



ANALYSIS ON INFLUENCE OF STATIC CALIBRATION ON THE AXLE-GROUP WEIGH-IN-MOTION SYSTEM ACCURACY

Lai Zhengchuang^{1,2}, Yang Xiaoxiang^{1,3}, Yao Jinhui^{1,2}

¹ College of Mechanical Engineering and Automation, Fuzhou University, Fuzhou, China, lzcjjl@126.com

² Fujian Key Laboratory of Force Measurement (Fujian Institute of Metrology), Fuzhou, China, lzcjjl@126.com

³ Quanzhou Normal University, Quanzhou, China, yangxx@fzu.edu.cn

Abstract:

The axle-group weigh-in-motion system has two functions: static weighing and dynamic weighing. According to the weighing model, the accuracy of dynamic weighing is affected by the static performance. This paper analyses the size of various factors affecting the static performance, such as sensor tilt installation, platform deformation, platform tilt installation, and these errors will lead to sensor swing, bearing head tilt, gravity line of action and sensor axis direction is not consistent, thus affecting the static weighing accuracy. However static calibration is the best way to reduce or even eliminate the above errors. The dynamic truck scale of different manufacturers with or without static calibration is used in the test process. The results show that the dynamic performance index can meet the requirements only after the static calibration is used.

Keywords: Static Calibration; Axle-Group weigh-in-motion; Dynamic Weighing; Weighing Accuracy

1. INTRODUCTION

The Axle-Group weigh-in-motion system consists of static truck scale platform and dynamic weighing technology, mainly including load carrier (scale platform), strain type weighing sensor, junction box and weighing instrument [1]. Its quality model can be expressed as follows:

$$y(t) = W + \sum_i A_i \sin(W_i t + \vartheta_i) \quad (1)$$

where W is the weighing value and A_i , W_i and ϑ_i are the amplitude, frequency and phase of interference signal. W is the basis of dynamic weighing data and determines the basic weighing accuracy. Its model is expressed as:

$$W = k_{n_v}, \quad W_s = k_{n_v} \cdot \left(\sum_{i=1}^N \omega_i m_i \right) \quad (2)$$

where N is the number of support points, m_i is the load value (kg) allocated to each load cell in the static mode and ω_i the weight coefficient allocated to each load cell. n_v is the running speed and k_{n_v} is the quality conversion coefficient between the static part and the dynamic part based on the data processing algorithm in the n^{th} running speed. W_s is the static weighing data and also the only parameter that can control the error in the calibration process of the above model, which plays an important role in the accuracy of the dynamic weighing instrument. Therefore, the static weighing performance needs to be guaranteed in the calibration.

According to the full-bridge method of tension and compression elastic elements, theoretically the output strain value of the sensor is only related to the magnitude of the axial force F_n along the strain direction of the elastic body axis, and is not related to the tangential force and the additional bending moment generated by the tangential force F_t [2]. The relative error of the measurement is:

$$e = \frac{F_n - F_N}{F_N} = \cos(\alpha_1 + \alpha_2 + \alpha_3) - 1 \quad (3)$$

$$(i = 1, 2, 3, 4)$$

where α_1 is the inclination angle of the upper indenter, α_2 is the inclination angle of the sensor strain elastomer axis and α_3 is the angle between the external force direction and the axis of the upper indenter.

2. ANALYSIS OF THE FACTORS INFLUENCING THE ACCURACY OF STATIC WEIGHING

2.1. The Impact of the Tilt Installation of the Column Load Cell on the Weighing Accuracy

The axle group dynamic truck scale supported by four points is selected as the research object. When the supported sensors have different angles of

rotation, the weighing platform has a horizontal frictional force on the sensors, as shown in Figure 1. The sensor strains the elastomer to roll purely between the upper and lower indenters, taking the contact point when the elastomer is not deflected as the reference point, and when the elastomer deflects by angle α_{21} , the horizontal displacement of the upper indenter can be expressed as follows.

$$S_{21} = 2R\alpha_{21} - (2R - h) \sin \alpha_{21} \quad (4)$$

where α_{21} is the inclination of the axis of the strained elastomer and S_{21} is the horizontal displacement of the contact point caused by the deflection of the elastomer. Meanwhile, there is the following geometric relationship:

$$OH = (2R - h) \sin \alpha_{21} \quad (5)$$

$$HK = 2R - (2R - h) \cos \alpha_{21} \quad (6)$$

Assume that the two sensors on the left have equal installation angles and the two sensors on the right are equal. When the deflection angle of the elastomer is small, the rolling friction resistance is less than the maximum rolling friction resistance couple, and the weighing platform does not produce translation, so the friction force of the weighing platform against the elastomer is zero. When the inclination of the elastomer is greater than the critical angle, the weighing platform has a tendency to move in translation under the action of the restoring force, and the weighing platform generates friction against the elastomer. Suppose the initial angular displacements during installation are α_{01} and α_{02} , respectively, and the state after loading is shown in Figure 1.

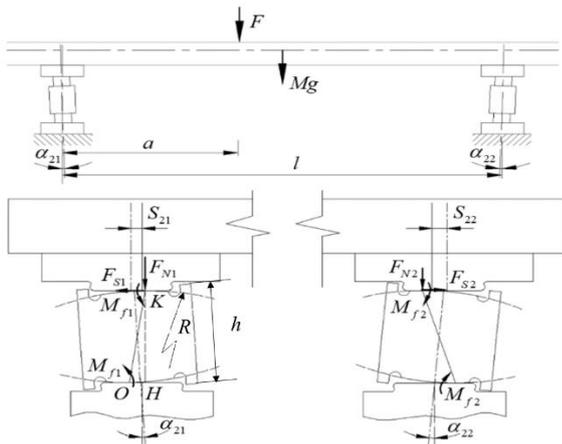


Figure 1: Supporting structure diagram of tilt installation of column load cell

Taking the force direction shown in Figure 1 as the positive direction. According to the moment balance relationship between the elastomer and the support point O, we can obtain:

$$F_{N1}(2R - h) \sin \alpha_{21} - 2M_{f1} - F_{S1}[2R - (2R - h) \cos \alpha_{21}] = 0 \quad (7)$$

$$F_{N2}(2R - h) \sin \alpha_{22} - 2M_{f2} - F_{S2}[2R - (2R - h) \cos \alpha_{22}] = 0 \quad (8)$$

$$F_{S1} = F_{S2} \quad (9)$$

with $F_{N1} = 0.25Mg + 0.5F(l - a)/l$ and $F_{N2} = 0.25Mg + 0.5Fa/l$. When the angle is small, $\cos \alpha_{21} = \cos \alpha_{22} \approx 1$.

The deflection of the elastomer causes the horizontal displacement of the elastomer and the left and right reference points of the weighing platform to be equal.

$$S_{21} - S_{01} = -(S_{22} - S_{02}) \quad (10)$$

S_{01} and S_{02} are the horizontal displacement of the reference point caused by the sensor deflection during initial installation.

When the initial installation tilt angle is satisfied: $(R - 0.5h) \sin \alpha_{01} \leq \delta$ and $(R - 0.5h) \sin \alpha_{02} \leq \delta$, the torque on the elastomer is not enough to overcome the rolling friction couple, and the weighing platform does not produce friction.

When the inclination angle of the sensor on one side is greater than the critical angle, the elastomer has a rolling tendency, and the weighing platform generates horizontal frictional force. The value and direction of the rolling friction couple on both sides of the elastomer depend on the rolling tendency.

Suppose that the inclination angle of the right elastomer satisfies: $(R - 0.5h) \sin \alpha_{02} > \delta$, and the load is continuously increased, so that the rolling friction of the elastic bodies on both sides reaches the maximum rolling frictional couple, that is, $M_{f2} = \delta F_{N2}$. When the torque is greater than the maximum rolling friction couple, the elastomer will turn to the left until a new equilibrium state is formed. At this time, the rolling friction of the elastic bodies on both sides is equal to the maximum rolling friction couple. From equations (7)-(9), we can obtain:

$$F_{S2} = \frac{2F_{N2}[(R - 0.5h) \sin \alpha_{22} - \delta]}{h} \quad (11)$$

$$(R - 0.5h)(F_{N1} \sin \alpha_{21} - F_{N2} \sin \alpha_{22}) + \delta(F_{N2} + F_{N1}) = 0 \quad (12)$$

$$(2R - h)(\sin \alpha_{21} + \sin \alpha_{22} - \sin \alpha_{01} - \sin \alpha_{02}) = 2R(\alpha_{21} + \alpha_{22} - \alpha_{01} - \alpha_{02}) \quad (13)$$

We can obtain the value of rotation angle of elastomer α_{21} and α_{22} by simultaneous equations (12) and (13).

According to the above inference, we found that the rotation angle of the elastomer has nothing to do with their respective inclination angles before being loaded but is related to the sum value of the inclination angles. During the loading process, the sum of the inclination angles remains unchanged.

When the sensor elastomer generates the above-mentioned rotation angle, the relative error magnitude of the weighing result of each sensor can be obtained by equation (3). After loading, the inclination of the elastomer will not restore the state before loading and will affect the subsequent weighing. In addition, the presence of friction also reduces the weighing value.

2.2. Deformation of the Weighing Platform Affect on the Weighing Accuracy

If the rigidity of the weighing platform is small, and the external load is large, the weighing platform will produce excessive deformation. This deformation will cause the angular displacement of the elastomer and affect the weighing accuracy, as shown in Figure 2.

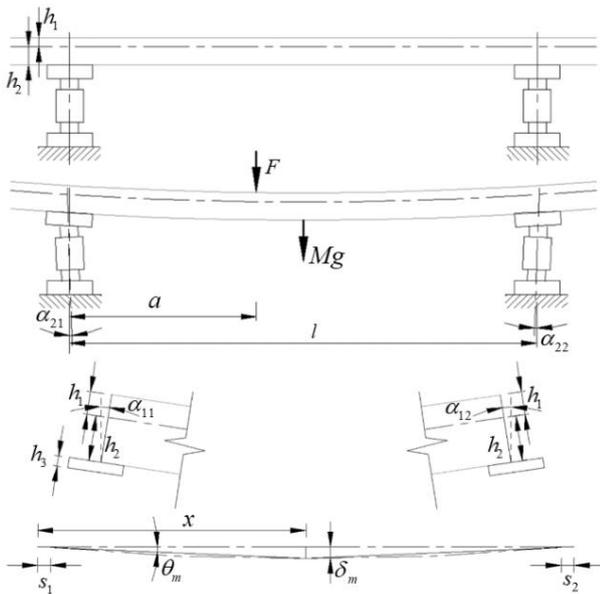


Figure 2: Schematic diagram of load-bearing deformation of weighing platform

When the weighing platform is loading, the distance between the contact points of the elastic bodies on both sides changes due to the deformation of the weighing platform, and the elastic bodies on both sides will deflect in the opposite direction.

When the rotation reaches equilibrium, the contact point of the elastomer reaches the maximum rolling friction couple, as shown in Figure 3. According to the loading and deformation process

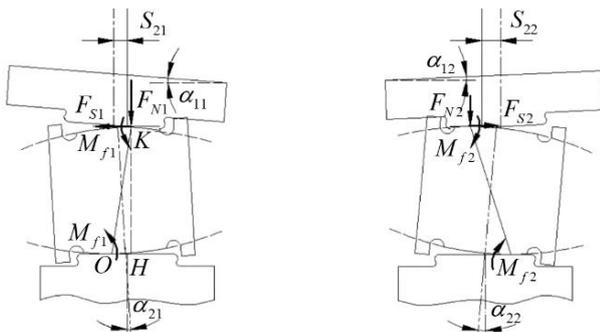


Figure 3: Loading model of column load cell when the weighing platform is deformed

of the weighing platform, the direction of the rolling friction of the elastomer is the opposite direction when the figure is $0 < a < l/2$, and the direction is the same as the figure when $l/2 < a < l$.

According to the moment balance relationship of the elastomer to the fulcrum O, we can obtain:

$$F_{N1}[(2R - h) \sin \alpha_{21} + R \sin \alpha_{11}] - 2M_{f1} - F_{S1}h = 0 \quad (14)$$

$$F_{N2}[(2R - h) \sin \alpha_{22} + R \sin \alpha_{12}] - 2M_{f2} - F_{S2}h = 0 \quad (15)$$

$$F_{S1} = F_{S2} \quad (16)$$

The bending deformation of the neutral layer of the weighing platform reduces the horizontal distance of the neutral axis position of the original support point cross section by $s_1 + s_2$. According to the displacement relationship of the initial contact point, a supplementary equation is obtained.

$$2R(\alpha_{21} + \alpha_{22}) - (2R - h)(\sin \alpha_{21} + \sin \alpha_{22}) = (h_2 + h_3)(\sin \alpha_{11} + \sin \alpha_{12}) - (s_1 + s_2) \quad (17)$$

From equations (14)-(17), the relationship between the angle of the elastomer and the magnitude and position of the load can be obtained.

Treat the weighing platform as a simply supported beam supported on both sides. Ignore the initial deformation of the weighing platform and the rolling friction couple of the elastomer.

$$\begin{cases} \delta_m = \frac{Fa(2al - a^2)^{3/2}}{9\sqrt{3}lEI} & (0 \leq a \leq \frac{l}{2}) \\ \delta_m = \frac{F(l - a)(l^2 - a^2)^{3/2}}{9\sqrt{3}lEI} & (\frac{l}{2} \leq a \leq l) \end{cases} \quad (18)$$

$$\begin{cases} \alpha_{11} = \frac{F(l - a)(2al - a^2)}{6lEI} & (0 \leq a \leq \frac{l}{2}) \\ \alpha_{11} = \frac{F(l - a)(l^2 - a^2)}{6lEI} & (\frac{l}{2} \leq a \leq l) \end{cases} \quad (19)$$

$$\begin{cases} \alpha_{12} = \frac{Fa(2al - a^2)}{6lEI} & (0 \leq a \leq \frac{l}{2}) \\ \alpha_{12} = \frac{Fa(l^2 - a^2)}{6lEI} & (\frac{l}{2} \leq a \leq l) \end{cases} \quad (20)$$

$$\begin{cases} x = l - \sqrt{\frac{l^2 - a^2}{3}} & (0 \leq a \leq \frac{l}{2}) \\ x = \sqrt{\frac{l^2 - (l - a)^2}{3}} & (\frac{l}{2} \leq a \leq l) \end{cases} \quad (21)$$

$$\theta_m = \arcsin \frac{\delta_m}{x} \quad (22)$$

$$s_1 = x(1 - \cos \theta_m) \quad (23)$$

$$s_2 = (l - x)(1 - \cos \theta_m) \quad (24)$$

where δ_m is the maximum deflection of the weighing platform, EI is the bending stiffness of the weighing platform beam, l is the supporting length of the weighing platform, a is the horizontal distance from the load to the left end support point, x is the horizontal distance from the position of δ_m to the left end support point, s_1 is the left side horizontal displacement of the neutral layer at the cross section of the supporting point, s_2 is the horizontal displacement of the neutral layer at the cross section of the right supporting point.

As can be seen from Figure 4, when the load begins to move away from the support point, the inclination angle of the upper head increases, and decreases slowly when approaching the centre, and quickly decreases to zero after passing the centre.

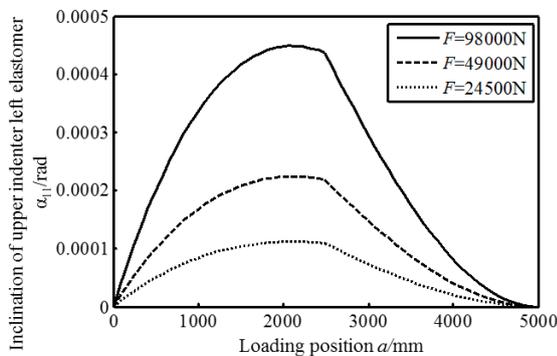


Figure 4: Curve of inclination of upper indenter on left elastomer

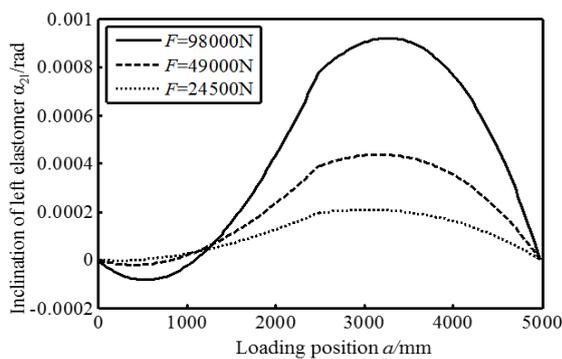


Figure 5: Curve of left elastomer inclination

As can be seen from Figure 5, when the load begins to move away from the support end, the elastomer of the support end deflects to the right by a small angle first, and then deflects to the left. The extreme point is on the other side of the midpoint, and then decrease to zero. At the same time, the greater the load, the greater the tilt angle of the upper head and the outward rotation angle of the sensor elastomer. When the sensor elastomer generates the above-mentioned rotation angle, the relative error magnitude of the weighing result of each sensor can be obtained by equation (3).

2.3. The Influence of Tilting Installation of Weighing Platform on the Weighing Accuracy

When the weighing platform is installed obliquely, the gravity of the weighing platform to the column load sensor will deviate from the axis direction of the strained elastomer. Due to the rolling friction between the strained elastomer and the upper and lower indenters, the strained elastomer will change from a static state to a rolling state as the tilt angle of the weighing platform increases, as shown in Figure 6.

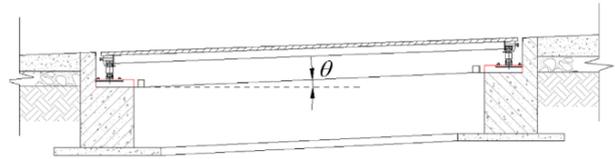


Figure 6: Weighing platform tilt installation

When the tilt angle of the weighing platform exceeds the critical angle, the moment of the weighing platform against the gravity of the sensor exceeds the maximum rolling friction of the elastomer, and the elastomer produces a tilt angle. The tilt angle of the elastomer is approximately linearly related to the tilt angle of the weighing platform. Under the same tilt angle of the weighing platform, the greater the height of the elastomer, the smaller the radius of the ball head, and the greater the tilt angle of the elastomer. When the sensor elastomer produces the above-mentioned rotation angle, the relative error magnitude of the sensor weighing result can be obtained from equation (3).

In addition, the elevation difference of the sensor installation and the non-linear characteristics of the sensor itself have an influence on the result of the weighing.

3. THE CALIBRATION SITUATION OF AXLE GROUP WIM SYSTEM

In section 2, we analysed the main factors affecting the weighing accuracy, such as tilt installation of the column load cell, stiffness and tilting installation of the weighing platform, the elevation difference of the sensor installation and the non-linear characteristics of the sensor itself. These influencing factors will cause the output of the WIM system to show obvious nonlinearity, as shown in Figure 7. Line 1 is the ideal output of WIM, line 2 is the output after static calibration, line 3 is the output before static calibration. According to equations (1) and (2), W_s is the static weighing value, which affect the dynamic output directly. Therefore, it is necessary to carry out static calibration to ensure static accuracy, in order to ensure the results of dynamic weighing.

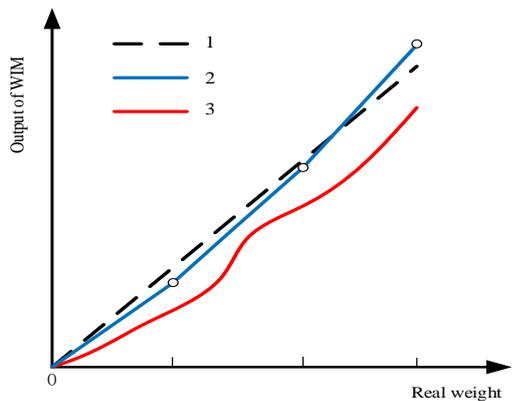


Figure 7: Principle of static calibration influence on dynamic accuracy

4. EXPERIMENT

In order to verify the effect of static calibration on the dynamic weighing results. Three different manufacturers' axle group weigh-in-motion instruments (factory A, factory B, factory C) were selected to be calibrated by means of three methods respectively.

First method: without any static calibration method (no calibration). Second method: Only using the reference vehicle calibrate the total weight of the tested weighing instrument (single-point calibration). Third method: The static calibration of full scale and full performance are carried out by Load Measurement Apparatus according to regulations (static full-scale calibration), as shown in Figure 8.

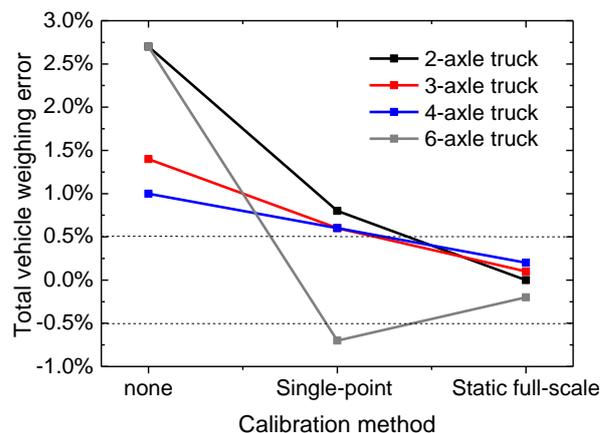


Figure 8: Static calibration test

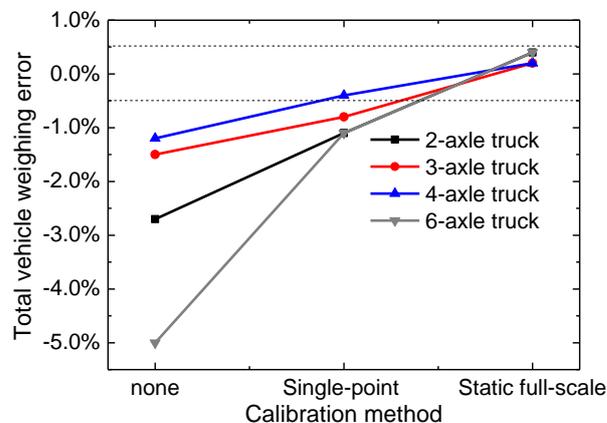


Figure 9: Dynamic weighing test

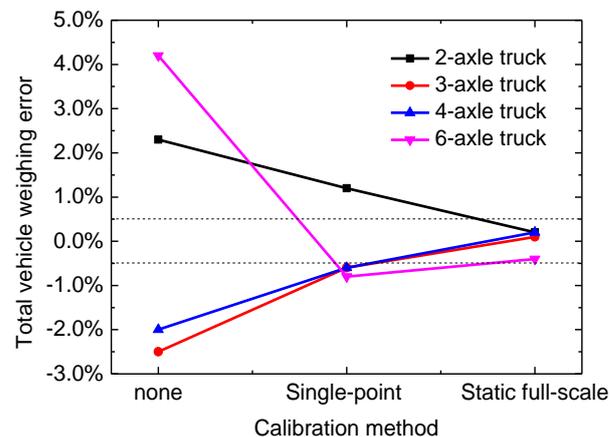
After static calibration, we chose 2-axle rigid, 3-axle rigid, 4-axle articulated trailer and 6-axle articulated trailer at a speed of 5 km/h to test the dynamic weighing result, as shown in Figure 9.



(a)



(b)



(c)

Figure 10: Test results of dynamic weighing; (a) test result of factory A, (b) test result of factory B, (c) test result of factory C

The testing result of the three manufacturers' axle group weigh-in-motion are shown in Figure 10 (a), (b) and (c). It can be seen from Figure 10, only when the static measurement performance fully meets the requirements of medium accuracy truck scales, the error of the dynamic part is (+0.1 ~ +0.4) %, it can meet the legal error of

$\pm 0.5\%$. If any index of partial load or weighing fails in the static measurement performance, the error of the dynamic part is $(-5.0 \sim +4.2)\%$, which far exceeds the legal maximum allowable error of $\pm 0.5\%$, and cannot meet the level 1 dynamic road vehicle requirements for automatic weighing instruments.

5. SUMMARY

There are many factors that affect the static weighing accuracy of the axle group weigh-in-motion system, including sensor tilt, scale platform deformation, scale platform tilt sensor height difference and other factors, and the static weighing data is the decisive data of the dynamic weighing accuracy. When dynamic verification is carried out, the static performance calibration must be carried out first. The test data show that the accuracy of dynamic weighing can meet the error requirements of regulations only when all indexes of static performance meet the requirements.

6. REFERENCES

- [1] R. Bajwa, E. Coleri, R. Rajagopal, P. Varaiya, C. Flores, "Development of a cost-effective wireless vibration weigh-in-motion system to estimate axle weights of trucks", *Computer-Aided Civil and Infrastructure Engineering*, vol. 32, no. 6, pp. 443-457, 2017.
- [2] J. Richardson, S. Jones, A. Brown, E. O'Brien, D. Hajjalizadeh, "On the use of bridge weigh-in-motion for overweight truck enforcement", *International Journal of Heavy Vehicle Systems*, vol. 21, no. 2, pp. 83-104, 2014.
- [3] A. T. Papagiannakis, "Calibration of weigh-in-motion systems through dynamic vehicle simulation", *Journal of Testing and Evaluation*, vol. 25, no. 2, pp. 197-204, 1997.
- [4] U. Sonmez, N. Sverdlova, R. Tallon, D. J. Klinikowski, D. Streit, "Static calibration methodology for weigh-in-motion systems", *International Journal of Heavy Vehicle Systems*, vol. 7, no. 2-3, pp. 191-204, 2000.
- [5] P. Lou, H. Nassif, D. Su, P. Truban, "Effect of overweight trucks on bridge deck deterioration based on weigh-in-motion data", *Transportation Research Record*, vol. 2592, pp. 86-97, 2016.