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Improved method of processing the output parameters of the diesel locomotive engine for more efficient maintenance

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Highlights

- Expert-based determination of the fault limit values of the engine parameters.
- Methodology for simpler display of fault parameters from the diagnostics.
- Improved diagnostics by faster, easier and more accurate fault evaluation.
- Increased maintenance effectiveness by shortening locomotive's downtime.

Abstract

Modernization of aged rolling stock is one of the possibilities to adapt it to the current requirements for better environmental friendliness and economy of railway transport. However, some vehicle upgrades lead to new failures that were not observed in the original vehicles. The cause is the so-called "hybrid design", built on a combination of original and selected new components. The aim of the work was to improve the situation with frequent failures and unavailability that occur on the modernized locomotive where a new diesel engine and new electronic control system was installed. Within the work, a simplified methodology for evaluating the outputs of diagnostic equipment was developped based on and applied to specific locomotive type and its diesel engine. The methodology resulted in a significant reduction of the time for assessing the condition of the vehicle's diesel engine and more effective maintenance. The paper also presents other possibilities in the analysis of big data in the maintenance of rolling stock e.g. using fuzzy logic.

Keywords

maintenance, locomotive, diesel engine, control parameters.

1. Introduction

The basic function/purpose of maintenance of railway vehicles is to keep them running safely and economically for expected life cycle. Therefore, fundamental is to do everything to avoid failures that could end with serious consequences, primarily derailment of a vehicle and train. European Union is aware of importance of good technical condition of rail vehicles and the role of maintenance. So it adapted extensive requirements and legislation in the area of rail safety. Conscience overview on legal requirements regarding railway transport safety in the European Union the practical solutions developed for railway operators as a part of the implementation of maintenance management systems can be found in [42]. Methodology for building a strategy of maintenance focused on safety of railway vehicles using RAMS (Reliability, Availability, Maintainability, Safety) analysis is described in [45] where on the example of a diesel locomotive it was found that this analysis enables proper classification of hazards, quantification of the frequency of occurrence of hazards and the adoption of the appropriate criteria for risk assessment of the created strategy. As stated also in [39], vehicle reliability is strongly linked to rail safety.

Maintenance plays an essential role in a system's life cycle. At the system level, the maintenance influences the reliability and availability of the system [7]. Achieving quality maintenance of any technical system, including railway technology, requires choosing the right maintenance strategy. However, we must realize that more comprehensive maintenance means higher life cycle costs, although this may not lead to a significant improvement in reliability. Measuring and assessing maintenance performance is critical to the competitiveness and future survival of any company providing production or services. As stated Mlynarski et al. the economic indicators of the operation process are one of the most important indicators of the use of vehicles in transport systems. This is because it is the operation management that largely determines the proper functioning of the entire business company [28].

2. Problematic of rail vehicle maintenance and modernization

Macián considers maintenance to be one of the largest expenditures for the transport companies together with fuel (or energy) costs and drivers (personnel) [24], which is, however, the most important one

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from the view of controllability, attending that fuel and labour costs are more externally driven (crude prices volatility, taxes, personnel policies and salaries, etc.) [23]. As in a free market, the optimal maintenance strategy can not only guarantee the availability of railway system but also have the best economic benefits [43].

The maintenance dealing with safety critical components is in particular concerning the wheelsets and parts connected with running gear in general, such as bearings, suspension etc. In this area the durability and prevention of any failure is the most important task. There are numerous standard and verified methods used in technical condition assessment and remaining utilization life prediction methods. With new diagnostics technology and computer support, extensive research is carried out.

In [21] a general reliability study using both classical and Bayesian semi-parametric degradation approaches for reliability analysis are presented. It is illustrated how degradation data can be modelled and analyzed to determine reliability to support preventive maintenance strategy based on a data-driven framework. With the proposed classical approach, both accelerated life tests and design of experiments technology are used to determine how each critical factor affects the prediction of performance, in this study demonstrated on a locomotive wheel-set reliability, being a safety critical component. Other safety critical components requiring higher attention and monitoring are axle bearings. Authors in [35, 51] present the prognostics and health monitoring concept in rail vehicles, specifically focused in bearing health state and remaining useful life. This concept is rapidly growing field of research with the aim of improving the reliability and availability of railway systems switching from time-based to event-driven maintenance policies.

Assessment of the reliability based on statistical methods is so far mostly used. Practical example can be found in the study [16] where statistical methods of quality management were used to identify the most problematic types of diesel locomotive equipment and specific causes of failures. Similar approach to reliability of power equipment on electric locomotives is described in [17], where failure occurrence and reliability analysis was done considering the negative impact of climatic factors on operation and technical condition of the rolling stock.

Increasing demands on the economy and safety of operation of various devices lead to the prediction of remaining service life (RUL). Most researchers devoted to improve the accuracy of the prediction results, and have investigated many effective methods for RUL prediction, including various neural networks (NN), support vector regression (SVR), stochastic process, and other methods. Ramezani et al. give a comprehensive summary to various methods [37]. The researchers form NASA Ames Research Center suggests that the perfectly and precisely prediction of engineering systems behavior is not possible in practical engineering applications due to prognostics uncertainty, and divided the sources of uncertainty into four categories: present state uncertainty, future uncertainty, modeling uncertainty and prediction method uncertainty [40].

In the literature, apart from the classical maintenance models [31], there are numerous maintenance models available on the required reliability level of an entire system [53], some of them based on the application of simulation methods [10, 29]. Some models include the possibility of partial maintenance [28], some others make use of additional inspection of object's technical state when it can be performed while the system is in actual operation [6]. A detailed and comprehensive classification of existing preventive renewal models is provided in [49]. In practical engineering, besides the randomness that can be modeled by probabilistic theory with probability distribution functions, epistemic uncertainty is another issue, caused by factors such as loss of information, limited knowledge, and inevitable man-made mistakes [15], which cannot be well explained by randomness and probabilistic models.

For the system maintenance and availability analysis, there are mathematical formulating and model-based analysis approaches. Garmabaki et al. presented the Multi-Attribute Utility Theory (MAUT), which used multiple objective functions to evaluate the cost and reliability of the maintenance optimization [11]. A gamma deterioration process was proposed by Meier-Hirmer et al., and it was applied to analyze the track maintenance [25]. Furthermore, the Maintenance Engineering Department of French National Railway Company (SNCF) introduced a formal method to estimate the maintenance strategy [3, 43].

Availability studies for degrading systems have been carried out by numerous researchers, but these are mainly based on Markov model using constant failure and repair rates, which is unrealistic in actual operating conditions. Markov model is a stochastic model which is used to model randomly changing systems over time. The basic assumption of a Markov Process is that the behavior of a system in each state is memory less which illustrates that the future evolution of the process depends only on the present state and not on the past sequence of traversed states prior to current state [19].

An interesting observation about relation between operation and maintenance is described in [46], where it is emphasized that maintenance strategy contributes higher efficiency of railway vehicles. One of new solutions that improve economy and thus effectiveness of maintenance is use of mobile maintenance points, as reported in [47].

The purpose of all the technical solutions in condition monitoring and reliability analysis after all is to create more effective maintenance system - maintenance planning and execution. Knowledge of distributions of times to failure is fundamental for maintenance planning [41]. The proposed methods for improved maintenance schedules and new algorithms for overhauls planning are defined in [20, 34].

From the investigation of the state-of-the-art approaches to the railway vehicle operation and maintenance, the principles of RAMS method [7, 45] was used to improve especially reliability, maintainability and availability of the investigated locomotive type with "hybrid design" (old vehicle with modernised propulsion system) by simpler and faster analysis of data from the diagnostic system of the diesel engine through. For processing of diagnostic data, statistical methods for assessment of the diesel engine reliability were used, similar as in the [16]. Outcome of the solution should improve the locomotive operation economy.

The expected service life (durability) of traction rail vehicles is about 30 years, while the service life of individual components/subsystems is usually not the same. The body and chassis generally last longer [44, 50], but e.g. the diesel engine or control systems have a shorter service life. Developments in the field of technology are advancing rapidly, and thus the vehicles are becoming technically obsolete and economically and ecologically disadvantageous. The operating and maintenance costs of such vehicles increase with age. One possibility is to replace them with new vehicles, which is very costly. Another possibility is to modernize them, which is a more acceptable and economically viable option for a large number of rolling stock operators, in particular in Central and Eastern Europe.

At present, apart from technological and economic factors, an environmental factor is gaining significance in restoring vehicle parts to fitness (regeneration) [26]. The use of regenerated parts reduces negative impact of production processes on the environment [9]. The positive effects are especially in saving energy and material that are not consumed for new products.

There are numerous examples of locomotive modernisation [22] or freight wagons [36]. One of them, ŽOS Vrútky, a Slovak company is active both in locomotives [12] and passenger wagons. Example of modernisation of a diesel locomotive is described in [4] where the proposed solution, an electronic rotations and power governor of diesel engine, was applied. By this solution a new optimal operational characteristic were realized. Efficiency of the modernisation has been assessed and supported by an LCC (Life Cycle Cost) analysis.

Sometimes the companies modify only specific components of the locomotive drive [2]. Similarly, a small change in maintenance technology is often a way to improve the reliability of vehicles, for example by adjusting the cleaning of the fuel system as mentioned in [14] or by maintaining the technical condition of the fuel system components [33]. For example, using powder details in various units of rolling stock proved to be more reliable, safe and economically profitable [27]. Usually, the benefits of modernization are in the improvement of economic and environmental parameters of rolling stock operation, for example by reducing a vehicle weight by using light materials [52].

In many European countries, including Slovakia, there are locomotives, which are obsolete and technically less suitable, are still in service on the railways. Therefore, the issues and tasks of modernization of diesel locomotives are very important. The aim of modernization is a positive change or affecting several important parameters of a locomotive at the same time. In the first place, these are operating parameters such as safety, reliability, energy efficiency, performance and much more. Another important factor of modernization are design improvements, which mainly result in less demanding maintenance, improvement of the overall care of the traction vehicle, simplification of operation, comfort and good ergonomic of a train driver and the like. Last but not least, the modernization also improves a number of environmental parameters of the vehicle [48], because modern construction elements and equipment applied in a modernized vehicle give priority to the maximum elimination of negative effects on the environment in the vicinity of railway lines from the operation of diesel traction vehicles.

The advantage of built-in diagnostics [8] is the interconnection of a large number of components, which provides the basis for a solid overview of the technical condition of most components as well as their functionality. A certain disadvantage of electronic diagnostics is the rather large number of error codes and the subsequent hierarchy of faults at several levels, which in part complicates the accurate identification of a specific problem. Diagnostics applied in the locomotive also facilitates the work of workers in repair/maintenance, in finding and identifying the specific cause of the failure. Another concrete application of diagnostic system used on diesel locomotives can be found in [1], which is used for checking the technical condition of some systems on the diesel Diesel locomotive, namely the electronic system for measuring, controlling and monitoring the speed and consumption of fuel as well as for control and signalling system.

As can be seen from the literature research, various researches and scholars use a variety of approaches to design an appropriate maintenance methodology. Some approaches are more focused on pure theoretical solutions to the maintenance problem, other are more practical oriented. However, each industry is specific and uses its methods. Different specifics are in industrial production and others has the transport sector. However, the suitability of the method used also affects the age, resp. date of manufacture of the technical equipment. In case of means of transport, e.g. in the automotive industry, where the requirements for operation efficiency and ecology change significantly every 5 years and the average age of cars in the EU is about 11 years, the development of maintenance methodologies is also more intense than, for example, railway vehicles, where the lifetime counts for decades. This, of course, corresponds to equipment of maintenance facilities with appropriate maintenance technology qualification of personnel. Due to the high investment in the purchase of new rolling stock, another specific feature of transport companies is that after the end of life of rolling stock they try to modernize vehicles, which leads to the creation of „hybrid“ designs, where a large part of the original, technically obsolete design is combined with a modern and economical propulsion unit, which is equipped with automatic control unit and fault evaluation. In such a case, it is necessary to choose an individual approach for the proposal of the maintenance methodology of the vehicle, taking into account all the factors mentioned. In our article we are dealing with such a “hybrid” case.

3. Subject of the study

The subject of the study is the locomotive series 757 (Fig. 1), which represents the latest project of the locomotive manufacturer for the modernization of diesel locomotives used for expressed trains haulage. The modernization was carried out from the original locomotive series 750 (T 478.0) or 754 (T 478.4), which were manufactured from the late sixties to the end of the seventies of the 20th century. The design change brought better operational and economic parameters as well as lower service costs [54].

The locomotive series 757 is a four-axle diesel-electric cabinet locomotive with alternate-direct current power transmission, total mass of 75.4 t and maximum operating speed 100 km/h. Its main utilisation is for medium heavy-duty rail track service on regional and state railway tracks with 1 435 mm gauge, in particular for passenger transport on non-electrified track of ŽSR (Slovak Railways). On the locomotive, an old diesel-electric generator unit was replaced by a new unit, composed of Caterpillar diesel engine, model 3512CHD with installed power of 1550 kW at 1800 rpm (188.5 rad/sec), traction alternator Siemens 1FW2 631-6 and auxiliary alternator Siemens 1FW4 630-10.

Fig. 1 Locomotive series 757[54]

The electric equipment includes an electronic control system MORIS RV07 [32]. The function of the modular control system MORIS RV07 is to control and monitor the parameters of components of diesel-electric locomotive with the purpose of simplifying the driver’s control and reliability of operation. It controls the diesel engine Caterpillar as well as the alternators Siemens. The communication is executed with regulator through electric controllers and display unit of the control system PIXY with diagonal 10´´ on both control posts. The electronic system enables also the diagnosis of electronics, which creates a new information database on technical condition of the vehicle and new information links for assessment of scope, extent and duration of corresponding maintenance task for a particular vehicle.

The modernisation of the locomotive brought improvements in environmental parameters of the locomotive (lower fuel consumption and emissions, lower noise emissions, higher power). However, more frequent failures of the sophisticated control system consisting of a larger number of control and management elements appeared.

The output data system is complex and difficult to use for a locomotive driver as well as maintenance workers. For this reason, a simplification (user friendliness) of the output data system has been developed within our work to make it easier to identify and understand the data. By this, faster and clearer fault identification is achieved, which shortens maintenance time and increases the availability of locomotive utilisation in operation. This brings a direct economic effect in reduced maintenance costs as well as higher dependability of rail transport. Data from diesel engine control system can be used also for statistical processing after longer time of diesel operation and reveal the faultiest parts of the diesel engine, thus contribute to reliability improvement.

3. Data records processing and analysis

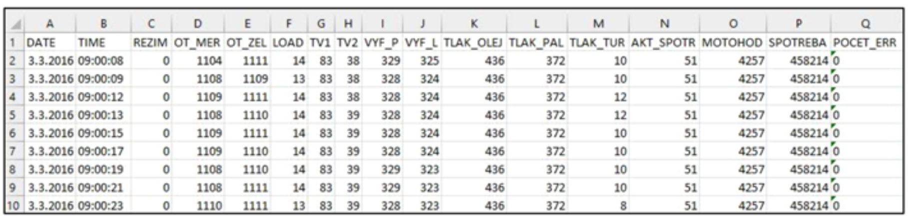
The technical condition of a vehicle is characterized by a relatively large set of parameters. In general, a parameter is a measurable quantity that describes the technical, economic or operational properties of an object. The limit values of the parameters in the vehicle are usually a criterion for the satisfactory function of the object and exceeding them is a criterion for failure. Each object is characterized by parameters that determine its qualitative indicators, either in terms of ensuring its basic characteristics and functional accuracy, or in terms of the effectiveness of its work, impact on the environment, etc. e.g. in the case of vehicles these can be speed, power, energy consumption, loading capacity, safety or mechanical and strength characteristics, kinematic and dynamic parameters of the vehicle or its components [5].

For determining the limit states and calculating the indicators of the so-called parametric reliability, it is important to thoroughly classify failures and determine for which failures it makes sense and whether limit states can be determined. To evaluate parametric reliability, the failures are divided according to the nature of the origin and course of processes leading to the fault.

Fig. 2. Control system MORIS RV07 [32]

The diagnostic system installed in the locomotive series 757 creates a large number of files in which it records operating parameters (physical and numerical). It creates in total 15 types of files. The created files are stored in the internal memory in the MORIS RV07 control system (Fig. 2), in which it creates a loop of data files for 2 weeks period. After this time, the oldest files are automatically deleted and replaced with the newly created files. The memory capacity is 5 GB and the stored files for the mentioned 2 weeks have a size of approximately 2.5GB. Files are saved in .dbf and .log formats.

Within the work, a CAT file was selected from all 15 types of files, which contains the physical and operational quantities of the locomotive‘s internal combustion engine and stores them in 17 subsystems. An example of a „CAT“ file generated by the diagnostics is shown in Fig. 3.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	DATE	TIME	REZIM	OT_MER	OT_ZEL	LOAD	TV1	TV2	VYF_P	VYF_L	TLAK_OLEJ	TLAK_PAL	TLAK_TUR	AKT_SPOTR	MOTOHOD	SPOTREBA	POCET_ERR
2	3.3.2016	09:00:08	0	1104	1111	14	83	38	329	325	436	372	10	51	4257	458214	0
3	3.3.2016	09:00:09	0	1108	1109	13	83	38	328	324	436	372	10	51	4257	458214	0
4	3.3.2016	09:00:12	0	1109	1111	14	83	38	328	324	436	372	12	51	4257	458214	0
5	3.3.2016	09:00:13	0	1108	1110	14	83	39	328	324	436	372	12	51	4257	458214	0
6	3.3.2016	09:00:15	0	1109	1111	14	83	39	328	324	436	372	10	51	4257	458214	0
7	3.3.2016	09:00:17	0	1109	1110	14	83	39	328	324	436	372	10	51	4257	458214	0
8	3.3.2016	09:00:19	0	1108	1110	14	83	39	329	323	436	372	10	51	4257	458214	0
9	3.3.2016	09:00:21	0	1108	1111	14	83	39	329	323	436	372	10	51	4257	458214	0
10	3.3.2016	09:00:23	0	1110	1111	13	83	39	328	323	436	372	8	51	4257	458214	0

Fig. 3. An example of a „CAT“ file generated by the diagnostics

The „CAT“ file currently contains several quantities being recorded by the system. Specifically, these are the quantities that are summarized in the Tab. 1. However, some of these values do not have sufficient explanatory value for use in mathematical modelling or in real use. For this reason, we have made several changes in the „CAT“ file. In the new “CAT” file, fields have been deleted that have no or only insignificant value for assessing the condition of the diesel engine and some important were added.

The first change in the “CAT” file was the recalculation of diesel engine rotations (rpm), measured (OT-MER) and required (OT-ZEL), to their difference. The difference between these two values has better informative value for the correctness of the diesel engine operation.

The second change was the addition of the value “VYF_ROZ”, which records the difference in exhaust gas temperatures on the left and right side of the diesel engine, as it is a ‘V’ type engine (the cylinders in the form ‘V’ shape). This change will bring better condition monitoring of the group of cylinders on both sides of the diesel engine (temperature difference can signalize the variations in Air-fuel ratio, failure on injector, failure of valve, etc).

Table 1. Quantities recorded by the diesel engine diagnostics in the “CAT” file

Used abbreviations	Explanations
DATE	Date of values recording
TIME	Time of values recording
REŽIM	Mode selected by the locomotive operator
OT_MER	rpm measured
OT_ZEL	rpm required
LOAD	Instantaneous relative thrust
TV1	Coolant temperature 1st circuit
TV2	Coolant temperature 2nd circuit
VYF_P	Exhaust gas temperature on the left
VYF_L	Exhaust gas temperature on the right
TLAK_OLEJ	Oil pressure
TLAK_PAL	Fuel pressure
TLAK-TUR	Turbocharger pressure
AKT-SPOTR	Instantaneous consumption
MOTOHOD	Hours
SPOTREBA	Instantaneous fuel volume in the tank
POCET_ERR	Number of error messages

Another change concerned the recording of the lubricating oil pressure. The pressure is currently sensed before and after the filter, but only one of the values is recorded. For this reason, it is not possible to objectively evaluate the instantaneous lubricating oil pressure in the lubrication system. By sensing the pressure before and after the filter and comparing them, we have full control over this system and we can evaluate its condition in a short time. Based on this, we added a recalculation of the oil pressure difference before and after the filter. This fact will give us the opportunity to monitor the correct operation of the oil pump, the condition of which will be evaluated by the pressure sensor before the filter and at the same time the condition of the lubricating oil filter, the condition of which is monitored by the pressure difference before and after the filter. The situation is similar with fuel pressure. The fuel pressure is monitored before and after the filter, but only one of these values is recorded in the „CAT“ file. By adding of the second value and at the same time their difference in to the new “CAT” file, we get complete control over the operation of the fuel pump and the condition of the fuel filter.

The changes were implemented in the form of adding new recorded parameters and modifying the already existing values.

Table 2. Explanation of creation of limits (intervals)

<AA, BB, CC, DD, EE>	AA, EE - parameters indicating fault limit values
	BB, DD - parameters indicating changes in the system leading to a fault
	CC - parameters indicating that the monitored system is OK

Table 3 Parameter intervals and differences in the new „CAT" file

Parameter	Interval / Difference
OT_ROZ	Difference max 50 rpm
TV1	<70 - 83 - 95 - 100 - 105>
TV2	<30 - 40 - 50>
VYF_P	<100 - 400 - 550 - 650 - 702>
VYF_L	<100 - 400 - 550 - 650 - 702>
VYF_ROZ	Difference between P and L max 30 ° C
TLAK_OLEJ_ROZ	Difference max 150 kPa
TLAK_PAL_ROZ	Difference max 150 kPa
TLAK_TUR	<150 - 210 - 250>

To evaluate the state (condition) of the diesel engine, it was necessary to define the limits (intervals) of the values of the selected parameters. In Table 2 the principle of creation of limits are explained.

Some parameters contained five values in the interval, for some it was sufficient to express three values. All parameters from the new „CAT" table and their intervals or differences between the two values were processed into Table 3.

Appropriate selection of intervals and values of differences from the real operation of locomotive series 757 were specially consulted with experts from the operation and maintenance departments of locomotive depots.

The next step was to create the „CAT" file itself in the „xlsx" format, in which all the changes mentioned above are incorporated. The new „CAT" file contains 10 000 data for each recorded quantity, which in total is approximately 90,000 values. The fault conditions were artificially changed beyond the intervals of Table 3. It is also important to mention that the fault-free values of the individual locomotive systems were selected from the locomotive diagnostics in a state where the locomotive had the driving mode selected, which is the most frequently used and most important in operation. Thus, the locomotive was in motion under load and the engine rotations were higher than 1450 rpm (151.8 rad/sec). For other modes (e.g. idling and transient modes) it is necessary to specify other intervals of parameter values (e.g. turbocharger pressure is lower at idling and run-out mode than in driving mode and rotations above 1450 rpm (151.8 rad/sec).

In Fig. 4, a part of the new „CAT" file is shown. There are measured and recalculated values of the engine parameters, which are compared with the defined intervals and values of the limit states of the parameters characterizing the failure.

The next step in preparing the data for evaluating the state of the diesel engine was to clearly define the faults using zeros and ones. If the parameter value fell outside the predefined interval, the parameter was assigned the number 0 (fault). If the parameter fell within the interval, it was assigned the number 1 (operation without failure). The overall condition of the locomotive was evaluated based on the condition of the individual locomotive systems (the column marked "LOKO" in the Fig. 5). If only one locomotive system acquires the value 0, then also in the column for the total locomotive state will be 0. The value 1 for the total locomotive state will be only if all the locomotive systems acquire a value of 1 and thus only then the locomotive is operational (up-state).

The original recording of the data did not provide the graphical output. A suitable tool for closer identification of the condition is a graphical representation of the course of the monitored values. The graphic visualisation simplifies the identification of incorrect values. As an example, the course of the engine rotations (rpm) is given, where the desired values are shown in red and the actually measured in green (Fig. 6). In the figure, an example of rotation stabilisation after their change is presented.

	A	B	C	D	E	F	G	H	I
1	OT_ROZ (ot/min)	TV1 (°C)	TV2 (°C)	VYF_P (°C)	VYF_L (°C)	VYF_ROZ (°C)	TLAK_OLEJ_ROZ (kPa)	TLAK_PAL_ROZ (kPa)	TLAK_TUR (kPa)
2	100	133	27	568	217	351	145	174	172
3	48	46	31	535	152	383	73	42	97
4	1	84	19	410	373	37	219	107	60
5	37	104	23	220	550	330	204	48	318
6	108	50	13	461	447	14	168	62	215
7	15	83	27	322	586	264	196	244	234
8	59	47	11	614	348	266	36	179	294
9	15	58	17	530	448	82	30	25	129
10	71	43	63	666	153	513	63	201	119
11	49	124	34	194	426	232	30	79	271
12	137	97	15	467	521	54	130	157	286

Fig. 4. Example of a modified set of measured data „CAT"

K	L	M	N	O	P	Q	R	S	T	U
LOKO		OT_ROZ	TV1	TV2	VYF_P	VYF_L	VYF_ROZ	TLAK_OLEJ_ROZ	TLAK_PAL_ROZ	TLAK_TUR
0		0	0	0	1	0	0	1	0	1
0		1	0	1	1	0	0	1	1	0
0		1	1	0	1	0	0	0	1	0
0		1	0	0	0	1	0	0	1	0
0		0	0	0	1	1	1	0	1	1
0		1	1	0	0	1	0	0	0	1
0		0	0	0	1	0	0	1	0	0
0		1	0	0	1	1	0	1	1	0
0		0	0	0	0	0	0	1	0	0
0		1	0	1	0	1	0	1	1	0
1		1	1	1	1	1	1	1	1	1
1		1	1	1	1	1	1	1	1	1
1		1	1	1	1	1	1	1	1	1
1		1	1	1	1	1	1	1	1	1
1		1	1	1	1	1	1	1	1	1

Fig. 5. Evaluation of the overall condition of the locomotive based on the individual systems condition

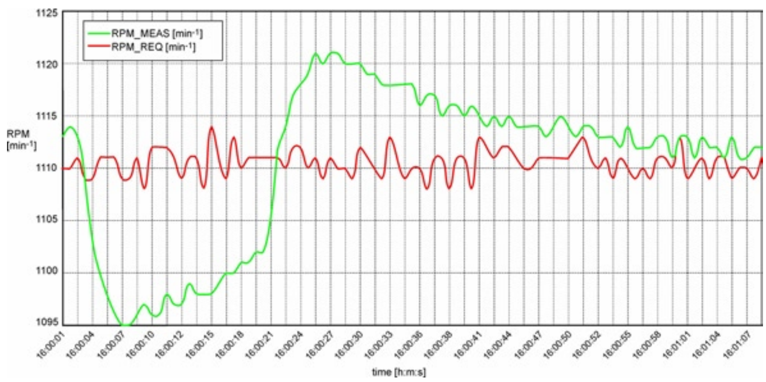


Fig. 6. Graphical representation of required and measured engine rotations

4. Improvement of the maintenance by new processing of data files – case example

Locomotive maintenance is often performed only on the basis of experience with its several years of operation. However, maintaining and diagnosing a locomotive in this way is very time-consuming and costly. It often happens that the locomotive returns to the depot after the maintenance, because the same failure reappeared despite the deployment of new components. Upon further inspection of the locomotive, it is determined that the failure might be caused by another component, which will then be replaced/repaired. Maintenance carried-out in this way is very inefficient in terms of time and finances.

Within the cooperation with the locomotive depot, which operates five locomotives series 757, an access to records of measurements of the operation of locomotives operated by the depot was provided. For the purposes of the work, the records on unplanned locomotive outages were separated from the records on all maintenance.

Records on unplanned outages of a particular locomotive 757. 016-1 (one of five in the depot) for the first four months of the year 2020 were processed (Table 4). On average, three to five unplanned outages per month occurred on this locomotive. The downtime ranged from one hour to repairs lasting several days. Interestingly, in March, faults occurred for three consecutive days, with one fault occurring repeatedly (heating failure) and the repair of the other (low insulation state of the excitation circuit) taking three days. This represents a very long downtime of the vehicle.

Every hour of an unplanned outage of the locomotive brings a loss to ZSSK – Slovak raiways, as the locomotive does not fulfil the tasks for which it was purchased. The average time of an unplanned locomotive outage is 4 days per month which is 48 days per year. The cost of unplanned outages of the locomotive must also include the cost of the work of the people performing the repair and diagnostics of the locomotive. The hourly work costs ranges from 20 to 28 Euros.

The vehicle maintenance time is divided into several parts. Some of them can be influenced and shortened (analysis of diagnostic files), some cannot be influenced directly (delivery of spare parts, repair by an external company). The proposed methodology reduces the time required for analyses of the files and work with them. Until now, the analysis of diagnostic files has been performed using a large number of files that contain a considerable amount of data and are often confusing. This fact affects and significantly extends the time needed to analyse the problem.

In the new method, after downloading the files, they are analysed and in this step the methodology can significantly reduce time. Only one ".log" file is analysed, which contains data for only one, specifically determined hour, using a record of the time of failure. The data is clearly arranged, it is possible to quickly and easily create a graph of parameters. The main advantage is the immediate display of data indicating the error and the display of the generated and signalised fault. This results in a faster return of the locomotive to operation, thus eliminating losses caused by the locomotive's downtime in maintenance. From experience in practical operation, the diagnostic process, which includes downloading files and analysing them, can currently take approximately 3 hours. Using the new method, this time can be reduced to an hour and a half, of which the analysis itself takes only half an hour.

5. Possibilities of further procedure in data analysis of large files in vehicle maintenance

When analysing and classifying data, e.g. from various electronic systems for monitoring the technical condition of vehicles to the planning and performance of maintenance from a statistical point of view, fuzzy files and logic become a valuable tool for modelling and processing inaccurate data, or for creating flexible techniques for handling accurate data. The so-called linguistic variables appear to be one of the promising ways of expressing values, described by quantitative or qualitative quantities. Qualitative quantities in many cases appear to be the result of the formalization of expert estimates. Each object or process is described by a group of indicators.

The use of the fuzzy method is applied in various fields, for example in the prediction of the reliability of structures, as mentioned in [13]. Prediction of structural performance is a complex problem because of the existence of randomness and fuzziness in engineering practice. In this area, reliability analyses have been performed using probabilistic methods. This work investigates reliability analysis of structure involving fuzziness and randomness. In particular, the safety state of the structure is defined by a fuzzy state variable, fuzzy random allowable interval, or fuzzy random generalized strength.

There are a number of methods for constructing a fuzzy set membership function based on expert estimates. Two groups of methods can be distinguished: direct and indirect. Direct methods assume that the expert immediately formulates rules according to which the value of the membership function characterizing the element is determined.

Table 4. An overview of faults occurred on the locomotive 757.016-1

Locomotive	Start of maintenance (date – time)	Finish of maintenance (date – time)	Fault description	Duration (hour:min)
757.016-1	16.01.2020 - 10:00	16.01.2020 - 12:00	Low insulation state of traction motor (TM)	2:00
757.016-1	03.02.2020 - 12:11	07.02.2020 - 17:00	4th TM faulty	100:49
757.016-1	09.02.2020 - 11:11	09.02.2020 - 15:00	Combustion engine in performance signals high crankcase pressure	3:49
757.016-1	25.02.2020 - 15:00	27.02.2020 - 17:00	Low insulation state of TM	50:00
757.016-1	10.03.2020 - 09:00	10.03.2020 - 18:00	Low insulation state of 3th TM	9:00
757.016-1	15.03.2020 - 07:00	15.03.2020 - 11:00	Non-functional train heating	4:00
757.016-1	16.03.2020 - 13:00	16.03.2020 - 14:00	Non-functional train heating	1:00
757.016-1	17.03.2020 - 11:11	20.03.2020 - 12:00	Low isolation state of the TM excitation circuit. Critically low oil pressure at start.	72:49
757.016-1	26.03.2020 - 04:48	26.03.2020 - 09:35	The locomotive without power	4:47
757.016-1	26.03.2020 - 17:28	27.03.2020 - 08:20	Defective primary circuit cooling inverter	14:52
757.016-1	07.04.2020 - 16:45	08.04.2020 - 17:00	Insufficient power of train heating	24:15
757.016-1	11.04.2020 - 04:00	12.04.2020 - 12:00	Fault 88.04 - power supply for NOV sensors, source of traction current sensor. The brake rod lock is missing on the 4th axis on the left.	32:00
757.016-1	23.04.2020 - 12:00	23.04.2020 - 17:00	Charging circuit	5:00

Indirect methods for calculating the values of the membership function are used when there are no elementary measurable properties.

The decision-making process is the most important moment in the management of various objects or processes, to which can be assigned the process of planning and implementation of vehicle maintenance based on the collection of large amounts of data from electronic systems monitoring their actual technical condition during operation. An essential component of this process is the selection of a decision from a set of acceptable alternatives. In many cases, the analysis of input situations as well as the selection of the best decision is carried out by comparison with decisions that have been made in the past, e.g. established maintenance system of the relevant vehicle. At the same time, it is necessary to minimize the costs of analysing input situations by determining the sequence of the most important indicators. The solution of the problem of recognizing the situation in decision-making is expressed in the form of analytical expressions or in the form of so-called Decision Tree.

The decision tree is created on the basis of a decision table describing N input situations (data and data on the technical condition of the vehicle, measuring and other samples). Each example is made up of the values of the input and output attributes, which for the maintenance of the vehicle means preparation, and the process of managing and performing the maintenance itself.

Fig. 7 shows the sequence of steps and operations required to make a decision tree.

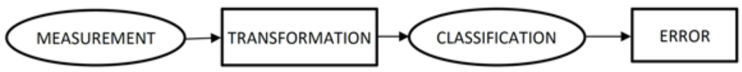


Fig. 7. Decision tree creation sequence scheme

The fuzzy logic method is suitable for analysing data from the diagnostics of complex systems [38]. It can be used also for diagnostics of locomotive series 757 due to the ability to process large amounts of data generated by the vehicle control system. The compilation of a decision tree for a diesel-electric locomotive series 757 in order to identify data from the electronics of the locomotive control systems focused on the maintenance of this locomotive will be the aim of another solution.

6. Conclusions

Safety, reliability, maintainability and operability are nowadays highly monitored parameters of locomotives performing line service on ŽSR lines. Quick maintenance is one of the most important indicators of the efficiency of locomotive operation. Therefore, any reduction in maintenance time is beneficial, as presented in the case of the locomotive series 757. Suggestions for improving the evaluation of the locomotive state based on diagnostics are beneficial for their practical use.

The specific changes are summarized in the following points:

1) creation of intervals (limits) for selected parameters of the internal combustion engine of the locomotive series 757, on the basis of which the algorithmic calculation evaluates the occurrence of the ICE failure,

2) the developed methodology (method) can display the parameters of the locomotive series 757 faster, easier and clearer and is able to immediately recognize the locomotive fault or faults based on the diagnostically created „.log" file,

3) the methodology enables the sorting of the monitored locomotive parameters and the display of selected parameters in a graph, which has an important benefit in practice in terms of the possibility of comparing two interdependent parameters of the locomotive,

4) creating a diagnostic report has benefits and advantages in terms of maintenance, namely in the area of better registration of interventions on the locomotive, control and registration of faults and the actual maintenance performances, maintenance rationalization and assessment of the results of the diagnostics itself,

5) based on long-term monitoring, the data can be more precisely statistically evaluated with the purpose of identification of individual failures and to define critical components of the propulsion unit.

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