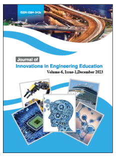

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Analysis of vehicle braking dynamics with hydraulic braking system

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Abstract

The stopping distance in vehicle is the distance require to safely stop after the driver has applied the brakes of vehicle. The stopping distance varies from road types to experience of driver. The objective of this study is to determine the stopping distance of vehicle for two different road condition: dry asphaltic and wet asphaltic. The methodology includes studying various factors involve in braking dynamics and validating the analytical calculation with Numerical methods. The velocity in which vehicle is travelling, coefficient of friction between road and vehicle tire plays important role in calculation of stopping distance. It was found that during wet season the stopping distance increased from 89 m to 99 m for vehicle travelling at 100 km/hr. The stopping time obtained from simulation in CarSim was 5.1 seconds for dry road and 6.4 seconds for wet road conditions.

1. Introduction

Braking dynamics refers to the science of designing and analyzing braking systems in vehicles to ensure safe and efficient deceleration. This involves studying the various factors that influence braking performance, including the design of brake components, tire friction, road surface conditions, and vehicle weight distribution. The goal of braking dynamics is to optimize braking performance in terms of stopping distance, stability, and comfort.

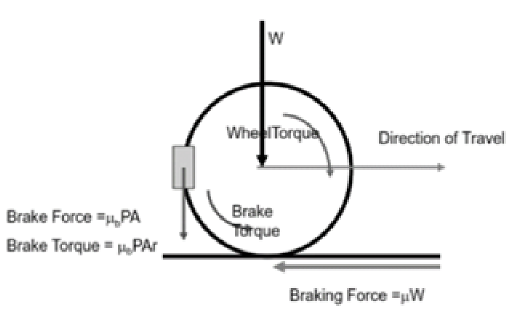

Figure 1: Forces acting during braking

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The braking distance is the distance a vehicle travels from the time the brakes are applied until it comes to a complete stop. It depends on several factors such as the speed of the vehicle, the road conditions, the tires, and the braking system. In general, the higher the speed, the longer the braking distance. The various force acting on wheel while braking is shown in Figure 1. (where PA is the actuation force and W is the weight of vehicle.) It is essential to understand the brake dynamics to safely stop the vehicle when brakes are applied in emergency.

2. Objectives

Braking performance is highly affected by surface of road like dry, wet, bitumen, concrete etc. The main aim of these article is to study the effect of road type in determining the safe stopping distance. The specific objective is:

1. To calculate the stopping distance of a vehicle considering the dry and wet road conditions.
2. To simulate the vehicle and compare the results.

3. Literature Review

Road accident has been leading cause of death and injuries worldwide[1]. The major factors causing road accidents in Nepal and worldwide ranges from road conditions, driver's response time and weather conditions[2]. Driver's error contributes up to 75 % of roadway accidents[3]. The reaction time of drivers to the obstacle can change rapidly depending upon the factors such as workload, fatigue, willingness to work and motivation[4]. The basic calculation for stopping distance of vehicle can be divided into two components: the distance travelled by vehicle after the driver has seen the obstacle (brake reaction distance) and distance travelled by vehicle to once the brake has been applied braking distance). Fambro et al. [5] claims driver's performance, driver visual capabilities, driver eye and vehicle heights have major roles in determining stopping distance. Determining the safe stopping distance to avoid accident is not only the part of driver; environmental factors, road conditions, vehicle conditions and other road users are also responsible for causing traffic accidents. Figure 2 shows the various time taken by vehicle to completely halt to rest.

a:Driver reaction duration (721 ms), b:Braking system reaction duration(316 ms), c:Brake pressure increase duration (428 ms), d:Efffective braking duration(712 ms), e:Low acceleration raking duration(296 ms)

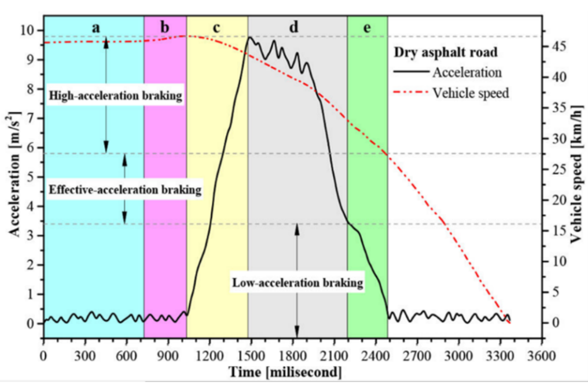

Figure 2: Variation of braking acceleration and vehicle speed depending on time

4. Research methodology

4.1. Mathematical modelling

The stopping distance (SD) due to vehicle speed and human errors is given by equation 1, [6].

$$\mathrm{SD} = \left(V\left(T_r \times k_{\mathrm{exp}} + k_{\mathrm{bs}} - RT + T_{\mathrm{dd}}\right) + \frac{V^2}{2 \times g}(f \pm G)\right) \times k_{\mathrm{bp}} \tag{1}$$

where V is the vehicle speed in km/h, Tr is the reaction time in s, g is the gravitational acceleration in m/s, kexp is the driver experience in %, . kbs-RT is the response time of brake system in s, Tdd is the driver distraction time in s , f is the road friction coefficient, ±G is the road gradient in %, kbp is the braking performance coefficient depending on the type of tire, tire thread and road type in %, reaction time Tr was calculated using equation 2[7] which takes into account of drivers age, gender and vehicle speed.

$$T_r = 0.002 \cdot \mathrm{Age} + 0.035 \cdot \mathrm{Gender} + 0.001 \cdot V + 0.017 \cdot d \tag{2}$$

Where V is the vehicle speed in km/hr., age is the driver age in years, gender (driver's) for male is 0 and female is 1, d is the safe stopping distance in meter. The effect of driver's age, driver gender and driver experience on stopping distance is not considered here as the it only contributes <3% in total[8].

Table 1: Coefficient of friction according to the road type and surface[9]

Road Surface Type	**Coefficient of Friction (μ)**
Gravel and dirt road	0.35
Wet, grassy field	0.2
Dry asphaltic concrete	0.65
Wet asphaltic concrete	0.50
Dry concrete	0.75
Wet concrete	0.60
Snow	0.20–0.25
Ice	0.10–0.15

The stopping time (ST) is given by equation 3, [10].

$$ST = \frac{V}{D} \tag{3}$$

Where V is velocity of vehicle in km/hr., and D is the deceleration of vehicle after the brakes has been applied.

4.2. Assumptions

- Road is straight with no curves.
- For temperature >7 °C, brake performance coefficient is 50% [11]; $k_b = 0.5$.
- K_{exp} for beginning level driver with experience <6 years is 0.8, fairly experienced driver with 6-20 years' experience is 0.84, experienced driver with >21 years experience is 0.74 [7]; $K_{\mathrm{exp}} = 0.84$.
- Driver distraction time, T_{dd}, is 2 s [12].
- Response time of brake system usually lies between 0.1 to 0.4 s [13], so $k_{\mathrm{bs\text{-}RT}} = 0.2$ s.
- $g = 9.81$ m/s^2.

4.3. Determination of stopping distance

The stopping distance mainly concerned when the vehicle is prone to accident. The risk of accident mainly depends upon velocity of vehicle [14]. The human factor including gender, age, scenario, drivers experience, driving intensity could affect the stopping distance[15]. The condition of vehicle, weather conditions, road condition, tire conditions, brake pedal pressure also plays role in determining the actual stopping distance [16] Figure 3 shows standard of stopping distance of different country.

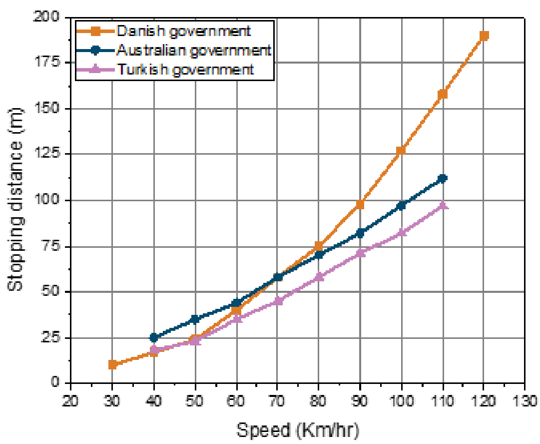

Figure 3: Danish[17], Australian and Turkish[8] government standard for braking distance.

The stopping distance based on equation 1 for two different road condition is shown in Figure 4. The road condition referred as wet road is wet asphaltic road with the value of coefficient of friction as 0.5 and the dry road is the dry asphaltic road with value of coefficient of friction as 0.65. The stopping distance for the wet road is 99 m when the brakes are applied of the vehicle travelling 100 km/hr. Similarly, the stopping distance for the dry road condition is 89 m at same speed. It can be seen that the vehicle travelling in wet road needs more stopping distance.

The stopping time depends upon the weight of vehicle being used and the velocity in which the vehicle is travelling. Figure 5 shows the stopping time against velocity in which vehicle is travelling. It can be seen that time needed to completely stop the vehicle travelling at 100 km/hr is 3.6 seconds for wet road and 2.9 seconds for dry road.

4.4. Vehicle dynamics model

CarSim is a multi-body vehicle dynamics software with real time simulation capability. The vehicle mass properties, brake dynamics, steering dynamics, aerodynamics, power train, suspension, tire dynamics can be easily evaluated using CarSim. Different vehicle models with different road conditions can be created in CarSim. The CarSim vehicle model can be linked to Simulink model for further analysis. The final stopping distance, braking dynamics, stopping time, and force for braking can be viewed in CarSim. The results can be viewed through various graphical plots and 3D animations. Figure shows a model of vehicle used for analysis of this research work.

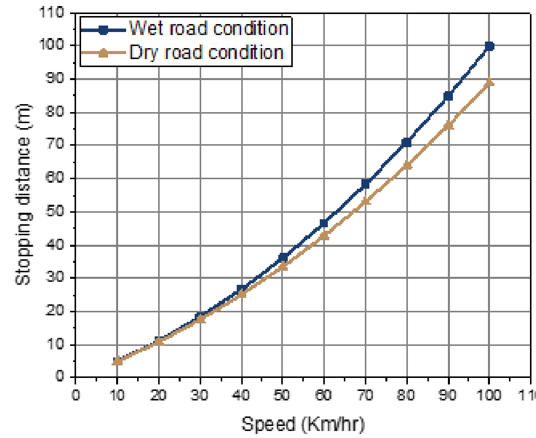

Figure 4: Stopping distance for different road condition

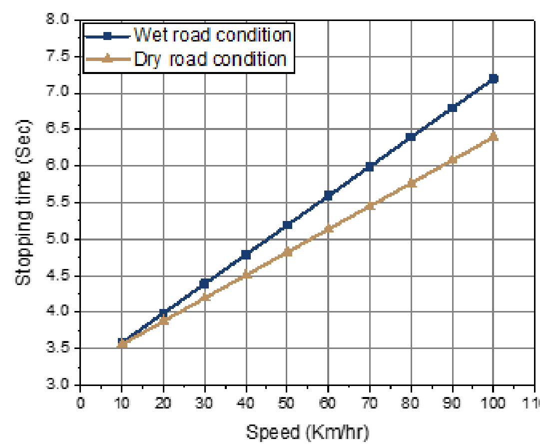

Figure 5: Stopping time needed for vehicle traveling at different speed

Aerodynamics drag model

The effect of aerodynamics can be studied in CarSim. But it has not been be considered in this simulation. At 100 km/hr if the drag coefficient of vehicle is 0.411, the braking distance can be reduced up to 7% [18]. The vehicle used in simulation has drag coefficient of 0.28, thus it

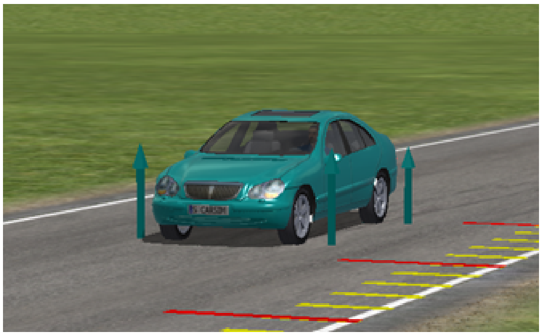

Figure 6: vehicle used for simulation

has no major contribution in stopping distance.

Road model

The effect of road curvature, grade, friction coefficient plays major role in stopping distance[13]. For the simplicity of our calculation, the author has considered the straight road with friction coefficient shown in table 1.

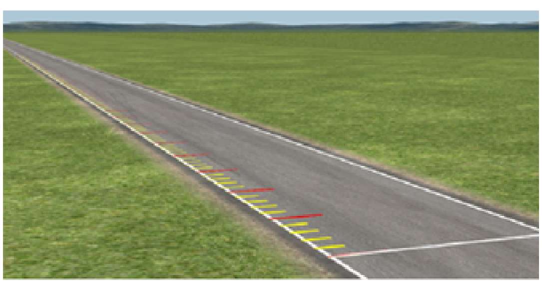

Figure 7: Road model used for analysis

Brake model

There is various brake model available such as hydraulic, electric, pneumatic, brake in all four wheels, brake only in two wheels etc. The hydraulic brake was chosen for analysis. The brakes were not equipped with ABS. The brake master cylinder was given spike value of 5 MPa at 10 sec after the vehicle was started with 100 km/hr. speed. This is because average drivers apply around 5 MPa force on cylinder[13]. The time taken resembles that vehicle has been in speed of 100 km/hr for 10 second and brakes are suddenly applied.

Vehicle model

There are various types of car model available for analysis. These vehicle range from A class hatch backs to E class sedans, but not limiting to SUVs, van, pickup vehicles, and utility vehicles. The vehicle chosen was Sedan of E type with engine capacity of 250 KW, 7 speed gear. The dimension of vehicle can be seen in figure.

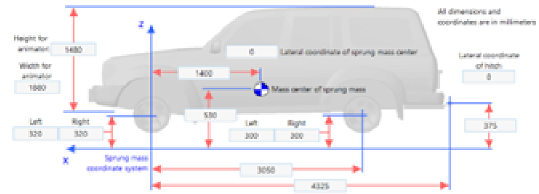

Figure 8: Dimensions of vehicle used in simulation

Procedure

The vehicle was given the initial velocity of 100 km/hr. The road condition was as shown in Figure 7. The road was straight with varying coefficient of friction. The friction coefficient for dry road condition was 0.65 whereas friction coefficient for wet road condition was 0.5. The analysis was carried out for vehicle beginning with 100 km/hr. until the vehicle reached 0 km/hr. All the other parameters such as aerodynamics coefficient, road conditions, vehicle model and brake model were same for both analyses. Additional settings related to driver control such as speed limit, braking with ABS, Steering mechanism were not included in this analysis. The built in solvers were used as mathematical model for analysis. The time step for analysis was default, meaning the simulation was supposed to end as the vehicle come to rest.

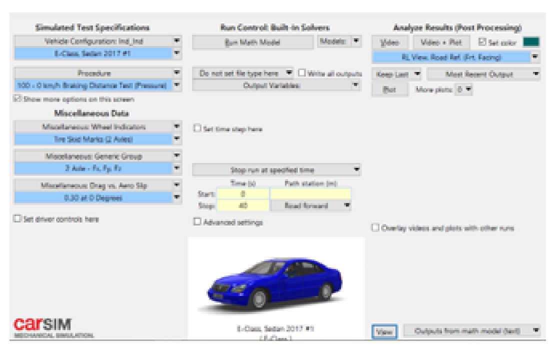

Figure 9: Procedure in CarSim

5. Results and discussion

The results CarSim shows that the stopping distance for wet road condition is 92 m at 100 km/hr. Similarly, the stopping distance for dry road condition is 73 m at 100 km/hr. The difference between these two distances is due to the coefficient of friction between road and tire. The results can be seen in Figure 10 . The stopping time for dry road conditions is 5.1 seconds. It can be seen from Figure 11 that the vehicle travellng at 100 km/hr. takes 5.1 seconds to fully stop.

The stopping time for vehicle travelling in wet road can

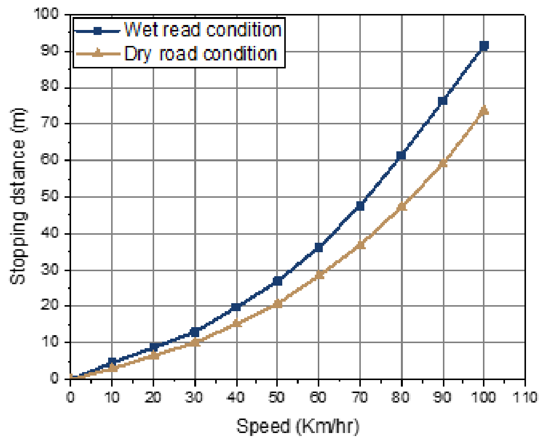

Figure 10: stopping distance for different road conditions

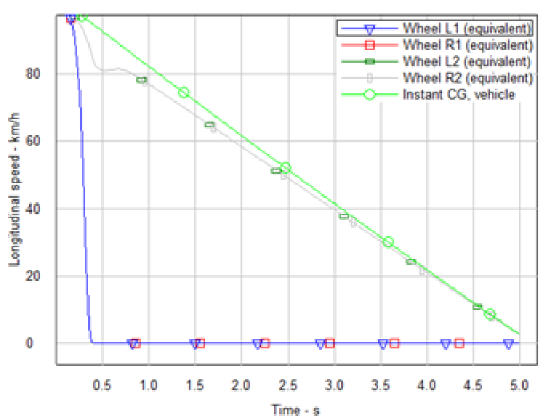

Figure 11: Stopping time for dry road

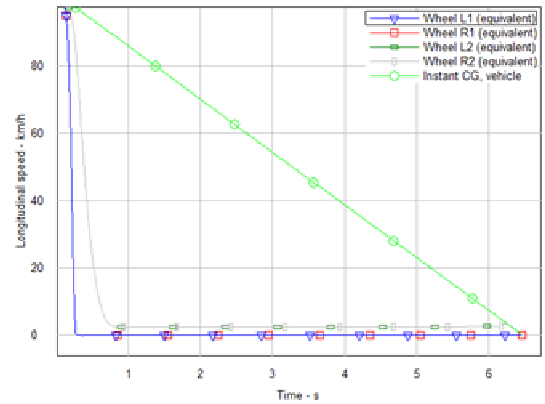

Figure 12: stopping time for wet road

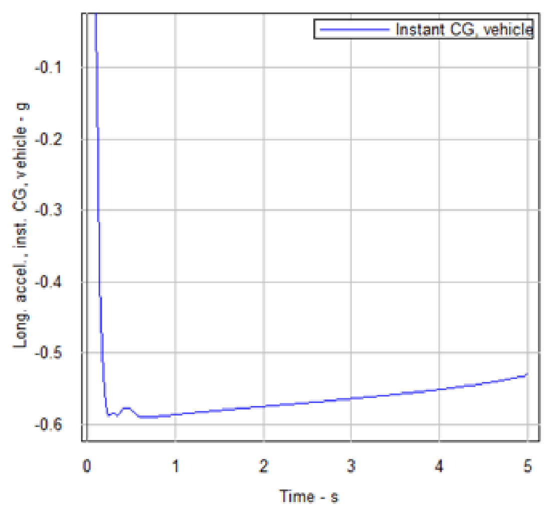

Figure 13: Retardation of vehicle for dry road

be seen in Figure 12. It takes nearly 6.6 seconds for vehicle to completely stop when brake is applied after the obstacle has seen. The simulation shows the difference in vehicle CG and other 4 wheels. Although the final stopping time is similar, this could be due to fact that load shifts toward front when brakes are suddenly applied [19] and the vertical displacement of CG depends upon the suspensions which in fact determine the position of vehicle when brakes are applied [20].

The stopping time calculated analytical for vehicle travelling at 100 km/hr was 7.2 seconds in wet road and 6.4 second in dry road (Figure 5). The simulation data shows the vehicle stops 0.6 second early in wet road and 1.3 seconds early in dry road. It may be due to property of tire and vehicle geometry which has not been considered while calculating analytically.

The acceleration with which the vehicle stops can be seen in Figure 13 and Figure 14. The acceleration in dry road reaches to maximum -0.55 g (5.39 m/s^2) at 5 seconds. Similarly, the acceleration reaches to maximum of -0.45g (4.41 m/s^2) at 5.5 seconds in wet road conditions. The authors [5] [21] have defined a range as 3.4-5.8 m/s^2 for effective braking. Similarly, Authors [22] [23] have defined an upper limit up to 10m/s^2 for the effective braking. On the other hand, retardation is directly proportional to coefficient of friction, which can be seen in both dry and wet conditions.

The forces in tire of vehicle can be seen in Figure 15. Before starting to retardate there was equal forces in both the tire,however the tire forces increase in front when brakes were applied. This is due to the tire characteristics such as tire dimensions, slip ratio, longitudinal stiffness, contact patch length, inflation pressure, peak tire/road adhesion coefficient and vertical load [23]. If the wheel with ABS is used the stopping distance could be decreased [24]. The results could vary if the vehicle's weight is to be considered.

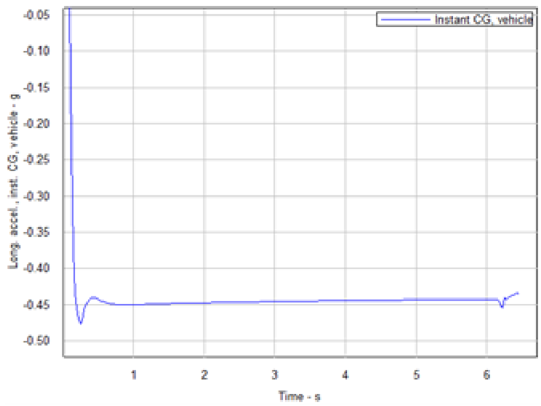

Figure 14: Retardation of vehicle for wet road

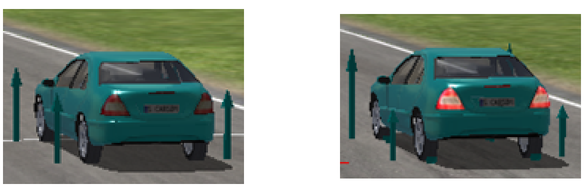

Figure 15: Vehicle wheel forces during starting vs during braking

6. Conclusion

The stopping distance of vehicle travelling with the speed of 100 km/hr. is carried out. The effect of friction on road surface has been studied. There are various forces to be considered while calculating the stopping distance. The stopping distance was also calculated using simulations.

- The stopping distance for a vehicle traveling at 100 km/hr is 99 m in dry road conditions and 89 m in wet road conditions.
- The comparisons between stopping distances show variations of small magnitude: 7% in dry road conditions and 17% in wet road conditions. Similarly, the stopping time variations are 8% for dry road conditions and 20% for wet road conditions.

The simulation for dry road conditions can be considered validated and can be used a reliable tool for simulation of vehicles in straight road conditions.

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