Modelling of Tilting and Steering Control System for a Tadpole Three-Wheeled Vehicle

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Abstract. Three-Wheeled Vehicle with tadpole configuration is a vehicle which has one wheel at the back and two wheels at the front. This vehicle promotes and ensures safety as it does in a four-wheeled vehicle. However, the vehicle’s dynamics is much different compared to a four-wheeled vehicle. The objective of this research is to find the relationship between turning, steering, and tilting of this vehicle to ensure and determine the safety limit of it. Physics modelling and iteration is done to see how each of the three components (turning, steering, and tilting) could affect each other.

1. Introduction

Three-wheeled vehicle is a vehicle that operates on three wheels. Three-wheeled vehicle has two configurations which are the tadpole configuration and the delta configuration. A tadpole configuration is a three-wheeled vehicle which has two wheels upfront and one wheel at the back while the delta configuration has two wheels at the back and one wheel at the front.

The dynamics system of a tadpole configuration three-wheeled vehicle could be very complicated. Few matters to be considered are the turning and tilting system, components such as: turning radius, center of gravity, wheel track, etc. This components are then can be measured and determined to ensure the ride safety of the vehicle. For a three-wheeled vehicle to maintain its stability, a tilting system is developed. Tilting was meant to lower the CG so the maximum lateral acceleration that could be taken by the vehicle is higher which results in better stability, and so is the safety. The modelling aims to represent the physics that is happening with the vehicle for future research in active steering and tilting assist for a three-wheeled vehicle.

2. Methods

2.1. Design and constraint

The design that was made to be the test subject for this research is a three-wheeled vehicle with a one rear wheel and two front wheels, a tadpole configuration, with a wheelbase of 1050 mm and a track-width of 625 mm. The center of gravity point is located at the center of its y-axis, measured to be 441 mm from the front and 609 mm from the back with respect to the x-axis, and has a height of 825 mm from the ground. The vehicle has a total weight of 74 kg without any driver on it, and test was done with a driver with weight of 52 kg.
The coordinate system that is used is the SAE Coordinate system which goes like in figure 2 below.

2.2. Geometric ‘bicycle’ modelling
The basic vehicle model is by using the ‘Bicycle’ model which refers to the model made by Milliken and Milliken. This ‘Bicycle’ model represents the whole vehicle as a bicycle, where the front system is represented as a single-wheel model and so is the rear. The definition of this model includes no load transfer either on longitudinal or lateral axis, no roll, pitch, and yaw motion, constant velocity, no aerodynamic effects, no vehicle chassis and suspension compliance effects, and full position control. These assumptions are justified since the purpose of this model is to study the basic motion of the vehicle.

This model does not include roll as it’s degree of freedom but we could calculate the lateral force that is undergoing when the vehicle is turning to be used later for the rollover equation. The lateral force
could be found by implementing the linear dynamics equation on the ‘bicycle’ model, where the lateral force is:

\[ \Sigma F_y = 0 = F_{Yf} + F_{Yr} - (m \times a) \]  \hspace{1cm} (1)

\[ \Sigma M_{cg} = 0 = (F_{Yf} \times L_{a}) - (F_{Yr} \times L_{b}) - 1a \]  \hspace{1cm} (2)

In the lateral force equation, we replace the “m” with the total weight of the vehicle (W_T) divided by gravity (g) and “a” with velocity (v) divided by the turning radius of the vehicle (R) in equation (1), respectively, with:

\[ m = \frac{W_T}{g} \]  \hspace{1cm} (3)

\[ a = \frac{v^2}{R} \]  \hspace{1cm} (4)

Consider for the moment only the steady-state condition of constant angular velocity; it is in this steady-state condition (or as close to it as can be reasonably approximated on a skidpad) that the maximum lateral acceleration level is to be obtained. Therefore, in this limited case, the matter reduces to just a consideration of how the lateral forces are influenced by the weight and center of gravity (“Iα = 0”). We get:

\[ F_{Yr} = F_{Yf} \frac{L_a}{L_b} \]  \hspace{1cm} (5)

\[ \frac{W_T v^2}{g R} = F_{Yf} + F_{Yf} \frac{L_a}{L_b} = F_{Yf} \left(1 + \frac{L_a}{L_b}\right) = F_{Yf} \left(\frac{L_a + L_b}{L_b}\right) = F_{Yf} \left(\frac{L}{L_b}\right) \]  \hspace{1cm} (6)

Now solve for “F_f”, and “F_r”, then substitute “W_t” for “Wt L_a/L”, “Wf” for “Wt L_a/L”, and “a_y” for “v^2/gR”:

\[ F_{Yf} = W_f a_y \]  \hspace{1cm} (7)

\[ F_{Yr} = W_r a_y \]  \hspace{1cm} (8)

2.3. Two-dimensional weight transfer

In the static case the normal loads would be equal, force at inner tire equals to outer tire (Ni = No). However, it is not the static case, but that of dynamic equilibrium in a steady-state turning situation, in which we are interested. In such a case, a “weight transfer moment” occurs which alters the lateral force generation potential by decreasing the normal load on the tire closest to the turn center (“inner tire”) and increasing, by an equivalent amount, the normal load on the tire furthest from the turn center (“outer tire”).

When the vehicle is turning right, the outer tyre has the most weight transferred to it. The difference of normal load that is occurring on both tires could be represented by:

\[ N_{i/a} = \frac{W}{2} \mp W a_y \frac{h_{cg}}{t} \]  \hspace{1cm} (9)
2.4. Rollover condition
A rollover condition is where the vehicle is turning over if it exceeds some speed. By calculating from formula (9), the speed could be used to determine the height needed in order to turn safely where the height is later translated to the tilt angle. The rollover equation is as follows:

$$a_{rollover} = \frac{t}{2h_{cg}}$$

where if the undergoing acceleration of the vehicle in equation (4) exceeds the maximum rollover acceleration in equation (10), the vehicle would roll over and safety is compromised.

2.5. Control diagram
Figure 4 shows the control diagram for the dynamic using the steering and tilting input of the system. The steering input is used to determine the turning radius that the vehicle is having while the tilting input is extracted from the linear potentiometer sensor which goes in the suspension system. Where in the iteration, the rollover acceleration should be less than the lateral acceleration or a rollover condition would happen. Therefore, every time the lateral acceleration is increasing due to a rise in speed or a reduction in the turning radius (see equation (4)), a new tilting angle has to be set in order to reduce the center of gravity in order to also reduce the height difference ($h_{cg}$) in the vehicle.
3. Results and discussion
The turning radius that is used for this iteration is varied between 0 meter to 4 meter maximum, while the speed is also varied at 30 kph maximum. The iteration is done by using the diagram in figure 4 above.

3.1. Lateral acceleration
The results of the lateral acceleration occurred on the vehicle where the speed is varied between 2 – 30 kph and the turning radius is varied between 1 – 4 meter is on the figure 5. below,

![Lateral Acceleration Graph](image)

Figure 6. Lateral acceleration results to undergone speed with varied radius

The resulted lateral acceleration keeps going down in terms of increasing turning radius. Where if the speed is increasing, the lateral acceleration would also increase.

3.2. Rollover condition and maximum center of gravity
The results of the maximum lateral acceleration which is calculated based on the test subject compared to the varied turning radius and speed on the vehicle results in a table on figure 6. below. The maximum turning speed on a normal road which has an approximate turning radius of 4 meter is 22 kph and on the smallest road possible which has 1 meter turning radius is below 10 kph. If the condition goes onto the red zone, beyond the speed limit, the vehicle would result in a roll over condition.

The diagram shows where the CoG should be located within the vehicle (from the ground). The color shown by purple is unsafe for the vehicle to turn as it is much safer for a vehicle to turn at a low speed in a long turning radius. The brighter the color, the safer the vehicle will turn.

4. Conclusions
Based on the modelling and iteration that has been done, the following conclusion could be drawn:
- The higher the speed that a three-wheeled vehicle with a tadpole configuration is in when turning, the higher the lateral acceleration on the vehicle it would be.
- The smaller the turning radius on a normal road, if it is going with the same speed respectively, the higher the lateral acceleration.
- Higher Center of Gravity will result in smaller maximum lateral acceleration where if the lateral acceleration exceeds the maximum, a roll over accident would happen.
- On a normal road condition with a turning radius of 1 –4 meter, a vehicle speed when turning is maximum compromised at 22 kph.
Figure 7. Center of gravity shifts in relation with varied turning conditions

Acknowledgments
This paper was supported by Hibah PITTA (Publikasi Internasional Terindeks untuk Tugas Akhir) – Universitas Indonesia

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