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Statistical comparison of fleet types on track forces in Isfahan metro using field test data

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A B S T R A C T

The maintenance of a railway track in the urban rail fleet includes an intensive schedule of maintenance operations, which must be carried out by personnel during night time shift to ensure the safety of the system. Several factors affects the maintenance of a railway track, and a bulk of researches are also available in this regard. The impact of fleet type and design is one of these factors that has not been mentioned properly. The variety of the fleet types, always raises the challenges of determining effect the fleet type and its design on the track forces and maintenance costs. In general, the track forces can be classified into two categories: static (including vehicle and passenger load) and dynamic (including track and fleet defects, track irregularities, etc.). In this study, with the help of field test on an instrumented track, the forces from Pozhen and Dalian fleets in Isfahan metro were measured and compared. Static and dynamic forces were measured and the results were compared and analyzed. The preliminary results showed that the static and dynamic forces between the two types of fleets are statistically comparable. Also, the obtained results showed the effectiveness of the statistical comparison method based on the field data in order to check the performance of different fleets.

1. Introduction

The dynamic interaction between metro trains and railway tracks is a critical aspect of urban transportation systems. As metro networks expand to meet growing urban populations, understanding the dynamic loads imposed by trains on tracks becomes essential for ensuring safety, comfort, and longevity of infrastructure. These forces have several adverse effects, including track degradation, noise, and vibrations.

The dynamic loads accelerate track degradation by causing wear, fatigue, and plastic deformation. Wear occurs due to the repeated contact between wheels and rails, leading to material loss and changes in track geometry. Fatigue results from cyclic loading, which can cause cracks and fractures in rails and sleepers [1]. Plastic deformation, particularly in ballast and subgrade layers, leads to permanent track settlement, affecting alignment and stability [2].

Dynamic loads are also generating noise and vibrations, which are major concerns in urban environments. Noise arises from wheel-rail contact, particularly at irregularities such as joints and corrugations. Vibrations are transmitted through the track to the surrounding infrastructure, potentially causing discomfort to passengers and nearby residents [3]. Prolonged

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exposure to vibrations can also damage nearby buildings and structures [4].

The dynamic loads arise from various sources, including train speed, track irregularities, wheel-rail contact forces, and environmental conditions. These loads can be broadly categorized into train-related, track-related, and environmental factors.

Track-related factors include track geometry, stiffness, and irregularities. Track geometry, such as alignment and curvature, directly affects the distribution of dynamic loads. Misaligned tracks or sharp curves can cause uneven load distribution, leading to localized stress concentrations [5]. Track stiffness, which depends on the materials and construction methods used, influences how dynamic loads are transmitted to the underlying infrastructure. Stiffer tracks tend to distribute loads more evenly, while softer tracks may deform under heavy loads, exacerbating dynamic effects [4]. Track irregularities, such as rail corrugation, joints, and unevenness, are significant contributors to dynamic loads [6], [7]. These irregularities cause impact forces as the train wheels pass over them, leading to vibrations and noise. Research has shown that even minor irregularities can significantly increase dynamic loads, particularly at high speeds [3].

Environmental factors, such as temperature variations and moisture, also influence dynamic loads. Temperature changes cause thermal expansion and contraction of rails, leading to track buckling or gaps. These deformations create irregularities that increase dynamic loads [8] . Moisture, particularly in the form of rain or snow, affects the friction between wheels and rails. Reduced friction can lead to wheel slip and increased dynamic loads during braking or acceleration [9].

The train-related factors include speed, axle load, and suspension systems. As metro trains operate at high speeds in urban environments, the inertial forces generated by accelerating and decelerating trains significantly impact the track. Studies have shown that higher speeds increase the magnitude of dynamic loads, particularly at curves and transitions between straight and curved tracks [10]. Rail welds impacts have a linear relationship with train speed [11]. Axle load, also plays a crucial role. Heavier trains exert greater vertical and lateral forces on the track, leading to increased wear and failures [12].

The suspension system of a metro train is designed to absorb vibrations and reduce dynamic loads. However, poorly maintained or outdated suspension systems can amplify these loads. For instance, stiff suspension systems transmit more vibrations to the track, while softer systems may lead to excessive bouncing [13]. To address the challenges posed by dynamic loads, various mitigation strategies have been proposed and implemented. These strategies focus on improving train and track design, maintenance practices, and monitoring systems. Advances in train design, particularly in suspension systems, have significantly reduced dynamic loads. Modern metro trains are equipped with active suspension systems that adapt to track conditions in real-time, minimizing vibrations and impact forces [13]. Lightweight materials, such as aluminum and composite alloys, are also being used to reduce axle loads without compromising structural integrity [12]. However, these train optimizations mostly refer to improve a better performance for train without studying their effect on track. This study aims to compare effects of to different metro design on a metro track in similar operation condition. An instrumented track is used for data gathering and results are compared.

2. Test execution

The test was conducted in Isfahan subway line in Iran as it is shown in Figure 1. It also shows the instrumented track section. The instruments were installed on tangent line. Because of metro train operation nature, some parameters including speed, bogie normal function, axle load and etc. can be monitored accurately.

Figure 1. Test location in Isfahan city.

The designed arrangement for measuring wheel force including measuring static force using strain gauges and dynamic force using accelerometers are shown in Figure 2. A total of 5 accelerometers and a half-bridge array were used for the strain gauge to ensure the minimum accuracy of the results. In total, about 3 meters of track length is covered by the sensors so that the wheel circumference can be completely covered in this area once. Also, the data acquisition frequency should be sufficient and, given the frequent traffic of each wagon, the repeatability of the data can also be observed well. Table 1 and Table 2 show the technical specifications of the sensors used for measurement.

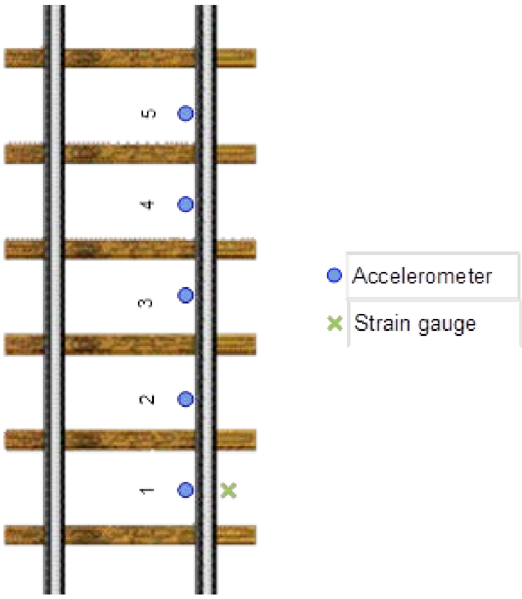
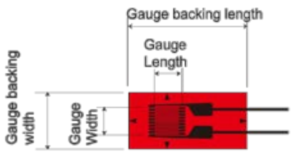


Figure 2. Sensors arrangement for measuring wheel forces.

Table 1. Technical specifications of TML straingauges model no. FLA-05-11.



		Applicable specimen	Metal, Glass, Ceramics
		Backing	Special plastics
		Operational temperature (°C)	-196 ~ +150°C
		Strain limit	5% (50000×10-6 strain)
		Fatigue life at room temperature	1×106 (±1500×10-6 strain)
Gauge width (mm)	1.2	Temperature compensation range (°C)	+10 ~ +100°C
Backing width (mm)	2.2	Applicable adhesive	CN, P-2, EB-2
Element	Cu-Ni	Gauge length (mm)	0.5
Backing length (mm)	5	Resistance (Ω)	120

Table 2. Technical specifications of accelerometers.

AC102-1A		MTN/P1100	
Sensitivity (±10%)	100 mV/g	Charge Sensitivity	1100 pC/g ±10% nominal at 80Hz
Frequency Response (±3dB)	0,5-15000 Hz	Capacitance	4000 pF nominal (4400 pF max.)
Frequency Response (±10%)	2,0-10000 Hz	Transverse Sensitivity	Less than 5%
Dynamic Range	± 50 g, peak	Mounted Base Resonance	10 kHz (nominal)
Settling Time	<2.5 seconds	Temperature Range	-55 to +250 ºC
Voltage Source	18-30 VDC	Dynamic Range	±100 g
Constant Current Excitation	2-10 mA	Isolation	Base non - isolated
Spectral Noise @ 10 Hz	14 µg/√Hz	Case Material	Stainless steel
Spectral Noise @ 100 Hz	2.3 µg/√Hz	Connector	T.N.C.
Spectral Noise @ 1000 Hz	2 µg/√Hz	Weight	250 gms (nominal)
Output Impedance	<100 ohm	Mounting	¼" -28 UNF female
Bias Output Voltage	10-14 VDC	Torque	8 Nm
Case Isolation	>108ohm	Sealing	IP65

For calibration, as it was not possible to test all the possibilities due to budget and timing, a drezin with known axle load was hired for system initial calibration and the calibration procedure including load and speed is described in Table 3.

Table 3. Calibration condition for drezin.

Test condition	Number of tests
Static test	2
Low speed passing	2
Operation speed passing	2

3. Test results

This section represents the data presentation and the results calculated from the measured data. At first the data should be pre-processed.

3.1. Data preparation

Strain gauge and accelerometer sensor data are different in nature and require different filters. For strain gauges, the data must first be sourced and then the noise in the signal needs to be removed using an averaging window of 50 points. One of the important noise factors in strain gauges is the presence of electricity in the rail when the train passes, which disrupts the ground connection of the strain gauges when the train passes. However, the noise created is white noise in nature.

3.2. Primary results

After data preparation, the time interval of the train passing and the passing of the wheels must be identified. This step also performs the train axle counting. Therefore, the passing wheels are automatically identified and the time interval of each wheel passing over the strain gauge and the covered area is determined according to Figure 3.

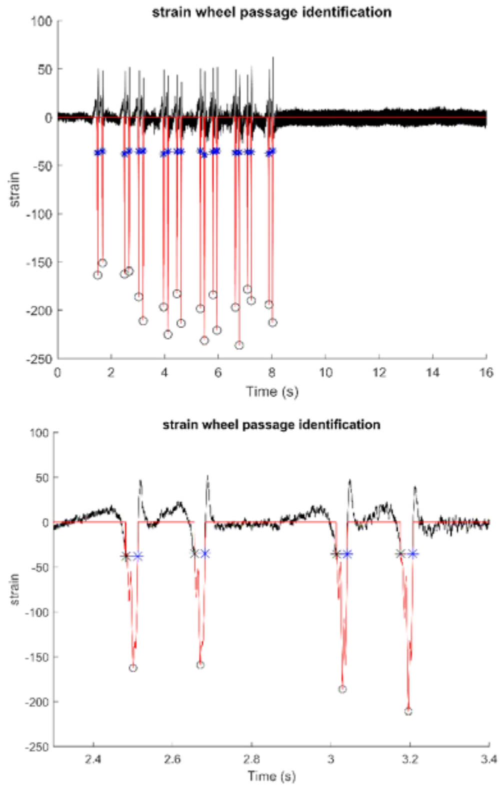
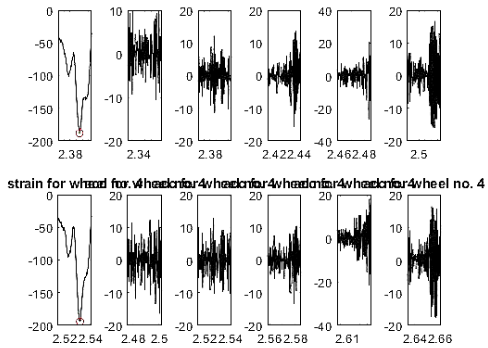


Figure 3. Wheel passage isolation.

By knowing the dimensions and distance of the train wheels from each other, the speed of each wheel can be calculated. The minimum and maximum speed values and the average speed are also calculated. Then the phase difference values of the acceleration signal are calculated according to the identification made in the strain gauge signal. This is important in determining the time of passage of each wheel over each accelerometer. Finally, the values of the strain gauge and accelerometers are determined for each passing wheel at the moment of passage. Some examples of the results are presented in Figure 4.



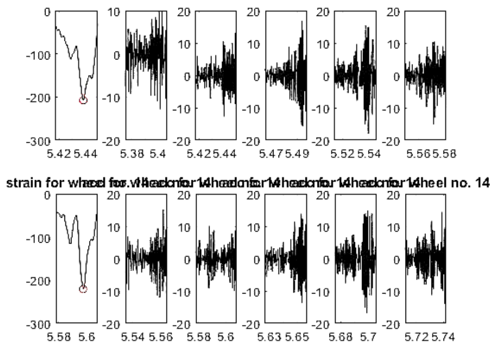


Figure 4. Wheel passage event.

The maximum acceleration value recorded during each wheel passage is the basis for the maximum dynamic force calculation. By knowing the maximum acceleration and strain values and the conversion function of the accelerometer and strain gauges, the static and dynamic force values are calculated. Figure 5 shows results for impact factor, static and dynamic measured loads for two trains as an example.

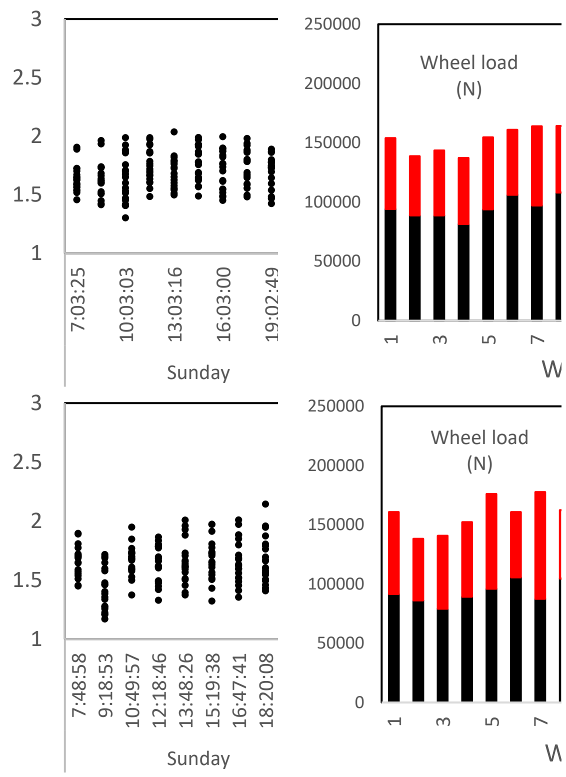


Figure 5. The example results of impact factor for all wheels from train no. 131 (up) and train no. 102 (down).

3.3.1. Descriptive Statistics

Table 4 presents the descriptive statistics for the two fleets type, Puzhen and Dalian. Puzhen's fleet consists of 1860 data points, while Dalian's fleet includes 640 data points. The mean values of Puzhen and Dalian impact factor are 1.6220 and 1.6257, respectively, indicating similar central tendencies. However, Dalian trains show higher variability with a larger standard deviation (0.2038 vs. 0.1861) and variance (0.0415 vs. 0.0346). The coefficient of variation is higher for Dalian's fleet (12.54%) compared to Puzhen (11.47%), indicating greater relative variability. The range is larger for Puzhen (1.5007) compared to Dalian (0.9487), suggesting more extreme outliers in Puzhen's fleet.

Figure 6 shows the histograms for both fleets, highlighting the distribution shape and variability. Puzhen's fleet displays a broader spread, while Dalian's fleet exhibits a more concentrated distribution around the mean. Figure 7 presents the box plots for both fleets, where Dalian's fleet shows a narrower interquartile range (IQR) but more extreme values at the upper end, while Puzhen's fleet shows a wider spread with more frequent outliers. These results indicate that while both fleets have similar central tendencies, Dalian's fleet is more variable, consistent with the higher standard deviation and coefficient of variation.

Table 4. Statistical parameters of the study.

Variable	Puzhen	Dalian	Variable	Puzhen	Dalian
Count	1860	640	Range	1.5007	0.9487
Mean	1.6220	1.6257	Median	1.6256	1.6041
Std. Dev.	0.1861	0.2038	Skewness	0.07	0.20
Variance	0.0346	0.0415	Kurtosis	0.49	-0.67
Coef. of Variation	11.47%	12.54%			

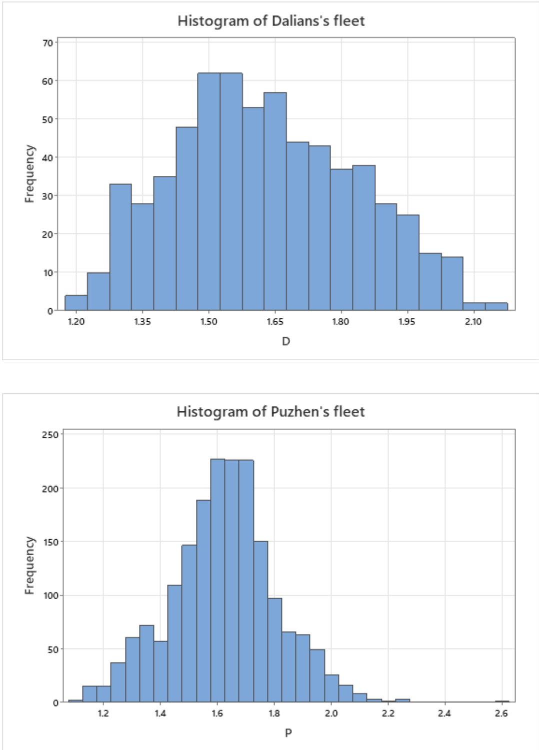
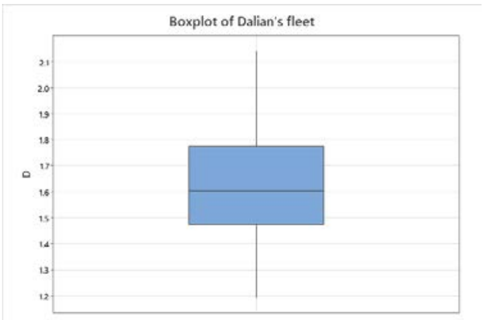


Figure 6. Impact factor histogram for the two types of studied fleet.

3.3.2. Mann-Whitney U Test

A normality test was conducted to determine if the data distribution of both fleets (Puzhen and Dalian) follows a normal distribution. The Anderson-Darling (AD) test results indicated that both datasets significantly deviate from normality at a 0.5% significance level (p-value < 0.005). Since the data were not normally distributed, the Mann-Whitney U Test was employed to compare the differences between the two fleets.



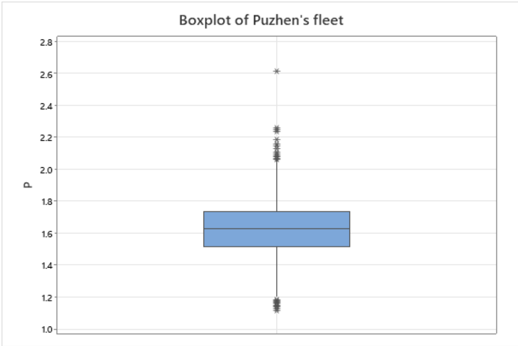


Figure 7. Impact factor histogram for the two types of studied fleet.

Table 5. Calculated P-value.

Method	P-Value
Not adjusted for ties	0.727
Adjusted for ties	0.727

6. Conclusions

In this study with the help of field test in Isfahan metro, the two types of fleet including Dalian and Puzhen are compared. the main aim of this study is to examine effects of different train type on track loading if the main parameters of trains are kept constant. Measured data from strain gauges and accelerometers are used to extract static and dynamic wheel load and the impact factor for all wheels of the passing trains. In order to compare the measured results in detailes, statistical analysis are employed.

The analysis reveals that fleets Puzhen and Dalian have similar central tendencies but different variability patterns. Fleet Puzhen shows greater deviation from normality and more pronounced outliers, while Dalian exhibits more consistent but slightly skewed behavior. Despite these differences, the Mann-Whitney U test confirms that the medians of Puzhen and Dalian are not statistically different at the 5% significance level.

References

For journal papers, books and conferences papers use the following formats;

[1] G. N. Haidemenopoulos, A. D. Zervaki, P. Terezakis, J. Tzanis, A. E. Giannakopoulos, and M. K. Kotouzas, “Investigation of rolling contact fatigue cracks in a grade 900A rail steel of a metro track,” Fatigue Fract. Eng. Mater. Struct., vol. 29, no. 11, pp. 887–900, Nov. 2006, doi: 10.1111/j.1460-2695.2006.01048.x.

[2] B. Indraratna, W. Salim, and C. Rujikiatkamjorn, Advanced Rail Geotechnology – Ballasted Track, 2nd ed. London: CRC Press, 2023. doi: 10.1201/9781003278979.

[3] D. J. Thompson, D. Thompson, C. J. C. Jones, and P.-E. Gautier, Railway noise and vibration: mechanisms, modelling and means of control. Amsterdam Boston: Elsevier, 2009.

[4] G. Kouroussis, O. Verlinden, and C. Conti, “A two-step time simulation of ground vibrations induced by the railway traffic,” Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci., vol. 226, no. 2, pp. 454–472, Feb. 2012, doi: 10.1177/0954406211414483.

[5] G. Kouroussis, D. P. Connolly, and O. Verlinden, “Railway-induced ground vibrations – a review of vehicle effects,” Int. J. Rail Transp., vol. 2, no. 2, pp. 69–110, Apr. 2014, doi: 10.1080/23248378.2014.897791.

[6] M. Naeimi, J. A. Zakeri, M. Esmaeili, and M. Shadfar, “Influence of uneven rail irregularities on the dynamic response of the railway track using a three-dimensional model of the vehicle–track system,” Veh. Syst. Dyn., vol. 53, no. 1, pp. 88–111, Jan. 2015, doi: 10.1080/00423114.2014.998243.

[7] M. Naeimi, J. Ali Zakeri, M. Shadfar, and M. Esmaeili, “3D dynamic model of the railway wagon to obtain the wheel–rail forces under track irregularities,” Proc. Inst. Mech. Eng. Part K J. Multi-Body Dyn., vol. 229, no. 4, pp. 357–369, Dec. 2015, doi: 10.1177/1464419314566833.

[8] Y. Guo, Z. Yu, and H. Shi, “Effects of rail thermal stress on the dynamic response of vehicle and track,” Veh. Syst. Dyn., vol. 53, no. 1, pp. 30–50, Jan. 2015, doi: 10.1080/00423114.2014.973420.

[9] B. White et al., “Effect of the presence of moisture at the wheel–rail interface during dew and damp conditions,” Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit, vol. 232, no. 4, pp. 979–989, Apr. 2018, doi: 10.1177/0954409717706251.

[10] W. Zhai, K. Wang, and C. Cai, “Fundamentals of vehicle–track coupled dynamics,” Veh. Syst. Dyn., vol. 47, no. 11, pp. 1349–1376, Nov. 2009, doi: 10.1080/00423110802621561.

[11] M. Shadfar, H. Molatef, and A. Nasr, “An Index for Rail Weld Health Assessment in Urban Metro Using In-Service Train”.

[12] J. C. O. Nielsen and A. Igeland, “VERTICAL DYNAMIC INTERACTION BETWEEN TRAIN AND TRACK INFLUENCE OF WHEEL AND TRACK IMPERFECTIONS,” J. Sound Vib., vol. 187, no. 5, pp. 825–839, Nov. 1995, doi: 10.1006/jsvi.1995.0566.

[13] M. Yu, S. A. Evangelou, and D. Dini, “Advances in Active Suspension Systems for Road Vehicles,” Engineering, vol. 33, pp. 160–177, Feb. 2024, doi: 10.1016/j.eng.2023.06.014.