TRANSPORT PROBLEMS 2023 Volume 18 Issue 3
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2023.18.3.11

Keywords: rail transport; railway infrastructure; track geometry measurement; ARTIW, TOPSIS

Gintautas BUREIKA[1]

AN APPROACH TO TECHNOLOGICAL EQUIPMENT SELECTION FOR MEASURING RAILWAY TRACK GEOMETRY

Summary. The most-used railway track geometry measurement systems are considered in this study. The advantages and disadvantages of considered systems and the necessity and application of these technologies in European railways were examined. The decisive factors of the operation of measurement equipment were considered. Real-time railway track condition monitoring systems were evaluated by 14 experts according to a scale of 13 criteria. Questionnaire data were processed using Kendall's rank correlation method, and the mean ranks were normalized using the average rank transformation into weight method. The most relevant evaluation criteria describing the principles of operation and quality of the most promising technologies were defined. The most important criteria for assessing the suitability of technologies were determined by applying the technique for order of preference by similarity to ideal solution. Finally, basic conclusions and recommendations were formulated.

1. INTRODUCTION

Railway transport is a type of land transport characterized by a large volume of cargo transportation, safety, and low environmental pollution compared to whole transport. Recently, this type of transport has become increasingly relevant, both in Europe and around the world.

Worldwide, railway transport occupies a strong position in countries' land transport sectors. It should be noted that the railways of Western European countries are dominated by passenger traffic. Europe's railways carry millions of passengers and huge amounts of freight every day. The stability, smoothness, and continuity of train movement are ensured by high-quality contact between rolling stock wheels and rails [1]. Thus, in order to ensure the safety of cargo and the comfort of passenger transportation, railway companies must constantly control and monitor the technical condition of the railway infrastructure. Existing railway track (infrastructure) monitoring systems are constantly being improved, and their functionality is being expanded.

The managers of the railway infrastructure of each country install the most appropriate railway track maintenance systems, which are adapted according to the specifics of the country's railway infrastructure. With a wide choice of technologies, it is difficult for managers to choose the most suitable model or combination of systems. That problem could be eliminated or reduced by the creation of a public access database. This would systematize the functionality parameters of the new technologies for technical diagnostics and the on-line monitoring of railway tracks. A generally accepted mathematical tool for evaluating and comparing these technologies would also be useful.

Taking into account global trends, the main issue examined in this paper is the timely detection of railway track damage in order to avoid train traffic disturbances or traffic accidents (i.e., rolling stock derailment). The objective of this study is to assess non-contact measuring technologies and equipment (devices) of railway track geometric parameters.

[1] Vilnius Gediminas Technical University, Department of Mobile Machinery and Railway Transport; Plytinės g. 25, LT-10105, Vilnius, Lithuania; e-mail: gintautas.bureika@vilniustech.lt; orcid.org/0000-0003-3934-0005

The continuous monitoring of the geometrical parameters of the railway superstructure using trains in operation is of increasing interest to railway infrastructure operators, managers, and railway workers [3, 5]. Continuous monitoring of the track is the best way to determine the current state of the geometry of the track and the rolling surface of the wheels due to the relationship between the reaction of the vehicle running gear (vertical acceleration of the axle boxes) and the vertical damage of the track [2]. It is very important that critical damage is identified in time. Other measured parameters of track geometry, such as track curves, track twists, or transverse alignment of the track, are examined, which are also necessary to ensure the necessary maintenance and safety of train traffic to plan track repairs. It should be noted that there are also unattended on-line measurement systems on the market, which are installed in operating trains. These systems measure all track parameters while trains are running on the lines, but these systems use expensive inertial platforms (e.g., Mermec in UK railway systems).

The following advanced basic sensors and devices are commonly used to determine the change of geometrical parameters of tracks over time: accelerometers, geophones, railway track video cameras, digital image correlation, position-sensitive devices mounted on sleepers/rails to detect laser position, and multi-depth deflectometers).

Rail-mounted optical systems can also be used to detect rail breaks or as strain sensors to measure forces during wheel-rail interaction. Technologically, it is particularly important to measure the geometrical parameters of the railway track under the axle load of the rolling stock of approximately 150–200 kN (15.5–20.5 tons). This reproduces the operational displacements of the track, which occur under the action of a real axle load during operation.

The profile and dimensions of the rolling surface of the rail head are measured by laser cameras mounted on passing vehicles. Gauges are monitored by distance sensors installed on the rails. The most common distance sensors are laser sensors. Infrastructure managers usually use a special track geometry car or a tracked registration car. These track geometry measurement systems meet the requirements of all six parts of the EN 13848 and EN 14363 standards [5, 6]. The following parameters of track geometry are described in the stand: track width, longitudinal level, transverse level, and leveling. In recent years, railway infrastructure managers have been using an unattended track geometry measurement system (UTGMS). For example, the company Mermec, which is based in Italy, provides inertial and optical UTGMS, which are designed to measure all geometrical parameters of a track and all its profiles while a train is running at a high speed. Examples of track measurement systems are shown in Fig. 1.

Acceleration measurement comes with pre-processing techniques. This is the most popular choice due to the robustness of the accelerometers. In comparison, optical sensors, such as laser sensors and camera-based sensors, must be cleaned regularly to function and, therefore, require special care to prevent dirt from entering in-use vehicles or measuring systems. The robustness of the devices is the most important feature of the system, which is applied in the running of in-service gear rolling stock because the monitoring system should not require additional maintenance or affect the reliability or availability of the vehicle itself [2, 12].

The most accurate measurement is based on the acceleration of the axle box of the bogie and the vertical displacements of the axle box from the accelerometer, even though displacement transducers are more vulnerable and expensive than accelerometers. The need for displacement transducers is avoided by installing accelerometers in the axle box, which, together with the dedicated signal, can be used as conversion transforms and the like.

The Plasser system measures all the spatial data of the railway track geometry [7]. The scheme of this track geometry track system is presented in Fig. 2. Noticeably, an inertial measurement unit, global positioning system (GPS), and optical track measurement system are integrated into the measurement system. The system consists of several subsystems mounted on a wheelset. Each subsystem has a specific purpose: to monitor rolling flatness, rail integrity, and rail elements. The system consists of two optical boxes consisting of a photo camera and an infrared light emitting diode light installed under the vehicle frame (Fig. 1).

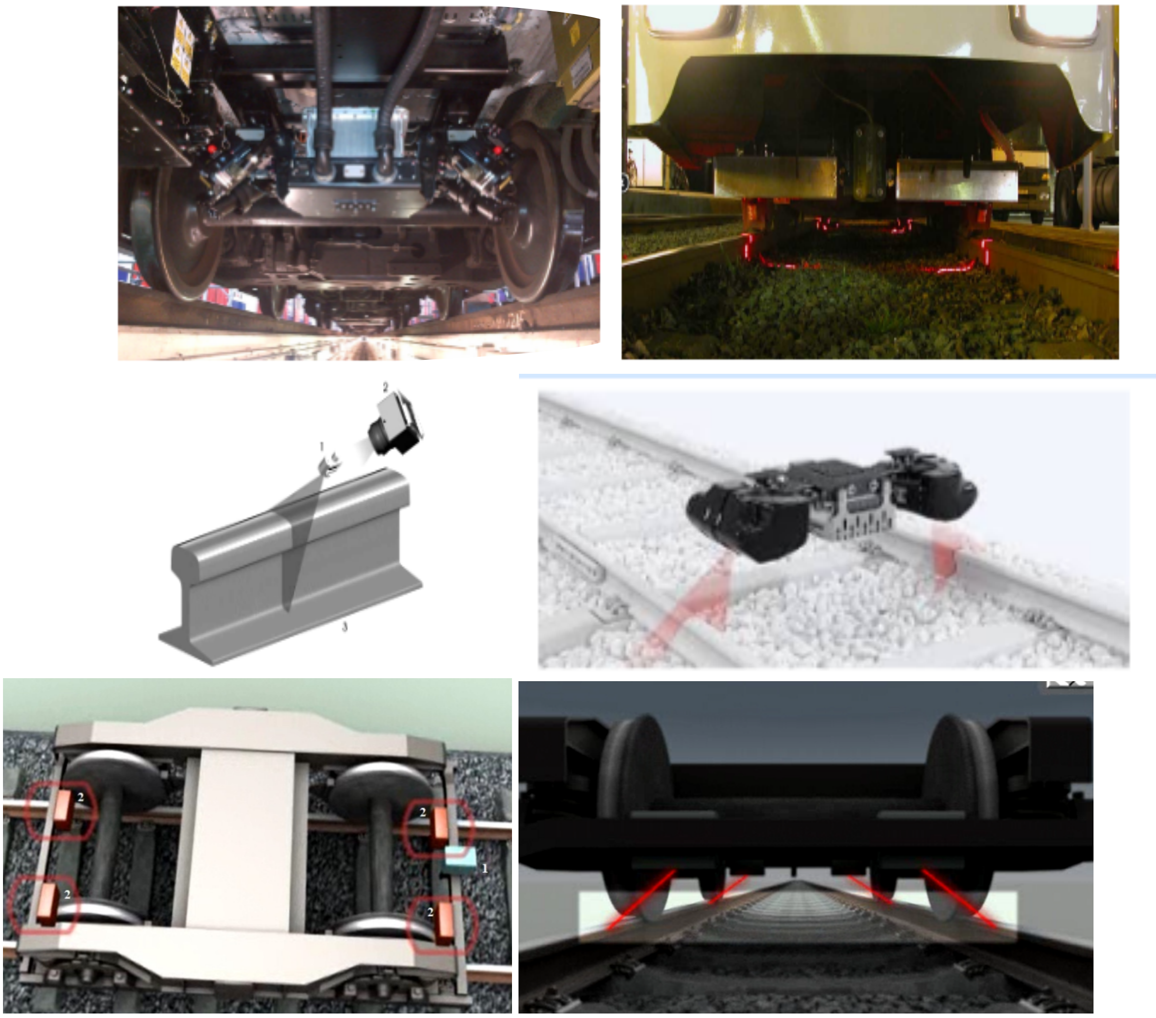

Fig. 1. Track measurement optical system: 1 – inertial measurement unit; 2 – optical gauge measurement system; 3 – IMU lasers directed to the track rails

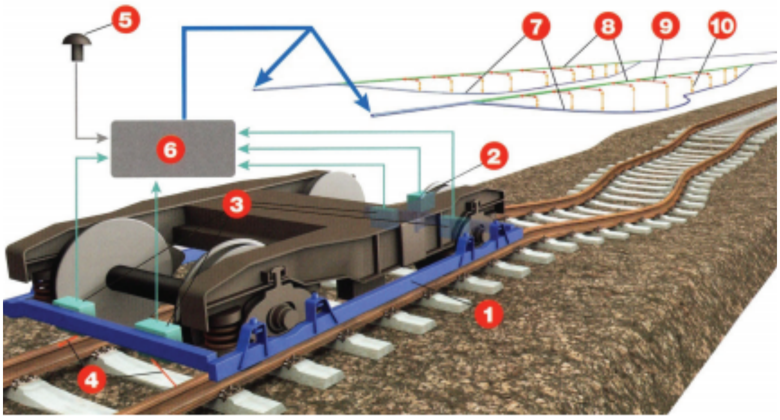

Fig. 2. Elements of track geometry car Plasser EM-140 running gear and measuring devices [7]: 1 – measuring frame with a fixed position parallel to the rails; 2 – inertial measurement system; 3 – optical system for measuring geometric parameters; 4 – laser beam; 5 – GPS navigation system antenna; 6 – GPS navigation computer; 7 – the spatial curve of both rails, obtained after measuring along the track and aligned with GPS data; 8 – track design profile; 9 – deviations of the track in the plan obtained from the spatial curve; 10 – vertical path deviations obtained from the spatial curve

2. METHODOLOGY OF THE COMPARATIVE ASSESSMENT OF MEASURING TECHNOLOGIES

Assessment criterion is a definition of the technological properties of the object under consideration (e.g., equipment price, operation costs, durability). When evaluating different decision options, it is necessary to use criteria that reflect the purpose of the operation [8].

Technical indicators of on-line condition detection technologies could be used as a mathematical tool to evaluate the attractiveness of a system. Data on specific measurement systems and the values of the required indicators were collected from suppliers/manufacturers of track-measuring equipment. The values of the indicators of the on-line technologies of railway gauge measurement are presented in Table 1. An operation is a system of actions, the purpose of which is to achieve a certain goal. Thirteen criteria are distinguished for the evaluation of railway track geometry measurement technologies.

The benchmarking criteria for on-line track measurement technologies are (Fig. 3):

A. System dimensions
B. The power used by the measuring system
C. Resistance to environmental (atmospheric) factors
D. Operating temperature (ambient)
E. Running speed during measurement
F. Durability of the measurement system
G. Accuracy of received data
H. Duration of data archiving
I. User-friendliness
J. Duration of calibration
K. System maintenance costs
L. The urgency of providing technical assistance
M. System price

All the above-mentioned criteria were estimated (ranked) by 14 experts who had at least five years of railway infrastructure maintenance experience. The average rank transformation into weight (ARTIW) method was applied. The defined values of the total ranks of all comparative criteria of the measurement systems are presented in Fig. 3.

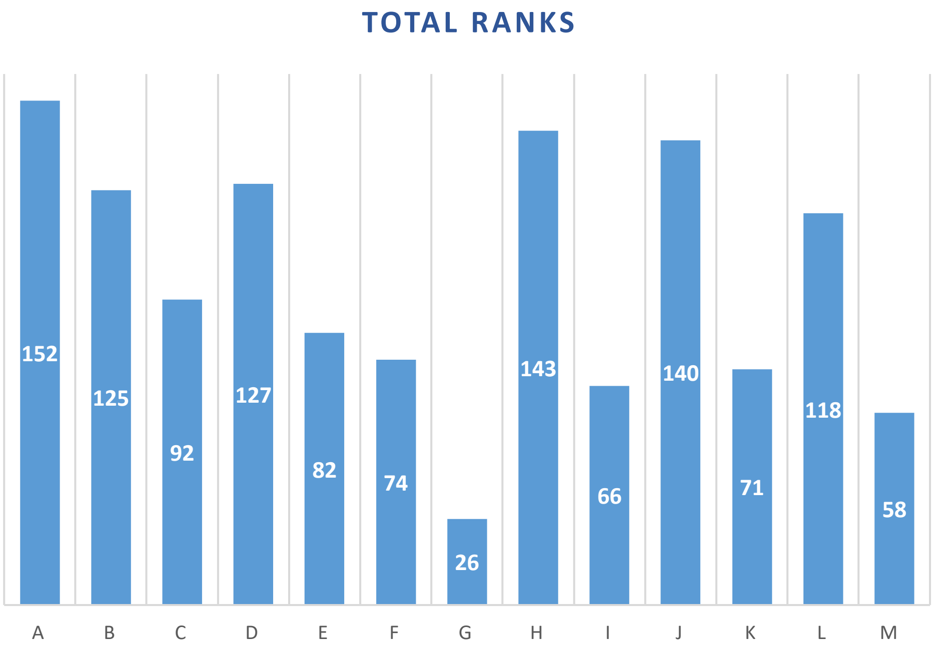

Fig. 3. Bar chart of *R*j sums of expert ranks

As shown in Fig. 3, the highest rank was assigned to Criterion *A* – system dimensions. The second rank was assigned to Criterion *H* – duration of data archiving, and the third rank was assigned to Criterion *J* – duration of calibration.

3. MULTICRITERIA COMPARATIVE EVALUATION OF TRACK MEASUREMENT SYSTEMS

The technique for order of preference by similarity to ideal solution (TOPSIS) was the preferred mathematical method for multicriteria evaluation [4, 13]. TOPSIS is a widely known multicriteria decision analysis method. It is possible to compare a set of alternatives based on a pre-specified criterion. The method is used in businesses across various industries (including the railway industry) whenever there is a need to make an analytical decision based on collected data. The essential logic of TOPSIS is based on the concept that the chosen alternative has the shortest geometric distance from the best solution and the longest geometric distance from the worst solution. Such a methodology allows trade-offs between criteria to be found when poor performance in one criterion can be canceled by a rational performance in another. This provides a comprehensive form of modeling because no alternative solutions are excluded based on pre-defined thresholds. The TOPSIS algorithm encompassing the whole process can be encapsulated in seven steps [13].

Criteria weights have a significant influence on the results of multicriteria evaluation. In practice, the subjective criteria weights of specialists (experts) are usually applied. Subjective weights indicate the opinions of qualified experts in the field under consideration, who have extensive theoretical and practical experience and special knowledge [9, 14].

In experimental studies, the opinions of experts can guide decisions, but their opinions cannot be contradictory. When making a decision based on the average assessment of experts or respondents, it is necessary to determine the degree of compatibility of their opinions according to the concordance coefficient *W* [9]. The rank correlation method is used to determine the compatibility of the opinions of the group of experts [8]. Kendall's concordance coefficient is associated with the sum of the ranks R_j of each *j*-th indicator (criterion) given by n experts ($j = 1, 2, ..., m$):

$$R_j = \sum_{i=1}^{n} R_{ij}; \tag{1}$$

Specifically, the sum of the ranks R_j is related to the sum *S* of the squares of the deviation of the quantities R_j from the overall mean of the ranks $\bar{R}$:

$$S = \sum_{j=1}^{n} (R_j - \bar{R})^2; \tag{2}$$

where R_j is the sum of ranks given by the *j*-th criterion, and $\bar{R}$ is the average rank of each criterion.

The importance of expert opinions in choosing track on-line measurement systems was used to calculate rank averages $\bar{R}_j$, the concordance coefficient *W*, and critical Pearson chi-square χ^2. The critical value $\chi^2_{(v.\alpha)}$ taken from the chi-square distribution table with v=13–1=12 degrees of freedom, and the significance is 26.217 when the level $\alpha = 0.01$. The empirical value $\chi^2 = 85.149$ is greater than the critical value $\chi^2_{(v.\alpha)} = 26.217$. This shows that the experts' assessments are consistent [11].

Further, the data provided in Table 1 are used to determine the most appropriate measurement system. The detailed ranks R_{ij} of 14 expert opinions according to each of the 13 criteria are shown in Table 2. The normalized values of the comparative evaluation of railway track geometry measurement systems are presented in Table 3.

Table 1

Values of the parameters of on-line railway track condition measurement technologies

Parameters	Measurement technology							
	"Plasser" optical measurement system	**Laser profile sensor**	**Laser distance sensor**	**Time of Flight (ToF) camera**	**High Speed Digital Image Correlation (DIC)**	**Laser Systems, Displacement**	**Thermal Measurement System**	**Stereo Measurement Technology**
Weight (size), kg	>5	<0.4	<0.2	<1.5	<0.2	<0.3	<0.8	<0.2
Power, W	<5	<12	<1.5	<50	<5	<5	<5	<2
Operating temperature, °C	-10 to +70	from 0 to +45	-20 to +50	-40 to +105	0 to +40	-10 to +40	-15 to +50	0 to +45
Measurement accuracy	±1 mm	±2 µm	±0.6	±3 mm	±0.9 mm	±75 µm	±1	±1
Operating frequency, Hz	1500	4000	-	600	100	-	60	100
Repeatability of Measurement, mm	±1 mm	±1 mm	<±1 mm	±1 mm	±1 mm	>±1 mm	±1 mm	±1 mm

Table 2

Criteria ranks based on expert opinions

Expert code, *i*=1, 2, …, *n*	Criteria of on-line track condition measurement systems, *j*=1, 2, …, *m*													
	A	B	C	D	E	F	G	H	I	J	K	L	M	Sum
E1	4	7	8	9	1	10	2	12	3	13	5	11	6	91
E2	12	13	6	7	3	5	2	11	8	9	4	10	1	91
E3	13	12	5	6	2	11	1	10	3	9	4	8	7	91
E4	6	2	7	8	5	4	1	11	3	12	10	13	9	91
E5	11	13	10	12	9	4	1	8	2	7	3	5	6	91
E6	10	9	8	5	13	1	6	11	7	12	2	3	4	91
E7	13	6	12	11	9	5	1	7	4	10	3	8	2	91
E8	11	10	5	9	7	4	3	8	6	12	2	13	1	91
E9	7	8	9	10	2	1	3	11	4	13	6	12	5	91
E10	13	11	5	9	10	7	1	12	2	8	3	6	4	91
E11	13	8	2	12	9	7	1	11	6	5	4	10	3	91
E12	13	6	2	5	3	8	1	11	9	10	12	4	7	91
E13	13	9	8	12	5	4	1	11	3	10	6	7	2	91
E14	13	11	5	12	4	3	2	9	6	10	7	8	1	91
$R_j = \sum_{i=1}^{n} R_{ij}$	152	125	92	127	82	74	26	143	66	140	71	118	58	1274
$\bar{R}_j = \sum_{i=1}^{n} \frac{R_{ij}}{n}$	10.85	8.92	6.57	9.07	5.85	5.28	1.85	10.21	4.71	10	5.07	8.42	4.14	91
$\sum_{i=1}^{n} R_{ij} - \frac{n(m+1)}{2}$	54	27	-6	29	-16	-24	-72	45	-32	42	-27	20	-40	0
$\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)$	2916	729	36	841	256	576	5184	2025	1024	1764	729	400	1600	18080

Table 3

Normalized values for the evaluation of measurement systems

Criterion indicator and Measurement technology	Criteria						Sum	Normalized values and ranks
	Size	Energy consumption	Operating temperature	Measurement accuracy	Frequency compatability	Measurement repeatability		
Ranking of criteria								
Weight of criterion	0.127	0.143	0.139	0.25	0.155	0.186	1.00	-
Rank of criterion	7	5	6	1	4	2	-	-
Ranking of technologies								
"Plasser" optical measurement system	0.254	0.286	0.139	0.5	0.31	0.372	**1.861**	**0.126 (the 3rd)**
Laser profile sensor	0.254	0.143	0.139	0.75	0.465	0.372	**2.123**	**0.144 (the 2nd)**
Laser distance sensor	0.254	0.429	0.139	0.75	0.31	0.558	**2.440**	**0.165 (the 1st)**
Time of Flight (ToF) camera	0.254	0.143	0.417	0.25	0.155	0.372	1.591	0.108
High Speed Digital Image Correlation (DIC)	0.254	0.286	0.139	0.5	0.155	0.372	1.706	0.115
Laser Systems, Displacement	0.254	0.286	0.139	0.75	0.155	0.186	1.770	0.120
Thermal Measurement System	0.127	0.286	0.139	0.5	0.155	0.372	1.579	0.107
Stereo Measurement Technology	0.254	0.286	0.139	0.5	0.155	0.372	1.706	0.115
						Total:	**14.776**	**1.00**

4. CONCLUSIONS

After the technologies used for measuring the transverse position of the wheelset in the track and the track profile were compared, it was found that the distance sensor laser is the most suitable, whereas the thermal measurement systems are the least suitable. According to operational appropriateness, the systems are ranked as follows: the laser distance sensor (the first), the laser profile measurement (the second), and the Plasser optical measurement system (the third).

Regarding the importance of track geometry measurement criteria, the highest values were assigned to the following criteria: the accuracy of the received data (0.133), the price of the system (0.109), and user-friendliness (0.102). Consequently, when acquiring a modern track measurement system, at first, it is necessary to assess the accuracy of the data provided by the system, the cost of the system, and the ease of processing gained data.

The opinions of all experts were consistent, as the concordance coefficient W=0.5068 is equal to the lowest concordance value (i.e., W_{min}=0.5068). The use of Pearson's chi-square statistic ensures that the experts' opinions are aligned, as χ^2 = 85.1491 is greater than the critical value corresponding to the number of degrees (12) and the significance level (0.01), which is equal to $\chi(\upsilon,\alpha)^2$ = 26.217. Thus, the data used in the performed survey are valid.

The greatest sum of criterion value (2.440) was obtained for the laser distance sensor. The second-ranked criterion was the laser profile measurement (2.123), followed by the Plasser optical measurement system (1.861).

The least significant important criteria of track measurement equipment are system weight (size), data archiving duration, and calibration duration. These criteria are of secondary (minor) importance when preparing tender specifications for the procurement of new measurement systems.

References

1. Bracciali, A. & Cavaliere, F. & Macherelli, M. Review of Instrumented Wheelset Technology and Applications. *Proceedings of the Second International Conference on Railway Technology*. PStirlingshire, Scotland. 2014. No. 167. P. 1-16.
2. Bureika, G. & Levinzon, M. & Dailydka, S. & Steišūnas, S. & Žygienė, R. Evaluation criteria of wheel/rail interaction measurement results by trackside control equipment. *International journal of heavy vehicle systems.* 2019. Vol. 26(6). P. 747-764.
3. Bureika, G. & Vaičiūnas, G. & Shi, D. & Zanuy, A. C. Influence of track geometry condition monitoring on railway infrastructure maintenance processing. *Transport Problem.* 2022. Vol. 17(4). P. 211-220.
4. Chakraborty, S. TOPSIS and Modified TOPSIS: A comparative analysis. *Decision Analytics Journal.* 2002. Vol. 2. No 100021. DOI: 10.1016/j.dajour.2021.100021.
5. EN 13848. Railway applications – Track – Track geometry quality.
6. EN 14363. Railway applications – Testing for the acceptance of running characteristics of railway vehicles – Testing of running behaviour and stationary tests.
7. K/259. Savaeigio kelio matavimo vagono EM-140 matuojamų geležinkelio kelio geometrinių parametrų įvertinimo instrukcija. Lithuanian Railways – LTG. [In Lithuanian: Instruction for evaluating the geometrical parameters of the railway track measured by the self-propelled track geometry car EM-140].
8. Kendall, M. & Gibbons, J. D. *Rank correlation methods*. London. Edward Arnold. 1990.
9. Maskeliūnaitė, L. & Sivilevičius, H. Expert evaluation of criteria describing the quality of travelling by international passenger train: technological, economic and safety perspectives. *Technologies and Economic Development of Economy*. 2012. Vol. 18(3). P. 544-566.
10. Orugbo, E.E. RCM and AHP hybrid model of network maintenance prioritization. *The Baltic Journal of Road and Bridge Engineering.* 2015. Vol. 10(2). P. 182-190.
11. Podvezko, V. Agreement of expert estimates. *Technological and Economic Development of Economy.* 2005. Vol. 11(2). P. 101-107. DOI: 10.3846/13928619.2005.9637688.

12. Skrickij, V. & Šabanovič, E. & Shi, D. & Ricci, S. & Rizzetto, L. & Bureika, G. Visual measurement system for wheel-rail lateral position evaluation. *Sensors. Basel:* 2021. Vol. 21(4). P. 1-16.
13. Zalewski, W. Application of TOPSIS method for evaluation of the financial condition of the power distribution companies. *Economics and Management*. 2012. Vol. 4. P. 153-161.
14. Zavadskas, E.K. & Podvezko, V. Integrated determination of objective criteria weights in MCDM. *International Journal of Information Technology & Decision Making*. 2016. Vol. 15(2). P. 267-283.

Received 03.03.2022; accepted in revised form 04.09.2023