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APPROACH MODELLING OF CONSTANT INTERFAILURE PROCESS OF RENEWAL MULTI-UNIT FLEET

PODEJŚCIE DO MODELOWANIA STAŁEGO PROCESU MIĘDZYAWARYJNEGO ODNOWY WIELOELEMENTOWEJ FLOTY PASAŻERSKIEJ

While railway companies operate rolling-stock, a substantial part of its expenses goes to maintenance and repair. However, the amount of repair works is directly proportional to the average age of a rolling-stock fleet or its reliability. When renewal an existing fleet of a few dozen rolling-stocks, the installation of the new vehicles reduces the overall failure amount of the fleet proportionally to the number of acquired vehicles. This article provides a concept for creating the model of a passenger rolling-stock's failure intensity according to the mileage. According to this model, a vehicle fleet renewal algorithm can be created and used in order to limit the fluctuation of the fleet's average failure intensity as much as possible and to achieve the most accurate correlation between the number of failures and the fleet's average mileage. Thus a railway company has an opportunity to avoid the unplanned expenses for repairing the vehicles during the unforeseen failure peaks. The SPLINE method is proposed in order to indicate the vehicle failure flow's dependency on the vehicle mileage. After using this method to indicate the variation of the fleet's constant interfailure according to the mileage, the fleet's failure intensity can be modelled according to the algorithm of installing the acquired vehicles for operation.

***Keywords**: rolling-stock maintenance, rolling-stock reliability, rolling-stock interfailure process, failure intensity, SPLINE method.*

Znaczna część wydatków ponoszonych przez przedsiębiorstwo kolejowe z tytułu eksploatacji taboru kolejowego, to wydatki na konserwację i naprawy. Jednakże, należy pamiętać, że liczba prac remontowych jest wprost proporcjonalna do średniego wieku floty taboru lub jej niezawodności. Przy odnawianiu istniejącej floty kilkudziesięciu pojazdów kolejowych, wprowadzenie nowych pojazdów zmniejsza ogólną ilość awarii floty proporcjonalnie do liczby nowo nabytych pojazdów. W artykule przedstawiono koncepcję stworzenia modelu intensywności uszkodzeń taboru pasażerskiego w funkcji przebiegu kilometrowego. Zgodnie z tym modelem, można stworzyć algorytm odnowy floty pojazdów, z wykorzystaniem którego można maksymalnie ograniczyć wahania średniej intensywności uszkodzeń floty oraz osiągnąć najbardziej dokładną korelację między liczbą uszkodzeń a średnim przebiegiem pojazdów floty. W ten sposób przedsiębiorstwo kolejowe ma szansę uniknąć nieplanowanych wydatków na naprawy pojazdów podczas nieprzewidzianych okresów wzmożonej awaryjności. Zaproponowano metodę SPLINE, za pomocą której można określić zależność awaryjności pojazdu od jego przebiegu kilometrowego. Zastosowanie tej metody pozwala ustalić zmiany w stałym procesie międzyawaryjnym zależne od przebiegu, co z kolei pozwala na modelowanie intensywności uszkodzeń floty według algorytmu wprowadzania nowo nabytych pojazdów do eksploatacji.

***Słowa kluczowe**: konserwacja taboru kolejowego, niezawodność taboru, proces międzyawaryjny w taborze, intensywność uszkodzeń, metoda funkcji sklejanej SPLINE.*

Introduction

Railways are made up of huge complex of mechanical and electrical systems, which consist of thousands moving parts. If a railway service is to be reliable, the equipment must be kept in good working order and regular maintenance (repair) is the essential ingredient to achieve this. Rolling-stocks are the most intensive exploited segment of the railway system and they are the most vulnerable if maintenance is neglected. A stalled train will block a railway line immediately and will reduce a timetable on an intensively used system to an uncontrollable shambles for the remainder of the day. Reliability is the key to successful railway operation and maintenance should be the number one priority to ensure reliability is on-going. Lithuanian and many scientists worldwide carry out comprehensive research works to ensure the both technically and economical effective maintenance system of rolling-stock in railway companies [3, 4, 7, 9, 10, 17]. Om the other hand, Swedish scientists assessed the most popular maintenance approaches, i. e. strategies, policies, or philosophies, using a fuzzy multiple criteria decision making (MCDM) evaluation methodology [1]. The fuzzy AHP method proposed is a simple and effective tool for tackling the uncertainty and imprecision associated with MCDM problems, which might prove beneficial for plant maintenance managers to define the optimum maintenance strategy for each piece of equipment [14, 18].

Rolling-stock maintenance can be programmed in one of three ways: by mileage, by time or by conditioning monitoring [5, 11]. Of these three methods, condition monitoring is the most recent [6]. Many railway undertaking administrations adopted a mileage based maintenance system, although this is more difficult to operate as one has to keep records of all rail vehicle mileages and this is time consuming unless they have a modern train control and data gathering system [19]. The maintenance of rail vehicle can be characterized into two types: corrective maintenance and preventive maintenance. The time intervals at which preventive maintenance is scheduled are dependent on both the life distribution of the components and the total cost involved in the maintenance activity, but corrective maintenance cannot be avoided when component failure component occurs. The total cost of rolling-stock maintenance depends on the percentages in performing preventive maintenance and corrective maintenance. In general, more frequent preventative maintenance drives up the total maintenance costs for rolling-stock. On the other hand, proper preventative maintenance can potentially reduce the risks associated with rolling-stock mechanical failure. Thus, railway operators are constantly left weighing the safety risks against the maintenance costs. The railway safety is defined as the most crucial factor for the selection of a rolling-stock maintenance strategy [4].

Researchers Wang and Chen principally for equipment evaluated four maintenance strategies (such as corrective maintenance, time-based preventive maintenance, condition-based maintenance, and predictive maintenance) for different equipment [18]. In order to avoid the fuzzy priority calculation and fuzzy ranking procedures in the traditional fuzzy AHP methods, a new fuzzy prioritization method was proposed. This fuzzy prioritization method can derive crisp priorities from a consistent or inconsistent fuzzy judgment matrix by solving an optimization problem with non-linear constraints. Iranian scientists examined a new approach for selecting optimum maintenance strategy using qualitative and quantitative data through interaction with the maintenance experts [2]. This approach has been based on linear assignment method (LAM) with some modifications to develop interactive fuzzy linear assignment method (IFLAM). The proposed approach is an interactive method which uses qualitative and quantitative data to rank the maintenance strategies.

In contrast to maintenance strategy selection in the manufacturing industry, the maintenance of rolling-stock impacts also both traffic safety and passenger comfort [4, 16]. Because preventative maintenance and corrective maintenance affect these three factors (safety, comfort, and cost), railway system operators must establish a maintenance strategy that strives for an optimum balance. Given this, a method that defines a proper rolling-stock maintenance strategy is invaluable to system operators (railway companies), system safety supervisors (governments), and system customers (passengers). Iranian researchers proposed to apply the fuzzy Delphi method in Simple Additive Weighting (SAW) for solving the maintenance strategy selection problem [8].

Rolling-stock performance in respect of failures can be measured by MTBF (Mean Time Between Failures) or MDBF (Mean Distance Between Failures). It is sometimes measured by numbers of failures per year, month or week, but this may not represent an accurate rate consistent with mileage [18, 19]. On the other hand, rolling-stock does deteriorate rapidly in storage and this, in itself, produces failures, although these may not be the same failures seen under normal service conditions. Scientist Falco described the three case studies for existing rolling-stock, mid-life overhaul and new build rolling-stock [6].

Chinese researchers proposed to permit an approach for selecting a maintenance strategy for rolling-stock and obtaining possible spare parts' quantities and replacement intervals for the components of rolling-stock [4]. The methodology adopts an analytic network process (ANP) technique for the strategy evaluation, because ANP considers the important interactions among evaluation factors. Two Greek researchers introduced a reliability modelling and analysis framework based upon the distinct class of non-stationary Functional Series (FS) models [15]. The FS framework was applied for the modelling and analysis of two rail vehicle reliability series named as Times Between Failures (TBFs). Two models, one based on fuzzy logic (FL) and the other on artificial neural networks (ANN), were developed by Wang to predict the vehicle breakdown duration [19].

In order to improve the rolling-stock's maintenance system, it is favourable when the number of failures is proportional to the vehicle mileage or moto-hours. Then the number of failures can be predicted according to the mileage prognosis. The future needs of works and spare parts can be foreseen according to the prognosis for the number of failures. As seen from experience, the number of rolling-stock's failures is not always proportional to the mileage. Due to the rolling-stock's maintenance, the number of its failures pulsates. Since each rail vehicle is a unique product, the repair of each vehicle is somewhat distinctive, it is impossible to foresee every potential work or complication. Therefore, after the repair, the amount of failures increases for some time. This is the main reason for the pulsation of the number of failures. Each newly-installed vehicle has its own influence on the overall pulsation of the number (as well as the intensity) of the fleet's failures. This means that the pulsation of the overall number and intensity of the rolling-stock's failures depends on the fleet renewal algorithm. If renewing an existing fleet with a few dozen vehicles, the acquisition of the new vehicles reduces the overall failure amount of the fleet proportionally to the number of acquired vehicles. However, for a newly formed fleet, a different consistent pattern applies which is necessary to be studied. When researching the consistent pattern of a renewal vehicle fleet, a model concept for the change of passenger rolling-stock's interfailure according to the mileage has been formed. In accordance with this model, a fleet renewal algorithm is planned to be created in the future in order to limit the fluctuation of the fleet's average failure intensity as much as possible (by limiting the sinusoid amplitudes) and to achieve the most accurate correlation between the failure intensity and the fleet's average mileage. In order to reach this goal, the Lithuanian rail vehicle reliability researches were performed according to the vehicle types: electric multi-unit reliability research and diesel multi-unit reliability research. According to the results of these researches, a mathematical model of the renewal rolling-stock fleet's failures was created. One of the peculiarities of this methodology is that the failure flow's dependency on the vehicle mileage is proposed to be indicated using the SPLINE method [12].

2. Technical background and methodology

2.1. Indicators of the rolling-stock interfailure and reliability

Usually the research focuses on the number of failures per multi-unit or per wagon during a year. If multi-units are operated and recorded without re-forming them, then it is advisable to study the number of failures per multi-unit a year. If the composition of the multi-units constantly changes and the rolling-stock's mileage is recorded for the wagons, then the number of failures per wagon a year is studied. One of the main indicators of the reliability theory is the failure intensity (in the reliability theory it is called an intensity density of a random event). This indicator is characterized by the number of failures (of a multi-unit or wagon) per mileage unit. The period between the repairs of some vehicles is characterized by kilometres (or thousands of kilometres), sometimes – by moto-hours (thousands of moto-hours). This depends on the recommendations from the rolling-stock's manufacturer: the manufacturer provides the recommended type of a maintenance system. The railway companies usually comply with the repair system type recommended by the manufacturer, in order to avoid troubles during the technical operation of a rolling-stock.

The following rolling stock operational parameters were used when modelling the failure intensity of a passenger rolling stock fleet: the number of failures per wagon (or per multi-unit) a year and the failure intensity, the number of failures per mileage unit (per 1000 kilometres) of a wagon (or multi-unit) or the duration of a rolling-stock's operation (per 1000 moto-hours).

2.2. Research on the electric multi-unit reliability

In 2011-2012 the authors conducted a passenger multi-unit fleet's reliability research at State Company „Lietuvos geležinkeliai" (*Engl.* "Lithuanian Railways" , hereinafter – LG). The fleet consisted of four RA-2 series diesel multi-units and fourteen electric multi-units. During the research it was assumed that the reliability of the vehicles continuously declines at an established intensity as they age. When the fleet is supplemented with new rolling-stock, the overall failure amount of the fleet declines proportionally to the number of the new rail vehicles. Consequently, the dependence of the number of failures per wagon on the average age of the electric multi-units was measured first. This dependence of the number of failures is shown in Fig. 1.

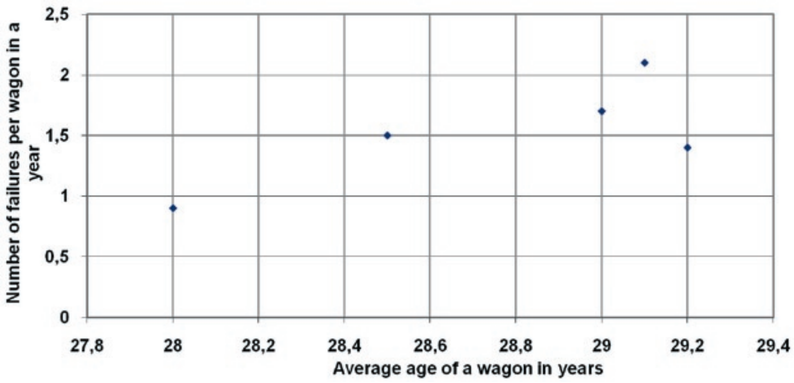

Fig. 1. Dependence of number of electric multi-unit one wagon failures on wagon's average age

The research results showed that, if the vehicles' age increases by one year, the number of their failures increases by (0.5 – 0.7) per electric multi-unit's wagon a year. During the research it was assumed that, after installing new rolling-stock to the electric multi-unit fleet, the average age of the fleet will decrease proportionally to the number of the installed multi-units' wagons. When the rolling-stock fleet's average age decreases, the failure intensity decreases proportionally. The decrease of the electric multi-units average age when their fleet is being renewed (by installing new rolling-stocks) is shown in Fig. 2.

The calculation results, presented in diagram form in Fig. 2, showed that, if the electric multi-unit fleet was renewed each year by adding three wagons (this constitutes one electric multi-unit), after five years the average age of the fleet would decrease by 10 years. The electric multi-unit's failure amount is expected to decrease proportionally to the reduction of the fleet's average age. The dependence of the failure amount's decrease on the number of newly-acquired electric multi-unit wagons is shown in Fig. 3.

The calculation results (the diagram in Fig. 3) show that, if 6 wagons were acquired, the fleet's failure amount would decrease by 0.109 failures per wagon a year, and if 3 wagons were acquired – by 0.044 failures per wagon a year. This means that, on average, each newly-acquired electric multi-unit's wagon reduces the overall electric multi-unit failure amount by (0.015 – 0.018) failures per wagon a year.

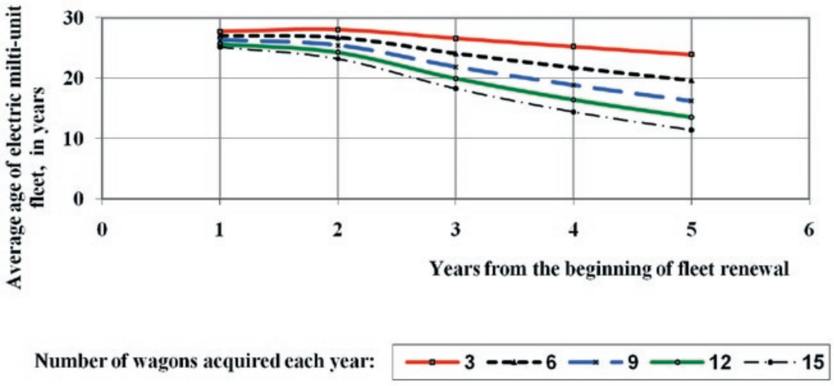

Fig. 2. Decrease of the electric multi-unit fleet average age during the fleet renewal process

To sum up the results, the following preliminary conclusions of the electric multi-unit reliability research are made. According to the results of the vehicle failure intensity research, a mathematical model was made that indicates a consistent pattern between regular renewal of the passenger vehicle fleet and the vehicle failure intensity. The mathematical model was implemented using the LG electric multi-unit fleet as an example. It was learned that, if the existent electric multi-unit fleet of 108 wagons was supplemented by one multi-unit (3 wagons), the fleet's average failure amount (0.6 failures a year) per wagon would decrease by 0.044 failures a year – in other words, if 3% of the vehicle fleet was renewed, its failure amount would decrease by 7.3%. This model can be used for predicting the change of failure amount when planning to acquire a small number of passenger vehicles (1-2 diesel or electric multi-units consisting of 3 wagons) for a period of several years (up to 5). In other words, the model is to be used for predicting the changes of electric multi-unit fleet's failure amount in the beginning of the fleet renewal (in the first decade of the new wagon mileage), when renewing the fleet by (10 – 20) %. This mathematical model should not be relied on when predicting the vehicle fleet's failure intensity for longer periods or bigger number of acquired vehicles. The model could be improved by evaluating more factors and their consistent patterns of influencing the vehicle failure amount. The essential weakness of this model is that it does not consider the aging process of the newly-acquired wagons and its influence on the whole fleet's failure amount.

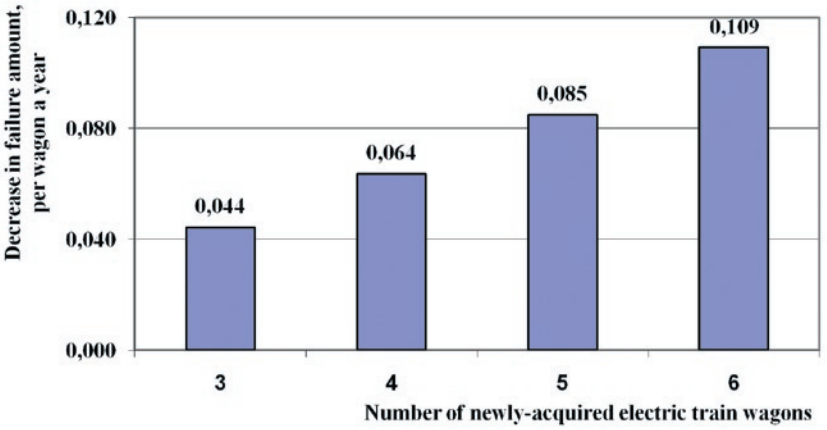

Fig. 3. Dependence of the decrease in electric multi-unit failures on the number of newly-acquired electric multi-unit wagons

Further LG passenger vehicle researches showed that the vehicles with an internal combustion engine, i. e. diesel multi-units, have the most complex aging process [7, 17].

2.3. Investigation of diesel multi-unit failure amount

When studying the failure intensity of the vehicles with internal combustion engines, it can be seen that the intensity is closely related to the vehicle maintenance system type. In the beginning of operation, the failure intensity increases due to the peculiarities of installing the vehicles for operation. The rolling-stock manufacturer is not always able to anticipate the real (factual) conditions of the produced vehicles' operation (e.g., load, usage intensity, climate conditions, maintenance work culture etc.). Consequently, in the beginning of the vehicle operation the failure intensity increases for some time (such failures are sometimes called "childhood diseases"). During the unscheduled maintenance, these failures are removed, the most appropriate operational materials are selected (depending on the load, climate), as well as more experience on how to properly operate such vehicles is gained. The failure intensity decreases (stabilizes) for the time being. However, after a while, a permanent repair needs to be done. The vehicle constructions and materials used for manufacturing are constantly improving; therefore each permanent repair of a vehicle is partly unique. After the repair, unforeseen consequences appear. Manufacturer's repair recommendations are not always explicit and specific. Various components and parts of a rolling-stock are often produced by different manufacturers who provide completely different recommendations for operating and repairing the vehicles. For instance, the recommended period for changing engine oil is provided by both a diesel engine manufacturer and an engine oil manufacturer. The recommended period sometimes differs by two or even three times. When planning the works of vehicle's permanent repair, the decision makers of railway companies are not always certain which recommendations to follow. In such cases, the decision makers improvise. Such decisions not always are the best, resulting in the increase in rolling-stock's failure amount when starting its operation after an ordinary permanent repair. When operating the rolling-stock, the mistakes and defects made during the repairs are removed, therefore the resulting vehicle failure intensity decreases (is "contained") for the time being. But due to an elementary deterioration of rolling-stock's parts, the failure intensity starts increasing again until the next permanent repair. Thus forms periodic failure intensity's dependence on rolling-stock's operation as the first permanent repairs are performed on a regular basis. The periodic failure intensity dependence of the LG diesel multi-units RA-2 on the diesel multi-unit mileage is presented in Fig. 4. The failure intensity values provided in the fig. 4 diagram are calculated as a ratio of the failure amount to multi-unit mileage.

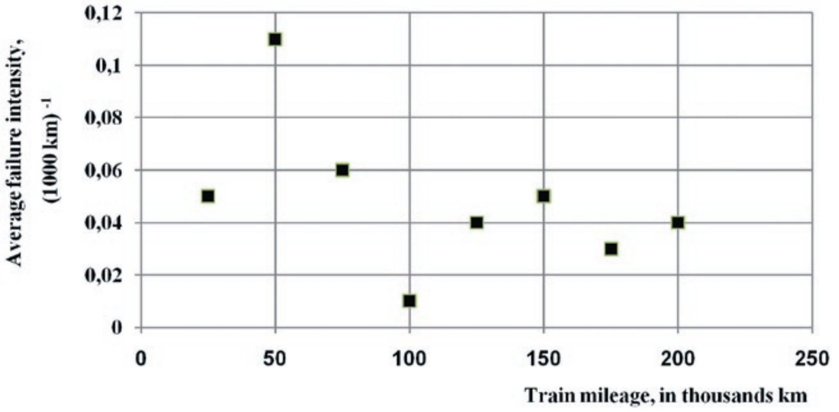

Fig. 4. Failure intensity dependence on diesel multi-unit mileage

The periodic failure intensity dependence on the diesel multi-unit mileage is characterized by the fact that, when the mileage is around 50 000 km, the failure intensity peaks to more than 0.1 failures per 1000 km mileage. When the mileage reaches 100 000 km, the failure intensity falls to 0.01 failures per 1000 km mileage, i. e. by ten times. Later, when the mileage is 150 000 km, the failure intensity rises again to (0.04 – 0.05) failures per 1000 km mileage. Such a variation is determined by the scheduled diesel multi-unit repair warning system used by LG [7]. Until the first permanent repair, the failure intensity stays around 0.5 failures per 1000 km mileage, after the repair it increases more than twofold, later decreases by around 10 times due to the unscheduled repairs. After this cycle has passed, at (100 – 125) thousands km mileage the second cycle starts: due to the repair peculiarities, the failure intensity this time increases not twofold, as in the first cycle, but only by a quarter (from 0.04 to 0.05 failures per 1000 km mileage).After 150 000 km mileage, the failure intensity decreases once more. When the mileage reaches around 200 000 km, the failure intensity steadies around 0.04 failures per 1000 km mileage. The variation consists of 25% – this is trivial compared to the variation during the first 100 000 km mileage. The amplitudes of this variation are likely to be reduced by improving the rolling-stock repair technologies. It should be noted that the failure intensity itself is regular and its periodicity of a sinusoid form cannot be removed. Acquiring diesel multi-units on a regular basis, it would very unacceptable, if the failure intensity maximums of several multi-units coincided – "added up" (e.g., when the mileage of one multi-unit was 50 000 km, the mileage of another multi-unit would be 150 000 km). Such a coincidence would substantially destabilize the fleet's overall failure intensity, i.e. greatly reduce the technical readiness level of a fleet. When modelling the failure intensity, it was learned that the it changes quite consistently, if diesel multi-units are acquired after every 50 000 km mileage under the formula "2+2+1". Such a change of the diesel multi-unit fleet failure intensity is shown in Fig. 5.

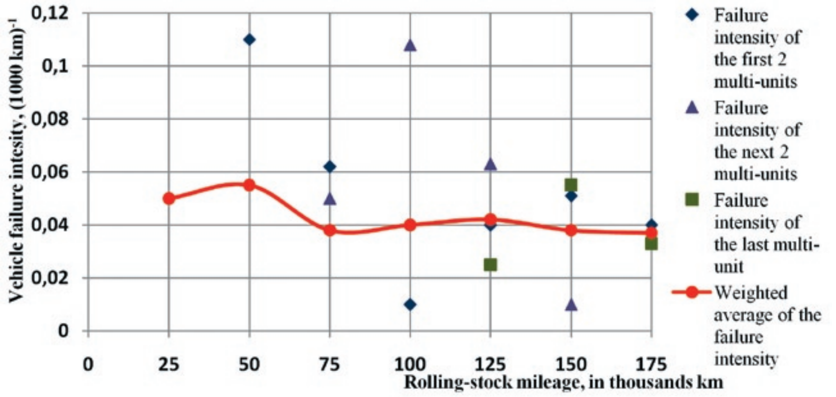

Fig. 5. Failure intensity of diesel multi-unit fleet when the fleet is renewed according to the formula „2+2+1"

When the diesel multi-unit fleet is formed under the formula "2+2+1" (after every 50 000 km mileage), two diesel multi-units are installed at first. In Fig. 5, this moment matches the 0 on the X axis. When the mileage of the first two multi-units reaches 50 000 km (reaches the maximum failure intensity), two more new diesel multi-units are installed. When the mileage of the first two multi-units reaches 100 000 km (the mileage of the other two multi-units then reaches 50 000 km), one more diesel multi-unit is installed. The result of following such a method for rolling-stock renewal (acquisition) can be seen in Fig. 5. When the mileage of the first two multi-units is 50 000 km, the curve in Fig. 5 shows the maximum failure intensity. When the mileage of these multi-units is 100 000 km, the curve in Fig. 5 shows the maximum failure intensity of the other multi-units. When the mileage of the first multi-units is 150 000 km, the curve shows the maximum failure intensity of the last multi-unit. The average failure intensity of a fleet is calculated as a weighted average, taking into account the number of diesel multi-units:

$$\lambda = \frac{\sum \lambda_i \cdot n_i}{\sum n_i}; \qquad (1)$$

where: λ_i – the failure intensity of a multi-unit group (instalment) No. i, (1000 km)$^{-1}$; n_i – the number of multi-units of a multi-unit group (instalment) No. i.

After implementing the Formula (1) on the 2+2+1 basis, it would look like this:

$$\lambda = \frac{\lambda_1 \cdot 2 + \lambda_2 \cdot 2 + \lambda_3 \cdot 1}{5}. \qquad (2)$$

It should be noted that, in the denominator of the Formula (2), "*5*" appears only if all five multi-units are installed, i.e. if all 3 summands are in the numerator. The multipliers "*2*" , "*2*" and "*1*" in the numerator are weighted coefficients that take into account the number of multi-units. The diagram of Fig. 5 shows the failure intensity after the weighted coefficients are taken into account. That is why the maximum at 150 000 km mileage is two times lower than the two first maximums. The line curving around 0.04 failures per 1000 km mileage is the average failure intensity. The more appropriate modelling approach is when the continuous functions are used. The examples of modelling that have been presented in this article so far are the cases of discrete modelling. The failure intensity's (or another parameter's) values are discretely attributed to the mileage intervals based on which the required actions with the sets are performed. For visualization, the diagram points that represent parameters are connected, thus making the imitation of a continuous function. Such modelling approach is simple, visual and is well-suited for modelling non-complex processes (when one or several extremes are present). However, if there are more extremes or the dependence function is more complex, then it is better to analyse the dependence by using the continuous function. Fig. 6 shows an example of diesel multi-unit failure intensity's approximation by the continuous function.

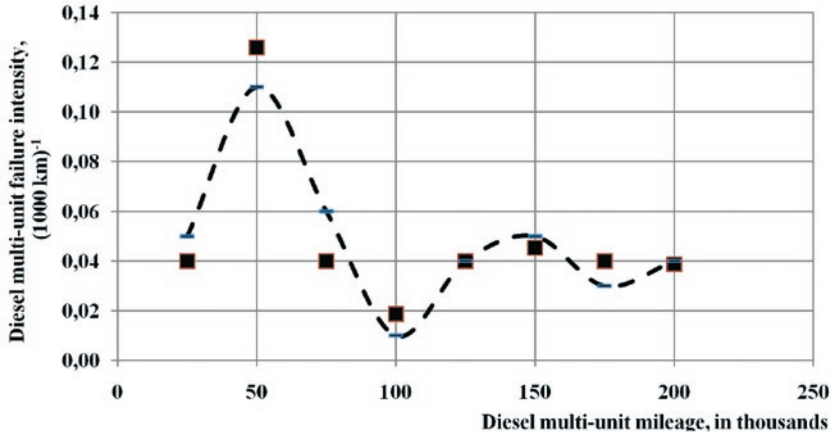

Fig. 6. Approximation of diesel multi-unit failure intensity by continuous function

In Fig. 6, the discrete approximation of points function is made on the basis of the exponentially diverging sine function:

$$\lambda = A \cdot e^n \cdot \sin(C \cdot x - B) + D; \qquad (3)$$

where: A – amplitude coefficient; B – phase coefficient; e^n – decrease pattern; C – wavelength ratio; D – average divergence. The measuring units of A and D coefficients matches the measuring unit values marked according to the Y axis.

The units of coefficients B and C are radians per 1000 km or per 1000 moto-hours. The dispersion of the diesel multi-unit failure intensity equals 0.00095. According to these values, a conclusion can be made that the approximation is fairly appropriate.

3. Applying of SPLINE method for multi-unit interfailure modelling

In mathematical science the SPLINE approximation is a known method of compromise [12]. Its basic principle is to divide the dependence function domain into segments where data is approximated by functions in such a way that they would form one consistent pattern. The points at which the diagram goes from one segment to the other are called spline knots. The most simple is the approximation by the splines of the second degree. Coefficients of quadratic equations are calculated from the condition that the derivatives of both functions at the spline knot must be equal. Thus at that point the tangent of both function graphs is the same straight line. If the splines are made from the curves of the third degree (the function coefficients of the third degree are calculated), an additional condition appears, and stating that at the knots the second derivatives of the functions must also be accordingly equal. This method was also applied when researching the LG diesel multi-unit failure amount. At first, the approximation by the linear splines was used, later – the one by the second degree splines. A conclusion was made that the lowest spline degree, when the approximation is getting adequate to the physical phenomena, is the third one. As a basis for creating the third degree splines, the following equation is used:

$$\mathrm{f}(x) = y_i + a \cdot (x - x_i) + b \cdot (x - x_i)^2 + c \cdot (x - x_i)^3; \qquad (4)$$

where: x and y – point coordinates; a, b and c – coefficients of the third degree equation. These last-mentioned coefficients are calculated according to the following formulas:

$$a = \frac{y_{i+1} - y_i}{x_{i+1} - x_i} - \ddot{f}_{i+1} \frac{x_{i+1} - x_i}{6} - \ddot{f}_i \frac{(x_{i+1} - x_i)}{3}; \qquad (5)$$

$$b = \frac{\ddot{f}_i}{2}; \qquad (6)$$

$$c = \frac{\ddot{f}_{i+1} - \ddot{f}_i}{6 \cdot (x_{i+1} - x_i)}. \qquad (7)$$

The following are the results of the solution found using the MAPLE software package. Practically speaking, this method has one limitation. The diesel multi-unit mileage is indicated in kilometres: 50 000 km, 100 000 km etc. The SPLINE diagram does not accept such indication method as it needs a reference system on the basis of *1, 2, 3, 4*, etc. Mark "*2"* of the SPLINE diagram matches the 50 000 km mileage, mark "*4"* – 100 000 km, etc. Therefore, when reading the formulas and diagrams, the rolling stock mileage has to be calculated separately. Firstly, the splines are indicated by the formulas (third degree functions with corresponding coefficients, within the range of the "*x*" mileage):

$$\begin{cases} 17+\frac{1223}{1991}\cdot x-\frac{51453}{3982}\cdot x^2+\frac{17151}{3982}\cdot x^3, x<2; \\ \frac{238407}{1991}-\frac{305617}{1991}\cdot x+\frac{23217}{362}\cdot x^2-\frac{33989}{3982}\cdot x^3, x<3; \\ -\frac{587901}{1991}+\frac{520691}{1991}\cdot x-\frac{295485}{3982}\cdot x^2+\frac{27219}{3982}\cdot x^3, x<4; \\ \frac{640707}{1991}-\frac{400765}{1991}\cdot x+\frac{165243}{3982}\cdot x^2-\frac{11175}{3982}\cdot x^3, x<5; \\ \frac{94082}{1991}-\frac{72790}{1991}\cdot x+\frac{34053}{3982}\cdot x^2-\frac{2429}{3982}\cdot x^3, x<6; \\ -\frac{704254}{1991}+\frac{326378}{1991}\cdot x-\frac{99003}{3982}\cdot x^2+\frac{4963}{3982}\cdot x^3, x<7; \\ \frac{36663}{181}-\frac{148285}{1991}\cdot x+\frac{36615}{3982}\cdot x^2-\frac{1495}{3982}\cdot x^3, x<8; \\ \frac{779613}{1991}-\frac{289405}{1991}\cdot x+\frac{71895}{3982}\cdot x^2-\frac{2965}{3982}\cdot x^3, x<9; \\ -\frac{2266149}{1991}+\frac{725849}{1991}\cdot x-\frac{153717}{3982}\cdot x^2+\frac{5391}{3982}\cdot x^3, x<10; \\ \frac{160441}{181}-\frac{2671}{11}\cdot x+\frac{8013}{362}\cdot x^2-\frac{2671}{3982}\cdot x^3, otherwise. \end{cases} \quad (8)$$

The domain is divided into 11 segments (subdomains) each of which has one consistent pattern (see Formula (8)). This mathematical expression is shown in diagram form in Fig. 7.

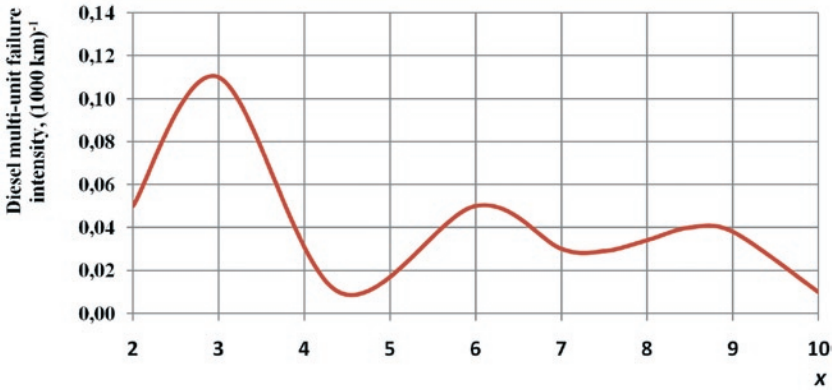

Fig. 7. Approximation of diesel multi-unit failure data by splines of the third degree

From the diagram in Fig. 7, it is obvious that, using the spline method, a fairly complex pattern can be indicated by non-complex mathematical functions. This is very convenient for indicating the failure intensity of a rolling-stock – in this instance, diesel multi-units. The main advantage of this method is that the spline limits (as well as the domain section limits) can be chosen according to the physical phenomena of a process. In the rolling-stock operation this can be the maintenance regularity, in certain cases - the moments of crashes or failures. After indicating the rolling-stock failure patterns by one of the above-mentioned methods (discrete, continuous function or spline), the failure patterns of the whole fleet of a railway company can be modelled in the longer term, taking into account the fleet formation (renewal) algorithm. After making such rolling-stock renewing schedule, a railway operator can avoid the unwanted failure intensity peaks, as well as the unexpected costs of manpower and financial expenditures for repairing the rolling-stock.

4. Conclusions

During this study of the new rail vehicles acquisition influence on the fleet's overall failure amount, it was noticed that this influence depends on whether the fleet is renewed or newly formed. If renewing a large existing fleet with a few dozen or hundred vehicles, then it can be assumed that the acquisition of the new vehicles reduces the overall failure amount of the fleet proportionally to the number of acquired vehicles. This assumption should not be applied when the fleet is newly formed. When forming a new fleet, the rolling-stock is to be acquired in certain cycles. If the rolling-stock failure intensity fluctuates, especially if the fluctuations are regular, the peaks of the newly-acquired vehicle failure intensity can coincide with the peaks of the earlier-acquired vehicle failure intensity. The research showed that, if the failure intensity fluctuation extremes coincide, the unexpectedly large peaks of the fleet failure intensity, as well as the vehicle repair costs, are possible. Therefore, when forming a new rolling-stock fleet, it is necessary to as gradually as possible disperse in time the total failure intensity extremes.

In order to avoid the possible and unexpectedly large peaks of the whole rolling-stock fleet failure intensity, it is necessary to mathematically model the patterns of their failure intensity dependence on operation, and to use these models for choosing the appropriate moment to install a new vehicle. For modelling the vehicle failure intensity dependence on operation, the discrete method, polynomial approximation, and sine pattern approximation are proposed. The more radical proposal of the authors is to approximate this pattern using splines. The latter method is convenient, as the spline limits can be chosen according to the physical phenomena of a process, thus evaluating the moments of maintenance.

After indicating the rolling-stock failure patterns by one of the above-mentioned methods, the failure patterns of the whole vehicle fleet can be further modelled, taking into account the fleet formation (renewing) algorithm. After making such rolling-stock fleet renewing schedule, in the future a railway company can avoid the unexpected failure intensity peaks, as well as the unforeseen costs for unscheduled repair of the rolling-stock.

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