

# Simulation of Vehicle Steering Angle and Lateral Acceleration in Mitigating Potential Run-Off-Road Crashes

D. M. Cham<sup>\*1</sup>, M. Shanmugavel<sup>1</sup> and V. R. Sampathkumar<sup>1</sup>

<sup>1</sup>Department of Mechatronics Engineering, School of Engineering, Monash University Malaysia, 47500 Selangor, Malaysia

<sup>\*</sup>Corresponding author: da.cham@monash.edu

ORIGINAL ARTICLE

Open Access

## Article History:

Received  
29 Apr 2017

Received in  
revised form  
25 July 2017

Accepted  
25 Aug 2017

Available online  
1 Sep 2017

**Abstract** – This paper proposes and presents the preliminary results of an integrated safety warning system for road vehicles based on lateral g-force monitoring. The proposed system issues a warning to the driver when the lateral load increases above a threshold level thereby reducing the risk of run-off-road crashes and loss of control. From the vehicles dynamic model, soft and hard speed limits are obtained. When the soft limit is breached, it warns the driver using a LED, and when the hard limit is breached, assistive braking is activated. Simulations were conducted to obtain the safe vehicle speed for various steering angle to ensure the lateral g-force remains in the range of 0.7 and 0.9. Vehicle parameters of the Proton Saga 1.3L were used for simulation. Simulation runs to study the effects of changes in steering-wheel angle and vehicle speed on the variation of lateral acceleration was performed, based on which a safe speed is obtained. Simulations were also conducted on both banked and unbanked roads. The results of this study would help in the design of a working prototype of the safety system.

**Keywords:** Driver warning system, steering limit, speed limit

**Copyright** © 2017 Society of Automotive Engineers Malaysia - All rights reserved.  
Journal homepage: [www.journal.saemalaysia.org.my](http://www.journal.saemalaysia.org.my)

## 1.0 INTRODUCTION

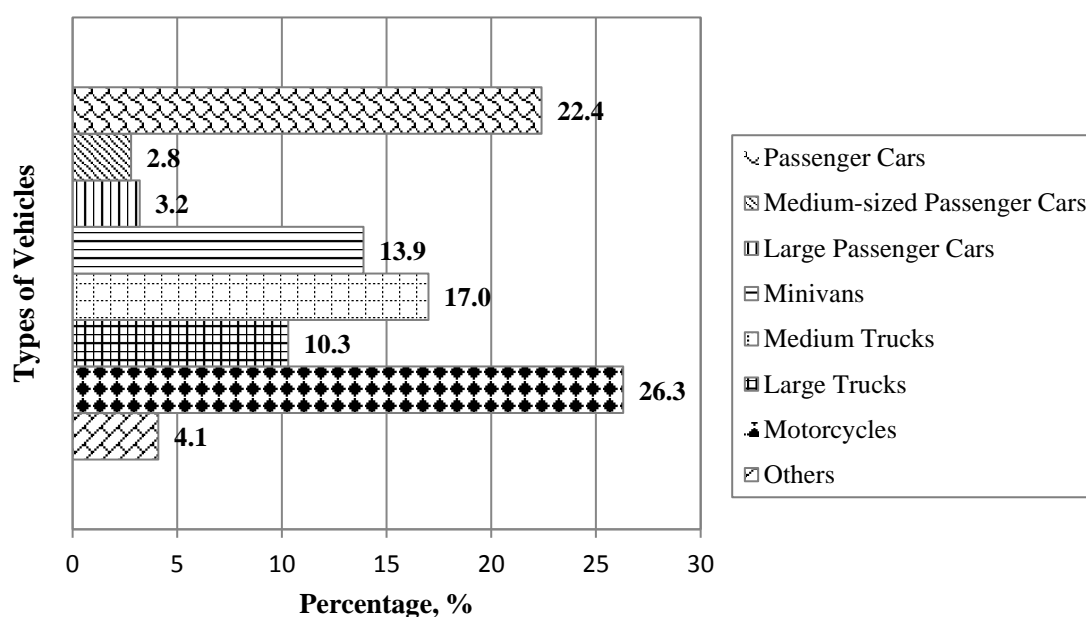
Human error is the critical reason for more than 90% of vehicle crashes (NHTSA, 2001). According to Malay Mail Online in 2015, the number of lives lost due to fatal accidents in Malaysia is 1,713, and the primary cause of those accidents is the loss of control of the vehicle. Wet roads, over speeding in sharp turnings and under steer conditions, lead to such accidents. Malaysia, a mountainous country, has many popular hill destinations - Genting Highlands, Cameron Highlands, outskirts of Sabah and Sarawak - with scenic mountain roads and lots of twists and turns. The sharp turns of the road segments in the azimuthal and lateral planes pose many hazards. Modern high-end cars have active systems to mitigate these risks. But to our knowledge, there are no such warning systems available in the low- and medium-segment

passenger cars. Therefore, we propose a passive early warning system to alert drivers of the possibility of exceeding the hazard limits.

### 1.1 Background Information

Studies by Qian et al. (2017) and Zhou et al. (2017) reported the various dangers heavy vehicle pose on mountain roads and also the implementation of assistive driving system for real-time speed warning. Wang et al. (2017) used lateral acceleration and road data in a safe speed model to prevent side-slip accidents for commercial vehicles. This paper presents a preliminary research study to support the need for a passive warning system, which will test the drivers to mitigate accidents.

According to Lin et al. (2013), 28.4% (22.4+2.8+3.2) traffic accidents of total cars involved in mountainous roads are passenger cars (Figure 1). Therefore there is a need to reduce these figures. Active safety system is available for various subsystem of an automobile such as active steering, active suspension, active braking, and integrated chassis control. However, it would be cost-effective, and lifesaving by alerting the driver with a warning signal when a high probability of accident is predicted. The proposed system would be cost-effective as it needs a flasher such as an LED, steering input, inertia measurement unit and the on-board speedometer.



**Figure 1:** Major accidents on mountain highways according to vehicle type (Lin et al., 2013)

Other than that, preventive measures is much valued than correcting the vehicle's loss of control. This proposal is in line with Road Safety Plan of Malaysia 2014–2020, where, it is predicted that there will be an increase of fatalities from road accidents from 2010 to 2020 will be 56% under Business as Usual (without any intervention) (Road Safety Department, 2014). It is proposed to implement five strategic approaches to reduce the road accidents. “Use of safer vehicles” is one of them, and this approach is expected to meet three ultimate outcomes: (i) reducing the speed, (ii) reducing risk of motor cyclists, and (iii) improving vehicle safety standards. Under this, installation of speed monitoring devices in the vehicles is included as one of the mid-term outcome. However, it would be better to include early warning system which could alert the driver based on the lateral stability of the vehicle.

Under steer is a condition whereby front wheels of the vehicle loss traction and the vehicle goes straight instead of turning according to its steering angle. This is common in front-wheel-drive vehicles and most passenger cars in Malaysia have front engine, front wheel drives which are prone to under steer. Therefore, it is required to issue a warning to the drivers when the vehicle is predicted to under steer. In mountainous roads, banked angles and inclination may reduce traction of the vehicle's tires that causes under steer. In addition, losing control of the vehicle going downhill will increase the chances of fatal accidents. Currently, road dividers act as passive safety device when the vehicles go out of control (road) while turning or skidding on mountain roads. They will help to prevent the vehicle from falling off a cliff or hitting opposing traffic. However, they will not prevent the accident. Recently, the road dividers have rollers to prolong the energy dissipation duration and in turn smooths the impact to increase the chance of the passengers' survival. However the purpose of this research is to induce the driver to take action proactively by predicting the danger reduces the need to use road dividers and to warn the drivers of the potential loss of control.

A large lateral force is one of the main causes of under steer; therefore it is essential to limit the lateral force in turnings. Race cars have better performance as compared to typical sedans being able to have lateral force of 0.9g to 1.2g (Motor Trend Staff, 2015). NHTSA (2001) stated that the lateral force should not exceed 0.7g for road vehicles. Therefore the soft limit and hard limit are set to be 0.7g and 0.9g respectively to reduce the possibility of under steer. This research focuses on using the driver's steering input and the instantaneous speed of the vehicle to warn the driver of under steer. Steering angle measured using an optical encoder, vehicle speed measured using wheel speed sensor, and along with acceleration and yaw rate the threshold to warn the driver before under steer occurs is estimated. When the threshold is approached, the vehicle will alert the driver by issuing a warning by flashing an LED or by beeping sound. If the driver does not act upon the warning, the assistive breaking will be initiated (if installed in the vehicle) (Ghoneim, 2013; Chung & Yi, 2007).

## 2.0 MODELLING

Using the kinematic equation of the vehicle, the steering angle,  $\delta_f$  in Figure 2 can be estimated for each turning. Knowing the wheel base, and track, the radius of curvature can be calculated from the steering angles for Ackermann Steering system. By obtaining the radius of curvature, and speed from the odometer, the lateral acceleration can be calculated. Lateral acceleration will then be used as a guideline on how much steering can be applied for specific speeds. Therefore the steering, speed and steering limits can be calculated.

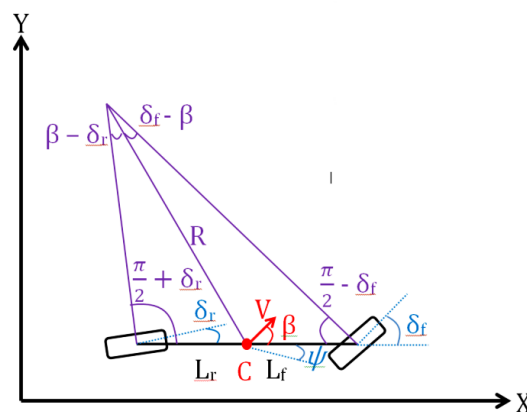
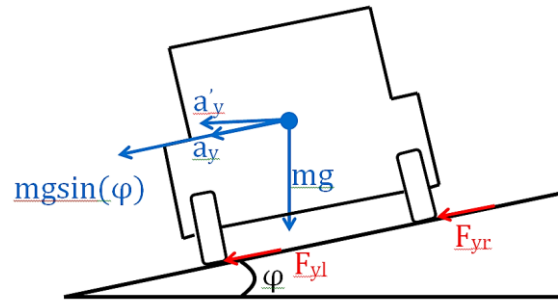


Figure 2: Bicycle model representation of vehicle (Rajamani, 2006)

The popular bicycle model was used for the study and simulation for both flat and banked road (Figure 3). It is assumed the vehicle has Ackermann steering and therefore simplifying the four-wheel vehicle to two wheels. Then the limits of steering angle for each speed of the vehicle are obtained from the Equations 3, 4 and 8 (Table 1).

**Table 1:** Kinematic equation derived from bicycle model (Rajamani, 2006)

Symbol	Nomenclature	Equation
X	Global X axis coordinate	$\dot{X} = V \cos(\psi + \beta)$ (1)
Y	Global Y axis coordinate	$\dot{Y} = V \sin(\psi + \beta)$ (2)
$\psi$	Yaw angle, orientation angle of vehicle with respect to global X axis	$\dot{\psi} = \frac{V \cos(\beta)}{L_f + L_r} (\tan(\delta_f) - \tan(\delta_r))$ (3)
$\beta$	Vehicle slip angle	$\beta = \tan^{-1} \left( \frac{L_f \tan(\delta_r) + L_r \tan(\delta_f)}{L_f + L_r} \right)$ (4)
C	Center of gravity location	



**Figure 3:** Banked road vehicle parameters (Rajamani, 2006)

$$m\dot{u} = F_{xr} + F_{xf} \cos \delta_f - F_{yf} \sin \delta_f + mV\dot{\psi} \quad (5)$$

$$m\dot{v} = F_{yr} + F_{xf} \sin \delta_f + F_{yf} \cos \delta_f - mV\dot{\psi} + mg \sin \phi \quad (6)$$

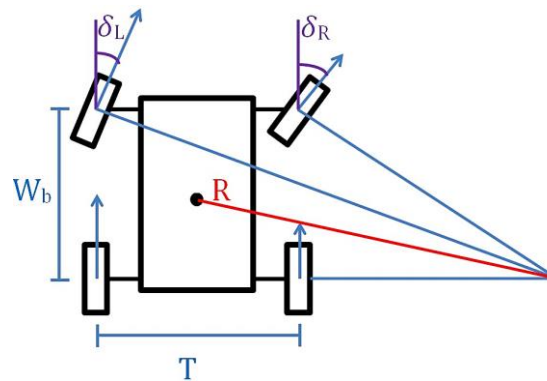
$$I_z \dot{\gamma} = aF_{xf} \sin \delta_f + aF_{yf} \cos \delta_f - bF_{yr} + \frac{d}{2}(F_{xfr} - F_{xfl}) \cos \delta_f + \frac{d}{2}(F_{xrr} - F_{xrl}) \quad (7)$$

For this study, the main concern is the lateral acceleration of the vehicle. The main reason for vehicle under steer when the lateral force exceeds the tire traction. Therefore Equation 6 will be mainly used for the study of lateral acceleration on banked roads.

### 3.0 CALCULATING SAFETY LIMITS

First a relationship is established between angle of steering wheel rotation to that of wheel (steering angle). The steering wheel angle of a typical road vehicle is  $0^\circ - 480^\circ$  from end to end. This should be proportional to that of the steer angle of the wheels. We will use the geometric constraint from Ackermann steering layout for calculating the steering wheel angle for a given turning radius of the vehicle. The vehicle's turning radius R is (Figure 4):

$$R = \sqrt{L_r^2 + \left( \frac{T}{2} + (L_r + L_f) \tan(\delta_R) \right)^2} \quad (8)$$



**Figure 4:** Vehicle with Ackermann Steering System

The turning radius of the New Saga is known to be 5.1m (Proton, 2016). Therefore, by assuming Ackermann's steering, the vehicle's steering angle can be obtained with relation to the driver's steering wheel angle as shown in Equation 9. After substituting  $R = 5.1\text{m}$ , the steering angles for both left and right ranges are obtained and is presented in Table 2. However, Ackermann's steering can only be achieved accurately in very low speeds and is impractical in high speeds. Therefore there is a need to further research in high speed steering relationship between steering angle and driver's input steering.

**Table 2:** Vehicle steering range

Parameter	Left Turn Range	Right Turn Range
Steering wheel	$0^\circ - 480^\circ$	$0^\circ - 480^\circ$
Ackermann	$0^\circ - 52^\circ$	$0^\circ - 52^\circ$

$$\delta_f = \frac{52^\circ}{480^\circ} \delta_{sw} = 0.1083 \delta_{sw} \quad (9)$$

A relationship between the steering wheel angle and steering angle also known as steering ratio of the vehicle is established in Equation 9. It is found that they are directly proportional to each other. This show for every 10 degree turning of steering wheel turns the wheel by one degree (steering angle). It is worth mentioned here that while deriving this relationship, it is assumed that the CG of the vehicle lies at the midpoint of vehicle's longitudinal axis.

An optical encoder can be mounted into the steering wheel to detect the steering wheel angle and to be used as an input for the LED alarm as well as the assistive braking. Other than the steering wheel input, the speed of the vehicle and lateral acceleration are used to obtain the dynamics of the vehicle. The dynamics will be able to determine if the vehicle's lateral acceleration is above the tire limits.

On the banked road, the lateral acceleration is shown in Equation 6 and the vehicle has the same yaw rate as stated in Table 1. Other than that, the normal and lateral forces on the front and rear tires are assumed to be equally distributed for flat roads. Then the limits of  $0.7g$  and  $0.9g$  are taken as set points to calculate the vehicle's speed and steering wheel angle for the limits.

## 4.0 SIMULATION AND RESULTS

### 4.1 Vehicle Parameters for Simulation

Simulation was carried out using vehicle parameters of Proton Saga 1.3L shown in Table 3. It is assumed the vehicle dimensions are symmetrical. Therefore the  $L_r$  and  $L_f$  are obtained from half of vehicle wheel base. The height of CG of the vehicle is also assumed to be half of the vehicle's height.

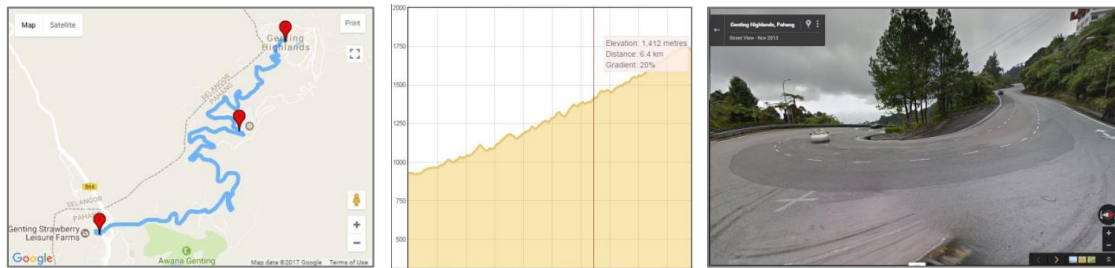
**Table 3:** Nomenclature and parameter values of 2016 Proton Saga 1.3L (Proton, 2016)

Parameter	Symbol	Values and Units
V	Vehicle Speed	(m/s)
$\beta$	Sideslip angle at CG	(rad)
$\psi$	Yaw rate	(rad/s)
$\phi$	Roll angle	(rad)
$\dot{\phi}_r$	Roll rate	(rad/s)
$\delta_f$	Front steering angle	(rad)
$\delta_L$	Front left steering angle	(rad)
$\delta_R$	Front right steering angle	(rad)
$\delta_{sw}$	Steering wheel angle	$0^\circ - 480^\circ$
$m_s$	Sprung vehicle mass	(kg)
m	Vehicle mass	1035 kg
$I_x$	Roll moment of inertia at CG	(kgm <sup>2</sup> )
$I_z$	Yaw moment of inertia at CG	(kgm <sup>2</sup> )
$L_r$	Distance from CG to rear axle	1.233 m
$L_f$	Distance from CG to front axle	1.233 m
Wb	Vehicle wheel base	2.465 m
T	Vehicle track width	1.689 m
h	CG height from roll axis	0.746 m
$C\phi$	Combined roll damping coefficient	(Nms/rad)
$k\phi$	Combined roll stiffness coefficient	(Nm.rad)

### 4.2 Region of Interest – Genting Road – A View from Google Map

Figure 5 shows Google map of a route from Gohtong Jaya to Genting having many hairpin turns of gradients ranging from  $20^\circ - 30^\circ$  (Chris, 2000). These turns are dangerous and under steer would cause fatalities when driving down. By combining the sharp turns and large inclination of  $30^\circ$ , vehicle that over speed have the tendency to lose control and cause a major accident.

In certain areas, there are humps built on the roads to slow down the speed. The inclination of  $20^\circ$  with sharp hairpin turn is a dangerous place to under steer and lose control of the vehicle. In addition to inclination of gradient  $20^\circ$ , the road is also banked to the left of the road which may decrease the ability of the vehicle to turn.

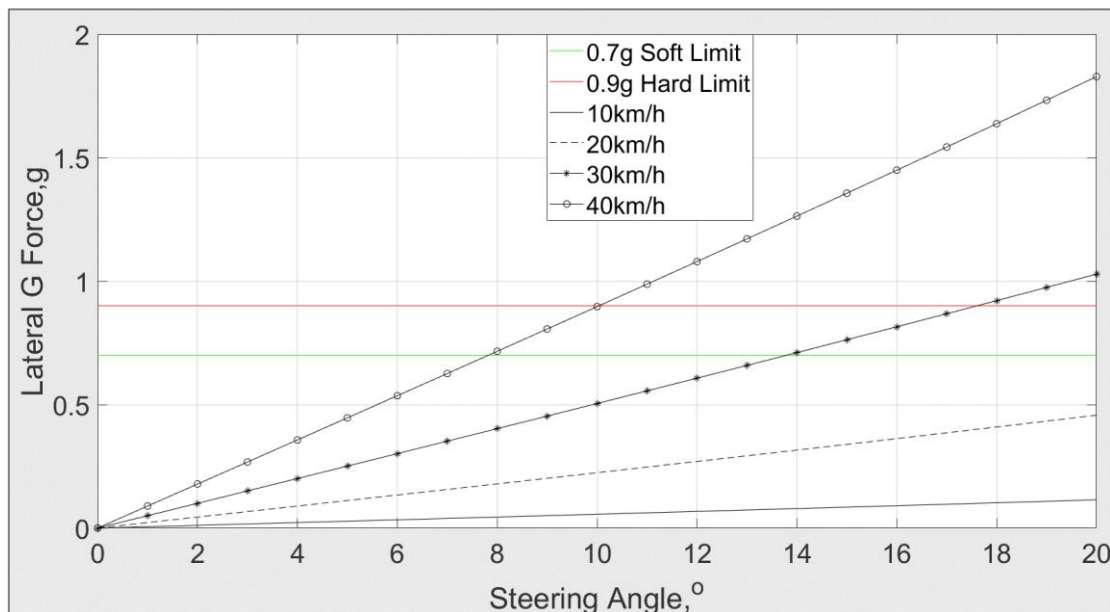


**Figure 5:** Elevations of the route up to Genting Highlands from Gohtong Jaya showing a hairpin turn with its gradient of 20° (Chris, 2000)

### 4.3 Results and Discussion

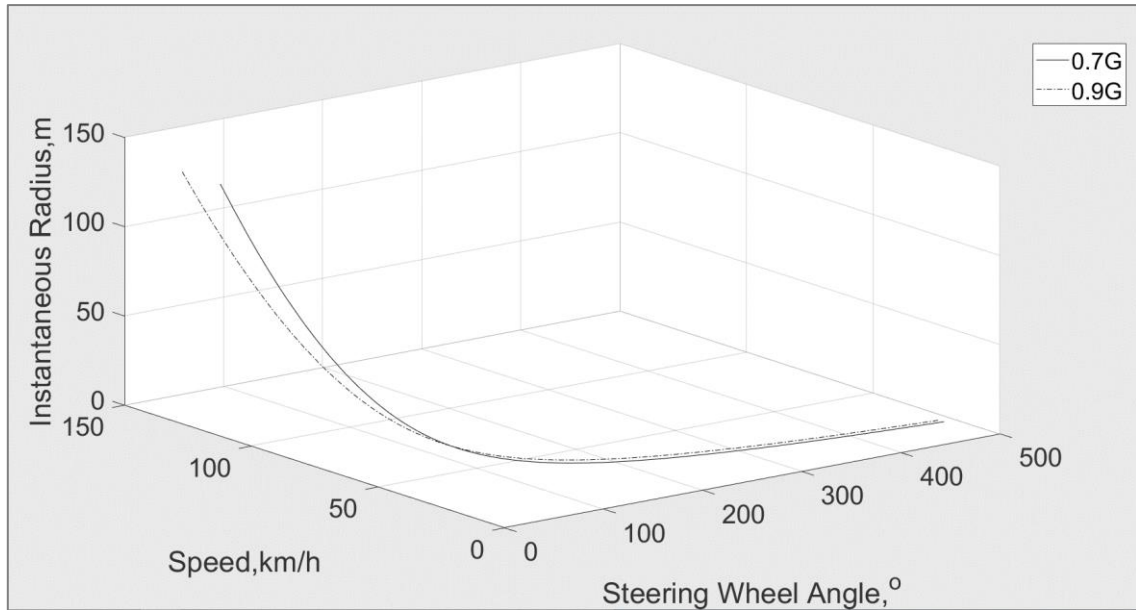
Simulation uses the lateral acceleration from Equation 6. The, slip angle,  $\beta$  is assumed to be equal to the kinematic model in Table 1. By varying the banked angle for  $-10^\circ - 10^\circ$ , simulations are done to obtain the steering wheel and speed limits for both soft and hard limits.

Using the soft and hard limits of 0.7g and 0.9g the lateral acceleration of vehicle on flat and banked roads is compared. When the lateral acceleration reaches its limits, the corresponding speed limits at the specified steering angle are recorded. As shown in Figure 6, the steering angle of the vehicle for 0.9g lateral acceleration is  $10^\circ$  when vehicle speed is 40km/h. Iterations are done to obtain the exact instantaneous speed whereby the lateral g forces are 0.7g and 0.9g for both soft and hard limits.



**Figure 6:** Lateral acceleration limits and vehicle's lateral acceleration

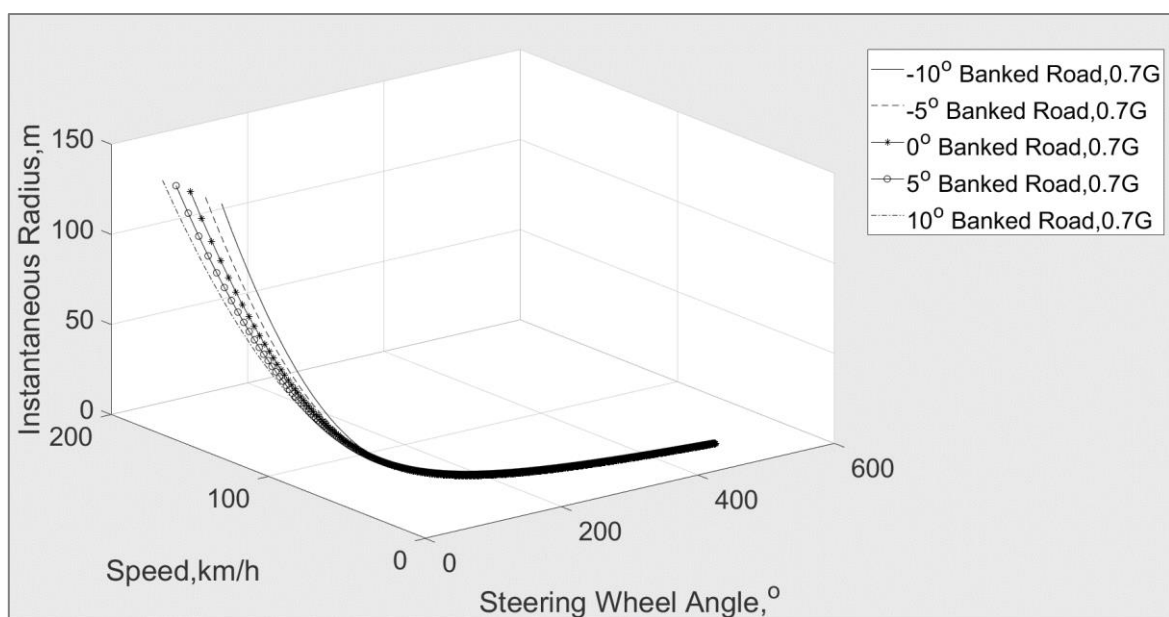
Figure 7 shows instantaneous change in curvature for a set of speed and steering angle on flat road with different curvature. The instantaneous radii are obtained using calculation from Equation 8. These values are then used to calculate the lateral acceleration using  $\frac{v^2}{R}$ . These data will be used as a hard limit to ensure the vehicle does not have lateral forces above 0.9g.



**Figure 7:** Speed limit for each steering wheel angle and instantaneous radius

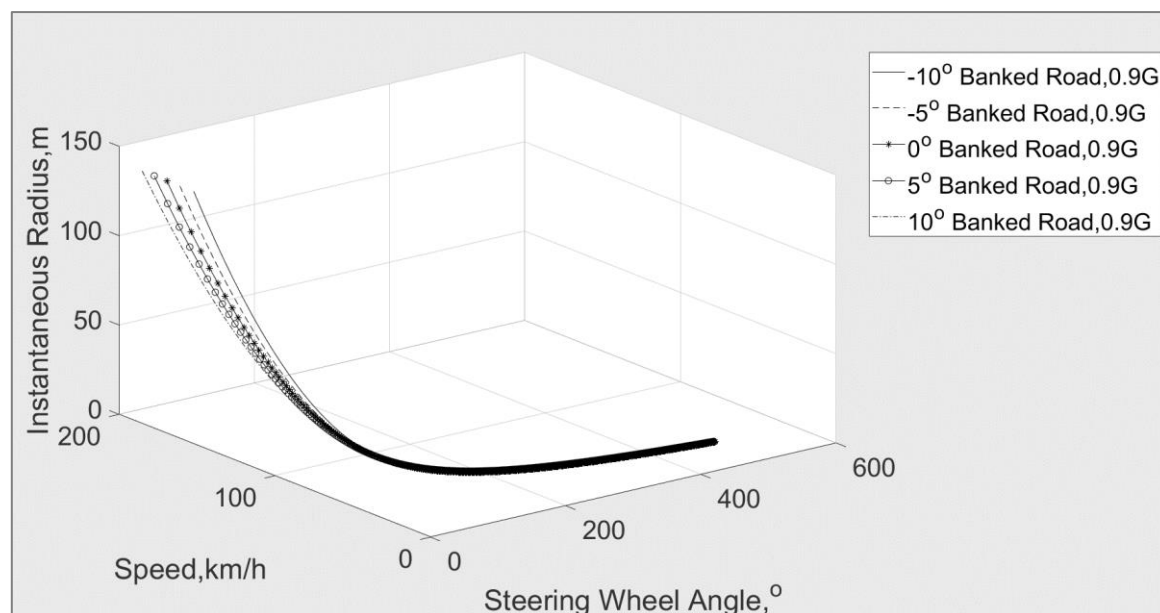
Figures 8 and 9 show the simulation for banked road at 0.7g and 0.9g loads. The bank angle causes the vehicle to have different speed limits for same turning radii. This is due to the weight of the vehicle being able to hold or push the vehicle off the road.

In real time, the bank angle can be estimated using the dynamic model and yaw rate sensor. Instantaneous speed of the vehicle is obtained using the speedometer readings as displayed to the driver. When the banked angle is above 5°, the dynamic model will be used to calculate the maximum steering angle for the current speed. Other than that, the kinematic model will be used to calculate the maximum steering angle. In any condition when the vehicle's lateral g-force exceeds 0.7g, an LED light will be flashing to warn the driver of under steer risk. In addition, assistive braking will occur when the vehicle exceeds the predefined steering angles when lateral force is above 0.9g.



**Figure 8:** Speed limit for each steering wheel angle and instantaneous radius of banked road for 0.7g





**Figure 9:** Speed limit for each steering wheel angle and instantaneous radius of banked road for 0.9g

#### 4.0 CONCLUSION

This paper reports the results of a preliminary study undertaken on an early warning device which alerts the driver of vehicle slip and loss of control when the lateral g-load increases above a given threshold. The steering wheel angle is taken as the primary input and using the Ackermann steering model, the lateral acceleration is estimated, base on which an early warning strategy is proposed. Initially, a warning (a flashing light or beeping sound) is given when the car reaches a lateral acceleration of 0.7g. If the warning is ignored, as a second safety measure, assistive braking is triggered. This study included the effects of banking. However, it does not include tire and vehicle slip. A further study including obtaining and measuring terrain data and slip angles to improve the results further has been planned.

#### ACKNOWLEDGEMENTS

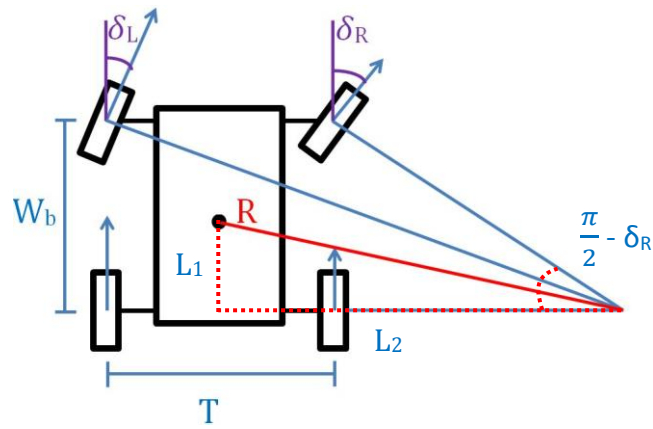
The authors acknowledge Ministry of Higher Education Malaysia (FRGS/2/2014/SG04/MUSM/03/1) and Monash University Malaysia for providing financial aid to carry out this research.

#### REFERENCES

- Chris, B. (2000). Google maps elevation for a route. Retrieved from <https://www.doogal.co.uk/routeelevation.php>
- Chung, T., & Yi, K. (2007). An investigation into differential braking strategies on a banked road for vehicle stability control. *Journal of Automobile Engineering*, 221(4), 443-455.
- Ghoneim, Y. A. (2013). Vehicle dynamics approach to driver warning. *International Journal of Vehicular Technology*, 2013, 1-18. doi: 10.1155/2013/109650

- Lin, L., Jinhai, L., & Yan, W. (2013). Traffic crash characteristic analysis on mountain roads. *Proceedings of the 2013 5<sup>th</sup> International Conference on Measuring Technology and Mechatronics Automation (ICMTMA)*. doi: 10.1109/ICMTMA.2013.312
- Malay Mail Online (2015). *Police: Drivers losing control of vehicles main cause of fatal accidents in 2015*. Retrieved from <http://www.themalaymailonline.com/malaysia/article/police-drivers-losing-control-of-vehicles-main-cause-of-fatal-accidents-in>
- Motor Trend Staff (2015). *2015 Motor trend best driver's car*. Retrieved from <http://www.motortrend.com/cars/mercedes-benz/amg-gt/2016/2015-motor-trend-best-drivers-car/>
- NHTSA (2001). *Notice of proposed rulemaking*. Washington, DC: National Highway Traffic Safety Administration, US Department of Transportation (DOT). Retrieved from <https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=6&cad=rja&uact=8&ved=0ahUKEwi2ycrajovUAhUKn5QKHWXMCUYQFghEMAU&url=https%3A%2F%2Fwww.nhtsa.gov%2Fcars%2Frules%2Fulings%2FRollover%2F2001Standards%2FRolloverResistance.DOC&usg=AFQjCNGLD76heVQjTERx2z4LwEpS9TInPQ>
- Proton (2016). *Proton SAGA owner's manual*. (pg. 126-133). Shah Alam: Proton Holdings Bhd.
- Qian, K., Tan, G., Zhou, R., Mei, B., & Xia, W. (2017). *Vehicle-GIS assistant driving system for real-time safety speed warning on mountain roads* (SAE Technical Paper 2017-01-1400). Warrendale, PA: SAE International. doi: 10.4271/2017-01-1400
- Rajamani, R. (2006). Lateral vehicle dynamics. *Vehicle dynamics and control*. (pp. 15-49). Boston, MA: Springer US.
- Road Safety Department (2014). *Road Safety Plan of Malaysia 2014-2020*. Putrajaya: Road Safety Department, Ministry of Transport Malaysia. Retrieved from [http://www.mot.gov.my/SiteCollectionDocuments/Darat/Road\\_Safety\\_Plan\\_2014-2020\\_booklet-EN.pdf](http://www.mot.gov.my/SiteCollectionDocuments/Darat/Road_Safety_Plan_2014-2020_booklet-EN.pdf)
- Wang, Q., Yang, B., Tan, G., Xiong, S., & Zhou, X. (2017). *Safe travelling speed of commercial vehicles on curves based on vehicle-road collaboration* (SAE Technical Paper 2017-01-0080). doi: 10.4271/2017-01-0080
- Zhou, S., Tan, G., Ji, K., Zhou, R., & Liu, H. (2017). *Over-the-horizon safety speed warning system for heavy-duty vehicle in mountain areas* (SAE Technical Paper 2017-01-0091). doi: 10.4271/2017-01-0091

### Appendix I. Derivation of Equation 8



$$L_1 = L_r$$

$$L_2 = \frac{T}{2} + (L_r + L_f)\tan(\delta_R)$$

$$R = \sqrt{L_1^2 + L_2^2}$$

$$R = \sqrt{L_r^2 + \left(\frac{T}{2} + (L_r + L_f)\tan(\delta_R)\right)^2}$$