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# Tortuosity Decoder as a Tool for Evaluating Tramway Overhead Contact Line Parameters

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**Abstract:** This paper describes a tortuosity decoder used to measure the parameters of overhead contact lines for tram systems. The decoder is integrated into the pantograph of the measuring tram operated by Dopravný podnik Bratislava, a. s. (Bratislava Transport Company). Its primary function is to assess the tortuosity of the overhead contact lines, which is linked to the wear of carbon strips on trams. Additionally, it monitors the stable and reliable contact between the pantograph and the overhead contact line. This measurement is crucial for ensuring the smooth operation of urban public transport, directly impacting the quality of services and overall transportation safety. The maintenance of tram infrastructure relies on the regular collection and analysis of these measured data. The tortuosity decoder is connected to the computer in a tram in where we can evaluate data set and make measurement results. Along with the graphs, the evaluation is also carried out through the balance table of uncertainties, where we chose tortuosity as the main measurement parameter. There is also designed a measurement model for tortuosity, which also considers influencing factors.

**Keywords:** Measurement, Overhead Contact Line, Quality, Safety, Tortuosity Decoder, Tram.

## 1. Introduction

To measure the tortuosity of the overhead contact line for tram operations, a tortuosity decoder is used, which is integrated into the pantograph of the measuring tram. The primary objective is to ensure the proper functioning of trams and the safety of their operation. A key factor in this process is monitoring the geometry of the overhead contact line, ensuring it complies with technical standards and requirements for smooth and efficient tram operation. This also relates to the uniform wear of the carbon strip on the pantographs of the trams. The paper discusses this issue in the context of the tortuosity of the overhead contact line, its security, and the data evaluation necessary for practical application in the operations of Dopravný podnik Bratislava, a. s. (Bratislava Transport Company) [1].

## 2. Methods for Inspecting and Measuring Tram Lines

When considering methods for inspecting and measuring tram lines, we can use meters tailored to specific quantities or employ more complex measurement techniques, such as those involving a measuring vehicle. This vehicle is typically adapted for the specific measurement tasks and can assess basic parameters. At the

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same time, it also measures parameters such as temperature, humidity, pressure, and voltage in the network. Additionally, measuring trams are equipped with an observation post, where either a person or a camera system monitors the interaction between the pantograph and the overhead contact line during operation. The contact between the tram pantograph and the overhead contact line is closely observed, and the data collected is crucial for ensuring the safety and reliability of transport services [1,2,8].

After inspection and measurement by the vehicle, repairs are carried out on the identified problem areas. Visual inspection using a camera system offers additional advantages, as the camera captures a large volume of data that can be evaluated retrospectively. For this purpose, a specially modified carbon insert is used in the pantograph, which evaluates the tortuosity (tortuosity decoder). The values are provided in centimetres, and the tortuosity is typically assessed in relation to the rails or pantograph [3].

The tortuosity of the overhead contact line is a crucial parameter for several reasons. The main reasons are: It monitors the interaction between the overhead contact line and the tram pantograph, which is linked to the uniform wear of the carbon strips on trams, ensuring stable and reliable contact [1].

### 2.1. Measurement with a Tortuosity Decoder

The tortuosity decoder is used to measure the tortuosity of the overhead contact line and is installed on the tram pantograph. It consists of a specially modified carbon strip on the pantograph, which evaluates the tortuosity of the overhead contact line in comparison with the rails. Modified carbon strip is made of lightweight aluminium, into which inductive (touch) sensors are mounted. They record the value in centimetres and are placed two centimetres apart. To ensure correct measurement, analogue eddy current sensors with a resolution of 4 micrometres and supply voltage 12 V were selected. The pantograph provides electric current to the vehicle from the overhead contact line. For better guidance along the line, the pantograph is equipped with two contact carbon strips. Due to the uniform wear of these carbon strips, the tortuosity of the line along the track is assessed to ensure consistent wear. In practice, however, the middle part of the carbon strip tends to wear the most. Tortuosity is one of the key parameters evaluated during measurements to ensure stable and reliable contact between the pantograph and the line. A higher tortuosity variance typically results in more even wear of the pantographs on the operated vehicles and is closely linked to the lifespan of the carbon strips [3,8,9,12].

However, if the variance is too large, the line may slide along the edge of the pantograph, causing the pantograph's pressure to push it into an upright position. Therefore, during evaluation, maximum tortuosity values are determined, which are selected by the operator and become the monitored parameter. If the values exceed the tolerance limits, the affected sections must be repaired to restore the system to an operational state and ensure the smooth operation of the trams. In the evaluation software, tortuosity can have two states: a positive state and a negative state. A positive state corresponds to values recorded to the right of the centre of the carbon strips, while a negative state refers to values recorded to the left of the centre of the carbon strip. [1,2].

## 3. Results of Tortuosity Measurement

Once the carbon strip (Figure 2) is installed on the measuring tram /its collector/ (which is used solely during the measurement due to its durability and sustainability), the data collection process can begin. The strip is connected to the tortuosity decoder via the connector on the bottom of the measuring strip.

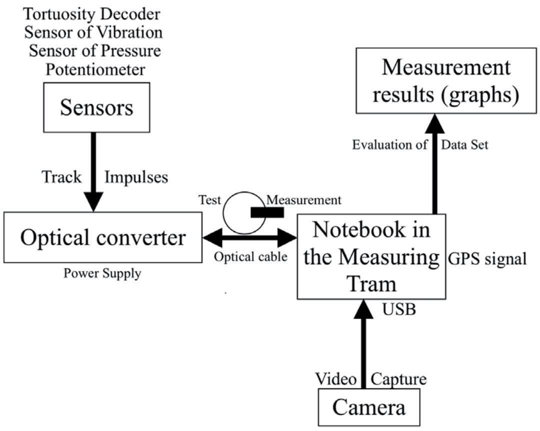



Figure 1. Schematic Representation of Measuring Chain with all Connected Sensors [7]; modified.

Communication is established only when the entire device is powered on, meaning it is activated

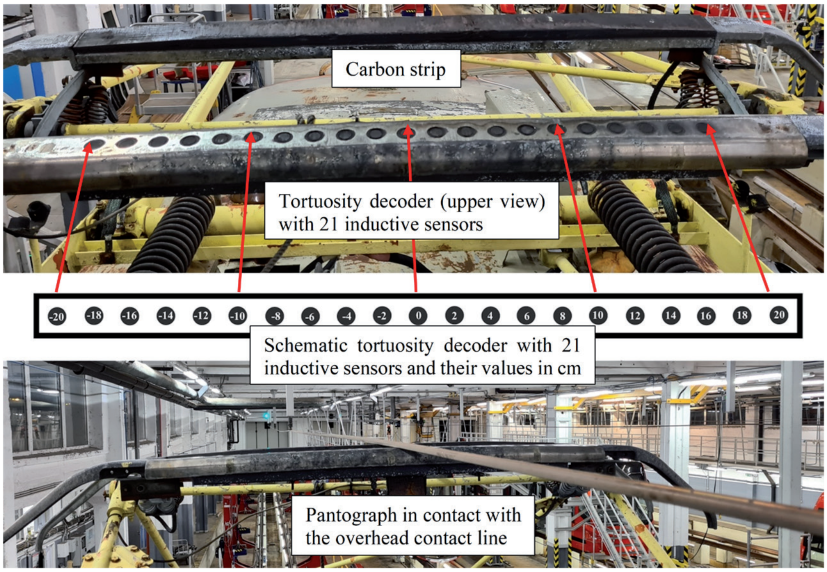


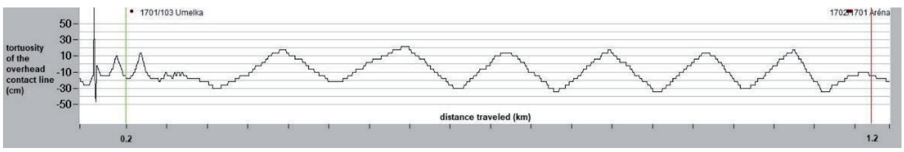

Figure 2. Carbon Strip with Tortuosity Decoder, Mounted on the Pantograph of the Measuring Tram. Schematic Representation of Touch Sensors with their Values and Contact of Overhead Contact Line. Source: Own.

only after establishing communication with the evaluation unit, which in our case could be a computer or a mobile phone. All components are connected within the tram (Figure 1). The power supply module is connected to the computer on the measuring tram, and it is remotely powered on only during the measurement. The measured tortuosity data (sample data) are presented in the Graph 1 and Table 1.

The measurement takes place while the measuring vehicle is in motion. For this purpose, specialized measuring software is used, which records a file containing the measured parameters of the overhead contact line. Before the actual departure and start of the measurement, it is essential to verify the functionality of the measuring device by switching to simulation mode. In this mode, pulses are generated experimentally without the need for the vehicle to be in motion. This allows all measuring functions to be tested in depot conditions prior to operating on the track. During this phase, we verify that the data is correctly saved, test the video recording functionality, and, if necessary, check the functionality of the GPS system, which provides comprehensive data for collecting overhead contact line information. Once the functionality has been verified, the measuring vehicle sets off to gather data for the city's tram network [2].

The measured values include the impact on the pantograph, driving speed, height of the overhead contact line, and tortuosity. Additionally, temperature, humidity, and pressure are important factors to consider. All this data is linked to the route travelled and associated with GPS coordinates. From this data, we can determine the absolute value of the tortuosity, the upper and lower limits of the height values, the amplitude of the shock, and the limitations for the selected measured section of the track. All values are presented in centimetres, except for the distance travelled, which is given in kilometres [1,2].

After the measurement, the obtained data is evaluated based on established standards and




Graph 1. Recording of Measured Tortuosity Data /Selected Section of Track/ [7].

Table 1. Table of Samples of Recorded Data, including Tortuosity Values on a Selected Section of Track, Data provided by the Software for Evaluating this Data are Cited [7].

| MEASUREMENT OF OVERHEAD LINE PARAMETERS | | | | |
|---|---|---|---|---|
| TORTUOSITY (cm) | SPEED (km/h) | SHOCKS (-) | HEIGHT (cm) | POSITION (km) |
| MEASURED AREA "1701/103 UMELKA" | | | | |
| -14 | 20 | 276 | 511 | 0.2565 |
| -14 | 19 | 174 | 512 | 0.2571 |
| -14 | 19 | 154 | 511 | 0.2576 |
| -14 | 19 | 140 | 512 | 0.2581 |
| -10 | 19 | 132 | 512 | 0.2586 |
| -10 | 19 | 126 | 512 | 0.2592 |
| -10 | 18 | 122 | 512 | 0.2597 |
| -10 | 19 | 116 | 512 | 0.2602 |
| -6 | 18 | 162 | 512 | 0.2608 |
| -6 | 19 | 176 | 512 | 0.2613 |
| -6 | 19 | 224 | 512 | 0.2618 |
| -2 | 19 | 188 | 512 | 0.2624 |
| -2 | 18 | 176 | 512 | 0.2629 |
| 2 | 18 | 144 | 512 | 0.2634 |
| 2 | 19 | 180 | 512 | 0.2639 |
| 2 | 19 | 166 | 512 | 0.2645 |
| 6 | 18 | 160 | 512 | 0.2650 |
| 6 | 18 | 170 | 511 | 0.2655 |
| 10 | 18 | 132 | 511 | 0.2661 |
| 14 | 18 | 128 | 511 | 0.2666 |
| 14 | 18 | 170 | 511 | 0.2671 |
| 14 | 18 | 168 | 511 | 0.2676 |
| 14 | 18 | 130 | 511 | 0.2682 |
| 14 | 18 | 132 | 511 | 0.2687 |
| 10 | 18 | 152 | 511 | 0.2692 |
| 6 | 18 | 136 | 511 | 0.2698 |
| 6 | 18 | 132 | 511 | 0.2703 |
| 2 | 18 | 114 | 510 | 0.2708 |
| 2 | 18 | 118 | 510 | 0.2714 |
| -2 | 18 | 118 | 511 | 0.2719 |

technical parameters. Any deviations are analysed and may result in adjustments to the design or maintenance of the overhead contact line, such as tensioning, repairs, replacement of the overhead contact lines, or realignment based on the assessed tortuosity [3].

The aim of these measurements is to ensure the smooth, safe, and efficient operation of tram traffic, while ensuring that the overhead contact line does not negatively impact tram travel.

From the first graph we can see a decreasing trend of shocks to the overhead contact line, and we can assume a decreasing or constant trend until the measuring tram rides through the irregularities. On rails these can be switches, crossings, welds or expansion joints, on overhead contact lines these can be an exchange field, section insulator of overhead crossing. The second graph is purely informative and is influenced by the driver of the measuring tram. From the graph we can see that the driver tires to maintain a constant speed of around 20 km/h. The third graph depicts the tortuosity. First, we see the rising character of the curve then it starts to fall. To determine a more accurate prediction, we look at Graph 1. from which we see the alternating trend of the curse, where it always rises first and then falls. The last graph shows a constant function of the height of the overhead contact line. We can safely say that if there is no underpass on the measured route, the height will not change and will remain constant. The position of the measuring tram gradually accumulates into a linear function, but this is also a parameter that does not affect the measurement, is tied to the GPS position and helps us determine places on the track that are out of tolerance.

The uncertainty balance table is one of the most basic tools in the field of metrology and statistics for evaluating and displaying data from various measurements and experiments. It helps organize the results so that they are easy to understand and interpret. It focuses on estimates of the measured quantities, further on their evaluated statistical uncertainties, which in our case we determined using the type A method, approximate distribution and finally on sensitivity coefficients.

All devices are subject to calibrations, within the framework of internal calibration intervals. Calibrations are provided by an external company. However, the results of previous calibrations are not processed into the result, which is a suggestion for us for future improvement, so that we take them into account when calculating the results [3,10].

We primarily deal with the tortuosity quantity,

Table 2. Table of Uncertainties, with their Values and Distribution.

| **Measured parameter $X_i$** | **Estimation $x_i$** | **Value of standard uncertainty of type A $u_{xi}$** | **Approximate distribution** | **Sensitivity coefficient** | **Contribution to the standard uncertainty** |
|---|---|---|---|---|---|
| shocks (-) | 131.42 | 26.54 | NORMAL | 1 | 26.54 |
| height (cm) | 510.00 | 8.24 | EQUAL | 1 | 8.24 |
| speed (km/h) | 25.15 | 3.52 | EQUAL | 1 | 3.52 |
| tortuosity (cm) | -8.35 | 15.12 | DIRAC | 1 | 15.12 |

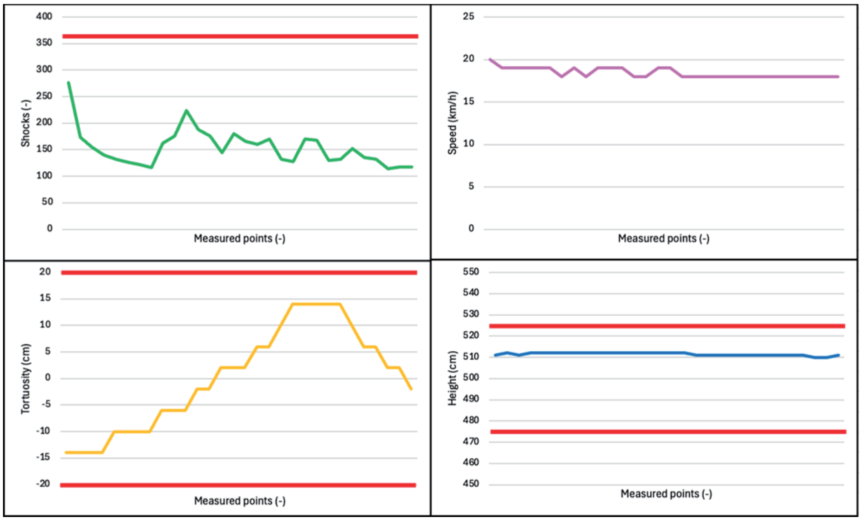



Figure 3. Graphs of the certain parameters from the table above.

which is a key parameter in the measurement evaluation and on which the results of other quantities also depend. We performed a sample measurement on the tram line section from the tram stop Šafárikovo námestie (Safarik Square) via tram stop Starý Most (Old Bridge) to the housing estate Petržalka. From the total number of 1670 measured data, the average value of tortuosity turned out to be negative, i.e. -8.35 cm (Table 2). The negative value came out precisely because the lead on the Starý Most is concentrated on the left side. Tortuosity values have a bimodal or Dirac distribution. The values of the bimodal distribution accumulate around the sinusoidal curve and therefore we assume a higher uncertainty than the average value. We confirmed this fact by calculation and the uncertainty value is equal to $u_{ATor}$= 15.12 cm. Such an uncertainty determined by the type A method confirms to us that the overhead contact line on the Šafárikovo námestie - Sad Janka Kráľa (Janko Kráľ Garden) tram line section is located to the left of the rail axis.

The measurement of the given section took place without significant problems, from the point of view of data evaluation, all data were within tolerance and therefore significant repairs on the track were not necessary. Tolerances are entered in the software based on technical documentation or associated standards. As for the uncertainties determined by the type B method, these are not included in the software, but it will be desirable to take them into account in the future.

The processing of selected influencing measurement parameters is quite complex in tram lines; the mentioned issue must be looked at comprehensively. In DPB, a. s. the mentioned issue is solved mainly from the point of view of measuring the overhead contact line and the cooperation of the streetcar collector with this line, in practice we mainly measure the following quantities: shocks, driving speed, height of the overhead contact line and tortuosity, where we relate the mentioned quantities to the tortuosity and operational wear of the collector. In this understanding, for us, tortuosity is a monitored quantity, which is affected by several influencing factors. These factors are primarily the overall grip of the trolley line, which is given by the construction of the track, and is specified in more detail by the standard STN EN ISO 333 516, which deals with the routing of tram and trolleybus tracks. Meteorological conditions also have an influence, as well as the vehicles themselves during the passage in the given section, which cause impacts to the overhead contact line, considering the geometrical parameters of the track (height and quality of the rail top). While the measurement must also consider the driving speed, which has an impact on the overall wear of the carbon strips (dimensions of the operated rail) on the streetcars' pantographs. The tortuosity is important, because the equal wear and tear of these carbon strips is essential for the correct operation of the trams, it is through the strip that electricity is transferred to the vehicle, so pay particular attention to quality and proper functioning/wear and tear. For this purpose, we developed a simple and generalized measurement model that considers the influencing parameters due to the tortuosity of the overhead contact line.

We are based on the knowledge of practice, where we try to consider and generalize the relationship for determining tortuosity and influencing parameters. We could write the specific

$$Tor_{\text{standard}} = \left| Tor + \delta Sh + \delta Sp + \delta He + \delta Gr + \delta MC + \delta Tr + \delta GP + \delta WAT + \delta OtF \right| \quad (1)$$

relation like this:

where each factor stands for: $Tor_{\text{standard}}$ – the tortuosity of the overhead contact line given in centimetres (the value given by the standard when building the track), $Tor$ – the tortuosity measured by measuring tram, given in centimetres, $\delta Sh$ – the influence of shocks of the collector to the overhead contact line (-), $\delta Sp$ – the influence of speed of the ride given in kilometres per hours, $\delta He$ – the influence of height of the overhead contact line, $\delta Gr$ – the influence of the overall grip of the overhead contact line, $\delta MC$ – the influence of meteorological conditions, $\delta Tr$ – the influence of the vehicle passing in the section, $\delta GP$ – the influence of the geometrical parameters of the track, $\delta WAT$ – the influence of the wear and tear of carbon strips, $\delta OtF$ – the influence of the other factors.

There is mutual influence between the individual influencing parameters, while these components contribute to the resulting uncertainty of the measurement. In the further development of this issue, it will be necessary to identify the sources of individual dependence (correlations) and determine a pair of individual estimates for each source. These estimates are determined based on measurements (previous and experimental), and in this way we determine the correlation coefficient, which expresses the degree of dependence between individual estimates. Upon closer elaboration, these dependencies can take on values from -1 to +1. If these values are close to zero, they indicate weak dependence for these estimates, otherwise, when they are close to 1, these estimates are dependent on each other. This area requires further mathematical elaboration in the future; it is a question for further research [10].

## 4. Discussion and Conclusions

When ensuring transport service, it is crucial to maintain the overall infrastructure. To properly care for it, we must first understand its condition. An example of this is the tortuosity of the overhead contact line. Assessing this condition allows us to collect and evaluate data. Measuring the parameters of tram lines is essential for ensuring accurate, efficient, safe, and comfortable transport [4].

On tram lines, the key parameter is the condition of the overhead contact line, which depends on factors such as the distance travelled, travel speed, tortuosity, height, voltage, and others. During measurement or when operating a measuring tram, it is essential to consider ambient temperature, vehicle speed, pantograph pressure, the condition of the tracks, surrounding vehicles, and structural elements of the line. These include the method and distance of suspension. Therefore, the quality of tram lines depends on a comprehensive assessment of several monitored variables [1,2,5].

The tortuosity of the overhead contact line is influenced by factors such as improper tensioning of the wire, poorly positioned supports, insufficient stability of the overhead contact line, wear and fatigue, long-term operation, mechanical wear, and temperature fluctuations. These issues can lead to power supply problems, resulting in power outages and losses, as well as vibrations and noise. Additionally, they can shorten the lifespan of components, increasing repair and replacement costs. Furthermore, if the system is improperly set, safety risks may arise. The measurement and control of tortuosity are performed using various methods that enable the evaluation of geometric accuracy. Techniques such as optical measurement, measuring vehicles, and laser scanning serve as the basis for repairs and preventive measures [1,6].

The measurement and proper maintenance of overhead contact lines are crucial to prevent power supply issues and minimize wear-related problems. With the above steps, we can increase the quality of services provided, prevent collisions, and provide safe operating conditions for tram lines [11].

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