Basic study on weigh-in-motion of vehicles in acceleration and deceleration

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Received: 15 July 2019; Revised: 17 September 2019; Accepted: 23 December 2019

Abstract
Static weight estimation of a vehicle in motion is challenging, especially when the vehicle is accelerating and decelerating. This paper presents a new estimation method for accelerating and decelerating vehicles. This method uses at least two miniature load measurement devices cascaded in traffic lane and consideration of transfer load between the front and rear wheels of a motorbike. Both individual axle load and the gross mass of the motorbike are estimated with accuracy under field conditions.

Keywords: Weigh-in-motion, Signal processing, Acceleration, Deceleration, Mechanical vibration, Axle load

1. Introduction

Weigh-in-motion (WIM) is a technology for estimating the static axle load of vehicles in motion. WIM helps detect overload trucks, which may damage traffic infrastructure such as pavement and bridges and may increase the risk of traffic accidents and loss of revenue to commercial carriers. There are several specifications of accuracy classes in the world, but according to the COST 323, the assessment of WIM quality is divided into seven classes, in which B(10), C(15) classes mean the estimation errors of less than 10% and 15% (in 95% measured data), respectively. B class is suitable for enforcement or pre-selection. (Jacob et al.).

In general, the WIM system uses force sensors such as a piezoelectric strip sensor, load cell, or bending plate. Currently, piezoelectric strip sensors based on ceramic, polymer, or quartz are popular. Strip sensors have a length of 2 to 7 cm in the traffic direction and a width of approximately 1 to 6 m of the traffic lane (Loo and Znidaric, 2019). The advantage of strip sensors is that they are easy to install and maintain. However, the sensor’s signal cannot express the total distributed load in a tire’s imprint area because the sensor’s size is much smaller than that of the tire’s imprint. The static axle load estimation using such types of sensors significantly depends on traveling time, vehicle speed, tire pressure, road profiles, vehicle suspension’s dynamic characteristics, and other factors (Ahmad, 2011) and (Morikawa et al., 2016). Therefore, calibration requires a long time and many test-runs using various vehicles for reference. In fact, there is a paper (Haugen et al., 2019) that reported taking 6 to 12 months using a variety of trucks for calibration but still not reaching a satisfactory accuracy of C(15) class. This is one of the biggest hurdles to weight enforcement until now. Moreover, it is impossible to measure the static axle load of a truck in a stationary condition. In addition, vendors of WIM provide only the parameters of sensors but do not disclose the raw signal data of the WIM system to end users. The calibration procedures of the sensors are not also standardized, and these differing circumstance leads to differing estimation results.

More importantly, the current commercial WIM systems work only for trucks running at constant speeds and not for those in accelerative movement (Beatrix et al., 2019). In a previous paper (Pham et al., 2020), the authors presented a basic study of static weight estimation based on an averaging algorithm and the estimation in the cases of acceleration and deceleration. Although the experimental results were acceptably accurate about the estimation of the gross weight,
the inaccuracy of axle load estimation (front and rear wheels) was still very high. One of the main reasons for this result is the inaccuracy of time detection when a wheel is getting off a loading plate. The authors assumed that the inaccuracy of time detection led to the inaccuracy in estimating acceleration. This is because the time for the test motorbike to pass on the loading plate is very short; approximately 0.07 second at a vehicle’s speed of 25 km/h. Also, the sensor signal in the loading plate is complex due to being composed of static and dynamic components. This inaccurate time detection and acceleration estimation led to the inaccuracy of transfer load calculation. Furthermore, the height of the center of gravity of the test motorbike is needed for the estimation of transfer load. If the height was only assumed by referring ready reference texts (Cossalter, 2006) then, the value of the height seems to be inaccurate.

In this paper, the authors present an improvement over the existing axle load estimation of an accelerating or decelerating motorbike by using two miniature devices in cascaded placement within a distance of 2.3 m of each other in a test traffic lane.

2. Measurement devices

We developed two plate-type miniature devices, each of which has four load cells at the four corners under the loading plate as shown in Fig. 1(a). Each load cell is composed of a small cantilever and four strain gauges connected in the form of the Wheatstone bridge circuit and works as a single-point load sensor in the vertical direction. The total output signal from four load cells is converted to the value of applying load. The loading plate can be assumed to behave a rigid plate within the load range up to approximately 300kgf. Then, the resultant output realizes the insensitivity of loading position on the loading plate. The size of the loading plate is 400 x 520 mm where the 520 mm side is in the vehicle’s running direction. Before starting the experiments, the sensor signals of the two devices are calibrated using some known weights by means of static weighing, and the good linearity of the sensor signal is also verified. Fig. 1(a) and Fig. 1(b) show the front view of the miniature device and the setup of the experiment respectively.

![Four load cells inside](image1)

![Two measurement devices](image2)

Fig. 1 The miniature measurement devices in this study.

The experiments are conducted with a Honda PCX 125 motorbike in Tokyo Institute of Technology. Table 1 lists the static axle loads of the test motorbike, including the weight of the rider. The weights are measured in a stationary condition by using a digital platform scale on the site prior to the experiment of WIM. It is verified that the static axle loads vary approximately ±4 kgf from the values in Table 1. The fluctuation of ±4 kgf is observed by changing the rider’s body posture forward and backward on the seat.

<table>
<thead>
<tr>
<th>Model of motorbike</th>
<th>Front load (kgf)</th>
<th>Rear load (kgf)</th>
<th>Gross weight (kgf)</th>
<th>Wheelbase (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCX125</td>
<td>78</td>
<td>131</td>
<td>209</td>
<td>1.315</td>
</tr>
</tbody>
</table>

Note: the measurement varies approximately ±4 kgf depending on changing the rider’s body posture forward and backward on the seat.
A wooden runway is used for the moving motorbike as shown in Fig. 1(b). The two devices and wooden runway are covered with an elastic pad with a thickness of 1 mm to attenuate the impulsive excitation force for the loading plates at the moment when the motorbike is moving over the devices. The sensor signals of two measurement devices are acquired at a sampling speed of 2 kHz.

3. Estimation method

3.1. Appropriate distance between two measurement devices

An appropriate placement distance between the two measurement devices for the experiments is determined to attenuate the influence of dynamic load due to the motorbike’s bounce and/or pitching mode. The right distance will enhance the accuracy of static axle load estimation.

Equation (1) expresses the axle load downward onto the loading plate of a measurement device

\[ W = W_s + W_d \]  

where \( W_s \) and \( W_d \) are static and dynamic axle loads respectively. The measured axle load is composed of static and dynamic components.

Assume that the dynamic load appears due to the motorbike’s bounce and/or pitching vibration. It is expressed simply by Eq. (2)

\[ W_d = W_0 e^{-\frac{\pi}{f_n} \sin \varphi} \]  

where \( W_0 \), \( f_n \), and \( \alpha \) are the amplitude, natural frequency, and damping factor of the bounce and/or pitching mode respectively and \( \varphi \) is the initial phase.

According to literature (Cossalter, 2006), general motorbikes have the natural frequency of bounce and/or pitching mode at frequencies in the range from approximately 1.5 to 2.6 Hz. We conducted experiments of PCX125 with a rider seated on to find the natural frequency of bounce and/or pitching mode. It is in the range from 2.2 to 2.4 Hz. Then, we assume the general frequencies in the literature as the frequency \( f_n \) of Eq. (2). If the dynamic load superposes to the static load on two measurement devices that are out-of-phase mutually, the averaging method will work well to remove or reduce the influence of the dynamic load. The theoretically shortest time shift to make Eq. (2) mutually out-of-phase between the first and the second measurement device is expressed by Eq. (3)

\[ \delta t \approx \frac{1}{2f_n} \]  

where \( \delta t \) is the theoretically shortest time shift.

In our experiment, when a test motorbike runs at a speed of approximately 40 km/h \( (V = 11.1 \text{ m/s}) \), the placement distance between the two measurement devices is calculated as in Eq. (4)

\[ L = V \delta t = \frac{V}{2f_n} \approx 2.1 \text{ to } 3.7 \text{ (m)} \]  

where \( L \) is the distance between the centers of the two devices. Therefore, the placement distance of the two measurement devices is set as 2.3 m in our experiment. In case of very slow speed, this distance will not be important because dynamic load will become weak.

3.2. Axle load estimation method based on averaging method

The theory of the method and algorithm were presented in a previous paper (Pham et al., 2020). Here, we explain the method with focus on why the earlier method tends to underestimate the axle load.

The measurement devices in this study are designed for the sensor output to be insensitive to the position of the load
on the loading plates. Assuming a constant speed of the vehicle passing on the loading plate, the time history of the static axle load is expressed as a rectangular function even though it will be a trapezoidal function. Considering the measurement device as a damped mass-spring model, the equation of motion in Eq. (5) is expressed as

$$m\ddot{z} + c\dot{z} + kz = F(t) \begin{cases} F_0 & 0 \leq t \leq \Delta t \\ 0 & t > \Delta t \end{cases}$$

(5)

where $F_0$ is a constant static axle load acting on the loading plate and $\Delta t$ is the duration time for the axle load to cross on to the loading plate.

The vibration response of the loading plate is classified into two different behaviors. One is forced vibration response when the axle load is crossing the plate. Another is a residual-free vibration response after the axle load has finished crossing the plate. In the forced vibration response, the external force is expressed as a step function with up and down. Here, the sensor signal of the vibration response is expressed by Eq. (6) and depicted in Fig. 2.

$$y = \frac{EF_0}{E} \left[ 1 - e^{-\omega_0 t} \cos(\omega_0 \sqrt{1-\zeta^2} t) \right] \quad (0 \leq t < \Delta t)$$

(6)

where $\omega_0$, $\zeta$, and $E$ are the natural angular frequency, the damping ratio of the loading plate’s vibration, and a sensor calibration factor to convert the unit of the sensor signal to the unit “kgf” of force respectively. The sensor signal vibrates around the static load $F_0$ with some degree of attenuation as shown in Fig. 2. The envelope curves are expressed as the function in Eq. (7).

$$D(t) = \frac{EF_0}{E} \left( 1 \pm e^{-\omega_0 t} \sqrt{1-\zeta^2} \right)$$

(7)

In Fig. 2, it is possible to identify the magnitude of the static load $F_0$ by means of averaging the upper and lower envelope curves. In a similar manner, the averaging is executed for the response functions in blue but not for the envelope curves in green. It is noted that the first overshoot peak is generally much bigger than the subsequent overshoot peaks. This is because of the transient change of the external force from zero to a magnitude of $F_0$, as expressed in Eq. (5), and the damping of the vibratory system. In addition, the first overshoot is easily affected by uncertain excitation factors such as a shock generated by a wheel traveling from the end edge of the wooden runway to the front edge of the loading plate with a degree of difference in level. Therefore, the signal data in the time zone for the first overshoot should be excluded.
in the averaging process. Consequently, the following data sampling for averaging is proposed in this paper:

Step 1: Find the first rebound bottom point after the first overshoot.

Step 2: Find the last signal point in the period when an axle load keeps moving on the loading plate.

Step 3: Average all the signal data from the first rebound bottom point until the last signal point. The result is the estimation of static axle load.

The dynamic load in the signal decays with some degrees due to structural damping in the measurement device, as can be seen on the schematic in Fig. 2. Therefore, the result in Step 3 will have a little underestimated bias theoretically.

In practice, a little underestimation is better than overestimation for enforcement of WIM.

3.3 Estimation of speed and acceleration/deceleration using two loading plates

Various sensing systems are available today to measure or estimate vehicle speed and acceleration rate from a stationary point on the ground such as radar Doppler system or inductive loop detector system. In this paper, we present another method using the sensor signal from two measurement devices of WIM. It is efficient to use the devices for not only weighing but also sensing vehicle speed and acceleration.

As shown in Fig. 3, let us place two identical measurement devices, with a distance of $L$ between the front edges of two loading plates. The moments the front wheel of the motorbike gets on the loading plates of the two devices are denoted by $t_{f1}$ and $t_{f2}$ and for the rear wheel by $t_{r1}$ and $t_{r2}$. The average speed during which the front wheel moves from the front edge of the first measurement device to that of the second one is calculated by Eq. (8). Let us assume that the speed is the instant speed at time $\frac{(t_{f1} + t_{f2})}{2}$ for the front wheel. The average speed during which the rear wheel travels from the front edge of the first measurement device to that of the second one is calculated by Eq. (9).

$$v_1 = \frac{L}{t_{f2} - t_{f1}}$$  \hspace{1cm} (8)

$$v_2 = \frac{L}{t_{r2} - t_{r1}}$$  \hspace{1cm} (9)

$$a = \frac{2(v_2 - v_1)}{(t_{r1} + t_{r2}) - (t_{f1} + t_{f2})}$$  \hspace{1cm} (10)

$$\ddot{v} = \frac{(v_1 + v_2)}{2}$$  \hspace{1cm} (11)

Let us assume that the speed is the instantaneous speed at time $\frac{(t_{r1} + t_{r2})}{2}$ for the rear wheel. Consequently, the acceleration is obtained as the increment rate of speed in the period from $\frac{(t_{f1} + t_{f2})}{2}$ to $\frac{(t_{r1} + t_{r2})}{2}$ by Eq. (10). The values in the columns labeled “Velocity (km/h)” in Tables 2, 3, and 4 are the speed calculated by Eq. (11).

Even when using the sensor signal, it is not easy to pinpoint the exact time at which a wheel gets on and off a loading plate. Nevertheless, the estimation of the moment a wheel gets on is more reliable than the moment it gets off because the first overshoot peak can be clearly pointed out. In the previous paper (Pham et al., 2020), the authors proposed an estimation algorithm to determine the moment a wheel gets on and off a loading plate from the first overshoot point and the first rebound bottom point of the sensor signal. They calculated this after the plate is released from the axle load using the time constant of the measurement device’s dynamics. We propose an improvement of the estimation of the duration a wheel travels from the front edge of the first plate to that of the second one, as shown in Fig. 3, by using the first
overshoot points in the sensor signal at the moment a wheel just gets on two loading plates. The time of getting off the loading plates is not utilized.

Let us denote the time constant from the time a wheel gets on a loading plate to the first overshoot point by \( c \). The times \( t_{f1} \) and \( t_{f2} \) at the moment the front wheel gets on the first and the second loading plate are estimated by \( \hat{t}_{f1} - c + \epsilon_1 \) and \( \hat{t}_{f2} - c + \epsilon_2 \) respectively. Here, \( \hat{t}_{f1} \) and \( \hat{t}_{f2} \) are the times of the first overshoot points in the sensor signal from the first and the second loading plates, and \( \epsilon_1 \) and \( \epsilon_2 \) are inaccuracy quantities in estimation. We then obtain the following Eq. (12) and Eq. (13):

\[
t_{f2} - t_{f1} = (\hat{t}_{f2} - c + \epsilon_2) - (\hat{t}_{f1} - c + \epsilon_1) = \hat{t}_{f2} - \hat{t}_{f1} + \epsilon_2 - \epsilon_1
\]  

where \( (\epsilon_2 - \epsilon_1) \) can be expected to be much less than \( \epsilon_1 \) and \( \epsilon_2 \) because \( \epsilon_1 \) and \( \epsilon_2 \) are considered almost the same quantities. In the same way, we obtain

\[
t_{r2} - t_{r1} = (\hat{t}_{r2} - c + \epsilon_2) - (\hat{t}_{r1} - c + \epsilon_1) = \hat{t}_{r2} - \hat{t}_{r1} + \epsilon_2 - \epsilon_1
\]  

for the rear wheel’s movement. Eventually, the denominator of the fraction to estimate the acceleration in Eq. (10) becomes free from inaccuracy quantities because of Eq. (14)

\[
(t_{r1} + t_{r2}) - (t_{f1} + t_{f2}) = (\hat{t}_{r1} + \hat{t}_{r2}) - (\hat{t}_{f1} + \hat{t}_{f2})
\]  

The first overshoot point will be pointed out clearly in most cases. Namely, Eq. (10) is obtained by Eq. (15)

\[
a = \frac{2v_{f2} - v_{f1}}{(t_{r1} + t_{r2}) - (t_{f1} + t_{f2})}
\]

In the previous paper (Pham et al., 2020), using a single loading plate, the time a wheel just gets on and off a loading plate is estimated by \( \hat{t}_{f1} - c + \epsilon_1 \) and \( \hat{t}_{r2} - c + \epsilon_b \). Here, \( \hat{t}_{r2} \) and \( \epsilon_b \) are the time of the first rebound bottom point after the wheel gets off the loading plate and an inaccurate quantity respectively. Note that \( \epsilon_b \) is considered bigger than \( \epsilon_1 \) because of the big dynamic load’s inclination, with some uncertainties toward the sensor signal. The duration time \( \Delta t \) of a wheel crossing on the loading plate is calculated as per Eq. (16)

\[
\Delta t = (\hat{t}_{r2} - c + \epsilon_b) - (\hat{t}_{f1} - c + \epsilon_1) = \hat{t}_{r2} - \hat{t}_{f1} + \epsilon_b - \epsilon_1
\]

The estimation of this \( \Delta t \) will be worse in accuracy than the abovementioned algorithm in Eqs. (12) and (13).

### 3.4 Estimation of transfer load between front and rear wheels

The theory of calculating transfer load between front and rear wheels with respect to the acceleration rate is already presented in the previous paper (Pham et al., 2020). Here is described a brief review and some comments about the estimation accuracy of our experiment in Eq. (17):

The transfer load is calculated by

\[
N = \frac{h_G}{2h} ma
\]

where \( B \), \( h_G \), and \( m \) are the vehicle’s wheelbase, the height of the center of gravity, and the mass of the vehicle, respectively, and \( a \) is acceleration. The method in Section 3.3 has potential to estimate more accurate acceleration than the method in the previous paper (Pham et al., 2020). However, note that the wheelbase and the height of the center of gravity of vehicle are necessary to calculate the transfer load. The static axle loads, \( W_f \) and \( W_r \), of the front and the
rear wheel are obtained by Eq. (18) and Eq. (19)

\[ W_f = F_f - N \] (18)
\[ W_r = F_r + N \] (19)

where \( F_f \) and \( F_r \) are the measured axle loads about the front and the rear wheel and \( N \) is the transfer load calculated by Eq. (17).

In this study, the wheelbase \( B \) is known as \( B=1.315 \text{ m} \) in the specification of the motorbike. However, the exact height, \( h_G \), of the center of gravity of the motorbike in moving condition with a seated rider is difficult to measure. The test rider’s weight is approximately 78 kg, and the weight of the motorbike is approximately 131 kg.

A ready reference (Cossalter, 2006) reports that the ratio of the height, \( h \), of the center of gravity above the ground for a general motorbike without a rider, with respect to the wheelbase \( B \), is approximately 0.3 to 0.4. The wheel diameter of the test motorbike in this study is approximately 0.52 m, and the wheelbase \( B \) is 1.315 m. Therefore, the height, \( h \) of the center of gravity is calculated as \( h \approx 0.52 \text{ m} \). The height of the mass center of the test rider seated on the motorbike is assumed at approximately 1.1 m above the ground. As a result, the height of the center of gravity from the ground of the test motorbike, including a test rider, in running conditions is assumed as \( h_G \approx 0.74 \text{ m} \).

### 4. Experiments and results

One of the objectives of this paper is to propose a new method of static axle load estimation under acceleration and deceleration conditions by means of using two or more axle load measurement devices. Here, experimental results in constant speeds are shown at first and then those in accelerative motion are presented. Let us evaluate the experimental results using the inaccuracy ratio defined by Eq. (20)

\[ \frac{W - W_s}{W_s} \times 100\% \] (20)

where \( W \) and \( W_s \) are estimation results and the static axle loads in Table 1 respectively.

#### 4.1 Experiment with constant speed

Fig. 4 shows the sensor signal data of four experimental runs in constant speed conditions. Note here that the test rider tried to drive the motorbike at constant speeds but small fluctuations in speed were unavoidable. The signal data of each trial has four rectangular risings in signal in time domain with some degrees of vibration because the test motorbike runs on two measurement devices within a distance of 2.3 m. The first and the second risings in signal are the axle load of the front and the rear wheel respectively measured by the first measurement device. The third and the fourth risings in signal are the axle load measured by the second device. The time distances between the rising points due to the axle load of the front and rear wheels differ according to the different speeds of the motorbike. The time distances between the rising points in signals from the two devices also differ. Table 2 shows the estimation results from the data. It is unnecessary to consider transfer load in this estimation because of almost constant speeds. The axle loads are obtained by averaging the estimations by the first and the second measurement device. As can be seen in the table, the estimation errors are small.

#### 4.2 Experiment during accelerative condition

Fig. 5 and Fig. 6 show the sensor signal data for acceleration and deceleration and the influence of the movement on the data. In accelerative condition, the front axle load is lower than its static load, and the rear axle load is higher. The case is reversed in deceleration.
Table 2 The estimation results in constant speed conditions.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Velocity (km/h)</th>
<th>Front load (kgf)</th>
<th>Front error (%)</th>
<th>Rear load (kgf)</th>
<th>Rear error (%)</th>
<th>Gross weight (kgf)</th>
<th>Gross error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>19.9</td>
<td>71.2</td>
<td>-8.7</td>
<td>135.5</td>
<td>3.5</td>
<td>206.8</td>
<td>-1.1</td>
</tr>
<tr>
<td>Trial 2</td>
<td>20.3</td>
<td>71.9</td>
<td>-7.8</td>
<td>133.9</td>
<td>2.2</td>
<td>205.7</td>
<td>-1.6</td>
</tr>
<tr>
<td>Trial 3</td>
<td>32.9</td>
<td>79.2</td>
<td>1.6</td>
<td>132.7</td>
<td>1.3</td>
<td>211.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Trial 4</td>
<td>33.2</td>
<td>77.3</td>
<td>-0.9</td>
<td>138.0</td>
<td>5.3</td>
<td>215.2</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Note: “Front errors”, “Rear error”, “Gross error” are calculated using the values in Table 1 for W, by Eq. (20).

Tables 3 and 4 show the estimation results from the data. In Table 3, the estimation errors are shown in round brackets. The errors of the front and rear wheels with consideration of transfer load are much smaller than without the consideration. Also, the errors of both wheels are bigger than of the gross weight. However, the static front and rear axle loads fluctuate in the range of 74–82 kgf and 127–135 kgf, respectively, depending on the position of the seated rider’s upper body in the static measurement in this study. Therefore, the estimation results are still considered acceptably accurate.
Fig. 6 Sensor outputs for four trials in deceleration condition.

Table 3 Estimation results in acceleration condition

<table>
<thead>
<tr>
<th>No</th>
<th>Velocity (km/h)</th>
<th>Acc. (m/s²)</th>
<th>Front load (kgf) without TF</th>
<th>Rear load (kgf) without TF</th>
<th>Gross weight (kgf) without TF</th>
<th>Front load (kgf) with TF</th>
<th>Rear load (kgf) with TF</th>
<th>Gross weight (kgf) with TF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>25.7</td>
<td>1.5</td>
<td>54.1 (-30.6%)</td>
<td>150.6 (14.9%)</td>
<td>204.6 (-2.1%)</td>
<td>71.6 (-8.2%)</td>
<td>133.1 (1.6%)</td>
<td>204.6 (-2.1%)</td>
</tr>
<tr>
<td>Trial 2</td>
<td>26.8</td>
<td>1.7</td>
<td>51.7 (-33.8%)</td>
<td>150.5 (14.9%)</td>
<td>202.2 (-3.3%)</td>
<td>71.3 (-8.6%)</td>
<td>130.9 (-0.1%)</td>
<td>202.2 (-3.3%)</td>
</tr>
<tr>
<td>Trial 3</td>
<td>27.0</td>
<td>1.5</td>
<td>56.9 (-27%)</td>
<td>151.0 (15.3%)</td>
<td>207.9 (-0.5%)</td>
<td>75.2 (-3.6%)</td>
<td>132.7 (1.3%)</td>
<td>207.9 (-0.5%)</td>
</tr>
</tbody>
</table>

Note: Acc: the rate of acceleration
deceleration in this case
without TF and with TF: without and with consideration of transfer load
effects in round brackets: calculation by Eq. (18) referring the static axle loads in Table 1

Table 4 Estimation results in deceleration condition

<table>
<thead>
<tr>
<th>No</th>
<th>Velocity (km/h)</th>
<th>Acc. (m/s²)</th>
<th>Front load (kgf) without TF</th>
<th>Rear load (kgf) without TF</th>
<th>Gross weight (kgf) without TF</th>
<th>Front load (kgf) with TF</th>
<th>Rear load (kgf) with TF</th>
<th>Gross weight (kgf) with TF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>23.7</td>
<td>-1.7</td>
<td>94.9 (21.7%)</td>
<td>105.6 (-19.4%)</td>
<td>200.6 (-4.0%)</td>
<td>76.0 (-2.6%)</td>
<td>124.6 (-4.9%)</td>
<td>200.6 (-4.0%)</td>
</tr>
<tr>
<td>Trial 2</td>
<td>25.2</td>
<td>-1.6</td>
<td>101.3 (29.9%)</td>
<td>101.3 (-22.6%)</td>
<td>202.7 (-3.0%)</td>
<td>82.8 (6.1%)</td>
<td>119.9 (-8.5%)</td>
<td>202.7 (-3.0%)</td>
</tr>
<tr>
<td>Trial 3</td>
<td>26.2</td>
<td>-2.2</td>
<td>107.8 (38.2%)</td>
<td>94.8 (-27.6%)</td>
<td>202.6 (-3.1%)</td>
<td>82.5 (5.8%)</td>
<td>120.1 (-8.4%)</td>
<td>202.6 (-3.1%)</td>
</tr>
<tr>
<td>Trial 4</td>
<td>27.0</td>
<td>-2.0</td>
<td>103.7 (33.0%)</td>
<td>98.1 (-25.1%)</td>
<td>201.8 (-3.4%)</td>
<td>80.9 (3.7%)</td>
<td>120.9 (-7.7%)</td>
<td>201.8 (-3.4%)</td>
</tr>
</tbody>
</table>

Note: Acc: the rate of acceleration (deceleration in this case)
deceleration in this case
without TF and with TF: without and with consideration of transfer load
effects in round brackets: calculation by Eq. (18) referring the static axle loads in Table 1
The experimental study shows the possibility of static axle load estimation of vehicles even under accelerative motion with practically acceptable accuracy. Note here that the information about the height of the mass center of vehicles is required and that the acceleration rate should be almost constant while the vehicles run over the two measurement devices.

5. Conclusions

In this paper, the authors first presented a method to analyze the rate of a vehicle’s acceleration using two or more weigh-in-motion measurement devices in cascaded placement in a traffic lane. This method improves the accuracy of acceleration measurement from the previous method (Pham et al., 2020) that uses a single weigh-in-motion measurement device. Next, they presented that the static axle load of the vehicle in accelerative condition can be estimated accurately by considering the transfer load between front and rear wheels. The results of a basic experimental study using two measurement devices and a motorbike were presented to demonstrate the validity of this theory. From this, it was found that averaging the axle loads from the two measurement devices has the potential to enhance the reliability and accuracy of axle load estimation. Note that the gross weight of the test motorbike even in accelerative condition was estimated with inaccuracy less than 5%, which was more accurate than the results of the previous study with errors up to 15%.

Acknowledgement

The authors greatly appreciate Dr. T. Kawaguchi, the President of Resonic Japan Ltd., for his support and also appreciate Assoc. Prof. H. Sakamoto of Tokyo Institute of Technology and Lecturers Dr. Meifal Rusli and Dr. Lovely Son of Andalas University, for their valuable discussions with us.

References


