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Operational risk assessment model for city buses

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Highlights

- Sustainable public transport has to be catered to the expectations of the user.
- The cooperation between the carrier and the user can be assessed based on the integrated operational risk of vehicle incapacity.
- The integrated risk includes the following: vehicle faults, lost income and user migration.
- The optimum life cycle criterion is based on a balance between the operational risk and the residual value of the vehicle.

Abstract

The development of public transport systems presently focuses on sustainability. In this situation, the issue of user (passenger) migration has become important to the transport company as a service provider. This paper presents an integrated model of the operational risk of vehicle incapacity, including the following: costs of incidental repairs, costs of unplanned downtime and costs resulting from potential user migration. The paper presents the results of operational research on buses of two makes over a period of 6 years, in the mileage range of 0–420 000 km. The authors have determined the risk as a regression function of operational mileage to estimate the optimum life cycle. The quality of the vehicle was assessed using the criterion of the maximum cost of the operational incapacity risk being equal to the current residual value of the vehicle. The research results confirmed the suitability of the integrated risk model for a comparison of vehicle makes and assessment of their reasonably foreseeable life cycle in a balanced carrier-vehicle-user system.

Keywords

sustainable public transport, operational risk, reliability, optimum bus life cycle

1. Introduction

A transport company that offers transport services should ensure the continuity of its services and the credibility of transport. The continuity and credibility of transport services build the prestige of the company and improve its competitive potential. The contemporary transport market is focused on sustainability. This creates new options for the movement of people by enabling unrestricted access to various types of transport, including car-sharing and other shared vehicle systems. In this situation, the issue of customer migration has become important to the transport company as a service provider. Important reasons for customer migration may include losing confidence in the service provider due to unexpected incapacity of the vehicles or organizational shortcomings of the carrier. Where a road transport company has a specific fleet of vehicles, the reliability of the vehicles should be considered as the reliability of the system [18, 8].

This paper analyses the continuity of the functioning of the system, assuming the availability of reserve vehicles to increase the reliability of the fleet according to the redundancy law [8]. Another option is to consider introducing intelligent transport vehicles with self-diagnostic and learning systems capable of sustainable self-maintenance [1].

Ensuring a high level of reliability, in addition to the availability of reserve vehicles, also requires a cyclical replacement of worn-out vehicles. The practice of enterprise management involves important problems as regards the methods used to determine the optimum life cycle and vehicle make [16, 17]. In paper [16] operational efficiency assessment model was presented. Model includes unplanned incidental repairs costs, downtime costs, as well as the likelihood of losing customer-passenger's trust. In paper [17] the risk assessment model in the form of cost was used, which was based on the

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determination of operational efficiency, referring the probable costs of ensuring the reliability of the transport system to the estimated threshold income. It included costs: incidental repairs, unplanned downtime and resulting from the presumed loss of client's trust.

Available literature describes a wide range of methods used to determine the life cycle and assess the suitability of vehicle makes [23, 14, 19, 22]. Authors of paper [13] proposing simulation-based approach. Based on couple of probability distributions technical object's reliability is forecasted. The most frequent criteria, as listed by Piasecki [19], include the following:

- maximum profit,
- maximum return,
- maximum productivity,
- minimum costs.

To calculate the maximum profit generated by a single vehicle of make q, the author uses the following formula:

$$F_q = \frac{\left(aW_q - U_q\right) * Z_q - C_q - G_q}{\frac{Z_q}{\lambda} + \tilde{\iota}_q} \quad (1)$$

where:

F_q – profit generated by a vehicle of make q per unit of calendar time, a – price per transport service, W_q – efficiency – the number of transport services per unit of time of operation of the vehicle, Z_q – vehicle durability (maximum life cycle),
u_q – direct operational costs per unit of time (fuel, materials, operators), C_q – cost of acquisition of the vehicle, G_q – vehicle maintenance costs, λ – intensity of use (in km per unit of time in service), $\tilde{\iota}_q$ – total duration of maintenance.

The last component expresses the variable operational cost and may be used as a criterion to select the vehicle make.

A common method for estimating the time until the decommissioning of the vehicle is to adopt the maximum maintenance costs of a worn-out vehicle as less than the sum of expected maintenance costs and depreciation of the new vehicle. Beichelt [3] proposes using a criterion for the "maximum total maintenance costs in the full replacement cycle", where the object is replaced with a new one when the total maintenance cost in the cycle reaches a specific level. Raposo et al. [20] present the following list of criteria for the determination of vehicle life cycle:

- physical wear of the object,
- exceeding of the planned service life,
- exceeding of the limit for modal ageing, i.e., loss of competitiveness relative to new technologies required according to specific requirements, e.g., climate protection, safety regulations or market prestige,
- loss of competitiveness relative to new, more economically feasible solutions.

Rapaso [20] presents an original econometric model for the determination of the vehicle replacement cycle and the size of the reserve fleet. To analyse the problem, it is also necessary to investigate the relationship between reliability indicators, such as the mean time to repair (MTTR) and availability coefficient (A), and economic indicators, such as the return on investment (ROI) and uniform annual income (UAI). The assessment model is shown here in the form of two formulas. Formula (2) describes the minimum required annual income as a function of maintenance and operational costs. Formula (3) describes the return on investment as a function of annual income (CF) generated by the vehicle and the cost of acquisition (CA).

$$\begin{cases} UAI_n = \frac{i_A(1+i_A)^n}{(1+i_A)^{n-1}}\left(CA + \sum_{j=1}^{n} \frac{t\,MTTR\frac{CM_j}{d} + CO_j}{(1+i_A)^j} - \frac{V_n}{(1+i_A)^n}\right. & (2) \\ ROI = \sum_{j=1}^{n} \frac{CF_j}{(1+i_A)^j} - CA & (3) \end{cases}$$

where:

n – number of years of the vehicle in service, n ϵ {1, 2, 3… N}, j – 1, 2, 3…n, i_A – resultant rate of the change in the value of assets as the superposition of the capitalisation rate and inflation rate, CA – cost of vehicle acquisition, t – number of time intervals in calculations of the mean time to repair and maintenance MTTR, d – number of days of the year, CM_j – annual cost of maintenance and repairs, CO_j – annual cost of operation, V_n – value of additional equipment, CF_j – annual income generated by the vehicle.

Dziedziak and other in paper [7] presents unique approach for assessing vehicle's reliability based on data from periodic technical inspection station. Vast amount of data allowed for a wide analysis in term of vehicle make, model, mass, engine size, maximum power. Information were summarized accord to car's age travelled distance, way of usage – private or business and others. That approach could also be used for determining the life cycle and vehicle's suitability but lack of information about defects that occurred between inspections and were fixed and also cost of repairs cause that decision could be biased.

The methods for estimating the optimum life cycle and assessing the operational suitability of the vehicles that are provided in the papers are largely economic [22, 24, 26]. They are characteristic in their focus on the business perspective on the objectives and measures of the operations of the enterprise. However, this is a general perspective. In many cases, there are specific aspects that are also important to the business, e.g., safety, reliability and user comfort.

The models described in the literature do not describe the methods for a holistic approach to vehicle reliability along with the analysis of the consequences of incidental damage on contracted transports and the impact on orders in the future. Furthermore, there are no such models using a risk-based approach.In this paper, the authors present a new method for assessing the optimum life cycle and selecting the make of the vehicle, taking into consideration the aspects of the continuous functioning of the carrier-vehicle-user system that are related to reliability as exemplified by city buses.

The quality of the vehicle make was assessed based on the maximum cost of the operational incapacity risk. The optimum life cycle is determined based on the mileage of the vehicle until the maximum risk level is reached.

2. Research methods

Considering the assumptions for the formulation of the research problem specified at the beginning, this paper presents an original definition of the operational and technical system of vehicle use. The system consists of the carrier, vehicle and user of the vehicle (CVU), unlike in the conventional approach to the human engineering system described, in particular, by Smalko et al. [23], Będkowski et al. [6] and Laskowski et al. [10] where the primary elements of the system are the vehicle and vehicle operator. A diagram of the CVU system is shown in figure 1.

Fig. 1. Diagram of the operational and technical system of vehicle operation (CVU) [15].

The carrier is the service provider to the user as well as the owner of the vehicle. The carrier is responsible for the economic and technical maintenance of the vehicle. The vehicle is an element of a system with redundancy, which means that reserve vehicles might be used. The user (customer) is the person using the transport service, e.g. a bus passenger or a renter of a car in the car-sharing system. In general, users also include individual car owners who use their vehicles exclusively for their own purposes. The primary requirements of the users include the punctuality and quality of transport.

According to IEC 1069 [8], the reliability of a technical object is described as dependability (fig. 2). This approach to vehicle reliability is also used in this paper, taking into account the fact that the characteristics essential to reliability in this case include vehicle reliability, availability and security of operation.

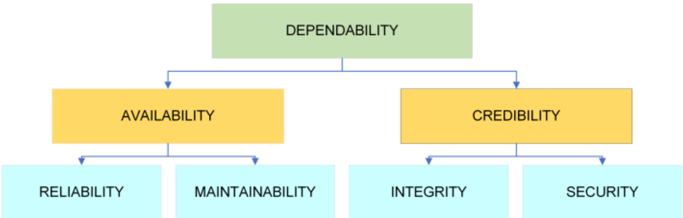

Fig. 2. Classification of reliability characteristics according to IEC 1069 [8] [23].

On this basis, the operational suitability of the vehicle was defined as the condition where the vehicle is technically and organisationally suitable to perform a service according to the requirements of the user (customer). It was assumed that where the vehicle was unavailable due to technical incapacity, the task would be performed by a replacement vehicle included in a reserve fleet planned in advance.

2.1. Model of the integrated risk of the operational incapacity of the vehicle

This paper, similarly to [5, 17, 18, 23, 26, 27, 28] uses the term "operational risk" as the "risk of all incidents occurring during road transport that have a negative effect on the provision of a transport service with specific operational costs and according to defined logistics and quality parameters".

Paper [27] indicates that the operational risk concerns a broad category of risks, including failures in any aspect connected to the operational activities of the organisation. This includes irregularities in operational management, faults of the system or software failure, human error, process inefficiency and procedural errors. The paper [29] describes the operational risk in the context of the theory of organisation as the risk of material losses and harm to reputation as well as legal liability resulting from the failure to adapt the process and the required resources or from their unreliability [4].

The authors of this paper used model of operational risk. This model is characterised by a comprehensive approach to the causes of operational risk, including the following:
- technical causes (vehicle faults),
- economic causes (loss of income by the carrier due to vehicle downtime),
- psychological causes (potential customer migration).

It was assumed that the risks would be measured by the decrease in the residual value of the vehicle in the time interval under consideration, whereas this decrease is assumed to be equal to the required (minimum) income from transport services according to formulas (4) and (5).

$$S_p(p_k) = C_0 - C(p_k) \tag{4}$$

where: $S_p(p_k)$ – decrease in the residual value of the vehicle [PLN], $C(p_k)$ – residual value of the vehicle after operational mileage p_k [PLN], C_0 – cost of acquisition of the vehicle [PLN], p_k – least upper bound of the k-th mileage interval [km].

The developed model uses the following condition (5):

$$S_p(p_k) = P_p(p_k) \tag{5}$$

where: $P_p(p_k)$ – (required) threshold income from transport services [PLN].

It was assumed that the three risk components, referred to as sub-risks, would be aggregated. The general notation is shown in formula (6).

$$R(p_k) = R_N(p_k) + R_G(p_k) + R_W(p_k) \tag{6}$$

where: $R(p_k)$ – integrated risk of operational incapacity, $R_N(p_k)$ – risk of losses connected with costs of incidental repairs, $R_G(p_k)$ – risk of losses connected with the absence of income during downtime, $R_W(p_k)$ – risk of losses due to customer (service recipient) migration.

After considering that the risk is a product of the probability and severity of the risks, formula (6) can have the form of a sum of products of unreliability and risk:

$$R(p_k) = M_N(p_k) \cdot N_N(p_k) + M_G(p_k) \cdot N_G(p_k) + M_W(p_k) \cdot N_W(p_k) \tag{7}$$

where: $M_N(p_k)$ – measure of unreliability due to vehicle unreliability [-], $N_N(p_k)$ – measure of risk due to vehicle unreliability [PLN], $M_G(p_k)$ – measure of unreliability due to unavailability [-], $N_G(p_k)$ – measure of risk due to unavailability [PLN], $M_W(p_k)$ – measure of unreliability due to potential customer migration [-], $N_W(p_k)$ – measure of risk due to the absence of protection against customer migration [PLN].

The first term of formula (6) expresses the sub-risk of incapacity due to technical faults and repair. The measure of unreliability in this case is determined by a new conventional measure of vehicle unreliability. This measure is the ratio of the cumulative cost of incidental repairs to the expected threshold income (formula 8).

$$M_N(p_k) = \frac{\sum_{i=1}^{k} n_i}{P_p(p_k)} = \frac{N(p_k)}{P_p(p_k)} \tag{8}$$

where: n_i – cost of a single repair of an incidental fault at specific operational mileage p_k [PLN], $N(p_k)$ – cumulative cost of incidental repairs in the operational mileage interval $(0, p_k)$ [PLN].

The term "incidental repairs" means that the analysis considers only unscheduled repairs, occurring at random and causing unplanned downtime of the vehicle. To ensure the consistency of formula (8) in the case of more than one fault occurring at the same operational mileage p_k, the cost of such repairs should be added up and regarded as a single repair in the calculations. Assuming a measure of unreliability according to formula (8) and a measure of risk according to formula (5), the sub-risk of losses connected with the costs of incidental repairs is given by formula (9).

$$R_N(p_k) = \frac{N(p_k)}{P_p(p_k)} \cdot P_p(p_k) \tag{9}$$

The measure of unreliability due to vehicle unavailability is expressed by the following formula (10).

$$M_G(p_k) = 1 - K_g(p_k) \tag{10}$$

where: $K_g(p_k)$ – availability at mileage p_k – is expressed by formula (11).

$$K_g(p_k) = \frac{T_0}{T_0 + U_0} \tag{11}$$

where: T_0 – average life cycle according to the requirements for quality and punctuality, U_0 – average duration of vehicle downtime due to technical or organisational reasons.

The measure of the risk of losses connected with the absence of income during downtime was adopted as the lost threshold income in the particular interval of operational mileage – formula (12).

$$\Delta P_p(p_k) = P_p(p_{k+1}) - P_p(p_k) \tag{12}$$

where: $\Delta P_p(p_k)$ – required threshold income in the mileage interval (p_k, p_{k+1}).

Ultimately, the sub-risk of incapacity due to the absence of income during downtime based on formulas (10) and (12) is expressed by formula (13).

$$R_G(p_k) = \sum_{i=1}^{k} [1 - K_{gi}(p_k)] \cdot \Delta P_{pi}(p_k) \tag{13}$$

The measure of unreliability due to customer migration is modelled by the Weibull distribution to the first fault according to formula (14).

$$F_W(p_k) = 1 - e^{-\left(\frac{p_k}{a}\right)^b} \tag{14}$$

where: $F_w(p_k)$ – Weibull distribution of time to first fault, a – scale parameter, b – shape parameter, e – natural logarithm base.

Since the model is to be used in real transport systems, providing personal or cargo transport services or vehicle rental services, it is necessary to introduce a correction coefficient, which should be selected according to the nature of the particular transport system. Then, unreliability due to customer migration is given by formula (15).

$$M_W(p_k) = m \cdot F_W(p_k) \tag{15}$$

where: m – correction coefficient.

The measure of risk, similarly to risk R_N, is expressed by formula (5). Ultimately, based on formulas (5), (14) and (15), the sub-risk of incapacity due to customer (user) migration is expressed by formula (16).

$$R_w(p_k) = m \cdot (1 - e^{-\left(\frac{p_k}{a}\right)^b}) \cdot P_p(p_k) \tag{16}$$

The sub-risk of incapacity due to customer migration depends on psychological factors.

Ultimately, the total risk of operational incapacity *$R(p_k)$* has the following form (17):

$$R(p_k) = \frac{N(p_k)}{P_p(p_k)} \cdot P_p(p_k) + \sum_{i=1}^{k} [1 - K_{gi}(p_k)] \cdot \Delta P_{pi}(p_k) + m \cdot (1 - e^{-\left(\frac{p_k}{a}\right)^b}) \cdot P_p(p_k) \tag{17}$$

Risk $R(p_k)$ describes the cumulative financial expenditure on the acquisition and maintenance of a reserve vehicle fleet per one active (operational) vehicle in the mileage interval (0, p_k) [15].

3. Experimental research

3.1. Research objects and conditions

The model of the integrated risk of operational incapacity was tested on a group of vehicles. Research was carried out on a group of 42 buses in a mid-sized urban agglomeration in Eastern Poland, which included the city of Lublin and 7 nearby communes with a demand for approx. 10^8 passenger transport services per year. The research sample included city buses of two makes provided by different manufacturers, which were referred to with letters S and M for the purposes of this paper. The research sample of S vehicles included 20 buses, and the sample of M vehicles included 22 buses. The technical specifications of the investigated buses are given in table 1. The net cost of acquisition of the vehicles has also been included.

Table 1. Technical specifications of the investigated buses [16].

Make of buses	S	M
General specifications	two-axle, single-deck, low-floor	
Number of seats	29	27
Number of standing places	74	78
Engine type	compression ignition	
Engine displacement [dm3]	9.2	7.2
Max. engine power [kW]	188	210
Vehicle weight [kg]	10900	10860
Cost of acquisition [PLN thous.]	750	830

The documentation provided by the public transport company was used to prepare a source set of operational data. The database was limited to operational information connected with random faults that generated unscheduled costs to the carrier. The costs of periodic maintenance, fuel costs and costs of wages were excluded. A sample of an operational documentation log was included in table 2. Due to the absence of information about the duration of repairs, it was decided that a single repair would result in an entire day of vehicle downtime. The record of returns to the depot and downtime was filled out for every vehicle fault. The record contained information concerning vehicle identification, the date and time of the commencement of maintenance, type and cause of the fault and the time connected with vehicle downtime [21].

The average mileage of M vehicles was 420 200 km, corresponding to 65 months in service. The average mileage of S vehicles was 420 100 km, also during 69 months (table 3).

Table 2. Record of returns to the depot and downtime [21].

Report on emergency return to the depot and incomplete mileage										
Item	Line number	Number of the vehicle schedule	Time		Driver number (planned)	Driver number (actual)	Vehicle number	Lost mileage	Fault group	Fault cause
			Return	Departure						
1	55	055/01	6:15 AM	6:35 AM	2925	2925	22377	7.229	B	Road closed – fault not attributable to the public transport company (MPK)
2	14	014/04	6:49 AM	6:52 AM	3962	3962	22237	1.352	A1	Starter
3	8	008/01	2:06 PM	2:17 PM	3228	3228	22314	2.357	A2	Collision – fault attributable to the public transport company (MPK)

Table 3. Details of the research sample.

Name of the indicator	**Make of buses**	
	S	**M**
Size of the sample [-]	20	22
Average mileage in the investigated period [thous. km]	420.1	420.2
Average monthly mileage [thous. km]	6.1	6.5
Time of observation [nb of months]	69	65

3.2. Study Results

The sub-risk and integrated risk at mileage points spread apart by 30 000 km are given in tables 4 and 5 and in figure 3. The tables also specify the relative values of risks referred to the cost of acquisition of vehicles C_0.

Table 4. List of risks and the fraction of the cost of acquisition of M vehicles.

Operational mileage p_k [thous. km]	$R_N(p_k)$ [PLN thous.]	R_N/C_0 [%]	$R_G(p_k)$ [PLN thous.]	R_G/C_0 [%]	$R_W(p_k)$ [PLN thous.]	R_W/C_0 [%]	$R(p_k)$ [PLN thous.]	R/C_0 [%]
6.5	0.0	0.0	0.9	0.1	0.0	0.0	0.9	0.1
32.3	0.2	0.0	2.4	0.3	0.4	0.1	3.1	0.4
58.2	0.5	0.1	6.8	0.8	1.2	0.1	8.6	1.0
90.5	0.9	0.1	9.5	1.1	2.5	0.3	12.8	1.5
122.8	1.2	0.1	13.0	1.6	3.9	0.5	18.1	2.2
148.7	1.4	0.2	14.5	1.7	5.1	0.6	21.0	2.5
181.0	2.4	0.3	16.5	2.0	6.7	0.8	25.6	3.1
213.3	7.4	0.9	18.4	2.2	8.2	1.0	34.1	4.1
239.2	14.0	1.7	20.3	2.4	9.5	1.1	43.8	5.3
271.5	20.4	2.5	24.0	2.9	11.0	1.3	55.4	6.7
303.8	27.2	3.3	27.5	3.3	12.5	1.5	67.1	8.1
329.7	31.4	3.8	30.7	3.7	13.7	1.6	75.8	9.1
362.0	37.7	4.5	34.2	4.1	15.1	1.8	87.1	10.5
394.3	44.2	5.3	38.2	4.6	16.6	2.0	99.0	11.9
420.2	51.3	6.2	40.4	4.9	17.7	2.1	109.4	13.2

Table 5. List of risks and the fraction of the cost of acquisition of S vehicles.

Operational mileage p_k [thous. km]	$R_N(p_k)$ [PLN thous.]	R_N/C_0 [%]	$R_G(p_k)$ [PLN thous.]	R_G/C_0 [%]	$R_W(p_k)$ [PLN thous.]	R_W/C_0 [%]	$R(p_k)$ [PLN thous.]	R/C_0 [%]
6.1	0.0	0.0	0.4	0.1	0.0	0.0	0.4	0.1
30.4	0.0	0.0	3.5	0.5	0.5	0.1	4.0	0.5
60.9	0.3	0.0	6.3	0.8	1.4	0.2	8.0	1.1
91.3	0.9	0.1	9.3	1.2	2.5	0.3	12.8	1.7
121.8	1.6	0.2	12.9	1.7	3.8	0.5	18.3	2.4
152.2	2.2	0.3	16.3	2.2	5.1	0.7	23.7	3.2
182.6	3.1	0.4	21.6	2.9	6.5	0.9	31.1	4.1
213.1	3.7	0.5	23.8	3.2	7.9	1.0	35.4	4.7
243.5	5.4	0.7	26.9	3.6	9.2	1.2	41.5	5.5
274.0	11.3	1.5	31.2	4.2	10.6	1.4	53.1	7.1
298.3	17.3	2.3	36.6	4.9	11.7	1.6	65.6	8.7
328.8	22.8	3.0	42.1	5.6	13.0	1.7	78.0	10.4
359.2	29.6	3.9	46.1	6.1	14.4	1.9	90.0	12.0
389.6	35.5	4.7	48.9	6.5	15.7	2.1	100.2	13.4
420.1	43.0	5.7	53.6	7.1	17.0	2.3	113.6	15.1

According to formula (9), the sub-risk R_N generated by random vehicle faults is measured by the costs of incidental repairs N(p_k). As shown by tables 4 and 5, the risk R_N for both makes increases along with vehicle mileage in a similar fashion. In the initial period, up to approx. 180 000 km for make M and approx. 240 000 km for make S, the increase can be regarded as moderate, but in the later period risk R_N increases rapidly (fig. 3). This result is consistent with the results of paper [20].

The chart of the risk of losses due to the absence of income during downtime R_G relative to mileage p_k shows that both vehicle makes, M and S, are characterised by a uniform and comparable increase of risk R_G in the mileage interval until approx. 150 000 km. Over this interval, the increase of risk R_G is faster for make S than M. The cumulative risk R_G is approximately R_G(420 000 km) = PLN 40 400 for make M, which constitutes 4.9% of the cost of acquisition of a new vehicle C_o and R_G(420 000 km) = PLN 53 600 for make S, which constitutes 7.1% of cost of acquisition of C_o.

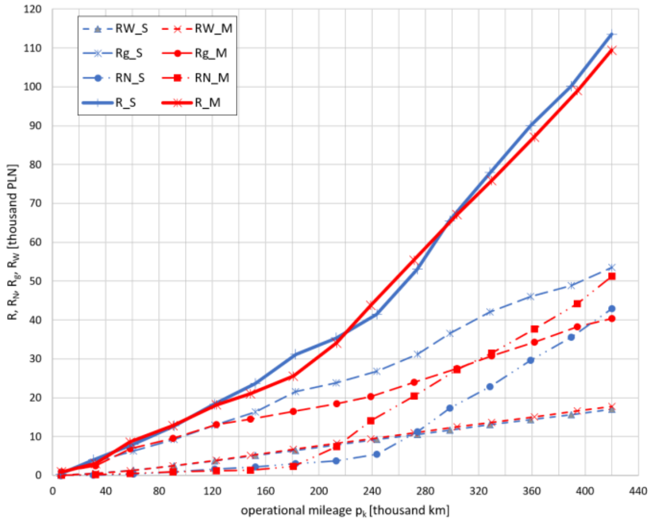

Fig. 3. Comparison of integrated risk R and sub-risks R_N, R_g and R_w for S and M buses.

The risk of losses due to customer migration R_w was calculated according to formula (16) as a product of cumulative time distribution function up to the first fault $F_w(p_k)$, correction coefficient m and threshold income P_p (p_k). The value of the correction coefficient was selected according to the results of the research conducted by Zakład Transportu Miejskiego, the municipal local government agency responsible for all matters connected to public bus transport. The research concerned an assessment of the demand for transport services and passenger preferences regarding the quality of services. Based on the collected opinions, if a bus is late, one per 25 passengers is willing to change their mode of transport. This means that the requirements for punctuality of the expected transport service are regarded as a priority by 4% of the passengers. According to research by Zwierzchowska [30], the punctuality of transport was selected by 6.33% of the respondents. In this paper, the authors assumed m = 0.04. The customer migration risk calculated for this assumption R_w is PLN 17 700 for make M and PLN 17 000 for make S at mileage p_k = 420 000 km, amounting to 2.1% and 2.3% of the cost of acquisition of new buses, respectively.

Sub-risks R_N, R_G and R_w were added up according to formula (6) to determine the integrated risk of operational incapacity R relative to mileage p_k. For make M, the result was R = PLN 109 400 for a mileage of 420 000, which constitutes 13.2% of the cost of acquisition C_0. For make S, in turn, the risk was R = PLN 113 6 00, constituting 15.1% of the cost of acquisition C_0.

Based on the research results shown in tables 4 and 5 and fig. 3, the bus makes can be compared in terms of their reliability in the technical aspect (vehicle), economic aspect (company) and psychological aspect (service recipient, passenger).

For large mileages (p_k = 420 000 km, t_k = 6 years in service), the difference in “technical” unreliability between bus makes measured by the difference in sub-risks R_N is PLN 8 300. This constitutes 1% of the average cost of acquisition of the vehicles. It is, therefore, negligible in practice. By comparison, the average cost of fuel used in the considered period is approx. PLN 70 000, and the average cost of scheduled maintenance is PLN 44 000. For the mileage p_k = 180 000 km, in turn, characterised by a rapid increase of the costs of incidental repairs, the difference in R_N between the makes is approx. PLN 700. It can thus be regarded as negligible, which means that the two makes are comparable in practice.

Extending the criteria for the analysis of operational risks to include economic and psychological risks is equivalent to the assumption that the service recipient (potential user) considers the new transport options that have become available. However, this increases the requirements not only with respect to vehicle reliability, but also the continuity of business of the carrier. Both of these criteria are included in the model of integrated risk R(p_k). Thus, the difference between R(p_k) of specific vehicle makes can be used for their multi-criteria comparison. In the case described in this paper, the difference R(p_k = 420 000 km) between makes M and S is PLN 4 200. Considering the ratio to the cost of acquisition of the buses, this value was regarded as negligible.

3.3. Assessment of the optimum life cycle of the vehicles

During the next stage of the analysis of bus research results, the authors checked if the integrated risk R(p_k) could be used to estimate the optimal life cycle of the vehicle. To do so, the authors determined the maximum risk R^{max}, assuming as the basic condition the requirement to not exceed the residual value of the vehicle C(p_k) expressed with formula (16) [15].

$$R(p_k) \leq R^{max} = C(p_k) \quad (18)$$

where: R^{max} – maximum risk of operational incapacity R, C(p_k) – residual value of the vehicle at mileage p_k.

For comparison with condition (18), the authors also used the criterion defined by formula (19), which only considered the sub-risk generated by incidental repairs R_N (P_k), formula (19):

$$R_N(p_k) \leq R_N^{max} = C(p_k) \quad (19)$$

where: R_N^{max} – maximum sub-risk of incidental faults.

Table 6. Maximum risks and optimum bus mileage.

Make M			
R^{max} [PLN thous.]	221.4	p_R^{max} [thous. km]	624.1
R_N^{max} [PLN thous.]	160.3	p_{RN}^{max} [thous. km]	691.0
Make S			
R^{max} [PLN thous.]	184.7	p_R^{max} [thous. km]	550.0
R_N^{max} [PLN thous.]	112.0	p_{RN}^{max} [thous. km]	620.0

Based on the bus maintenance standards observed by the investigated transport company, we adopted an annual depreciation rate W = 0.1 as the factor determining the loss of vehicle value, i.e., also its current residual value. The chart of the residual value relative to the mileage of S and M buses is shown in figs. 4 and 5, respectively. The authors approximated time series $R(p_k)$ and $R_N(p_k)$ to determine the risk regression functions $\hat{R}(p_k)$ and $\hat{R}_N(p_k)$ relative to mileage.

By extrapolating regression functions $\hat{R}(p_k)$ and $\hat{R}_N(p_k)$, the authors determined the maximum risks R^{max} and R_N^{max} and optimum mileages P_R^{max} and P_{RN}^{max}, assuming the criterion of the estimated risk being equal to the residual value according to formulas (18) and (19). The summary of maximum risks R^{max} and R_N^{max} and corresponding optimum mileages P_K^{max} is shown in table 6.

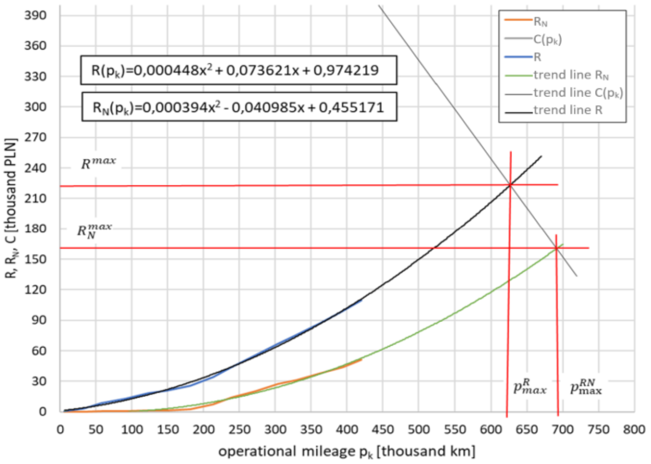

Fig. 4. Maximum risk and optimum mileage of M buses according to criteria R^{max} and R_N^{max}.

As indicated by table 6 and charts 4 and 5, the maximum risk R^{max} reaches R^{max} = PLN 221 400, i.e., 26.7% of the cost of acquisition of bus M, and R^{max} = PLN 184 700, i.e., 24.6% of the cost of acquisition of bus S, respectively. However, it should be noted that the above-mentioned costs of integrated risk ensure the continuity and profitability of the transport services in different intervals of mileage: p_R^{max} = 624 100 km for make M and p_R^{max} = 550 000 km for make S. The difference Δp_R^{max} = 74 100 km is equivalent to a one-year extension of the life cycle. The cost of such extension is the increase of risk R^{max}, equivalent to the cost of an increase of the reserve fleet, by an amount of PLN 36 700.

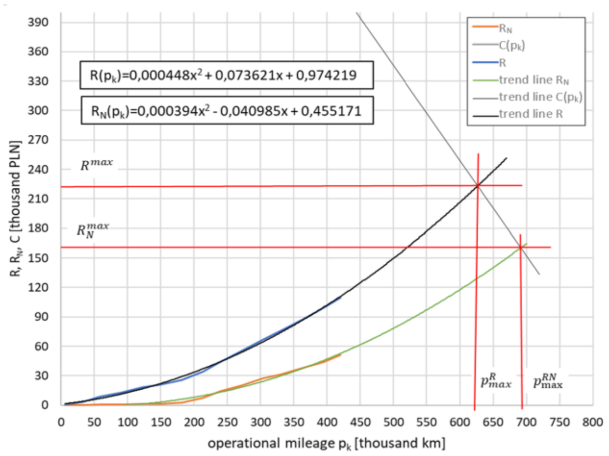

Fig. 5. Maximum risk and optimum mileage of S buses according to criteria R^{max} and R_N^{max}.

The analysis of operational reliability provides interesting conclusions after comparing the results of the assessment of the maximum integrated risk R^{max} and the corresponding optimum vehicle mileage p_R^{max} with risk R_N^{max} and mileage p_{RN}^{max} resulting from technical causes (vehicle reliability, spare parts). As indicated in table 6, the cumulative technical risk is R_N^{max} = PLN 160 300 for make M and R_N^{max} = PLN 112 000 for make S. These risks are much smaller than the costs of integrated risks ΔR^{max} = PLN 61 100 (7.4% of the cost of acquisition of bus M) and ΔR^{max} = PLN 72 000 (9.7% of the cost of acquisition of bus S). When only the R_N risk is considered, the optimum mileage increases as well. For both bus makes, this would increase the mileage by approx. 70 000 km.

Make of buse	for p_k=420 thous. km		
	R_n [%]	R_g [%]	R_w [%]
S	37,8%	47,2%	15,0%
M	46,9%	36,9%	16,2%

Fig. 6. Share of individual sub-risks in relation to R.

In summary, based on the results of the research using method for vehicle make assessment as compared with the methods described in the references (formulas (1), (2) and (3)), it should be emphasized that the original method uses fewer variables and has an increased focus on purely random causes of the discontinuity and uncertainty of vehicle use. This way, the procedure for analyzing the suitability of the vehicle and assessing the optimum life cycle is less time-consuming than, for instance, in papers [14, 22, 23] and indicates the sources of operational risks related to reliability in a clearer and more accurate fashion.

4. Conclusions

1. The results of research using model of the integrated risk of operational incapacity prove that the model is suitable for the assessment of optimum bus mileage .
2. Experimental research showed that reliability risks should be considered in the following aspects:

 - technical aspect (by analyzing the direct costs of incidental repairs),

 - business aspect (by estimating income lost due to repair-related downtime),

 - psychological aspect (due to potential customer migration in an environment where there is no restriction on the choice of the means of transport).

3. The acceptable risk cost of operational failure was adopted as a criterion for assessing vehicle quality. This is equal to its present residual value. The results of the study confirmed the suitability of the integrated risk model for comparing vehicle makes due to reliability risks. An assessment of the reasonable service life of vehicles in a balanced carrier-vehicle-user system was carried out.

4. Directions for further research will be directed towards the application of the model on other groups of vehicles (other vehicle makes) in order to develop a set of correction factors.

Symbols

$S_p(p_k)$	decrease of the residual value of the vehicle	$K_g(p_k)$	availability at mileage p_k
$C(p_k)$	residual value of the vehicle after mileage p_k	T_0	average life cycle according to the requirements for quality and punctuality
C_0	cost of acquisition of the vehicle	U_0	average duration of vehicle downtime due to technical or organisational reasons
p_k	least upper bound of the k-th mileage interval	$\Delta P_p(p_k)$	required threshold income in the mileage interval (p_k, p_{k+1})
$P_p(p_k)$	(required) threshold income from transport services	$F_w(p_k)$	Weibull distribution of time to first fault
$R(p_k)$	integrated risk of operational incapacity	a	scale parameter
$R_N(p_k)$	risk of losses connected with costs of incidental repairs	b	shape parameter
$R_G(p_k)$	risk of losses connected with the absence of income during downtime	e	natural logarithm base
$R_W(p_k)$	risk of losses due to customer (service recipient) migration	m	correction coefficient
$M_N(p_k)$	measure of unreliability due to vehicle unreliability	t_k	calendar time in service
$N_N(p_k)$	measure of risk due to vehicle unreliability	R^{max}	maximum risk of operational incapacity R
$M_G(p_k)$	measure of unreliability due to unavailability	R_N^{max}	maximum sub-risk of incidental faults
$N_G(p_k)$	measure of risk due to unavailability	p_R^{max}	maximum operational mileage due to R^{max}
$M_W(p_k)$	measure of unreliability due to protection against customer migration	p_{RN}^{max}	maximum operational mileage due to R_N^{max}
$N_W(p_k)$	measure of risk due to the absence of protection against customer migration	$\hat{R}(p_k)$	operational incapacity risk regression function
n_i	cost of a single repair of an incidental fault at specific operational mileage p_k	$\hat{R}_N(p_k)$	regression function of the risk of losses connected with costs of incidental repairs
$N(p_k)$	cumulative cost of incidental repairs in the operational mileage interval $(0, p_k)$		

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