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QUANTILE ANALYSIS OF THE OPERATING COSTS OF THE PUBLIC TRANSPORT FLEET

Summary. The aim of this paper is to develop a quantile method of cost analysis allowing identification of the most cost-generating malfunctions occurring in a fleet of public transport vehicles. The exemplification of this method has been performed for a fleet of a specified type of trams. The idea behind the quantile method of public transport vehicle operating cost analysis is the reversing of the accumulated function of costs, for the determination of which a cost database from a given operating time of a public transport vehicle fleet has been used. The paper presents data on the malfunctions from the first five years of operation of trams in a large transport company. The assumed time of five years results from the warranty period provided by the manufacturer. The recorded number of indexes of replaced parts was 547. The group contained inoperative parts that were renewed several times.

1. INTRODUCTION

Vehicles of public transport are assets that represent a high investment. They are designed to work in very demanding safety conditions and must display a very low occurrence of failures [1-3]. The main cost-generating factor in fleets of public transport vehicles, except the one-off cost of purchase, are the costs generated during operation. The costs generated at this stage of the tram fleet life cycle are analyzed in detail both from the fleet supplier (most often the manufacturer) perspective and from that of the end-user (public transport operator). The manufacturer (supplier) of the fleet is interested in the costs of the operation stage because he has to bear the financial costs of warranty claims and service contracts at the initial stage of vehicle operation. The knowledge related to the costs of the vehicle operation phase allows the supplier to reduce the risk of voiding the warranty and increase their sales capacity of tram rolling stock. It may also increase the sales potential and bidding advantage when negotiating sales terms, which may lead to additional financial benefits [4-10]. The methods of calculating lifetime cost varies mainly according to the number of divided phases; nevertheless, common elements can be found in these methods, like defined cost structure or economic efficiency, e.g. the inflation and discount rate, net present value, or discounted payback period [11-15].

The public transport operator, knowing the costs of the operation phase, can control them in a more efficient way, thus reducing the financial risk related to preventive and unplanned maintenance, reducing the risk of decreasing fleet accessibility, and significantly reducing safety-related risks [13, 14]. Besides, knowing the forecasted cost of operation, at the stage of selection of the supplier itself, the operator can assess the efficiency of alternative bidding offers. The costs of the operating phase are composed of the running cost (energy, consumables), the costs of scheduled maintenance (service inspections, spares, adjustment), and unscheduled maintenance forced by random faults (e.g. replacement of cracked or broken glasses, post-accident repairs, or preventive maintenance) [15, 16].

The costs of planned and preventive maintenance are directly influenced by the reliability of the spare parts that can be expressed by the following indicators: reliability, availability, and maintainability. In the EN 50126 standard, these parameters have been defined and named RAMS, also including safety as a last parameter [16]. The above allows an effective control of these parameters and their management throughout the object's life cycle according to PN-EN 60300-3-3 standard [17]. A comprehensive explanation of these issues concerning description-, definition-, and calculation-specific indicators can be found in detail in other scientific articles [18-23].

In order to perform a detailed cost analysis of a fleet of public transport vehicles at the operation phase, with a possible attempt to forecast all types of costs, all events that generate costs must be recorded. The creation of a database related to reliability, including all types of costs of public transport vehicle fleet operation is one of the main activities in the process of servicing and repair cost planning. Therefore, maintenance plans must be devised, and forecasting of failures is needed to keep them within an acceptable level. Maintenance actions associated with the repair of suddenly occurring vehicle failures represent costs that are difficult to forecast at the time of construction of the means of transport [24-27].

Having a database of reliability, as well as operation and service costs obtained from the public transport vehicle fleet maintenance documentation (trams operated by a large city operator), one may identify the most cost-generating parts and determine a series of significant reliability characteristics useful in the planning of future fleet operation [28-30].

The aim of this work is to formally develop a quantile method of cost analysis allowing an identification of the most cost-generating malfunctions occurring in a public transport vehicle fleet. The exemplification has been performed for a fleet of trams of a given type for unplanned renewal of parts in the variant of total costs and costs broken down into part renewal and work hours.

2. RESEARCH PROBLEM AND RESEARCH METHOD FOR THE EXEMPLIFICATION OF THE QUANTILE METHOD

In the paper, the authors propose a proprietary method for quantile analysis of cost of operation of a fleet of public transport vehicles. This method is an analogue of a known ABC method based on Pareto's statistical law, applied mainly in problems of decision making and quality management. An example of the application of the ABC method in malfunction analysis of mining equipment is [30]. For a change, the quantile method of cost analysis presented in [31] refers to the quantile function known from probability theory and is increasingly applied in modern stochastic analysis [32]. Rather than to the cumulative distribution, the process of reversing is applied to the accumulated function of costs, the determination of which is performed on the basis of the cost database from a given period of public transport fleet operation.

The method of quantile cost analysis of public transport vehicle fleet operation has been developed for an evolving source database $B_{(t_1,t_2)}$ of used spares and performed services in a set time (t_1, t_2) of fleet operation. The authors assumed that this time covers the period of service under warranty. The information in the database, in general, pertains to planned service procedures as per the manufacturer's recommendations and unplanned repairs of malfunctioning spares and proactive service.

The costs of planned renewals are usually known and are easily included in the costs of vehicle operation. A greater challenge is forecasting the costs that are not a consequence of planned service. The analysis of costs is then limited to those that cannot be planned, as they appear randomly during operation, usually in between service inspections, or they may appear during service inspection as an unexpected cost of a proactive activity.

The source database includes fields related to the following:

- item number of renewed part (chronologically),
- index number of a spare part,
- technical group,
- vehicle mileage at which the malfunction occurred,

- name of renewed part,
- date of repair,
- cost of spare part,
- cost of work hours,

as well as other data that, at this stage of research, are not used (cause of malfunction). The database is then composed of appropriate records. Example records have been presented in table 1.

Table 1

Structure of the source database

Item	Part index	Technical group	Mileage [km]	Name of part	Date of repair	Cost of part [plz]	Cost of work hours [plz]
1.	0004-010-219	8	196006	Pressure sensor	2015-06-15	488.67	330.00
2.	3400-003-454	24	125588	Door controller	2013-04-24	29 333.88	660.00
3.	3400-003-574	8	196006	Horizontal shock absorber	2013-10-16	1 286.00	220.00

Individual replaced or repaired parts are specified in the tram fleet service document, which includes numbers attributed to them on a given level of decomposition, as per the system assumed by the manufacturer, compliant with PN-EN 15380 Railway – System of Classification of Rail Vehicles – Part 4: Function Groups [33] and with PN-EN 81346 Industrial Systems, Installations, Equipment and Industrial Products – Structuring principles and reference designations – Part 1: Basic Rules [34]. For example, index 0004-010-219 denotes a pressure sensor, 3400-003-454 a door controller, and index 3400-003-574 denotes a horizontal shock absorber. Each part index refers to a vehicle component that can be repaired or renewed. The parts were aggregated and attributed to technical groups as per the PN-EN 50126 standard railway applications – Specifications of Reliability, Accessibility, Maintainability and Safety [11]. This standard describes problems related to the monitoring of maintenance activities for railway vehicles. The algorithms for the creation of the code of modules and components in the process of decomposition or reproduction of design and functional structures of an operative complex technical object have been discussed in [35, 36]. These algorithms serve the purpose of creating an index of components in a hierarchical structure of a system and clearly describe their mutual relations. In this paper, the authors assume that the knowledge of the hierarchical structure of a means of transport is given in the form of a full list of spare part index. The dynamically created database on the repair works is modified as the fleet operation time passes after each cost-generating event.

To simplify the notation, we assume that the time $t > 0$ of cost monitoring of the costs of repairs of a fleet of vehicles starts with a set initial moment t_1; hence, $t = t_2 - t_1$. With this simplification of notation, the evolving source database will be marked as B_t. On the basis of the source database B_t evolving in time t related to the costs of operation of a fleet of public transport, database $B_t^{k\geq}$ is created, whose records are ordered non-increasingly in terms of total accumulated cost generation, i.e. the cost of spare parts plus work hours related to the part renewal. As a result of this ordering, the modified database $B_t^{k\geq}$ for a given time of operation t in the subsequent records contains information on the decreasingly costly part renewals starting from the most cost-generating ones.

The following notation is introduced:

- I – set of all index of renewable spare parts for a given means of transport,
- $Z(t)$ – set of index of parts that were renewed during fleet operation in time t,
- i – index of a renewed spare part of a means of transport,
- $k_i(t)$ – total accumulated costs of parts of the index i in time t of fleet,
- $\prec$ – the relation defined on the set $Z(t)$, which organizes the costs.

With the introduced notation, one can see that a temporary equivalence occurs in the evolving database $B_t^{k_\geq}$

$$\underset{i,j\in Z(t)}{\forall}\big(i \prec j \Leftrightarrow k_i(t) \geq k_j(t)\big) \tag{1}$$

Let $Z_\geq(t)$ denote a non-decreasingly ordered (in terms of total accumulated costs) set of index of spare parts renewed in time t. The index of spare parts of the greatest total accumulated costs are ordered in a decreasing fashion in the database $B_t^{k_\geq}$ and $k_{(j)}(t)$ denotes total accumulated cost of a j-th part, in terms of cost height. Let $K(t)$ denote the total accumulated cost of unplanned part renewals of indexes from set $Z(t)$ in time t of the vehicle fleet operation. With these notations, the quotient

$$c_{(j)}(t) = \frac{k_{(j)}(t)}{K(t)} \text{ for } j = 1, 2, \dots, m(t) \tag{2}$$

denotes a relative total cost of renewal of a part of the index (j) in time of operation t, practically expressed in percent. Symbol (1) denotes the index of the most cost-generating part out of the renewed ones and $c_{(1)}(t)$ denotes a relative share of the most cost-generating part in the total costs of unplanned renewals. The sum

$$C_j(t) = \sum_{l=1}^{j} c_{(l)}(t) \tag{3}$$

presents an accumulated relative cost of renewals j of the most cost-generating parts. An example graph of the function of a relative total cost for 55 parts of the highest cost (i.e. the graph of pairs $(j, C_j(t))$ for $j = 1, 2, \dots, 55$) has been presented in the next paragraph in Fig. 1. Besides, Fig. 2, on a pie chart, presents a percentage share in the total cost and is broken down into costs of spare parts and work hours for 55 parts out of those generating the highest cost. Note that $C_{m(t)}(t) = 1$. The idea behind the quantile method of cost analysis is determining the index of these parts from set $Z(t)$, whose renewal is the most cost-generating for a given accumulated relative cost $p \in (0, 1)$, referred to as the quantile of order p of the highest cost. This quantile, expressed in percent, is a percent of the highest costs of the order of $100p\%$. Formally, in the coordinate system $Z_\geq(t) \times C_{m(t)}(t)$, the function of cost is a non-decreasing point function of the value from the range $[0, 1]$. The quantile function of variable $p \in (0, 1)$ for a given time t of operation of a fleet of vehicles is a reverse function C^{-1} against the function of costs described with the following formula:

$$C^{-1}(t; p) = \max\{j \colon C_{(j)}(t) \leq p\} \tag{4}$$

For a given time t of the operation of a fleet of vehicles and for a given p this function tells us how many renewed parts of the highest cost generates at most $100p\%$ of the total cost. If $C^{-1}(t; p) = l$, then the parts of index $(1), (2), \dots, (l)$ generate the highest total cost. The presented quantile analysis of total costs can be applied in the breaking down of the total costs into costs of spare parts and work hours. The presented quantile analysis can be applied for specific databases related to the structure of the generated cost of maintenance of a fleet of vehicles. The potential of the quantile analysis is limited only by accessibility to such a base and its content. An example application of a quantile analysis method has been provided in the following paragraph.

3. METHOD FOR THE EXEMPLIFICATION OF THE QUANTILE METHOD

The presented method of quantile analysis of costs was applied in a database related to the malfunctions of a fleet of trams of a large tram operator. The research is conducted under the PBS3/B6/30/2015 project [37]. The data pertain to the time of operation $t = 5$ years and cover the warranty period that the manufacturer provided to the operator. The recorded number of unplanned spare part renewals in this period of time amounted to $m = 547$. The parts include those that were renewed several times.

The cost information systematized according to the developed quantile method can be easily shown in a graphic form. To graphically present the information obtained from database B_t, the authors used Tableau software that has an advanced option for result presentation in the form of graphs. Upon ordering the source database limited only to the unplanned spare part renewal, database $B_t^{k_\geq}$ was created containing information on the accumulated percentage of costs for the 100 most cost-generating parts. The graph of the empirical accumulated function of total cost is shown in Fig. 1. The marked value of 84% is the result of costs accumulated for the 55 most cost-generating parts in relation to the total costs.

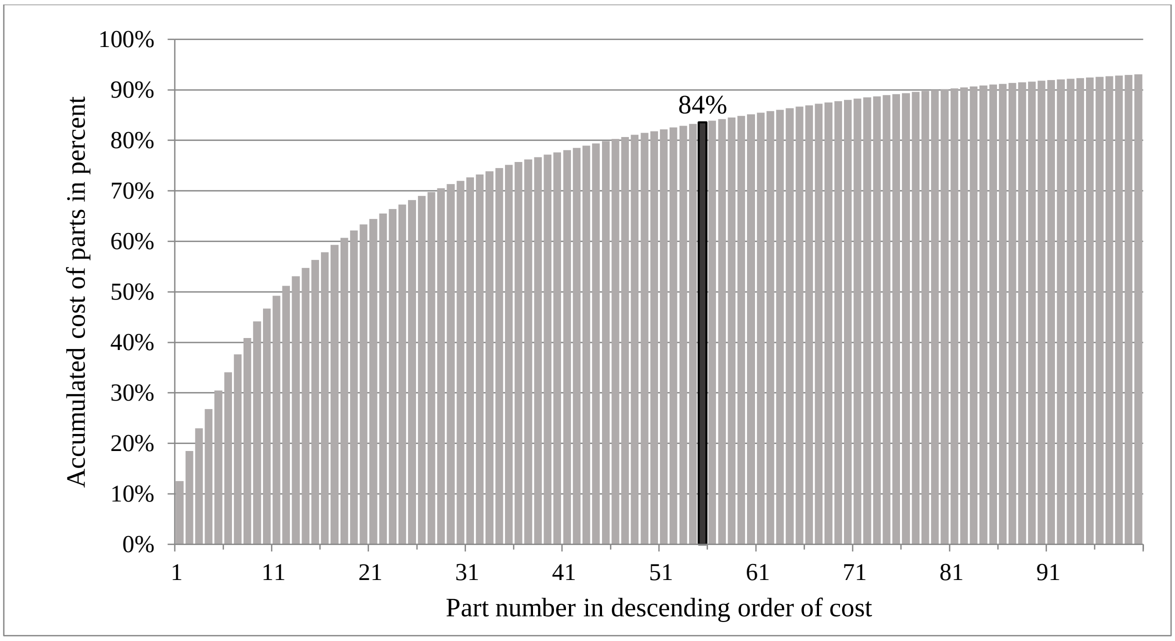


Fig. 1. Accumulated cost of parts in percent

On the pie charts (Fig. 2) the percentage share of the costs of renewal of the 55 most cost-generating parts is shown, constituting 10 percent of all parts of the index from set $Z(5)$. The values have been presented in three variants in relation to the sum of total costs (Fig. 2a), costs of spare parts (2b), and costs of work hours (2c).

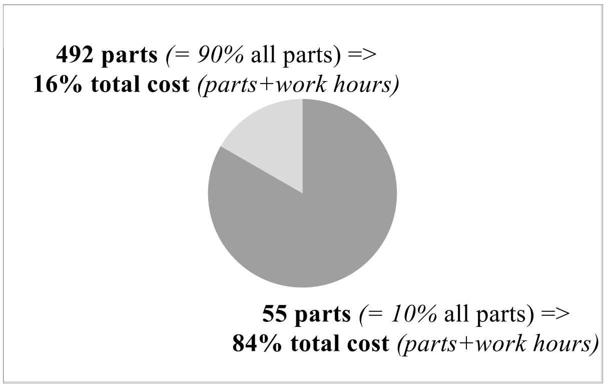
From the pie chart in Fig. 2a we may infer that the renewal of 55 different types of parts (with possible repeated renewals), constituting 10% of all performed types of renewals, generates 84% of costs for all recorded unplanned repairs, in the first 5 years of fleet operation. Figure 2b shows the division of costs for the analyzed group of 55 parts only in terms of costs of materials for repair. It results from the above that the renewal of 55 parts of different indexes generates costs at the level of 87.47% of all costs incurred in renewing these parts in the analyzed 5-year period of operation. Figure 2c presents a relation pertaining to the same group of 55 parts in terms of work-hour costs only. These costs constitute 55 percent of the costs of all repairs expressed in man-hours in the analyzed period.

For the same database, graphs have been presented in figure 3 showing accumulated costs for the 55 most cost-generating parts broken down into total costs (Fig. 3a), costs of parts (Fig. 3b), and costs of work-hours (Fig. 3c).

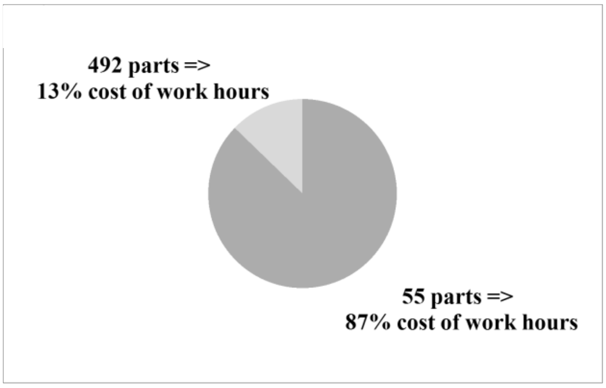
From the presented results, we also learn that a small group of malfunctioning parts of trams (merely 10%) generates almost 84% of the total costs. The costs of renewal of the 55 most cost-generating parts are slightly over 87% of the costs of all parts, whereas the costs of work-hours expressed in work-hours generated by the 55 most cost-generating parts in relation to the total costs of work hours is almost 55% of this value.

4. CONCLUSIONS

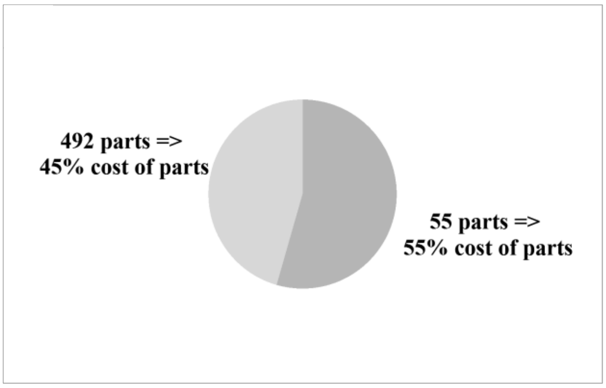
The presented quantile analysis of costs is a universal method that can be applied to any fleet of public transport vehicles. The scope of application of this analysis depends on the level of detail of the information contained in the database and the accessibility to this database. As has been mentioned in the introduction, the exploration of the unplanned costs during operation allows the fleet manufacturer to estimate the costs of warranty and service contracts for future transactions. It also indicates the need to redesign certain spare parts and contributes to a reduction in the risk for voiding the warranty, a reduction in the risk for liability, and allows increasing the bidding potential, besides providing competitive advantage in negotiations of the sales terms.



(a) total costs

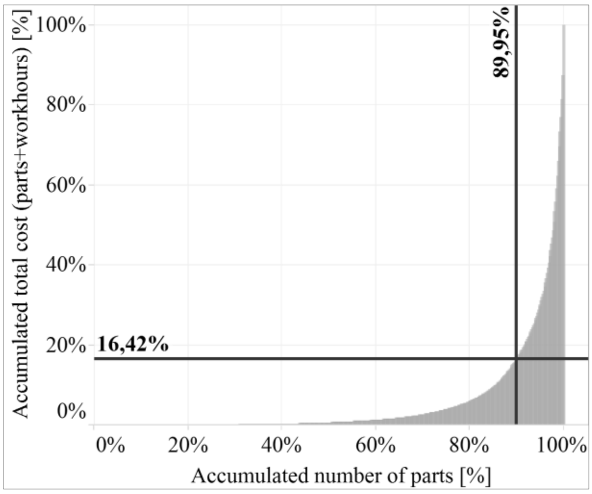


(b) costs of spare parts

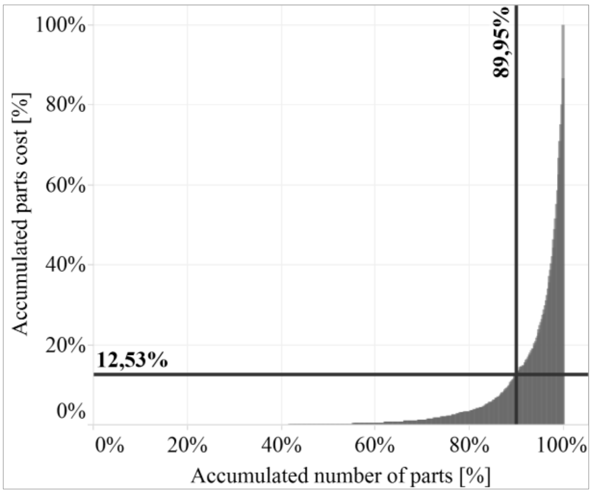


(c) cost of work hours

Fig. 2. Share of the most cost-generating parts in the total costs

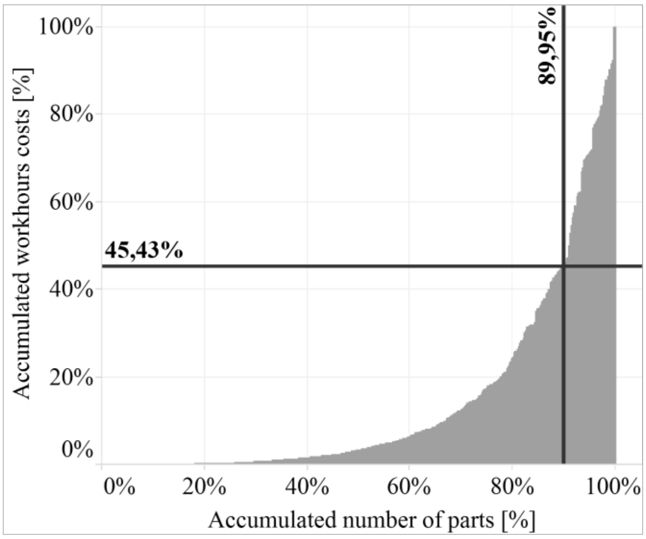


(a) total



(b) costs of spare parts

Fig. 3a,b. Accumulated costs



(c) costs of work hours

Fig. 3c. Accumulated costs

On the other hand, the fleet operator, knowing the costs of operation, has better control of the costs, reduces the financial risk, limits the risks of inaccessibility of the means of transport, and minimizes safety-related hazards. Knowing the forecasted costs, at the stage of selection of the fleet supplier itself, the operator can evaluate alternative bidding solutions.

The presented method of cost analysis is a basis for the development of both structural analysis of costs and the methods of cost forecasting in the coming years of fleet vehicle operation. The ultimate objective of the performed research is the implementation of the results of the research in the routines of fleet operators and public transport vehicle manufacturers.

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