Optimum Train Weighing in Motion using Inertial Sensors

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Abstract: Continuous monitoring with advanced equipment and innovative scientific techniques is essential for timely and perfect maintenance. The interaction and dynamic force between wheel and rail is one of the most widely monitored issues. In this paper's case study of ballasted railway tracks in Iran, a set consisting of two separate strain gauge arrays and three different positions for installing accelerometers were designed according to the conditions. After installation, the system was calibrated with a predetermined passing axle load. The dependency of the arrays' and the equipment's installation location with the velocity of the passing axle load was examined as part of the field study after repeated investigation and comparisons of the setups' results. In order to gather data with the least error and the highest level of accuracy, it was decided on the more appropriate array with less dependence and a better installation position.

Keywords: Railway monitoring; Maintenance; Measurement; Strain gauges; Accelerometer

1 Introduction

In today's world, a country's infrastructure is viewed as its capital and national wealth since its capacity to develop and progress is determined by how effectively its infrastructure performs. The rail transport industry, which significantly influences people's everyday lives and the environment, is an essential measure of a country's growth. As a result, a condition monitoring system must be established to detect any defects that may appear as safety issues. Consequently, precise information may be acquired by designing novel equipment or integrating cutting-edge technology into a complete monitoring system [1, 2, 3]. Both experimental and numerical studies have the potential to produce big advances. When monitoring railway tracks, many researchers in this field are interested in the interactions and dynamic forces between wheels and rails. However, little experimental research has been conducted on the dynamic effect of heavier freight trains on railway tracks. Strain gauges and accelerometers are two monitoring-related technologies that, based on their functional capacity and sensitivity, should be employed in ideal conditions and an ideal combination, requiring a scientifically intelligent design. Keith et al. [4]. In one research, experimental field tests were conducted to investigate how heavy loads induced by large axle loads influenced the dynamic behavior of the railway track. It is demonstrated that when various speed and axle load changes are applied to the wheel-rail dynamic force, dynamic deformation of the track structure, and track vibration behavior, some of the indicators reflecting the dynamic behavior of the railway track increase roughly linearly with train running speed and axle load, while others are barely influenced. Zhiyong *et al.* [5]. The project created a wheel load detector based on a strain gauge for monitoring wheel-rail contact forces at insulated rail joints (IRJs). The laboratory and field testing results showed that the design followed generally recognized theoretical assumptions. Field data vividly depicted the wheel-rail impact force produced across the joint gap, demonstrating its use in recognizing the wheel-rail contact-impact force signature at IRJs. Manicka *et al.* [6]. The necessary fusion technique and the outlined theoretical relationships between the samples gathered by various sensors demonstrated in a comprehensive analysis that the features of the wheel defects used in the data generation step were entirely represented in the defect signals reconstructed by the suggested method. Consequently, the proposed technique enables early defect detection and identification, including small and long-wave flaws. The number of sensors, the effective zone size, and the wheel's circumference, which acts as the defect signal's basic period, all impact the fusion process. Alemi *et al.* [7]. Wheel flaws on railroad wagons have been discovered as a substantial cause of damage to the railroad's infrastructure and rolling equipment, in addition to creating costly noise and vibration emissions. A sensor network is being created for permanent installation on the railway network. Shelling, flat areas, and a lack of roundness are all issues. It outperforms current defect identification approaches for flat spots and predicts the other two kinds of defects. The neural network technique explicitly simulates the multisensory structure of the measurement system via numerous instances, learning, and shift invariant networks to increase performance on wheels with flat areas and non-roundness. Gabriel *et al.*

[8]. Vertical overloads may cause track degradation and safety breaches, but wheel-rail lateral contact forces are more directly connected to running safety. According to the computational and experimental data, the size of the lateral force may be estimated using an independent coefficient obtained from the applied loads. Bruner *et al.* [9]. The curvature of the wheel profile impacts a train's performance in various ways. In a field test, the station monitors the lateral and vertical wheel/rail forces at the point of contact in a 484-meter-radius curve at speeds up to 100 km/h. In a bogie, the four-wheel positions have markedly distinct force signatures. While the strength of the three other high rails increases with distance, the leading high rail has strong forces unaffected by the change in running distance. Palo *et al.* [10]. The issue's placement and sensor needs were investigated in a study on the static and dynamic behavior of ballasted railway tracks. It could be helpful to estimate stress transfer from the train passage to the track using predictive computational models. Georges *et al.* [11]. Weighing in motion systems would assist in solving the shortcomings of conventional static weighing, such as costs and traffic management. Weigh-in-motion systems, however, do not allow direct measurement of the static load since the dynamic interaction between the train and the track results in dynamic loads added to the static ones. Investigating the effect of track unevenness and train speed on the weights measured by the weigh-in-motion system. A rigorous statistical investigation based on multiple computations was done to achieve that purpose. In order to estimate the static load, a technique to rectify the direct result supplied by the weigh in motion system is presented. This strategy is based on the results and patterns discovered throughout the extensive parametric investigation. Mosleh *et al.* [12]. The successful operation of a field test system methodology and the system's optimization should be thoroughly evaluated with regard to various types of trains. This is influenced by the type of sensors and where they are set up. Mosleh *et al.* [13]. The installation of sensors along a railway track's entire length will allow real-time monitoring of the states of its technical components, and the proposal of a diagnostic sensor system based on railway track stress-strain analysis. Avsievich *et al.* [14]. The initial stage in data processing is to determine the speed of a passing train after identifying it (time, date, and direction). For the purpose of calculating train speeds, each peak of a vertical acceleration signal represents the passage of a train axle above the considered accelerometer. Blanc *et al.* [15]. The ability to predict failure of track infrastructure components can be improved through maintenance prioritization and procedures, thereby enhancing the safety of railway operations. Edwards *et al.* [16]. It may be helpful to use an alternative model-based method based on the local response function method that can forecast accurate stress results in particular locations without the need for direct measurement data at those locations. Menghini *et al.* [17]. The degree of fit between actual and estimated track forces and irregularities is demonstrated through point-by-point graphs of actual and estimated values, and indicators of the accuracy of estimates are generated using R-Squared values, which represent the percentage by which the variance of mistakes is less than the variance of actual values. Gadhave *et al.* [18]. When performing calibration and the primary test according to the desired plan, it is crucial to take into account the impact that imbalanced vertical loads have on the data recorded in the monitoring system. Silva *et al.* [19]. A signal analysis approach

based on the analytical domain and monitoring equipment suitable for conditions in the environment will be productive in providing a suitable instrument for studying experimental non-stationary vibration signals comprising shock. Salehi *et al.* [20]. Physical calibrations are crucial in the strain recovery process, in addition to placing the strain gauges optimally to reduce uncertainty in the simulation model. Nieminen *et al.* [21]. The installation of sensors should take into account the best site for installation, and the layout of the sensors really offers a platform for simple installation and a more accurate data recording system. Jing *et al.* [22]. The smart rail pad demonstrated excellent signal response to fluctuations in loading, with an average percent error of 6%. It can be used for load sensing and as an axle counter to measure wheel loads. Schalkwyk *et al.* [23]. In order to track the structural performance of the track and to identify changes in traffic volumes and loading circumstances, analyzing rail pads—a crucial component of railway structural design—that are fitted with various types of sensors is very beneficial. Sol-Sánchez *et al.* [24]. A simulation study is conducted as part of the additional analysis of the findings to establish the precise location of the sensors based on the rail's fatigue life, the likelihood of mistakes and redundancy, and various railway traffic situations. Pillai *et al.* [25]. Comparison of the distributed acoustic sensor (DAS) results with point location measurements made using a conventional strain gauge and deflections determined via imaging and digital image correlation (DIC), provides accurate distributed strain measurements with the capability for continuous spatial and temporal coverage across substantial tracts of track. These measurements translate to estimates of track deflection and load. Milne *et al.* [26]. When a sizable high number of strain gauge pair installations are made in the track, a realistic assessment of the static load may be made. Therefore, a statistical correlation must be taken into account when calculating the static load from weigh-in-motion (WIM) systems with fewer sensors. This means that the estimation of the static load interval should take a certain level of confidence into account for each of the vehicle wheelsets. Pintão *et al.* [27]. Shear strain data at specific locations has been used to develop mechanics-based algorithms to estimate the speed and wheel loads of trains passing over a bridge under study. The speed estimation algorithm uses shear strain at quarter span and takes the train's speed variation into account. For wheel load estimation, two algorithms are studied. The shear strain algorithm only makes use of the peak value of the shear strain measured at an axial location close to the bridge. [28]. With the advancement of the transportation industry and the demand, the settlement and wear of the ballast caused by dynamic stresses at high frequencies is still an important issue on high-speed tracks, leading to high maintenance costs. Khairallahet *et al.* [29]. A more thorough, real-time, and current understanding of the railway track condition would be made possible by predictive maintenance operations carried out with cutting-edge monitoring systems. As a result, maintenance expenses would go down because interventions would only be made when they were truly necessary. In-depth discussion will also be given on monitoring systems that keep track of temperature, stresses, displacements, strain measurements, train speed, mass, and position, axle counts, wheel flaws, rail settlements, wear and tear, and the condition of railroad bridges and tunnels [30, 31]. A field investigation Two stiff common crossings were the subject of experimental observations under the dynamic stress of a high-speed train. According to the findings, the maximum displacements within a specific velocity range increased by 2.5 times. Due to the relative displacement measurements between the rail and the sleeper, the different dynamic impact loading for the wing rail, and the lack of a difference in displacements between the trailing and facing travel directions, measured maximal strains are not as explicit as the displacement results. Kovalchuk *et al.* [32]. Ingenious methods and routine inspections are two of the key factors that influence the cost of railway maintenance, according to both laboratory and numerical studies. Modern monitoring techniques, prognostics, and health management strategies provide a wealth of opportunities for improving inspection and maintenance procedures. [33, 34].

However, there are still lots of required optimization for different stages of measuring wheel-rail force from software and hardware points of view. Most research are presented with a fixed arrays of sensors, which is one of the major challenge in correct data acquisition. It also needs to consider track maintenance issues. The challenge of correct data acquisition mainly lies in sensor array and arrangement design, which determines quality of the signal. In this paper, different arrays and locations of the strain gauges and accelerometers are studied for data collection. The results are analysed and discussed and sensitivity against velocity are also considered.

2 Field test

2.1 Scope of Study

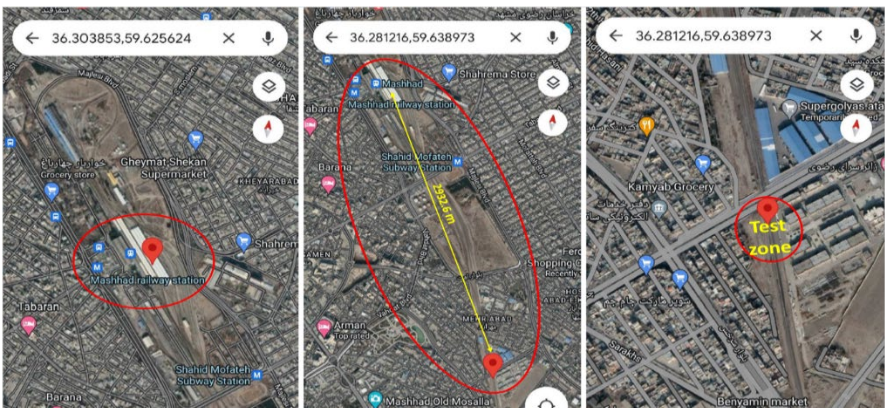


Figure 1

The test site and its location relative to Mashhad railway station

The location of the study area which is between the Chaman and Sarkhes bridges and 2,392 meters away from the Mashhad railway station, is shown in more detail in Figure 1, along with its position in relation to the Mashhad railway station. The aforementioned location has two input and output lines that are connected to the Chaman concrete deck bridge on the west side and the railway switches on the east side, respectively. The passing train speed is approximately 80 km/h, and test equipment was installed on tangent railroad part in the exit line.

2.2 Railway Track System

Figure 2 depicts the layout of a ballasted railroad track. The sleepers are attached to two rails (there is an elastic pad between the rail and the sleepers). This set is situated on a ballast layer, allowing for the safe and easy passage of trains. The characteristics of the ballast layer, rails, and rail pads affect the track's dynamic performance. To keep track performance, maintenance actions are needed which are mainly focused on the aera between two sleepers. The tamping machine is used to keep the ballast layer quality in check which uses rail web on the area between sleepers and support. There are also some actions required for bolt tightening. Considering all of this, the rail web in the area on the sleeper would be the safest place for sensor installation. The sensor must be able to provide accurate data on this location, too. The following is a quick list of the test site pavement's technical specifications:

- Rail type: UIC60 heavy, rail weight is 60.34 kg/m
- Sleeper type: Mono block concrete sleeper, total weight of the sleeper is 260 kg
- Fastening type: Weslo type spring fastener, its weight is 503 gr
- Ballast type: Mostly made of porphyry and metamorphic rocks

As mentioned in the Introduction, accelerometers can measure track dynamic performance, whereas strain gauges are typically less sensitive to track dynamics and track structure failures. As a result, both kinds of sensors should be used to measure all static and dynamic components of a contact force measurement.

Figure 2
Railway components details

2.3 Test Equipment

As previously mentioned, the instruments were installed on a tangent part of the railroad so the operation conditions, such as speed and bogie normal function, would be under control, and any abnormality within the bogie and wheels would be monitored with higher accuracy. Specifications for used strain gauges, accelerometers, and data logger can be found in Tables 1 to 3.

Table 1

Strain gauge technical specification used for field test (detailed)

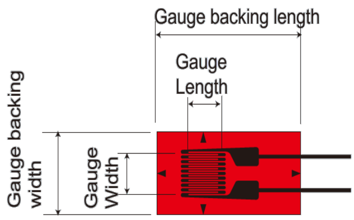
<table>
<tr><td colspan="2" rowspan="3">
</td><td>Applicable specimen</td><td>Metal, Glass, Ceramics</td></tr>
<tr><td>Backing</td><td>Special plastics</td></tr>
<tr><td>Element</td><td>Cu-Ni</td></tr>
<tr><td>Operational temperature (°C)</td><td>-196 ~ +150°C</td><td>Temperature compensation range (°C)</td><td>+10 ~ +100°C</td></tr>
<tr><td>Strain limit</td><td>5% (50000×10^{-6} strain)</td><td>Applicable adhesive</td><td>CN, P-2, EB-2</td></tr>
<tr><td>Fatigue life at room temperature</td><td>1×10^{6} ($\pm1500\times10^{-6}$ strain)</td><td>Gauge length (mm)</td><td>0.5</td></tr>
<tr><td>Gauge width (mm)</td><td>1.2</td><td>Backing length (mm)</td><td>5</td></tr>
<tr><td>Backing width (mm)</td><td>2.2</td><td>Resistance (Ω)</td><td>120</td></tr>
</table>

Table 2
Technical specification of the wired accelerometer used in field test

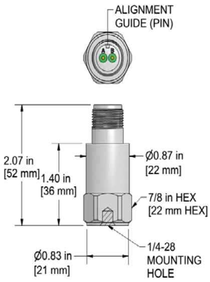
AC102-1A				
	Sensitivity (±10%)	100 mV/g	Spectral Noise @ 10 Hz	14 µg/√Hz
	Frequency Response (±3dB)	0,5-15000 Hz	Spectral Noise @ 100 Hz	2.3 µg/√Hz
	Frequency Response (±10%)	2,0-10000 Hz	Spectral Noise @ 1000 Hz	2 µg/√Hz
	Dynamic Range	± 50 g, peak	Output Impedance	<100 ohm
	Settling Time	<2.5 seconds	Bias Output Voltage	10-14 VDC
	Voltage Source	18-30 VDC	Case Isolation	>10^8ohm
	Constant Current Excitation	2-10 mA		

Table 3
Technical specification of data logger used in field test

Analog inputs	8 ch voltage, IEPE, current (with ext. Shunt)
ADC type	16 bit SAR with 100 kHz 5th order analog AAF filter or bypass (500 kHz)
Sampling rate	Simultaneous 1 MS/s
Ranges	±10 V, ±5 V, ±1 V, ±0.2 V
Typ. SNR @ 100 kHz	89 dB
Input coupling	DC or AC (1 Hz)
Input impedance	1 MΩ
IEPE mode	4 or 8 mA excitation; Sensor detection (Short: <4 V; Open: > 19 V)
TEDS	Supported in IEPE mode
Overvoltage protection	50 V continuous; 200 V peak (10 msec)
Typical power consumption (max.)	15 (22 W)

2.4 Tested Rail Fleet

The fleet used in this project includes Siemens locomotives and passenger wagons are made in Germany, whose pictures are shown in Figure 3 and their technical specifications are in Tables 4 and 5.

Figure 3
Passing locomotive and wagons used in the test program

Table 4
General specification of Locomotive used in field test

Fleet	Loco type	Made in	Min speed (km/h)	Max speed (km/h)	Ax-to-Ax distance of two bogies (mm)	Ax-to-Ax distance of two axles in a bogie (mm)	Wheel diameter (mm)	Axle load (tonne)
Locomotive	ER24PC BO-BO	Germany 2011-2016	39.4	160	10362	2700	1100	20

Table 5
General specification of Wagons used in field test

Fleet	wagone type	Made in	Min speed (km/h)	Max speed (km/h)	Wagon weight - empty (tonne)	Wagon weight – full (tonne)	Bogie type of wagon	Axle load (tonne)
Wagon	RL11	Germany	-	140	45	50	MD36	11.25

3 Test Plan

The following key factors should be taken into account when measuring the wheel-rail contact force:

- Repeatability of measurements, taking train wheel radius and speed into account.
- Installation time should be minimized; the instruments should not interfere with maintenance vehicles if long-term measurement is required.
- To be able to avoid the need for expensive speed detectors, the vehicle's speed should be calculated with the highest degree of accuracy.
- The force calculation method should be able to analyze all data as quickly and accurately as possible and report the results.
- The configuration should be safe and not require routine manual calibration and maintenance.

The sensor formation was designed with the previously mentioned issues in mind. Figure 4 shows a schematic representation of the rail web with the installed equipment and sensor configuration. All the accelerometers are in vertical direction and strain gauges are installed as half-bridge circuit. The strain gauge arrays in this paper come in two varieties: "V" and "<". In comparison, the "<"-shaped array is concentrated on the bending strain, and the "V"-shaped arrays deal with shear strain when there is a wheel passage. Normally, calculation of wheel vertical force focuses on bending strain, which has an interference with maintenance issues. The V array is introduced to cover this shortcoming.

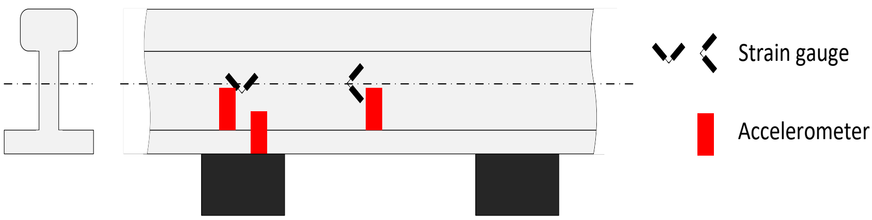


Figure 4
Configuration of strain gauges and accelerometers on the rail web

To make sure that no data is missing, it is necessary to measure in a complete round. So, for every passage, the whole wheel surface is scanned. The designed sensor arrangement and localization are done to ensure the mentioned condition is met. This arrangement is also able to analyze the wheel multiple times with the help of different combinations of installed sensors, so the error would reduce noticeably. It means a higher calculation volume with no change in the response time of the device. With the configuration shown in Figure 5, one side of the passing train is completely covered, allowing for accurate comparisons. Accelerometers are very sensitive to the track structure's defects, in contrast to strain gauges, whose results are essentially independent of such defects. So keeping track's quality high in the instrumented area is crucial. The accelerometers' installation position can also help determine the wheel's dynamic component. In order to investigate the dynamic component of the vertical forces of the wheels, three different accelerometer positions are taken into account: 1) on the rail foot in the rail's position on the sleeper, 2) on the sleeper, and 3) on the rail foot, between the sleepers.

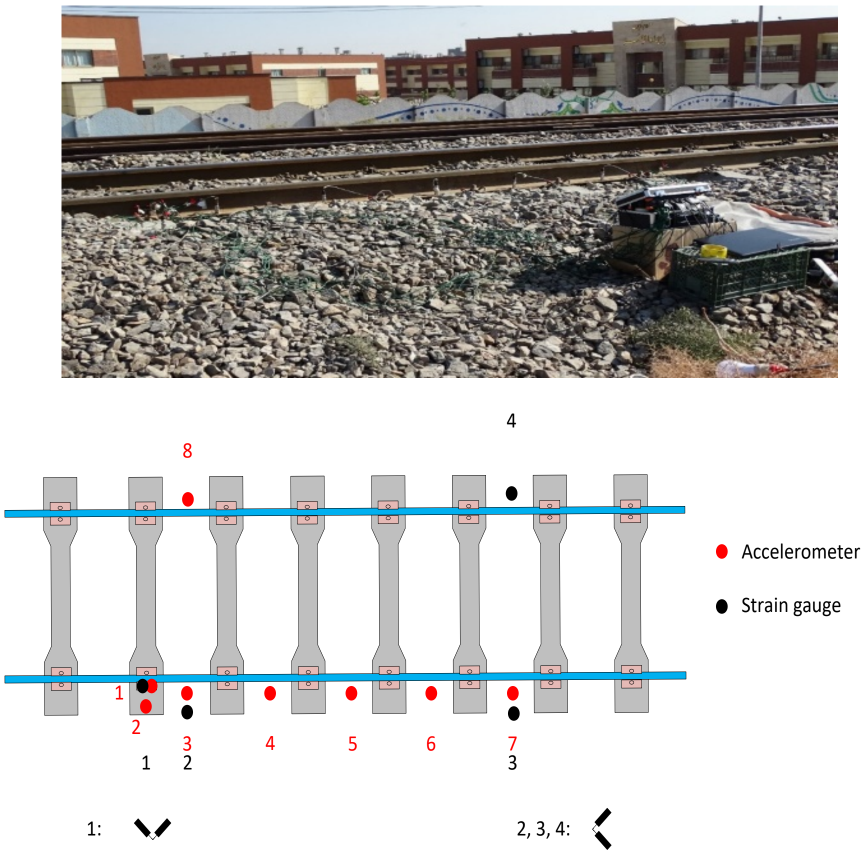


Figure 5
Locations of sensors and their types

In order to control operation conditions like speed and bogie normal function and to more accurately monitor any abnormalities within the bogie and wheels, the instruments were installed on a tangent track, as it is shown in Figure 6.

Figure 6
Instrumentation location on tangent track

Figure 7
The drezin used for system calibration

As shown in Figure 7, the system was initially calibrated using a drezin (a light rail vehicle) with known axle load. Table 6 describes the calibration procedure, which also includes load and speed. Using locomotives from passing trains with axle loads of 19.75 tons, the main calibration is carried out (9.875 tons per wheel).

Table 6
Calibration condition for drezin

Test condition	Number of tests
V=5 km/h	2
V=10 km/h	2
V=20 km/h	2
V=40 km/h	2

4 Result

4.1 Strain Gauge Results

Results of recorded data caused by drezin passage is illustrated in Figures 8 for strain channels. The sudden jump in the diagram is caused by shear strain, which is proportional to the axle load and velocity as the wheel passes over the sensor. These quantities can be found and measured to determine the wheel load. By calculating the phase difference between these sensors, velocity can also be determined.

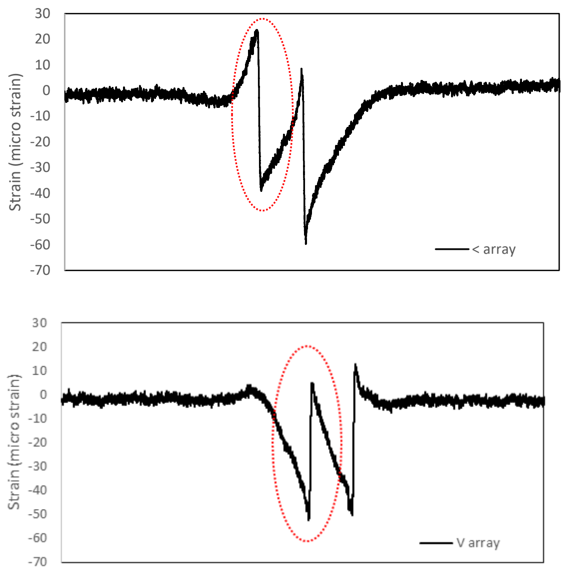
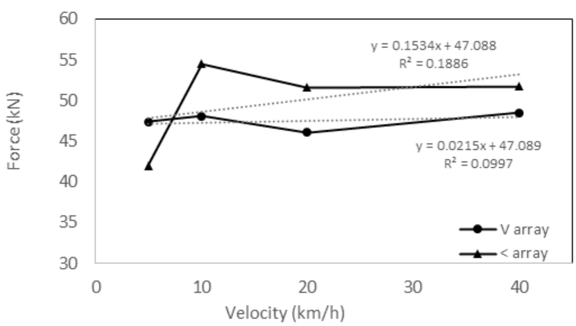


Figure 8
Measured strain for "<" array (up) and "V" array (down)

The drezin used for primary calibration weighs 4.8 tons and has a wheelbase of 2.7 meters. By plotting the shear strain mentioned in Figures 8 in terms of velocity, Figure 9 is obtained. The value shown for each speed is the average of all channels and passages. The dependency of the two mentioned arrays on velocity is relatively low and linear. It should also be noted that the proposed "V" arrangement has a lower dependency on velocity compared to the "<" arrangement. These would enable measuring the static components of the signal with higher accuracy due to the probable error in the velocity calculation. Additionally, the mean squared error for "V" array is lower than the conventional "<" array.



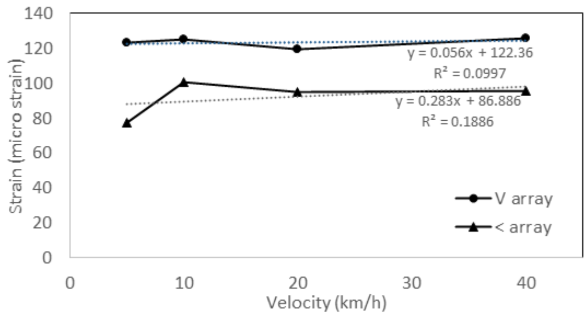


Figure 9

Linear pattern for velocity – drezin passage results, Force (up) and Strain (down)

The results of the entire passage for a passenger train pulling a locomotive weighing 79 tons are shown in Figure 10. The values in Figure 10-top are for Channel 1 in Figure 5 with the "V" arrangement, and the rest are for Channels 2–4 with the "<" arrangement, respectively. The train passages are completely recorded by both arrays, which display the same pattern. Therefore, the "V"-shaped array can be considered an alternative to the "<"-shaped array, which conflicts with track maintenance activities.

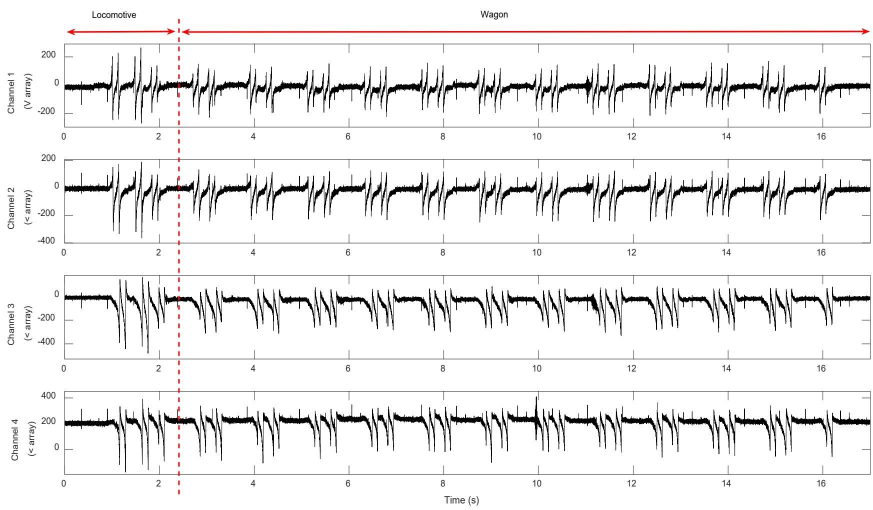


Figure 10

Strain results for a passenger train

Figure 11 displays the strain results proportional to vertical loads for a locomotive (79 tons in weight) for various passages. Higher speeds and axle loads can produce the same patterns and outcomes (compared to primary calibration). Despite the different velocity dependencies, the pattern is still linear. While this parameter has increased for the "<"-shaped array from 0.283 to 0.4833, it has decreased from

0.056 to 0.0326 for the "V"-shaped array. So calibration is required for various speed ranges. These findings demonstrate the benefits of a "V"-shaped array's lower dependence on speed when needed. It should be noted that more research should be done to determine how sensitive this arrangement is to track failures. Similar to the drezin test, as it is shown in figure 11, values for error is lower in "V" array.

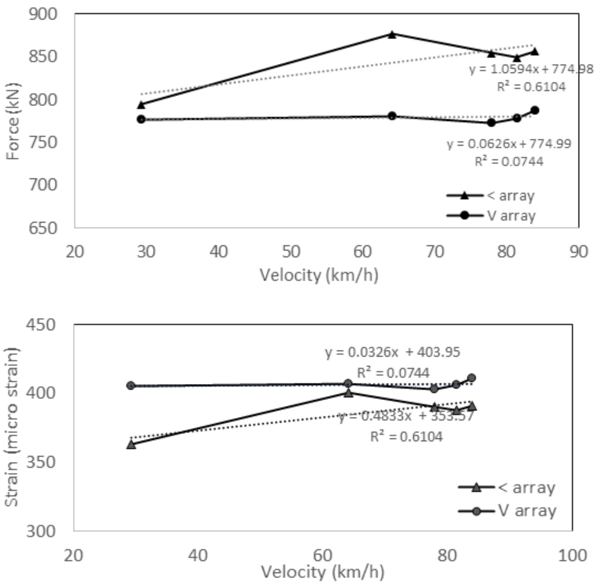


Figure 11

Linear pattern for velocity in vertical load calculation – Locomotive passage results, Force (up) and Strain (down)

4.2 Acceleration Results

As earlier described, accelerometers are much more sensitive than strain gauges to the track structure's defects, the results of which are essentially independent of them. So keeping track's quality high in the instrumented area is crucial. The accelerometers' installation position can also help determine the wheel's dynamic component. In this research, the authors installed accelerometers at three different positions: on the rail foot in the position of the rail on the sleeper, on the sleeper, and the rail foot in the distance between sleepers, to investigate the dynamic component of the vertical forces of the wheel and rail (see Figures 4 and 5). Figure 12 shows the three positions' time domain and Short Time Fourier Transform (STFT) [35] values. This transformation has a 1024-point window with a 1000-point overlap. The window type is Gaussian, and the sampling frequency is 10 kHz.

The wheel passage is clearly shown in Figure 12-b. In other words, the rail and rail pad had a low-pass filtration influence on the acceleration signal as it passed through them. There is also much noise in Figures 12-a and 12-c. This illustration emphasizes the importance of signal filtering in order to identify various failures. The characteristics of the track superstructure have a significant impact on the accelerometer's response as well. In summary, it can be said that moving the accelerometer from between the sleepers (channel 3) to the sleepers (channel 1) has no detrimental impact on the precision of the measured signal. But results from channel 2 can be used with minimum pre-processing.

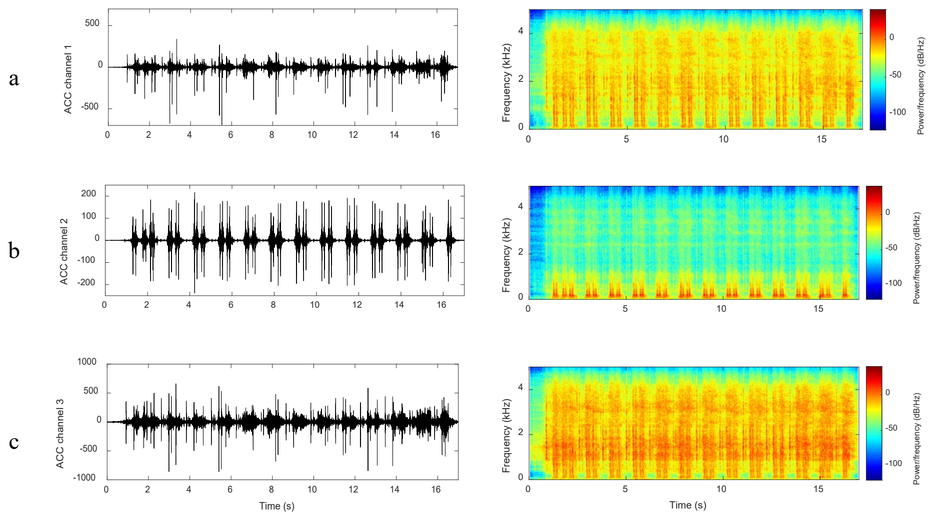
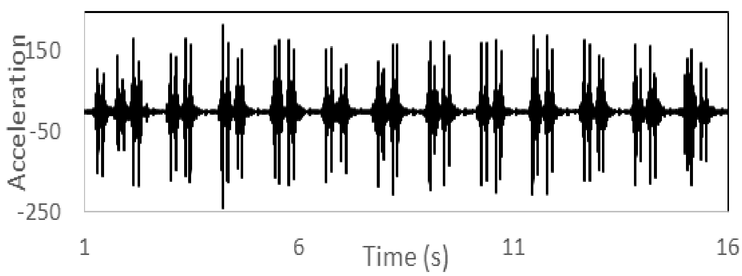


Figure 12
Acceleration results for a passenger train

So, the strain gauges V-array and sleeper mounted acceleration can accurately measure static and dynamic forces of wheel-rail system. Combining results from these two sensors would results to figure 13. The region 1~3 is healthy wheel (or monitor state), 3~4 stands for maintenance schedule, 4~5 is maintenance priority and >5 is immediate action. Te presented array and setup could provide condition monitoring of rail fleet to increase safety and reduce maintenance costs.



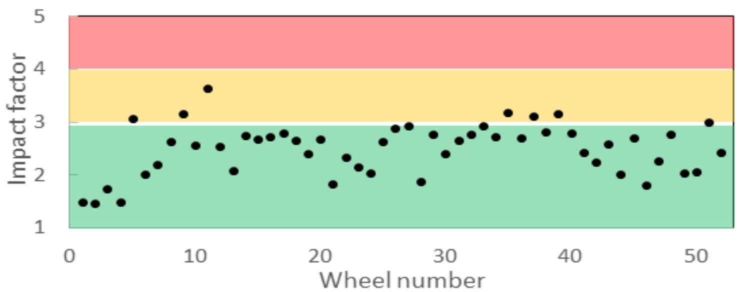


Figure 13

Converted results in impact factor (acceleration's unit is m/s^2, hence wheel number's is piece)

Conclusions

In this study, with the help of a field test, the results of two different strain gauge arrangements and accelerometer installation positions and their differences in measuring the dynamic force between the wheel and the rail were investigated and compared. In Iran's Mashhad railway station, the railroad track was instrumented for a field test, and the results were analyzed in two steps: 1) a light rail vehicle (drezin) with low weight and speed, and 2) a passenger train with relatively high axle load and speed. The results are summarized as follows:

"V" and "<" arrays were put to the test as half bridges for strain gauges. When there are only minor velocity changes, the "V" arrangement is practically velocity-independent.

The "V"-arrangement has an advantage because of its installation location, which causes less interference with track maintenance operations.

The "V" array showed lower error compared to the "<" array.

The results must be calibrated for various speed ranges. In contrast to the "<" array, the "V" array also demonstrated a decrease in velocity dependence with increasing velocity. Further research is required into the "V" array's dependence on the state and caliber of the track.

For the acceleration, the installed accelerometer on the sleeper showed lower noise and dependency to track dynamics, which will require less data preparation. The reason is the filtering phenomenon of the passing signal through rail pad and sleeper.

The presented arrays can be used for optimum condition monitoring of wheel-rail system.

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