Analysis of the vehicle operation process including diagnostic information

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Abstract. Modern telecommunications techniques allow for continuous transmission of information from vehicles to dispatch centres during the operation process. The information included in this transmission may contain diagnostic data that make it possible to monitor the state of responsible components of the vehicle construction. The article presents the issues related to the analysis of the vehicle operation process including information received with the use of a CAN bus. The model of the vehicle operation process was presented, and the diagnosis state was taken into account. The use of transport telematics systems and intelligent transport systems in transport allow for the rolling stock profiling at the next stage. Owing to the rolling stock profiling, operational databases powered by a telematics interface are created. This, in turn, will allow to carry out the operational application process along with further optimisation of the operation process.

1 Introduction

Modern telecommunications techniques allow for continuous transmission of information from vehicles to dispatch centres during the operation process [1, 2]. The information included in this transmission may contain diagnostic data that make it possible to monitor the state of responsible components of the vehicle construction. It is encouraged by the fact that the control of individual actuators of the vehicle equipment is carried out with the use of on-board communication buses, the messages of which constitute a medium of information on specific load parameters of the devices. The information techniques, in turn, based on specialised IT equipment, and the use of advanced methods for information processing allow to observe changes in the size of diagnostic symptoms with a minimum delay, and often in real time [3, 4].

This situation makes it possible to modify the applied vehicle maintenance strategies including the transport telematics technical capabilities in the area of information transmission and processing [5-7]. The article analyses the vehicle operation process including diagnostic information. The reliability and operating approach was presented [8-10], and the diagnosis state was taken into account. The use of transport telematics systems and intelligent transport systems [11-14] in transport allow for the rolling stock profiling at the next stage. Owing to the rolling stock profiling, operational databases powered by the telematics interface are created [15].

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2 Use of CAN buses of vehicles in obtaining diagnostic information

On-board vehicle data exchange systems evolve with the development of means of transport. They constitute specialised structures created from scratch in order to fulfil specific tasks, which are posed by modern control systems [16].

In the automotive industry, the development of an engine operation control unit, ECU (Electronic Control Unit), can be considered as the beginning of the creation of a protocol capable of reliable and safe exchange of data between sensors and actuators. It was the moment of the birth of bus systems in vehicles. One of the most common is the CAN bus [17, 18]. From the very beginning, the main objective of the CAN standard designers was to ensure reliability of operation while simplifying the vehicle's electric bundle. The reconciliation of contradictory expectations had to result in the search for a solution simultaneously on several layers of the protocol stack.

In the CAN standard, a differential signal transmission system was used. It increases the resistance to interference. The induced voltage acts similarly on both wires maintaining a mutual voltage relation, which allows the receiver to correctly read the right signal value, even under strong interference conditions. As a consequence, the redundancy of the CAN bus physical layer planned by the constructors brings another advantage in the form of resistance to damage to one of two bus wires. As a result, the system can function on one wire by closing the circuit with the use of connection to the vehicle mass at both ends, on the transmitter and receiver sides. In such a situation, in most vehicles, the driver will not be even informed about partial unfitness of the system, because there are no current consequences for operation. Another important feature of CAN is the orientation of transmission to the message, which, in short, means that there is no need to address the devices themselves, but only to give a distinguishing feature to a type of the message transmitted by any device connected to the bus. This feature has a double implication. On the one hand, it provides the solution flexibility, expected in multi-series production of many versions of the same vehicle, but on the other hand, it opens the door to Cyber Security threats [17, 18].

The current generations of the bus systems are focused on new functionalities related to the maintenance of real-time systems, such as fully mechatronic steering systems, however, the vehicle's IT framework includes the buses based on a proven and reliable CAN solution.

The use of the CAN buses in vehicles makes it possible to obtain numerous diagnostic information. Modern vehicles have many buses that exchange data with each other. The vehicle telematics equipment capable of reporting the events marked as essential for operation sends data via radio to the processing centre. These data can be used to determine the technical condition of the vehicle and its reliability and operation analysis.

3 Reliability and operation analysis of the vehicle including the diagnosis process

The process of the vehicle operation is always accompanied by degradation processes. They consist in a change of the state towards deterioration of its functional properties [19]. The used vehicle is always subject to degradation (even due to wear), only the intensity of these changes can be different. A significant role is played by external factors basically related to an unfavourable environmental impact, to which the vehicle has to adapt its operation, many times, at the expense of the increased rate of degradation. The vehicle response to unfavourable external conditions leading to maintaining the same level of efficiency of operation usually results in an increase in the rate of degradation.

In order to prevent, stop or reduce the technical degradation processes of vehicles and restore their service potential, various operation strategies are used [20, 21]. The following main maintenance strategies can be distinguished:

- repair strategy after damage (*Corrective Maintenance*),
- on-condition maintenance strategy (*On-condition Maintenance*),
- time based maintenance strategy (*TBM- Time Based Maintenance*).

In the vehicle operation process, an important role is played by monitoring. Monitoring is an activity based on continuous observation of changes in the object condition [22]. It is a kind of supervision, the concept of which includes activities involving, in general, discrete (at certain time intervals) or continuous observations.

The monitoring process uses such diagnostic signals, the observation of which does not interfere with the object functioning, and in particular, its operation process.

By carrying out the vehicle functioning analysis, it can be stated that the relationships taking place in it, in reliability and operation terms, can be visualised as shown in Fig. 1.

The state of usability S_Z is a state, in which the vehicle functions properly. The state of partial usability S_{ZC} is a state, in which the vehicle is partially usable, but it carries out the tasks that it was assigned to. The state of diagnosis S_{D1} is a state, in which the processes related to diagnosing of the vehicle state are conducted, but it is usable. The state of diagnosis S_{D2} is a state, in which the processes related to diagnosing of the vehicle state are conducted, but it is partially usable. The maintenance state Q_O is a state, in which the activities necessary to restore the usability state of the vehicle are carried out. The state of unfitness Q_N is a state, in which the vehicle does not implement the tasks that it was assigned to.

The vehicle being in the state of usability S_Z performs periodic diagnoses. It is illustrated by the transition to the state of diagnosis S_{D1} with the intensity λ_{ZD1}. The diagnosis time is determined by the intensity of transition μ_{D1Z}. This process takes place during the stop, and it makes it possible to obtain diagnostic information, which is collected from the on-board telematics systems of the vehicle. Being in the state of usability S_Z, it is possible to transit to the state of partial usability S_{ZC} with the intensity λ_{ZZC} in case of exceeding the limit value for the state of usability by the diagnostic symptom. By being in the state of partial usability S_{ZC}, the periodic diagnoses are performed. It is illustrated by the transition to the state of diagnosis S_{D2} with the intensity λ_{ZCD2}. Being in the state of diagnosis S_{D2}, a decision (based on diagnostic information) was made whether the vehicle, which is partially usable, is still operated, or renovation is necessary. In the first case, there is a transition to the state of partial S_{ZC} with the intensity μ_{D2ZC}. In the second case, there is a transition to the state of renovation S_O with the intensity λ_{D2O}. Being in the state of renovation, the vehicle operational potential is restored, and at the same time, there is a transition to the state of usability S_Z with the intensity μ_{OZ}. In the system, the transitions to the state of unfitness S_N from the state of usability S_Z (with the intensity λ_{ZN}) or from the state of partial usability S_{ZC} (with the intensity λ_{ZCN}) are possible. The mentioned situations occur when the diagnostic symptom reaches the value characteristic for the state of unfitness. Being in the state of unfitness S_N, there is a transition to the state of renovation S_O with the intensity λ_{NO} in order to restore the operational potential.

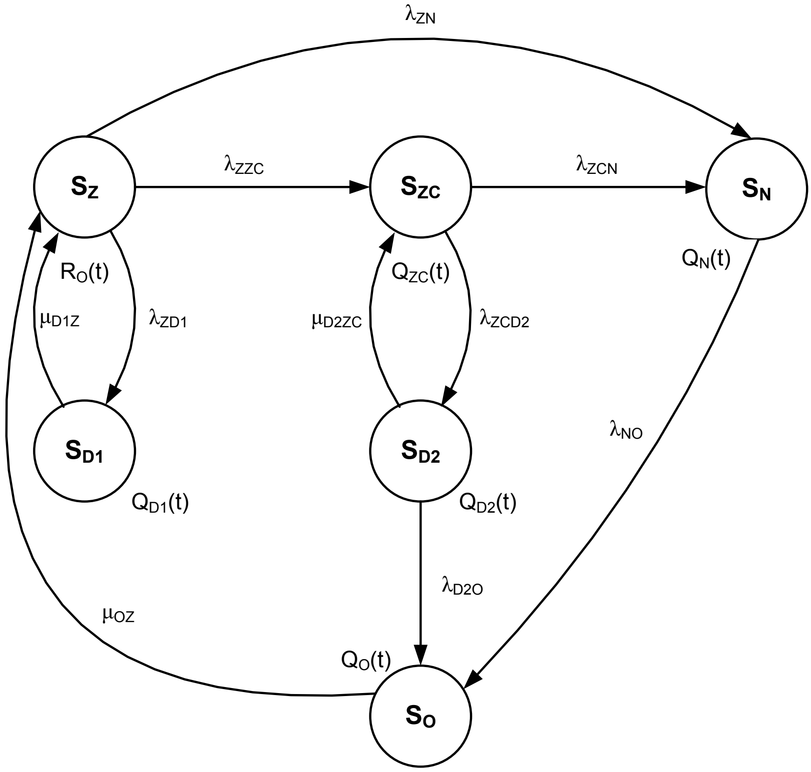

Fig. 1. Relationships during the vehicle operation.

Markings in Fig.:
$R_O(t)$ – probability function of the system's staying in the state of usability
$Q_{ZC}(t)$ – probability function of the system's staying in the state of partial usability,
$Q_{D1}(t)$ – probability function in the system's staying in the state of diagnosis 1,
$Q_{D2}(t)$ – probability function of the system's staying in the state of diagnosis 2,
$Q_O(t)$ – probability function of the system's staying in the state of maintenance,
$Q_N(t)$ – probability function of the system's staying in the state of unfitness,
λ_{ZZC} – intensity of transitions from the state of usability to the state of partial usability,
λ_{ZN} – intensity of transitions from the state of usability to the state of unfitness,
λ_{ZD1} – intensity of transitions from the state of usability to the state of diagnosis 1,
μ_{D1Z} – intensity of transitions from the state of diagnosis 1 to the state of usability,
λ_{ZCD2} – intensity of transitions from the state of partial usability to the state of diagnosis 2,
μ_{D2ZC} – intensity of transitions from the state of diagnosis 2 to the state of partial usability,
λ_{ZCN} – intensity of transitions from the state of partial usability to the state of unfitness,
λ_{D2O} – intensity of transitions from the state of diagnosis 2 to the state of maintenance,
λ_{NO} – intensity of transitions from the state of unfitness to the state of maintenance,
μ_{OZ} – intensity of transitions from the state of maintenance to the state of usability.

The system presented in Fig. 1 can be described by the following Chapman–Kolmogorov equations:

$$R_0'(t) = -\lambda_{ZZC} \cdot R_0(t) - \lambda_{ZN} \cdot R_0(t) - \lambda_{ZD1} \cdot R_0(t) + \mu_{D1Z} \cdot Q_{D1}(t) + \mu_{OZ} \cdot Q_O(t)$$

$$Q_{D1}'(t) = \lambda_{ZD1} \cdot R_0(t) - \mu_{D1Z} \cdot Q_{D1}(t)$$

$$Q_{ZC}'(t) = \lambda_{ZZC} \cdot R_0(t) - \lambda_{ZCN} \cdot Q_{ZC}(t) - \lambda_{ZCD2} \cdot Q_{ZC}(t) + \mu_{D2ZC} \cdot Q_{D2}(t) \quad (1)$$

$$Q'_{D2}(t) = \lambda_{ZCD2} \cdot Q_{ZC}(t) - \mu_{D2ZC} \cdot Q_{D2}(t) - \lambda_{D2O} \cdot Q_{D2}(t)$$

$$Q'_{N}(t) = \lambda_{ZCN} \cdot Q_{ZC}(t) + \lambda_{ZN} \cdot R_0(t) - \lambda_{NO} \cdot Q_N(t)$$

$$Q'_{O}(t) = \lambda_{D2O} \cdot Q_{D2}(t) + \lambda_{NO} \cdot Q_N(t) - \mu_{OZ} \cdot Q_O(t)$$

Assuming the baseline conditions:

$$R_0(t) = 1$$

$$Q_{D1}(t) = Q_{D2}(t) = Q_{ZC}(t) = Q_N(t) = Q_O(t) = 0 \tag{2}$$

and applying the Laplace transform, we obtain the following system of linear equation:

$$s \cdot R_0^*(s) - 1 = -\lambda_{ZZC} \cdot R_0^*(s) - \lambda_{ZN} \cdot R_0^*(s) - \lambda_{ZD1} \cdot R_0^*(s) + \mu_{D1Z} \cdot Q_{D1}^*(s) + \mu_{OZ} \cdot Q_O^*(s)$$

$$s \cdot Q_{D1}^*(s) = \lambda_{ZD1} \cdot R_0^*(s) - \mu_{D1Z} \cdot Q_{D1}^*(s)$$

$$s \cdot Q_{ZC}^*(s) = \lambda_{ZZC} \cdot R_0^*(s) - \lambda_{ZCN} \cdot Q_{ZC}^*(s) - \lambda_{ZCD2} \cdot Q_{ZC}^*(s) + \mu_{D2ZC} \cdot Q_{D2}^*(s)$$

$$s \cdot Q_{D2}^*(s) = \lambda_{ZCD2} \cdot Q_{ZC}^*(s) - \mu_{D2ZC} \cdot Q_{D2}^*(s) - \lambda_{D2O} \cdot Q_{D2}^*(s) \tag{3}$$

$$s \cdot Q_{N}^*(s) = \lambda_{ZCN} \cdot Q_{ZC}^*(s) + \lambda_{ZN} \cdot R_0^*(s) - \lambda_{NO} \cdot Q_N^*(s)$$

$$s \cdot Q_{O}^*(s) = \lambda_{D2O} \cdot Q_{D2}^*(s) + \lambda_{NO} \cdot Q_N^*(s) - \mu_{OZ} \cdot Q_O^*(s)$$

The probabilities of the system's staying in the distinguished functional states from the symbolic (Laplace's) perspective have the following form:

$$R_0^*(s) = \frac{b \cdot e \cdot f \cdot (c \cdot d - \lambda_{ZCD2} \cdot \mu_{D2ZC})}{\begin{gathered} a \cdot b \cdot c \cdot d \cdot e \cdot f - c \cdot d \cdot e \cdot f \cdot \lambda_{ZD1} \cdot \mu_{D1Z} - a \cdot b \cdot e \cdot f \cdot \lambda_{ZCD2} \cdot \mu_{D2ZC} + \\ + e \cdot f \cdot \lambda_{ZCD2} \cdot \lambda_{ZD1} \cdot \mu_{D1Z} \cdot \mu_{D2ZC} - b \cdot c \cdot d \cdot \lambda_{NO} \cdot \lambda_{ZN} \cdot \mu_{OZ} - \\ - b \cdot e \cdot \lambda_{D2O} \cdot \lambda_{ZCD2} \cdot \lambda_{ZZC} \cdot \mu_{OZ} - b \cdot d \cdot \lambda_{NO} \cdot \lambda_{ZCN} \cdot \lambda_{ZZC} \cdot \mu_{OZ} + \\ + b \cdot \lambda_{NO} \cdot \lambda_{ZCD2} \cdot \lambda_{ZN} \cdot \mu_{D2ZC} \cdot \mu_{OZ} \end{gathered}} \tag{4}$$

$$Q_{D1}^*(s) = \frac{e \cdot f \cdot \lambda_{ZD1} \cdot (c \cdot d - \lambda_{ZCD2} \cdot \mu_{D2ZC})}{\begin{gathered} a \cdot b \cdot c \cdot d \cdot e \cdot f - c \cdot d \cdot e \cdot f \cdot \lambda_{ZD1} \cdot \mu_{D1Z} - a \cdot b \cdot e \cdot f \cdot \lambda_{ZCD2} \cdot \mu_{D2ZC} + \\ + e \cdot f \cdot \lambda_{ZCD2} \cdot \lambda_{ZD1} \cdot \mu_{D1Z} \cdot \mu_{D2ZC} - b \cdot c \cdot d \cdot \lambda_{NO} \cdot \lambda_{ZN} \cdot \mu_{OZ} - \\ - b \cdot e \cdot \lambda_{D2O} \cdot \lambda_{ZCD2} \cdot \lambda_{ZZC} \cdot \mu_{OZ} - b \cdot d \cdot \lambda_{NO} \cdot \lambda_{ZCN} \cdot \lambda_{ZZC} \cdot \mu_{OZ} + \\ + b \cdot \lambda_{NO} \cdot \lambda_{ZCD2} \cdot \lambda_{ZN} \cdot \mu_{D2ZC} \cdot \mu_{OZ} \end{gathered}} \tag{5}$$

$$Q_{ZC}^*(s) = \frac{b \cdot d \cdot e \cdot f \cdot \lambda_{ZZC}}{\begin{gathered} a \cdot b \cdot c \cdot d \cdot e \cdot f - c \cdot d \cdot e \cdot f \cdot \lambda_{ZD1} \cdot \mu_{D1Z} - a \cdot b \cdot e \cdot f \cdot \lambda_{ZCD2} \cdot \mu_{D2ZC} + \\ + e \cdot f \cdot \lambda_{ZCD2} \cdot \lambda_{ZD1} \cdot \mu_{D1Z} \cdot \mu_{D2ZC} - b \cdot c \cdot d \cdot \lambda_{NO} \cdot \lambda_{ZN} \cdot \mu_{OZ} - \\ - b \cdot e \cdot \lambda_{D2O} \cdot \lambda_{ZCD2} \cdot \lambda_{ZZC} \cdot \mu_{OZ} - b \cdot d \cdot \lambda_{NO} \cdot \lambda_{ZCN} \cdot \lambda_{ZZC} \cdot \mu_{OZ} + \\ + b \cdot \lambda_{NO} \cdot \lambda_{ZCD2} \cdot \lambda_{ZN} \cdot \mu_{D2ZC} \cdot \mu_{OZ} \end{gathered}} \tag{6}$$

$$Q_{D2}^{*}(s)=\frac{b\cdot e\cdot f\cdot\lambda_{ZCD2}\cdot\lambda_{ZZC}}{\begin{array}{c}a\cdot b\cdot c\cdot d\cdot e\cdot f-c\cdot d\cdot e\cdot f\cdot\lambda_{ZD1}\cdot\mu_{D1Z}-a\cdot b\cdot e\cdot f\cdot\lambda_{ZCD2}\cdot\mu_{D2ZC}+\\+e\cdot f\cdot\lambda_{ZCD2}\cdot\lambda_{ZD1}\cdot\mu_{D1Z}\cdot\mu_{D2ZC}-b\cdot c\cdot d\cdot\lambda_{NO}\cdot\lambda_{ZN}\cdot\mu_{OZ}-\\-b\cdot e\cdot\lambda_{D2O}\cdot\lambda_{ZCD2}\cdot\lambda_{ZZC}\cdot\mu_{OZ}-b\cdot d\cdot\lambda_{NO}\cdot\lambda_{ZCN}\cdot\lambda_{ZZC}\cdot\mu_{OZ}+\\+b\cdot\lambda_{NO}\cdot\lambda_{ZCD2}\cdot\lambda_{ZN}\cdot\mu_{D2ZC}\cdot\mu_{OZ}\end{array}} \tag{7}$$

$$Q_{N}^{*}(s)=\frac{b\cdot f\cdot(c\cdot d\cdot\lambda_{ZN}+d\cdot\lambda_{ZCN}\cdot\lambda_{ZZC}-\lambda_{ZCD2}\cdot\lambda_{ZN}\cdot\mu_{D2ZC})}{\begin{array}{c}a\cdot b\cdot c\cdot d\cdot e\cdot f-c\cdot d\cdot e\cdot f\cdot\lambda_{ZD1}\cdot\mu_{D1Z}-a\cdot b\cdot e\cdot f\cdot\lambda_{ZCD2}\cdot\mu_{D2ZC}+\\+e\cdot f\cdot\lambda_{ZCD2}\cdot\lambda_{ZD1}\cdot\mu_{D1Z}\cdot\mu_{D2ZC}-b\cdot c\cdot d\cdot\lambda_{NO}\cdot\lambda_{ZN}\cdot\mu_{OZ}-\\-b\cdot e\cdot\lambda_{D2O}\cdot\lambda_{ZCD2}\cdot\lambda_{ZZC}\cdot\mu_{OZ}-b\cdot d\cdot\lambda_{NO}\cdot\lambda_{ZCN}\cdot\lambda_{ZZC}\cdot\mu_{OZ}+\\+b\cdot\lambda_{NO}\cdot\lambda_{ZCD2}\cdot\lambda_{ZN}\cdot\mu_{D2ZC}\cdot\mu_{OZ}\end{array}} \tag{8}$$

$$Q_{O}^{*}(s)=\frac{b\cdot\begin{pmatrix}c\cdot d\cdot\lambda_{NO}\cdot\lambda_{ZN}+e\cdot\lambda_{D2O}\cdot\lambda_{ZCD2}\cdot\lambda_{ZZC}+\\+d\cdot\lambda_{NO}\cdot\lambda_{ZCN}\cdot\lambda_{ZZC}-\lambda_{NO}\cdot\lambda_{ZCD2}\cdot\lambda_{ZN}\cdot\mu_{D2ZC}\end{pmatrix}}{\begin{array}{c}a\cdot b\cdot c\cdot d\cdot e\cdot f-c\cdot d\cdot e\cdot f\cdot\lambda_{ZD1}\cdot\mu_{D1Z}-a\cdot b\cdot e\cdot f\cdot\lambda_{ZCD2}\cdot\mu_{D2ZC}+\\+e\cdot f\cdot\lambda_{ZCD2}\cdot\lambda_{ZD1}\cdot\mu_{D1Z}\cdot\mu_{D2ZC}-b\cdot c\cdot d\cdot\lambda_{NO}\cdot\lambda_{ZN}\cdot\mu_{OZ}-\\-b\cdot e\cdot\lambda_{D2O}\cdot\lambda_{ZCD2}\cdot\lambda_{ZZC}\cdot\mu_{OZ}-b\cdot d\cdot\lambda_{NO}\cdot\lambda_{ZCN}\cdot\lambda_{ZZC}\cdot\mu_{OZ}+\\+b\cdot\lambda_{NO}\cdot\lambda_{ZCD2}\cdot\lambda_{ZN}\cdot\mu_{D2ZC}\cdot\mu_{OZ}\end{array}} \tag{9}$$

where:

$$a=s+\lambda_{ZZC}+\lambda_{ZN}+\lambda_{ZD1}$$

$$b=s+\mu_{D1Z}$$

$$c=s+\lambda_{ZCN}+\lambda_{ZCD2}$$

$$d=s+\mu_{D2ZC}+\lambda_{D2O}$$

$$e=s+\lambda_{NO}$$

$$f=s+\mu_{OZ}$$

The solution of the above set of equations in the field of time is the next step of the analysis and it is not discussed here.

The obtained relationships allow to determine the probabilities of staying of the vehicle operation system, including data collected from the on-board telematics systems of the vehicles, in the states of: usability S_Z (4), diagnosis S_{D1} (5), partial usability S_{ZC} (6), diagnosis S_{D2} (7), unfitness S_N (8) and maintenance S_O (9).

4 Conclusion

Modern vehicles are equipped with a large number of electronic devices that form on-board IT networks. Almost all the systems that initially consisted of autonomous devices are currently connected with each other via bus systems. As a result, the electric bundles were simplified consequently reducing the vehicle wiring mass, but above all, it was allowed to exchange information between any elements of the system or even between separate systems. Thus, the data transferred in the buses are used for the current control of the processes of many systems, but they also have information potential that can be used to rationalise the maintenance of the vehicle fleet.

The article presents the reliability and operation analysis of the vehicle, while the diagnosis process was taken into account. It made it possible to determine the relationships that allow to define the values of probabilities of the vehicles' staying in the distinguished states of operation. In further studies, the authors plan to use operational data received via telematics interface in order to develop a database. It will allow for profiling the rolling stock which consists in distinguishing individual vehicles or their collections due to their functional properties. This, in turn, will allow to carry out the operational application process along with further optimisation of the operation process. It leads to the rolling stock operation specification that provides the opportunity to rationalise the operation and maintenance.

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