Steering Dynamics of Tilting Narrow Track Vehicle with Passive Front Wheel Design

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Abstract. In recent years, narrow track vehicle has been emerged as a potential candidate for the next generation of urban transportation system, which is greener and space effective. Vehicle body tilting has been a symbolic characteristic of such vehicle, with the purpose to maintain its stability with the narrow track body. However, the coordination between active steering and vehicle tilting requires considerable driving skill in order to achieve effective stability. In this work, we propose an alternative steering method with a passive front wheel that mechanically follows the vehicle body tilting. The objective of this paper is to investigate the steering dynamics of the vehicle under various design parameters of the passive front wheel. Modeling of a three-wheel tilting narrow track vehicle and multibody dynamics simulations were conducted to study the effects of two important front wheel design parameters, i.e. caster angle and trail toward the vehicle steering dynamics in steering response time, turning radius, steering stability and resiliency towards external disturbance. From the results of the simulation studies, we have verified the relationships of these two front wheel design parameters toward the vehicle steering dynamics.

1. Introduction

Narrow track vehicles \cite{1} that are greener with a smaller footprint similar to a motorcycle are getting a lot of attentions in recent development of new urban transportation system. In order to maintain its rollover stability due to the tight wheel track, this type of vehicles has a symbolic characteristic of vehicle tilting. There are many studies on such vehicle tilting \cite{2}, \cite{3}, including discussions on optimum lean angle \cite{4} and tiling position \cite{5}. However, another challenge in developing such tilting vehicles is that the coordination between active steering and vehicle tilting requires considerable driving skill in order to achieve effective stability. To address this issue, we have proposed a passive front wheel that mechanically follows the vehicle body tilting as an alternative way of steering for a tilting three-wheel narrow track vehicle.

2. Passive Front Wheel Steering for Tilting Narrow Track Vehicle

2.1. Passive front wheel steering concept

In contrast to conventional active front wheel steering, in this work, we propose a steering approach with passive front wheel that mechanically follows the vehicle body tilting for a tilting three-wheel narrow track vehicle (Fig. 1). We have developed a three-wheel narrow track vehicle with a link structure attaching the rear wheels and it is controlled by a motor for vehicle tilting. The passive front
wheel attached on the steering axle with a caster angle is free to be turned mechanically with respect the vehicle tilting motion.

**Figure 1.** Steering concept of the tilting narrow track vehicle with passive front wheel design.

2.2. Passive front wheel design parameters and analyses by simulations
The objective of this work is to investigate the steering dynamics of the vehicle under various design parameters of the passive front wheel. We have constructed the 3D model of the proposed tilting three-wheel narrow track vehicle for multibody dynamics analysis [6], [7] using ADAMS [8] software (Fig. 2 (left)). The vehicle model consists of four rigid bodies: body, front wheel, right rear wheel, and left rear wheel. The system has 10 degree of freedom (DOF): 6 DOF on the body, 1 DOF on the front wheel steering axis, and 3 DOF on the three rotating wheels.

The vehicle model is designed to have a total mass of 288 kg with a dimension of 2 m length, 0.63 m width and 1.55 m height. The wheelbase is 1.49 m and the wheel track is 0.495 m. The front wheel size is 100/100R12 and the rear wheels size is 90/90R12. We have determined two important front wheel design parameters: caster angle and trail (Fig. 2 (right)) for our simulation studies. For the practicability reason of actual vehicle construction, the comparative studies between caster angle and trail are fixed into two set of front wheel configurations: default caster angle 0 deg versus trail 50, 100, 150 mm, and default trail 62.0 mm versus caster angle 0, 13.5, 27 deg.

**Figure 2.** Simulation model (left) and passive front wheel design parameters: caster angle and trail.

We have designed three simulation scenarios (Fig. 3) in order to study the vehicle steering dynamics in steering response time (Fig. 3 (a)), turning radius (Fig. 3 (b)), steering stability and resiliency towards external disturbance (Fig. 3 (c)).
3. **Steering Dynamics Analyses**

3.1. **Steering response time towards vehicle body tilting**

In the simulation study of steering response time towards vehicle body tilting (Fig. 3 (a)), the vehicle is programmed to perform a J-Turn in a fixed travel speed 20 km/h. In the simulation, after the vehicle achieved the fixed speed in a straight path travel, a 15 deg of vehicle body tilting is triggered (input) to steer the vehicle. Fig. 4 shows the simulation results of the vehicle steering (angle) response in J-Turn with a fixed wheel trail and caster angle 0, 13.5, 27 deg.

![Figure 4](image)

**Figure 4.** Steering (angle) response in J-Turn with a fixed wheel trail and caster angle 0, 13.5, 27 deg.

For the comparative studies between caster angle and trail, the simulations are run in the designated two set of front wheel configurations. The response time for the vehicle to reach 95% of the steady state steering angle is recorded and the plots of the response time results are shown in Fig. 5. From both plots in caster angle (Fig. 5 (a)) and wheel trail (Fig. 5 (b)), it is observed that there are no significant impact (maximum difference is less than 0.04 s) towards the vehicle steering response time in both caster angle and wheel trail changes.
3.2. Effects on vehicle turning radius

In the simulation study to investigate the effects on vehicle turning radius by passive front wheel steering (Fig. 3 (b)), the vehicle is programmed to perform a circular turning in a constant travel speed of 20 km/h and 15 deg of vehicle body tilting. Fig. 6 illustrates the simulation results of the vehicle constant circular turning path (turning radius) with a fixed wheel trail and caster angle 0, 13.5, 27 deg.

Figure 5. Comparison of passive front wheel designs (caster angle and trail) on steering response time towards vehicle body tilting.

Figure 6. Vehicle constant circular turning (turning radius) with a fixed wheel trail and caster angle 0, 13.5, 27 deg.

The simulations are repeated in the designated two set of front wheel configurations for the comparative studies between caster angle and trail, and the plots of turning radius results are shown in Fig. 7. From the caster angle plot in Fig. 7 (a), an increasing trend (greater than 1 m) in vehicle turning radius is observed as the front wheel caster angle increased. However, no significant impact (less than 1 m difference) towards the vehicle steering turning radius is observed in the wheel trail changes in Fig. 7 (b).
3.3. Steering stability and resiliency towards external disturbance

In the simulation study of steering stability and resiliency towards external disturbance (Fig. 3 (c)), the vehicle is programmed to travel straight forward in a constant speed of 20 km/h, and a 10 Nm reverse torque (impulse) (Fig. 3(c)) is applied on the front wheel as an external disturbance, with a slight lift on the rear left wheel to induce steer. Fig. 8 shows the simulation results of the vehicle steering (angle) response towards the external disturbance (reverse torque) with a fixed wheel trail and caster angle 0, 13.5, 27 deg.

The simulations are conducted in the designated two set of front wheel configurations for the comparative studies between caster angle and trail, and the maximum displacement of steering angle results are plotted in Fig. 9 for the vehicle steering stability analysis. It is observed that both caster angle plot (Fig. 9 (a)) and wheel trail plot (Fig. 9 (b)) are showing decreasing trend of maximum displacement of steering angle (greater than 0.1 deg difference) as the parameters decreased, especially in the wheel trail case, as large as 1 deg difference in maximum displacement of steering angle is recorded.

In the study of steering resiliency towards external disturbance, steering angle recovery time (time needed to return steady state) results are plotted in Figure 10 (a) (caster angle) and Figure 10 (b) (wheel trail). It is observed that there are no significant impact (maximum difference is less than 0.3 s) towards the vehicle steering angle recovery time in both caster angle and wheel trail changes.
4. Conclusion

In this work, we propose an alternative steering method with a passive front wheel that mechanically follows the vehicle body tilting. The objective of this paper is to investigate the steering dynamics of the vehicle under two important design parameters, i.e. caster angle and trail of the passive front wheel. From the results of the multibody dynamics analyses in three simulation scenarios, we have verified the relationships of these two front wheel design parameters toward the vehicle steering dynamics in steering response time, turning radius, steering stability and resiliency towards external disturbance. The analyses results are summarized into Table 1 below. The increments of caster angle and trail are shown to have improvement or minor impact towards the steering dynamics. However, the side effect (on other vehicle performance) and limit of such parameters should also be studied in future work to ensure overall improvement.

| Table 1. Summary of the steering dynamics analyses with respect to the passive front wheel design parameters (caster angle and trail). |
|---|---|---|---|---|
| Caster angle (↑) | Minor impact | Increased (↑) | Improved* | Minor impact |
| Trail (↑) | Minor impact | Minor impact | Improved* | Minor impact |

* Maximum displacement of steering angle reduced and hence, steering stability improved.
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