New Method for Distance-based Close Following Safety Indicator

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Objective: The increase in the number of fatalities caused by road accidents involving heavy vehicles every year has raised the level of concern and awareness on road safety in developing countries like Malaysia. Changes in the vehicle dynamic characteristics such as gross vehicle weight, travel speed, and vehicle classification will affect a heavy vehicle’s braking performance and its ability to stop safely in emergency situations. As such, the aim of this study is to establish a more realistic new distance-based safety indicator called the minimum safe distance gap (MSDG), which incorporates vehicle classification (VC), speed, and gross vehicle weight (GVW).

Method: Commercial multibody dynamics simulation software was used to generate braking distance data for various heavy vehicle classes under various loads and speeds.

Results: By applying nonlinear regression analysis to the simulation results, a mathematical expression of MSDG has been established. The results show that MSDG is dynamically changed according to GVW, VC, and speed.

Conclusions: It is envisaged that this new distance-based safety indicator would provide a more realistic depiction of the real traffic situation for safety analysis.

Keywords: heavy vehicle, gross vehicle weight (GVW), distance-based safety indicator, close following, vehicle type/classification

Introduction

Road accidents over the past decade in developing countries like Malaysia showed worrying trends. In 2010, there were about 414,421 cases of road accidents recorded compared to only 162,491 cases in 1995 (Jabatan Kerja Raya 2010). Statistics also showed an increase in number of fatalities from 5,712 to 6,872 over the same period. The casualties resulting from accidents involving heavy vehicles accounted for 25% of total road fatalities. It should be noted that the percentage represents fatalities of vehicle operators, which includes drivers, co-drivers, and/or assistants. Although the number of registered heavy vehicles barely makes up 5% of total registered vehicles in Malaysia, the composition of heavy vehicles in the traffic stream may reach 20% of all traffic on the road (depending on locations). This suggests that the percentage of fatalities involving heavy vehicles with other road users is much higher than the existing statistics. Because heavy vehicles vary in type and size, the gross vehicle weight (GVW) varies considerably, especially when loaded. This situation is more serious when overloading exists.

Road accident statistics have consistently shown that driver errors and misbehavior are the main contributing factors of traffic crashes. Human behavior, the roadway environment, and vehicle failure are factors found to contribute approximately 94, 34, and 12% of crashes, respectively (Evans 1991). Human factors involved in injury caused by traffic crashes can be subdivided into 4 groups: (1) following too closely, (2) failing to grant right of way, (3) driver losing control, and (4) speeding, causing 30.73, 20.71, 13.09, and 10.60%, respectively, of the crashes involved (Ivan et al. 2012).

The most common critical error made by drivers, whether they are heavy vehicle operators or other involved drivers, appears to be following too closely or misjudging the distance gap between 2 vehicles or more, which happens when the driver follows a vehicle too closely and is overconfident in his ability to stop the heavy vehicle without colliding. The driver’s consciousness of the safe distance gap is crucial for heavy vehicle drivers to prevent collision with the vehicle in front. Therefore, some countries have imposed rules and practices concerning the minimum time gap allowed between 2 vehicles on the road to prevent front-end and rear-end collisions (Hutchinson 2008).
Review of Safety Indices

In the literature, there are several safety indicators that have been applied for safety analysis. Generally, such safety indicators can be classified into 4 groups, namely, time-based, distance-based, deceleration-based, as well as other composite measures. One of the most frequently used time-based measures is time-to-collision (TTC). TTC, which is defined as the time that remains until a collision between 2 vehicles, is one of the most well-recognized safety indicators in transportation safety (Chin and Quek 1997; Matsui et al. 2013; Shariat-Mohaymany et al. 2011). Another time-based safety index is the perceptual risk estimate (PRE) developed by Aoki et al. (2011). PRE is the inverse of TTC and is corrected by the subject vehicle’s velocity and relative acceleration to reflect the driver’s perceptual errors. PRE proposes a simple method to predict car-following tendency based on the driver’s maneuvering habits and to forecast the driver’s car-following tendency on public roads.

There are 4 important distance-based safety indices, including (1) proportion of stopping distance (PSD), (2) stopping distance algorithm, (3) possibility index for collision with urgent deceleration (PICUD), and (4) predicted minimum distance (PMD), as shown in Table 1. PSD was defined by Allen et al. (1978) as the ratio between the remaining distance to the point of collision expressed over its minimum acceptable stopping distance. The mathematical expressions are shown in Eqs. (1) and (2) (see Table 1).

Another commonly used measurement in distance-based safety indicator is the stopping distance algorithm (SDA; Wilson et al. 1997). Equation (3) in Table 1 shows the formula to calculate SDA. The collision avoidance system based on a stopping distance algorithm gives a collision warning when the calculated intervehicular distance \(d\), called the stopping distance (SD), becomes smaller than the safety distance \(d_s\). The velocities \(v_f\), \(v_p\) in Eq. (3) are not preset values but are updated constantly, whereas the driver reaction time, \(T\), and the decelerations \(a_f\), \(a_p\) are set by predefined parameter. Consequently, the warning provision timing can be changed by adjusting these parameters.

PICUD was introduced by Uno et al. (2002). They believed that PICUD could address weak points in the TTC measurement. TTC can be used in a situation where the lead vehicle with a higher speed cannot be identified, and PICUD can indicate safety risk in that situation. PICUD is an index to evaluate the possibility of 2 consecutive vehicles colliding by assuming that the leading vehicle applies its emergency brake. PICUD is defined as the distance between 2 vehicles considered when they completely stop (Uno et al. 2005). The 2 parameters required to predict PICUD are reaction time and maximum deceleration rate. They assumed the reaction time as 1 s and 3.3 s for emergency braking in their study on a weaving road section. Equation (4) in Table 1 shows the equation to calculate PICUD.

PMD was introduced by Polychronopoulos et al (2004). PMD can be defined as the minimum distance between a vehicle and a potential obstacle predicted in real time (if PMD = 0 then the impact is forecasted, if PMD > threshold, then the obstacle is not to be considered dangerous). Equation (5) in Table 1 shows the formula to calculate PMD.

Table 1 summarizes the main distance-based safety indicators that can currently be applied to highway safety analysis. The focus of the study in this article will only emphasize the distance-based safety indices. Although a small number of researchers have been working on distance-based safety indices such as those listed in Table 1, there is no detailed investigation on a heavy vehicle’s GVW and vehicle classification (VC). These 2 parameters are assumed to be the same for all types of vehicles. Vehicle weight is one of the essential parameters in vehicle design study that can affect vehicle driving, braking, and handling performance characteristics (Bixel et al. 1998). Generally, a vehicle’s dynamic characteristics will influence driver behavior in controlling the vehicle (Wong 2008). The studies by Saifizul et al. (2011a, 2011b) have shown that a heavy vehicle’s GVW has a direct influence on the vehicle’s acceleration, whether the vehicle is traveling in a vehicle-following situation or in a free-flow condition. In addition, depending on their size and weight, the existence of heavy vehicles in a traffic stream will definitely cause a significant difference in vehicle-following behavior (Sayer et al. 2000). Thus, it is important to extend the study on the influence of both heavy vehicle’s GVW and its class on the safety indicator in a vehicle-following situation to further understand the subject not only from the driver’s visual input perspective but also from the vehicle dynamics perspective.

### Table 1. Summary of distance-based safety indices formula

| Indicator | Description | \(RD\) = remaining distance to the potential point of collision (m). | \(MSD\) = minimum acceptable stopping distance (m), which is defined as | \(V_f\) = velocity of following vehicle (m/s) | \(RT\) = Reaction Time = 1.0s | \(a_f\) = Acceleration for following vehicle (m/s\(^2\)) | \(a_p\) = Acceleration for leading vehicle (m/s\(^2\)) | \(V_{L1}\) = Velocity of leading vehicle (m/s) | \(V_{L2}\) = Velocity of leading car 1 and 2, respectively | \(S_o\) = distance between car 1 and 2 | \(\Delta t\) = driver’s reaction time | \(p_d\) = predicted distance | \(d\) = distance (m) | \(X_{cf}(k+i)\) = minimum unbiased Estimator | \(X_{cf}(k+i)\) = fused estimator | \(PMD = \min pd(k+i)\) |
|-----------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Proportion of Stopping Distance (PSD) | (Allen et al. 1978) | \(PSD = \frac{ds}{ds + d_s}\) | (1) |                      |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |
| Stopping Distance Algorithm (SDA) (Wilson et al. 1997) | \(D_s = -x_k - v_f \times RT + \left(\frac{V_f^2}{2a_f}\right)\) | (2) |                      |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |
| Potential Index for Collision with Urgent Deceleration (PICUD) (Yang et al. 2010) | \(PICUD = \left(\frac{V_{L1}^2 - V_{L2}^2}{2a_f}\right) + S_o - V_{L1} \times \Delta t\) | (4) |                      |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |
| PMD (predicted minimum distance) (Polychronopoulos et al. 2004) | \(pd(k+i) = d \times X_{cf}(k+i)\) | (5) |                      |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |
There are 2-fold objectives in this study. The first is to investigate the effect of GVW and VC on braking distance (BD). The second objective is to propose a new distance-based safety indicator, namely minimum safe distance gap (MSDG) that incorporates the factors GVW and VC. The outcome of the analysis is to establish a regression model of MSDG with respect to vehicle speed, GVW, and VC.

Methodology

In previous studies, BD was always assumed to be the same for both following vehicle (FV) and leading vehicle (LV) when they were traveling at the same speed regardless of the vehicles’ braking capability. However, in this study, the effect of speed, GVW, and VC on BD will be discussed. The brake performance of a vehicle can be analyzed in several different ways. This can be done through an actual experimental work or through computer simulation. Obviously, the process of building and instrumenting the prototype for an actual experimental testing involves significant engineering time and cost. Furthermore, some actual tests that involve 2 vehicles following closely at high speeds are quite dangerous and difficult to implement. Additionally, it is difficult to ascertain the safe following gap time in a close vehicle-following situation. With the evolution of computer science, computer simulation offers a better advantage in understand physical problems such as the one considered under this study. This simulation technique is often used as an alternative for very costly and risky experimental methods. In this study, an industrial standard multibody dynamics modeling software package, MSC.ADAMS/Truck (MSC Software Corporation 2012) was used to generate BD data for 2- to 4-axle single unit truck (SUT) under various GVWs, VCs, and speeds.

There are 3 main steps involved in obtaining the BD data from MSC.ADAMS/Truck: (1) virtual vehicle modeling, (2) simulation, and (3) data acquisition and interpretation. The 2 steps are detailed in the following subsections.

Virtual Vehicle Modeling

Because the aim of this study is to develop a model that can reflect actual 2- to 4-axle BD situations, it is important to develop a realistic simulated SUT model. Thus, in this study, the vehicle models and the SUT specifications of the 2-axle, 3-axle, and 4-axle trucks have been developed in accordance to the type of vehicle that is available on the road as shown in Table A1 (see online supplement). All of these SUTs will be reconfigured according to the existing SUTs’ parameters. Figure A1 (see online supplement) shows an example of the final view of a 3-axle SUT that has been constructed from the given template in MSC.ADAMS/Truck. The braking analysis and tire properties to run this simulation are shown in Tables A2 and A3 (see online supplement). Furthermore, the air drum brake and parabolic leaf spring suspension are used for the heavy vehicle category.

Simulation

Once all of the HVs are constructed, the workflow proceeds to simulation. The simulation was carried out to emulate the vehicle traversing a flat and dry road at constant forward velocities before the brake is applied. The vehicle will then decelerate until it stops and the braking distance will be recorded. A brake force of 285 N was applied as suggested by Mazzae et al. (1999), which represents the average maximum brake pedal force during emergency braking on dry pavement. An additional simulation was conducted using MSC.ADAMS to study the effect of a heavy vehicle’s braking force on braking distance above and below 285 N at various constant forward velocities. The results from this simulation suggested that the variation in brake pedal force above 100 N showed minimal effect on the BD as shown in Figure 1. Brake forces between 100 and 500 N emulated an emergency braking situation in which the brake mechanism at all wheels were fully engaged. Below 100 N, the brake mechanism was not fully engaged, resulting in longer braking distance. The findings from these simulations showed outcomes similar to those of Fitch et al. (2010). Their experimental study revealed that the braking forces have a little effect on the braking distance when the brake mechanism was fully engaged, as shown in Figure A2 (see online supplement).

As stated in the objectives of this study, GVW is a crucial element for this simulation. The lump mass added in the storage compartment will be assigned with different masses (5,000 kg increments) for each simulation done. After a heavy vehicle is loaded, its GVW is calculated. The whole event is conducted under constant velocity starting from 30 km/h in 10 km/h intervals up to 100 km/h. After each speed interval was tested, the next GVW with a 5,000 kg increment was tested. Once the respective heavy vehicle had gone through all of the simulation steps, the procedures were repeated for the remaining heavy vehicles that were constructed.

Data Generation and Interpretation

Data generation and interpretation is the last stage in this methodology. All of the results were acquired from ADAMS/PostProcessor MD ADAMS (2011). This window is capable of displaying all relevant data in a graphical manner, which allows users to make data comparisons. All of the acquired data were processed and exported to Microsoft Excel for analysis.
The New Proposed Safety Indices—Minimum Safe Distance Gap Concept

Keeping a safe following distance from the LV is critical to mitigate rear-end crashes in a vehicle-following situation because a safe distance will allow the FV to have a sufficient distance to stop the vehicle gradually. Thus, in this article, the concept of MSDG is introduced. MSDG is defined as the minimum distance required by the FV to decelerate and stop safely without colliding into the LV when both the leading and following vehicles brake during an emergency situation.

The value of MSDG (as illustrated in Figure 2) is obtained by considering the BD of the FV ($BD_{FV}$) and the LV ($BD_{LV}$) as well as the perception–reaction distance of the FV’s driver. The overall concept of the system is shown in Figure 2. The FV is considered to be in an unsafe condition when the gap distance calculated between FV and LV is lower than the MSDG value. Different compositions of leader–follower pairs, say, for example, in the case of a heavy vehicle following a car, will affect the MSDG value due to the difference in braking performance and braking capability of the vehicles. Similarly, the FV’s driver’s physical and psychological condition will affect the perception–reaction distance, hence affecting the MSDG value. In this study, for the purpose of maximum safety, only a passenger car was chosen as the LV because it has a different maximum braking capability compared to a heavy vehicle.

The general equation for MSDG incorporating BD and perception–reaction distance (RD) can be expressed as Eq. (1):

$$MSDG = BD_{FV} - BD_{LV} + RD,$$

where $RD$ is the FV’s driver’s perception–reaction distance, and $BD_{FV}$ and $BD_{LV}$ are the braking distance of the FV and LV, respectively. Numerous factors influence the $BD$ and $RD$. According to Wong (2008) and Warshawsky-Livne and Shinar (2002), BD can be influenced directly by factors related to the vehicle and the road surface (coefficient of friction, CoF). In this study, we used a constant CoF to simplify the simulation process. However, the changes in CoF may be considered in the MSDG concept in further studies on the matter.

The RD is proportional to the driver’s reaction time (RT) and vehicle speed as shown in Eq. (2). The driver’s perception–reaction time (RT) is often defined as the distance interval between an obstacle appearance and the driver’s response initiation. Studies have shown that RT can be as low as 1 s, but in a previous study, it was found that most RTs were between 1.5 and 4 s (Evans 1991). In this study, an RT of 1.5 s was used to calculate the RD.

$$RD = Speed \times RT$$

Results and Discussion

Effect of GVW and Vehicle Classification on Braking Distance

In this research, a total of 232 sets of simulation data were generated and grouped according to VC, GVW, and speed for analysis. Simulation data on the passenger car’s braking time as a function of speed are shown in Table A4 and Figure A3 (see online supplement). Based on Figure A3, a braking distance model for passenger car (sedan) with various constant forward velocities can be expressed as in Eq. (3):

$$BD_c = 0.4387V - 14.0831,$$

where $BD_c$ is the braking distance for passenger car in seconds and $V$ is vehicle speed. The heavy vehicle simulation data were grouped according to vehicle class and GVW, and scatter plots and fitting lines from the simulation results were plotted to indicate the effect of VC, speed, and GVW on the BD of a 2-axle, 3-axle, 4-axle, and 5-axle SUT as shown in Figures 3 and 4.

Based on fitting lines in Figure 3, it can be inferred that for heavy vehicles traveling at a minimum or low speed, the GVW does not significantly influence the total BD. However, the increase in BD is significant when the heavy vehicle travels at medium or high speeds. From this result, it is important to note that the heavier the heavy vehicle’s GVW, the longer the BD for the heavy vehicle to stop. Thus, in an emergency situation, an overloaded vehicle of the same classification will not be able to stop at the same distance as a non-overloaded vehicle, no matter how hard the driver presses the brake pedal.

Figure 4 shows the effect of VC on BD for the same GVW but at different speeds. From the plot line, it is clearly shown that the BD is affected not only by speed but also by VC. In this case, BD will decrease with an increase in the number of axles on the truck, because different VCs have different dynamic characteristics. It can be deduced that heavy vehicles with more axles will result in shorter BD due to better weight distribution and braking performance of the vehicle. For example, a 2-axle truck with a GVW of 35 tons traveling at a speed of 50 km/h will need around 20 m to stop, whereas a 3-axle truck with the same GVW and speed will only need around 18 m to stop because of the lower load exerted on each axle, allowing the brake to function at its optimum performance. It should also be mentioned that simulation of the BD is based on ideal vehicle and road surface conditions (dry). For less than ideal conditions—for example, poor brake condition, bad tires, and wet or icy road surfaces—the BD will be much longer.

The New Proposed Distance-Based Safety Indicator—MSDG

From the plots in Figure 3, BD models for each category of heavy vehicle are proposed. The proposed model incorporating GVW and travel speeds of the SUT can be expressed as Eq. (4):

$$BD_t = aw + b,$$

where $a = C_1 V + C_2$ and $b = C_3 V + C_4$, $BD_t$ is the braking distance for the truck in seconds, $w$ is GVW, and $V$ is speed.
First, regression was performed to determine the coefficients of the regression lines, $a$ and $b$ in Eq. (4), for various speed. The value of these coefficients and coefficients of determination, $R^2$, for all cases are described as in Table A5 (see online supplement). Another regression was performed to determine the coefficients of the regression lines $C_i$, where $i = 1, 2, 3$, and 4 in Eq. (4) and coefficients of determination, $R^2$, for all cases are described as in Table A6 (see online supplement).

The regression coefficients in Table A6 indicate that there is a positive straight line or linear relationship between BD and GVW. In this case, BD increases as GVW increases for medium- or high-speed cases. The BD variation is small for low-speed cases. In Eq. (4), the respective values of BD can be determined for the different VC and GVW at various speeds as shown in Table 2.

Using Eqs. (1), (3), and (4), for which BD is taken from Table 2, and with an RT value of 1.5 s, the respective values of MSDG can be determined for the different compositions of follower–leader pairs that are traveling at various speeds as shown in Table 2. As expected, the MSDG varies for different combinations of the FV’s VC, GVW, and travel speeds.
This study aims to investigate and establish a new distance-based safety indicator algorithm known as MSDG, which takes into account the gross vehicle weight, vehicle classification, and travel speed for various vehicle-following situations. It has been established that a vehicle’s braking performance is of utmost importance in relation to the vehicle’s braking distance and, hence, it has to be incorporated into the safety indicator. The simulation data (for vehicle BD) were generated during emergency stops on dry roads. This increases the possibility of rear-end collisions for heavy vehicles compared to other vehicles. It is envisaged that this safety indicator would provide a more realistic depiction of safety analysis in real traffic situations.

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### Supplemental Materials

Supplemental data for this article can be accessed on the publisher’s website.

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### Table 2. Proposed Model for Braking Distance (BD	extsubscript{t}) and Minimum Safe Distance Gap (MSDG)

| Vehicle Type | Braking Distance (BD	extsubscript{t}) | MSDG |
|--------------|-------------------------------------|------|
| 2 Axle       | 0.008 V	extsubscript{w} − 0.132 w  | 0.008 V	extsubscript{w} − 0.132 w |
|              | + 0.667 V − 19.299                  | + 1.73 V − 5.216                   |
| 3 Axle       | 0.017 V	extsubscript{w} − 0.502 w  | 0.017 V	extsubscript{w} − 0.502 w |
|              | + 0.404 V − 11.880                  | + 1.465 V − 2.203                  |
| 4 Axle       | 0.023 V	extsubscript{w} − 0.674 w  | 0.023 V	extsubscript{w} − 0.674 w |
|              | + 0.178 V − 4.620                   | + 1.239 V − 9.463                  |

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**Note:** BD	extsubscript{t} and MSDG are derived from a nonlinear regression model based on this study, which takes into account the gross vehicle weight (V	extsubscript{w}), vehicle size (V), speed (V), and vehicle classification (VC). The model aims to provide a more realistic depiction of safety analysis in real traffic situations.