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.

Result: 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 & Quek 1997; Matsui et al. 2013; Shariati-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 index 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 $d_i$ called the stopping distance (SD), becomes smaller than the safety distance $d_s$. The velocities $v_i, v_j$ in Eq. (3) are not preset values but are updated constantly, whereas the driver reaction time, $T$, and the decelerations $a_i, a_j$ 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 1s and 3.5s 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 $< 0$, 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 Saifzul 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

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of Stopping Distance (PSD) (Allen et al. 1978)</td>
<td>$P_{SD} = \frac{d_{PSD}}{d_{MAX}}$ (1)</td>
</tr>
<tr>
<td>Stopping Distance Algorithm (SDA) (Wilson et al. 1997)</td>
<td>$d_{SD} = \frac{v_i - v_j}{R_T} + \left(\frac{v_i^2 + v_j^2}{2vt}\right)$ (3)</td>
</tr>
<tr>
<td>Potential Index for Collision with Urgent Deceleration (PICUD) (Yam et al. 2010)</td>
<td>$\text{PICUD} = \frac{d_{SD}^2}{a_j} + \frac{S_i}{V_j} - \frac{v_i}{\Delta t}$ (4)</td>
</tr>
<tr>
<td>Unit: meter PMD (predicted minimum distance) (Polychronopoulos et al. 2004)</td>
<td>$d = \text{distance(m)}$ $X_{k+i} = \text{minimum unbiased Estimator}$ $X_{k+i} = \text{fused estimator}$ $P_{MD} = \min p_{SD}(k+i)$ $i = 1, \ldots, \text{max point}$</td>
</tr>
</tbody>
</table>

**Notes:**
- TTC: Time-to-Collision
- PSD: Proportion of Stopping Distance
- SDA: Stopping Distance Algorithm
- PICUD: Potential Index for Collision with Urgent Deceleration
- PMD: Predicted Minimum Distance
- $d_{PSD}$: Remaining distance to the potential point of collision (m)
- $d_{MAX}$: Maximum acceptable stopping distance (m)
- $R_T$: Reaction Time (s)
- $a_j$: Acceleration for following vehicle (m/s²)
- $\Delta t$: Time to stop (s)
- PMD: Predicted Minimum Distance (m)
- Unit: meter
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/Track (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/Track: (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/Track. 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.

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