Empirical Analysis on the Effect of Gross Vehicle Weight and Vehicle Size on Speed in Car Following Situation

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Abstract: This study explores empirically how the gross vehicle weight (GVW) of a following vehicle and the size of leading vehicle will affect the driver behavior in controlling their speed under different compositions of leader-follower pairs in a car-following situation. A large sample of traffic and vehicular data for various vehicle types were obtained continuously using a weigh-in-motion (WIM) based transport data collection system installed at Federal Route 54 in Malaysia. Then, statistical analysis was applied to explore the driver behavior in controlling the speed in a car-following situation from two different perspectives: driver’s visual input and vehicle dynamics capability. The main finding of this study is that when we incorporate the vehicle dynamic’s capability in a car-following situation, the GVW of the following vehicle and the size of the leading vehicle were significant sources of variation in the following vehicle’s speed and relative speed, and their interaction influences the driver behavior in controlling the speed.

Key Words: Weigh-in-motion (WIM), Gross Vehicle Weight (GVW), Car-following, Speed Analysis

1. INTRODUCTION

The vehicle as one of the important elements in a traffic stream is completely a dynamic system. Equations of motion of vehicle dynamics can be found in many references related to fundamentals of vehicle dynamics such as Wong (1993) and Jazar (2008), which are derived analytically from Newton’s fundamental law. From macroscopic approaches, traffic stream models, either in two-variable or in three-variable models, is the relationship among speed, flow (vehicles/hour), and concentration (whether density or occupancy) (Gartner et al., 1992). Values of these variables of interest are obtained as a function of many implicit factors including vehicle dynamics. Thus, it can be said that implicitly, vehicle dynamics is considered in the model development.

On the other hand, microscopic traffic flow models focus on a single vehicle-driver unit. To date, one of the popular topics among the family of microscopic traffic models is a car-following model (Brackstone and McDonald, 1999). When deriving the models, the previous researches have made many assumptions that greatly simplified the models by merely describing the driving strategies of drivers in response to the leading vehicles.
As mentioned in Wang et al. (2008), car following strategies can be divided into two classes: one is when the driver is assumed to maintain a safe distance to the leading vehicle by controlling his own speed (Chandler et al., 1958), and another is when the desired speed of the following vehicle depends on the gap distance with respect to the leading vehicle (Bando et al., 1995). In order to reach good agreement with the field data, many improvements have been done to both classes of the model, including introducing a sensitivity function (Chung et al., 2005; Chang and Chon, 2005), considering the headway of the immediately preceding vehicle (Sawada, 2002), considering the effects of environment on driver behavior in a car-following situation (Ni et al., 2010), considering the effect of curvature or intersections (Suzuki et al., 2005), and considering the effect of driving style due to the different compositions of a leader-follower pair (Ossen and Hoogendoorn, 2011).

However, previous researches only address the modeling of car-following situations arising from the perspective of driver behavior. The characteristics of the vehicle such as performance, braking, and acceleration capability are assumed to be the same for all types of vehicles and for different compositions of a follower-leader pair in the model development. The main reason is that in the past it is difficult to obtain the weight, speed, acceleration, and classification data simultaneously and continuously over a period of time without disrupting the natural traffic flow.

As mentioned in Wong (1993), the behavior of a ground vehicle represents the results of the interactions among the driver, the vehicle, and the environment. Most of the time, vehicle dynamics influence drivers’ behavior in controlling their vehicles. Thus, the model can be improved to be more realistic if vehicle dynamics is incorporated.

This study attempts to explore and to provide a valid empirical evidence that the GVW of the following vehicle (FV) and the size of the leading vehicle (LV) will affect the driver behavior in controlling their speed under different compositions of leader-follower pairs (different weights of followers follow different sizes of leaders) in a car-following situation. The vehicle weight is one of the essential parameters that can affect vehicle driving, braking and handling performance characteristics identified in a vehicle design study (Bixel et al., 1998). The effect of weight on commercial vehicle performance is more considerable compared to its effect on non-commercial vehicles.

In discussing the development of the relationships or empirical models, the link with measurement capability of a transport data collection system is very important in order to have a practical and realistic model. The emerging technologies in the measurement field are undoubtedly changing the way some traffic measurements are obtained and will likely to provide the opportunity for acquiring more and better data to further advance understanding of the fundamental issues. One of the most difficult tasks related to measurement capability is to obtain weight data of moving vehicles. The only prominent technology used to obtain weight data is weigh-in-motion (WIM) technology. For the purpose of this study, a comprehensive, accurate and reliable traffic and vehicular data collection system using quartz weigh-in-motion sensor has been developed for measuring the speed, class, GVW, time headway and other traffic and vehicular data simultaneously and continuously 24 hours and 7 days. Further elaboration of the developed system is presented by Saifizul et al. (2010a, b).
2. THE DATA COLLECTION SYSTEM

The quartz WIM sensor is used to measure related traffic and vehicular data. The schematic diagrams of the developed system are shown in Figures 1 and 2.

![Figure 1. The data collection system layout](image)

![Figure 2. Schematic diagram of WIM system layout](image)

The data-collection system was installed on Federal Route 54, which is located 35 km from the city center and the traffic direction considered is from city to a rural area. The road type is rural single carriageway with standard width and layout, and the road geometry consists of a straight and flat road. The traffic composition is of a high proportion of both commercial and non-commercial vehicle.

When a force is applied to the sensor surface, the quartz disks yield an electric charge that is proportional to the applied force through a piezoelectric effect. Then, the electric charge is converted by a charge amplifier into a proportional voltage, which then must be further processed as required. The sensor must be integrated into the road surface and is, thus, only viable for permanent installation applications. As a vehicle starts to drive over the sensor, the software begins gathering data. Data is gathered until the vehicle’s entire axle has passed completely over the sensor. When this is complete, the software analyzes the data that was captured to determine the desired parameters, such as speed, wheelbase, GVW, number of axles, and other parameters.
3. RESULTS

The following behavior of a driver can be affected by various internal factors and its surrounding environment such as driver’s condition and vehicle dynamics characteristics, and changes in roadside infrastructure, traffic condition, road geometry conditions and sight distance due to weather and day or night condition. Because the objective of this study is to provide valid empirical evidence that following vehicle (FV) GVW and leading vehicle (LV) size affect the following behavior, real data should be carefully selected to minimize the errors caused by changes in the surroundings. In addition, the collected real data is a mixture of restrained and unrestrained vehicles. The analysis should only consider the case of restrained vehicles where the follower and its leader have influence on each other.

A total of more than 500,000 data samples were collected in four months from the system. For the purpose of this study, in order to remove the influence of the surroundings and concentrate on the driver behavior in a car-following situation, data were filtered based on following conditions:

- Dry weather condition
- Daytime from 7 am (after sunrise) and before 7 pm (before sunset)
- No change in the infrastructure and surrounding at the site
- Time headway less than 4 s (assuming the follower and its leader have influence on each other if the time headway is less than 4 s)

After the filtering, the total number of samples was reduced to 61,381. The speed data (FV speed and relative speed) was then grouped according to FV GVW and LV wheelbase (19 FV GVW range and 3 LV wheelbase range, as wheelbase directly related to vehicle size). This yielded a total of 57 groups of data. The normal test was performed for each group of data and all data can be considered as having a normal distribution with slightly different Skewness and Kurtosis. The number of samples for each group is given in Table 1.

<table>
<thead>
<tr>
<th>GVW Range (t)</th>
<th>&lt;2.5</th>
<th>2.5-5</th>
<th>5-7.5</th>
<th>7.5-10</th>
<th>10-12.5</th>
<th>12.5-15</th>
<th>15-17.5</th>
<th>17.5-20</th>
<th>20-22.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>10986</td>
<td>3913</td>
<td>3807</td>
<td>1512</td>
<td>1307</td>
<td>1461</td>
<td>1363</td>
<td>786</td>
<td>429</td>
</tr>
<tr>
<td>Case 2</td>
<td>10921</td>
<td>2402</td>
<td>965</td>
<td>400</td>
<td>336</td>
<td>372</td>
<td>357</td>
<td>229</td>
<td>168</td>
</tr>
<tr>
<td>Case 3</td>
<td>8998</td>
<td>1993</td>
<td>508</td>
<td>249</td>
<td>196</td>
<td>245</td>
<td>232</td>
<td>164</td>
<td>133</td>
</tr>
</tbody>
</table>

To simplify the results generation and analysis, the analysis is divided into three cases according to LV wheelbase range as mentioned earlier and is shown in Table 2.

<table>
<thead>
<tr>
<th>LV Wheelbase</th>
<th>&lt;3m (Small size)</th>
<th>3-5m (Medium size)</th>
<th>&gt;5m (Large size)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FV Speed</td>
<td>Case 1</td>
<td>Case 2</td>
<td>Case 3</td>
</tr>
</tbody>
</table>
3.1 Analysis on Speed of Following Vehicle
The line plots of mean and standard deviation of the following vehicle speed as a function of GVW for all cases (following various sizes of leading vehicle) are shown in Figures 3 and 4.

The relationship is based on the assumption that a linear relationship exists between the mean of FV speeds and the logarithm of the mean of FV GVW, and between the standard deviation of FV speeds and the mean of FV GVW as expressed in Equation (1).
\[ \mu_{fv} = C_1 \log w + C_2 \]
\[ \sigma_{fv} = C_3 w + C_4 \tag{1} \]

where \( \mu_{fv} \) and \( \sigma_{fv} \) are means and standard deviations of FV speed and \( w \) is FV GVW. Coefficients of the regression lines, \( C_i \) where \( i=1,2,3,4 \) in Equation (1), and coefficients of determination, \( R^2 \), for all cases can be described as shown in Table 3:

Table 3. Regression coefficients with p-value and coefficients of determination of the mean and standard deviation of FV speed

<table>
<thead>
<tr>
<th>Case</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
<th>( C_4 )</th>
<th>( R^2 ) (Means)</th>
<th>( R^2 ) (SD)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-10.355</td>
<td>73.505</td>
<td>-.089</td>
<td>9.223</td>
<td>.939</td>
<td>.907</td>
<td>19</td>
</tr>
<tr>
<td>(p-value)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-7.791</td>
<td>68.274</td>
<td>-.109</td>
<td>9.600</td>
<td>.922</td>
<td>.841</td>
<td>19</td>
</tr>
<tr>
<td>(p-value)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-6.792</td>
<td>65.797</td>
<td>-.130</td>
<td>9.859</td>
<td>.881</td>
<td>.847</td>
<td>19</td>
</tr>
<tr>
<td>(p-value)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regression coefficients in Table 3 indicate that there is an exponential relationship between the mean of FV speeds and FV GVW’s. In this case, it was found that the mean of FV speed decreases very rapidly as the mean of FV GVW first increases, but then decreases much less rapidly as the mean of GVW increases further. The values of coefficients also indicate that the estimation of the intercept and slope may change under different cases (Case 1 to Case 3), but the forms of the relationships should remain valid.

In case of standard deviation, a negative straight-line or linear relationship between the standard deviation of FV speed and FV GVW was derived. However, there were some differences in the gradients of the regression lines for all three cases. In the case where light vehicles followed small size vehicles, the speed variation is substantially lower than when they followed large size vehicles. This situation is different for a heavy vehicle. The speed variation is small when heavy vehicles followed large size vehicles compared to when the followed small size vehicles.

Table 3 also indicates that the estimate of the slope and intercept for Equation (1) is significantly different from zero and the model adequately described the data (for each case, \( p < 0.001 \)).

3.2 Analysis on Relative Speed

In the previous subsection, the effect of LV speed on a car-following situation was not taken into consideration. By assuming that the leading vehicle was constantly traveling at the recorded speed after passing through the sensor until the following vehicle touches the sensor, the effect of FV GVW and LV size on relative speed in a car following situation can be performed. The relative speed in this study is defined as follows:

\[ \Delta V = V_{lv} - V_{fv} \tag{2} \]

where \( V_{lv} \) and \( V_{fv} \) are the speeds of the leading and following vehicles, respectively.
The line plots of mean and standard deviation of relative speed as a function of GVW for each case are shown in Figures 5 and 6.

Figure 5. Means plot of Relative Speed for all cases

Figure 6. Standard deviation plot of Relative Speed for all cases
For the case of relative speed, the relationship is based on the assumption that a positive curvilinear relationship exists between both the mean of FV GVW and the relative speed, and the standard deviation of relative speed and the mean of FV GVW as expressed in Equation (3).

\[
\begin{align*}
\mu_{\Delta V} &= D_1 \log w + D_2 \\
\sigma_{\Delta V} &= D_3 \log w + D_4
\end{align*}
\]

where \( \mu_{\Delta V} \) and \( \sigma_{\Delta V} \) are the mean and standard deviation of relative speed and \( w \) is the FV GVW. Coefficients of the regression lines, \( D_i \) where \( i=1,2,3,4 \) in Equation (3), and coefficients of determination \( R^2 \) for all cases can be described as shown in Table 4:

**Table 4.** Regression coefficients with p-value and coefficients of determination of mean and standard deviation of relative speed

<table>
<thead>
<tr>
<th></th>
<th>( D_1 )</th>
<th>( D_2 )</th>
<th>( D_3 )</th>
<th>( D_4 )</th>
<th>( R^2 ) (Means)</th>
<th>( R^2 ) (SD)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>3.355</td>
<td>.816</td>
<td>.426</td>
<td>7.604</td>
<td>.843</td>
<td>.099</td>
<td>19</td>
</tr>
<tr>
<td>(p-value)</td>
<td>&lt;0.001</td>
<td>=0.094</td>
<td>&lt;0.190</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(p-value)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 3</td>
<td>4.484</td>
<td>-5.066</td>
<td>-5.621</td>
<td>12.367</td>
<td>.784</td>
<td>.929</td>
<td>19</td>
</tr>
<tr>
<td>(p-value)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regression coefficients in Table 4 indicate that the means of relative speed increase rapidly as the means of FV GVW increase, but this increase tapers off beyond certain values of the mean FV GVW (i.e., in this case 10 tonnes).

For the case of the standard deviation, the coefficients of determination and the p-value of the slope coefficient for Case 1 indicate that the slope coefficient is not significantly different from zero and that the relative speed is not affected by the FV GVW. However, the situation is different for Case 2 and Case 3, where the variance of relative speed decreases very rapidly as the mean of FV GVW first increases, but then decreases much less rapidly as the mean of GVW increases further.

Values in Table 4 also indicate that the estimate of the slope and intercept for Equation (3) is significantly different from zero and the model adequately described the data (for each case, p < 0.001 except for Case 1 standard deviation).

**4. DISCUSSION**

The main findings of this study have established that when we incorporate the vehicle dynamics’ capability in a car-following situation, the GVW of the following vehicle and the size of the leading vehicle became significant sources of variation in FV speed and relative speed, and their interaction influenced the driver behavior in controlling the speed. More specifically, indications were found that the driver’s ability to achieve a desired speed is not only impeded by the leading vehicle size and speed but is also constrained by the vehicle weight.
In vehicle design study (as given in the aforementioned reference), the vehicle weight directly affects a variety of vehicle characteristics including traction, braking, and handling characteristics. Thus, most countries impose additional requirements or training to heavy vehicle drivers. The following subsections provide more detailed discussion of the results of statistical tests.

4.1 Effects on Speed of Following Vehicle
The results indicate that the decrease in the average speed of the FV with an increase in its GVW would most probably be due to the driver’s understanding of the heavy vehicle limitations and/or may also be due to the heavier vehicle having fewer dynamic performance capabilities. In the case where following vehicles follow various sizes of leading vehicles, the average speed of the FV also decreases with an increase in LV size. This may be due to the large size vehicle obstructing the visibility of the driver beyond the LV and/or the FV being impeded by the speed of the LV because vehicle size is inversely proportional to the speed. The same phenomena can be observed for heavy vehicles.

Results from linear regression also show that the variance of FV speed decreases with an increase in FV GVW, which may also be due to vehicle dynamics limitations. The speed variance of light FV is larger when they are following large LV in comparison to following small LV. However, the results show a reverse effect when heavy vehicles follow various sizes of LV as shown in Figure 4. The speed of heavy vehicles has less variance when they follow large LV compared to small LV. One possible reason for this observation is that light or small vehicles have better performance capability, which may allow the driver to accelerate or decelerate faster. The following subsection further discusses the results when LV speed is taken into consideration.

4.2 Effects on Relative Speed
Regression plots of an average relative speed show that for Case 1 (following small size vehicle), the relative speed increases as the mean of FV GVW increases. The results obviously show that light vehicles do not have difficulty in achieving their desired speed or in maintaining their speeds closely with the LV speed. However, for heavier vehicles, the drivers are constrained by vehicle dynamics capability, and the positive values of the average mean relative speed show that most of the time they are unimpeded by the speed of small size leading vehicles.

Furthermore, we can also observe that when light vehicles follow medium or large size vehicles, their average speeds are slightly higher than the leader. This is probably because, with better vehicle dynamics capability, they were trying to match the leader speed (especially when the gap distance allows them to accelerate) or in the process of attempting to overtake the leading vehicle.

But why, then do heavy vehicles have the same variation of relative speed when following small size vehicles as given in Figure 6? We postulate that this result can be explained as drivers of light and small vehicles not being constrained by their vehicles’ performance capability, allowing them to drive as they like. There are situations where the follower keeps away from the leader (positive relative speed) or the follower accelerates to get close to the leader (negative relative speed). But in the case of heavy vehicles following small size vehicles, the relative speed variations are mainly attributed to the loads that these vehicles carried. If the loading is within the vehicle design specification, the heavy vehicle drivers are
able to match their leader’s speed or are impeded by them as long as the leader speed is within their maximum vehicle capability. However, most of the cases, as shown in Saifizul et al. (2010a, b), in Malaysia, each vehicle class (according to the number of axle and wheelbase) can have large variations in GVW. For instance, there appears a difference in dynamic capability between 3-axle trucks and 5-axle trucks when both carry 50-tonne loads. Because of constraints in its dynamics capability, the drivers of 3-axle trucks obviously cannot drive at the same speed as 5-axle trucks. This causes a variation in relative speed when they follow a passenger car even though in both situations they are not always impeded by leader speed. The sketch of the proposed relationship among FV speed, GVW and LV size, and among relative speed, FV GVW and LV size are given in Figures 7 and 8.

Figure 7. The proposed relationship among FV speed, FV GVW and LV size

Figure 8. The proposed relationship among relative speed, FV GVW and LV size
5. CONCLUSION

Empirical analysis of car-following situations with different compositions of follower-leader pairs in terms of weight and size were undertaken based on real data collected from the developed continuous, reliable, accurate, and comprehensive traffic and vehicular data collection system.

Analysis explored the driver behavior by controlling the speed under car-following from two different perspectives: driver’s visual input and vehicle dynamics capability as shown in Figure 9.

The results of this study may be summarized as follows:

1. The study suggests that the FV GVW, LV size and LV speed were significant sources of variation in FV speed.
2. Drivers of heavy vehicles on average are constrained by vehicle dynamics limitations. In the case where the leader has better performance capability, the results on average show that the heavy vehicle followers are unable to maintain speeds close to the speeds of small size leader vehicles.
3. In the case where the follower-leader pair has almost same performance capability or the follower has better performance capability, the follower on average is impeded by its leader’s speed and/or size.
4. Light and heavy vehicles maintain different safe desired speeds with the LV according to the LV size. This can be caused either by the large vehicle moving at a low speed in comparison to small size leading vehicle or FV drivers unable to anticipate future traffic conditions due to drivers’ vision being obstructed by the large lead vehicle.
5. The observation provides a preliminary step for considering vehicle weight as an additional variable of interest in a car-following study.

REFERENCES


