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
0	(0), 0	1,1	(0),0	~	(0), 0	~	~	~	(0), 0	~	~	~	~	~	~	~
1	0,0	(1),1	(1),1	~	~	(1),1	~	~	~	(1),1	~	~	~	~	~	~

Table 4

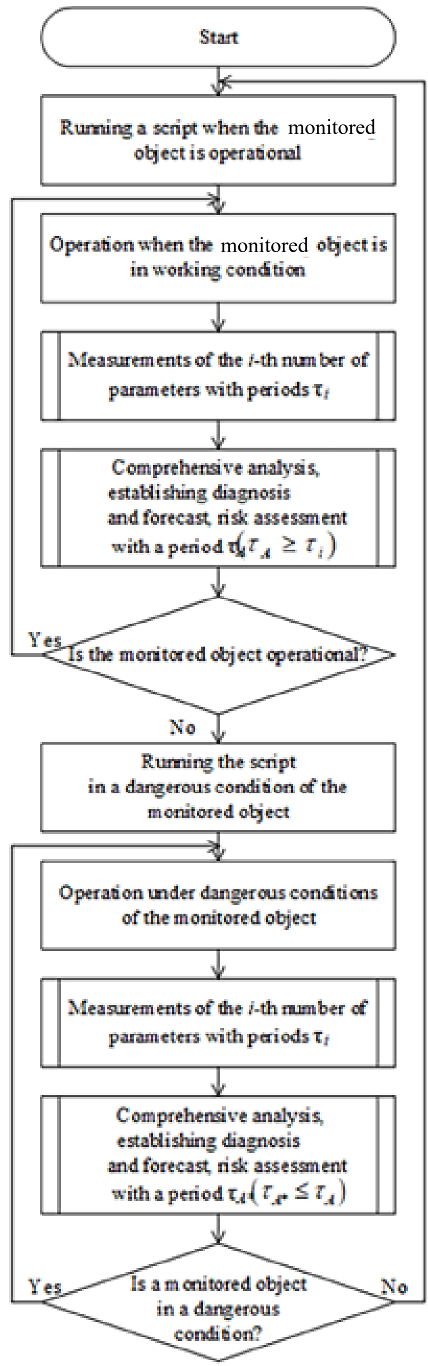
Table for determining values of functions Y_S, Y_R

$y(t-1)$	$y(t)$	
	0	1
0	0~	10
1	01	~0

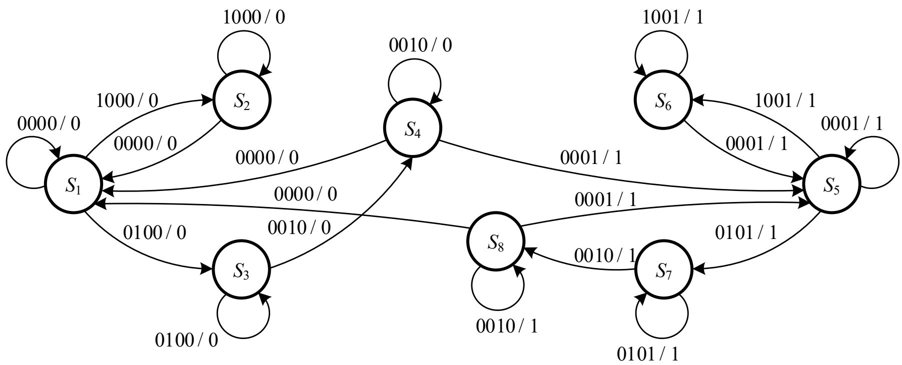
Table 5

Truth table of switching functions of Y_S and Y_R flip-flops

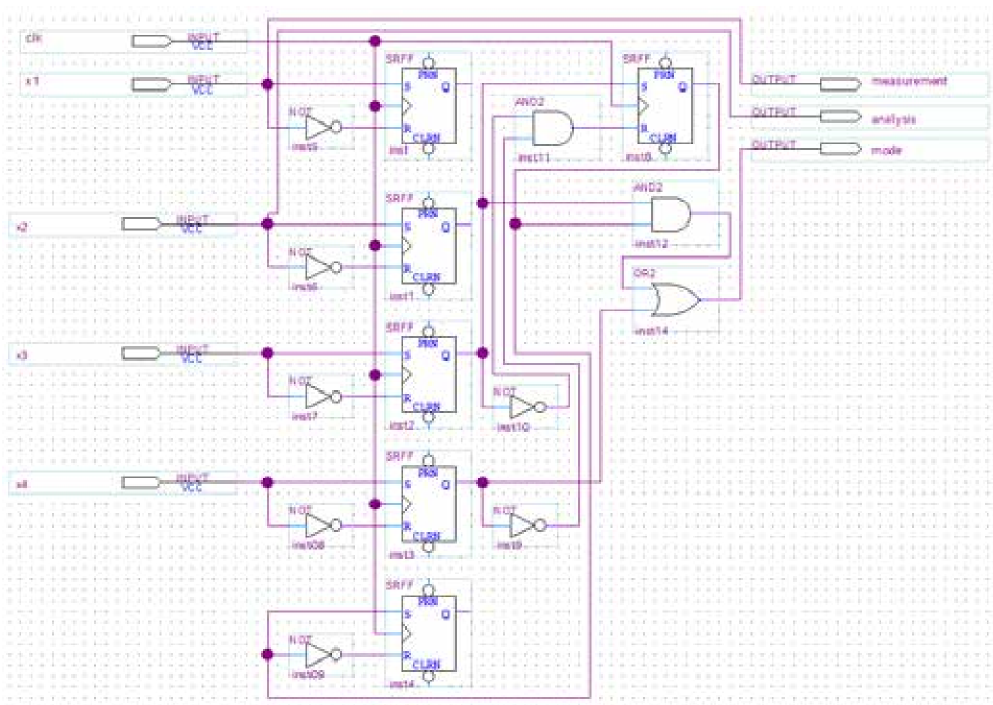
№	$x_1 x_2 x_3 x_4 y$	Y_{S1}	Y_{R1}	z
0	00000	0	~	0
1	00001	0	1	0
2	00010	1	0	1
3	00011	~	0	1
4	00100	0	~	0
5	00101	~	0	1
6	00110	~	~	~
7	00111	~	~	~
8	01000	0	~	0
9	01001	~	~	~
10	01010	~	~	~
11	01011	~	0	1
12	01100	~	~	~
13	01101	~	~	~
14	01110	~	~	~
15	01111	~	~	~
16	10000	0	~	0
17	10001	~	~	~
18	10010	~	~	~
19	10011	~	0	1
20	10100	~	~	~
21	10101	~	~	~
22	10110	~	~	~
23	10111	~	~	~
24	11000	~	~	~
25	11001	~	~	~
26	11010	~	~	~
27	11011	~	~	~
28	11100	~	~	~
29	11101	~	~	~
30	11110	~	~	~
31	11111	~	~	~



Pic. 4. Algorithm for data interoperability of SHMS and ITS [developed by the authors].



Pic. 5. Encoded ITS transition graph for two modes of operation of the monitored object [developed by the authors].



Pic. 6. Finite-state machine using RS flip-flops [developed by the authors].

Using the rules outlined in Table 4, let us create a table of the values of Y_S and Y_R RS flip-flop inputs for all input combinations. We will enter the data into Table 5.

Let us write down and minimise the functions from the truth table:

$$Y_{S1} = x_4;$$

$$Y_{R1} = \overline{x_3 x_4};$$

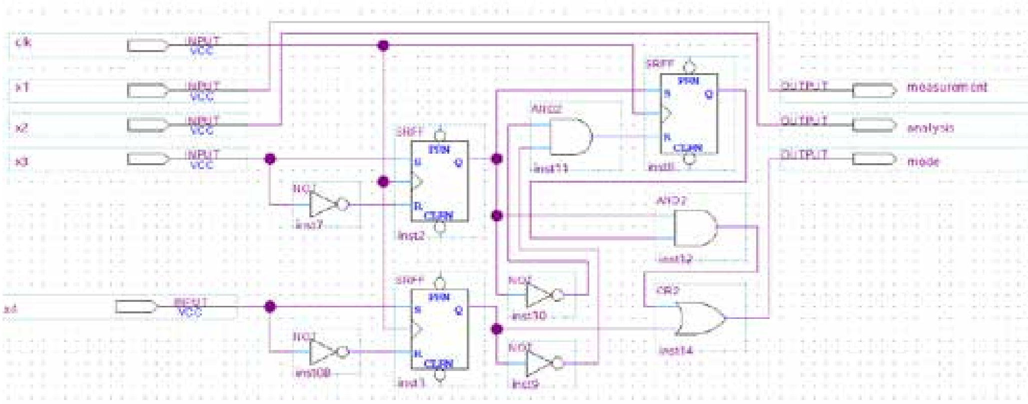
$$z = x_4 \vee x_3 y.$$

According to these formulas in Pic. 6, a finite-state machine is implemented in the Quartus environment [17]. After minimisation, it has the form shown in Pic. 7.

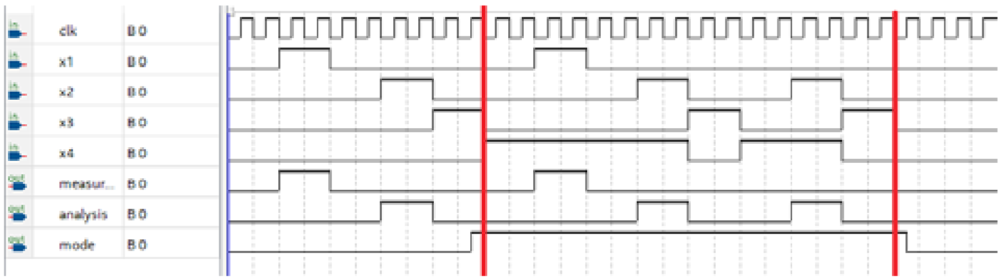
Pic. 8 shows a time diagram of the operation of the synthesised finite-state machine in the mode of running states along the following chain: $S_1 \to S_2 \to S_1 \to S_3 \to S_4 \to S_5 \to S_6 \to S_5 \to S_7 \to S_8 \to S_5 \to S_7 \to S_8 \to S_1$.

The following designations are used in the diagram: *clk* – synchronising pulse, $x_1 - x_4$ – circuit inputs, «measurement», «analysis», «mode» outputs – measurement, analysis and control mode, respectively.

Each state corresponds to 2 clock cycles of the synchronising pulse. The «Mode» output is shifted by half a pulse due to the logic of the flip-flops in the circuit. The shift depends on the length of the synchronising pulse, the parameters of which can be configured individually for a specific type of flip-flop (a fraction of a second). The vertical bold [red] stripes on the diagram



Pic. 7. Minimised finite-state machine using RS flip-flops [developed by the authors].



Pic. 8. Time diagram of the finite-state machine operation [developed by the authors].

mark the boundaries of transition from one mode to another.

The finite-state machine itself was synthesised for the experiment on a programmable logic integrated circuit MAX II EPM240T100C4 class CPLD (Complex Programmable Logic Device) [18]. The authors have already repeatedly used this scheme to implement digital control devices and experiments [19]. It contains 240 logic elements (LE), 192 macro elements and a maximum of 80 user I/O. The synthesised device required 3 logic gates (about 1 % of the total) and 8 user pins (10 % of the total). It is to note that the above example of implementation of data interoperability of SHMS and ITS was implemented with RS flip-flops in circuits with programmable logic. When developing a device, one can apply other memory elements, any other element base. Finite-state machine can be developed as a software as well.

CONCLUSION

Data interoperability of SHMS and ITS in terms of automatically launching scenarios when the dangerous state of a monitored object is detected will significantly improve road traffic safety. The results presented in this article on construction of a mathematical model of the device for data interoperability systems and an example of hardware implementation can be used in practice when implementing tightly integrated SHMS and ITS. This, in turn, makes it possible to manage the reliability and safety of the transportation process by minimising the failure rates of technical equipment [20].

Let us, however, pay attention to the still unsolved problem of ensuring diagnosis (and subsequent prognosis) with high, predetermined reliability. In addition, the road industry has still not solved the problem of developing technical requirements for secure data analytics platforms and automated monitoring systems included in the feedback chains of control systems. The solution to these and related problems, apparently, belongs to the prospects of the near future.

The development of ITS on the roads of the Russian Federation is a strategically and economically important area of activity for the scientific and engineering communities, bringing us closer to an absolutely safe transportation process.

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Article received 13.06.2023, approved 07.09.2023, accepted 15.11.2023.