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Quantifying Tram Overhead Contact Line Stagger and Its Impact on Carbon Strip Wear †

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Abstract

This study investigates the stagger of tram overhead lines and its effect on pantograph carbon strip wear. Using a specialized measurement vehicle equipped with a stagger decoder, field data were collected along selected tram routes. The measured wire geometry was compared with the original design documentation to assess deviations and their impact on energy collection efficiency and strip longevity. Results highlight areas where design tolerances differ from reality, providing insights for infrastructure optimization and maintenance planning. The findings demonstrate the importance of precise monitoring of overhead line alignment to ensure uniform wear and improve the reliability of tram systems.

Keywords: Field Measurement, Pantograph Carbon Strip Wear, Stagger, Tram Overhead Line

1. Introduction

Tram transport represents an efficient and environmentally sustainable mode of urban mobility, particularly in medium-sized cities, due to its high passenger capacity and low carbon footprint. [1, 2, 3] The reliability and safety of tram systems depend not only on vehicle performance but also on the condition and geometry of the overhead contact line, which directly affects current collection quality. [3]

A key parameter influencing the interaction between the pantograph and the contact line is the stagger of the overhead wire. Properly designed stagger ensures uniform contact strip wear and stable current collection, while deviations from design tolerances may lead to increased mechanical stress, uneven wear, and reduced system reliability. [4] Consequently, accurate monitoring and evaluation of stagger are essential for effective maintenance and infrastructure optimization.

This paper aims to quantify the stagger of tram overhead contact lines using field measurements and to assess its impact on carbon strip wear. Particular attention is given to the statistical characterization of stagger along selected track sections and its comparison with design tolerances. Furthermore, the relationship between stagger variability

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and wear is analyzed using quantitative methods to identify critical thresholds and support the development of predictive maintenance strategies. [5, 6]

2. Standard Provision of Tram Infrastructure

Stagger of overhead contact line is not defined by the decrees and laws of the Ministry of Transport of the Slovak Republic; the stagger is defined by the standard STN EN 50367 "Railway application. Fixed installations and rolling stock". Criteria to achieve technical compatibility between pantographs and overhead contact line. The normative name for stagger is the horizontal deflection of the overhead contact line. The permissible horizontal deflection of the contact wire from the track axis is calculated based on the pantograph working head in terms of serviceability and the disconnection limit value (horizontal interaction stability limit value). [6]

In general, the standards define two different pantograph dimensions. Pantograph head lengths of 1600 mm and 1950 mm. Each type of pantograph has its own permissible horizontal deviations of the contact wire from the track axis, which also depends on the track radius. All calculations assume a pantograph head length of 1600 mm due to the use of this pantograph head on all types of vehicles in Bratislava. [6]

The above-mentioned standard determines only the horizontal deflection, the angle at which the overhead line is deflected is not specified in either the standard or the regulations. The angle at which the overhead contact line is deflected is specified by the designer of the construction documentation regarding the location of the traction poles and the current situation on the track. This can be influenced by a larger intersection or the radius of the tracks. In the article, we also define this angle as a reference section of the stagger of the overhead contact line, how it should be deflected and how it is deflected today. [6]

The designer of the construction documentation does not directly determine the angle, he determines the distance from where the overhead line is in the axis of the track to the place where the overhead line reaches its maximum value, i.e. plus or minus 35 cm. The distance is in the interval from 25 to 35 meters and therefore from the given interval we choose the average value from which we can calculate the angle using goniometric functions. A more detailed illustration is shown in Figure 1.

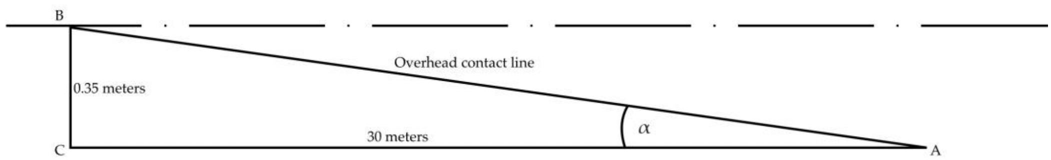

Figure 1. Determination of the angle for normative values of the stagger. Source: Own elaboration.

From the given triangle, we use goniometric functions to calculate the unknown angle α, at which the overhead line will deflect from the rail axis. From the known sides a, b, we expect a very small angle α.

$$\tan \alpha = \frac{a}{b}$$

Since the angle is an unknown quantity, we will adjust the formula.

$$\boldsymbol{\alpha} = \tan^{-1}\frac{\boldsymbol{a}}{\boldsymbol{b}} = \tan^{-1}\frac{0.35}{30}$$

$$\boldsymbol{\alpha} = 0.668420° = 0°40'6.3136''$$

After calculating the angle, we define the theory of stagger and at the same time our well-known standard according to which the overhead contact line should be designed (Table 1). From the evaluation and display software, we know that the step we move forward is 4 cm and at the same time the smallest value we can display is 2 cm to both the positive and negative values. It is from this knowledge that we will construct 9 triangles, from which we know the side a and the angle α. The angle α will be constant according to the calculation above, the side a will change as follows: 0.02 meters; 0.06 meters; 0.10 meters; 0.14 meters; 0.18 meters; 0.22 meters; 0.26 meters; 0.30 meters; 0.34 meters. The given values of the perpendicular distance of the overhead contact line deflection are also displayed by the software during the measurement in centimeters, and to determine the theory of stagger, we need to know at what distance the software will display the single values. It should be added that these values of the distance traveled assume a perfect straight track and the starting point of the measurement is the rail axis, or rather our point with the value 0.

Table 1. Normative parameters used for definition of stagger. Source: Own elaboration.

Software value of stagger (m)	Distance traveled at which software gives single values (m)
0.02	1.71
0.06	5.14
0.10	8.57
0.14	12.00
0.18	15.43
0.22	18.86
0.26	22.29
0.30	25.72
0.34	29.14
0.35	30.00

From the data, we graphically define the theory of tortuosity under straight line conditions and the starting point of measurement 0, respectively with the position of the overhead contact line in the line axis (Figure 2).

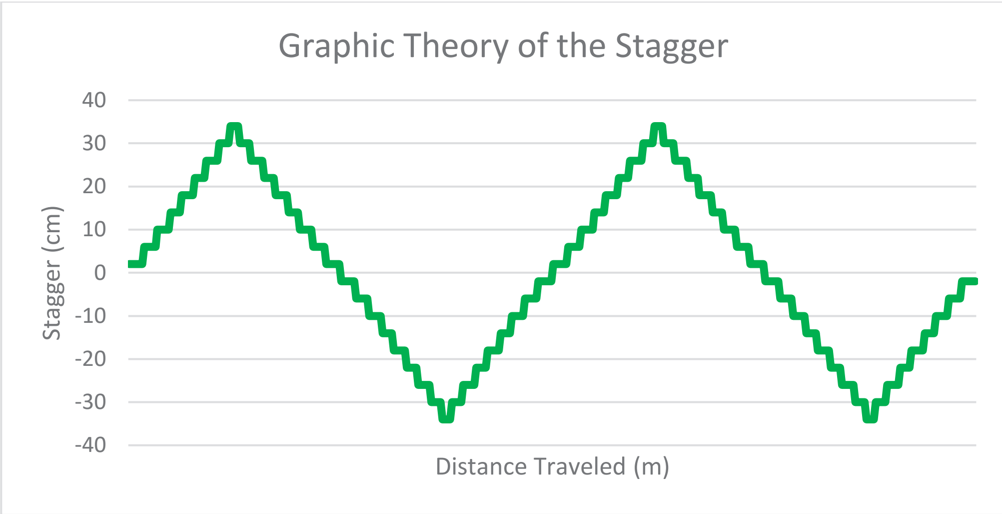

Figure 2. Graphic definition of the stagger of the overhead contact line, the deflection of the overhead contact line takes place under a specified angle. Source: Own elaboration.

3. Methodology

During the daily maintenance of trams after the end of service at the depot, it was found that the carbon strips were worn out, especially in the middle zone of the carbon strip. Trams that arrived at the depot in the evening with this anomaly were sent to line number 3.

Line number 3 has recently undergone changes. As part of the construction of the 2nd stage of the Petržalka tram (southern radial), line number 3 was extended to the southern end, where a classic turning point for one-directional trams was built. Until the new section was launched, trams turned at the dead-end turning point, only bi-directional trams were sent to this line, and the driver's station changed after each round. After the extension was launched, bi-directional trams of the Škoda 30T type continue to send to line number 3, but they use the classic turning point, and therefore the driver's station does not change. The driver's station change is currently ensured by the dead-end turning point at the depot by technical workers, due to the even wear of the wheel bearings at an interval of once every 2 months.

After the problem occurred, it was necessary to think about what could have caused the uneven wear of the carbon strips. After consulting with technical and measurement workers, together with the management of the transport company and the workers responsible for the overhead line, three factors were identified that caused the problem.

1. Bi-directional trams have stopped using the second driver's station, and therefore the carbon rails are worn down only on one side.

2. Emergency condition of the northern radial, where the subsoil of the tram track is washed away, the rails are loose in two axes and the rails adapt to the weight of the passing tram.

3. Incorrectly set stagger parameters on the newly opened section of the southern radial.

As part of the problem identification, it was also necessary to measure the stagger along the entire length of line number 3 to implement corrective measures and prevent, for example, pantograph breakage due to excessive wear of the carbon strip. A specially modified measuring vehicle is used to measure the stagger, which uses a stagger decoder instead of a second carbon strip (Figure 3). Modified stagger decoder is made of light-weight aluminium, into which inductive (touch) sensors are mounted. They record the value in centimetres and are placed four centimetres apart. The stagger decoder consists of 21 inductive sensors to identify the position of the overhead contact line. To ensure correct measurement, analog eddy current sensors with a resolution of 4 micrometers and supply voltage 12 V were selected. [7, 8]

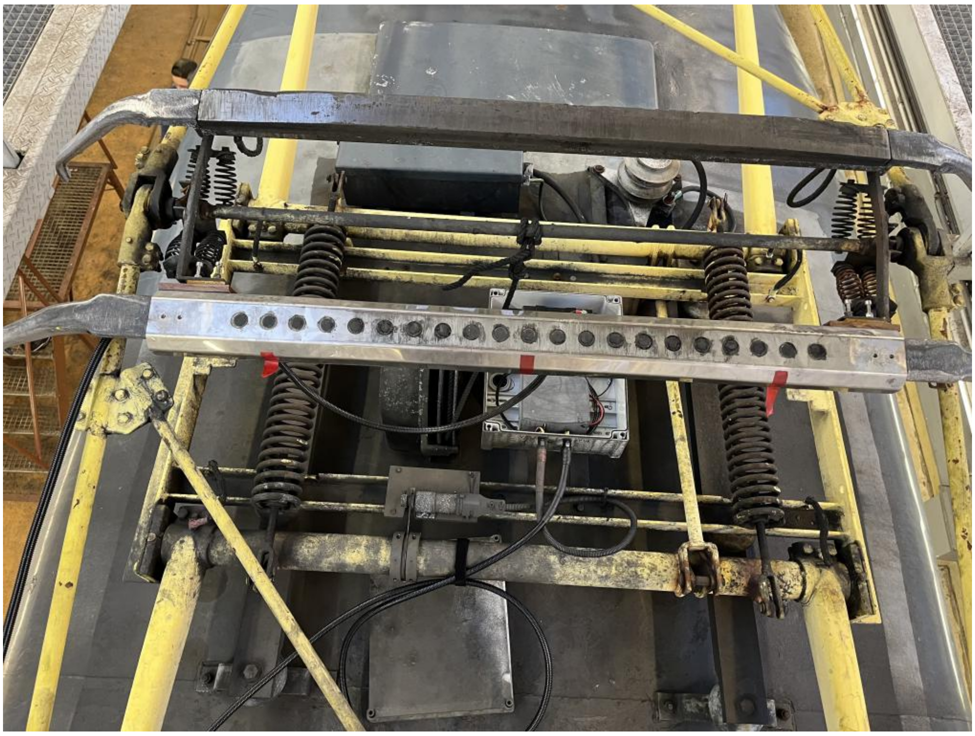

Figure 3. The installed torquing decoder on the pantograph (top view) with the converter box open. Photo taken after installation before measurement. The red tapes on the back of the torquing decoder are used to monitor the tolerance band in real time during the measurement via a camera at the rear of the tram on the roof. Source: Own photograph.

There is also a converter box on the roof of the tram under the pantograph. The converter box contains a dedicated space for the battery, which is needed to supply the measuring system, since the sensors are not supplied directly from the overhead contact line, in which 600 V direct current flows, but from the battery as a power supply. An optical cable was used to connect the converter and the laptop in the measuring tram for the fastest data transfer in real time (Figure 4). [8]

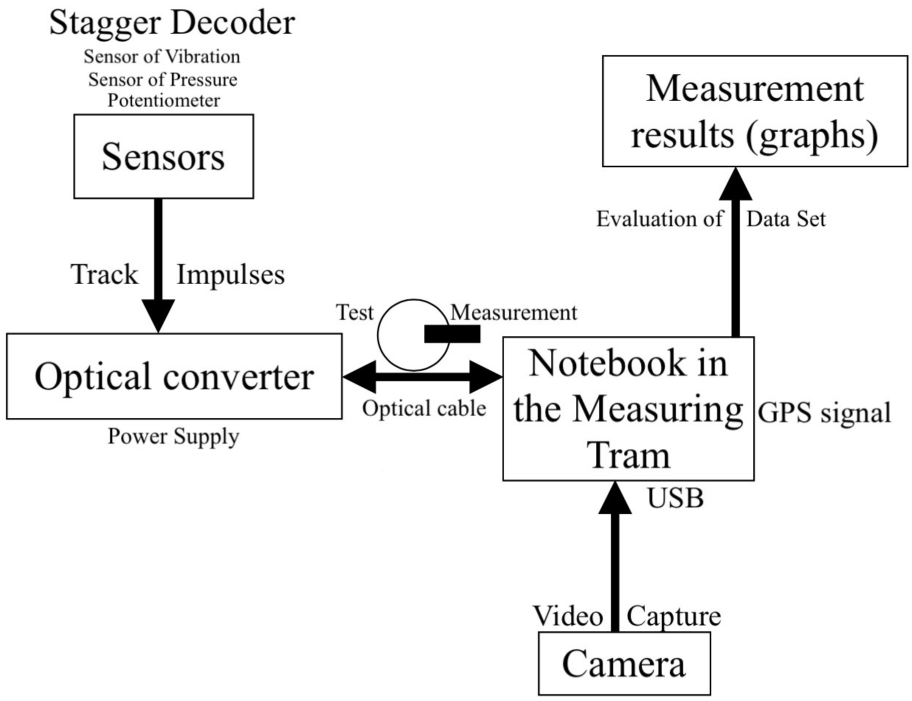

Figure 4. Schematic representation of the connection of sensors to a notebook in a measuring tram. The diagram also shows the data flow path. [8], Own elaboration.

4. Measurement – Analysis of Up-to-date Condition

This study demonstrates that tram overhead line stagger significantly influences pantograph carbon strip wear. Field measurements using a specialized vehicle with a meandering decoder revealed deviations from the original design documentation, highlighting sections where infrastructure does not fully meet design tolerances. These findings emphasize the need for continuous monitoring of overhead line geometry to optimize maintenance schedules, reduce uneven wear, and enhance energy collection efficiency. Implementing such measurement-based assessments can improve the reliability and longevity of tram systems, providing a practical framework for infrastructure planning and operational improvements.

Due to the large number of data (48,000 in one direction), we performed an evaluation of the new track section in southern radial to exclude point number 3 from the possible reasons for excessive wear of the middle zone of the carbon strip. The measured data are presented in the graphs in Figures 5 to 8.

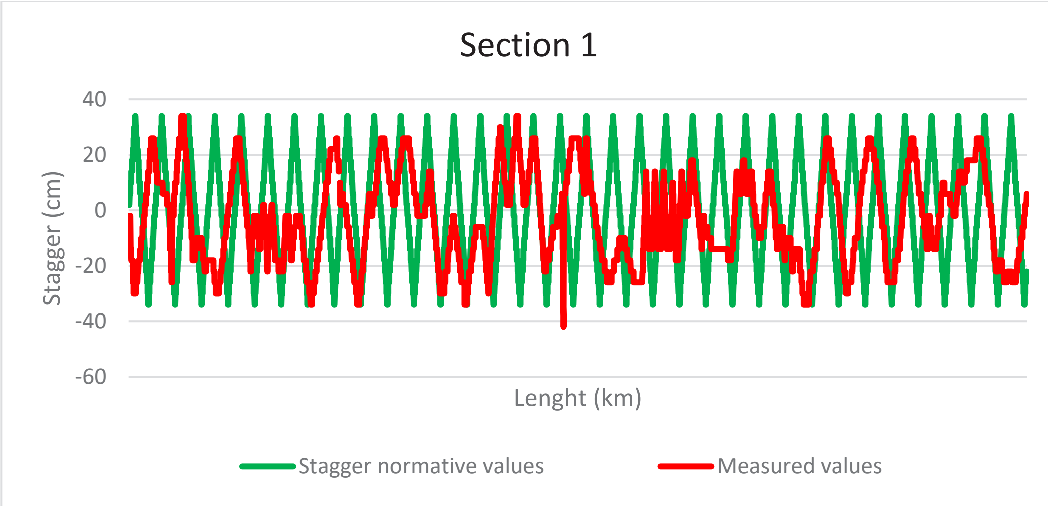

Figure 5. Measured data in the Section 1 in direction to the northern radial (the first exchange station). Source: Own elaboration.

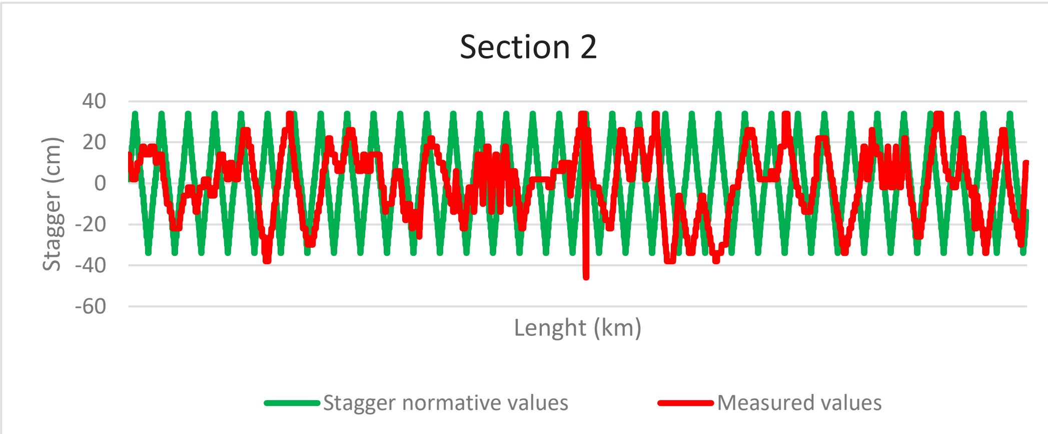

Figure 6. Measured data in the Section 2 in direction to the southern radial (the first exchange station). Source: Own elaboration.

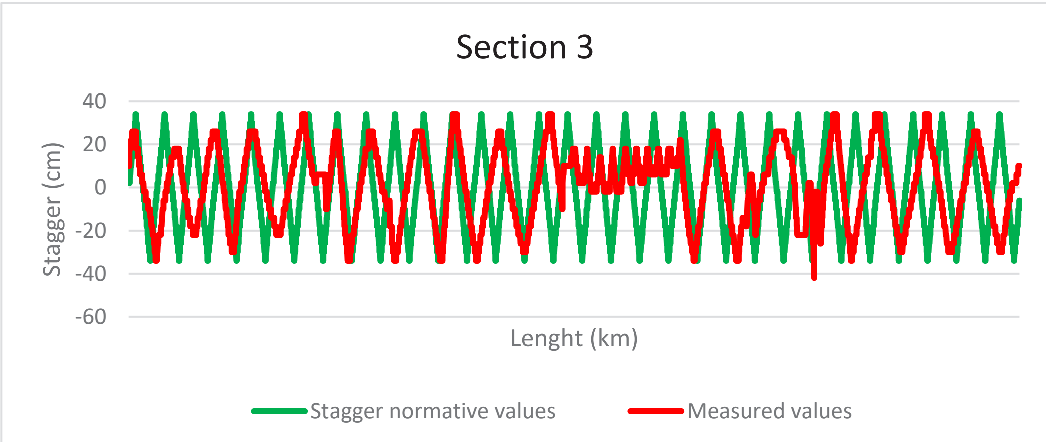

Figure 7. Measured data in the Section 3 in direction to the southern radial (the second exchange station). Source: Own elaboration.

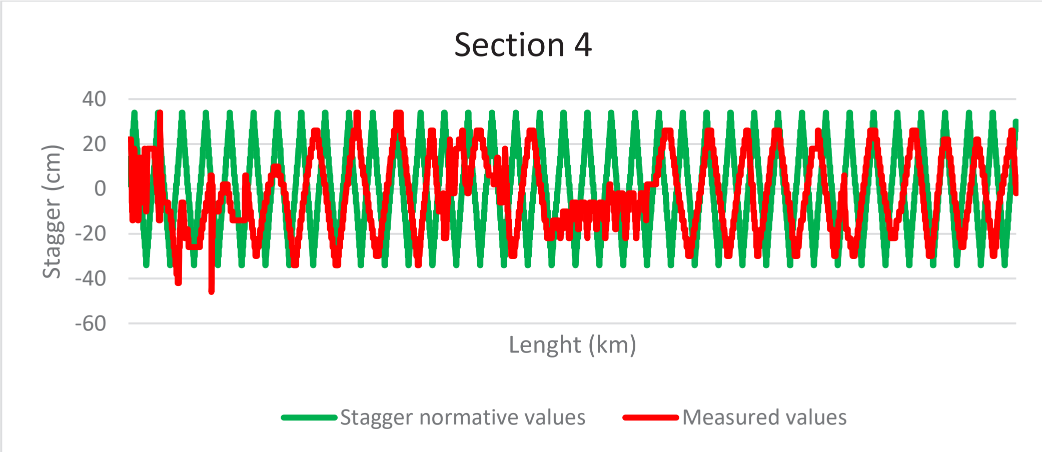

Figure 8. Measured data in the Section 4 in direction to the northern radial (the second exchange station). Source: Own elaboration.

As part of the evaluation of individual sections, we divided the southern radial into two equal sections according to the exchange stations that supply the entire radial. The first exchange station (Bosákova) supplies the southern radial on 5 stops. The second exchange station (Panónska) exchange station supplies the remaining section which contains 4 stops including turning point at the end of the southern radial. The newly opened track is supplied primarily from the second exchange station, two additional sections are supplied from the first exchange station. If we look at the graphs, we can see that the individual sections are mostly within tolerance, we will zoom in on the places that the stagger decoder evaluated as out of tolerance (Figure 9). We can also observe uniform use of the tolerance band across the entire radial, and therefore we can state that excessive wear of the middle zone of carbon strips on operational vehicles is not caused by poor adjustment of the stagger parameters.

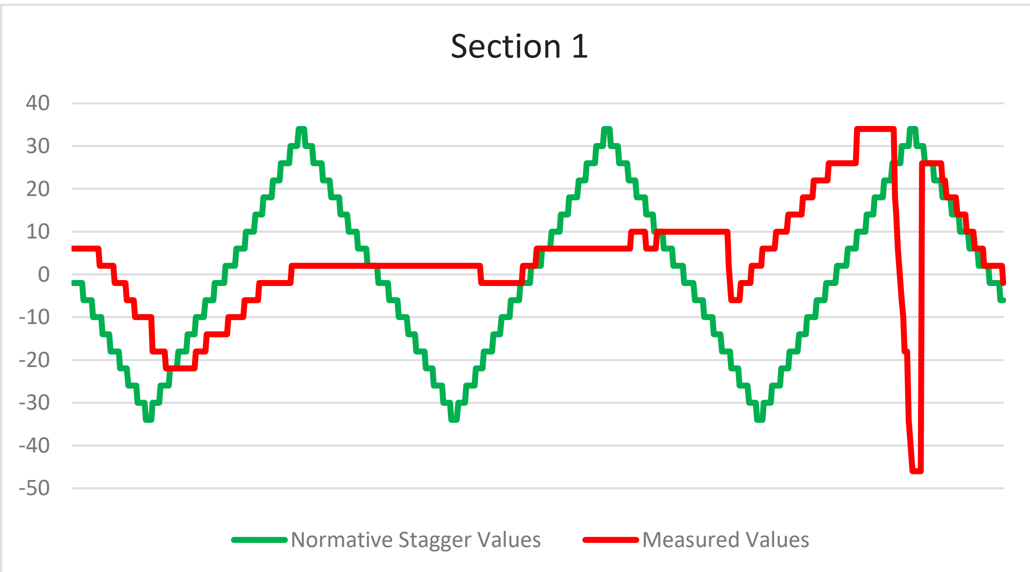

Figure 9. Measured data in the Section 1, in the selected section, we zoomed in values out of tolerance. Source: Own elaboration.

From graph no. 2 we have zoomed in on the section, from which the stagger decoder evaluated the section as out of tolerance. However, if we look at the data more closely, we can observe a smooth rise and a seemingly smooth descent, which at a certain point drop to a value out of tolerance. We can explain this phenomenon if we know the design parameters of the track.

The overhead contact line is not tensioned in a continuous length from the beginning to the end of the track. Just as it is divided into individual exchange station and subsequently into individual sections, which are separated from each other by neutral fields, it is also divided into individual tensioning sections. The tensioning sections are subsequently separated in so-called exchange fields, where the current overhead contact line is anchored to the mast and the upcoming overhead contact line, which also comes out of the anchoring on the mast, is tensioned to the upcoming section. There are different types of the anchoring (Figure 10). Fixed anchorage and manipulation anchorage. The fixed anchorage is mounted on the mast and cannot be moved in any way. The manipulation anchorage serves to eliminate unwanted overhangs caused by meteorological influences. When measuring the stagger of exchange fields, two overhead contact lines meet in different positions at certain points and the stagger decoder always records a worse value, regardless of the course of the measured data. [9, 10]

Figure 10. Two methods of tensioning the overhead contact line. On the left, using a tension pulley, on the right, using the addition or removal of weights. In the figure on the left, we can also see the ongoing replacement of overhead contact lines within the exchange field. Source: Own photograph.

When a tram passes through the exchange fields, the pantograph moves through areas where individual overhead contact lines are laterally displaced and tensioned into separate tensioning sections. As a result, the stagger decoder may record values outside the tolerance, even though the track itself conforms to the design parameters. This phenomenon is therefore a natural consequence of the structural division of the overhead line into tensioning sections and does not indicate an error in the stagger setting. The tram adapts the pantograph to small variations in the geometry of the overhead line as it passes through each section.

These minor deviations affect not only the mechanical load on the pantograph and carbon strips but also the vehicle's traction mechanics, particularly the uniformity of force transmission and the stability of current collection. Uninterrupted and stable contact is crucial for the optimal operation of the traction system and the powering of the tram's electric motors. Irregularities can lead to localized fluctuations in voltage and current, potentially impacting the overall efficiency of the drive system and the vehicle's energy balance. From the perspective of the entire system's operation, regular measurement and monitoring of the overhead line stagger are therefore essential, not only to minimize pantograph wear but also to ensure the reliability, safety, and energy efficiency of tram operations. [10, 11, 12]

5. Discussion

The results of this study confirm the importance of overhead contact line geometry, in particular the stagger, as a key factor influencing the interaction between the pantograph and the catenary. The measured data demonstrated that even small deviations from the design values can, over the long term, affect the wear pattern of carbon strips, although such deviations cannot always be interpreted as a technical fault or operational defect.

The analysis shows that the increased wear observed in the central area of the carbon strips is not caused by incorrect stagger settings on the newly constructed section, but rather by the natural variability resulting from the segmentation of the overhead line into tensioning sections and overlap zones. This finding is important for the correct interpretation of diagnostic data and helps prevent unnecessary interventions in the infrastructure.

The main scientific contribution of this work is the validation of a mobile measurement system with a stagger decoder for detailed mapping of overhead line geometry under real operating conditions, providing more accurate and continuous data than conventional inspection methods and enabling objective infrastructure assessment. In addition, the study confirms a clear relationship between contact line geometry and the wear of current collection elements, supporting a shift from reactive to predictive, data-driven maintenance. Practically, regular stagger measurements improve maintenance planning, reduce uneven carbon strip wear, extend component service life, and enhance energy transfer efficiency, while lowering operational costs. Overall, precise monitoring of overhead line geometry proves to be an effective tool for infrastructure quality management, integrating measurement, diagnostics, and tribological behaviour into a unified framework that directly improves tram operation reliability.

6. Conclusion

The study clearly demonstrated that the stagger of the tram overhead contact line has a significant impact on the wear of pantograph carbon strips. Field measurements conducted using a specialized measurement vehicle equipped with a stagger decoder revealed deviations from the original design documentation and identified sections where the infrastructure does not comply with the specified tolerances.

Analysis indicated that the excessive wear observed in the central zone of carbon strips on operational vehicles is not caused by incorrectly set stagger parameters on the newly opened section of the southern radial. The natural deviations are attributed to the structural segmentation of the overhead line into individual tensioning sections and exchange fields, which introduce minor irregularities in the measured values.

The results of the study emphasize the necessity of regular and precise monitoring of overhead line geometry. Such measurements enable the optimization of maintenance schedules, reduce uneven carbon strip wear, and improve energy collection efficiency. Implementation of measurement-based assessments provides a practical framework for infrastructure planning and enhances the reliability and service life of tram systems. Overall, the study confirms that accurate control of overhead line parameters is crucial not only for safe operation but also for minimizing maintenance costs and extending the operational lifespan of tram vehicles.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
STN	Slovak Technical Standard
EN	European Standard
KEGA	Scientific and Educational Grant Agency for Higher Education

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