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Examination of the cross-section shape of tram frogs

Abstract: The article refers to the problem of trams derailing when crossing the crossing frogs. The structural difference of tram frogs in relation to railway frogs is presented. The causes of the phenomenon of underestimating the need to monitor the wear of tram frogs were defined. National regulations governing the design, construction and maintenance of tram frogs have been reviewed and compared with the corresponding regulations for rail infrastructure. A review of the measurement methods and measuring devices used in the field of wear analysis of steel elements of rail surfaces was carried out, with particular emphasis on the latest technologies. Three selected examples of tests of tram frogs, differing in the measuring equipment used, are presented. In the summary, conclusions from the conducted research and analyzes were formulated.

Keywords: Tram tracks; Diagnostics; Frogs

Introduction

This article is a continuation of the considerations presented at the Infraszyn conference in 2019, and concerning the research that the author conducted on the Sępolno tram terminus in Wrocław. These tests consisted in determining the wear of steel elements of rail surfaces. In the previous article [1], the results of analyses on the wear of rails were presented, and as for the wear of tram frogs, the author decided to present these issues in the form of a separate article, which unfortunately, due to the pandemic, became possible only after three years. Returning to the Sępolno loop, in the case of rails it turned out to be an excellent testing ground, due to the large variety of types and ages of track surface elements, and as a result also a large variety of forms and sizes of their wear, this was not the case in the case of frogs, because this loop has only four crossing frogs. Therefore, the considerations contained in this article are, in a way, a summary of all tests of tram frogs that the author has carried out so far, whenever and wherever.

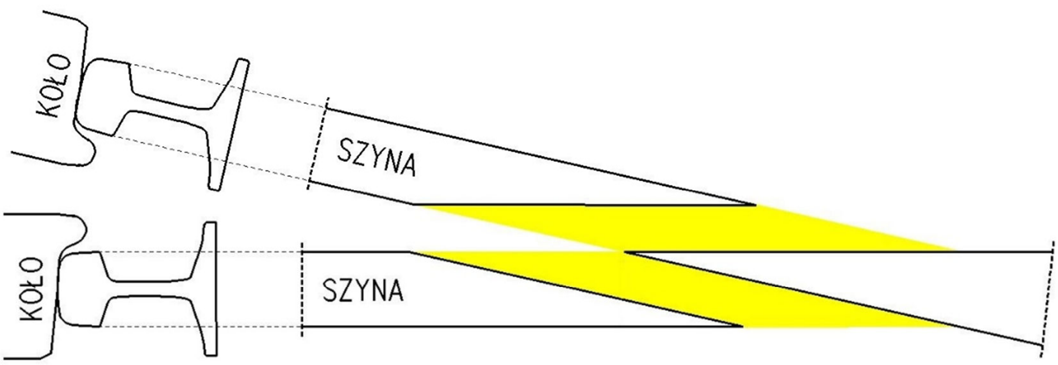
The author of the article has been employed at the Wrocław University of Technology for over 30 years, currently, as an assistant professor, and as part of teaching, he conducts the course "Diagnostics of railroads", including a lecture and laboratory classes, for students of master's studies in the railway specialty. As part of laboratory classes, together with students, he deals with wear measurements of track surface elements with the equipment he owns, on the obtained real samples of worn rails and frogs, or by field trips and measurements in operated tracks.

In addition to didactics, the author of the article participates in scientific research carried out by the university. In autumn 2011, at the request of the Wrocław Road and City Maintenance Authority, the Wrocław University of Science and Technology conducted comprehensive diagnostic tests of the entire Wrocław tram network lasting over a month, in which the assessment of the wear of track surface elements was one of their components [2].

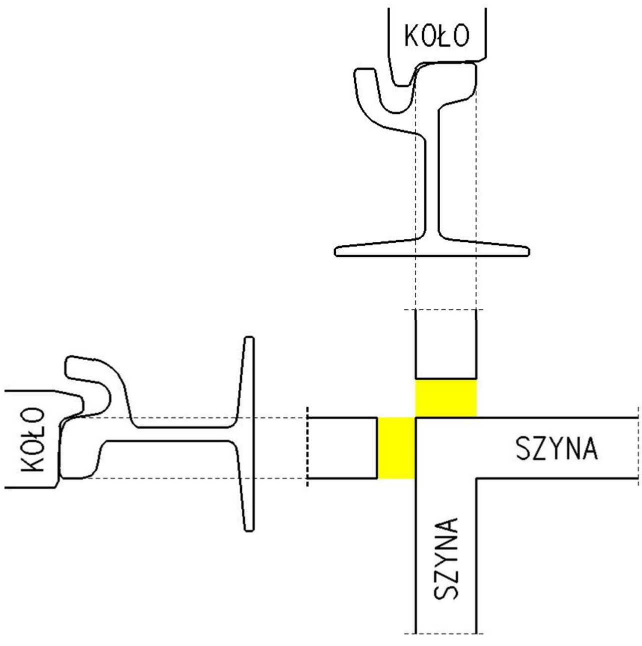
In addition, over the last dozen or so years, the Wrocław University of Technology was commissioned several times to carry out expert opinions [3, 4, 5, 6, 7] regarding problems in the form of derailments on new or operated points and frogs in Wrocław tram tracks.

Structural differences of tram frogs

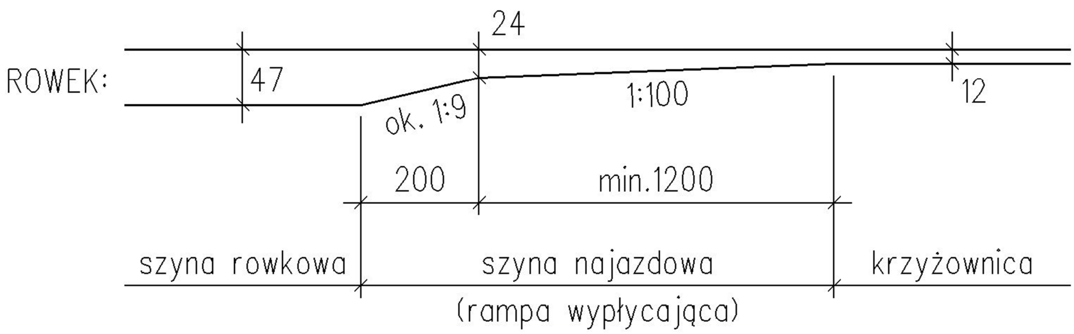
Tram crossings, to railway crossings, are characterized by structural differences - generally, this concerns the problem of the groove. While railway frogs (Fig. **1**) use small bevels (1: 9), relatively wide wheels (135 mm), and relatively wide rail heads (70 mm for 49E1), as a result of which the wheel passing through the frog does not fall off from the rail head, in the case of tram frogs (Fig. **2**) the bevels can be much larger (from 9° even to perpendicular intersections), the wheels are narrower (90 mm), similarly to the rail heads (56 mm for 60R2), therefore the wheels When passing through crossings, tram lines may fall from the level of the rail head into the groove. However, to prevent this from happening in tram frogs, the groove shall be shallower (Fig. **3**) from 47 mm to 12 mm, so that the wheel crossing the frog rolls through it with its rim, and not the raceway (Fig. **4**).



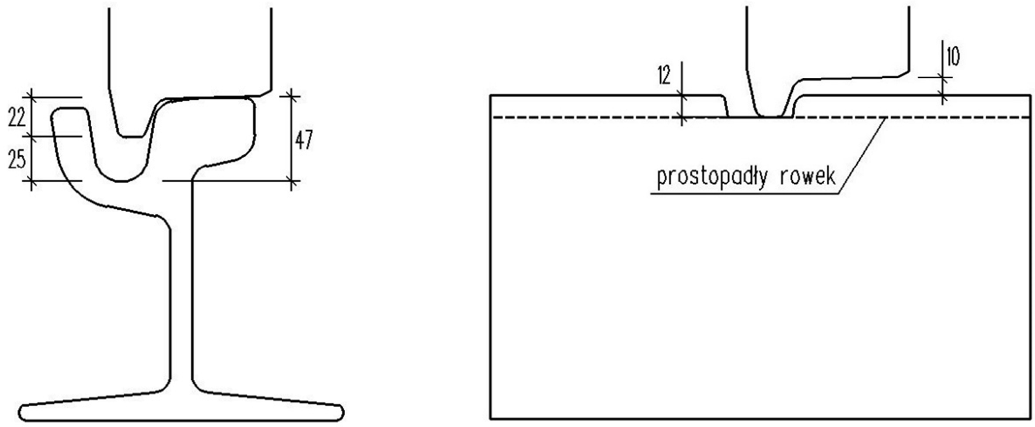
1. Schematic diagram of the construction of a railway frog



2. Schematic diagram of the construction of a tram frog



3. Shallowing the groove in the tram frog



4. The passage of a tram wheel on the rail (left) and through the frog (right)

However, this way of solving the problem of the wheels passing through the tram crossing poses a certain threat - a wide and shallow groove may cause the wheels not to fit into "their" groove or will enter the upper surface of the crossing, which most often will end in a derailment.

Origin of the problem

For the author of the article, the inspiration to undertake the considerations described in it was the event that took place on April 15, 2015, at Bema Square in Wrocław. At 1.52 pm, a Skoda 16T line 6 tram, turning left at this intersection (from the direction of Drobnera Street, towards Poniatowskiego Street), was derailed by the second and third bogie. Fortunately, no one was hurt, although as a result of the centrifugal force in the curve, the tram with the second and third trolleys partially entered the stop platform, the passengers moved away in time.

And what happened next? Well, at 14.05, i.e. only 13 minutes later, another tram - this time a two-car Konstal 105N, also turning left at the same intersection, but in a different route (from the direction of the Młyńskie bridges, towards Drobnera street) was also derailed the first trolley second car.

Already for the first derailment, the MPK ambulance crane was called, which, after arriving at the scene, first dealt with the "rerailing" of the second of the derailed trams, because it is much easier to do it in the case of an old-type single-carriage two-bogie tram than with a modern multi-section articulated low-floor tram. Tram traffic at the intersection was restored after about an hour.

As already mentioned, no one was hurt in the events presented, but unfortunately, this is not always the case. Several decades ago, a similar derailment occurred in Kraków.

The last wagon of the tram turning left from Dietla Street into Stradomska, as a result of the derailment and centrifugal force on the curve, hit the tenement house sideways and unfortunately, a pedestrian walking on the pavement died there.

Summing up the previous considerations, according to the author of the article, the problem of tram derailments in crossings has not been given enough attention so far.

Reasons for underestimating the problem of tram derailments in frogs

The main reason for underestimating the analyzed problem is the fact that trams passing through intersections move at low speeds: 15 or even 10 km/h (depending on the internal regulations in force in a given city). Therefore, if there are derailments, their effects are rather not catastrophic inland traffic.

What's more, sometimes, if the derailment took place on built-up tracks and the wheels remain at the level of the roadway, experienced tram drivers can skillfully, slowly, and gently, back up or move forward, "rerail" the tram. However, if this is not possible, or if the tracks are not covered and the wheels, as a result of the derailment, have fallen below the level of the rail head - a crane is needed and tram traffic is stopped for at least several dozen minutes.

According to the author of the article, the very need to monitor the wear of tram frogs is underestimated. Here, in turn, the reason may be the fact that the basic form of wear of frogs - in the form of deepening the bottom of the groove - works in favor of the safety of the crossing. The result of this is that tram frogs are often operated without any maintenance activities until the proverbial "overtaking", i.e. until they break, or when they get such deformed groove shapes that they are no longer suitable for regeneration by surfacing and grinding.

To identify further reasons for downplaying the analyzed problem, the author of the article will review the applicable regulations and measuring devices in the next two chapters..

Regulation overview

Currently, the rules for constructing and diagnosing tram frogs are regulated by two documents:

- guidelines - the so-called "tram" [8] from 1983 (95 pages) and
- Polish standard - the so-called "acceptance standard" [9] from 1998 (7 pages), admittedly withdrawn by the Polish Committee for Standardization in 2020, but no analogous document appeared in return, which is why it is still provided by ordering parties as valid in all kinds of Descriptions of the Subject of the Order or Specifications of the Essential Terms of the Order regarding tram track works.

What information about frogs appears in these documents? In the "tram" guidelines we read that:

- frogs should be made of steel blocks,
- the depth of the shallowed groove should be from 10 to 14 mm,
- the slope of the shallowing ramp should be 1:100,
- frogs with curves in the same direction should be avoided,
- the minimum crossing angle is 9°, and the recommended angle should be greater than 13°,
- permissible track width - as outside crossings,
- cracks in frogs are unacceptable.

There is not a word in the "acceptance" standard about frogs, and there are no illustrations in either document.

So there is little information, and even those that are given are strong:

- not specified (different dimensions of the groove - such as width, the inclination of side walls and roundings, lengths of shallowing ramps, crossings in tram loop tracks - often with curves in the same direction),

• obsolete (for many years frogs with grooves shallower than 12 mm has not been used).
And if we compare the "tram" and "railway" regulations (Table **1**), the disproportion will be striking, both in terms of volume and timeliness.

Tab. 1. Comparison of the volume and validity of regulations governing the design, construction, and maintenance of tram and railway infrastructure in Poland

	przepisy	
	tramwajowe	kolejowe
dokument	wytyczne / norma	obecne Id-4 / „stare" D 6
objetość:		
- całość	95 / 7 stron	ponad 2000 stron (wszystkie Id)
- o rozjazdach	4 / 0,5 strony	165 / 167 stron
- o krzyżownicach	1 / 0 stron	21 / 27 stron
aktualność:	1983 / 1998	2019 / 1991

This deficiency is compensated by some managers of the tram infrastructure in Poland with their own studies. Tramwaje Warszawskie in 2017 developed its own guidelines: the main document with eleven annexes (169 pages in total), including the sixth annex - entirely devoted to turnouts (containing 13 pages and 11 illustrations) and two chapters devoted to frogs (separate for shallow and separate for deep - grooved).

Of course, in addition to the regulations, there are also studies by tram turnout manufacturers. Some Polish cities operating trams, when preparing tender conditions for track works, include recommendations copied from such materials. Unfortunately, these are often only textual descriptions that do not accurately reflect the original rules, usually presented in illustrative form.

Summing up this part of the considerations, another reason for downplaying the issue of wear of tram frogs, which the author would like to draw attention to, is the insufficient and already outdated approach to these issues in the regulations on the design, construction, and maintenance of tram tracks of national importance.

Overview of measuring devices

Among the measuring devices that are used to analyze the cross-sectional shape of steel trackway elements, two groups can generally be distinguished. The first one is various types of precise distance meters, starting from ordinary classic calipers, through special turnout calipers, then stylus devices, mechanical or electronic profile measurement gauges, templates, and feeler gauges.

The second group consists of devices that reproduce the shape - these are slightly more complicated devices, such as profile measurement gauges: mechanical (pen), mechanical-electronic (with a ball or roller track), optical-electronic (in other words laser, using the LIDAR technique, i.e. laser scanning).

The last of these devices do not necessarily have to be stationary devices, they can be heads mounted in bogie track gauges or measuring trolleys, and even in ordinary rail vehicles. At the beginning of 2020, MPK in Wrocław carried out comprehensive diagnostic tests of almost its entire tram network in only three days, using one of its trams, which was equipped with additional, appropriate equipment and software. During the measurements, the tram ran without passengers, as a "technical vehicle", but analogous devices are already in use, which can be installed in a few minutes on "cruise" passenger trains, such as the RILA system [10]. Such solutions are used by Dutch and British railways [11].

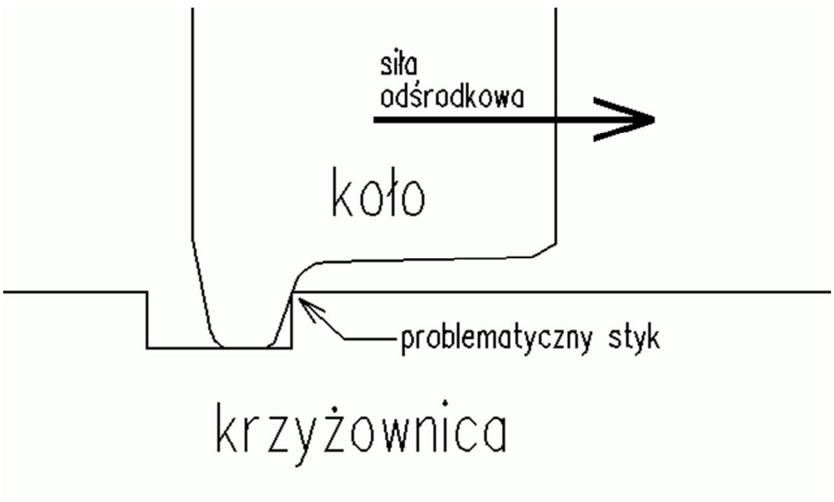
Summing up this part of the considerations, the author would like to draw attention to another reason for downplaying the issue of the wear of tram frogs. Well, due to the already mentioned design difference of tram crossings, most of the above-mentioned typically "railway" measuring devices (mainly the older ones) are not suitable for testing the wear of tram crossings, which is why these tests have not been performed so far. But this situation has recently changed - newer devices (mechanical-electronic and laser profile measurement gauges) no longer have such limitations, they can be used to test the wear of both rails, railway, and tram frogs.

Selected examples of conducted research

In the second part of the article, the author would like to present three selected examples of his research on the cross-sectional shape of tram frogs, from three different periods - using:

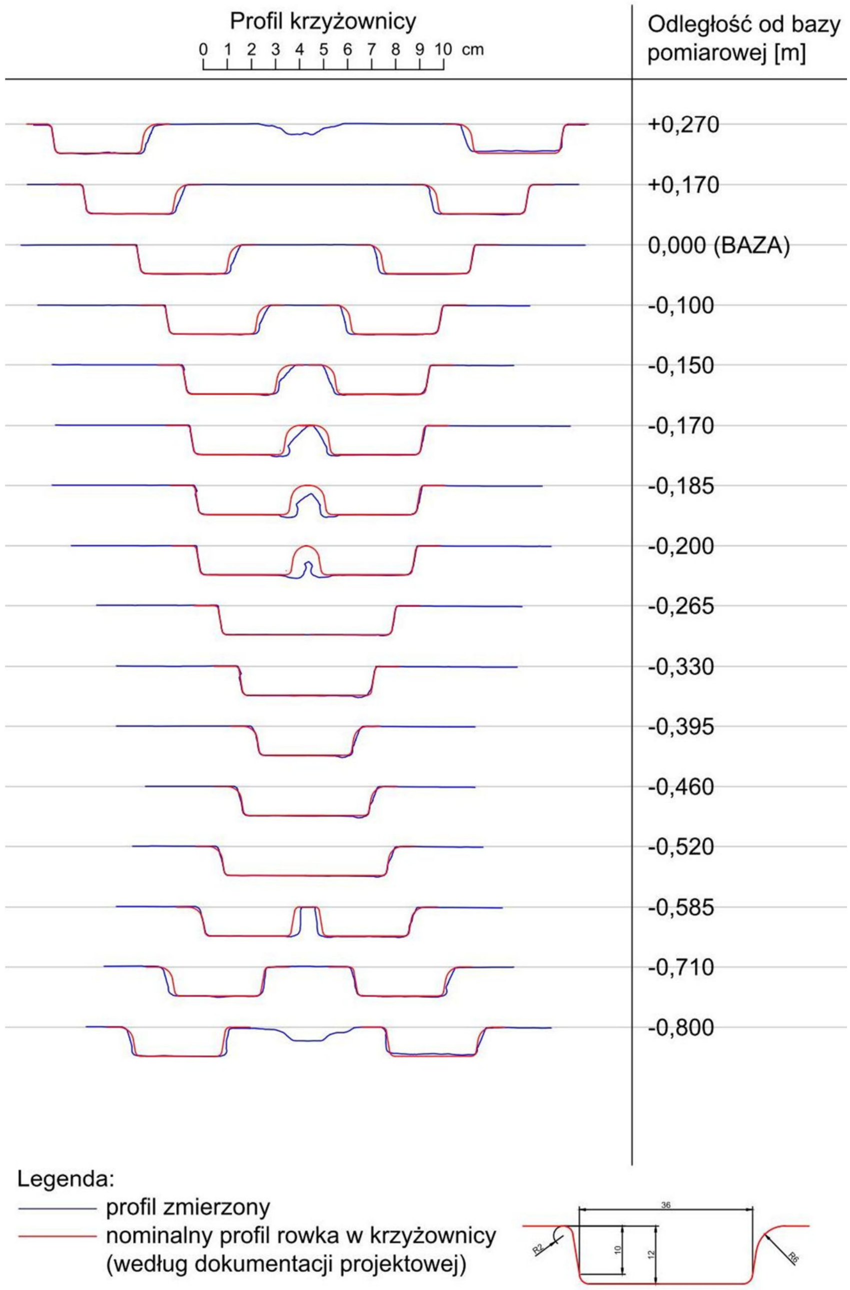
- calipers,
- mechanical and electronic profile measurement gauges,
- laser profile measurement gauges.

The first example is the research carried out for the reconstruction of tram tracks along Świdnicka, Widok, Szewska, and Grodzka Streets in Wrocław in 2005-07. In the newly built turnouts, monoblock crossings were used, whose shallowed grooves had the shape of a regular rectangle, 36 mm wide and 14 mm deep, and the tips and upper edges - did not have roundings. During the first test runs of the trams, there were problems with the wheelsets passing through the frogs - the rims of the wheels climbed onto the frogs, and after covering a dozen or so centimeters they fell back into the grooves, or only hit the frogs, causing, however, significant noise and vibrations. There were numerous traces of shearing as well as chipping and chipping of the rolling edges of frog grooves and run-on rails as well as crossing frogs' bows. Tracks were allowed for linear traffic, but only for older high-floor trams of domestic production, because modern low-floor Skoda 16T trams still had problems with crossing crossings. Thanks to the measurements carried out, the main cause of the problems was found to be the improper shape of the grooves in monoblock frogs and access rails with shallowing ramps - their rectangular shape did not correspond to the wheel rim profile. As a result, in the case of the groove for the course located in the arc (Fig. **5**), the wheel, under the influence of the centrifugal force, the contact of the inclined side surface of the rim and the sharp end of the upper edge of the groove, climbed up as if on a ramp and left the groove, resulting in a derailment.

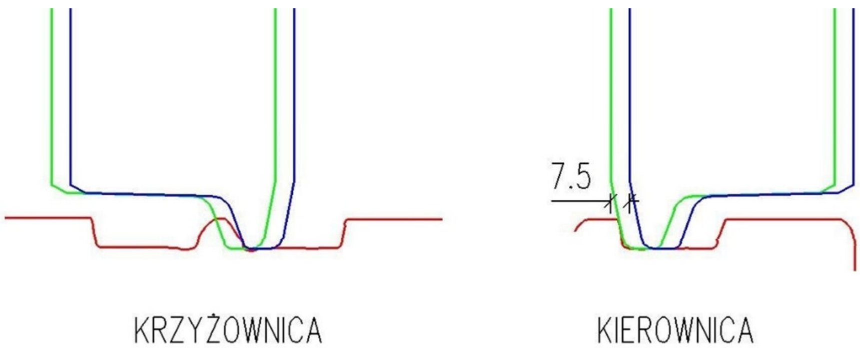


5. Schematic diagram of cooperation between the wheel rim and the groove of the tram frog [3, 4]

The second example is the research carried out on the Oporów tram terminus modernized in 2015. As a result of the reconstruction, this loop obtained a completely new geometric layout. In the first months of operation, there were several derailments of trams at the intersections of two entry turnouts. Just like on Szewska Street, modern low-floor trams (this time Pesa Twist) was derailed more often than older high-floor vehicles of domestic production, and even if there was no derailment, just like on Szewska Street - the rims of the wheels climbed onto the frogs, and then after driving several dozen centimeters they fell back into the grooves. This time, however, the grooves of the frogs did not (as in Szewska Street) have the shape of regular rectangles and sharp ends of upper edges. The turnouts used, however, had shallower grooves not only in the frogs but also in the rails of the "second" course (i.e. in the blades) - to avoid the effect of reverse cant in the arch. Observations and measurements carried out in the field showed that when entering the inner tracks - the nose of the frog was hit by the outer wheel of the first axle of the bogie, while when entering the outer tracks - the inner wheel of the second axle of the bogie hit the nose of the frog. Measurements of the cross-sectional shape of the tram crossings and steering wheels (Fig. **6**) made during the tests allowed for simple graphical simulations of the passage of the tram wheels through these crossings and steering wheels (Fig. **7**). Thanks to the measurements carried out, the main cause of the problems was found to be the improper shape of the grooves in the handlebars - limiting them only to shallowing them without simultaneously narrowing their width, paradoxically, instead of improving, unfortunately, it worsened the conditions of cooperation between vehicles and the track.

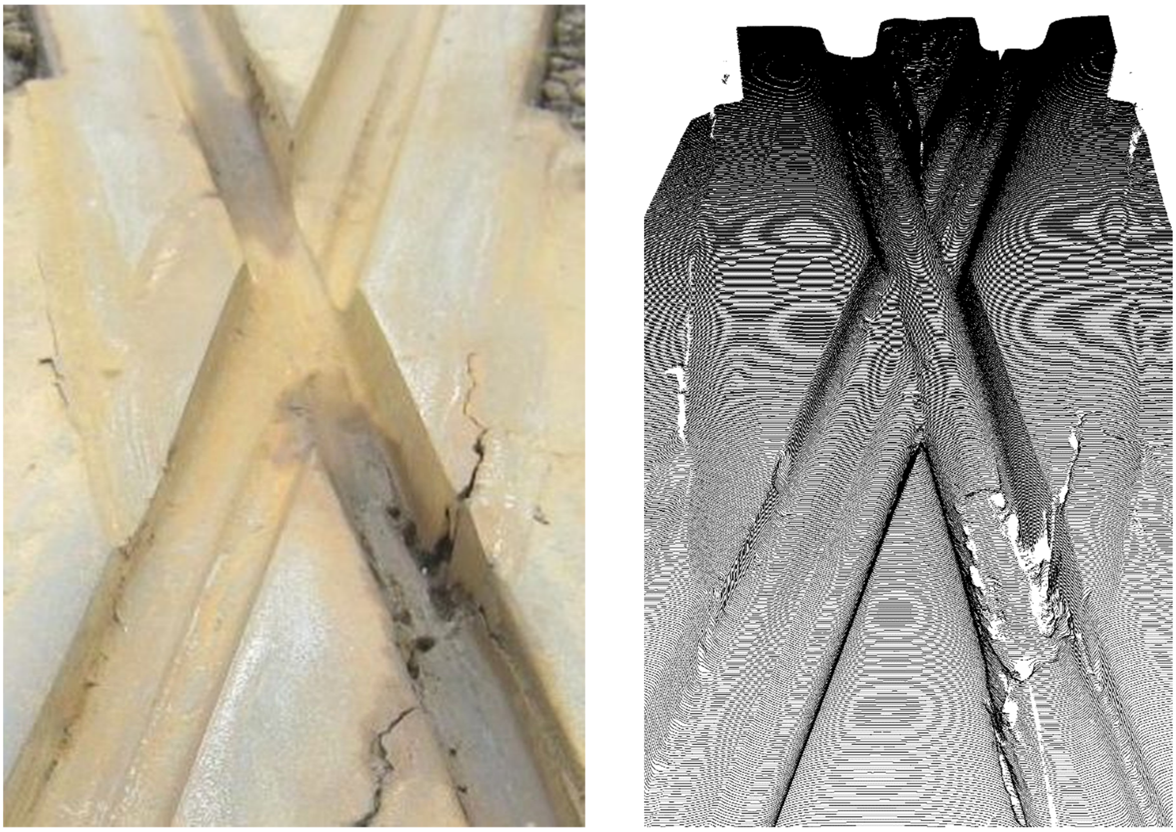


6. Measurements of the cross-sectional shape of a tram frog with a mechanical-electronic profile measurement gauge (developed by Adam Hyliński) [7]



7. Graphical simulation of tram wheels passing through the frog and steering wheel [7]

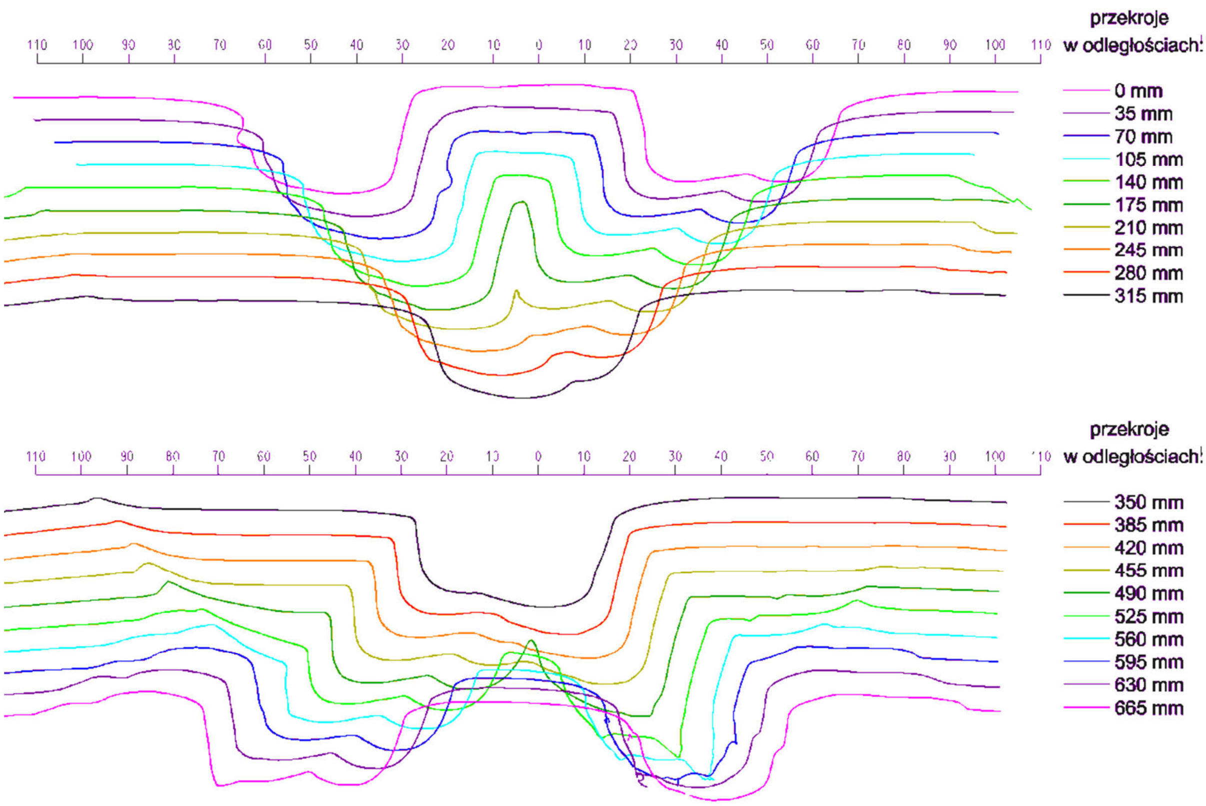
The third example is the research carried out in March 2020 on the Osobowice loop. These measurements were not related to the implementation of any expertise but resulted only from the need to learn how to use the laser scanner for track surfaces, which was purchased at that time. Figure **8** shows the tram frog of the first turnout on this loop. It was a frog about 20 years old, rail (not block), welded, curved (with a radius of 50 m in the turning track). This frog had characteristic (for tram traffic) forms of wear: two-wheel traces in an arc course, and one trace - in a straight course, as well as developing cracks and defects on one of the joints of its welded elements. Thanks to the measurement method used, in relation to the real object - documented here with a classic photograph, it was possible to generate its so-called digital twin, i.e. a digital twin.



8. Real view (left) and digital twin (right) of a tram frog [11]

Such a digital twin is, of course, a three-dimensional object. When viewing it in computer software, we can freely rotate it, which is facilitated by the "View Cube" tool (similar to Autocad). Of course, we can move it and zoom out and zoom in (and thus view certain details more accurately). We can do so-called "virtual walks". We can also generate cross-sections and longitudinal profiles from the 3D model.

Figure **9** shows a series of successive cross-sections in a cascade view - better-showing changes in the shape of the cross-section. The aforementioned characteristic wear patterns are visible.



9. Waterfall plot of cross-sections generated by the frog [11]

Summary

According to the author of this paper, the problem of tram derailments in crossings has not been given due attention so far. Of course, there are some reasons for this, such as those already mentioned:

- slow tram speeds,
- forms of wear that are beneficial to safety,
- outdated and very limited regulations,
- measuring devices that cannot be used,

which partly justifies this state of affairs. However, times are changing and some new circumstances have now emerged:

- an increasing share of trams in operation are modern low-floor multi-segment articulated vehicles, which, firstly, are much easier to derail than the older classic high-floor vehicles modeled on the PCC type tram, and secondly, if a derailment occurs, it is much more difficult to put them back onto the tracks than older type trams (in this case, the purchase of a larger crane does not work - MPK in Wrocław found out about this, which after several years of negative experience withdrew from this idea),
- if tram transport wants to rebuild its position in the so-called "modal split" from before the pandemic, it must offer high reliability, and after all, every derailment is at least several dozen minutes of traffic stoppage caused by waiting for a crane and taking appropriate actions - if this does not change, city dwellers they will not want to use such an unreliable means of transport, they will continue to drive cars,
- new measurement techniques have appeared, such as LIDAR, offering precise and highly automated tools that can be used in the assessment of changes in the shape of tram frogs (the use of this technique is an example of the so-called reverse engineering),

- BIM methodology is being implemented in the construction industry as a result of digitization and computerization processes, currently covering almost all areas of our lives,
- new methodologies appear in the areas of management, such as lean (lean management) or agile (agile management), which are proactive strategies characterized by anticipation, action in advance, and triggering changes in the environment in order to minimize the effects of unforeseen difficulties.

In this way, solutions of the so-called fourth industrial revolution enter rail transport - the BIM methodology, and with it digital twins, the Internet of Things (IoT), and modern forms of asset management possible thanks to these tools throughout the life cycle infrastructure elements (Life Cycle Cost). It becomes possible to use modern proactive methodologies in the maintenance of railroads, such as: predictive maintenance, data driven maintenance, or reliability centered maintenance [13, 14, 15].

In the case of the latest measurement techniques used to analyze the wear of steel rail surface elements, the principle of mapping the shape is already commonly used, and not, as in the past - point measurements of selected quantities. Analyzes are carried out graphically, not purely numerically. This is an example of the so-called pictorial and comparative analysis, whose precursor in Poland in the railway industry over 20 years ago was Professor Henryk Bałuch [16]. It is true that in programs such as SONIT or SOHRON, graphs of the measured geometrical parameters of the track were compared, and not mapped cross-sectional shapes of worn elements, but in the latter case the idea remains the same. This way of doing research:

- reveals the smallest nuances of cross-sectional shape changes,
- makes wear analysis more in-depth and detailed.

This methodology also fits into the so-called BIM 6D - i.e. the possibility of simulations carried out on digital models of objects.

To sum up, according to the author of this article, the time has come to assess the wear of tram frogs: firstly, to update and clarify the applicable regulations, and secondly to start using modern measurement techniques and methods of analyzing their results.

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