Keywords: running gear; wheel-rail interaction; measuring systems; correlation of measured value

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STUDY ON THE PREDICTABILITY OF THE VERTICAL IMPACT OF RAIL VEHICLES RUNNING GEAR ON RAILS CONSIDERING WEATHER CONDITIONS AND WAGON SUSPENSION LOAD

Summary. The faulty running gear of rail vehicles can be identified by the results of measurements of vertical forces caused by wheel running surface damages or other wrongness of bogie suspension. Several different automatic diagnostic systems are used in European railways (operating while the trains are in service) to detect damage to rail-wheel running surfaces. The principles of this trackside equipment operation and the reliability of their measurements may differ noticeably. This is especially true in different seasons of the year (winter/summer). Data collection and aggregation results should be checked in equivalency (comparability). The authors compared the efficiency of different automatic systems in detecting wheel failures according to wheel-rail loads in different seasons of the year and presented their results. The authors also compared the similarity of results of the different measurement systems.

1. INTRODUCTION

Problems still arise in controlling mechanical systems despite developments in technology. An example is the interactions between wheels and rails [1]. Research on this issue has involved the detection of wheel running surface damage by running gear impact load on the rail [2]. The impact effect depends on the properties of the wheel materials [3], as well as the nature and magnitude of the damage and geometrical irregularities of both the running gear and the track. In addition, circumstances such as tribology and frictional properties exist [4]. The fatigue of metal can also have a tactile effect [5]. Other research has addressed this issue for different reasons [6]. On the one hand, the impact of a wheel on a rail poses passenger comfort problems for passenger trains [7]. However, this is trivial compared to the risk to traffic safety [8]. Therefore, vertical forces are not the only forces measured. Digital tools and mathematical models are also developed to predict and study the scales of these forces [9]. The results of the measurements are particularly important when examining the effects of train dynamics on other infrastructure elements, such as bridges or viaducts [10]. Various diagnostic systems are used for measurements. The adequacy of measurement results, when measured by different systems, is one of the key issues. The authors also paid attention to different operating conditions: namely, the conditions in winter and summer.

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The authors draw attention to the fact that the interaction of the wagon wheel and the rail is determined not only by the characteristics of the track but also by the characteristics of the running gear, especially suspension components. Research has shown that wheel-rail contact can cause suspension failure [11]. The reason for this may be the vibrations resulting from the wheel-rail interaction [12]. As a result, the effect of vibrations on the suspension is especially considered [13]. Of course, vibrations depend on the quality of the railway track. Therefore, the influence of rail irregularities on vibrations is studied with particular care [14]. Depending on the structure and purpose of the wagon suspension, its vibration characteristics differ [15]. Passenger car suspension tends to be complex and, therefore, difficult to research [16]. In this case, passenger comfort issues also become important [7]. Various software packages are used for modeling [17]. However, the suspension characteristics of the freight wagon significantly influence the wheel-rail interaction [18]. New bogie schemes are being developed to improve these features [19], but as practice shows, this method is not very effective. The problems of the newly developed bogies are determined by the problems of changing the forces and determining the direction [20].

Various sensor systems are used to measure vertical forces. Sometimes they have names like systems, and sometimes they are considered as a collection of sensors and other equipment. For example, in a study carried out by Portuguese scientists, vertical forces were measured by sensors, and it was not emphasized what kind of system they formed as a whole [21]. The same researchers proposed to complement the vertical force measurement systems in such a way that they can be used to measure other quantities as well, such as vibrations. This would allow better separation of wheel surface defects from additional damage [22]. The measurement of the forces on the rail caused by the wheels of high-speed trains is an entirely different process. In this case, a high level of operational efficiency in the decency of information is required, which can also be found in scientific works [23]. By measuring not the force itself but the vibrations caused by the damage, it is possible to detect damage not only to the wheels but also to other parts; however, this requires complex algorithms [24].

According to the authors, the main factors affecting the quality of vertical force measurement are meteorological conditions and the vertical load of the freight wagon suspension. Since it is difficult to accurately assess the effect of the suspension, the authors evaluated only the presence of suspension load—that is, whether the freight wagon is loaded or empty.

2. MEASURING SYSTEMS AND PRINCIPLES OF OPERATION

There are many railway systems in the world that utilize different equipment, so wheel failure detection devices are also noticeably diverse. Their operating principle, accuracy, and installation features differ. The evaluation of the results of the various systems has been reviewed in scientific works [8]. Depending on the requirements of the work culture in one or another country, a higher or lower sensitivity of the system is required. The ability to install and maintain the system varies depending on the climatic conditions. Also, the principle of operation of the sensors and the principle of determining the force of the impact of the wheel are different.

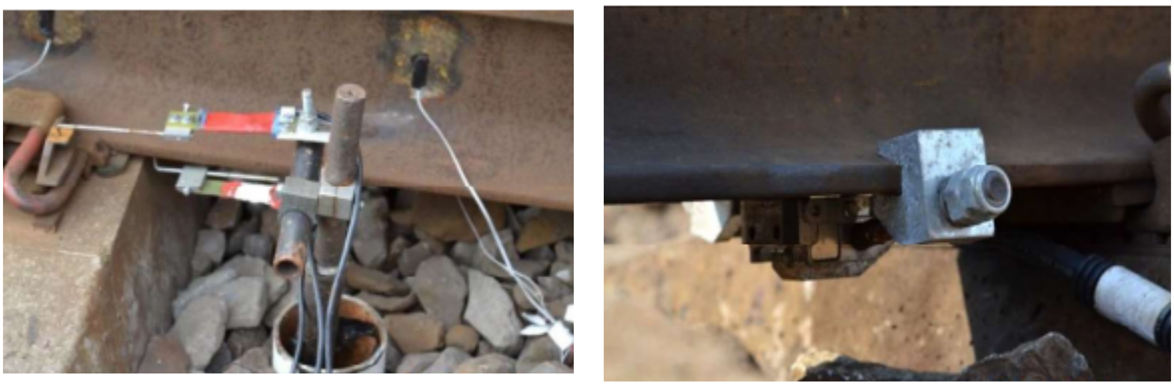
Despite the substantial diversity of the mentioned circumstances, several average systems (or, more precisely, several average principles of measuring the impact of the wheel on the rail) have established themselves in the market. In Central European countries, the operating conditions of railway vehicles are not particularly demanding from this point of view. There are no particularly low temperatures in winter here (it rarely falls below -30 °C), and there are rarely any sharp railway curves due to the mountainous terrain. This study was conducted in Lithuania, which has a typical Central European climate and flatland terrain. A state company, namely, Lithuanian Railways, uses the ATLAS-LG system to measure the wheel-rail interaction vertical force, as shown in Fig. 1.

The measuring range consists of 14 points at which the sleeper responses are measured and 12 points at which the axle load is measured. The latter points are also used to identify the wheels. The rail reactions and axle loads are measured by strain gauges mounted on the rail neck.

The authors compared this system with other operating systems: specifically, IC-VEIP and ATLAS-FO. The main difference between the ATLAS-LG and IC-VEIP systems is that the ATLAS-LG system measures the force itself, whereas the IC-VEIP system measures the rail displacement and then converts its value into the force value. The ATLAS-LG system differs from the ATLAS-FO system in that ATLAS-LG system uses strain gauges to measure vertical forces, while the ATLAS-FO system uses fiber-optic sensors.

Fig. 1. System ATLAS-LG used to measure wheel-rail interaction forces

Therefore, as can be seen in Fig. 2, the features of mounting the systems on the rails are slightly different. Despite the different structures and operating principles of the systems, the values of the measured forces should be the same. It is not possible to compare the results obtained by all three systems at once, but they can be compared in pairs. When comparing the results obtained by two systems, the vertical force values measured by one system are placed on one axis of the graph, and the values measured by the other system on the other.



a b

Fig. 2. Automatic rolling stock wheel damage detection systems: a) an IC-VEIP system and b) an ATLAS-FO system

All measurement systems were installed on different straight sections of the track. The type of rail was R65. Reinforced concrete sleepers were used in these sections. The research process and results are described in the following section.

3. RESEARCH PROCESS AND ANALYSIS OF RESULTS

The measurement results of the impact of the rail vehicle's vertical force on the rail were obtained by using installed force measurement sensors in the railway section. A comparison of the operation of the three measurement systems (ATLAS-LG, IC VEIP, and ATLAS-FO) in summer conditions was also made. Trains formed from freight wagons of various basements were used for the research. CNII-H3-0 bogies were used in the wagons. The wheel rolling diameter was 950 mm, and the wheel conicity was 1:20. When the wheels of a running train impacted rails, each system captured the average value of the vertical force (the average value of the running train wheels' impact on the rails) and the maximal value of the running train wheels' impact on the rail. The average value of the vertical force indicates the axial load level of the wheels, and the maximal value of the vertical force occurred due to the short damage length of the wheel rolling surface. The results of the test are provided in Figs. 3 and 4.

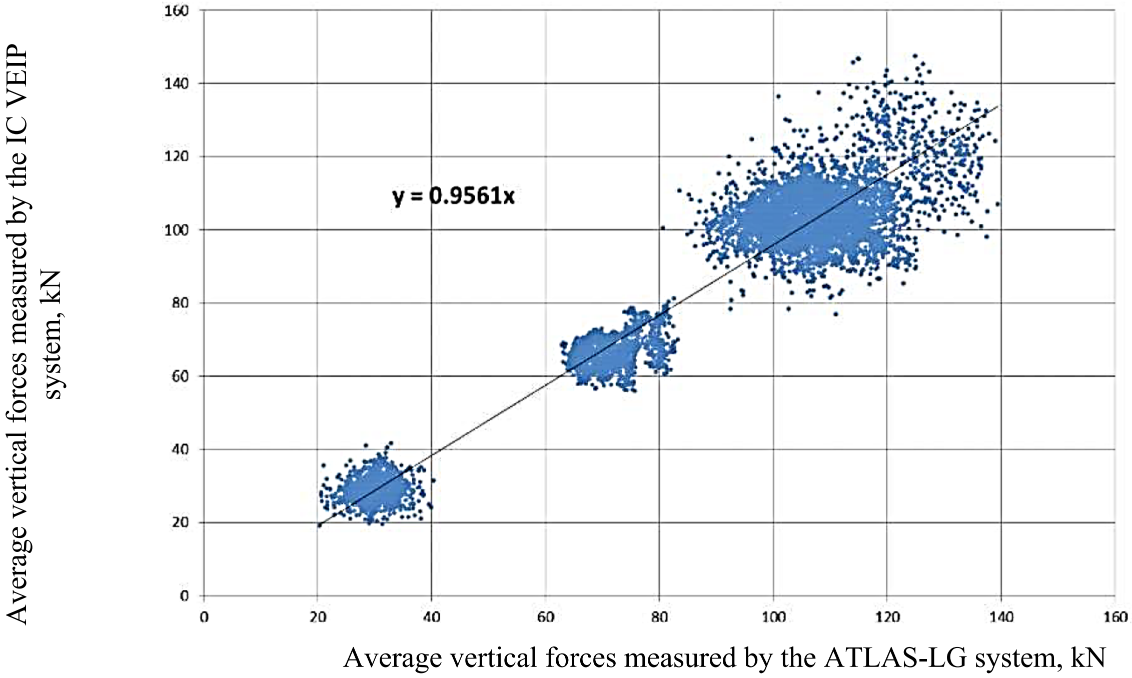


Fig. 3. Correlation comparison of average vertical forces measured by the ATLAS-LG and by IC VEIP systems (R^2=0.963)

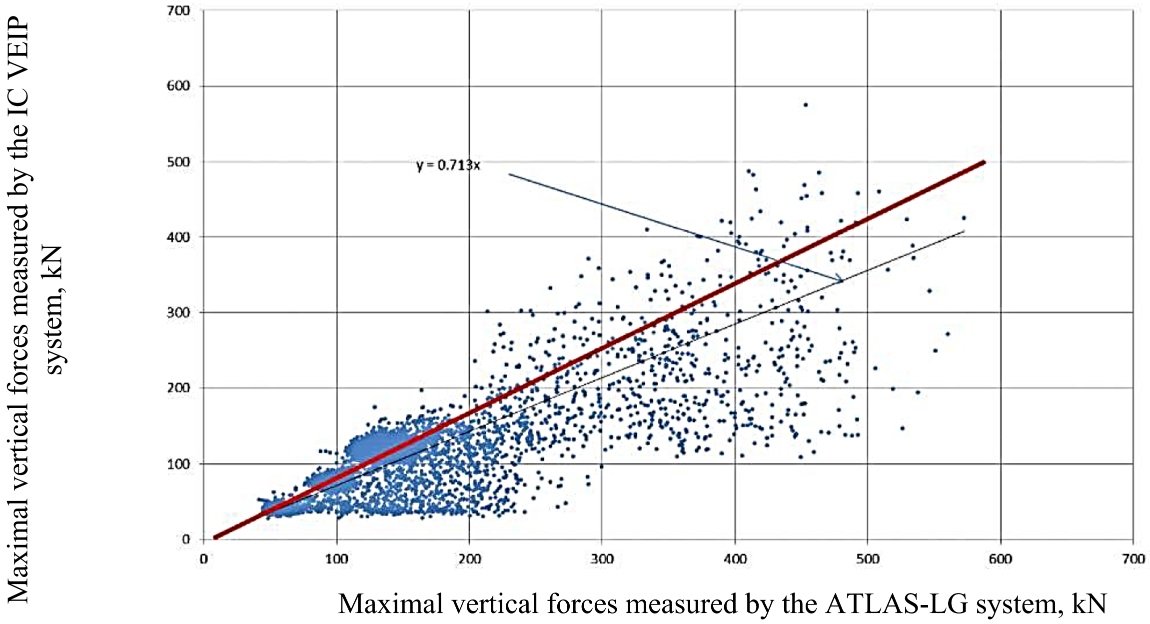


Fig. 4. The correlation comparison of maximal vertical forces measured by the ATLAS-LG and by IC VEIP systems (R^2=0.757)

A comparison of the average vertical force values measured by different vertical force measurement systems showed a high correlation coefficient (R^2=0.963), and linear dependence was observed (0.9561). The comparison of the maximal vertical force values shows that the correlation coefficients of the systems were quite high (R^2=0.757), and linear dependence was observed (0.713).

Since the correlation coefficients were very different for the average and maximal forces, the authors checked whether this difference depended on the operating conditions (winter or summer). The ATLAS-LG and ATLAS-FO systems were used for this study. The correlation comparison of average vertical forces measured by ATLAS-LG and ATLAS-FO in summer is shown in Fig. 5.

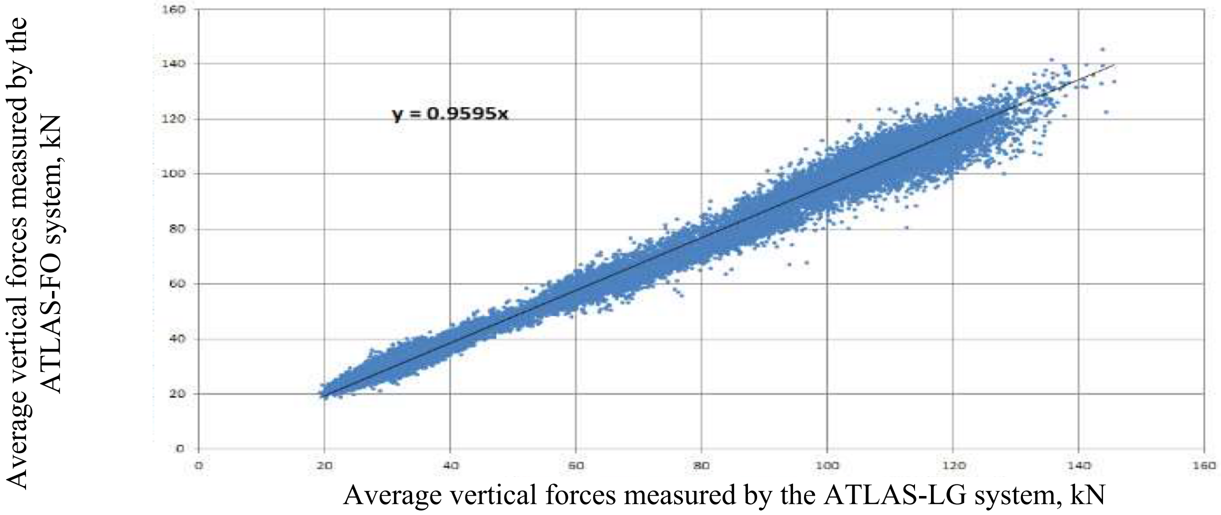


Fig. 5. Correlation comparison of average vertical forces measured by ATLAS-LG and by ATLAS-FO in summer (R^2=0.995)

A correlation comparison of maximal vertical forces measured by ATLAS-LG and ATLAS-FO in summer is shown in Fig. 6.

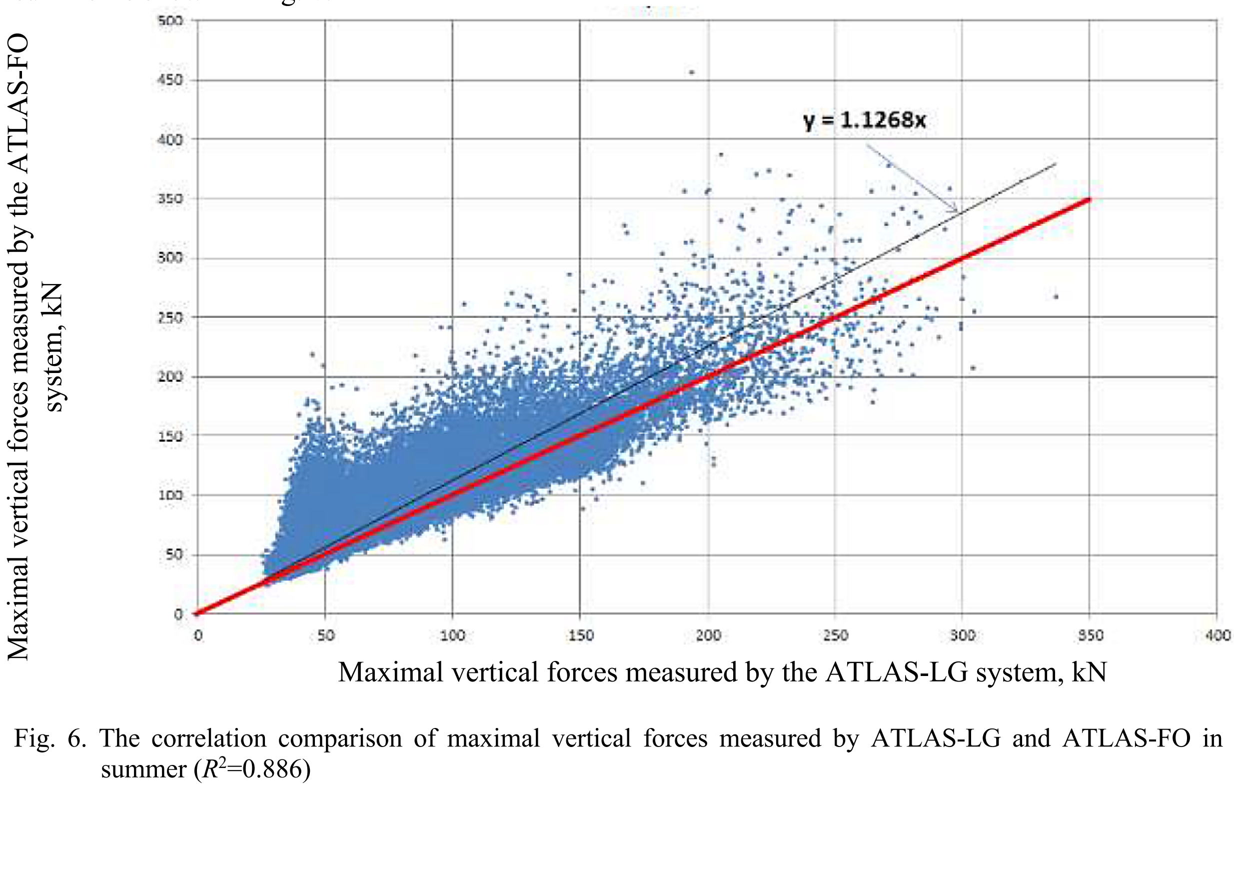


Fig. 6. The correlation comparison of maximal vertical forces measured by ATLAS-LG and ATLAS-FO in summer (R^2=0.886)

A comparison of the diagrams in Figs. 5 and 6 shows that the correlation coefficient for the analysis of the average forces (R^2=0.995) is higher than that for the analysis of the maximal forces (R^2=0.886). The linear dependence for the average forces is 0.9595, and that for the maximal forces is 1.1268. This indicates that systematic error is higher when measuring maximal forces. These coefficients were obtained from tests run in the summer. Appropriate tests were performed in winter conditions to check whether the outcomes were relevant in winter.

The correlation comparison of average vertical forces measured by ATLAS-LG and by ATLAS-FO in winter is shown in Fig. 7.

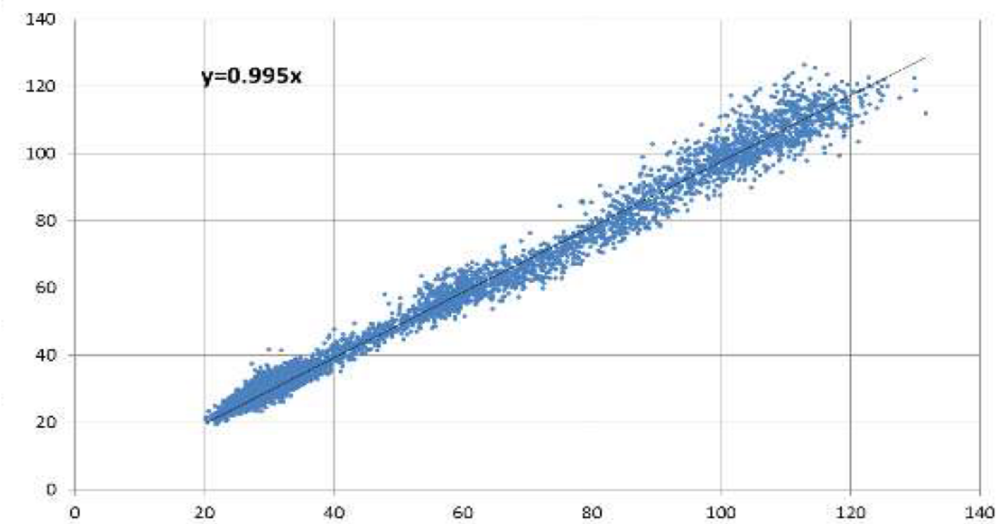


Fig. 7. Correlation comparison of average vertical forces measured by ATLAS-LG and by ATLAS-FO in winter (R^2=0.995)

The correlation comparison of maximal vertical forces measured by ATLAS-LG and ATLAS-FO in winter is shown in Fig. 8.

The data in Fig. 7 and Fig. 8 indicate that, when examining vertical forces in winter conditions (as well as summer conditions), the correlation coefficient in the analysis of average forces is higher (R^2=0.995) than in the analysis of maximal forces (R^2=0.848). The linear dependence for the average forces is 0.995, and that for the maximal forces is 1.306.

A summary of correlation coefficients (data from all tests) is presented in Table 1.

Table 1

Summary of correlation coefficients

Maximal or average forces	Correlation coefficients		Linear dependence	
	In summer	In winter	In summer	In winter
ATLAS-LG and IC VEIP systems				
Average forces	0.963	-	0.9561	-
Maximal forces	0.757	-	0.713	-
ATLAS-LG and ATLAS-FO systems				
Average forces	0.995	0.995	0.9595	0.995
Maximal forces	0.886	0.848	1.1268	1.306

The summary of the correlation coefficients presented in Table 1 shows that in both summer and winter, the correlation coefficient is significantly higher for the average forces than for the maximal forces. In addition, for the ATLAS-LG and ATLAS-FO systems, the correlation coefficients for the average forces are equally good (R^2=0.995) in winter and summer; for maximal forces, the coefficient is slightly higher in summer (R^2=0.886) than in winter (R^2=0.848).

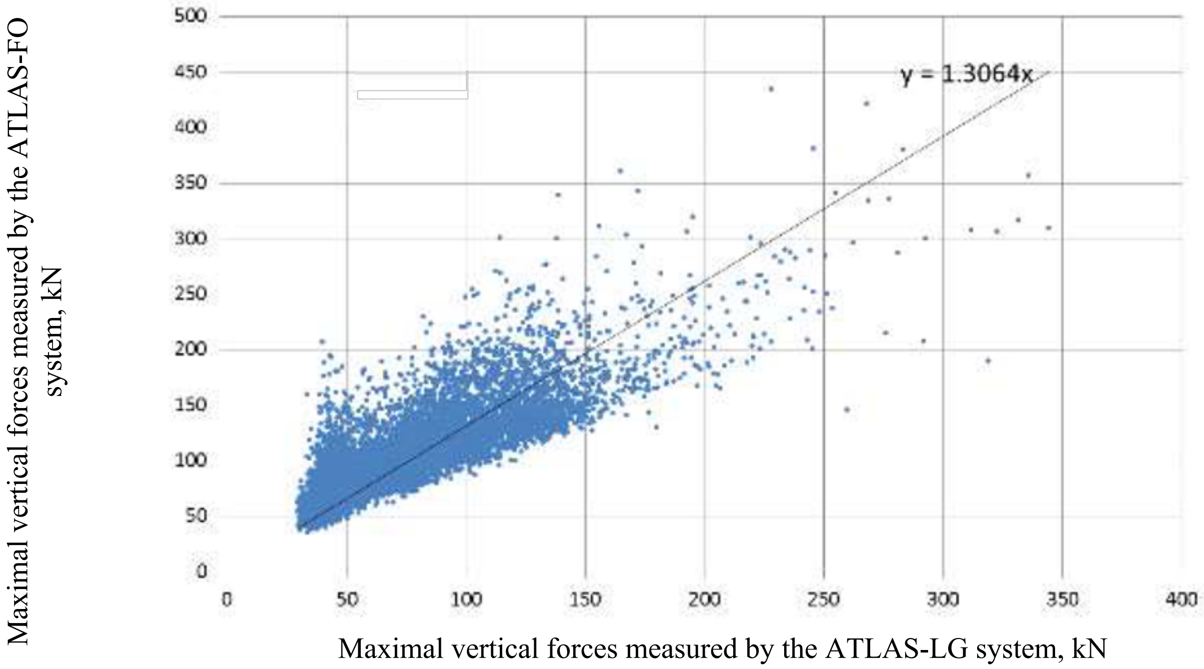


Fig. 8. Correlation comparison of maximal vertical forces measured by ATLAS-LG and ATLAS-FO in winter (R^2=0.848)

A comparison of the linear dependence indicates that in the case of maximal forces, the direction coefficient always deviates from 1 more extensively than in the case of average forces. A comparison of the linear dependence, according to the tests in winter and summer, reveals that the coefficients for the average forces are slightly closer to 1 in winter (0.995 in winter and 0.9595 in summer) and deviate more strongly from 1 (1.1268 and 1.306). Thus, systemic errors in measuring maximal forces were higher in winter conditions.

Estimated errors were not related to the speed of the rolling stock, the size of the wheel damage, or the load of the wagon (whether the wagon was empty or loaded). The aim was to consider as many points as possible and check whether (and how) the measurement results obtained by one measurement system correspond to the results obtained by another system. However, the reasons for the conformity (and deviations) could be better revealed by a more detailed examination of the wagon's operating conditions. Of course, the speed of the wagon should be taken into account, as the running speed determines many dynamic processes of the rolling stock. Another factor affecting dynamic processes is the mass of the wagon. This factor has a direct impact on the effect of the wheel on the rail. It should be noted that the weight of the wagon does not press the wheel onto the rail directly but through the suspension (most of the mass of the wagon is the suspended mass). Therefore, the wagon load should be interpreted primarily as a suspension load. The suspension load determines the wheel-rail interaction. Additional tests were performed to evaluate the speed of the wagon and its suspension load (wagon loaded or empty) to better understand the previously described difference in measurement quality between measuring average forces and measuring maximal forces. The tests were carried out in summer conditions using the ATLAS-LG system. The vertical forces of the wheel impact on the rail were measured with the damaged left wheel of the first wheelset of the wagon. The wheel had two breaks of 20x10x4 mm and 15x40x3 mm size. The test results are presented in the box-and-whisker form in Figs. 9-12. The values of the maximal forces and the values of the average forces, as well as the cases of loaded and empty wagons, were considered separately.

The diagrams in Figs. 9–12 show the field in which the 50% of the values closest to the mean (i.e., the two middle quartiles) were scattered with colored rectangles. A smaller scatter indicates better repeatability of the measurement and, accordingly, better quality of the measurement. Fig. 9 shows that when measuring values of maximal forces when the wagon is loaded, the best measurement quality was recorded when the speed was 30 km/h. As the speed increased, the quality of the measurement deteriorated, as the field of values was wider. However, a more detailed analysis is required to draw conclusions, which are presented below.

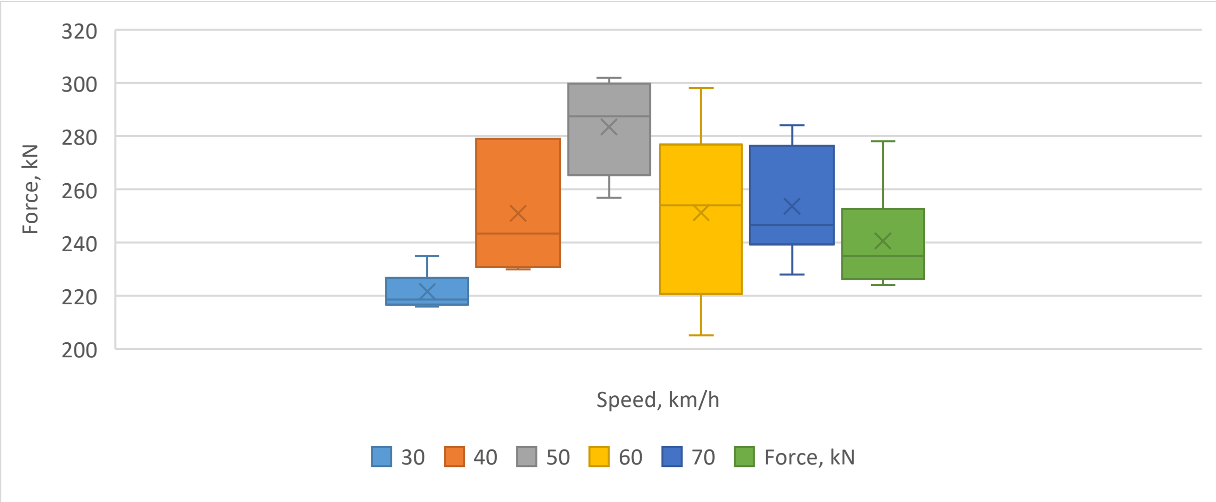


Fig. 9. Values of maximal forces when the wagon is loaded

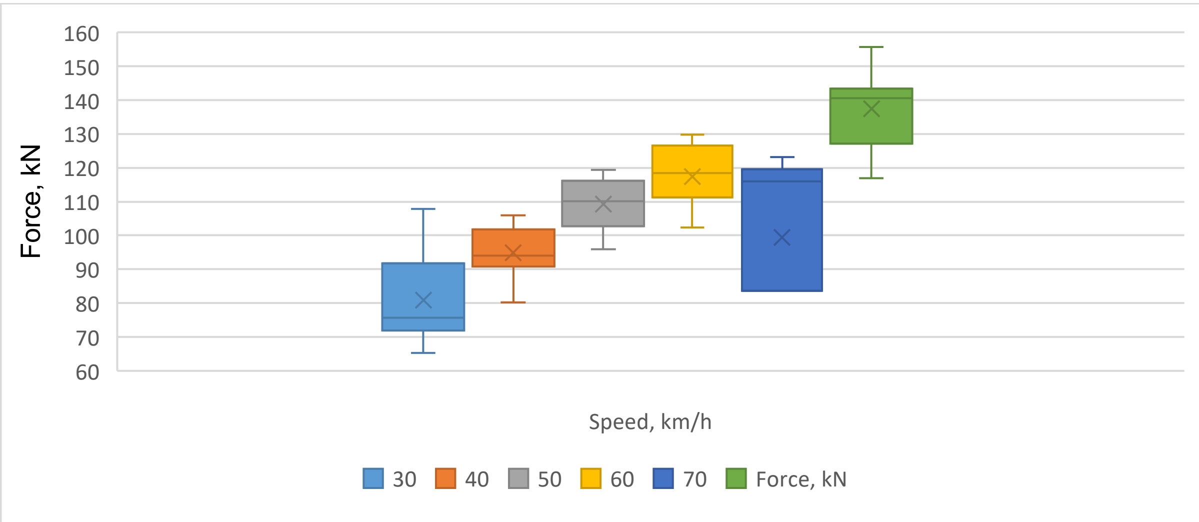


Fig. 10. Values of maximal forces when the wagon is empty

The diagram in Fig.10 shows that when measuring values of maximal forces in the case of an empty wagon, the measurement quality is similar in the entire speed range (the only exception is 70 km/h). A comparison of the data in Figs. 9 and 10 show that the measurement results are more accurate when the wagon is empty. In addition, during the operation of a loaded wagon, the width of the scattered field of the measurement values is highly variable as the speed of the wagon changes. Meanwhile, when operating an empty wagon, this width is relatively constant due to the lower suspension load and the softer effect of the suspension on the wheel-rail interaction. From this, it can be concluded that a loaded freight wagon is more problematic for the quality of vertical force measurement than an empty one. Therefore, in the case of a loaded wagon, it is more important to correctly select the driving speed for measurements.

The diagram of Fig.11 shows that when measuring average values of vertical force in the case of a loaded wagon, the measurement quality decreases as speed increases. That is, as the speed increases, the scattered field of the measurement values increases. A comparison of the data in Figs. 9 and 11 reveals that when measuring maximal forces, their measurement field changes chaotically as the speed changes (Fig. 9); meanwhile, when examining average forces, the scattering field of their values increases evenly as the speed increases (Fig. 11).

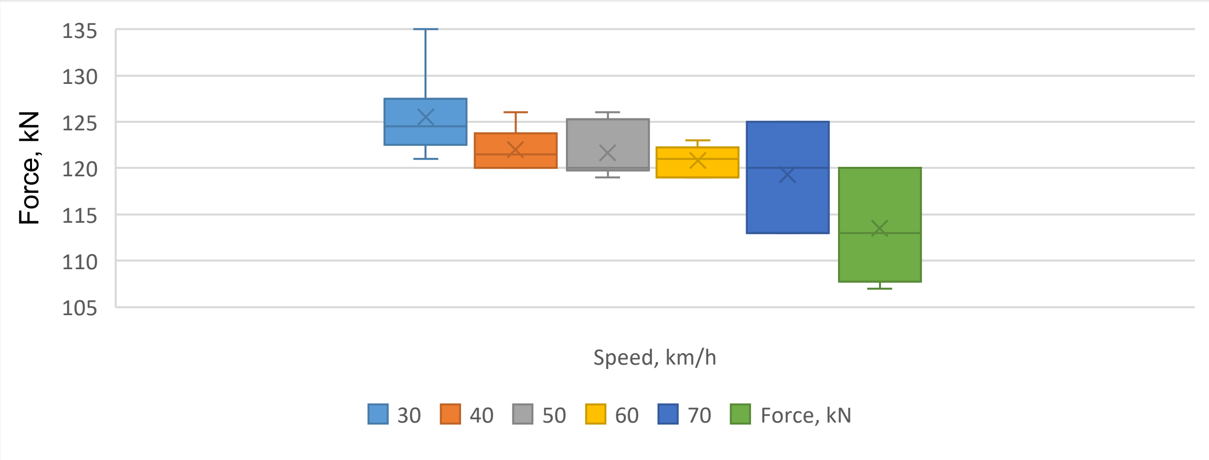


Fig. 11. Average values of vertical force when the wagon is loaded

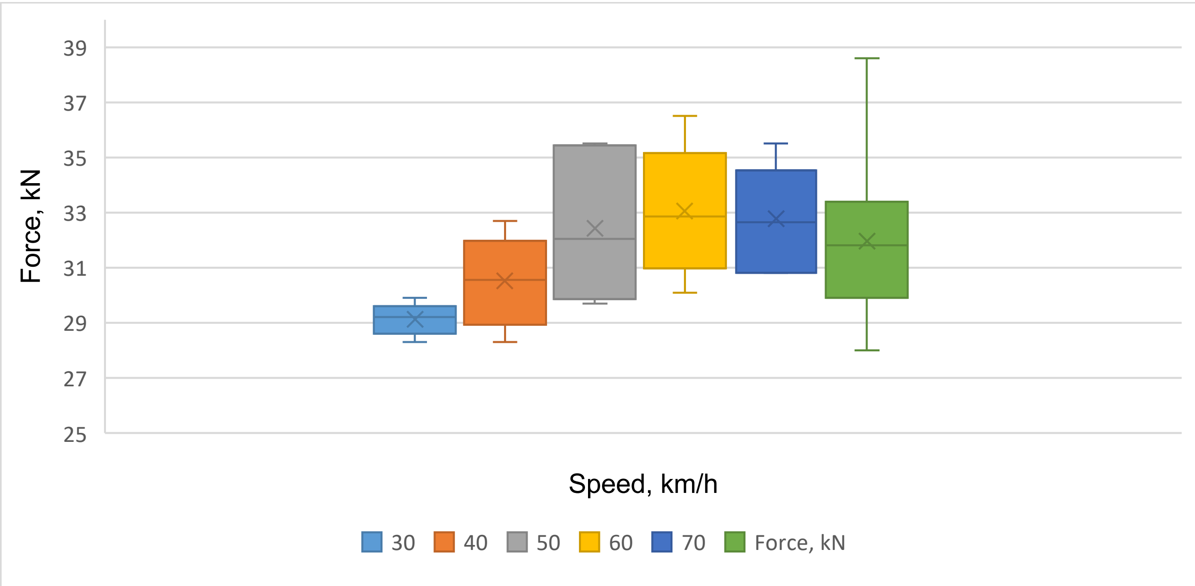


Fig. 12. Average values of vertical force when the wagon is empty

The diagram in Fig.12 shows that when measuring average values of vertical force in the case of an empty wagon, the measurement quality is best when the speed is 30 km/h. A comparison of the data from Figs. 10 and 12 show that when measuring the maximal force values when the wagon is empty, the scattered field of the values barely changes as speed increases. When measuring the average forces, this field changes slightly, but the variation is not significant.

When examining the dependence of the size of the scattering field of measurement values on the operating conditions of the wagon, until now, its size has been compared visually. In some cases, it is larger; in others, it is smaller. However, such comparisons do not always lead to final and more generalized conclusions. When analyzing the laws of the magnitude of the scattering fields of the measurement values (i.e., how this magnitude depends on the operating conditions of the wagon, for example, when the speed varies from 30 to 90 km/h) in the cases considered in Figs. 9-12, it is appropriate to calculate the indicator Q_{avr}:

$$Q_{avr} = \frac{\sum_{30}^{80} F_{max} - \sum_{30}^{80} F_{min}}{\sum_{30}^{80} F_{med}}, \tag{1}$$

where: F_{max} – coordinate of the upper two-quartile field; F_{min} – coordinate of the lower two-quartile field; F_{med} – the median of the field of two quartiles.

The lower the values of the indicator Q_{avr}, the better the measurement quality. The values of the indicator Q_{avr} based on the data in Figs. 9–12 are given in Table 2.

Table 2

Values of indicator Q_{avr}

According to the values of maximal forces when the wagon is loaded	According to the values of maximal forces when the cargo wagon is empty	According to the average values of force when the wagon is loaded	According to the average values of force when the wagon is empty
0.146	0.176	0.0573	0.0928

The data in Table 2 show that the values of the Q_{avr} indicator are lower when measuring the average values of the forces. Thus, the quality of the measurement is better in this case. When analyzing the data in Table 1, the authors noticed that the force values measured by different systems correlate better with each other when their average values are measured. From this, it can be concluded that the improved quality of measurement in different systems (by measuring the average values of the vertical forces of the wheel impact) leads to a better correlation of the measurement results between the systems. An analysis of the values of the indicator Q_{avr} shows that, in the case of a loaded wagon, the values of the indicator were lower than in the case of an empty wagon. This is the case of measuring average forces and maximal forces.

4. CONCLUSIONS

1. A summary of the values of the correlation coefficients shows that in both summer and winter conditions, the correlation coefficient is significantly higher for the average forces than for the maximal forces.
2. A comparison of the linear dependence according to the tests in winter and summer conditions shows that, for the average forces, these coefficients are slightly closer to 1 (0.995 in winter and 0.9595 in summer conditions) and deviate more strongly from 1.0 (1.1268 in winter and 1.306 in summer conditions) for maximal forces. Thus, systemic errors in measuring maximal forces are higher in winter conditions.
3. When measuring the average vertical forces in summer conditions, the results measured by all systems correlate the best (from R^2=0.963 to R^2=0.995), and the systemic errors are the lowest.
4. The results obtained by the different systems correlate the worst when measuring the maximal forces (from R^2=0.757 to R^2=0.886). The highest systemic errors are also observed in this case.
5. Several dedicated systems can measure the values of the wheel's impact on the rail with high correctness. The correlation coefficients of the results are quite high in summer and winter conditions (i.e., from R^2=0.757 to R^2=0.995).
6. In the case of a loaded wagon, the ~~correctness~~ predictability of force values is better than in the case of an empty wagon, both when measuring average and maximal forces.
7. A better correlation of measurement results between systems (when measuring average forces) is determined by better measurement quality in different systems.

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