Safe Following Distance Analysis
for Traffic Cellular Automata Modelling

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Abstract—Following another vehicle too close is known as tailgating. Tailgater may not have enough space and time to avoid a collision. Thus there is a need for a fundamental understanding on factors affecting safe distance between vehicles. This paper aims to study such factors and to adopt certain rules and principles into the proposed traffic cellular automata model. Rule of seconds is applied and some deductions are made to attain a realistic traffic model. The simulation also entail human reaction time in perceiving safe distance with the leading vehicle and the simulation results are as expected. However there is a trade off between reaction time and an optimum safe following distance. Hence ideal reaction time of 0.75s is selected to emulate real life traffic flow without deteriorating traffic stability.

Keywords—safe following distance, safety margin, rule of seconds, traffic modelling, cellular automata

I. INTRODUCTION

Reliability of a traffic model can be significantly improved by accommodating to traffic dynamic problems. Dynamic problems can be understood as problems stated in terms of the changing input data. From the intelligent transportation system (ITS) point of view, traffic engineers have been looking into various angles such as vehicle tracking by modelling its trajectory [1], [2], by means of image processing approach [3], [4], and dispersing of congestions via traffic light optimization [5].

The purpose of this paper is to investigate another angle of traffic dynamic problems, the safe following distance between vehicles and to adopt certain rules in determining its value. Safe following distance is the safety margins between a driver and the leading vehicle. Driving too close to the leading vehicle leaves limited space for things to change abruptly [6], [7]. Although a driver has no control over the space left behind, but a driver can control the amount of space in front of them.

This paper is organized as follows: Section II discussed factors affecting safe following distance in detail. Section III adopts certain rules and principles, specifically in determining the safe distance between vehicles. Section IV presents the simulation results, analysis and discussion. Finally the overall project is concluded in Section V.

II. FACTORS AFFECTING SAFE FOLLOWING DISTANCE

All drivers need to be able to assess a safe following distance at all times, in all kinds of traffic, weather and road conditions. Failing to do so causing no room in the traffic stream to absorb disruptions, and minor accidents can easily lead to queuing of vehicles. Therefore, different literatures have suggested different distances parameters to accommodate different traffic scenario.

As depicted in Fig.1 safe distance may vary depending on several factors: (a) driver’s current speed; (b) driving conditions; (c) type of vehicle.

A. Driver’s Current Speed

Driving at high speed require longer time to stop and avoiding a collision. Whether or not a driver is judged to have been speeding or driving too fast, the fact he was involved in a collision indicates he was driving too fast to have ‘stopped in time’ (stopping distances). That means, speed is always a causal factor, although usually in combination with other factors.

Stopping distances is the amount of time from the moment the driver see a hazard to the moment the car comes to a complete stop (1).

\[ \sum d_{stopping} = d_{thinking} + d_{braking} \]  

(1)

where,

\[ \sum d_{stopping} \] is the total stopping distances
\[ d_{thinking} \] is the thinking distances
\[ d_{braking} \] is the braking distances

Fig. 1. Factor affecting safe following distance.

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Thinking distances \((d_{\text{thinking}})\) is the distance it takes for a driver to respond to any perceived potential threat, sign or traffic control on the road. For instance, when a driver perceives a threat on the road, there is an image that forms in the back of the eye that has to be transmitted along nerves in the brain. Then an impulse is transmitted from the brain through the spinal cord to the nerves in legs and then down to the muscles in the foot. Transmission time from the back of the eye to the foot is called the reaction time \((t_R)\).

Experienced drivers are approximated to react in 0.75s because some reactions are by instinct and some are practiced a lot. If a driver has been driving for a while, he can react quicker without having to think. The average driver reaction time is approximately 2s [8], [9]. Thus thinking distances also can be further formulated as in (2).

\[
d_{\text{thinking}} = t_R \times u
\]

where \(t_R\) is the reaction time and \(u\) is space mean speed.

Table I shows the estimation for a driver travelling at the speed of 90 km/h, subjected to various reaction time. During that 0.75s of an experienced driver, he is still travelling at 25 m/s, where the car is not decelerate nor accelerate. Based on (2), that amounts 0.75s for about 18.75m.

Braking distances is the phase it takes for a car to stop completely after the driver hits the brakes. There are at least two main factors that may affect braking distances: (a) type of vehicle, (b) road/driving condition. Technically as a car travelling twice as fast, it will take twice the time to stop (3).

\[
KE = \frac{1}{2}mv^2
\]

where,

\(KE\) is kinetic energy  
\(m\) is mass of the car  
\(v\) is speed of the car

An object’s kinetic energy also discloses how much work is needed to stop it. Work is the product of friction force and distance. Thus (3) can reformulate to (4) and (5).

\[
F \cdot d = \frac{1}{2}mv^2
\]

\[
d_{\text{stop}} = \frac{1}{2}mv^2
\]

Based on (5), as the car that travelling twice as fast, it will need four times the distance (also four times the work) to stop. That indicates every time a driver double the speed, the braking distance quadruples.

<table>
<thead>
<tr>
<th>(t_R)</th>
<th>(d_{\text{thinking}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75s</td>
<td>18.75m</td>
</tr>
<tr>
<td>1.00s</td>
<td>25.00m</td>
</tr>
<tr>
<td>1.50s</td>
<td>37.50m</td>
</tr>
</tbody>
</table>

**B. Type of Vehicle**

In an accident, trucks and busses often strike the vehicle directly in front of them because their heavy weight prevents them from stopping quickly. If the vehicle in front of a large truck is a smaller vehicle like a compact car, the compact car could decelerate at a much faster rate than the truck, then causing the truck to slam into the compact car’s rear end before it can stop. That means a vehicle’s weight and length do affect the total stopping distance. The classis physics theory defines the coefficient of friction (\(\mu\)) as constant, and the friction force can be formulated as in (6).

\[
F = \mu N = \mu mg \tag{6}
\]

By substituting (6) into (5) and rearranging as in (7), causing the mass to be cancelled out from the equation. The absence of mass from (7) is where the confusion about mass not affecting friction comes from since both forces increase linearly at the same rate.

\[
d_{\text{stop}} = \frac{v^2}{2\mu g} \tag{7}
\]

However conventional pneumatic tires are non-linear in real life and it does not act according to the classical friction theory. This specific condition of tires can be characterised as ‘tire load sensitivity’, where in their standard operating range, the coefficient of friction effectively reduces with vertical load \((F_z)\) increases [10], [11] (see Fig.2).

According to Coulomb theory, the maximum horizontal force should be proportionate to the vertical load on a tire. Although in practice, the maximum lateral/horizontal force that can be formed does increases as the vertical load escalates, but at a diminishing rate.

To fathom tire load sensitivity better, assume friction force is used and both vehicles (a truck and a car) use the same rubber compound on their tires and other factors such as wind resistant remain constant. If both cars travelling at 90 km/h, and let to decelerate, the friction force needed to bring both vehicles to a halt can be re-formulated as in (8).

\[
F_{\text{friction}} = \mu_0(m_0g)^\alpha \tag{8}
\]

where,

\(\mu_0\) is the coefficient of friction measured at load \(m_0\)  
g is the gravity (9.8 ms\(^{-2}\))  
\(\alpha\) is an exponent ranges between 0.7 and 0.9 (usually approximated at 0.8).

![Fig. 2. Forces acting on tire.](image-url)
Therefore, the stopping distance in (5), with regard to the mass of the vehicle can be re-formulated as in (9) - (11).

\[
d_{\text{stop}} = \frac{1}{2f_{\text{friction}}} m a v^2
\]  

(9)

\[
d_{\text{stop}} = \frac{m a^2}{2(\mu g a)}
\]  

(10)

\[
d_{\text{stop}} = \frac{m a^2 a^2}{2(\mu g a)}
\]  

(11)

C. Driving Conditions

As discussed earlier, an experienced driver take about 0.75s to react, but the total stopping distances could be affected by the surrounding factors such as road surface, slope or ramp and alignment on the road, as well as weather conditions. During daylight with good, low traffic volume and dry roads, drivers are suggested to maintain a safe distance from the car ahead by following the ‘three second rule’ (or ‘two second rule’ in some countries) [12]. A dry road that is sealed and level facilitates enough friction between the tires and the road thus enable the car to stop earlier.

Driving in wet weather condition requires gentle control over the vehicle’s system (steering, clutch, brake and accelerator) and a larger room for errors. Furthermore it is more challenging to see other vehicles, road signs and the road itself (see Fig.3). If the weather conditions are extremely poor, drivers are recommended to triple the three-second rule to nine seconds to determine the safe following distance (rule of seconds will be discussed further in next section).

Table II shows how coefficient of friction (\(\mu\)) of asphalt varied depends on the driving condition [13].

<table>
<thead>
<tr>
<th>Case</th>
<th>Condition</th>
<th>(\mu)</th>
<th>Rule of seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>Dry road is sealed and level enable adequate friction between tires and road.</td>
<td>0.50 – 0.90</td>
<td>3s</td>
</tr>
<tr>
<td>Non-ideal</td>
<td>Wet weather causing wet road that is sealed and level has less friction.</td>
<td>0.25 – 0.75</td>
<td>Light rain: 6s Heavy rain: 9s</td>
</tr>
</tbody>
</table>

D. The Rule of Seconds

Braking distances increase exponentially with speed, and it is interdepended to safe following distance. If a driver has adequate safe following distance with the leading vehicle (safe distance), then the driver would have been able to ‘brake in time’ (braking distances) to avoid collision.

As discussed earlier, different type of vehicle can affect the safe following distance to a great extent. If a heavier vehicle (longer vehicle tends to be heavier) travelling too close to a compact car, there is a higher chance for the heavy vehicle to slam into the compact car’s rear end, and the impact would be devastated. The American Association of Motor Vehicle (AAMV) has been included a technique called ‘The Rule of Seconds’ in the Commercial Driver’s Manual [14]. This technique not only applicable to trailer drivers but all drivers in general could practice this technique for road safety. Therefore, safe following distance can be determined by taking the three factors (driver’s current speed; driving conditions; type of vehicle) into consideration in applying the rule of seconds.

So, what is this rule of seconds about? Think about a trailer traveling at the speed of 90 km/h, which is also at 25 m/s. According to the rule of seconds, drivers are required to allow one second’s worth of travel distance for every 3m of the length of their trailer, plus ‘one extra second’ for safety between themselves and the leading vehicle.

If the length of the trailer is 12m (common commercial trailer in Malaysia may range from 10m to 12m), the driver should keep 125m behind the leading vehicle when travelling at 90 km/h. That is about 25-car length between the trailer and the leading vehicle (see Fig.4).

III. ADOPTING SAFE FOLLOWING DISTANCE IN TRAFFIC CELLULAR AUTOMATA MODELLING

Based on the contributing factors discussed above, this section aims to implement an optimum safe following distance value onto traffic cellular automata model. However, not all factors can be modelled directly into traffic simulation.

For example, tire load sensitivity cannot be applied to determine a car’s safe following distance precisely (e.g.: to compare safe following distance for two different vehicles with different mass, such two vehicles would have two different coefficient of friction, \(\mu\), where \(\mu\) decreased as the mass increased, thus resulted in two dependent variables), although it can be deduced that heavier vehicle requires longer stopping distance based on (11).

Nonetheless safe following distance still can be incorporated into TCA model by applying the rule of seconds, where one second’s worth of stopping distance is added for every 3m of the length of the vehicle.

Fig. 3. Effect of road condition on braking distance.

Fig. 4. Rule of seconds for safe following distance between vehicles (assuming average car length is 5m).
Equation (12) shows vehicle’s length (l) is divided by 3m and added to driver’s reaction time (t_R), then multiplied by current space mean speed (u).

\[ d_{SPD} = \frac{u_x}{3} + t_R \]  

(12)

where,
- \( u_x \) is vehicle space mean speed (ms^{-1})
- \( d_{SPD} \) is the actual safe following distance (m)
- \( l \) is vehicle length (m)
- \( t_R \) is driver’s reaction time (s)

Equation (13) shows the safe following distance in term of number of cell on cellular automata modelling.

\[ d_{cell} = \frac{u_x \times t_R}{w_{cell}} \]  

(13)

where,
- \( d_{cell} \) is the safe following distance (cell)
- \( w_{cell} \) is width of the cell (m)

As the interest of this research is to analyse the influence of driving behaviour on traffic flow, specifically tailgating, thus other external factors such as road condition is assumed ideal.

Table IV summarises the parameters set to acquire the safe following distance. Based on (13), Table V shows the analysis for safe following distance subjected to three different level of reaction time (t_R).

![Fig. 5. Adopting rule of seconds in TCA modelling.](image)

**TABLE IV. ADOPTING SAFE FOLLOWING DISTANCE PARAMETERS**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average vehicle length</td>
<td>5m</td>
</tr>
<tr>
<td>Average occupied space</td>
<td>7.5m</td>
</tr>
<tr>
<td>Reaction time (experienced)</td>
<td>0.75s</td>
</tr>
<tr>
<td>Reaction time (average)</td>
<td>1.00s</td>
</tr>
<tr>
<td>Reaction time (inexperienced)</td>
<td>1.50s</td>
</tr>
<tr>
<td>Road condition</td>
<td>Dry</td>
</tr>
<tr>
<td>Rule of seconds</td>
<td>1sec/3m</td>
</tr>
<tr>
<td>Maximum speed on highway</td>
<td>110 km/h</td>
</tr>
<tr>
<td>Maximum speed on non-highway</td>
<td>90 km/h</td>
</tr>
</tbody>
</table>

**TABLE V. SAFE FOLLOWING DISTANCE SUBJECTED TO DIFFERENT REACTION TIME**

<table>
<thead>
<tr>
<th>( v_{max} ) (m/s)</th>
<th>( t_R ) (s)</th>
<th>( d_{minit} ) (m)</th>
<th>( d_{SPD} ) (m)</th>
<th>( d_{cell} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.50</td>
<td>0.75</td>
<td>5.63</td>
<td>18.13</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>7.50</td>
<td>20.0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>11.25</td>
<td>23.75</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>15.00</td>
<td>0.75</td>
<td>11.25</td>
<td>36.25</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>15.00</td>
<td>40.00</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>22.50</td>
<td>47.50</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>22.50</td>
<td>0.75</td>
<td>16.88</td>
<td>54.38</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>22.50</td>
<td>60.00</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>33.75</td>
<td>71.25</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>30.00</td>
<td>0.75</td>
<td>22.50</td>
<td>72.50</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>30.00</td>
<td>80.00</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>45.00</td>
<td>95.00</td>
<td>13</td>
</tr>
</tbody>
</table>

Relationship between TCA speed (cell/s) and actual speed on road (km/h). If a car on TCA platform is travel at \( v = 1 \) cells (3,600 cell/hour). Then actual speed on road is 3,600*7.5 = 27 km/h. So, \( \frac{v}{v} = \frac{27}{54} \text{ km/h} \).

**TABLE III. DIFFERENT TYPE OF VEHICLE AND ITS LENGTH IN MALAYSIA**

<table>
<thead>
<tr>
<th>Type</th>
<th>Model</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact car</td>
<td>Perodua Kancil</td>
<td>3.395</td>
<td>1.405</td>
<td>1.413</td>
</tr>
<tr>
<td></td>
<td>Perodua Viva</td>
<td>3.575</td>
<td>1.457</td>
<td>1.530</td>
</tr>
<tr>
<td></td>
<td>Perodua Axia</td>
<td>3.640</td>
<td>1.620</td>
<td>1.510</td>
</tr>
<tr>
<td>Sedan</td>
<td>Proton Saga</td>
<td>4.331</td>
<td>1.689</td>
<td>1.491</td>
</tr>
<tr>
<td></td>
<td>Toyota Vios</td>
<td>4.300</td>
<td>1.700</td>
<td>1.460</td>
</tr>
<tr>
<td></td>
<td>Honda City</td>
<td>4.517</td>
<td>1.705</td>
<td>1.489</td>
</tr>
<tr>
<td>SUV</td>
<td>Honda CRV</td>
<td>4.587</td>
<td>1.854</td>
<td>1.689</td>
</tr>
<tr>
<td></td>
<td>Toyota Land Cruiser J300</td>
<td>4.950</td>
<td>1.970</td>
<td>1.880</td>
</tr>
<tr>
<td></td>
<td>Range Rover</td>
<td>4.999</td>
<td>2.073</td>
<td>1.835</td>
</tr>
<tr>
<td>MPV</td>
<td>Toyota Avanza</td>
<td>4.120</td>
<td>1.630</td>
<td>1.695</td>
</tr>
<tr>
<td></td>
<td>Toyota Alphard</td>
<td>4.480</td>
<td>1.805</td>
<td>1.935</td>
</tr>
<tr>
<td></td>
<td>Toyota Innova</td>
<td>4.555</td>
<td>1.770</td>
<td>1.750</td>
</tr>
<tr>
<td>Van</td>
<td>Honda Odyssey</td>
<td>4.830</td>
<td>1.820</td>
<td>1.685</td>
</tr>
<tr>
<td></td>
<td>Toyota Sienna</td>
<td>5.085</td>
<td>1.986</td>
<td>1.796</td>
</tr>
<tr>
<td></td>
<td>Toyota Hiace</td>
<td>5.380</td>
<td>1.880</td>
<td>2.105</td>
</tr>
<tr>
<td>Truck</td>
<td>Toyota Hilux</td>
<td>5.260</td>
<td>1.760</td>
<td>1.810</td>
</tr>
<tr>
<td></td>
<td>Nissan Navara</td>
<td>5.255</td>
<td>1.850</td>
<td>1.820</td>
</tr>
<tr>
<td></td>
<td>Ford Ranger</td>
<td>5.359</td>
<td>1.850</td>
<td>1.815</td>
</tr>
</tbody>
</table>

Dimension taken for most models are based on 2014-2018 generation, which are the most commonly used. As for the discontinued models but still on the road, the dimension is based on their last generation.
IV. MODELLING RESULTS & DISCUSSIONS

The proposed traffic cellular automata model is developed based on the famous Nagel-Schreckenberg prototype model [17]. The construction of the TCA road structure allows the moving pattern of the vehicles not to be merely random but also having structured and repetitive behaviour, which is imperative in calculating a credible safe distance value between vehicles [18]. Fig. 6 shows the simulation results of a typical traffic model. Most models use the common approach to avoid collision, where each vehicle is set to decelerate as in (14). Table VI shows the input parameters fed into the traffic model.

\[ d_{\text{cell}} < \bar{u}_v + 1 \]  

(14)

where,

- \( d_{\text{cell}} \) is the distance between vehicles in term of cell
- \( \bar{u}_v \) is the following vehicle’s space mean speed

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>road length</td>
<td>133 cells</td>
</tr>
<tr>
<td>number of sample</td>
<td>20</td>
</tr>
<tr>
<td>maximum speed limit</td>
<td>4 cell/s</td>
</tr>
</tbody>
</table>

TABLE VI. PARAMETERS SET UP

Fig. 6a – Fig. 6d are part of the iterations under one simulation. The actual width of the traffic platform is 1km in length (7.5m * 133 cells ~1km). Fig. 6a shows the 5th iteration of the simulation, with three cars just entered the traffic stream. Car-1, car-2 and car-3 are at cell-11, cell-4 and cell-1 respectively. At this iteration, all cars are having good safety margin with respect to each individual speed. For example, car-2 at cell-4 is moving at speed of \( v = 2 \) (54 km/h) and has gap of 7 cells (7 * 7.5m = 52.5m) with car-1. Hence, car-2 has enough time and space for things to change abruptly. Fig. 6c shows a risky situation at the 30th iteration, with most cars on the platform traveling at speed of \( v = 4 \) (108 km/h) and small separation gap with the leading vehicles. Although the crash can be avoided based on (14), however in real life there is really no time and space to stop in time.

To improve the reliability of the TCA model and to reflect safe driving behaviour on road, new rules have been incorporated into the proposed model. Table VII shows the additional safe following distance rules. The same input parameters from Table VI are fed into the traffic model. The generated results are as expected (see Fig. 7).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>when ( v = 1 )</td>
<td>( d_{\text{cell}} = 2 )</td>
</tr>
<tr>
<td>when ( v = 2 )</td>
<td>( d_{\text{cell}} = 5 )</td>
</tr>
<tr>
<td>when ( v = 3 )</td>
<td>( d_{\text{cell}} = 7 )</td>
</tr>
<tr>
<td>when ( v = 4 )</td>
<td>( d_{\text{cell}} = 9 )</td>
</tr>
</tbody>
</table>

TABLE VII. RELATIONSHIP BETWEEN SAFE FOLLOWING DISTANCE AND SPEED

Fig. 6. Vehicle-Speed Distribution with conventional collision avoidance.

Fig. 7. Relationship between safe following distance and vehicle speed.
Note that only part of the traffic flow results is shown here for optimum visualisation purpose. Fig. 7a shows car-A at speed of $v = 1$ travelling behind car-B with $d_{SGD} = 18.13$m, and car-B at speed of $v = 2$ travelling behind car-C with $d_{SGD} = 36.25$m. Fig. 7b shows car-D at speed of $v = 3$ travelling behind car-E with $d_{SGD} = 54.38$m; Fig. 7c shows car-F at speed of $v = 4$ travelling behind car-G with $d_{SGD} = 72.50$m.

Table VII also shows the traffic model is based on the best-case scenario of drivers’ reaction time, which is approximated at 0.75s. Further simulations show longer reaction time that leads to a supposedly longer safe distance between vehicles could backfire. Bigger safety margins between vehicles can be viewed as a product of timid driving behaviour. Some researchers found that timid driving behaviour may contribute to traffic instability [19]. References [20], [21] also reckon timid driving behaviour is a much bigger contributor than aggressive driving behaviour in traffic jam. This may due to the aggressive drivers tend to react promptly to the change of speed of the leading car.

V. CONCLUSIONS

This paper starts with an overview of dynamic traffic that can be understood as problems stated in terms of changing input data. Given the dynamic nature of the road traffic flow, safe following distance between vehicles can be affected by combinations of numerous factors such as driver’s current speed, driving conditions and type of vehicle. Therefore this paper aims to study the rule of seconds and implementing realistic traffic parameters to determine safe following distance value. Although crash can be avoided in conventional collision avoidance approach, however it does not really reflect the real traffic nature. The proposed TCA model results show a more realistic traffic nature when factors such as human reaction time and vehicle length are put into consideration. However there is a trade off between reaction time and optimum safe following distance between vehicles. The simulation results reveal optimum safe distance can be attained when the best-case scenario of human reaction time (0.75s) is applied. However, a slower reaction time creates a bigger safety margins between vehicles and often view as a timid driving behaviour and further deteriorate traffic stability.

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