Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 17.6
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.17.6

Initiatives for Dynamic Track Condition Monitoring on Local Railways Using In-Service Vehicles

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Abstract

To ensure safe train operations, railway operators regularly inspect and maintain track conditions. However, many regional railway operators are unable to adopt dynamic track inspection methods—such as those using track inspection vehicles—commonly used on mainline railways, owing to cost and other constraints. Therefore, our institute started research on methods to efficiently assess dynamic track conditions by using in-service vehicles. In this paper, we introduce various methods for different types of irregularities used to inspect track conditions.

Keywords: track maintenance, track irregularity, gauge widening, derailment accidents, camera, vehicle vibration.

1 Introduction

Railway vehicles are supported and guided by track structures; therefore, track geometric conditions have significant influences on running safety. As repeated train operations gradually deform the track, railway operators manage track conditions by periodically measuring track irregularities according to deviations from the ideal track geometry and by conducting maintenance appropriately.

Since track deformation is caused temporarily under vehicle load, it is extremely important to measure track irregularities under loaded conditions. However, many local railway operators cannot use costly dynamic track inspection systems, including dedicated track inspection cars. As a result, static inspections by means of simple devices or manual measurements are commonly employed even though their inspection frequency and coverage are limited.

In response to these challenges, this study focuses on methods for efficiently monitoring dynamic track conditions by using in-service vehicles equipped with low-cost sensors. The objective is not to take the precise measurement of track geometry, but to identify locations, that require safety-related attention, in a reliable manner. This paper tries to present monitoring methods for each of key track irregularity parameters, which are commonly used in track maintenance management.

2 Management of track conditions according to track irregularities

Track conditions are usually managed according to five primary types of track irregularities: longitudinal level irregularity, alignment irregularity, cross-level irregularity, twist irregularity, and gauge irregularity as shown in Figure 1.

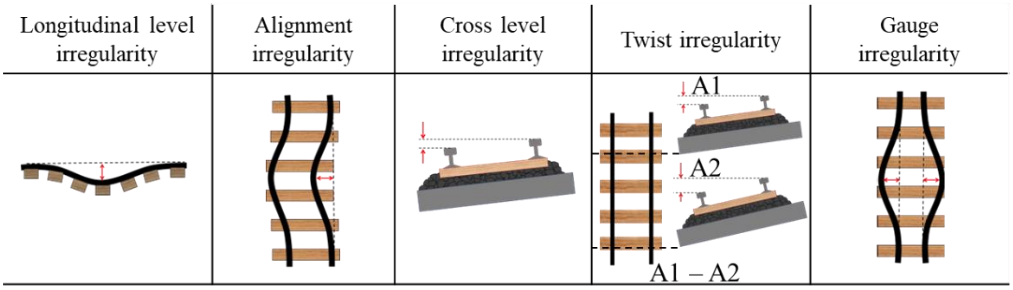

Figure 1: Types of track irregularities.

The longitudinal level irregularity represents the rail height variation in the longitudinal direction, while the alignment irregularity represents lateral deviation. The cross-level irregularity means the height difference between the left and right rails, the twist irregularities defined as the difference in cross level irregularity over a given length, and the gauge irregularity represents the deviation in the space between rails.

In curved sections, large lateral forces are applied to the rails. When rail fastening strength is decreased as a result of sleeper deterioration or other factors, gauge widening may be caused to significantly increase derailment risk. On the other hand, excessive twist, which represents track torsion makes wheel loads uneven to possibly lead to decrease of wheel load and derailment.

Dynamic measurements of these irregularities may be carried out if track inspection cars are available; however, static methods are still one of the first options for locally-operated lines. Therefore, alternative approaches capable of capturing dynamic track conditions at low cost are required.

3 Monitoring of dynamic track conditions by using in-service vehicles

Recent advances in sensing technology have enabled reductions in the sensor cost, size, and weight. Leveraging these development achievements, this study proposes multiple monitoring approaches by using relatively inexpensive sensors installed on in-service vehicles. These methods aim at capturing dynamic track behaviours more often and identifying locations which require maintenance attention.

For longitudinal level and alignment irregularities, approaches based on the relationship between track geometry and vehicle vibration characteristics are proposed. For cross-level and twist irregularities, rail displacement is measured in relation to the vehicle body by using a LiDAR sensor and by using the value of the vehicle body inclination corrected by a gyro sensor. For gauge widening, a vision-based method is developed with a focus on wheel–rail contact conditions.

Details of each method are as follows:

4 Identification of longitudinal level irregularity by focusing on vehicle vertical vibration

Compact devices equipped with accelerometers, gyroscopes, and GPS receivers are installed on in-service vehicles to measure vehicle vibration as shown in Figure 2.

The results of the field measurements conducted on an actual railway line indicate a clear correlation between vertical vehicle acceleration and longitudinal level irregularity.

Figure 2: Measurement of vehicle vibration by using a compact device.

Based on such a correlation, the degree of longitudinal level irregularity can be estimated solely from the measurement of vehicle vibration, even in the absence of recent track geometry data. For practical implementation, the vertical vibration acceleration threshold of 2.1 m/s^2, which corresponded to the vertical irregularity of 19 mm, was set as the maintenance target for a local railway. Since the correlation depends on vehicle type and operating conditions, threshold values must be determined individually.

This method enabled identification of critical locations, which required maintenance, even between annual inspections. Table 1 shows the results of a five-year evaluation which demonstrated a substantial reduction in the number of locations, whose maintenance thresholds were exceeded, to indicate improved management of the track conditions Table 1 shows.

Year	Number of locations exceeding maintenance thresholds		
	Left rail	Right rail	Total
2020	166	167	333
2021	101	102	203
2022	140	143	283
2023	95	85	180
2024	82	72	154

Table 1: Trends in locations where longitudinal level irregularity exceeds maintenance thresholds.

5 Identification of alignment irregularity using yaw angular velocity[1]

Alignment irregularity is closely related to vehicle yaw motion. Yaw angular velocity Y is generally expressed as Equation (1):

$$Y = V/R \tag{1}$$

where V is vehicle speed and R is a curve radius. Assuming relatively constant operating speed, yaw angular velocity and alignment irregularity are proportional. Alignment irregularity D is generally expressed as the versine of a 10 m chord, and its relationship with a curve radius is given by Equation (2):

$$D = 12500/R \tag{2}$$

From Equations (1) and (2), if the speed is assumed to be constant, yaw angular velocity and alignment irregularity are proportional. Therefore, assuming that train speed does not vary significantly at different locations, it is reasonable to estimate alignment irregularity based on yaw angular velocity.

The maximum yaw angular velocity and alignment irregularity values were obtained at 10 m intervals on an actual line. Figure 3 shows the graph based on such values, including the influence of geometric curve components. Accordingly, the coefficient of determination is 0.85. In consideration of this relationship, alignment irregularity, which require attention, can be detected by setting appropriate yaw angular velocity thresholds. Detection of short-wavelength irregularities remains to be studied further in future.

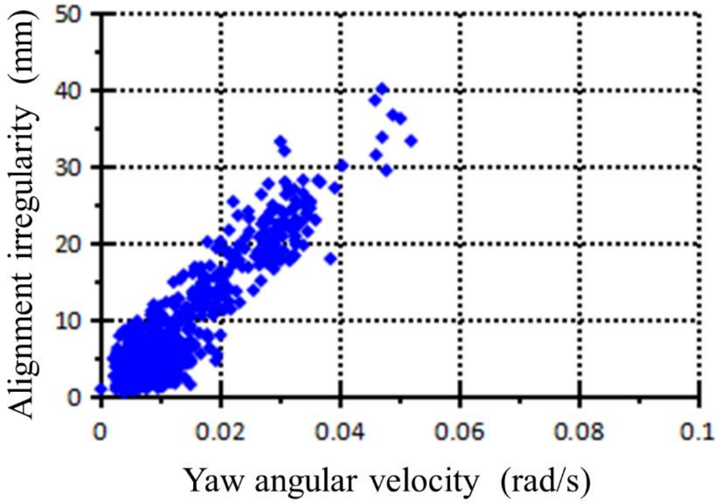

Figure 3: Relationship between angular velocity and alignment irregularity.
(Including curve components)

6 Measurement of cross-level and twist irregularities by means of onboard LiDAR

A LiDAR sensor installed beneath the vehicle floor measure distances between the vehicle body and both right and left rails as shown in Figure 4. Cross-level irregularity is calculated from rail height differences obtained after correcting vehicle body inclination by using gyroscope data. The LiDAR was selected in view of the costs, sampling rate, and measurement range.

In comparison with conventional static measurements over a 600-m section, the proposed system captures overall trends in cross-level irregularity, even though the measurement results may vary as shown in Figure 5. Possible causes for such variability include LiDAR sensitivity to external disturbances and inherent differences between dynamic and static measurements.

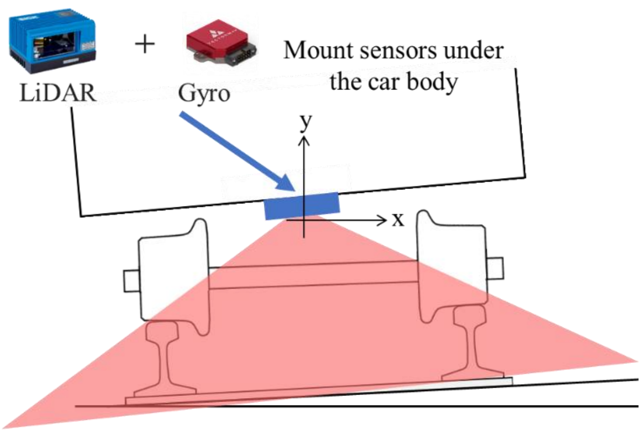

Figure 4: Image of sensor configuration.

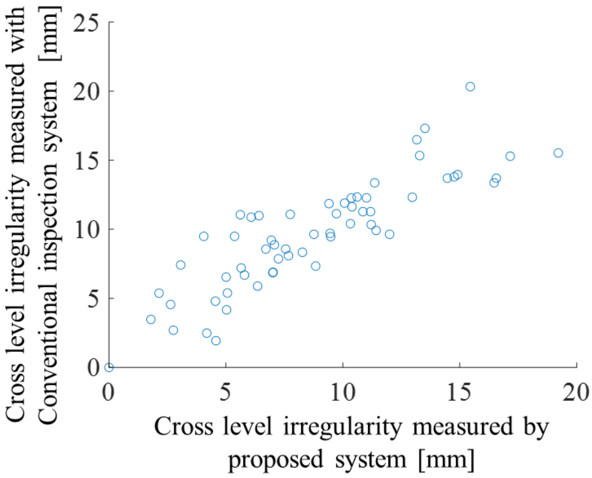

Figure 5: Relationship between conventional inspection system and proposed system [2].

Based on the measurement of the cross-level irregularity, twist irregularity was calculated as the difference between the cross-level values at two points, which were 5-m apart.

Figure 6 shows the results for a section of an 800-m radius curve. Orange represents the results from a conventional inspection system, and blue represents the filtered results from the proposed system. The curve has a cant of 70 mm, therefore, the structural track twist is caused in a transition curve. In this transition curve section, the proposed system measured twist irregularity with the accuracy comparable to that of the conventional system.

However, around the 19,840-m point, a significant discrepancy was observed, probably because rail height was misdetected by the LiDAR sensor. This remains to be improved in future.

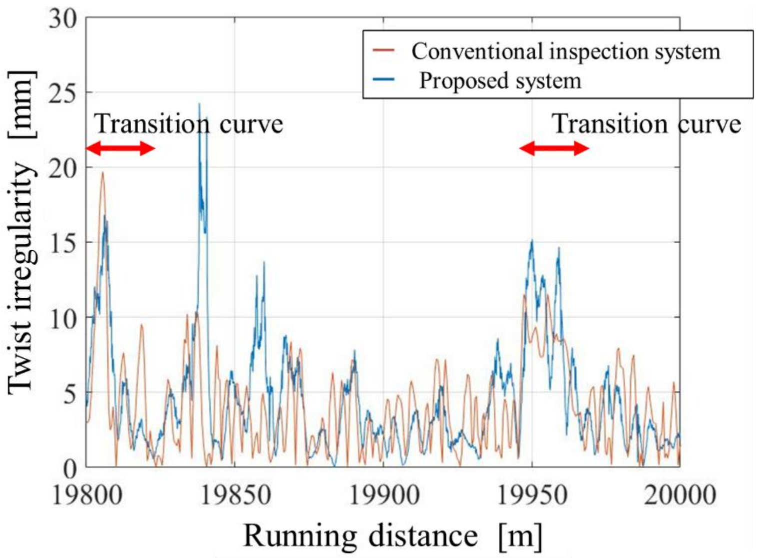

Figure 6:A verification result of twist irregularity.

7 Identification of gauge widening through wheel–rail contact observation

In sharp curves, large lateral forces are applied to the rails during train passage. As illustrated in Figure 7, when the fastening force continues to be reduced as a result of the sleeper deterioration over a certain distance, dynamic gauge widening may be caused.

Figure 7: Rotting of a wood sleeper [3].

As the gauge widens, the width of the rail head supporting the inside wheel—referred to as the wheel support margin—decreases. If the gauge is widen further and this support margin becomes zero, the inside wheel is no longer supported by the rail head and may drop between two rails as shown in Figure 8.

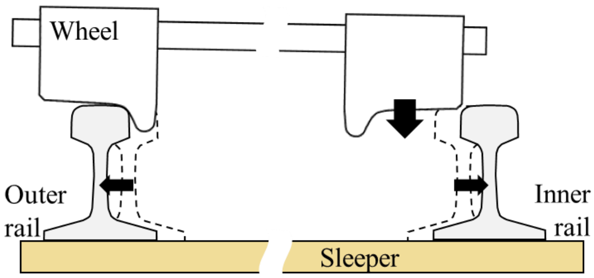

Figure 8: Gauge widening and derailment [3].

7.1 Wheel–rail contact relationship, which leads to derailment as a result of gauge widening

The geometric relationship between the wheel and rail is shown in Figure 9. Based on the minimum values of the distance between wheel back faces "a", wheel thickness "b", flange thickness "c", and the effective gauge "G" (including slack and gauge displacement), the wheel support margin δ is defined. In practical track management, in consideration of rail wear, chamfering at the wheel tread edge, and safety margins, a limit value for gauge displacement is obtained by subtracting a certain amount from δ. This limit is generally about 40 mm [4].

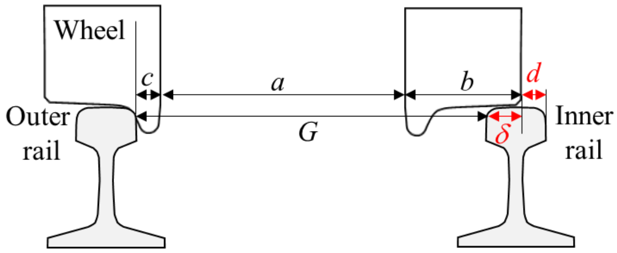

Figure 9: Wheel/rail contact when vehicle runs on section [3].

Therefore, even without directly measuring gauge displacement, dynamic gauge widening can be indirectly estimated by measuring the distance “d” between the outer surface of the inside wheel and the outer face of the rail head (hereinafter referred to as the index value “d”). When “d” exceeds a threshold, this means a reduction in wheel support margin and allows such locations to be identified as areas, which require attention for the reason of potential derailment risk.

7.2 Detection of wheel support condition

As stated above, a method to continuously obtain the index value “d” was developed. A compact camera installed beneath the vehicle captures images near the wheel–rail contact point and image processing is carried out to detect variations in “d”.

The objective of this method is not to measure the absolute gauge with high precision, but rather to identify locations, which require attention in curved sections. Although laser sensors could be used to measure the index value, a camera-based approach was used from the viewpoints of device simplicity, portability, and costs. A key feature of the proposed method is its ability to capture gauge widening behavior under dynamic loaded conditions by installing the camera on a running train.

7.3 On track experiments

With the cooperation of a local railway operator, compact cameras were temporarily installed beneath in-service vehicles with simple mounting fixtures, as shown in Figure 10. Since the inside rail changes depending on curve direction, two cameras were installed to capture both left and right wheels as shown in Figure 11.

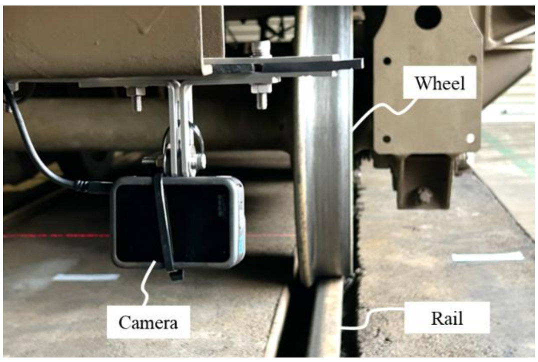

Figure 10: Cameras mounted under car body for capturing Wheel/rail contact point [3].

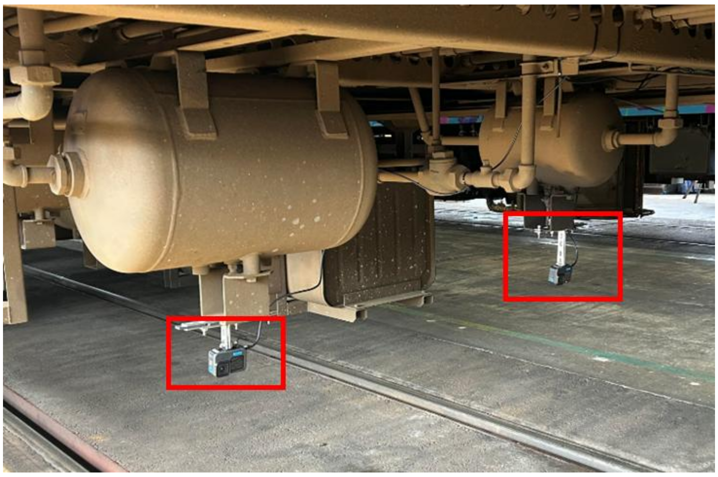
Figure 11: A total of two cameras at two Wheel/rail contact point[3].

The camera used is a compact, lightweight, waterproof video camera to allow easy installation beneath the vehicle. Full high-definition video was used to capture 120 frames per second (fps) with image stabilisation. At a train speed of 90 km/h, the frame to frame travel distance is approximately 20.8 cm, which is smaller than a typical sleeper spacing. This sampling interval is, therefore, sufficient for evaluating track conditions.

The images obtained during the travel are processed to efficiently identify points where the gauge widening is likely to be caused. The image processing for calculating the index value “d” from each frame of the images is as shown in Figure 12, where scopes of the wheel side and the rail side are shown. Edge detection is carried out on the rim edge on the side of the wheel, which is without flange, and the outside edge of the rail head.

At a vertical position near the wheel–rail contact point, the horizontal pixel distance between the wheel edge and rail edge is calculated and considered as the index value “d”.

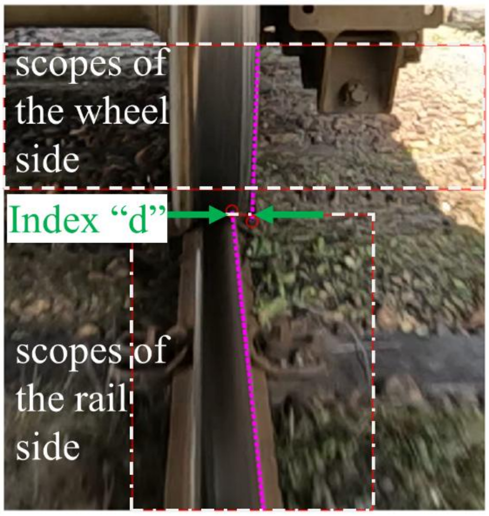

Figure 12: Examples of image processing near the wheel/rail contact point.

7.4 Results of the experiments

Figure 13 shows examples of images captured during mainline operations. The wheel and rail are clearly seen to provide sufficient image quality to assess their positions.

Figure 13: Examples of images captured during mainline operations.
(Left : The whole area of the rail top surface is covered by the wheel
Right : The partial area of the rail top surface is covered by the wheel)

In addition, the results of the image processing are presented. For example, this paper includes the results obtained in a section including an s-curve whose minimum curve radius is 400 m as shown in Figure 14. The first half of the s-curve is denoted as the curve No.1 where the left-side wheel is in the inside of the curve, and the second is the curve No.2 where the right-side is in the inside.

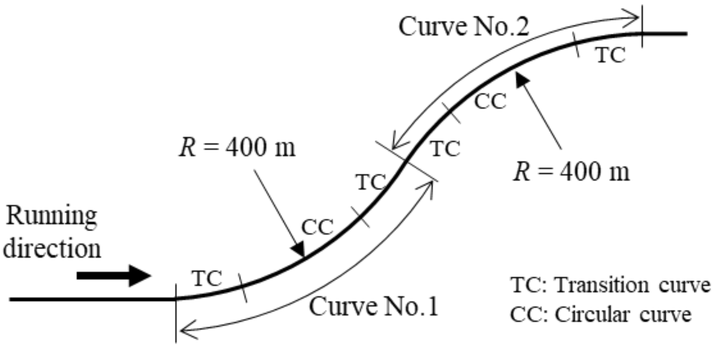

Figure 14: Schematic image of track[3].

Figure 15 shows the calculation results of the index along the track. Each frame of the videos is processed as stated above, and the results are shown according to the running distance of vehicle, which is obtained from GPS velocity. The waveform is filtered to eliminate errors.

When the index of Figure 15 is a negative value, the whole area of the rail top surface is covered by the wheel, whereas a large positive value of the index means an increase in the probability of gauge widening.

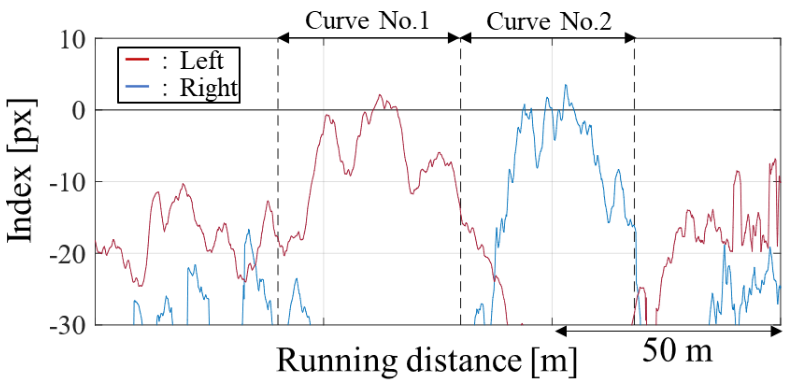

Figure 15: Results of index [3].

On the other hand, Figure 16 shows the results of track inspection of the gauge, including slack, conducted two months after the experiment. The data used is recorded every 1 m along the track. Based on geometric relation of wheel and rail, the index should be zero when gauge widening is 14 mm if the wheels and rails are as designed. Usefulness of the proposed method can be confirmed by comparing Figure 14 and Figure 15, since the values of the maximum gauge widening in both curve No.1 and the curve No.2 exceed 14 mm, and the index becomes positive for both curves. However, peaks along the running direction do not match. Therefore, further consideration will be needed to adjust the videos to the running position of the vehicle.

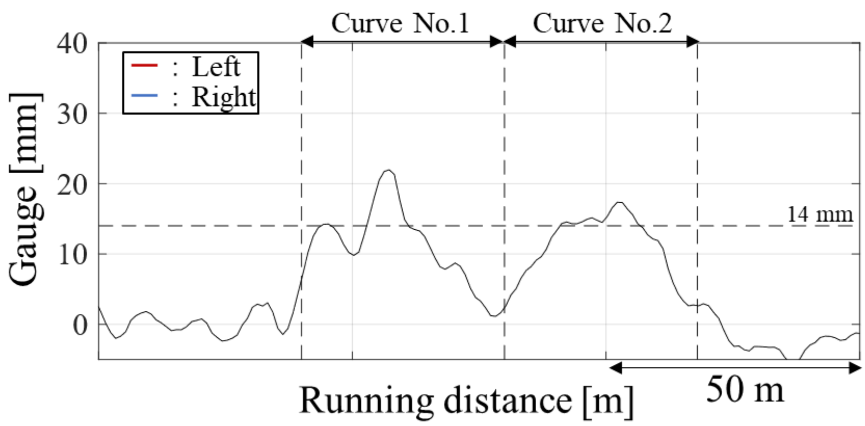

Figure 16: Measured irregularity of gauge [3].

8 Conclusions

This paper presented a set of methods for dynamic track condition monitoring by means of sensors installed on in-service vehicles. The proposed approaches enable more frequent identification of locations, which require maintenance attention, without dedicated inspection cars. Among the proposed methods, the one for the longitudinal level irregularity monitoring has already been introduced by some local railway operators. Ongoing work aims at further validation and deployment of the other methods, including those for alignment, gauge, cross-level, and twist irregularities, in practical railway maintenance.

Acknowledgements

The authors express their sincere gratitude to the railway operators who extended cooperation in the field measurement experiments.

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