Preliminary study to determine the maximum safe speed of vehicles based on rolling moments and vehicle skid to reduce of driving accidents

D A Sumarsono¹, R Siregar¹-² *, M Adhitya¹, N Nazaruddin¹-³, S Prasetya¹-⁴, F Zainuri¹-⁴, and G Heryana¹-⁵

¹Department of Mechanical engineering, Universitas Indonesia, 16424, Indonesia
²Department of Mechanical Engineering, Darma Persada University, 13450, Indonesia
³Department of Mechanical Engineering, Universitas Riau, 28293, Indonesia
⁴Department of Mechanical Engineering, Politeknik Negeri Jakarta, 16425, Indonesia
⁵Department of Mechanical Engineering, STT Wastukancana, 41151, Indonesia

*Email: rolansiregar@ft.unsada.ac.id

Abstract. Indonesia is one of the countries with the highest death rate due to road traffic accidents. Research on vehicle safety needs to be done immediately. Some travel companies, rental vehicles, and tourism vehicles have made permit speed regulations, but the basis for selecting these limits is not scientific. In this study will be presented how to determine the maximum speed allowed in a vehicle scientifically, and how to calculate the speed of the permit can be a reference to other vehicles. This research method is analytical and experimental methods. The normal force of the wheel when the vehicle turns will be different, where the normal force of the wheel inside will first be lifted due to rolling force, and will have an impact on the skid that might occur. So, this is becoming a reference in calculating the vehicle's maximum clearance speed. The maximum speed allowed of the vehicle under study depends on the turning radius. Therefore, knowing the wheel's normal force from various conditions and the maximum speed of the vehicle, a safety warning system can be developed in the future to avoid vehicle accidents.

1. Introduction

Data from the Traffic Division of the Indonesian National Police states that every year around 30,000 people die from traffic accidents in Indonesia[1]. Various ways have been carried out by the Indonesian government in reducing accidents such as vehicle speed restrictions that have begun to apply to the travel company vehicles and expedition trucks. This research presents about determining the maximum speed of vehicles that are still in the safe range. Because of the accident problem, this research takes an important role and must be followed up immediately in the driving accident reduction program. Vehicle speed will be related to the normal force of the wheel and automatically loaded brake in-vehicle unit[2]. Besides, the vehicle speed affects the stability of the vehicle motion, such as the risk of occurring oversteer and understeer. The instability of vehicle motion often occurs in turn conditions when the vehicle speed is outside the safe limit. Centrifugal force will pull the vehicle when circular motion and cause a decrease in normal force on the wheels inside. So, this maximum
speed limit needs to be applied to public vehicles such as rental cars, tourism cars, and travel vehicles, so the risk of accidents is reduced. The aim of the study is basic for the development of a safety warning system so that drivers use vehicles with safe speeds. This speed limitation is being widely applied in public passenger companies in Indonesia to avoid traffic accidents such as understeer/oversteer, brake failure, and crash. To achieve this aim, the objectives of this research are to determine the vehicle speed maximum in turning radius and its relation to skid and rolling.

2. Literature review and problem statement
A vehicle's safety level should be known so that the driver can use the vehicle at a safe speed. Driving comfort felt by the driver is not only related to individual satisfaction but also driving safety and the long-term health of the driver and passengers [3]. This research has been widely carried out by previous researchers regarding driving comfort such as driver speed [4], aerodynamic, road surface [5], driver character, suspension system [6][7], power train [8], brake system [2], and etc. Driver speed is related to the cause of traffic accidents [9]. Many traffic signs have been made to show safe speed to avoid accidents. Road roughness has also been studied because it is related to driving comfort such as noise from wheels, slips, road slope in turn conditions, and vehicle vibrations [10].

On the other, the most significant cause of accidents is human error, so many researchers are interested in creating a safety warning system [11]. The comfort of controlling vehicles at high speeds is also related to vehicle aerodynamics, and therefore vehicle manufacturers are competing to create more aerodynamic [12]. The braking system on a vehicle is one of the essential things, so drivers and passengers can drive safely [13]. Some articles that have been reviewed are related to the safe speed of the vehicle. This study presents preliminary studies on how to connect skid, rolling, and safe vehicle speed, so there is no vehicle motion instability.

3. Methodology
Schematic determination of vehicle speed limits can be done by calculating the rolling moment, skid, and speed of a vehicle. This research, the calculation approach for Toyota Avanza 1.5 is displayed. A more detailed schematic calculation of the vehicle's maximum speed is shown in Figure 1.

From the schematic, Figure 1 has shown the main sequence in determining the maximum speed limit of vehicles that can be applied to public passenger vehicles so that the risk of loss due to accidents can be reduced. The vehicle under review was a passenger vehicle Toyota Avanza 1.5. This type is chosen, assuming it has referenced other vehicle braking systems. These specifications can be seen in Table 1.

Table 1. Specifications of the vehicle being review

| No | Item             | Symbol | Value | Unit |
|----|------------------|--------|-------|------|
| 1  | Wheelbase        | L      | 2655  | mm   |
| 2  | Wheel track front| tf     | 1425  | mm   |
| 3  | Wheel track rear | tr     | 1435  | mm   |
| 4  | Curb weight      | W      | 1175  | kg   |

Curb weight is the empty weight of the vehicle, including standard accessories and a full fuel tank,
but does not include drivers or passengers as well as luggage items. This research will focus on the assessment of vehicle weight, i.e. driver only weight (DoW).

3.1. Calculation of the position of the Center of Gravity (CG)
In calculating the CG position obtained is the CG distance from the front wheel axle \((p)\), the CG distance from the rear wheel axle \((r)\), and the CG height from the ground \((h)\). CG calculation can be made in the form of programming Simulink as in Figure 2.

![Figure 2. Simulink diagram of CG calculations](image)

Data input is the beginning of the process to enter the number of passengers, passenger weight, passenger position following the seat, as well as vehicle geometry such as curb weight, wheelbase distance, wheel track, and etc. In the process section, there is a mathematical formula to process the input data so that the results obtained in the form of CG. Weighing is done with a slope of 13.14 degrees with the specifications of a medium-sized passenger vehicle, as shown in Figure 3.

![Figure 3. Weighing the vehicle weight](image)

Figure 3 can be explained that the weighing is done by thin and precision tools to facilitate the data collection process. The vehicle is weighed in a tilted condition with a standard vehicle.

3.2. The effect of rolling to normal force and allowable speed
The braking load on each wheel will be different when the vehicle turns, and the body roll causes this. Vehicles with critical speeds on turning roads can be overturned due to the body roll. The load on the outside wheel will be much higher than the load on the inside wheel. To avoid the car overturning, the driver can brake so that the speed decreases. The load distribution on each brake will be different when braking. Figure 4 shows the modeling of forces acting on the vehicle turning in the conditions of Ackerman [14], where the road is assumed to be flat.
Based on Figure 4, the sign notation can be explained $F_{gd}$ and $F_{gb}$ shows the frictional force of the road surface roughness for front and rear wheels, $\beta$ show the angle side slip vehicle when turning, $tr$ shows the width of the rear axle wheel track, and on the front wheels is $tf$. The $p$ and $r$ notations show the distance between the axle to the center where $p$ plus $r$ is called the wheelbase ($l$), wheels 1 and 2 are grouped into wheels inside, and wheels 3 and 4 are grouped into wheels outside. Bolt / rolling analysis is carried out to obtain a reasonable force on each wheel. The wheel will lift if the normal force on one of the wheels inside is zero. The normal force equation on each wheel can be displayed in equations 1, 2, 3, and 4 assuming the effect due to the wind is very small, so it does not count as well as the effect of suspension [15][16].

The normal force on wheel 1 can be seen in (1):

$$F_{z1} = \frac{W \cdot p}{2(p+r)} \cdot \left( \frac{p}{p+r} \right) \cdot F_c \cos \beta \cdot h + \frac{F_c \sin \beta \cdot h}{2(p+r)},$$

(1)

Then the normal force on the wheels 2 can be seen in (2):

$$F_{z2} = \frac{W \cdot r}{2(p+r)} \cdot \left( \frac{r}{p+r} \right) \cdot F_c \cos \beta \cdot h + \frac{F_c \sin \beta \cdot h}{2(p+r)},$$

(2)

The normal force on the wheels 3 can be seen in (3):

$$F_{z3} = \frac{W \cdot r}{2(p+r)} + \frac{F_c \cos \beta \cdot h}{2(p+r)} + \frac{F_c \sin \beta \cdot h}{2(p+r)},$$

(3)

The normal force on the wheels 4 can be seen in (4):

$$F_{z4} = \frac{W \cdot p}{2(p+r)} + \frac{F_c \cos \beta \cdot h}{2(p+r)} + \frac{F_c \sin \beta \cdot h}{2(p+r)}.$$  

(4)

The critical condition of the vehicle to be rolled over is when one of the forces on the inside wheel is zero. If the review is $F_{z1} = 0$ we will get the maximum allowable turning speed as in (5) assuming the angled side slip $\beta$ close to zero, and the wind load is so small that it doesn't count [15][16].
To get the value of the centrifugal force can be done by calculation using (6).

\[ F_c = \frac{m \cdot v^2}{R} \]  

(6)

And the value of R is the turning radius, which is approached under ideal conditions as in (7), and \( v \) is the vehicle speed in units (m/s).

\[ R = \frac{P + r}{\delta_f} \cdot 57.29 \]  

(7)

From the equations above can be explained notation \( \delta_f \) is the steering angle in degrees, \( m \) is the mass of the vehicle (kg), \( g \) is the acceleration of gravity (m/s²), \( h \) is the height of the center of mass to ground.

3.3. The effect of the skid on the normal force of wheel and allowable speed

The skid phenomenon in question is a shift in the car towards the outside body of the vehicle, which is not appropriate. Skid will occur if the lateral force, such as centrifugal force is greater than the lateral force of the wheel that holds it (Figure 5) [15].

![Figure 5. The force in which a vehicle is turning](image)

The critical condition of a vehicle is when the side forces (\( F_c \)) of the vehicle are the same as the lateral forces (\( F_{gd} + F_{gb} \)) acting on the wheel that holds it. The side forces acting on the front and rear wheels are the centrifugal force that has been distributed that is the centrifugal force on the front wheels and the centrifugal force on the rear wheels. The wind force that works is considered so small that it is ignored. Centrifugal force equation on the front wheels (\( F_{cd} \)) and rear (\( F_{cb} \)) can be displayed in (8) and (9) below [15] [16].

\[ F_{cd} = \frac{r}{p + r} (F_c \cos \beta) \]  

(8)

\[ F_{cb} = \frac{p}{p + r} (F_c \cos \beta) \]  

(9)

A critical condition where the front wheel will be skid for a moment if the centrifugal force on the front wheel is equal to the coefficient of road friction times the normal front wheel force, as shown in (10).
\[ F_{ed} = \mu \cdot Fzd \]  

(10)

Assuming angles side wall \( \beta = 0 \), the maximum speed of the vehicle turns so that the front wheels don't skid can be formulated in (11).

\[ v_{id} = \sqrt{\mu Rg} \]  

(11)

Where \( R \) is the turning radius of the road (m) and \( \mu \) is the coefficient of road friction. Furthermore, the critical condition where the rear wheel will skid if the centrifugal force of the rear wheel is equal to the multiplication coefficient of road friction with the normal force of the wheel (12).

\[ F_{rb} = \mu \cdot Fzb \]  

(12)

If the force and moment of the wind are ignored and the angle \( \beta = 0 \) then the maximum speed of the vehicle turns so that the rear wheels do not skid can be shown in (13).

\[ v_{ib} = \sqrt{\mu Rg} \]  

(13)

From (11) and (13) it can be seen that \( v_d = v_b \), it can be concluded that the vehicle will experience skid on the front or rear wheels together, but this rarely happens because in actual conditions the angle \( \beta \) influence, so skid will occur on one of the wheels inside. If the vehicle goes beyond the maximum allowable speed, the vehicle will skid. Skid on the front wheels occurs earlier than the rear wheels, the vehicle will tend to understeer, and if the rear wheels are skid, the vehicle will tend to be oversteer. Vehicles that have skid will make the vehicle difficult to control so that it can cause accidents. The turning radius scenario starts from 10 m, 30 m, 70 m, 150 m, and 310 m.

4. Results and discussion

Figure 6 shows the normal force chart of the wheel when the vehicle is in an unladen condition or often called a driver only weight (DoW) where the vehicle is moving at the maximum allowable speed. This calculation is carried out in turn motion, where the centrifugal force will cause a rolling moment in the vehicle.

![Image](Figure 6. The normal force of wheels when the vehicle turns)

From Figure 6 it can be explained that the first wheel lifted from the ground is the second wheel (inside) which is marked with zero normal force. Rolling occurs when a normal force on a wheel has a smaller value equal to zero on one or more wheels of the vehicle (it can be seen in section 3.2.). Based on calculations that have been made that the first wheel experiences a normal force equal to zero due
to rolling is the inner wheel which is the second wheel, and the next smallest normal force value is wheel 1, and continued with one of the outer wheels depending on the passenger vehicle. Then the permitted speed due to skid is the maximum speed of the vehicle that is permitted when moving on a turn where one of the vehicle's wheels will momentarily experience a skid to the side of the vehicle due to the centrifugal force that is pulling it. The graph in Figure 7 shows the maximum allowable speed of the vehicle at a certain turning radius.

Figure 7. Graph of the maximum allowable speed

Based on this graph, before one of the wheels of a vehicle is lifted, the vehicle has skid early, which means that the maximum speed allowed at a certain radius is the maximum speed of the skid effect. Then the reference to determine the maximum speed is the effect of skid not rolling.

The relationship of the maximum speed of the vehicle to the turning radius can be displayed in the form of an equation 2nd order polynomial (14).

\[ v = -0.0009\rho^2 + 0.6517\rho + 22.292 \]  

(14).

The greater the turning radius, the maximum vehicle speed will be higher. On highways or toll roads, the road is not always straight, and sometimes it turns sharply, sometimes turns slightly, therefore the maximum speed on a straight road needs to be made regulation. Vehicles that move straight when you find the road turn even though the turn is not significant, the vehicle can skid, so the vehicle is unstable. That large or insignificant turn can be assumed to be around 310 m with the assumption that it is approaching straight, then determining the maximum speed of the vehicle on the straight road is 140 km/h. That is the reason 140 km/h was chosen to be the maximum allowable speed so that when a vehicle moves straight at high speed and suddenly meets a turning road, it does not have an accident due to the instability of the vehicle's motion. So, the vehicle under review can be set so that the speed cannot exceed 140 km/h on any road.

5. Conclusion

The normal force of the wheel when the vehicle turns will vary where the normal force of the wheel (2) the inside will first be lifted due to rolling force. This becomes a reference in calculating the vehicle's maximum clearance speed. The speed of a vehicle moving on a turning road depends on the turning radius as in the following equation \( v = -0.0009\rho^2 + 0.6517\rho + 22.292 \), where \( \rho \) (m) is the turning radius, and \( v \) is speed \( (km/h) \). With various considerations, the vehicle's maximum speed on a straight road was chosen 140 km/h. This was chosen to avoid vehicle instability when it met at an insignificant turning radius. The basics of calculating the safe limit of vehicle speed can be a reference
in determining the maximum speed of certain vehicles such as travel vehicles, rental cars, cargo cars, etc.

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