

## Article

# Monitoring and Expertise of Sections with a Sudden Change in Railway Track Stiffness—Transition Zones of Bridges

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**Abstract:** The subject of the research is the investigation of the behavior of railway tracks in places with a significant change in the stiffness of the track. These parts can be designed from various structural elements and their materials, and this mainly results in a height change of the track level during its operation. These transition zones are monitored and expertly examined to detect undesirable deformations of the geometrical position of the track caused by the trains running. The transition zones are at the points where the fixed track transitions to the classic track bed, in our case it is their combination with bridge structures, especially at their supports. In Slovakia, under the conditions of the Railways of the Slovak Republic, the issue is topical within the framework of the modernization of trans-European railway corridors. The results of experimental measurements and their analysis will provide relevant data for subsequent research solutions for their new numerical modelling, which will ensure a smooth passage through these points of change without height fluctuations, vibrations, and shocks from the wheels of train sets.

**Keywords:** transition zones; railway bridges; monitoring and in situ expertise; railway track stiffness; geometric position of the track; height deflections



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## 1. Introduction

Scientific expertise monitors the state of the geometric position of the track (GPT) in the operated transition zones applied in the framework of the modernization of international railway corridors. Part of these lines are the so-called “transition zones” (TZ), i.e., sections with different stiffness of the track (sudden change of structural materials), such as the transition between a fixed track and a classic track bed, and also these structures in the places of bridge supports and their pillars, tunnel portals, structures of railway sub-structure, etc.

The issue of transition zones is very topical in the conditions of the Slovak Railways (SR). The results of monitoring and expertise indicate that their structural modification is necessary so that these places do not cause height fluctuations of rolling stock when the stiffness of the structural materials of the railway superstructure and sub-structure are changed. In the transition zones, structural layers are also designed and other objects in the railway track are built.

As part of the monitoring and expert investigation, documents will be prepared for future research tasks to solve this problem. The problem of transition zones in locations of “jumpy” changes in the stiffness of the railway and also the dynamic action of rolling stock lead to disturbances in the quality, i.e., the safety and even the service life of the track.

Realization of in situ measurements in the track for the long-term period 2013–2022 (in this article, the beginning of the evaluation was determined from 2016) of selected sections by continuous measurements with diagnostic measuring trolley KRAB [1] with the methodology used at Railways of Slovak Republic (ZSR), concludes that there are shock waves in these track sections and there are changes, for example, of the height course of GPT.

## 2. Current Status—Transition Zones

The International Federation of Railways UIC prefers rail transport as a carrier in terms of ecology, safety and track speed, transported people and goods (new construction  $V \geq 250$  km/h, reconstruction  $V \geq 160$  km/h), while in Slovakia modernization is underway at  $V = 160$  km/h. For this reason, this issue of transition zones is required in the Railways of SR.

All test sections for monitoring and research activities were established on the trans-European corridor “Va” to obtain a comprehensive evaluation from the point of view of the impact on the track in these sections.

The mentioned problem is also solved on foreign railways, and these experiences must also be incorporated into the conditions on the ZSR lines. Transition zones were also addressed by foreign researchers such as Heydari-Noghabi, H.; Zakeri, JA.; Esmaeili, M.; and Varandas, JN. [2] using additional rails and an approach slab. High-speed lines depending on the train speeds were part of the dynamic characteristics of a fixed reinforced-concrete track, published by authors Park, S.; Kim, JY.; Kim, J.; Lee, S.; and Cho, KH. [3]. The area of transition zones near bridge objects is addressed in Paixao, A.; Fortunato, E.; and Calçada, R. [4] as in situ measurements and numerical modelling. Another solution can be seen in Shan, Y.; Albers, B.; and Savidis, SA. [5], where the authors deal with the dynamic processes in the layers and objects of the sub-structure of the railway lines in the transition zones. In the research of Mottahed, J.; Zakeri, JA.; and Mohammadzadeh, S. A. [6], the transition from the classic track bed to bridge objects is solved using USPs effects. Numerical analysis of railway bed layers was presented by Zuada Coelho, B. and Hicks, M. [7]. Authors Fortunato E.; Paixao A.; and Calçada R. [8] propose a railway track in the area of transition zones within its analysis, monitoring, and numerical modeling. The dynamic responses of the transition zones of the high-speed railway, as part of the solution of the lower structural layers, are elaborated by Hu, P.; Zhang, Ch.; Wen, S.; and Wang, Y [9]. The problem of the dynamic behavior of railway lines of transition zones was addressed by the authors Varandas, JN.; Holscher, P.; and Silva, MAG. [10]. A substantial part was devoted to the issue by Le, THM.; Lee, TW.; Seo, JW.; and Park, DW. in the experimental investigation and numerical analysis of materials in structural layers for railway bridges [11]. The methodology of the complex analysis of railway transition zones is solved by authors Wang, H. and Markine, V. [12].

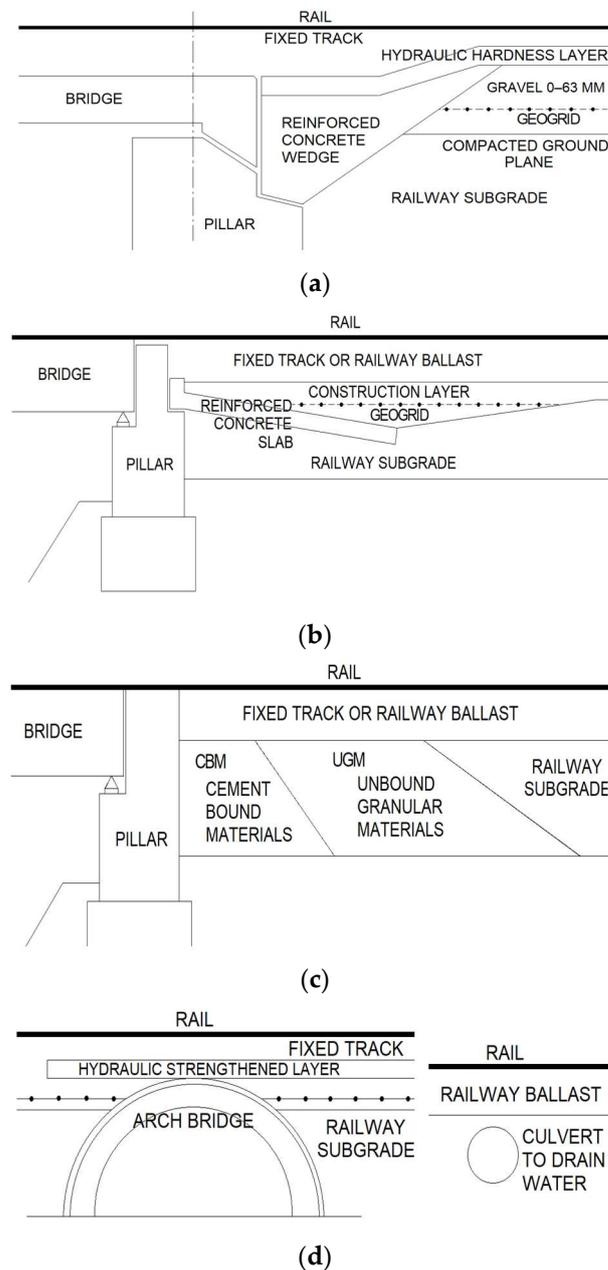
It can be concluded that these are authors with a significant relation to the issue of the design of railway tracks within transition zones. With the same intention, the results of monitoring and expertise activities at the Department of Railway Engineering (DRE) of the Faculty of Civil Engineering of the University of Zilina were also presented in [13–16].

## 3. Bridge Objects as Transition Zones

It is assumed that the experimental measurements of 2016–2023 provided a sufficient basis for future research tasks aimed at increasing the stiffness of the railway track in the area of its sudden change (change of material types used in the profile of the railway line). For this purpose, several test sections of transition zones were monitored and expertly examined in situ at bridge supports to obtain a comprehensive view of how they affect the rail track, i.e., mainly the geometric position of the track (GPT).

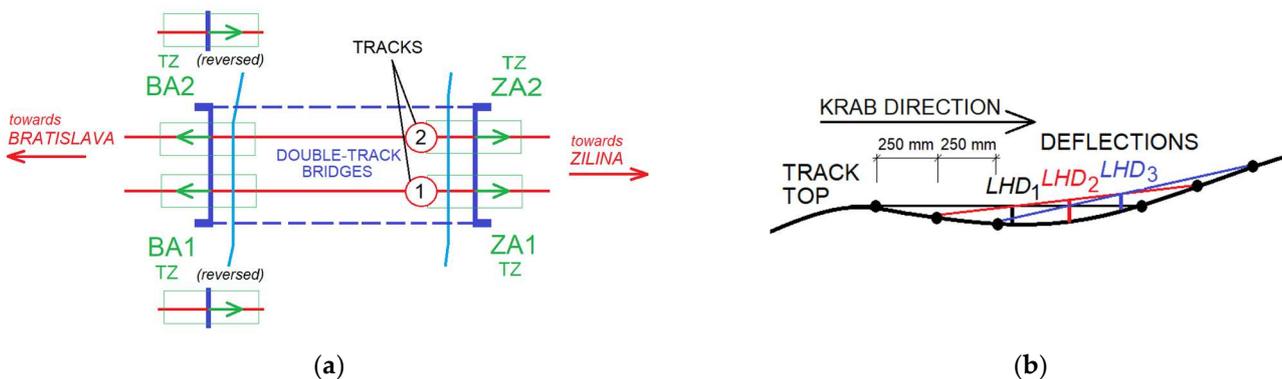
For this purpose, several transition zones were monitored: transition from gravel-free to gravel structure of the railway superstructure (this is the subject of other publications), transition in the location between the track and bridge supports (large and small span, including separate culverts of drainage), the transition between the track and tunnel portals, etc. The main research activities took place in the section with a fixed track near the “Turecký Vrch” railway tunnel near Trenčianske Bohuslavice city (tunnel, two bridges, and drainage), and the presented results are also from the section near the double-track railway bridge over the Vah river in the city of Trenčín (3 bridges). All track sections are part of the European Corridor.

It was found that in these transition zones, there are various types of structures to mitigate the effects of impacts from train wheels (on reinforced concrete wedges and slabs, structural layers of various types of materials, geo-materials, etc., according to Figures 1 and 2a).



**Figure 1.** Structural parts and layers in transition zones: (a) reinforced concrete wedge; (b) reinforced concrete slab; (c) CBM and UGM material; and (d) arch bridge and culvert.

Experimental measurements and in situ inspection of transition zones took place as part of the research tasks of the Department of Railway Engineering (DRE) near the city of Trenčianske Bohuslavice in 2013 and in the town of Trenčín in 2016. The paper presents the results of this monitoring from 2016, respectively, in places where the height change of the height wave is most pronounced in the gradients of the railway track, which is caused by the arrangement of materials of different stiffness in the track (rail R/L deflections). Research activities were addressed by the final outputs in Hodas, S. et al. [13,14], and within the VEGA projects [16] in recent years.

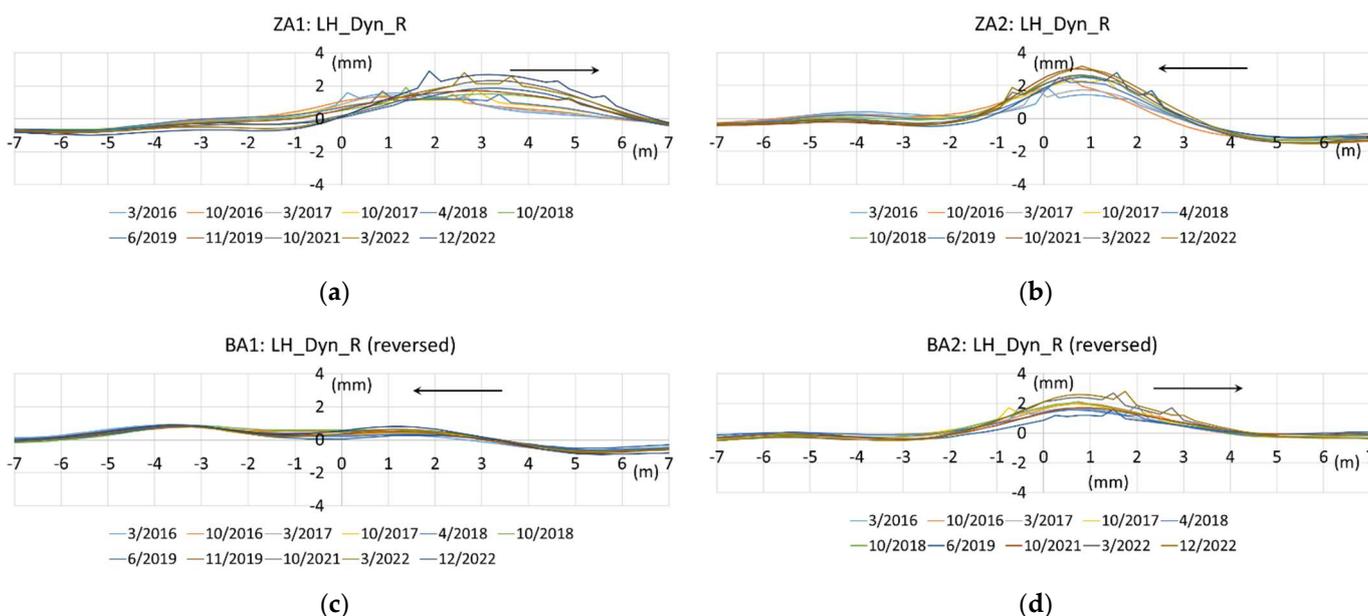


**Figure 2.** Selection and marking on bridges: (a) transition zones of bridges; (b) continuous measurements of rail deflections with 250 mm steps.

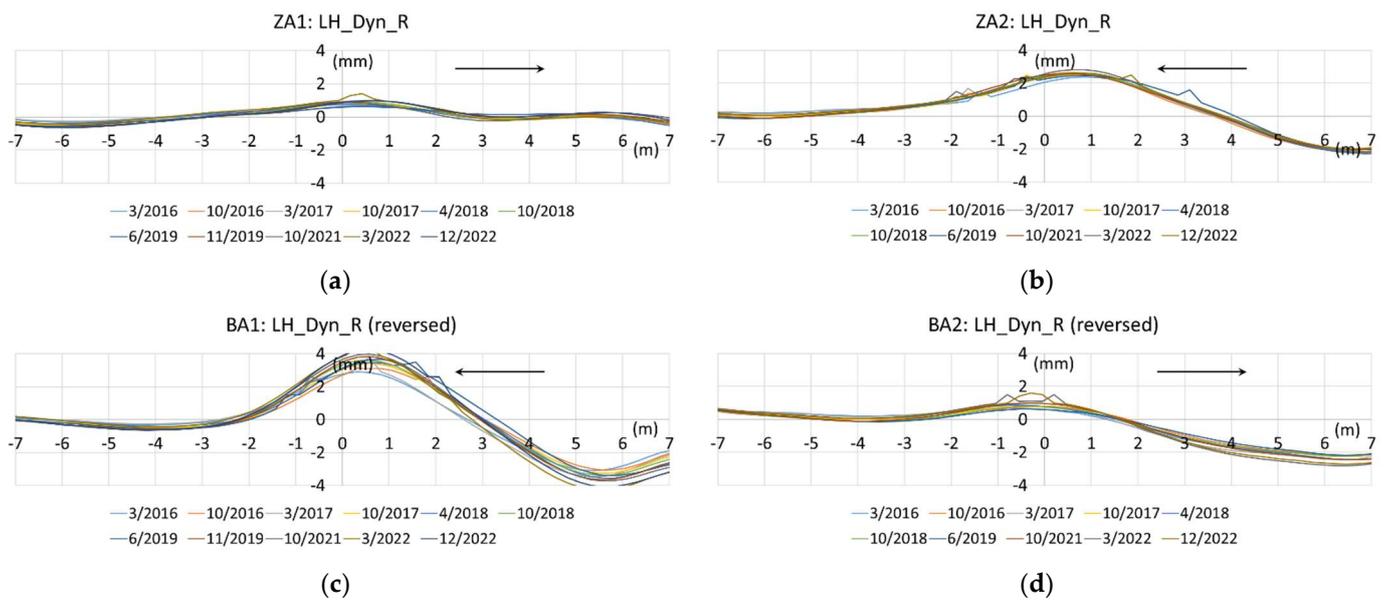
The new resulting measured values are presented in the research of the DRE department within the modification of these structural parts in transition zones removing height waves when trains are running (or minimizing them).

**4. Methods—Long-Term Monitoring in the Track**

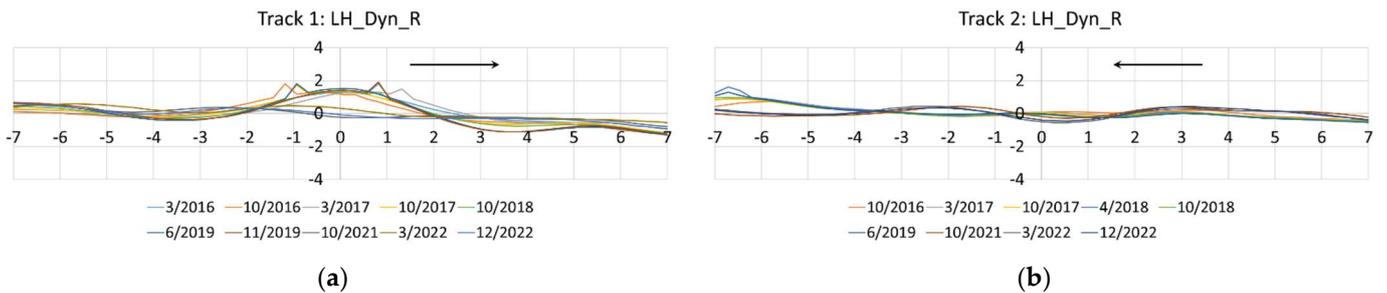
Long-term monitoring of both rails (R/L) of each track (No. 1, No. 2) revealed the course of their height curves, i.e., deformation of the level at this “jump” point in the transition zone. The paper presents the R curves. The curves of the second rail L are at the authors’ workplace, they have a similar course, or they differ only minimally. Near the city of Trenčianske Bohuslavice, monitoring was carried out in the transition zones at the supports of two small bridge structures with spans 25 m and 15 m in Figures 3 and 4, and one drainage in Figure 5. In the town of Trenčín, monitoring measurements were carried out on one small bridge with small span of 12.5 m in Figure 6 and on a long bridge with a span of 340 m over the river Vah in Figure 7 including its pillars No. 3 and No. 5 in Figure 8, and small bridge with a bridge length of span of 18 m in Figure 9.



**Figure 3.** Inspection of track geometry quality of BRIDGE 1—longitudinal height deflections (LH): (a) Axis No. 1 towards ZA; (b) Axis No. 2 ZA; (c) Axis No. 1 BA; and (d) Axis No. 1 BA.



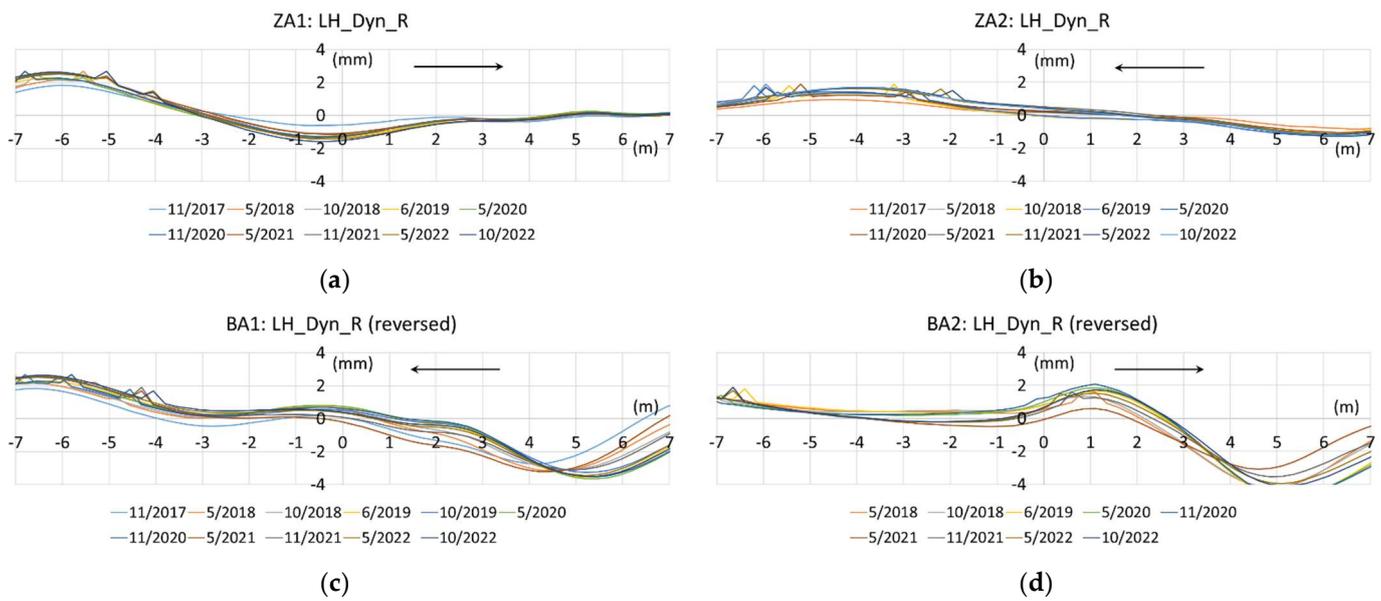
**Figure 4.** Inspection of track geometry quality of BRIDGE 2—longitudinal height deflections (LH): (a) Axis No. 1 toward ZA; (b) Axis No. 2 ZA; (c) Axis No. 1 BA; and (d) Axis No. 1 BA.



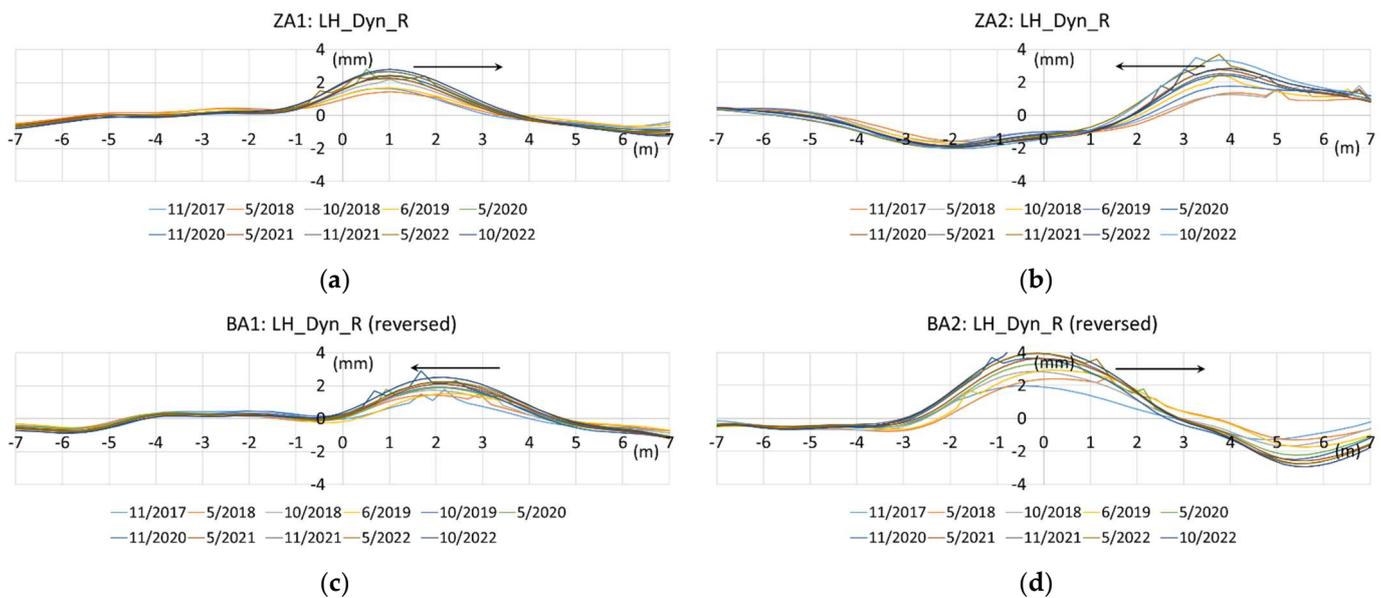
**Figure 5.** Inspection of track geometry quality of DRAINAGE 1 (CULVERT)—longitudinal height deflections (LH): (a) track 1; (b) track 2.

Expertise measurements were performed continuously with a KRAB measuring trolley [1] with a recording step of 250 mm. The KRAB method is very reliable in determining the characteristics of the geometric position of the track in both the horizontal and vertical directions, and in our case, the height deflections of the R/L rails. Of course, the gauge and elevation of the track are also recorded (they are not the subject of the article). If a wave of height deflection of the rail occurs as a deformation, the mentioned method reliably captures its development in the long term (this statement is confirmed by all inspection figures). We can conclude that the method has proved that a transition zone is a critical section of the railway line, which can be improved by its modifications or new design for other new lines, for example, including numerical modeling.

The values obtained by in situ measurements will be the basis for subsequent scientific projects, for example, VEGA 2024–2026 [17] (submitted in the approval process), where optimized proposals for numerical modeling of transition zones will be created. The purpose is to eliminate, or minimize, the height changes of the GPT gradient, arising as a deformation of the track during the movement of train sets through the transition zones, in this case just before and behind the bridges. The selection of treatment of materials with higher stiffness is considered comprehensively, including the railway superstructure and sub-structure in the transition zone at the support of the bridge object with the use of meters of forces acting between their structural parts.

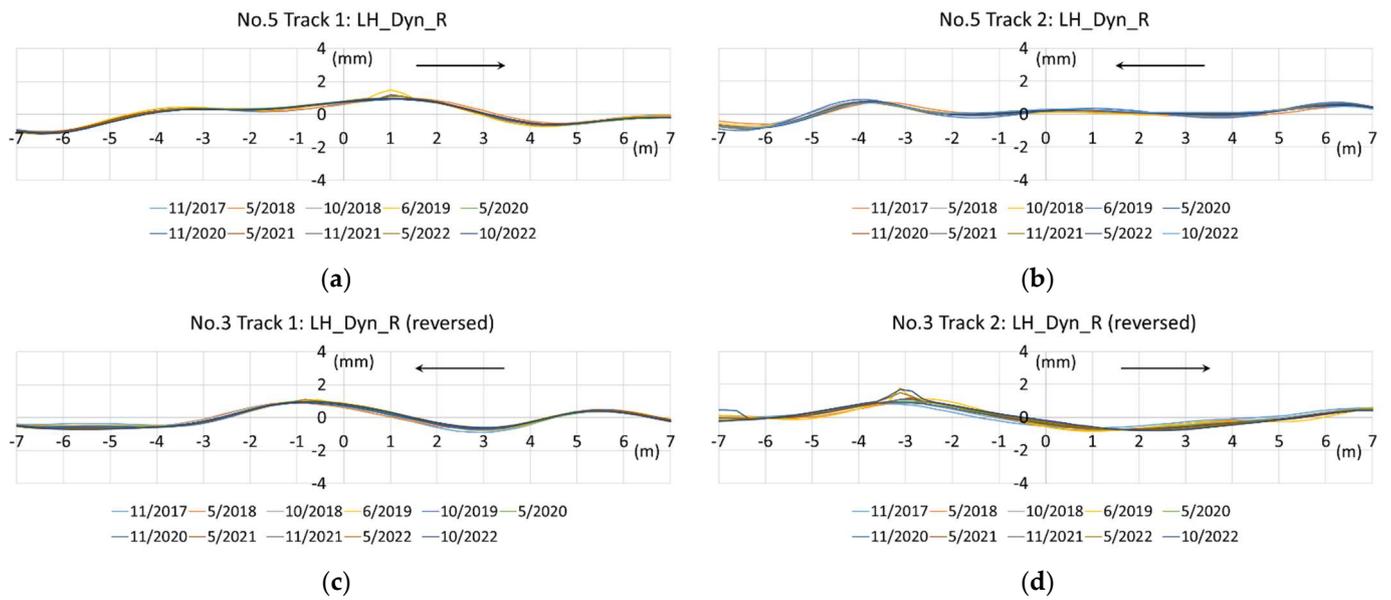


**Figure 6.** Inspection of track geometry quality of BRIDGE 1 in Trencin—longitudinal height deflections (LH): (a) Axis No. 1 towards ZA; (b) Axis No. 2 ZA; (c) Axis No. 1 BA; and (d) Axis No. 1 BA.

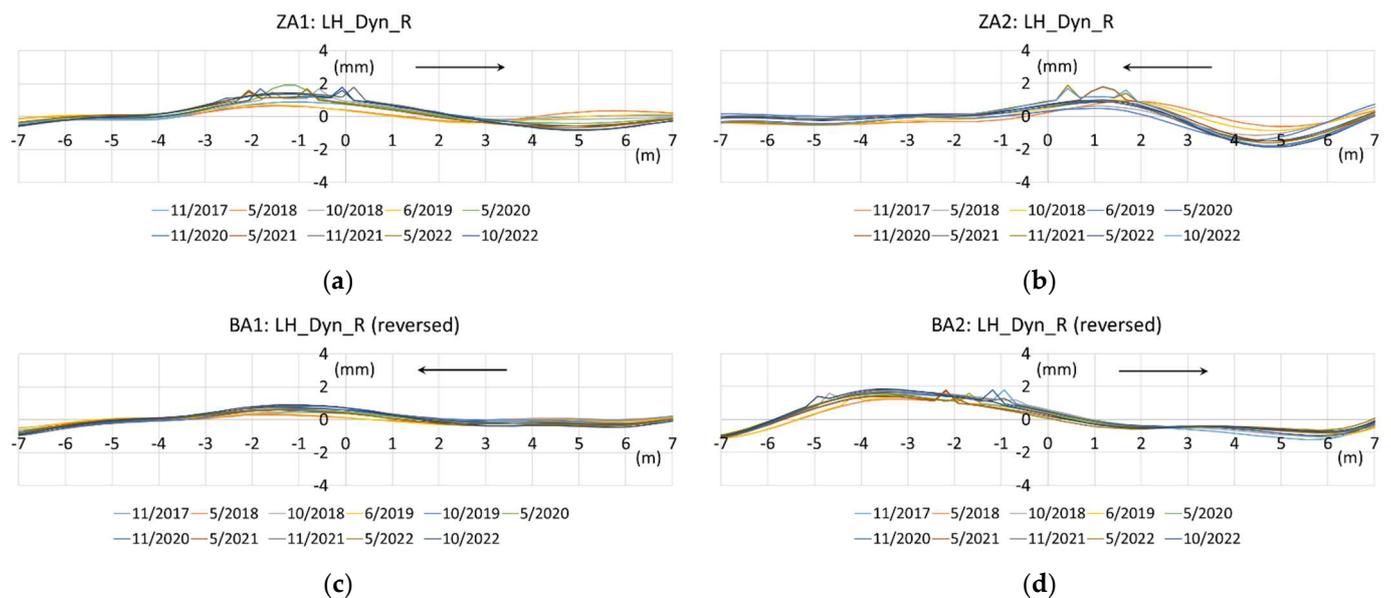


**Figure 7.** Inspection of track geometry quality of BRIDGE VAH in Trencin—longitudinal height deflections (LH): (a) Axis No. 1 towards ZA; (b) Axis No. 2 ZA; (c) Axis No. 1 BA; and (d) Axis No. 1 BA.

The complexity of the solution for the relevant final outputs to meet the future goals of the projects must be ensured by choosing suitable representative in situ sections of the track, i.e., test experimental sections. The arrow in the figures shows the prevailing direction of the train ( $\rightarrow$ , 70% to 90%).



**Figure 8.** Inspection of track geometry quality of BRIDGE VAH PILLARS in Trenčín—longitudinal height deflections (LH): (a) No. 5 track 1; (b) No. 5 track 2; (c) No. 3 track 1; and (d) No. 3 track 2.



**Figure 9.** Inspection of track geometry quality of BRIDGE 2 in Trenčín—longitudinal height deflections (LH): (a) Axis No. 1 towards ZA; (b) Axis No. 2 ZA; (c) Axis No. 1 BA; and (d) Axis No. 1 BA.

## 5. Discussion—Inspection Results and Evaluation of Expertise Measurements

Objects of transition zones were measured and systematically processed under the same conditions. The selection of research sections was carried out in each rail (R and L of each track No. 1 and No. 2), i.e., two transition zones towards the Zilina city (ZA1 and ZA2) and two transition zones towards Bratislava city (BA1 and BA2). The number means the track number No. 1 and No. 2 according to Figure 2a.

As can be seen from Figure 2, the figures of TZ in Figures 3–9 are turned with its solid part and gravel part once towards the ZA and once towards the BA. In order to be perceived as the same “jump” from hard to soft material (movement from the bridge abutment to the fixed track or gravel bed). Transition zones BA1 and BA2 are reversed to the opposite direction of run for their uniform evaluation.

On all sections according to Figures 3–9, there is a proven “jump” with subsequent pushing of material with lower stiffness (for example, track bed, lower layers of sub-structure, reinforced concrete transition slab, etc.) followed by pushing it out and raising the gradient, i.e., an unwanted height wave is created. In the figures with the highest wave of deflections, in Figures 3b, 4b–d, 5a, 6c,d, 7a–d and 8b,d, it was found within the framework of long-term measurements 2016–2023 that it is necessary to increase the stiffness of objects and structural layers by future modelling. Based on the facts, it is necessary to proceed with the design work to secure these zones already during their design itself (adjust the thickness of the layers, exchange of materials, additional structures of the railway superstructure and sub-structure, etc.).

The final results are drawn up in Figures 3–9. New reinforced concrete wedges, slabs, or blocks at the supports of bridge objects also play a big role, as a result of which, these maximums and minimums of height waves can be moved beyond these built-in block objects. Some of these transition zones are designed on high railway embankments of 4–12 m, and the subgrade of the railway sub-structure can also be deformed under forces. Others are located on the rocky ground as in Figures 3c and 6b, or are the pillars of the long bridge in Figure 8a–d.

#### 5.1. Experimental Sections: *Trencianske Bohuslavice*

Each subsequent experimental measurement confirmed the height deflections from previous periods. The BRIDGE 1 structure is located near the tunnel above the river, Figure 3 shows the height changes within the measurements of continuous deflections, but this is not found in Figure 3c (BA1), as it is assumed that this transition zone in track No. 1 has a stable subgrade. On this bridge, there are reinforced concrete structural blocks in front of the bridge.

The second BRIDGE 2 is located on a high embankment of 5–8 m; in Figure 4a (ZA1) the railway is stable in height. In other parts, there is extruded material in Figure 4b,d, but most of it is a “jump” in Figure 4c (the transition zone BA1).

In this part of the section, there is a culvert DRAINAGE 1 in Figure 5, where a classic track bed is designed, which is tamped by automatic tamping machines at a certain time interval (or if height deviations are exceeding the permitted deviations during operation, it must be covered with tamping), and in this case, it is the bedrock too.

#### 5.2. Experimental Sections: *Trencin*

In Figure 6, there is an arch BRIDGE 1 with a small span of approx. 12.6 m, where the structure parts are not modified as classic transition zones, only the consolidated layer according to Figure 1d. In terms of height, the gradient of the tracks is wavy.

The VAH BRIDGE of a large span with pillars in the river Vah in Figure 7 contains the adjustment of transition zones with reinforced concrete (RC) wedges approx. 6 m with a height of 1.8 m according to Figure 1a. In the transition zones, the material is pushed out behind these RC wedges. In all four cases of this bridge object, an adjustment of transition zones is necessary for future proposals for new designs or the reconstruction and modernization of railway lines. Height deformations do not occur on the pillars of this long bridge in Figure 8 (relative relation—fixed track on pillars and no subgrade, except foundations).

BRIDGE 2 in Figure 9 has proven smaller height waves approx.  $\leq 2$  mm; this is also a fixed track.

## 6. Resulting Shared Characteristics

All achieved monitoring results prove the phenomenon caused by shocks from the wheels of the bogies when the trains pass through the critical point of the transition zone (not only but also the state of the composition of the objects). This is also caused by the high weight of the rolling stock depending on their speed, as well as the quality of the construction work and the correct project design of the transition zone as a whole.

The research presents realistic determined values of height deflections of R/L rails. These values meet the recommended values of the criteria for operational deviations in the standards (in the case of new buildings, they are the criteria for construction deviations). But these measured values cause vibrations, resonances, and oscillations of train sets. We can state that these objects can follow several in a row (at the beginning and end of the bridge, or more bridges and other objects in a row).

It must be emphasized that if a permanent deformation of the deflection of the R/L rails occurs in the initial stages at the time of handing over the structures to operation, they will gradually develop further (individual stage monitoring measurements). Height deflections can already occur during the passage of work machines at the end of construction and subsequently are developed by passing trains during the operation on the track.

If valid operational criteria were exceeded, it would be necessary to adjust the tracks to the required condition. Modifications of a fixed track are very difficult (sometimes impossible). It is possible to adjust the height of the rails by changing the material of the railway superstructure, for example, new pads under the R/L rails with different heights. It is not possible to break a reinforced concrete fixed track (financially and time-consuming, although it is possible in some sections). The part of the transition zone with a gravel bed is usually adjusted with tamping machines (an iron-concrete tub with a rail bed and a classic gravel bed). At the point of contact between the track bed and the iron-concrete block of the transition zone or the support of the bridge structure, the tamping machines cannot adjust this critical place, sometimes they start tamping further by 0.5 to 1.2 m from this point. At this critical point, a vertical cut of the railway occurs (of course, this also impacts the train chassis on the objects of the transition zones).

## 7. Conclusions

The transition zones, in this case at the supports of bridge structures, must be designed in such a way that they achieve not only optimal stiffness grading for real operating loads but also use new progressive structural materials and elements. In some cases, it will not be possible to insert a new element into the structure, for example, thicker pads (2–4 mm to reduce the dynamic load) of the rail, since it is a concrete slab of a fixed track and there would be an increase in the gradient at this critical point in the transition zones (acute sections at the point of stiffness jump). But, it is possible to implement them in the transition zone, where there is a gravel bed because it is possible to change the height elements without changing the gradient of the track. Other elements can be changed, including the addition of new supporting structures, or the replacement of layers of materials with a change in their height, i.e., it is necessary to pay attention to the lower structure of the subgrade.

From the images from Figures 3–9, it follows that the height difference mainly arises from the compression and pushing of structural layers and materials in the railway sub-structure. The railway superstructure can be strengthened with additional rails, more rigid fasteners, pads, etc., but if the railway sub-structure or subgrade declines, this will also be reflected in the height change of the track geometry—gradient shortly after the track is put into operation, in our case the transition zones.

From the point of view of the transition zone, the expected benefit will be the differentiation of structural materials and elements and their effects on achieving an optimal gradation of the stiffness of the railway between places with different stiffness, i.e., bridge transition zones occur on every railway line.

After the analysis of the experimentally measured sections in situ, it is concluded that undesirable errors and deficiencies in the geometry of the track, especially its height changes, arise as a result, and it is necessary to identify and eliminate them already during the design or new modernization of these sections on the railway lines [17]. The part of the project will include a topic that is being solved by the PhD student Vrchovsky [18] of the Department of Railway Construction from 2022. The research work is devoted to measurements using built-in sensors directly in the track to transition zones. The research consists of two parts, namely for the railway superstructure and the objects of the railway

sub-structure, including numerical modelling under dynamic forces. Currently, as part of the research project [16], the selection of transition zones on the modernized track is underway, where these sensors are gradually inserted into the track. The issue abroad, which can be followed up on, is addressed by the authors Sanudo et al. [19], where transition zones are monitored directly by sensors. These transition zones have built-in added rails to increase the stiffness of the track. The authors Paixao, Varandas, and Fortunato [20] are engaged in research on the dynamic behavior of objects in transition zones. The research is carried out in the framework of the simulation of the long-term behavior of transition zones using three-dimensional finite element (3D FEM) methods.

The research work in [17] not only expands previous studies but other objects such as bridges, tunnel portals, drainage culverts, etc., will be included in the monitoring and inspection set. The transition zone file will be expanded with additional options of objects that belong to the transition zone family. In addition to classic and bridge transition zones, the next intention will be tunnel ones. All of them will be subjected to numerical designs by modeling them, taking into account the material of the railway superstructure (rails, fasteners, pads under the rails, sleepers, track bed) depending on the acting forces. Shock waves, which are created in these sections with negative effects, for example, the height deformations of these objects affecting the track gradient, and train sets oscillation. Sub-structure objects such as bridges, tunnels, and culverts connected to the railway are also a significant part, the project is focused on continuous measurements and measurements with built-in force measurement sensors.

Otherwise, their height adjustment will be necessary during the entire period of operation of these objects, and this is an unnecessary additional financial cost.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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