WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2025.153334
ARCHIVES OF CIVIL ENGINEERING
Vol. LXXI ISSUE 1 2025

pp. 275 –293

Research paper

Possibility analysis of the LiDAR technique utilization to research the wear of rails and turnouts in tram tracks

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Abstract: The introduction of the article highlights the importance of measuring the wear of rails and turnouts. The evolution of methods and devices used to measure the profiles of these elements is briefly presented. The principle of conducting research using the LiDAR technique is explained. The problem of geometric and structural differences of tram tracks in relation to classic railways is pointed out, and the resulting concerns about the possibility of adapting typical railway methods of measuring rail and turnouts profiles to tram tracks. The rest of the article describes the construction, basic parameters and method of operation of a precise stationary laser scanner, dedicated to measuring rail profiles and turnouts. Graphical analysis of the results for measurements carried out with the mentioned device on tram tracks are presented – for rails in curves with small radii, turnouts (half-switches and frogs), corrugated wear, and broken welds. The summary presents conclusions from the research conducted.

Keywords: tram tracks, wear, diagnostic imaging, LiDAR

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1. Introduction

The most important elements of railway tracks, from the point of view of ensuring the safety of train traffic on them, are rails and turnouts, because they are the components of direct contact between the vehicle and the road. For example, a cracked rail poses a much greater threat than a cracked fastening element or sleeper. Rails and turnouts, like any technical equipment in use, are subject to degradation. One of the forms of wear of these elements is an undesirable change in the shape of their cross-section, most often in the form of losses caused by: abrasion, corrosion, cracks and chipping.

The scope of proper maintenance of a rail road (understood as maintaining it in a state of operational suitability) includes determining the wear of its components, i.e. diagnostics [1]. In the almost two-hundred-year history of railway development, devices used to control changes in the shape of the cross-section of rails and turnouts have undergone improvements [2]. The first group includes precise distance meters, such as: rulers, calipers, graver (pin) devices, and templates with feeler gauges. They enabled direct point measurement (on the tested object) expressed only in numerical values (wear as the difference between the nominal and actual dimensions). The second group of devices are shape mapping devices – profilographs [3]. Thanks to them, the measurement has become continuous and indirect (on a generated model of a real object), and in addition to assessing changes in the numerical values of the measured quantities, analysis of shape changes has become possible (diagnostic imaging). The first profilographs had a mechanical structure, where, thanks to the movement of a pointing stick guided manually over the surface of the shape being examined, its representation was drawn on a sheet of paper [4]. The next generation of profilographs included the addition of electronics – thanks to which the mechanical movement of the pointing stick was converted into a series of data in the form of X and Y coordinates in a plane system (2D), and their processing was carried out by appropriate computer software [5]. The latest novelty is the use of the LiDAR technique, which enables performing a very large number of precise spatial (3D) measurements, for which the term "point cloud" is used, thanks to which a quasi-continuous spatial representation of the surface of the examined object is obtained [6]. Measurements in this case are non-contact and automated.

The word LiDAR (short for Light Detection and Ranging) sounds similar to the terms RADAR or SONAR – and not without reason, because it is an analogous method – but instead of radio waves (as in radar) or acoustic waves (as in sonar), laser light is used. It is a method of measuring the position or mapping the shape of the examined object by illuminating it with laser light and measuring the reflection of this light with a digital camera. The distance from the measured point is determined by measuring the time it takes for the laser beam sent to travel to the object and back.

LiDAR techniques are increasingly often used in the construction industry as a tool for obtaining information about the terrain or objects located there. They have become competitive methods in relation to previously used traditional techniques (geodetic measurements, photogrammetry) – in the case of which the data processing process was expensive and long-lasting.

Currently, devices using LiDAR technology, dedicated to railway track diagnostics, are already used. These can be stationary devices [6–8] – placed on or near the tracks, or mobile – mounted to: manual measuring trolleys [9,10], cars [11,12], mechanical inspection trolleys [13], measuring inspection cars [14–16], trams [17], trains [18–21], as well as drones [22, 23] or airplanes [24, 25].

The beginning of the use of profilographs in testing the wear of rails and turnouts made it possible to obtain a representation of the shape of their entire cross-section, and not, as before, only at selected distances. Analyzes began to be carried out graphically, rather than solely numerically [26, 27]. This method of diagnosis, called diagnostic imaging, comes from medical sciences and applications [28, 29]. This method of testing rail and turnout profiles namely:

- highlights the smallest nuances of changes in the shape of their cross-section,
- makes the analysis of existing wear more in-depth and detailed,
- makes it easier to detect less typical wear cases,
- allows for a more realistic connection between the measurement of side wear and track gauge (distance between rails) [30],
- makes it possible to compare measurements of wear of rails, half-switches and frogs with measurements of wear of wheel rims – which makes it possible to analyse the phenomenon of wheel-rail interaction [31].

Returning to the history of the development of methods and devices used to determine rail wear in the case of classic railways, not all of them could be directly applied to tram tracks. In their case, due to certain geometric differences (smaller values of the radii of horizontal curves) and construction (use of tracks built into the street roads – with grooved rails), some of the mentioned methods and devices required modification, and some of them – failed to find a direct application. The aim of this study is:

- checking whether the currently used diagnostic devices using LiDAR technology, dedicated to classic railway tracks, are also suitable for use on tram tracks,
- recognition – what are the benefits and limitations associated with it,
- proposing an innovative method for graphical analysis of wear profiles of tram rails and turnouts (image-comparative analysis) – obtained from tests using the LiDAR technique.

This article is a continuation of the author's previous work in this area [30–33].

2. Description of the measuring device

To carry out the measurements, a precise stationary 3D laser scanner, purchased by the Wrocław University of Science and Technology in 2018, dedicated to measuring rail and turnout profiles on railway tracks, called "Skorpion" (currently RAILPROFILE 3D) by GRAW (currently GOLDSCHMIDT) was used [6].

The components and appearance of the measuring device are shown in Fig. 1.

It consists of a rectangular, elongated supporting positioning frame placed on tracks, constituting a rigid reference base for the measurement, containing drive elements enabling the passage of a separate element – the measuring head, with batteries and a recorder with control panel. The head has two lasers and two scanning cameras (acting as photodetectors) on the bottom. Both lasers do not emit spots (as in laser rangefinders), but a line that moves as the measuring head passes over the positioning frame. Additional equipment includes a transverse

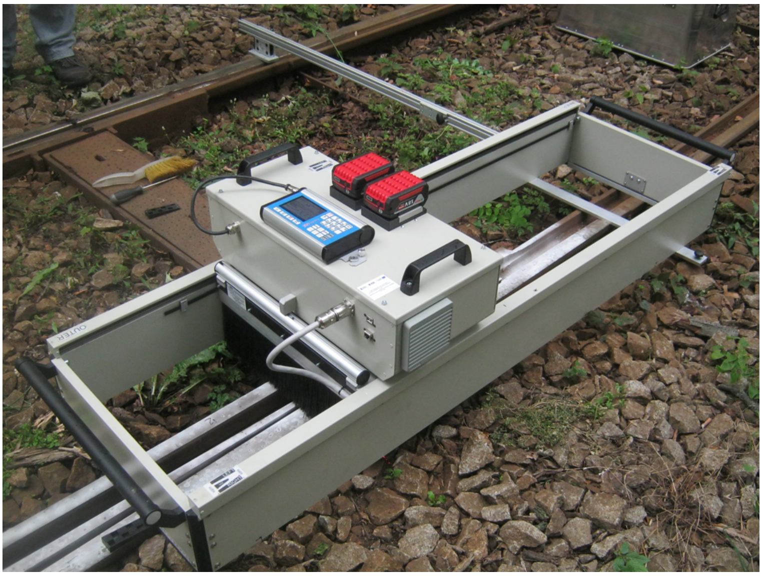


Fig. 1. Measuring device during tests on a tram track (on a half-switch)

support beam – used in the event of instability of the supporting frame on a single rail, as well as a suitcase for transporting accessories.

The basic parameters of the measuring device are presented in Table 1.

Two people are needed to operate the device, and a medium-sized passenger car is sufficient to transport it. Measurements should not be taken on wet, frosted or contaminated elements or in excessive sunlight. The shiny surfaces of the tested elements should be coated with a matting agent (e.g. crack weld testing agent).

Thanks to computer software working with the measuring device, it is possible to generate a three-dimensional model of the actual object being tested (Fig. 2).

When viewing the model, you can freely rotate it, which is made easier with the "View Cube" tool (similar to Autocad). You can also move it and zoom out and zoom in, thus viewing certain details more closely. To perform more reliable analyses, it is necessary to establish a permanent reference line, based on which a series of cross-sections and longitudinal profiles can then be generated. The generated cross-sections can be viewed, described, measured and compared:

- with each other – and thus analyse changes in their shape, or
- with nominal cross-sections – and thus determine wear values.

In the case of longitudinal profile analyses, the procedure is analogical. Generated models, cross-sections and profiles can also be exported to raster or vector graphics or text (or rather numerical) formats, in order to perform more detailed analyzes in other, more advanced computer programs, as well as to prepare comprehensive reports on the research performed.

Unfortunately, the measuring device’s software does not allow generating cascade charts of subsequent cross-sections – which would make carrying out image-comparative analyzes much easier.

Table 1. Basic parameters of the measuring device [6]

Measurement accuracy	±0.1 mm
Measurement increment	1–10 mm
Measurement range in one pass (W × H × L)	160 × 70 × 1223 mm
Duration of a single measurement	2 min
Weight	frame 29 kg, measurement head 13 kg
Dimensions (W × H × L)	frame 1800 × 610 × 240 mm, measurement head 560 × 300 × 320 mm
Operating temperature*	–10°C to 50°C
Memory capacity	100 measurements
Data file format	DXF, CSV, ASC
Mounting	placed freely in the inspected area, no mechanical or magnetic fixtures
Operating time with one set of batteries	2.5 h (which is equivalent to 6–8 complete frog measurements), hot swapping of batteries possible

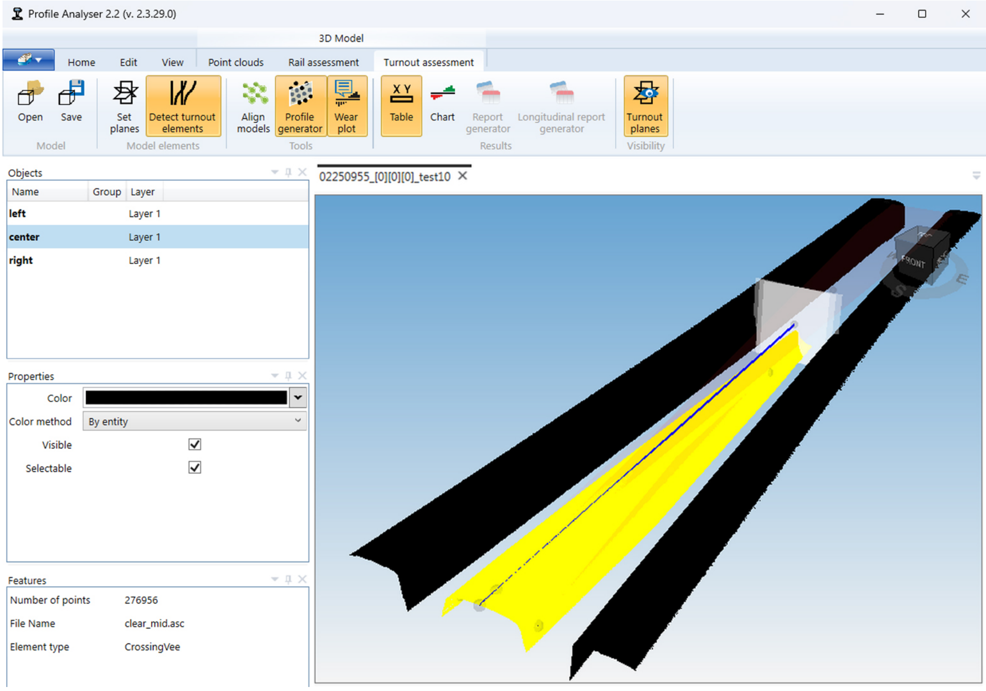
*Temperature changes affect the accuracy of measurements, the resulting error is included in the technical description and parameters of the device.

3. Measurements carried out and their analyses

The measurements were carried out on the tracks of the tram network of the city of Wrocław, located in Poland. This network has approximately 200 km of single track with normal gauge (1.435 mm). About 250 tram trains run on it, on just over 20 lines [34].

The research covered various types of tracks: at junctions, loops, stops, and on sections between them. At a total of 91 locations, wear of the cross-section of rails and turnouts (half-switches and frogs), as well as certain other characteristic forms of degradation – such as corrugation, and broken welds – were tested. Tracks with various types of rails, sleepers, substructures and structures were tested. The research did not include tracks using USPs (Under Sleeper Pads), as such tracks were used for the first time in Wrocław only recently (ul. Olszewskiego , 2021). This type of solution is increasingly used in the case of tram tracks due to the high effectiveness of vibration and noise damping and the possibility of reducing the thickness of the ballast under the sleepers [35–38].

The models generated by computer software were first analyzed visually, which was enabled by rotation, zoom in and out, and view panning tools. Then, a series of cross-sections and longitudinal profiles were generated from them, which were also first analyzed visually, and then measured, compared and assessed in detail – in terms of use or exceeding the permissible consumption values. Cascade charts were prepared for cross-sections, enabling the use of the innovative graphic assessment method proposed by the author of this article – analysis of the variability of the profile shape along the length and the occurrence of cases of shape



Objects

Name	Group	Layer
left		Layer 1
center		Layer 1
right		Layer 1

Properties

Color
Color method: By entity
Visible ☑
Selectable ☑

Features

Number of points	276956
File Name	clear_mid.asc
Element type	CrossingVee

Fig. 2. Screen view in 3D mode with analysis of the railway crossing measurement – with an established reference line

disturbances (image-comparative analysis). The distances between the cross-sections were selected depending on the type of the tested element and were: 200 mm – for rails in curves with small radii, 100 mm – for half-switches, and 35 mm – for frogs.

3.1. Rails in curves with small radii

Measurements were performed for single locations of the measuring device, separately for the inner and outer rail. Fig. 3 and 4 show the actual appearance and the 3D model for the track rails in a curve with a radius of $R = 27$ m at the exit from the Park Południowy tram loop.

The track here is made of 180S rails, attached directly with screws to wooden sleepers, laid on a 20 cm thick ballast. The track is approximately 30 years old. There was also a weld in the inner rail – along its length. Fig. 5 shows a cascade diagram of the cross-sections generated for these rails.

In the drawings above, in the inner rail, the mentioned weld is visible, as well as much greater side wear of the checkrail just behind this weld – most likely the result of the lack of tangency between the two parts of curve in this place. However, in the outer rail, much greater side wear is visible – this time of the rail head, corresponding to the checkrail side wear of the inner rail.

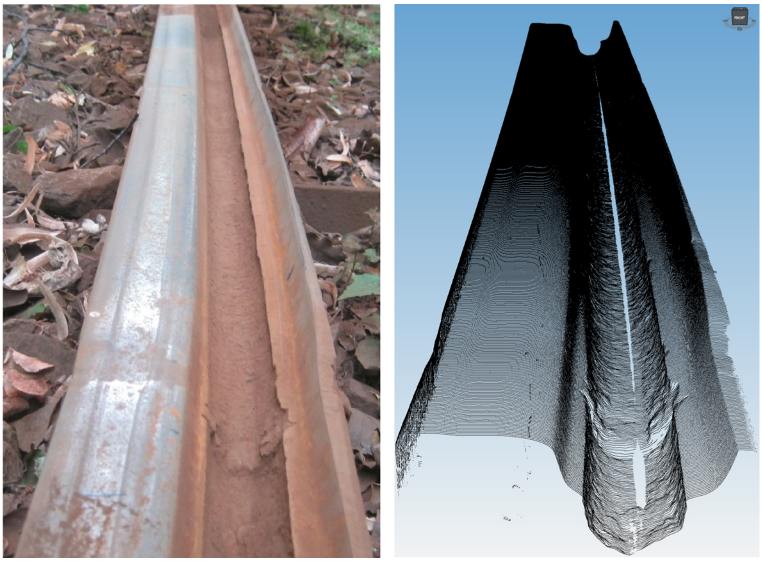


Fig. 3. Real view (left) and 3D model (right) of the inner rail (with weld) in a curve with a radius $R = 27$ m

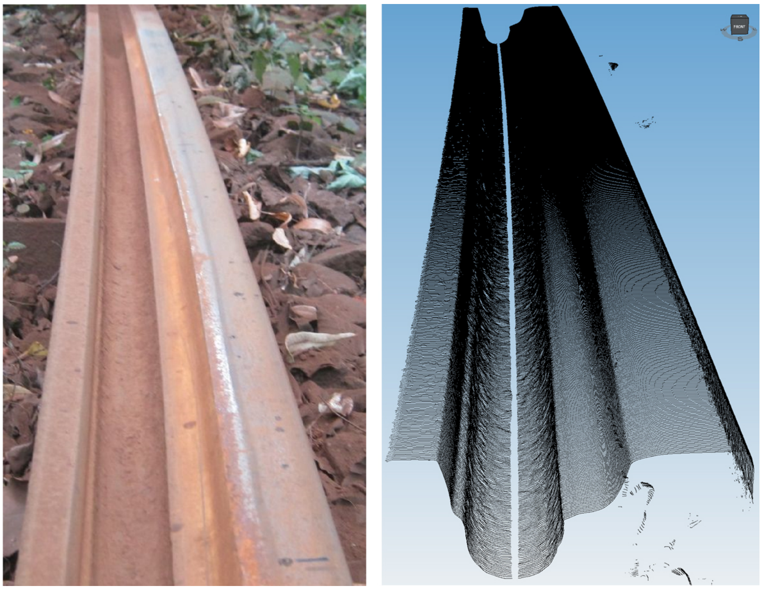


Fig. 4. Real view (left) and 3D model (right) of the outer rail in a curve with a radius $R = 27$ m

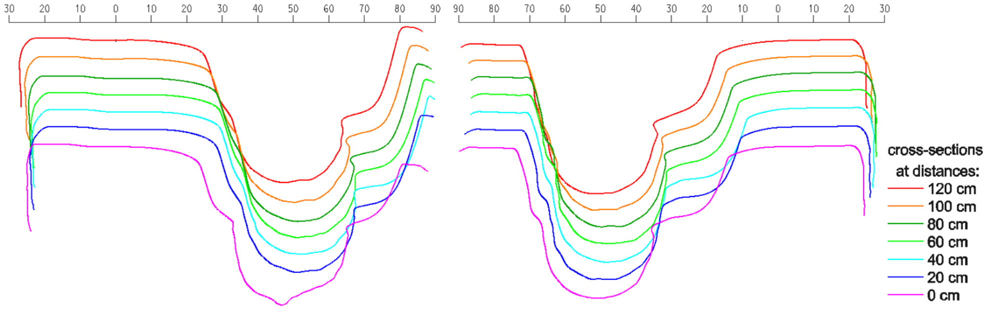


Fig. 5. Cascade diagram of generated cross-sections for rails as above

3.2. Half-switches

For each of the tested half-switches, measurements were made for a total of six separate locations of the measuring device, because due to the length of the switch rails being just over 3 meters in this type of half-switches, three subsequent locations of the positioning frame were necessary – every 110 cm, i.e. with overlaps of slightly over 12 cm, with three separate locations for the switch rail in the position for driving in the main direction, and three more – for the switch rail in the position for driving in the reverse direction. Fig. 6 shows the actual appearance and the 3D model for the beginning of one of the tested half-switches on the Park Poł udniowy loop, and Fig. 7 – a cascade diagram of cross-sections generated for it.

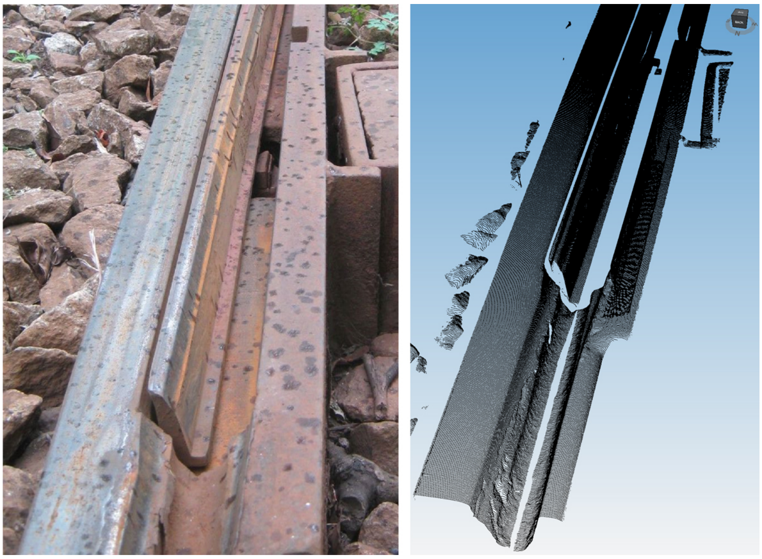


Fig. 6. Real view (left) and 3D model (right) of the beginning of the external tram half-switch

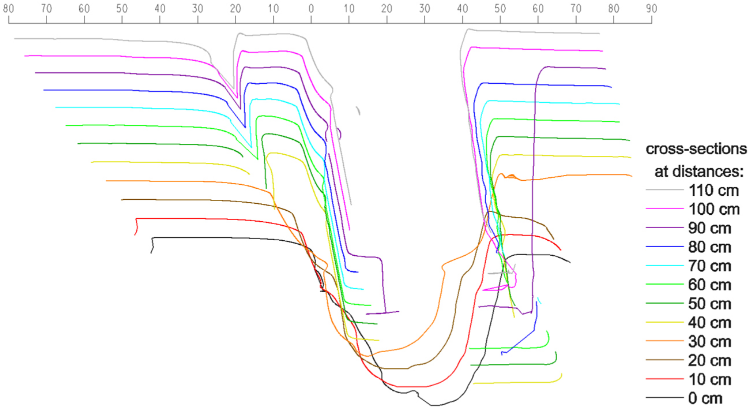


Fig. 7. Cascade diagram of generated cross-sections for the beginning of the half-switch as above

The presented example is an external half-switch, in the reverse direction switch rail position. The generated cross-sections clearly show the progressive lateral wear of the switch rail and the places where the shape of other elements changes.

3.3. Frogs

To measure one frog, a single location of the measuring device was sufficient. Fig. 8 shows the actual appearance and a 3D model for one of the tested frog on the Osobowice loop, and Fig. 9 and 10 – cascade diagrams of the cross-sections generated for it.

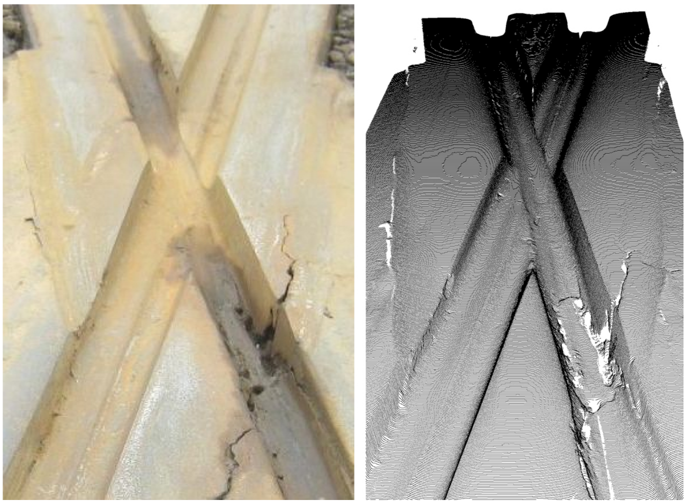


Fig. 8. Real view (left) and 3D model (right) of the tested tram frog, seen opposite to the direction of travel

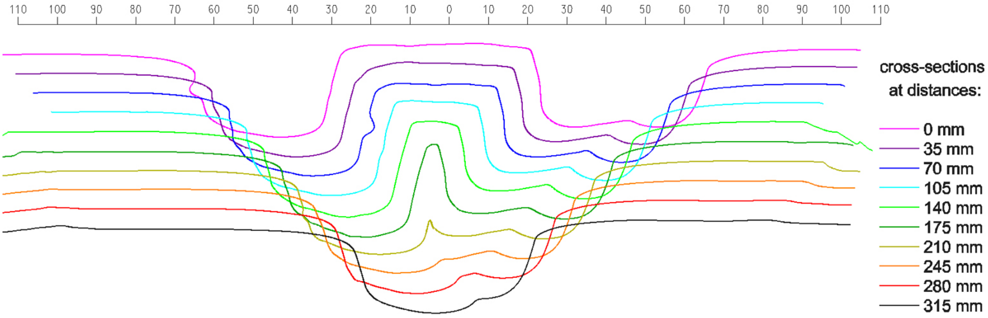


Fig. 9. Cascade diagram of generated cross-sections for the frog as above – from its beginning to the middle

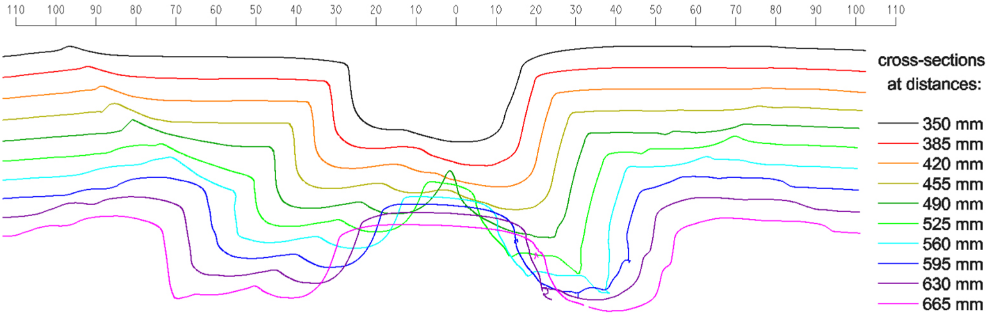


Fig. 10. Cascade diagram of generated cross-sections for the frog as above – from its middle to its end

The presented example shows a frog at the entrance to the passing tracks of the tram loop. In the drawings above, it is shown in a view opposite to the direction of travel. It was a frog, about 20 years old, made of bent, cut and welded rails (not by milling a steel block), with a straight-curve geometry (one groove in a straight track, the other – in a curve with a radius $R = 50$ m). The generated 3D model and the cross-sections clearly show the wear patterns typical of this type of frogs – namely:

- two traces of the wheel flanges – in a curve (groove /),
- one trace – in a straight line (groove \),
- developing cracks and defects – at the contact of its welded elements.

3.4. Corrugation

Measurements were made for six subsequent locations of the measuring device – every 110 cm (i.e. again with overlaps of just over 12 cm), for the selected rail track (left or right). In the presented example, the research was carried out at Ślężna street (between Pułtuska and Weigla streets), about a month after the suspension of tram traffic (caused by street renovation), therefore rusty traces are already visible on the rail head, which make it easier to identify corrugated wear. The track structure in this place consists of S49 rails on pre-stressed concrete sleepers with SB type fastenings, on a 20 cm thick ballast, and its age is approximately 15 years.

For testing this type of defect, instead of cross-sections, generated longitudinal profiles were analysed. Fig. 11 shows the longitudinal profile of the example measurement, compared to its real view, you can clearly see the overlap of the graph peaks with the rusty spots.

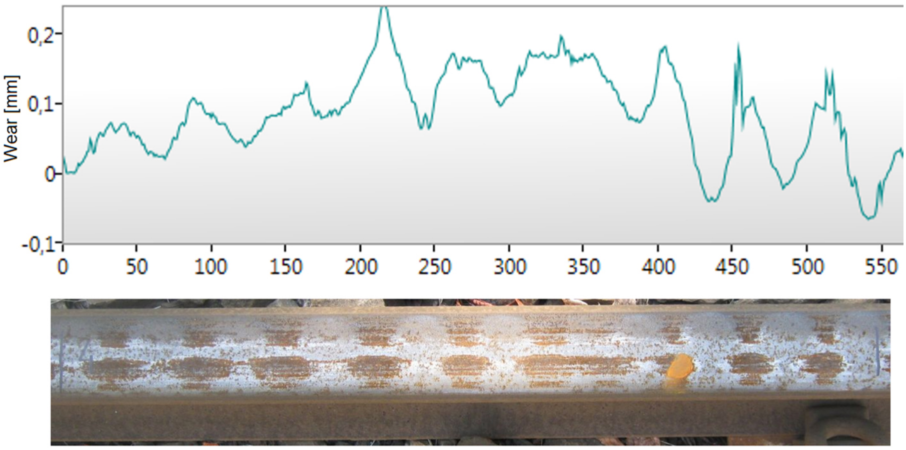


Fig. 11. Longitudinal profile of corrugated wear (top) and its real view (bottom) for an example measurement

In order to verify the correctness of the measurements carried out with a laser scanner, similar tests were performed with another device – an electronic inductive straightness gauge. Fig. 12 shows an example comparison of test results using two methods.

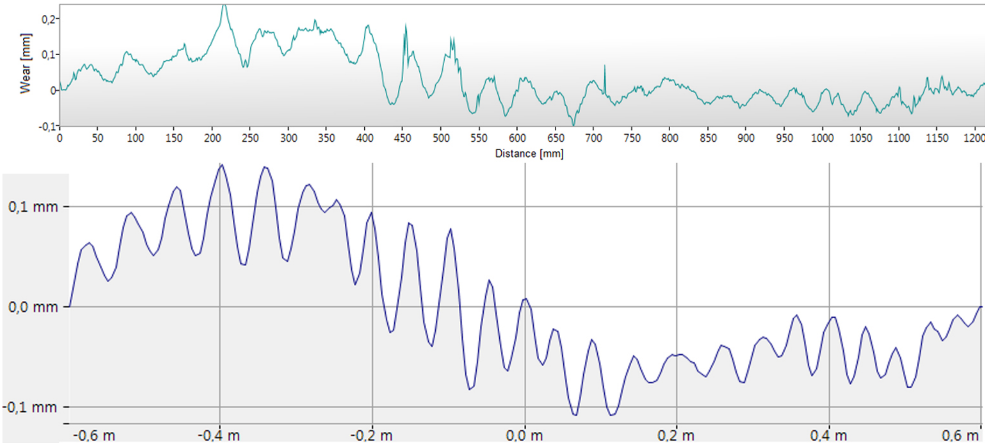


Fig. 12. Comparison of the results of corrugated wear measurements carried out with a laser scanner (top) and an electronic inductive straightness gauge (bottom) for an example measurement

The test results from both methods turned out to be consistent for all settings.

3.5. Broken welds

In the measurements carried out, the positioning frame of the measuring device was set so that the broken weld was in the middle of its measuring range along its length. Of course, the measuring device scanned not only at the point of the weld, but over the entire measuring range of the positioning frame. Fig. 13 shows the actual appearance and a 3D model for one of the tested broken welds at Ślężna street (track structure and age – as in the previous section), and Fig. 14 – the results of the analyses performed.

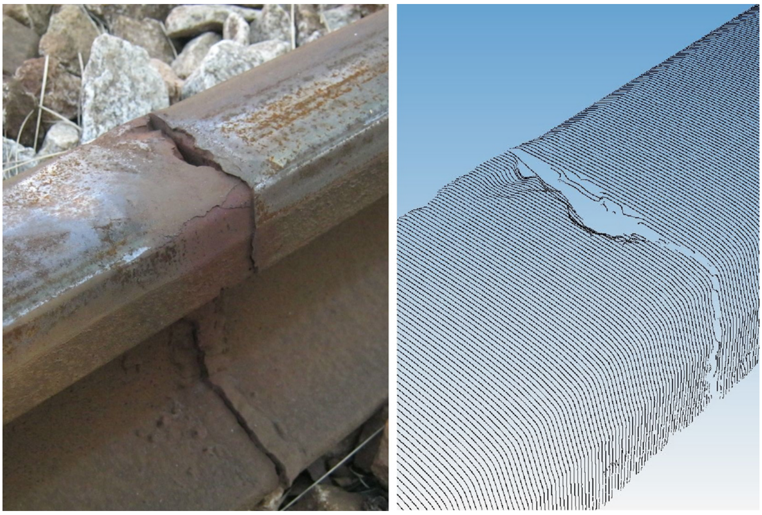


Fig. 13. Real view (left) and 3D model (right) of a broken weld (opposite to the direction of travel)

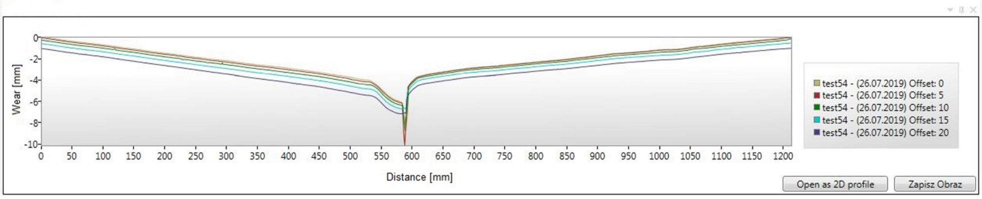


Fig. 14. Diagram of generated longitudinal profiles for a rail section with a broken weld as above (opposite to the direction of travel)

The generated longitudinal profiles (Fig. 14), the first one – in the axis of the rail head and the next four – made with shifts of 5 mm to the inside of the track, clearly show the lowering of the rail head grade and defects occurring at the point of break.

4. Conclusions

In this article, its author deliberately did not present any mathematical formulas, nor any calculations made according to them and their tabular summaries (although, of course, they were carried out as part of the preparation of the measurement results), but only graphical analyses. The aim of such a procedure was to highlight the entire range of inference possibilities in the presented article – based solely on graphic image analyzes (cascade charts of subsequent cross-sections, comparisons of charts and photographic documentation, comparisons of charts obtained from various measurement methods).

In answer to one of the questions posed in the introduction of this article, its author states that diagnostic tests of tram tracks carried out using a laser scanner, despite their certain differences, both geometrically and structurally, in relation to the tracks used in the case of classic railways, confirmed the usefulness of using the device under consideration for this purpose. Successfully applied all assessment tools used in railway track research – starting from generating a three-dimensional model and the possibility of its visual assessment, through generating a series of two-dimensional cross-sections and longitudinal profiles, with the possibility of: describing, measuring, comparing, and exporting to the graphic file format (illustrations), vector (dxf), numerical (XY coordinate values), which in turn makes it possible to perform more advanced analyzes as well as create comprehensive reports on the tests performed.

However, a certain inconvenience turned out to be the fact – much smaller radii of curves used in tram tracks (even only $R = 18$ m) compared to classic railways (probably not less than $R = 190$ m). For this reason, longitudinal profiles generated in a straight line in the case of rail tracks located in curves with small radii did not "follow" the correct trace of the wheel in the groove and gave a slightly distorted (slanted) image.

On the other hand, due to the limited measuring range of the laser scanner used (Table 1) and the slightly smaller dimensions of tram frogs compared to typical railway ones, it turns out to be a device more dedicated to the former.

The experience gained by the author of the article during the research leads him to the conclusion that rail profilographs using the LiDAR technique, compared to their older generations (mechanical or mechanical-electronic), offer the following advantages:

- they are much more efficient (the measurements result in point clouds),
- they are more convenient (you no longer need to guide the pointing stick manually).

Unfortunately, they also have some disadvantages:

- are more expensive (hardware, software),
- in the case of unfavourable weather conditions (strong sunlight, rainfall, frost) or contamination (grease or oil stains, dirt – especially in the grooves) may generate some distortions in the results obtained from the measurements.

The first of the advantages mentioned above (efficiency), unfortunately, also becomes a disadvantage, because to analyze a much larger amount of data – obtained thanks to the use of point cloud technology, traditional methodologies, such as reviewing test results presented in tabular or graphical form by an expert diagnostician, are no longer sufficient. The author of the research carried out this way, but it took him much more time than in the case of analyzing the results of analogous research carried out using classic techniques (mechanical or mechanical-electronic profilographs). In the case of analysis of research results obtained from profilographs using LiDAR techniques, one needs software supported by tools such as artificial intelligence (AI) [39, 40], machine learning (ML) [41–44], including deep learning [45–51], and neural networks [52–55]. Simply put, the amount of data obtained thanks to LiDAR devices, when analyzed, no longer corresponds to the perceptual capabilities of the person (in this case, the diagnostician) assessing them.

The second of the above-mentioned advantages (convenience), in the case of the type of device used for research by the author of this article (a stationary laser scanner placed on tracks), unfortunately also remains somewhat controversial. It is no longer necessary to guide the pointing stick manually along the tested surface, but all other necessary activities have not changed, or even become slightly more complicated. Not one, but two employees are needed to operate the device, and at least a medium-sized passenger car is needed to transport it. The measurement takes only 2 minutes, but this should include the time of: setting up the frame (so as to obtain a stable support), setting up the tent (in case of strong sunlight or rainfall), removing dirt (oil stains, grease, hardened mud from the rail grooves, half-switches and frogs) and covering shiny surfaces with a matting agent, which adds another 10 to 15 minutes to each measure cycle.

One of the features of the industrial revolution 4.0 is the use of the IoT (Internet of Things), in which, thanks to the use of sensors and innovative mobile and computing technologies (cloud, big data, artificial intelligence, machine learning), elements of the infrastructure used can obtain, collect and share data regarding their exploitation with minimal human intervention [56, 57]. Thanks to this, they can adapt and model every interaction related to their management, and as a result, implement maintenance activities as part of the so-called "Data Driven Maintenance”, i.e. maintenance based on data [58–61]. In the railway industry, such solutions are already being implemented – in the case of diagnostics of switch drives [62–64] and methods of monitoring the condition of tracks involving the installation of measuring devices, not on specialized rail cars, but on scheduled trains [65, 66]. Only such models of real infrastructure objects can be treated as their digital twins, because they already have the ability to self-update.

Considering the above, the use of a stationary laser scanner to diagnose wear on rails and turnouts on tram tracks does not seem to be a good solution. Instead, it would be advisable to install a LiDAR-type measuring device on a trolley that performs inspections of tram tracks [67], or even on one of the trams carrying out passenger transport in a city [68]. In the case of the city of Wrocław, if such a tram ran on a different line every day, it would update the data in a cycle of just over twenty days. If a faster data update rate was needed, the tram could change lines at subsequent loops and thus cover several of them in one day.

In addition to a laser scanner, such a tram or handcar should also be equipped with high-resolution video cameras, which could allow replacing traditional track inspections with automated detours [69]. Such solutions are currently being implemented on railways in Great Britain [15, 70].

Returning to LiDAR techniques – the problem may be that currently used mobile laser scanners (railroad, train, drone) do not yet provide such high measurement precision as stationary versions of these devices, but this technology is constantly developing [15] and this limitation will most likely disappear soon. In the case of classic trams, the advantage of this method of measurement is the fact that when passing through curves with small radii, as well as switches and frogs, they are obliged to slow down to a speed of even only 10 km/h (this is the case in Wrocław).

The use of this type of solution is also supported by the fact, that in the case of classic tram routes, a significant part of them has the form of tracks covered with a road surface, on which not only trams, but also cars and buses move (joint tram and bus routes – increasingly popular in Wrocł aw) and emergency services vehicles (so-called "life lanes"). In such conditions, making inspection rounds on foot and placing any stationary measuring devices on the tracks constitute both – a difficulty and a risk.

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Analiza możliwości wykorzystania techniki LiDAR do badania zużycia szyn i rozjazdów w torach tramwajowych

Słowa kluczowe: tory tramwajowe, zużycie, diagnostyka obrazowa, LiDAR

Streszczenie:

We wstępie artykułu uwypuklono znaczenie pomiarów zużycia szyn i rozjazdów kolejowych. Przedstawiono w skrócie ewolucję metod i urządzeń stosowanych do pomiarów profili tych elementów. Wyjaśniono zasadę przeprowadzania badań z wykorzystaniem techniki LiDAR. Wskazano na problem odmienności geometrycznej i konstrukcyjnej torów tramwajowych w stosunku do klasycznej kolei i wynikające stąd obawy, o możliwośc adaptowania typowo kolejowych metod pomiaru profili szyn i rozjazdów do torów tramwajowych. W dalszej części artykułu opisano budowę, podstawowe parametry oraz sposób obsługi precyzyjnego stacjonarnego skanera laserowego, dedykowanego do pomiaru profili szyn i rozjazdów kolejowych. Przedstawiono graficzne analizy wyników dla pomiarów przeprowadzonych wspomnianym urządzeniem w torach tramwajowych – dla szyn w łukach o małych promieniach, rozjazdów, zużycia falistego oraz złamań w spoinach. W podsumowaniu sformułowano wnioski z przeprowadzonych badań.

Received: 2023-09-25, Revised: 2024-03-26