Design and Prototyping of Weigh-In-Motion and Overload Detection System for Freight Vehicle

A H Masyhur¹, I P Nurprasetyo¹, B A Budiman¹,² and T P B Utomo¹

¹ Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Bandung, Indonesia
² National Center for Sustainable Transportation Technology, Institut Teknologi Bandung, Bandung, Indonesia

E-mail: hakim@ftmd.itb.ac.id, ipn@ftmd.itb.ac.id

Abstract. The high number of freight vehicles that exercised overloading in Indonesia has led to a significant reduction in the quality of road pavement. The obsolete overload detection system using weigh bridges have been ineffective, since it requires vehicles to maneuver and enter the weighing station. In the above system, after manual checking, overloaded vehicles will be penalized. The Weigh-in-Motion (WIM) device that is developed in this research utilized a bending plate sensor with strain gage. As overloaded vehicle runs over the WIM, axle weight will be automatically recorded, and the data is processed further to assess the compliance to maximum freight weight as specified for the vehicle. In this research work, the WIM prototype is developed and tested using motorcycle under normal operation and overloaded conditions at different speeds. Arduino based signal processing and analysis system has been developed such that the overload detection may be performed automatically. When the system senses an overloaded vehicle, it will automatically trigger the alarm and a camera will capture the vehicle. The error of the prototype is within acceptable range and the system has shown the potential to detect whether the vehicle, i.e., the motorcycle, is overloaded or not. As a continuation, the development of a reliable microcontroller-based WIM and a robust automatic overloaded freight vehicle will be our future work.

1. Background

Maintaining road pavement quality in several areas in Indonesia is essential since logistic distribution is mainly carried using land transportation. Based on Indonesian Minister of Public Works Regulation, the design service lifetime for main road in Indonesia is at least ten years, while for local road is about five years [1]. However, the quality of road pavement of most main road in Indonesia have been deteriorated before it reaches the design lifetime. This condition also causes the road maintenance cost to increase significantly [2]. Huge traffic of overloaded vehicle on the road is the main cause why the road pavement quality decrease faster than the expected lifetime. Wang et.al findings show that every 1% of overload in trucks would cause 1.8% reduction of road lifetime [3].

Weight measurement especially for truck becomes an important activity in order to prevent road damage and reduce the risk of road accident occurred due to overloaded vehicle [4]. Weighbridge is a common method that has been applied in Indonesia for measuring the total weight carried by a freight vehicle. However, this method has a drawback since the vehicle weight is measured in static condition. It is very difficult to weigh all commercial vehicles while it should stop by the weighing station, since
it could create congestion at the station. Based on this issue, a method called Weigh-in-Motion (WIM) is developed. The main strategy of WIM is to predict total weight of the vehicles by measuring the dynamic tire forces exerted by the wheels to the sensors on the ground. This method enables the weight measurement to be carried out while the vehicle is still moving.

In this research, a simple WIM device with overload detection system is developed. As a case study, the prototype is implemented to two-wheeler or motorcycle. The WIM prototype is based on bending plate – strain gage sensors, while the overload detection system is developed using Arduino microcontroller with the addition of alarm and camera connection.

2. Methodology

2.1. Bending Plate Design

There are three types of weight sensors that is commonly used for WIM application, i.e., piezoelectric, bending plate, and load cell. In this research, bending plate device using strain gage sensor is chosen after considering several aspects. Bending plate device is relatively easier to be designed and manufactured. In addition, obtaining strain gage in the market is also relatively easy as compared with the other two sensors.

The ideal position for the bending plate sensor should be in the road pavement to ensure level surface between the sensor and the road. However, due to location constraint, the bending plate will be placed over the road pavement. Wood panels with similar thickness and width with the bending plate is attached in order to compensate the effect of level difference between the plate and road surface that could produce sudden change in vertical acceleration while the vehicle passes through the plate. The layout of the testing rig is depicted in Figure 1.

The plate is made from low carbon steel. Coating treatment is applied to the plate surface in order to avoid corrosion.

![Figure 1. Testing rig layout](image)

Strain gage is attached at the bottom surface of the bending plate. The location of the strain gage should be in the middle of the plate and its orientation should be in parallel with vehicle direction of movement as illustrated in Figure 2. Since only one strain gage is used, the vehicle’s rider should ensure the vehicle tires make a contact with the bending plate at the point over where the strain gage is placed, such that it could reduce reading error by the WIM system.
In this bending plate system, the strain which is occurred at the plate by tire’s contact is converted into electrical voltage signal. Then, this signal is processed until the total weight of the vehicle is known and could be saved in the computer. The block diagram for WIM signal processing unit is shown in Figure 3.

![Block diagram for WIM signal processing unit](image)

**Figure 3.** Block diagram for WIM signal processing unit

2.2. Overload Detection System

The overload detection system is also developed in this research, such that the overloaded vehicle could be identified within a few seconds. This system utilizes the signal data that comes from the bending plate which is combined with the application of alarm and camera using Arduino Uno as a microprocessor. The microcontroller receives signal from the strain gage that has been amplified by the HX711 strain amplifier module. The alarm will be triggered once the system detects an overloaded vehicle and the camera will capture the picture of the vehicle including its identity. Figure 4 illustrates the block diagram for the overload detection system, while Figure 5 shows the position layout for each component of the system. In this case, the overloaded vehicle is defined as a motorcycle occupied by three passengers.
3. Analysis and Discussion

3.1. Static calibration
In order to obtain relation between exerted force to the bending plate as an input and output voltage, static calibration should be conducted first. The calibration process is carried out by measuring the weight distributed at the motorcycle’s front and rear tires in static condition. Three types of motorcycle with different curb weights are used for benchmarking. Variation of the data is also obtained by adding one passenger for each vehicle. Table 1 shows the weight data during static calibration.

| Motorcycle type | Without Passenger [kg] | With Passenger [kg] |
|-----------------|------------------------|---------------------|
|                 | Front                  | Rear                | Front  | Rear    |
| Type A          | 47                     | 67                  | 70     | 103     |
| Type B          | 37                     | 55                  | 63     | 88      |
| Type C          | 63                     | 71                  | 79     | 114     |
From the static calibration process, it is discovered that the relation between vehicle weight \( m_k \) and output signal from the bending plate \( V_S \) is linear with positive slope. Equation (1) as shown below can then be determined using simple regression method. The quality of the curve fitting is depicted in Figure 6.

\[ V_S = 0.0053m_k \]  

![Graph showing the linear relationship between weight and output signal](image1)

**Figure 6.** Static calibration result of the bending plate

### 3.2. Dynamic testing experiment

A straight path with distance of 30 m is set to be the lane for dynamic testing experiment. The WIM prototype is placed 20 m beyond the start line. The condition of road pavement for the testing lane is relatively flat and the testing is carried out by using single type of motorcycle with one passenger.

Three different speeds are chosen for reference, which are 10 km/h, 20 km/h, and 30 km/h. Each speed is repeated 30 times to satisfy statistic requirement. Speed variation occurred during the tests since the rider tends to maintain the speed manually. Figure 7 shows the box plot of the vehicle speed during the dynamic test. It can be seen that the variation of the speed is not significant which can be neglected in the next analysis.

![Box plot of speed variation during dynamic testing](image2)

**Figure 7.** Box plot of speed variation during dynamic testing
3.3. Noise reduction

Figure 8 illustrates a sample of the signal obtained during dynamic test for the WIM system. The signal is in the form of time series of the voltage coming from the HX-711 strain amplifier. It may be observed that there are two peaks with different values. The peak on the left, with lower maximum value than other peak, indicates the contact signal from the front tire, and the other peak appears as the rear tire make a contact with bending plate.

![Figure 8. Output signal from WIM dynamic testing](image)

The signal that is obtained from the data acquisition comes with high frequency noise with stable frequency. Averaging method is selected to reduce the noise level, considering its simplicity and effectiveness to remove harmonic effect in the signal [5]. The method is done by accumulating and divide the number of signals used in order to get the value of arithmetic average that can be written as in equation (2).

\[
AM = \frac{1}{n} \sum_{i=1}^{n} a_i
\]  

(2)

In this research, adjustment should be included in the averaging method in order to limit the amount of data that is used in this experiment. Sample signal that consist of noise only is separated with output signal. Then, the noise signal is translated in the time domain until the phase difference between noise signal and output signal is close to zero. Final result of the new output signal is obtained by subtracting the original output signal with noise signal after averaging, which is shown in Figure 9.
3.4. Vehicle speed correction factor

Vehicle speed data is required during testing and analysis. In testing process, group of data is decided based on vehicle speed, and vehicle speed correction factor should be determined in analysis process. The true vehicle speed is calculated by dividing vehicle wheelbase \( L_{\text{base}} \) with time difference \( \Delta t \) between the starting time of two peak signal coming from front and rear tire.

Measurement result from the bending plate for similar vehicle in dynamic testing are different from static test measurement. The condition of uneven road surface creates sudden acceleration in vertical direction. Change in acceleration and deceleration during dynamic testing contributes to the change of weight distribution at the axle for each wheel.

Different speed input also gives different output response both for front and rear tire as illustrated in Figure 10. Higher speed will have smaller signal amplitude that is probably caused by greater time constant in the bending plate and strain gage. The signal has not reach maximum amplitude or yet to be in steady state condition after the vehicle makes a contact with the bending plate in higher speed.

Equation (1) could be used to convert voltage signal output into weight value. However, additional variable is needed as correction factor due to effect given by vehicle speed to the output signal. Vehicle speed correction factor \( K_v \) is a function of vehicle speed \( v \) that is used to correct the value of output signal when the vehicle is moving in different speed. By adding this correction factor, the weight of the vehicle estimated by WIM system \( M_w \) can be determined by equation (3). The value of \( K_v \) is obtained
using equation (4) with $V_s'$ is the average of output signal amplitude from each tire at three different reference speed values.

$$M_w = m_k(V_s') \times K_v(v)$$  \hspace{1cm} (3)

$$K_v = \frac{0.0053 m_k}{V_{s}'}$$  \hspace{1cm} (4)

Value of $K_v$ for each reference speed is shown in Figure 11. It can be observed that the value of $K_v$ tend to increase when the speed becomes higher. This trend corresponds with our previous claim that time constant in the WIM system is causing the signal amplitude to be lower for the same load at the higher speed. Therefore, speed correction factor is required. Since the value of $K_v$ for each reference speed seems to have linear relation, by using linear regression, $K_v$ can be calculated using equation (5). By combining equation (1), (3), and (5), the weight of the vehicle can be predicted based on data measured from WIM system (signal amplitude $V_s$ and time difference $\Delta t$) using equation (6). This equation is developed based on the apriori knowledge about the wheelbase of the vehicle.

$$K_v = 0.0009v + 0.6443$$  \hspace{1cm} (5)

$$M_w = \left( \frac{V_s}{0.0053} \right) \times \left( 0.0009 \frac{L_{base}}{\Delta t} + 0.6443 \right)$$  \hspace{1cm} (6)

![Figure 11. Relation between speed correction factor with vehicle speed](image)

3.5. *Error in measurement results for WIM system*

Figure 12 gives an example of weight calculation results for motorcycle moving with reference speed of 10 km/h and 30 times repeated test. The upper and lower limit in the graph respectively indicates a value of twice standard deviation above and below the average value comes from WIM system measurement which is indicated by the straight line. By statistic, 95% of this measurement results will be within that range. Meanwhile, the dotted line indicates weight measured in static condition. It can be seen in the Figure 11 that the average WIM measurement for front tire always greater than static measurement. On the other hand, the measurement in rear tire gives a result in opposite way. These phenomena also occur for WIM measurement with reference speed of 20 and 30 km/h.
Sudden change in vehicle acceleration due to condition of uneven road surface is an unavoidable circumstance that produce random results for WIM measurement in this experiment. Based on best practice, WIM device should be placed in flat road surface with no obstacles within distance of 100 m. Another limitation that contributes to this result is the application of single strain gage. The ideal condition for the measurement is the contact between tires and bending plate should be exactly over the strain gage location. However, the contact does not always happen at the desired position and it leads to produce signal output with lower amplitude.

Table 2 shows comparison between static and WIM measurement for three reference speed values. It is obvious that errors in terms of total weight are relatively smaller since the drop of weight distribution in one axle will be compensated with increasing weight in another axle.

Figure 12. Results from WIM measurement with reference speed of 10 km/h.

Sudden change in vehicle acceleration due to condition of uneven road surface is an unavoidable circumstance that produce random results for WIM measurement in this experiment. Based on best practice, WIM device should be placed in flat road surface with no obstacles within distance of 100 m. Another limitation that contributes to this result is the application of single strain gage. The ideal condition for the measurement is the contact between tires and bending plate should be exactly over the strain gage location. However, the contact does not always happen at the desired position and it leads to produce signal output with lower amplitude.

Table 2 shows comparison between static and WIM measurement for three reference speed values. It is obvious that errors in terms of total weight are relatively smaller since the drop of weight distribution in one axle will be compensated with increasing weight in another axle.
Table 2. Vehicle’s weight data for static calibration

| Speed       | WIM Measurement [kg] | Measurement Error |       |       |       |       |       |
|-------------|----------------------|-------------------|-------|-------|-------|-------|-------|
|             | front                | rear              | total | front | rear | total |       |
| 10 km/h     | 62–93                | 79–105            | 149–190 | -11% | -23% | -14% | 9%   |
| 20 km/h     | 67–88                | 76–110            | 152–189 | -5%  | -26% | -12% | 9%   |
| 30 km/h     | 68–88                | 77–105            | 152–186 | -3%  | -25% | -12% | 8%   |

Front wheel load 70 kg
Rear wheel load 103 kg
Vehicle’s total weight 173 kg

3.6. Experiment Testing for Overload Detection System

The Instruments, which is used in previous experiment, has different gain value from HX711 module that is used for detection system. New calibration factor should be determined using an identical procedure from previous experiments and the result is shown in Figure 13.

![Figure 13. New calibration factor for overload detection system.](image)

By replacing calibration equation from previous equation, it is obtained new equation for determining total weight of the vehicle. In equation (7), the value of vehicle speed correction factor is the same as from previous experiment since it came from the same sensor with same characteristic. Therefore, different instrument would not affect the result significantly.

\[ M_w = \left( \frac{m_k}{4.0455} \right) \times \left( \frac{L_{base}}{\Delta t} + 0.6443 \right) \]  \hspace{1cm} (7)

In this experiment, an overloaded vehicle is defined as a motorcycle with three passengers, while only one passenger occupying the motorcycle to indicate normal vehicle. A motorcycle with three adult passengers has total weight within range of 360-450 kg. Whereas single occupant motorcycle has a total weight between 235-260 kg. Therefore, weight value of 320 kg is set as a minimum threshold for overloaded vehicle. If the system detects the total weight of vehicle greater than the threshold value, then the alarm and camera is activated.

This experiment proves that the overload detection system is able to differ whether the vehicle which passes through the bending plate is overload or not. The system is also able to trigger the alarm and activate the camera for taking picture of the vehicle when overloaded vehicle is detected and giving no
responses when normal vehicle is passing by. The camera should be located at the proper position, so that the identity of the vehicle will always be captured when it is indicated to be overloaded. The illustration when the overloaded vehicle is captured by camera is shown in Figure 14.

![overload](image)

**Figure 14.** Illustration for overloaded vehicle identity captured by camera

4. Conclusion

In this research work, Weigh-in-Motion (WIM) prototype based on bending plate technology using single active strain gage with overload detection system has been developed. Static and dynamic testing was carried out in order to check whether the WIM sensor could produce an output signal and perform the intended purpose in obtaining vehicle weight as it passes the sensor. Noise that appears in the output signal is alleviated by averaging method. Random WIM measurement results occur due to uneven road surface and inconsistent location of tire contact to the bending plate.

Over all, the overload detection system based on Arduino microcontroller and HX711 strain amplifier performed really well to trigger the alarm and camera when overloaded vehicle is detected. The above outcome gives an idea to develop a reliable microcontroller-based WIM and a robust automatic overloaded freight vehicle detection in our future work.

References

[1] Public Works Office 2011 *Minister of Public Works Regulation No. 19 Year 2011 on Road Technical Requirements and Design Criteria* (Jakarta: PUPR) – in Indonesian

[2] Budget Review Center, Indonesian People’s Representative Council 2017 *Road Preservation Study 2015 and 2016* (Jakarta: DPR RI) – in Indonesian

[3] Wang H, Zhao J and Wang Z 2015 *Impact of Overweight Traffic on Pavement Life Using Weigh-In-Motion Data and Mechanistic-Empirical Pavement Analysis* (Department of Civil and Environmental Engineering, The State University of New Jersey)

[4] Jacob B and Beaumelle V 2010 *Improving Truck Safety. Potential of Weigh-in-Motion Technology* *IATSS Research* **34**(1) 9

[5] Xiong L, Zhuo F, Liu X, Wang F and Chen Y 2015 *Optimal Design of Moving Average Filter and Its Application in Distorted Grid Synchronization*, 2015 *IEEE Energy Convers. Congr. Expo.* pp 3449-3454