Received: March 19, 2025 | Revised: May 6, 2025 | Accepted: May 14, 2025

JOURNAL OF APPLIED RESEARCH ON SCIENCE AND TECHNOLOGY
JARST
INSTITUTE OF RESEARCH AND DEVELOPMENT
RAJAMANGALA UNIVERSITY OF TECHNOLOGY THANYABURI
ISSN ONLINE: 2773-9473
https://ph01.tci-thaijo.org/index.php/rmutt-journal

Prototype inspection cart for detecting track geometry irregularities

Apisit Muanmuang, Pipat Pramot, Terdkiat Limpeteeprakarn and Manusak Janthong*

Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi, Pathum Thani 12120, THAILAND

*Corresponding author: manusak.j@en.rmutt.ac.th

ABSTRACT

This article presents the design and construction of a ride-on geometry inspection vehicle that is controlled by a joystick to measure the width and cross-level height of a model railway track with a gauge of 459 millimeters. The vehicle utilizes a rotary encoder combined with springs, linear guides, and rolling wheels as a measurement tool for the rail width. An Inertial Measurement Unit (IMU) is used to measure the tilt angle between the railway tracks for calculating the cross-level height. To ensure measurement accuracy, the sensors were calibrated with instruments that have been calibrated in accordance with ISO/IEC 17025 standards. The rotary encoder has a measurement deviation of 0.1 millimeters, and the IMU has an angular deviation of 0.05 degrees. During testing, different speeds of 0.1, 0.3, and 0.5 meters per second were evaluated. The average width measurement deviations were found to be 0.10, 0.04, and 0.13 millimeters, while the average cross-level height deviations were 0.09, 0.56, and 0.44 millimeters, respectively. Subsequently, an analysis was conducted to compare the differences in the average error values of the width and cross-level height measurements of the railway tracks using Analysis of Variance (ANOVA). The measured rail gauge values showed no significant differences, while the measured cross-level heights indicated significant differences at the 0.05 statistical level. It was found that the average measurement error for the geometric cross-level height of the railway tracks at a speed of 0.1 meters per second was lower than that at speeds of 0.3 meters per second and 0.5 meters per second, with errors of 0.14 millimeters and 0.17 millimeters, respectively.

Keywords: Cross level, Gauge, Track geometry, Railway tracks

INTRODUCTION

Currently, railways have rapidly evolved and become widely popular. In Thailand, there are two main types of trains [1] 1. Intercity trains: These use a meter-gauge track, with a total distance of 4,044 kilometers divided into various train routes [2]. 2.Electric trains there are two track gauges in use - the meter gauge, covering a distance of 41 kilometers, and the standard gauge, with a distance of 210 kilometers [3]. Railways are a crucial component of the infrastructure for train operations. Over time, the condition of railway tracks tends to deteriorate due to various factors. To ensure safe train operations, regular railway inspections are necessary. The Office of Transport and Traffic Policy and Planning [4] has developed a manual to guide the inspection, evaluation, and maintenance of railway infrastructure in Thailand. The manual includes assessment criteria, specifications, and maintenance guidelines in compliance with the Safety Standard for Working in Urban Passenger Heavy Rail Track (UPHR) S-T001-256x and UIC standards.

For railway inspection techniques, there are several methods, such as Anuwat Bumrungkit et al. [5] developed a mobile hydraulic parallel gauge to measure the rail gauge. The method involves increasing the pressure in the hydraulic cylinder until the rollers contact the rail surface and compress the springs. The experimental results showed a deviation of 0.89 mm. Qijin Chen and et al. [6] used the Amberg GRP1000 and Trimble GEDO CE trolley systems to survey rail gauge and cross-level. For greater accuracy, these tools were integrated with GNSS/INS technology, processed in dynamic mode using the Positioning and Navigation Data Analyst (PANDA) software developed by Wuhan University. Experimental results indicated improved accuracy, with Amberg GRP1000 measuring a cross-level deviation of ±5 mm during movement, which was reduced to ±1 mm when combined with GNSS/INS. Angular deviations were less than 0.01 degrees. Waldemar Odziemczyk and Marek Woźniak [7] tested single-wheel trolleys for detecting rail irregularities and compared their performance with dual-wheel trolleys to assess measurement errors. Wei Chen et al. [8], supported by Xinyun Engineering Co., Ltd., under China Railway First Group Co., Ltd., developed equipment to measure rails and analyze the geometry of subway tunnels. This device includes a laser

DOI: 10.60101/jarst.2024.260837

scanner, measure distance, angle sensor, and width measurement sensor. Experimental results showed that the laser scanner produced curves with average, maximum, and minimum errors of 0.14 mm, 0.3 mm, and 0 mm, respectively. The distance gauge accuracy was 5 mm for 5 meters and 10 mm for 15 meters. Width measurements had an average error of 0.073 mm and a maximum error of 0.23 mm. José L. Escalona et al. [9] developed the Track Geometry Measurement System (TGMS), a mobile system using laser scanners to project light onto the rail head and video cameras to capture images. The positional and directional data from the light line were combined with acceleration and angular velocity data from an Inertial Measurement Unit (IMU) to analyze track geometry irregularities. These included track alignment, vertical profile, cross-level, gauge, and twist measurements using non-contact technology.

This article presents the design and construction of a ride-on railway geometry inspection vehicle. The system consists of four main components. First, an Inertial Measurement Unit (IMU) sensor is used to measure tilt angles caused by cross-level differences in the railway tracks. Second, encoder sensors are employed to measure the rail gauge and the distance traveled. Third, a joystick control system is integrated to manage the vehicle's movement. Finally, a display and data recording system captures and stores data for analyzing rail geometry irregularities, such as gauge and cross-level measurements.

MATERIALS AND METHODS

1. Design of the vehicle chassis.

The design of the geometry inspection vehicle is intended for testing on a model railway track with a rail gauge of 459 millimeters, as this is the track size available in the Department of Mechanical Engineering and is required for testing. The structure of the geometry inspection vehicle is constructed from aluminum profiles measuring 30 x 30 millimeters. The vehicle itself measures 600 x 900 millimeters. For propulsion, the vehicle uses a brushless DC motor as the power source, with power transmitted from the motor to the wheels via a timing belt, as shown in Figure 1. In selecting the motor size for this research, the workload that the inspection vehicle must handle is defined as follows. The inspection vehicle can accommodate one operator and equipment, with a total weight of 200 kilograms. The model railway track used for testing is a flat track (no inclines). The inspection vehicle can travel at a maximum speed of no more than 1 meter per second.

2. The selection or design of a measurement system

The design of the measurement system for railway abnormalities follows the principles of measuring track gauge and cross level. The gauge is measured from the top surface of the rail down to 14 millimeters as the measurement point. Then, the distance between the left rail and the right rail is measured, as shown in Figure 3. The cross level is determined by measuring the angle formed by the two sides of the rail, which are not equal. This is then calculated in conjunction with the gauge width to obtain the cross level, as shown in Figure 1.

Figure 1 Model of the structure and equipment of the geometry inspection vehicle.

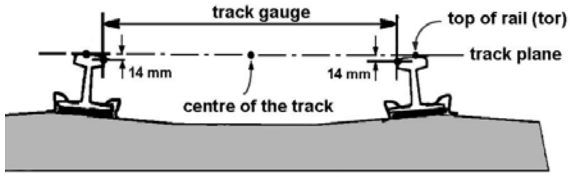


Figure 2 Measurement method of track gauge [10].

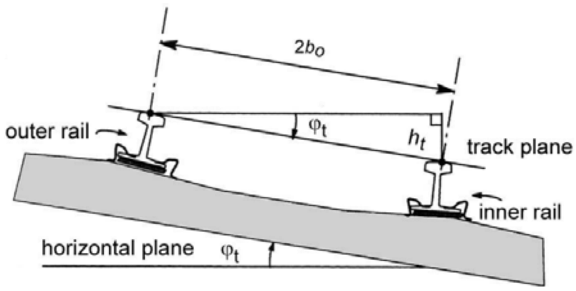


Figure 3 Measurement method of cross level [10].

3. The gauge (Gauge) of the model railway, which has a width between the rails of 459 millimeters, involves a measurement method for railway gauges. A gauge measuring device has been designed, consisting of a linear guide roller assembly that allows the rollers to move in one direction. A spring generates pressure to ensure that the rollers are always fully extended. On the sides of the roller assembly, there are mounts for the encoder's cable, as shown in Figure 4. This assembly is installed on both the left and right sides, with a spacing of 430 millimeters (the minimum

DOI: 10.60101/jarst.2024.260837

distance between the left and right gauge measuring devices) plus the extension distance of the gauge measuring devices on both sides, as shown in Figure 5.

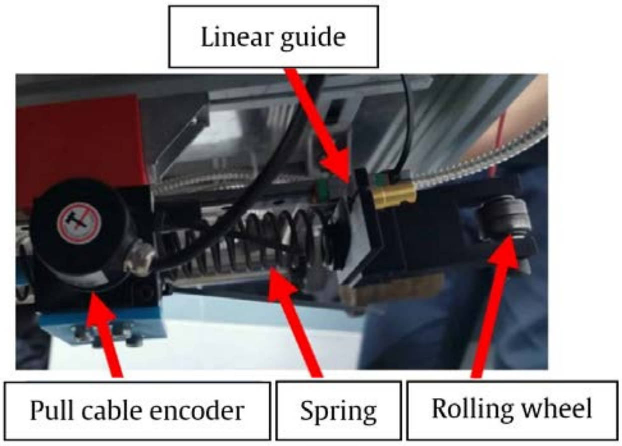


Figure 4 Railway Gauge Measuring Device.

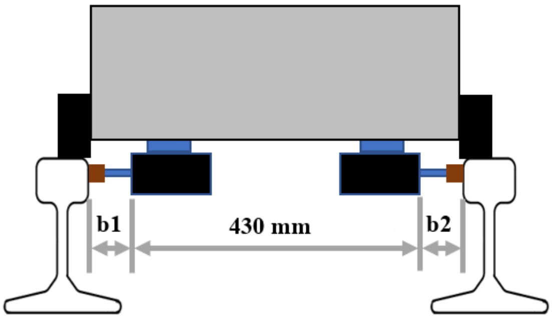


Figure 5 Measurement Method for Gauge of the Railway Geometry Inspection Vehicle.

$$b = (b_1 + b_2) + 430 \qquad (1)$$

When
b is the width of the railway,
b_1 is the value measured by the encoder on the left,
b_2 is the value measured by the encoder on the right,
430 is the constant representing the minimum distance between the left and right gauge measurement tools.

To measure the width of the railway, it is essential for the measuring tool to be perpendicular to the rails. Therefore, guide rails are required both at the front and rear of the vehicle. These guide rails are equipped with springs that generate a pushing force to keep the other side of the vehicle close to the rails while measuring the irregularities of the railway. This is illustrated in Figure 6.

Cross level refers to the difference in height between the running surface adjacent to the rail, calculated from the angle between the running surface and a horizontal reference plane, as shown in Figure 7.

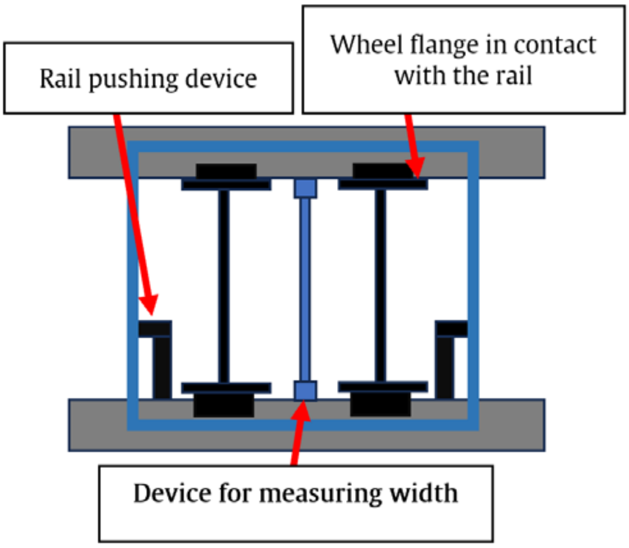


Figure 6 Equipment under the geometric irregularity measurement vehicle for the railway.

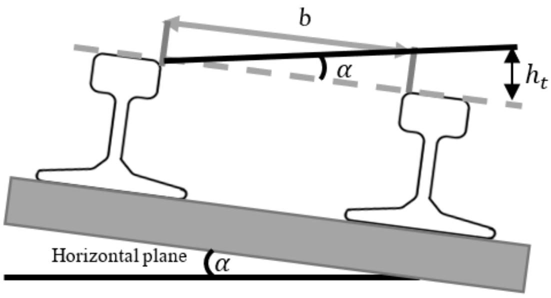


Figure 7 The cross level of the railway.

Considering the law of sines to calculate the cross-level value, we can derive the following equation 12.

$$h_t = b \cdot \sin(\alpha) \qquad (2)$$

When
h_t is the cross-level height of the railway.
α is the tilt angle of the vehicle caused by the different elevations of the rails as measured by the width sensor of the inertial measurement unit.

4. The design of the control and data collection system.

The geometric irregularity measurement vehicle can support a weight of up to 80 kilograms for the operator. It is controlled to move forward or backward using a joystick, with a movement speed of 0.5 meters per second. The vehicle is equipped with the capability to measure the rail gauge of 459 millimeters and the inclination of the railway.

4.1 The drive system, as shown in Figure 8, consists of a joystick (1.2) that inputs signals to a computer (3). The computer converts these signals into speed commands sent to the NI myRIO (2). When the start button on the joystick is pressed, pushing

DOI: 10.60101/jarst.2024.260837

the lever forward moves the vehicle forward, while pulling the lever back causes the vehicle to reverse. An encoder (1.1) is attached to a rubber wheel positioned on the railhead. As the vehicle moves, the encoder generates electrical signals from its rotation, which are sent to the NI myRIO. The data is then transmitted to the computer to record the distance traveled.

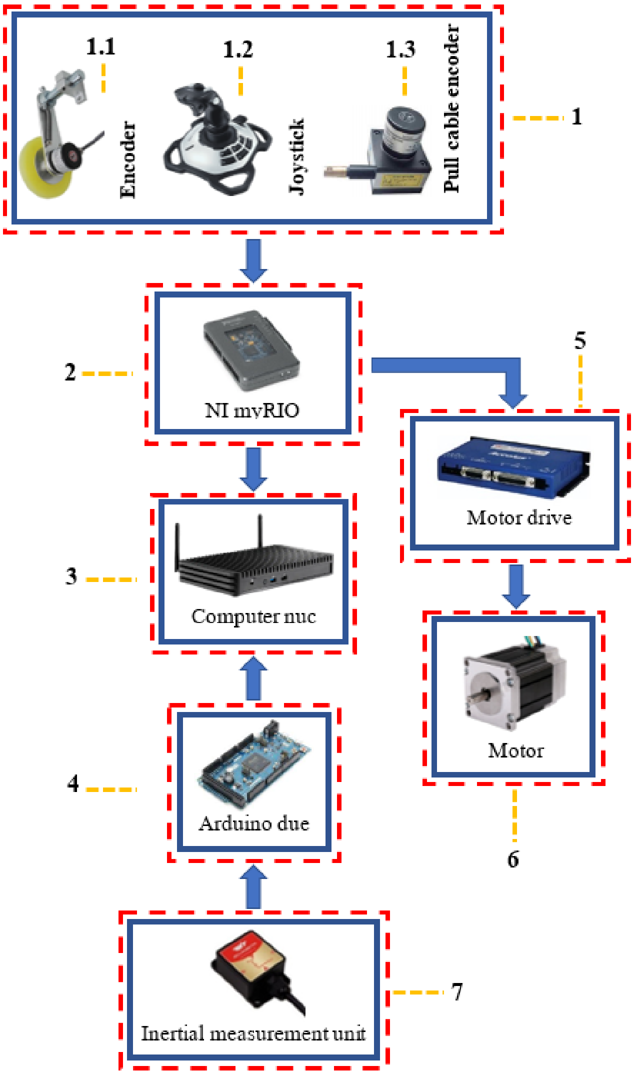


Figure 8 Details of the Equipment for the Geometric Irregularity Inspection Vehicle.

4.2 Data Collection is divided into three parts 1. Track Gauge Measurement. The track gauge is measured using the gauge measurement tool designed as shown in Figure 5. The equipment shown in Figure 8 includes a pull cable encoder (1.3) that transmits electrical signals to the NI myRIO (2). The data is analyzed using equation (11) and recorded on the computer (3). 2. Cross-Level Measurement. Cross-level measurement is performed using an Inertial Measurement Unit (IMU) (7), which detects the angles resulting from tilting across the transverse axis. These angle measurements, combined with the track gauge, are used to calculate cross-level values using equation (12) and then recorded on the computer. 3. Distance Measurement. The distance traveled during the inspection is measured using the encoder (1.1). It detects the movement of the vehicle, sends signals to the NI myRIO for analysis, converts the signals into distance data, and records the results on the computer.

5. Design of the measurement system.

Calibration of the Measurement System is divided into two parts. 1. Calibration of the Pull Cable Encoder Distance. The pull cable encoder is calibrated to ensure its measurements align with actual distances. This involves comparing the encoder's signal output with a known reference distance, adjusting for any discrepancies, and verifying repeatability to maintain accuracy. 2. Calibration of the Angle Measurement Device The angle measurement device, typically an Inertial Measurement Unit (IMU), is calibrated by comparing its angle readings with a precise reference standard. This process ensures that the IMU accurately detects and reports tilt angles, which are critical for cross-level calculations. Adjustments are made as necessary to align the device's output with the standard.

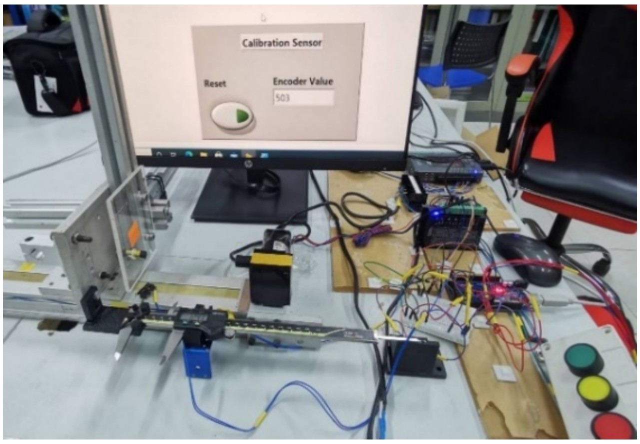


Figure 9 Testing the distance measurement of the pull cable encoder.

Table 1 Calibration results of the Pull Cable Encoder.

Actual compression distance. (mm)	The values measured by the pull cable encoder. (pulse)			
	Test 1	Test 2	Test 3	Average value
3	120	120	120	120
6	244	240	237	240
9	356	360	357	358
12	472	476	486	478
15	596	604	591	597

5.1 Calibration of the Pull Cable Encoder involves testing the accuracy of the pull cable encoder's distance measurement. The test is conducted to record

DOI: 10.60101/jarst.2024.260837

the precision of the pull cable encoder compared to a vernier caliper with an accuracy of ±0.01 millimeters, as illustrated in Figure 9, with the results presented in Table 1.

Based on Table 2, the calibration values for the Pull Cable Encoder indicate that the readings from the encoder have discrepancies from the actual collapse distance. Therefore, the obtained values are plotted on a graph, resulting in a linear equation as shown in Figure 10. This equation consists of the slope of the graph multiplied by the readings and added to a constant. The resulting linear equation is written as a function in the LabVIEW program, and the accuracy of the encoder is tested as shown in Table 2, revealing an average discrepancy of 0.05 millimeters.

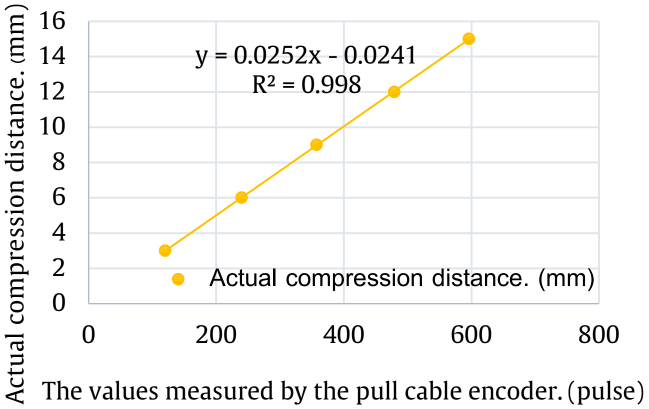


Figure 10 Calibration of the Pull Cable Encoder.

Table 2 Testing of Actual Collapse Distance Compared to Collapse Distance from Compensation Equation.

Vernier (mm)	Encoder value (mm)	Error value (mm)
4.87	4.83	0.04
7.39	7.34	0.05
9.86	9.83	0.03
12.37	12.34	0.03
14.9	14.85	0.05
17.4	17.34	0.06
19.92	19.84	0.08
22.42	22.35	0.07
24.87	24.92	0.05
Average Value		**0.05**

Plot the values from Table 1 in a graph, as shown in Figure 10.

Based on Table 2, the calibration values for the Pull Cable Encoder indicate that the readings from the encoder have discrepancies from the actual collapse distance. Therefore, the obtained values are plotted on a graph, resulting in a linear equation as shown in Figure 10. This equation consists of the slope of the graph multiplied by the readings and added to a constant. The resulting linear equation is written as a function in the LabVIEW program, and the accuracy of the encoder is tested as shown in Table 2, revealing an average discrepancy of 0.05 millimeters.

5.2 Calibration of the angle measurement instrument involves testing the accuracy of the tilt measurement. This process assesses the precision of the Inertial Measurement Unit (IMU) against a dual-axis digital angle protractor, which has an accuracy of ±0.01 degrees, as shown in Figure 11. The obtained values are presented in Table 3.

Plot the values from Table 3 to obtain the graph shown in Figure 12.

From Table 4, the calibration values of the Inertial Measurement Unit (IMU) indicate that the readings from the IMU have discrepancies compared to the actual incline. Therefore, the obtained values are plotted on a graph, as shown in Figure 12. A linear equation is derived, which consists of the slope of the graph multiplied by the recorded values, plus a constant. This linear equation is then implemented as a function in LabVIEW to test the accuracy of the IMU. It is observed that the average error is 0.01 degrees.

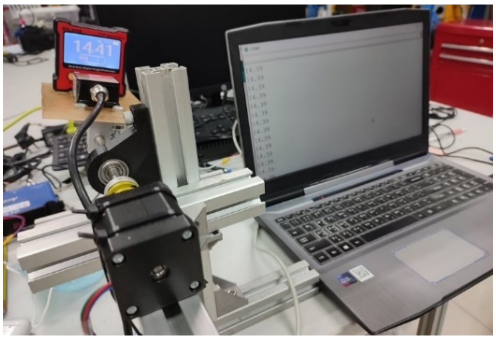


Figure 11 The calibration of the angle measurement instrument.

Table 3 presents the test results for measuring angles using the Inertial Measurement Unit (IMU).

Angle of Angle Gauges (degrees)	Angle of IMU (degrees)	Error value (degrees)
5.27	4.71	-0.56
3.08	2.5	-0.58
1.63	0.81	-0.82
-0.35	-1.24	-0.89
-2.19	-3.21	-1.02
-4.1	-5.19	-1.09
-6.06	-7.27	-1.21

DOI: 10.60101/jarst.2024.260837

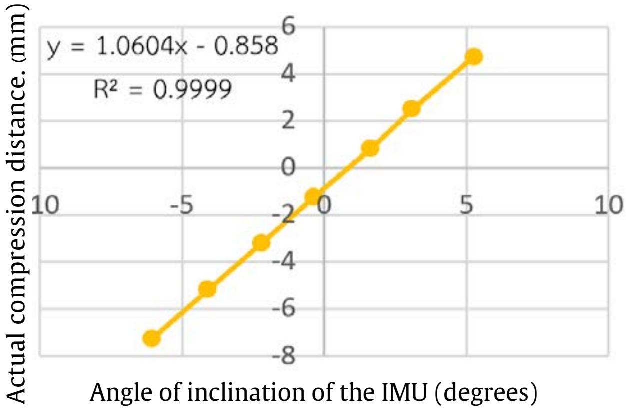


Figure 12 Calibration of the Inertial Measurement Unit (IMU).

Table 4 Testing Actual Incline Compared to Incline Distance from the Equation.

Angle of angle gauges (degrees)	Angle of IMU (degrees)	Error value (degrees)
10.5	10.51	0.01
8.31	8.30	0.01
6.3	6.29	0.01
0.11	0.10	0.01
-6.22	-6.20	0.02
-10.12	-10.13	0.01
-12.06	-12.05	0.01
Average Value		**0.01**

RESULTS AND DISCUSSION

In the testing of the geometric irregularity measurement vehicle, the vehicle is maneuvered to run on a straight track of 10 meters. The measurement vehicle will move at three different speeds: 0.1, 0.3, and 0.5 meters per second. Measurements of width, incline, and cross-level height of the railway will be taken every 0.5 meters. The tester has a mass of 70 kilograms, as shown in Figure 13.

The testing of width and cross-level height measurements of the railway over a distance of 10 meters, conducted at speeds of 0.1, 0.3, and 0.5 meters per second with a weight of approximately 70 kilograms, is compared with calibrated measuring instruments from a laboratory accredited under ISO/IEC 17025 standards, as shown in Figure 14.

Figure 13 The testing of measurements for the width, incline, and cross-level height of the railway.

Figure 14 The measuring instruments used to compare the measurements of gauge width and angle of inclination.

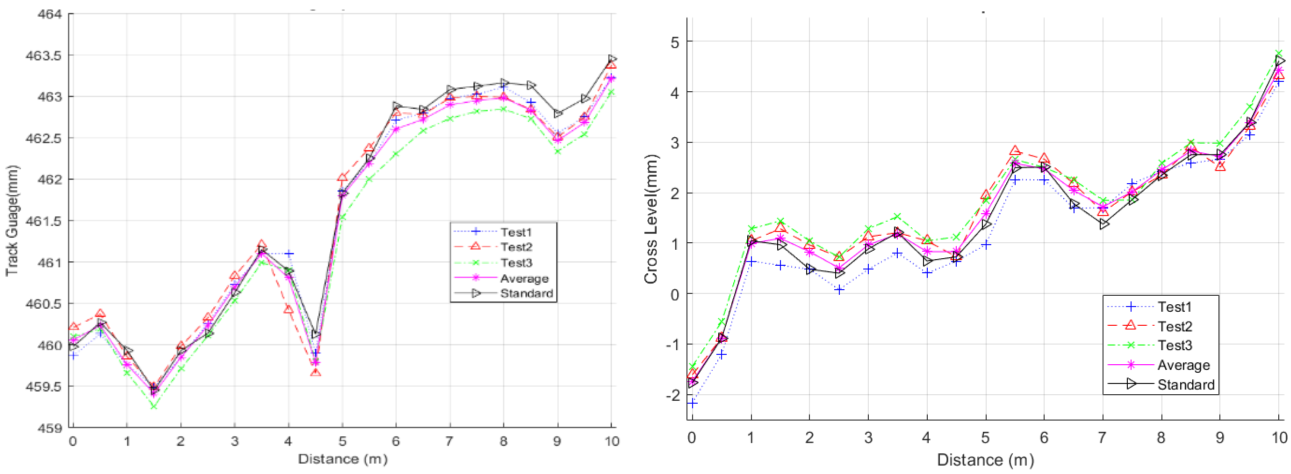


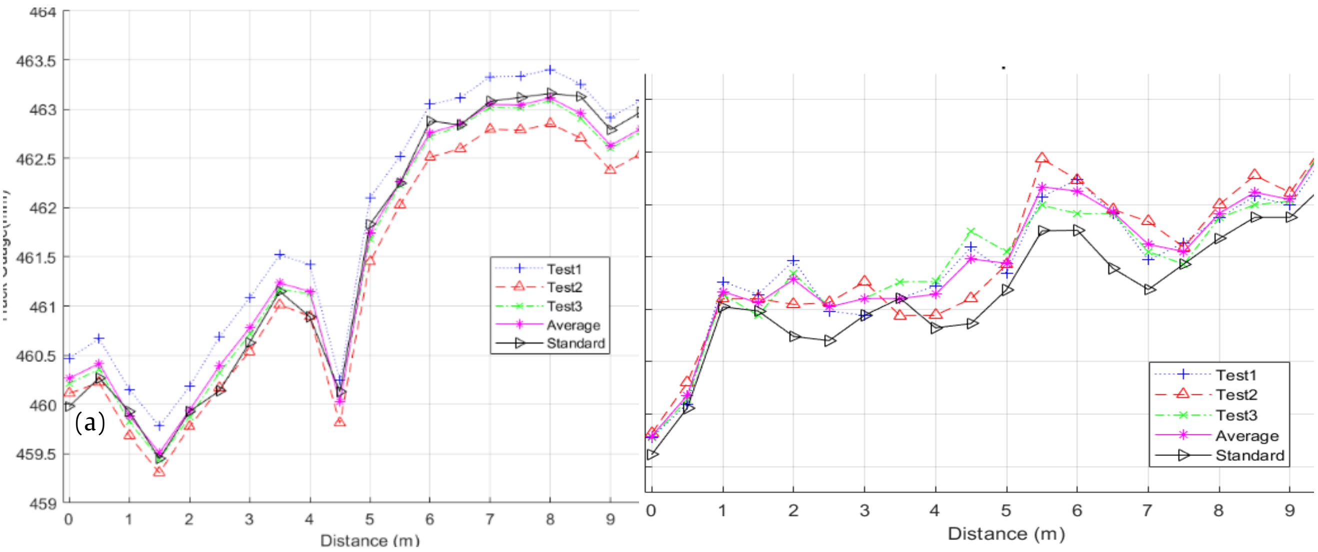
Figure 15 The measurement of railway irregularities at a speed of 0.1 meters per second (a) the width measurement and (b) the height differential of the railway track.

DOI: 10.60101/jarst.2024.260837

The testing of width and cross-level height measurements of the railway over a distance of 10 meters, conducted at speeds of 0.1, 0.3, and 0.5 meters per second with a weight of approximately 70 kilograms, is compared with calibrated measuring instruments from a laboratory accredited under ISO/IEC 17025 standards, as shown in Figure 14.

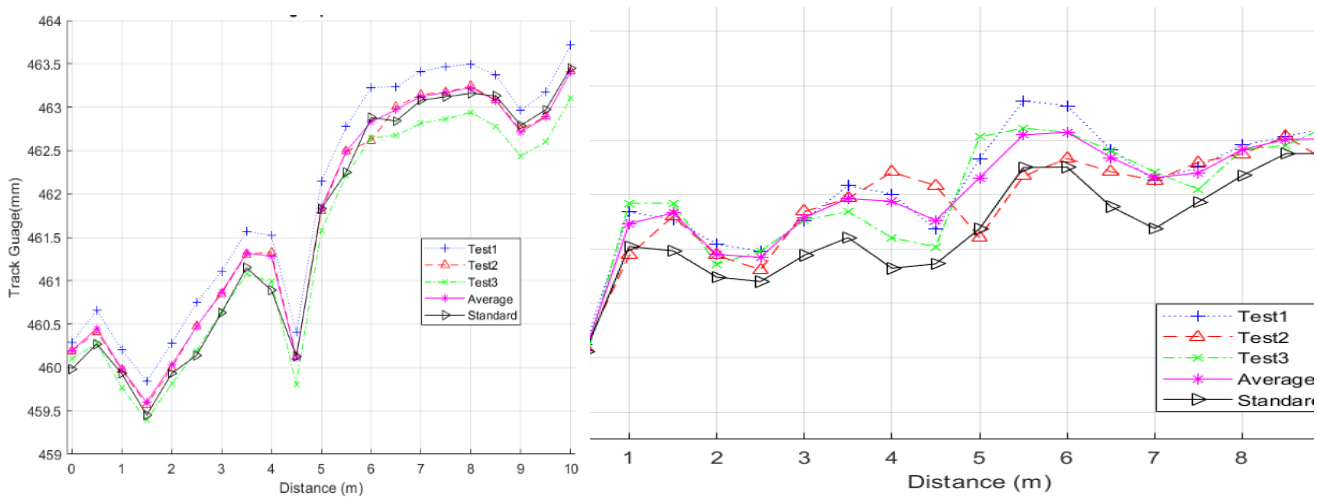
The experiment on measuring the geometric irregularities of railway tracks was conducted using measuring instruments (Figure 14). At a speed of 0.1 meters per second, the measurements showed that the width had a maximum error of 0.58 millimeters, a minimum error of 0.01 millimeters, and an average error of 0.11 millimeters, as illustrated in Figure 15(a). The height differential of the railway track recorded a maximum error of 0.56 millimeters, a minimum error of 0.01 millimeters, and an average error of 0.12 millimeters, shown in Figure 15(b).

When the measurement speed was increased to 0.3 meters per second, the width had a maximum error of 0.55 millimeters, a minimum error of 0.01 millimeters, and an average error of 0.12 millimeters, as seen in Figure 16(c). The height differential recorded a maximum error of 0.56 millimeters, a minimum error of 0.01 millimeters, and an average error of 0.56 millimeters, shown in Figure 16(d). Further increasing the measurement speed to 0.5 meters per second resulted in the width having a maximum error of 0.63 millimeters, a minimum error of 0.015 millimeters, and an average error of 0.13 millimeters, as depicted in Figure 16(e). The height differential had a maximum error of 0.18 millimeters, a minimum error of 0.02 millimeters, and an average error of 0.58 millimeters, shown in Figure 17(f). Finally, a comparison of the error levels was made.



(a) (b)

Figure 16 Illustrates the measurement of railway irregularities at a speed of 0.3 meters per second (a) track width and (b) track cross-level differential.



(a) (b)

Figure 17 Illustrates the measurement of railway irregularities at a speed of 0.5 meters per second (a) track width and (b) track cross-level differential.

DOI: 10.60101/jarst.2024.260837

For the comparison of the mean error levels in measuring railway track width and cross-level irregularities using Analysis of Variance (ANOVA) [11], it was found that track width measurement at speeds of 0.1 ($\bar{X}$ = 0.15), 0.3 ($\bar{X}$ = 0.12), and 0.5 ($\bar{X}$ = 0.13) meters per second, the data variability (F = 0.81) was low. The statistical probability (p-value = 0.45), being higher than the threshold of 0.05, indicates no statistically significant difference, as shown in Table 5. Cross-Level Measurement at speeds of 0.1 ($\bar{X}$ = 0.12), 0.3 ($\bar{X}$ = 0.56), and 0.5 ($\bar{X}$ = 0.55) meters per second, the data variability (F = 18.62) was high. The statistical probability (p-value = 0.00), being lower than the threshold of 0.05, indicates a statistically significant difference at the 0.05 level, as shown in Table 6.

When comparing the mean differences between two groups using Fisher's Least Significant Difference (LSD) method [12], it was found that the average error in cross-level measurement at a speed of 0.1 meters per second was significantly lower than the errors at speeds of 0.3 meters per second and 0.5 meters per second, as presented in Table 7.

Table 5 Comparison of Mean Error Levels in Railway Track Width Measurement by Speed Using Analysis of Variance (ANOVA) [11].

Factor	Compare differences					
	Speed	**$\bar{X}$**	**S.D.**	**F**	**df**	**p-value**
Mean error of railway track width measurement	0.1 m/s	0.15	0.11	0.81	60	0.45
	0.3 m/s	0.12	0.08			
	0.5 m/s	0.13	0.11			

Table 6 Comparison of differences in average cross-level height measurement error of the railway track categorized by speed using Analysis of Variance (ANOVA) [11].

Factor	Compare differences					
	Speed	**$\bar{X}$**	**S.D.**	**F**	**df**	**p-value**
Average error values in measuring the cross-level height of the railway track.	0.1 m/s	0.12	0.10	18.62	60	0.00*
	0.3 m/s	0.56	0.33			
	0.5 m/s	0.55	0.31			

*Statistically significant at the 0.05 level.

Table 7 Differences in the average error levels of railway elevation measurements classified by speed, obtained from testing using Fisher's least significant difference (LSD) method [12].

Speed	Mean Difference (I-J) refers to the difference in the average values between two groups (Group I and Group J).			
	Mean	**0.1 m/s**	**0.3 m/s**	**0.5 m/s**
0.1 m/s	0.12	-	-.44*	-.43*
0.3 m/s	0.56		-	.01
0.5 m/s	0.55			-

*Statistically significant at the 0.05 level.

CONCLUSIONS

This research has designed and developed a prototype vehicle for measuring geometric abnormalities, which can be further developed for use on railway tracks of 1 meter and 1.435 meters. These two sizes of tracks are commonly used in Thailand. An important aspect of the vehicle for measuring geometric abnormalities is the measuring instruments, including a width measurement tool and an angle measurement tool, which are designed to be easily attached to railway cars or inspection vehicles. The aim of this design is to ensure convenience in assembly, disassembly, and usage.

From the research findings, it can be concluded that the results of tests conducted at different speeds show that the measured width of the railway tracks using the measuring tools do not differ significantly. However, the measured height differences of the railway tracks using the measuring tools show a statistically significant difference at the level of 0.05, with values of 0.14 millimeters and 0.17 millimeters.

DOI: 10.60101/jarst.2024.260837

Considering the observed discrepancies, both tests can serve as a prototype for creating measurement tools for practical use.

ACKNOWLEDGEMENT

This research was Supported by The Science, Research and Innovation Promotion Fund (TSRI) (Grant no.FRB640013). This research block grants was managed under Rajamangala University of Technology Thanyaburi (FR645E0703C.4.)

REFERENCES

1. Inthara A, Rojanapunya P, Saiseng N. Thailand's railroad development and future high speed train development. Journal of Yala Rajabhat University. 2017;12(Special Issue):151-67.
2. State Railway of Thailand. Complete guide to SRT 4.0. Bangkok: State Railway of Thailand; 2019.
3. Bangkok Mass Transit System Public Company Limited. The BTS SkyTrain system [Internet]. 2022. [cited 2022 Apr 11]. Available from: https://www.bts.co.th/library/system-structuer.html.
4. Office of Transport and Traffic Policy and Planning. Railway structure maintenance manual. Bangkok: Office of Transport and Traffic Policy and Planning; 2018.
5. Bumrungkij A, Yamfang M, Janthong M. Development of a mobile measurement device prototype for parallelity measurement of rails. KMUTT Research and Development Journal. 2021;44(3):501-13.
6. Chen Q, Niu X, Zhang Q, Cheng Y. Railway Track Irregularity Measuring by GNSS/INS Integration: Chen et al.: Railway Track Irregularity by GNSS/INS. Navigation (Wash) [Internet]. 2015;62(1):83–93. Available from: http://dx.doi.org/10.1002/navi.78.
7. Odziemczyk W, Woźniak M. Analysis of railway track geometry measurement methods usability. Transportation Overview - Przeglad Komunikacyjny [Internet]. 2018;2018(8):40–50. Available from: http://dx.doi.org/10.35117/a_eng_18_08_05.
8. Chen W, Li D, Liu Y, Zhu Z, Huang Z, Yan J. Development and application of a multi-sensor integration detection and analysis device for metro gauge and track geometric state. AIP Adv [Internet]. 2021;11(6):065033. Available from: http://dx.doi.org/10.1063/5.0053474.
9. Escalona JL, Urda P, Muñoz S. A Track Geometry Measuring System based on multibody kinematics, inertial sensors and computer vision. Sensors (Basel) [Internet]. 2021;21(3):683. Available from: http://dx.doi.org/10.3390/s21030683.
10. Lindahl M. Track geometry for high speed railways: A literature survey & simulation of dynamic vehicle response, TRAIT-FKT Report 2001:54, ISSN 1103-470X.
11. Lomax RG, Hahs-Vaughm DL. Statistical concept a second course. 4 ed. United States of America: Taylo & Francis Group; 2012
12. Abdi H. The method of least squares [Internet]. 2010 [cited 2025 Mar 7]. Available from: https://personal.utdallas.edu/~herve/abdi-LSD2010-pretty.pdf.

DOI: 10.60101/jarst.2024.260837