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Evaluation of the Useful and Residual Life of a Class of Relay-Based Centralised Traffic Control Systems

Rumen Dimitrov
TINSA Ltd., Sofia, Bulgaria.
✉ *rudimitrov@mail.bg.*

Rumen DIMITROV

ABSTRACT

Currently in Bulgaria, the main railway lines (corridors) are being modernised to increase train speed up to 160/200 km/h, which necessitates adoption of modern European traffic control systems (ERTMS/ETCS, classified as so-called class A systems). The remaining sections continue to operate mainly relay-based systems for ensuring safety of train traffic (the so-called class B systems). These systems include, first, station centralised traffic control systems, most of which are currently route relay-based ones.

On the railways of Bulgaria, two classes of route relay-based centralised traffic control systems (RRCTCS) are operated, using respectively, the relays of so called «first class of reliability», and the relays of the so called «not first class of reliability».

The inevitable increase in the age of RRCTCSs makes it necessary to assess their technical condition and technical suitability to clarify strategies for their further operation.

Such an assessment is difficult due to the lack, first, of statistical data on the failures and reliability parameters during operation as per types of systems and their constituent elements and, second, of manufacturers' recommendations on the service life of RRCTCS.

The service life and residual service life, as well as the useful and residual life of RRCTCSs could, in the author's opinion, be assessed according to the following criteria:

- *Electrical and mechanical useful life/wear of the components.*
- *Reliability parameters of the relay components.*
- *Electrical and mechanical useful life or the condition of the external and internal cabling.*
- *Operating costs required to maintain RRCTCS within the range of predefined technical parameters.*

The article analyses and evaluates the average useful life and the average residual life of RRCTCS based on the first two criteria. It is concluded that neither electrical nor mechanical wear resistance of components is among leading characteristics for assessing useful and residual life.

Two approaches are used to consider some of reliability parameters of the relay components: deterministic and probabilistic one, which are based on the «intensity of dangerous failures» characteristic of the relay of the first reliability class. Based on that characteristic, the probability of a dangerous failure of the first-class relays in operation was calculated for 58 Bulgarian RRCTCSs of N-68 type with non-routed manoeuvres, as well as the probability of their safe operation; the latter probability is proposed to be used to calculate the average residual life of the relay, and based on that, to calculate the average residual life of RRCTCSs of that type. By early 2021, the estimated maximum of the latter is 11 years.

The consequences of implementing two strategies in subsequent years are considered: a) «nothing is done» and b) «RRCTCS useful life/age management» (based on the program of gradual decommissioning of N-68 type RRCTCSs and of re-equipment of relevant stations). This is also a prerequisite for safety management of train traffic.

It is argued that an average useful life of RRCTCS could be estimated as no more than 60 years in operation. Considering additional factors, this period should be understood as a predicted value of the expected time after which the corresponding RRCTCS will reach the limit state and will be decommissioned. The average useful life and the average residual life should be considered the best guideline for the expected age limit for this type of RRCTCS.

Keywords: *train traffic safety, station route-based relay centralised traffic control system (RRCTCS), relays of the «first class of reliability», relays of «not first class of reliability», external cable network, internal cable network, electrical and mechanical wear resistance of components, reliability parameters of relay components.*

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INTRODUCTION

Statement of the Problem

In the second half of the last century, to ensure safety of train traffic at stations, two classes of relay-based centralised traffic control systems were introduced in the system of the Bulgarian Railways, the distribution of which by type is as follows:

• Those using the relays of so-called «first class of reliability» (also called «first class relays») in the Soviet (manufactured in the former Soviet Union) and Bulgarian centralised traffic control systems of the following types:

– in the Soviet relay-based centralised traffic control systems for small stations (Bulgarian abbreviation: SMG);

– in the Soviet interlocking route relay-based centralised traffic control system with routed manoeuvres of IRRCTCSRM (BMRC) type;

– in the Bulgarian route relay-based centralised traffic control system with non-routed manoeuvres of N-68 type;

– in the Bulgarian route relay-based centralised traffic control system with routed manoeuvres of MN70 type;

– in the Bulgarian relay-based centralised traffic control systems for small stations of EC1 and ECM types.

• Using the relays of so-called «not first class of reliability» in centralised traffic control systems of WSSB1 and WSSB2 types, manufactures in the former DDR.

The first route relay-based centralised traffic control system, type WSSB1, was put into operation in 1959, and the least, type MN70, was commissioned in 1999.

After 1999, for various reasons, construction of relay-based centralised traffic control systems for stations was practically stopped, and therefore their age began to gradually increase, and for some stations it has approached and even significantly exceeded 50 years, for example:

• For some centralised traffic control systems of WSSB1 type, the service life by the beginning of 2021 was 61, 58 and 57 years, respectively.

• For a centralised traffic control system of N-68 type, this period was 51 years.

• For a centralised traffic control system of SMG type, it attained also 51 years.

These circumstances make it necessary to assess the technical condition and technical suitability of those centralised traffic control systems in terms of clarifying the strategy for their further operation.

While searching for applicable methodology for assessing the service life and residual service life, as well as the useful and residual life of centralised traffic control systems, the author, getting acquainted with the works [1–4] (but not exclusively those, see, e.g [1, 2]), came to the conclusion that the use of formalised mathematical methods of analysis and assessment of those values in this case is rather complicated due to the lack of statistical data in the country on failures during operation as per systems and their components, as well as on such parameters of reliability as time and mean time between failures, time and average recovery time after a failure, the system maintenance costs distributed over time considering inflation rates, etc.

In addition, there are no recommendations from RRCTCS manufacturers (both foreign and Bulgarian) who do not take responsibility for the duration of the service life, during which normal operation of these systems should most likely be guaranteed. On the one hand, this can be explained by marketing considerations related to market competition. On the other hand, such a strategy is understandable, since in the life cycle of RRCTCS, technical maintenance and prevention, which have an undoubted and sometimes decisive role, are outside the competence and responsibilities of manufacturers of these systems.

See the above, the current approach in the country to the question on the maximum service life of the corresponding types of RRCTCS is controversial. The first opinion can be summarised as that all the relay-based centralised traffic control systems aged over 45–50 years should be promptly decommissioned and the other one concludes that their operation can continue until signs of unsuitability appear, without specifying those signs.

The above circumstances prompted the author to try to suggest a slightly different methodology for assessing the residual service life, as well as the useful or residual resource of relay-based centralised traffic control systems operated at rail stations. In author's views, this assessment can be made according to the following criteria:

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[1] Guidance document RD 26.260.004-91 [In Russian]. Guidelines. Prediction of the residual life of equipment by changing the parameters of its technical condition during operation. Moscow, 1991.

[2] Guidance document RD 50-423-83 [In Russian]. Guidelines. Technological reliability. Methodology for predicting the residual life of machines and parts subject to wear. Moscow, Publishing house of standards, 1984.

• Electrical and mechanical useful life/wear of components and especially of the relay components as of the main element of the RRCTCS.

• Some reliability parameters of the relay components.

• Electrical and mechanical useful life or the condition of the external and internal cable networks.

• Other criteria such as operating costs required to maintain the facility in conformity with the range of predefined parameters.

From the point of view of operation of stations' RRCTCSs, the most important goal of such an assessment should be to determine the probability of a hazard (incident) accumulated during their operation referring to safety of train traffic.

Further presentation of the study refers to the author's research on the first two criteria of evaluation of RRCTCS using relays of the first reliability as the main components.

Terms and Definitions

For certainty and unity in understanding further presentation, it would be advisable to cite the following terms and definitions used in this article, compiled based on [1]:

• *Limit state* is a state of an object when its further operation is unacceptable or impractical, or when restoration of its operable state is impossible or impractical.

• *Object age* is the period from the date of commencement of operation to the current moment.

• *Service life* of an object is calendar time equal to the period of operation, counted from the date of commissioning of the object to the date when it reaches the limit state (decommissioning).

• *Useful life* of an object is the total operating time of the object, expressed in hours, kilometres, etc., counted from the date of commissioning of the object to the date when it reaches the limit state (decommissioning).

• *Average service life* (*average useful life*) is the average value of a random variable of service life (useful life), counted from the date of commissioning of the object to the date when it reaches the limit state (decommissioning).

• *Residual service life* is the calendar duration of operation of an object from the current moment to the moment when it reaches its limit state. It differs from the service life in that the current moment is taken as the starting point, up to which it has been in operation for some time and has exhausted part of the initial useful life.

• *Residual life* of an object is operating time of the object, expressed in hours, kilometres, etc., from the current moment until it reaches the limit state. It differs from the useful life of the object in that the current moment is taken as the starting point, until which it has been in operation for some time and has exhausted part of the initial resource [1].

RESULTS

1. Assessment of the Electrical and Mechanical Useful Life of the Relay Components

To assess the electrical and mechanical useful life of the relay components used in Soviet and Bulgarian RRCTCSs and based on relays of the first reliability class, the catalogue specifications of both the first-class relays (types NMSh, OMSh, DSSh) and of relays that do not belong to this class (types IMVSh, TSh, PMPSh, etc.) were analysed (Table 1, columns 2 and 3 [5; 6]).

The newer developed Bulgarian RRCTCSs for small stations of EC1 and ECM types along with some types of relays indicated in Table 1 have also used since mid-1980s small-sized relays of the first class of REL type (Table 2 [5]).

The main characteristics of these types of relays, which might refer to the useful life of stations' RRCTCS of relevant types, are electromechanical characteristics, which are associated with the electrical and mechanical wear resistance of these relays. These characteristics are measured by the number of on/off cycles for which the manufacturer guarantee normal operation with high probability. At the same time, as can be seen from columns 3 of the tables, this number is different for different types of load (active, with DC or AC power supply), as well as for different types of contacts (front and back, reinforced and unreinforced contacts).

The frequency of operation of the main part of the relay, mainly of relays of the first class (NMSh, REL, OMSh, DSSh types), depends on intensity of train traffic, measured in pairs of trains per day, while for relays operating in a pulsed mode (IMVSh, TSh), such dependence is practically absent, since with some insignificant exceptions (for example, relays of type IMVSh), they operate in a continuous pulse mode. Therefore, regardless of electromechanical wear

Table 1

No.	Relay type	Electrical and mechanical wear resistance: number of «on/off» cycles 20		Electrical and mechanical wear, ... years with traffic intensity, pairs of trains			Control check with control equipment with traffic intensity, pairs of trains		
				40	60	20	40	60	
1	2	3		4	5	6	7	8	9
1.	NMSh1-2000 [*neutral small-size plug-in relay*[3]]	$1{,}2 \cdot 10^6$		14600 on/off cycle per year for track relays – 82,19 years with active load	29200 on/off cycle per year for track relays – 41,09 years with active load	43800 on/off cycle per year for track relays – 27,4 years with active load	Once per 80 years[2]	Once per 40 years	Every 25 years
		Active load at front contact 2 A/24 V, DC or 0,5 A/230, AC	Active load at back contact 1A/24 V, DC or 0,3 A/230 V, AC						
2.	IMVSh-110 [*pulse small-size plug-in relay with rectifier*[3]]	20 000 000 $(2 \cdot 10^7)$		Continuous mode, 60 pulses/min 536 000 per year 0,634 years			Every 7–8 months		
		Load 0,5 A/16 V, DC							
3.	TSh-2000 *[transmitter-type plug-in relay*[3]*]*	15 000 000 $(1{,}5 \cdot 10^7)$		Continuous mode, 60 pulses/min 31 536 000 per year 0,476 years			Every 6 months		
		Load at front contact 300 VA, 110/230 V, AC	Load at back contact 150 VA 110/230 V, AC						
4.	DSSh-13A *[two-part sector-type plug-in relay*[3]*]*	100 000 $(1 \cdot 10^5)$		14600 on/off cycle per year for track relays – 6,85 years	29200 on/off cycle per year for track relays – 3,43 years	43800 on/off cycle per year for track relays – 2,28 years	Every 7 years	Every 3,5 years	Every 2 years
		Load at front contact 1A, 110 V, AC	Load at back contact 1A, 110 V, AC						
5.	PMPSh-150/150 [polarised starting small-size plug-in relay[3]]	Reinforced contact 100 000 (10^5) «on» cycle, 1000 (10^3) «off» cycle	Unreinforced contact 100 000 (10^5) on/off cycle	7300 on/off cycle per year (1 per 1 pair of trains) for unreinforced contacts 6,85 years	14600 on/off cycle per year (1 per 1 pair of trains) for unreinforced contacts 3,43 years	21900 on/off cycle per year (1 per 1 pair of trains) for unreinforced contacts 2,28 years	For unreinforced contacts – every 7 years	For unreinforced contacts – every 3,5 years	For unreinforced contacts – every 2 years
		Act. load at front contact 4A, 240 V, DC	Act. load at front contact 2A, 24 V, DC						
6.	OMSh2-40 *[light-out small-size plug-in relay*[3]*]*	600 000 $6 \cdot 10^5$		14600 on/off cycle per year (2 per 1 pair of trains) 41,10 years	29200 on/off cycle per year (2 per 1 pair of trains) 20,55 years	43800 on/off cycle per year (2 per 1 pair of trains) 13,7 years	Once per 40 years	Every 20 years	Every 14 years
		Loads at front contact 2 A/24 V, DC or 0,5 A/230 V, AC	Load at back contact 2 A/24 V, DC or 0,5 A/230 V, AC						

[3] Translator's note.

[4] Hypothetically.

Table 2

No.	Relay type	Electrical and mechanical wear resistance: number of «on / off» cycles				Electrical and mechanical wear, ... years with traffic intensity, pairs of trains			Control check with control equipment with traffic intensity, train pairs		
						20	40	60	20	40	60
1	2	3				4	5	6	7	8	9
1.	REL1-1600 *[electromagnetic DC relay[3]]*	$1{,}5 \cdot 10^6$		$3 \cdot 10^6$	10^7	14600 on/off per year for track relays – 102,74 years active load, 205,48 years, relay load	29200 on/off per year for track relays – 51,37 years active load, 102,64 years, relay load	43800 on/off per year for track relays – 34,25 years active load, 68,48 years, relay load	103 years, active load 205[3] years, relay load.	51 years, active load 103[2] years, relay load	34 years, active load 68 years, relay load
		Active load at front contact 2 A/24 V, DC or 0,5 A/230 V, AC	Active load at back contact 1A/24 V, DC or 0,3 A/230 V, AC	Relay load 50 мА/24 V, DC	Without load						

[5] Hypothetically.

resistance guaranteed by the manufacturer and that is 10–15 times higher, the wear resistance is exhausted in several months. This does not mean that these relays should be decommissioned, but it is required by the manufacturer (to ensure their further normal operation) to proceed with regular check followed by replacement of some components, first, of contact plates.

The following conclusions can be drawn from the performed analysis of the characteristics of the relays used, referring to the frequency of the recommended checks at control and test points (CTP):

• Regular check of electromechanical wear resistance of relays operating in a pulsed mode (such as IMVSh, TSh) should be performed every 6–8 months. If this is not done, the failure rate of these relays increases during operation, therefore, the number of failures of the corresponding types of RRCTCS also increases.

• Regular testing of electromechanical wear resistance of DSSh and PMPSh relays, depending on intensity of train traffic, should be carried out every 2–7 years. It is wrong to refuse such a check to «optimise» the CTP personnel. If this becomes a practice, then it results in an increase in the likelihood of a dangerous failure of DSSh-type relays and in a decrease in operational reliability of control circuits for some types of switches (due to PMPSh type relay).

• With a low intensity of train traffic, about 20 pairs per day, NMSh and OMSh types relays might be exonerated from control checks for the entire time before decommissioning. With an average train traffic intensity of about 40 pairs per day, these relays should be checked once every 40 years, which is to some extent commensurate with the resource of RRCTCS of the corresponding class, considered in the following sections. With a high intensity of train traffic (about 60 pairs per day), the relay of NMSh type should be subjected to a control check once every 25 years, and the relay of the OMSh type – once every 14–15 years.

Under relay load conditions, relays of REL type do not require periodic checks during the entire period of operation of the corresponding class and types of RRCTCS, since this period at high train traffic (about 60 pairs per day), as it is assumed, will be no more than complete electromechanical wear of the relay (68–70 years). With active load and high intensity of train traffic, it is possible to recommend checking the relay 34–35 years after RRCTCS was put into operation.

From the performed analysis it becomes clear that the electromechanical wear resistance of the components of station RRCTCS in which relays of the first and not the first class of reliability are used, cannot be considered as the leading criterion for assessing:

• Service life.

• Useful life.

• Average service life (average useful life).

• Residual service life and residual life of this class of relays and of relevant types of station RRCTCSs.

2. Assessment of the Useful and Residual Life of a Class of RRCTCS of a Railway Station

Soviet and Bulgarian developments of RRCTCS of railway stations ensured train traffic safety (along with the accepted principles of circuit synthesis) with the use of a safe component which is a relay of the first reliability class. The main distinctions of this type of relay are the following features:

• Almost complete absence of a probability of welding of front and axial contacts thanks to the use of special design and technological solutions.

• Guaranteed opening (under the influence of the mass of the heavy armature of the magnetic system of the relay) of the electric circuit with a closed front contact when the supply voltage is turned off.

In case of using such components in the schemes for ensuring safety of train traffic (mainly in the circuits of the so-called executive group of RRCTCS), the designer considers the first-class relay as a safe element, the behaviour of which after failure is not questioned, which is why this behaviour is usually not subject to analysis.

In fact, safety of a relay of the first reliability class has its own meter and it is called the «intensity of dangerous failures», measured in 1/h. In [6], based on the collected statistical data, the intensity of dangerous failures has been determined as $\lambda_{dang} = 1{,}4 \bullet 10^{-11}$ 1/h. To assess safety of existing relays of the first class, the inequation is accepted:

$$10^{-10}\ 1/h > \lambda_{dang} > 10^{-12}\ 1/h, \qquad (1)$$

moreover, 10^{-10} 1/h is recommended for relays in operation. The adoption of this value (for the purposes of this study) is also justified since the RRCTCSs operated in Bulgaria use relays of the first class of both Soviet and Bulgarian production (manufactured according to Soviet design documentation and with Bulgarian technology).

To calculate the useful and the residual life of RRCTCSs, whose executive circuits use relays of the first reliability class, two approaches are proposed which are respectively deterministic and probabilistic ones. The most numerous among currently operated Bulgarian RRCTCSs N-68 type RRCTCS with non-routed manoeuvres has been considered as an example. A fragment of an impersonal list of stations with the oldest (51–48 years) and less old (30–25 years) RRCTCSs is shown in Table 3.

The proposed approaches are based on the «hazardous failure rate» characteristics of the first-class relay, the numerical value of which in [7] is determined by the following formula:

$$\lambda dang(t) = \frac{r(t)}{N \bullet t},\ 1/h, \qquad (2)$$

where $r(t)$ is the number of dangerous failures during the monitoring period;

N – number of relays;

t – monitoring period.

2.1. Deterministic Approach

With this approach, the age of RRCTCS and the number of first-class relays in operation are considered as determined values.

RRCTCS of type N-68 (including modifications with indices «v» and «u») at a station with 10 switches, 2 derailers (derailing blocks), 8 exit (departure), 2 entrance (entry), 2 distant (warner) and 1 repeating (repeater) signals operates exactly 380 first-class relays. According to expert analysis, for stations of this type with the smallest number of specified objects, the total number of first-class relays is estimated at about 300, and for stations with the largest number of such objects it is estimated at about 460. In this regard, it can be assumed that RRCTCSs in operation are characterised by the deterministic parameters described in Table 4.

Based on (2) and the designations from Table 4, it can be written that the predicted number of dangerous failures that may occur under the considered conditions is:

$$O_{dang} = \lambda_{dang} \bullet I \bullet N \bullet J \bullet 365 \bullet 24, \qquad (3)$$

or:

$$O_{dang} = 1 \bullet 10^{-10} \bullet 58 \bullet 380 \bullet 40{,}71 \bullet 365 \bullet 24.$$

From the calculations it follows that by the beginning of 2021 $O_{dang} = 0{,}78599$, i.e., the total elapsed operating time of the relay can be considered insufficient for occurrence of the first

Table 3

No.	RRCTCS type	Year of commissioning	Age by the beginning of 2021, years	No.	RRCTCS type	Year of commissioning	Age by the beginning of 2021, years
1.	N68	1969	51	…	…	…	…
2.	N68	1971	49	52.	N68u	1990	30
3.	N68	1972	48	53.	N68u	1990	30
4.	N68	1972	48	54.	N68v	1991	29
5.	N68	1972	48	55.	N68u	1991	29
6.	N68	1972	48	56.	N68u	1993	27
7.	RRCTCS-N68	1972	48	57.	RRCTCS-N68	1994	26
8.	RRCTCS-NH68	1972	48	58.	RRCTCS-N68u	1995	25

Table 4

Total number of RRCTCSs, I	Age, years		Number of the first-class relays in operation*, pcs		Recommended calculated intensity of dangerous failures λ_{dang}, 1/h
58	Range	Average age for all RRCTCSs (*J*)	Range	Average *(N)*	$1 \cdot 10^{-10}$
	25–51	40,71	300–460	380	

* For the purposes of the study, it is assumed that, during operation of the corresponding local RRCTCS, the mounted relays of the first class, although they were subjected to periodic checks, were not replaced for new ones, and were not subjected to repair (replacement of parts). This circumstance is indeed characteristic of their real operation.

dangerous failure. If O_{dang} is considered as the probability Q_{dang} of occurrence of at least one dangerous failure of the first-class relays in operation, then the difference $1 - Q_{dang} = 0,21401$ can be taken as the probability of their safe operation $P_{s.}$

The author's thesis is that P_s is considered as a certain margin until the first dangerous failure of any relays of the first class in operation is reached, and this can be used as a basis for calculating the average residual life of these relays. From the point of view of ensuring safety of train traffic, the calculated average residual life of the relays can be taken as the average residual life of RRCTCSs. Based on that, we can write that:

$0,2140 = 11 \cdot 10^{-10} \cdot 58 \cdot 380 \cdot T_{res} \cdot 365 \cdot 24$,

hence:

$T_{res} = 0,21401/1 \cdot 10^{-10} \cdot 58 \cdot 380 \cdot 365 \cdot 24 = 11,0845$ years.

Therefore, it can be assumed that the average residual life of the first-class relays in operation until at least one dangerous failure is equal to about 11 years[5]. Hence, the average residual resource of RRCTCSs of N-68 type in operation, referring directly to safety of train traffic, could be estimated at 11 years as by the early 2021.

[5] According to earlier estimations made by the author in 2017, when 61 RRCTCSs of this type were in operation, the average residual life of the relays was 11,6 years.

Let us assume that during next 11 years a «nothing is done» strategy is applied to these RRCTCSs. This will mean that in 11 years the age of object No. 1 (Table 3) will reach 62 years. Then the probability Q_{dang} of a dangerous failure of the first-class relays for all RRCTCSs of this type in operation will be practically equal to 1 (0,9984). Therefore, to avoid a situation that can cause an accident with serious consequences, the strategy of «RRCTCS useful life/age management» is proposed.

For the purposes of the subsequent analysis, let us consider two variants of the limiting age of RRCTCS of this type: a) 60 years (Table 5) and b) 55 years (Table 6). Here, these options will have the meaning of «assigned», i. e., hypothetical useful life. This means that in 9 years, and, respectively, in 4 years, the «oldest» RRCTCS at station No. 1 (Table 3) should be decommissioned.

Column 3 of Tables 5 and 6 indicates Q_{dang} and P_s for all RRCTCSs of type N-68 at the following steps of the strategy development:

1. RRCTCS at station No. 1 has been in operation for 60 or 55 years, respectively (row 1 of Tables 5 and 6).

2. RRCTCS at station No. 2 has been in operation for 60 or 55 years, respectively (row 3 of Tables 5 and 6).

Table 5

No.	Steps of the strategy development	Q_{dang}	P_s
1	2	3	4
1.	RRCTCS at station No. 1 is in operation for 60 years	0,9598	0,0402
2.	At the time immediately after decommissioning of RRCTCS at station No. 1	0,9397	0,0603
3.	RRCTCS at station No. 2 is in operation for 60 years	0,9777	0,0223
4.	At the time immediately after decommissioning of RRCTCS at station No. 2	0,9577	0,0423
5.	RRCTCSs at stations No. 3–9 are in operation for 60 years	0,9764	0,0236
6.	At the time immediately after decommissioning of RRCTCSs at stations No. 3–9	0,8366	0,1634

3. RRCTCSs at stations No. 3–9[6] have been in operation for 60 or 55 years, respectively (row 5 of Tables 5 and 6).

4. The values of Q_{dang} and P_s at the moment immediately after decommissioning of RRCTCSs of the corresponding stations are indicated in rows 2, 4, 6 of Tables 5 and 6.

It can be seen that if we take the «assigned» average useful life of RRCTCSs equal to 60 years (Table 5), then before decommissioning RRCTCSs at stations 1–9, the probability of a dangerous failure remains close to 1. If this useful life is taken equal to 55 years, then before decommissioning of RRCTCSs at stations 1–9 there is a certain margin in probability P_s situated in the range of 0,12–0,14 (rounded off).

Hence, we can conclude that if we assume the average service life of 60 years as the average useful life of a RRCTCS of N-68 type, then it will be somewhat risky, while assuming the term of 55 years will be a rather pessimistic decision. Apparently, the average value should be considered more reasonable, i.e., 57–58 years. This will allow to consider the following additional factors for each specific RRCTCS:

• The state of the external cabling and of the internal wiring and conductors. In this case, it is necessary to assess the current changes in the characteristics of the cables. It should be borne in mind here that RRCTCSs with a longer service life are more vulnerable in terms of quality of cables and conductors used in the past. This aspect, from the point of view of occurrence of a dangerous failure, regardless of the likelihood of such a failure of a first-class relay, should not be neglected at all, therefore, it requires a separate consideration.

• Quality of maintenance, which affects the general technical state of a particular RRCTCS. Practices and observation show that RRCTCSs of one and the same age can either look completely worn or keep an acceptable technical state.

• The operating costs associated with keeping the characteristics of RRCTCSs within the range of predefined parameters can also be subject to assessment from the point of view of their economic viability.

In doing so, one should expect that the probability of a dangerous failure of the first-class relay in RRCTCSs of the indicated type will not reach $Q_{dang} = 1$.

To implement the strategy of «RRCTCS useful life/age management», it is necessary to develop a program for re-equipment of stations with RRCTCSs of N-68 type guided by a clear idea that this is a necessary condition for managing safety of train traffic.

[6] Station No. 9 is not indicated in Table 3.

Table 6

No.	Steps of the strategy development	Q_{dang}	P_s
1	2	3	4
1.	RRCTCS at station No. 1 is in operation for 55 years	0,8632	0,1368
2.	At the time immediately after decommissioning of RRCTCS at station No. 1	0,8483	0,1517
3.	RRCTCS at station No. 2 is in operation for 55 years	0,8828	0,1172
4.	At the time immediately after decommissioning of RRCTCS at station No. 2	0,8646	0,1454
5.	RRCTCSs at stations No. 3–9 are in operation for 55 years	0,8832	0,1168
6.	At the time immediately after decommissioning of RRCTCSs at stations No. 3–9	0,7550	0,2450

Table 7

Number of RRCTCSs, I	Estimated average useful life J, years
10	300,408
20	150,205
30	100,136
40	75,102
50	60,082
60	50,068
70	42,915
80	37,551
90	33,378
100	30,041

Additional comment 1

From the above, one might get the impression that if $O_{dang} = 1$ is substituted in (3), and since λ_{dang}, I and N are known, as in the case under consideration, then the average useful life for all RRCTCSs based on occurrence of the first dangerous failure can be determined as:

$$J = 1/\lambda_{dang} \cdot I \cdot N \cdot 365 \cdot 24, \text{ years.} \quad (4)$$

It turns out that this is not entirely true.

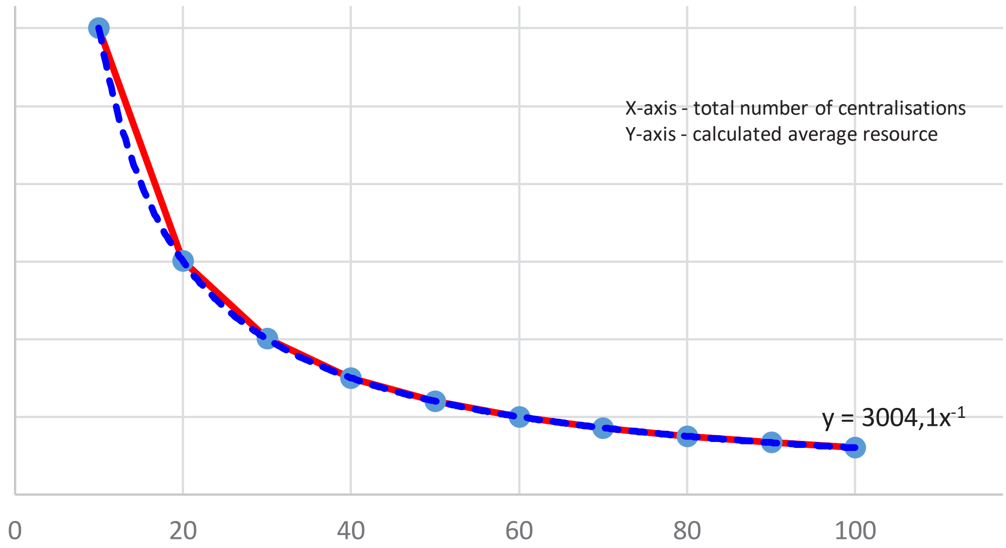
Table 7 and Pic. 1 give the dependence of the average useful life of RRCTCSs of N-68 type on the number of RRCTCSs in operation. It can be seen that if the number $I \leq 60$, then the calculated average useful life increases sharply. This is reasonable, because in such cases the total number of relays is not enough for the first dangerous failure to occur with a probability equal to 1. Then the key factor for determining the useful life of RRCTCS will be associated not with the probability of the first dangerous failure, but with the electrical and mechanical wear resistance/actual wear of the relays (see section 1, Tables 1 and 2), as well as with the condition of the cable network and operating costs required to maintain each individual RRCTCS within the range of assigned parameters.

If the number of RRCTCSs $I > 60$, the average useful life of RRCTCSs decreases. However, here it should be borne in mind that with such a number of RRCTCSs and due to their non-simultaneous construction, there will be RRCTCS both with an age much less and with an age greater than the calculated average useful life[7]. In these cases, the criterion «determination of the average residual life based on 100 % probability of the first dangerous failure» will prevail.

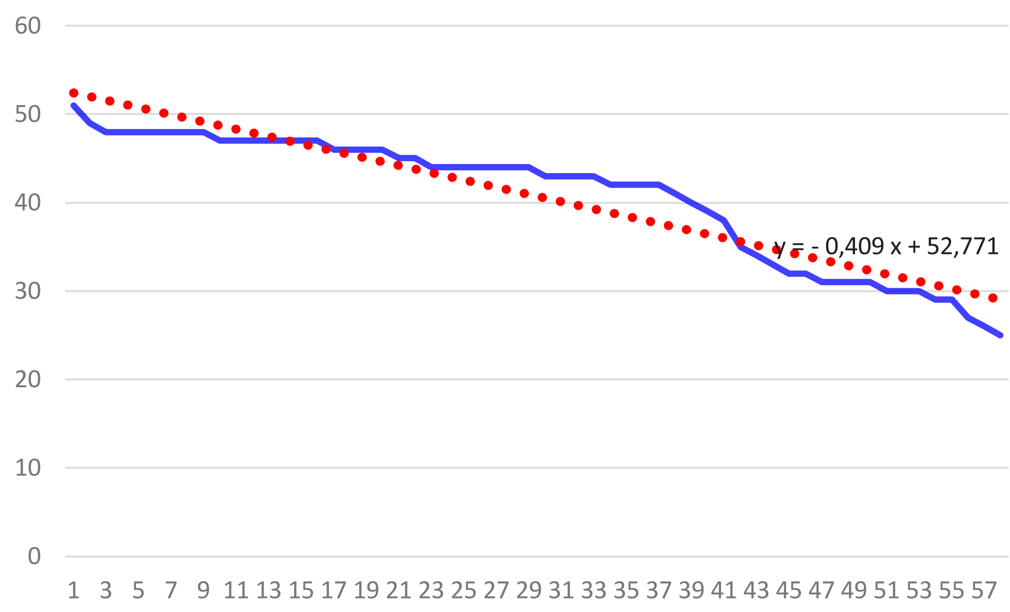
2.2. Probabilistic approach

To implement this approach, simulation was performed using the Monte Carlo method, for which:

[7] For comparison, see Table 3, where the average age of RRCTCSs is 40,71 years, while the age of the «oldest» TCS is 51, and the «youngest» TCS is 26 years old.



Pic. 1. Average useful life of RRCTCS of N-68 type before occurrence of the first dangerous failure.
Note: Red curve is an average estimated useful life depending on the total number of RRCTCSs; blue dotted curve is a trend line ($y = 3004,1.x^{-1}$).



Pic. 2. Age of RRCTCSs of N-68 type.
Note: x-axis – number of RRCTCSs, y-axis – age.

• The number of the corresponding RRCTCS is considered and modelled as a random number in the range of 1–58 using a uniform distribution.

• The age is considered as a random number, which is determined based on a random number of a RRCTCS with the linearised function y = *f(x)* of the real age of RRCTCSs (Pic. 2), which is the trend line y = -0,409 x + 52,771.

• The number of relays is considered and modelled as a random number in the range of 300–460 pcs. with a uniform distribution.

Modelling was performed for 20 series with 5800 scenarios for each series with the following final results: Q_{dang} = 0,78986, P_s = 0,21014, average age = 40,897 years.

It is evident that the values of Q_{dang}, P_s and average age obtained using probabilistic modelling practically do not differ from the calculations performed with determined values from section 2.1, which proves a high convergence of the results obtained based on both approaches (deterministic and probabilistic).

Additional comment 2

The proposed concept of safety management of rail stations' relay-based centralised traffic control systems which use relays of the first class, can be applied to other types of RRCTCSs of the same class. In this regard, for RRCTCS of MN70 type with routed manoeuvres, which were put into operation mainly after 1975 and the number of which is much less than of other types, this average useful life (no more than 60 years) can also be assumed as reasonable since the number of relays of the first class in them is at least 2 times more than of those used in RRCTCSs of N-68 type. Besides, the stations equipped with this type of RRCTCS have more controlled objects (switches and signals), and movement of trains and shunting operations are more intense. This allows us to discuss the following actions related to operation of RRCTCSs of the indicated types:

1. Replacement of track circuits with axle counters in RRCTCSs of N-68 type, which are currently more than 47–48 years old. This can be considered appropriate only if there is a problem with the supply of spare elements/blocks necessary to ensure the required operational availability of the track circuit equipment.

2. Dismantling of RRCTCSs of MN70 type on the modernised sections of the railway network, whose age at the time of decommissioning is within the range of 32–35 years. From the point

of view of the above, these RRCTCSs can be «redirected» to stations equipped with RRCTCS of N-68 type, whose useful life/reasonable age has expired despite the fact that RRCTCS of MN70 type would have to a certain extent a hardware redundancy in relation to really necessary performance characteristics. For the purpose of a certain modernisation, it is possible to use for these RRCTCSs the so-called «computer visualisation» instead of the control panel.

CONCLUSIONS

1. This study is an attempt to evaluate, to some extent empirically, the useful life and residual life of a class of rail stations' relay-based centralised traffic control systems using the relays of so-called «first class of reliability».

2. The analysis shows that the residual life and attainment of the limiting state of this class and types of centralised traffic control systems cannot be determined based exclusively on electrical and mechanical wear resistance/wear of relays of the first and non-first reliability classes used in them.

3. From the point of view of realisation of a probability of the first dangerous failure of a relay of the first reliability class, the number of relays in operation and their age is of decisive importance.

4. The average useful life of RRCTCS of N-68 type can be assumed to be equal to 57–58, but not more than 60 years, and their average residual life by the beginning of 2021 to be equal to not more than 9 years. However, these values should not be considered absolute, i. e., they should be understood as predicted values of the expected time, after which the corresponding RRCTCS will reach the limit state and will be decommissioned. This is due to the need to consider the additional factors mentioned in the study. In this regard, the calculated average useful life and the average residual life of RRCTCSs of this type represent the best guideline for their expected age limit.

5. Closure of individual low-density stations (following reasonable optimisation of the transportation process technology) or decommissioning of the stations with RRCTCSs using relays of the first reliability class, especially those with already long service life, can be considered as factors leading to better stability of the probability of occurrence of the first dangerous failure.

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Information about the author:
Dimitrov, Rumen, *Ph.D. (Eng), Senior Researcher, Expert of TINSA Ltd., Sofia, Bulgaria, rudimitrov@mail.bg.*

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