

Investigation of the Behavior of Three-Wheel Vehicles When They Pass Over a Low μ Road Surface

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ABSTRACT

In recent years three-wheel camber vehicles, with two wheels in the front and a single rear wheel, have been growing in popularity. We call this kind of vehicle a "Leaning Multi Wheel category Vehicle" (hereinafter referred to as a "LMWV"). A LMWV has various characteristics, but one of them stands out in particular. When a LMWV is cornering, if one of the front wheels passes over a section of road surface with a low friction coefficient, there is very little disturbance to the vehicle's behavior and can continue to be driven as normal. However, there has been no investigation into why these vehicles have this particular characteristic. Consequently, in this paper an investigation was carried out in order to determine the behavior of a LMWV in this situation. First, measurements were taken using an actual vehicle to confirm the situation described above. As a result, it was confirmed that there is only a small change in the vehicle's posture and also that the other front tire generates tire force that appears to compensate for the decrease in lateral force. Next, a multibody dynamics analysis was carried out. The results of this simulation indicated that the cause of this phenomenon is the steering turns toward the inside of the corner and the other front tire develops a slip angle which in turn generates a lateral force. The investigation and analysis described above clarified this phenomenon and demonstrated one of the factors that gives a LMWV its cornering stability.

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INTRODUCTION

If we take a look back at the evolution of personal mobility, there is a long history of various vehicles being proposed all around the world. In recent years there has been an increase in the number of three-wheel vehicles, particularly in Europe, that have two wheels in the front, a single wheel in the rear, and that feature large camber angles. These vehicles possess a mechanism that is different from both automobiles and motorcycles, but they keep stability and motorcycle-like handling. We call this kind of vehicle a "Leaning Multi Wheel category Vehicle" (hereinafter referred to as a "LMWV") and have been pursuing their development as well as investigating their characteristics[1]. LMWV are known to possess a number of characteristics[2], but the riders of these vehicles have indicated that one noteworthy characteristic is the vehicle's stability when cornering. One concrete example that has been reported was the case where one of the front wheels passed over a low μ road surface, such as a wet manhole cover, while the vehicle was cornering. Despite these conditions, the vehicle remains stable throughout the turn and can continue to be driven as normal because of little roll angle change. However, there has not been a thorough examination of this particular characteristic and so there is a need for a theoretical study from the standpoint of understanding these vehicles better. In addition, there are very few other examples of research into these types of vehicles, so this is another factor that is preventing a better understanding of LMWV.

Therefore, in this paper an investigation was carried out to examine the phenomenon that occurs when one of the front wheels of a LMWV passes over a low μ road surface during cornering. The purpose of this investigation is to determine the factors that contribute to the turning stability of these vehicles. First, measurements were taken using an actual vehicle during the situation where one of the front wheels passes over a low μ road surface during cornering to confirm the phenomenon. Next, a multibody dynamics analysis was carried out by simulating the same situation to investigate the cause of the above-mentioned phenomenon. This paper reports the results and new knowledge that were obtained from these analyses and examinations.

ACTUAL MEASUREMENT TEST

First, an actual measurement test was carried out to investigate and confirm this phenomenon. Fig. 1 shows the LMWV with 155 cm³ of displacement that was used for the test. Table 1 lists the vehicle specifications. Furthermore, in this paper, in order to focus on the vehicle characteristics, theoretically, when the vehicle is cornering, the examination was carried out using a geometry in which the difference in the left and right wheel steering angles was 0 degrees at the time of roll. The vehicle was equipped with an inertial GPS sensor, a steering torque sensor, and tire six-component force meter wheels on the left and right front wheels. Please see the references for more details about the measuring instruments[3]. The coordinate system uses the ISO

coordinate system, as shown in Fig. 2 and the origin point is located in the center of the right and left Fr.tire road contact point. It is a right-handed orthogonal coordinate system and the axis of rotation is positive in the direction of the right-hand screw. Fig. 3 shows the tire force coordinate system. The origin point is located in the each Fr.tire road contact point and the coordinate axes follow along the road surface. α in Fig.3 indicates the direction of slip angle.



Fig. 1. External Appearance of LMWV

Table 1. Vehicle Specifications

Vehicle spec					
Wheelbase	1350	mm	Overall length	1980	mm
Caster angle	20	deg	Trail	67	mm
Curb weight	165	kg	Engine displacement	155	cm³
Fr tire	90/80-14M/C	-	Max power	11.1	kW
Rr tire	130/70-13M/C	-	Max torque	14.4	Nm

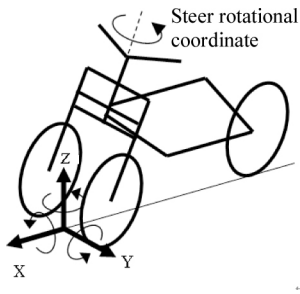


Fig. 2. Coordinate system

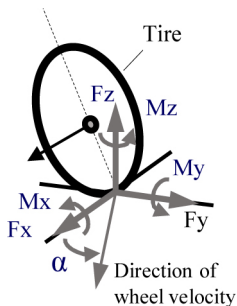


Fig. 3. Tire Force Coordinate System

Outriggers were attached to the vehicle during measurement in consideration of the rider's safety. Fig. 4 shows the external appearance of the test vehicle. A smooth, steel plate (670×670×2.5mm) in a wet state was prepared to be the low μ road surface. A skid resistance tester was used to take measurements in advance and as a result it was confirmed that the BPN(British Pendulum Number) was 13.9. The test was then conducted on a circular test course with a radius of 30 meters. The vehicle was driven counterclockwise around the course in a steady state circular turn and only the right front wheel passed over the low μ road surface. Rider always keeps a steady circular turn. The vehicle velocity was a constant 30 km/h. Fig. 5 shows the roll angle measurement results. All measurement data was passed through a 10 Hz low pass filter. The area where one wheel passed over low μ road surface was determined from the tire force measurement data. The roll angle changed by approximately 1 degree when one of the front wheels passed over the low μ road surface. This amount of fluctuation in the roll angle is small in respect to that found during a steady state circular turn and so it was concluded that the vehicle was maintaining its stability. This result matched the comments received from the vehicle's riders. Next, as a distinguishing characteristic of the data measured by using the tire six-component force meter, Fig. 6 shows lateral force measurement data which is shown as F_y in Fig.3 from the front tires. The graph indicates that when one of the front tires passed over the low μ road surface, as the lateral force of the tire on the low friction surface decreased, the other tire appeared to compensate for it. Next, Fig.7 shows the steer angle result. The result shows the steering angle changed on the inside of turn. Consequently, this verification testing and the actual measurement data that was obtained made it possible to confirm that this phenomenon, which occurs when only one of the front wheels of the LMWV passes over a low μ road surface while cornering, does in fact exist.



Fig. 4. External View of the Test Vehicle

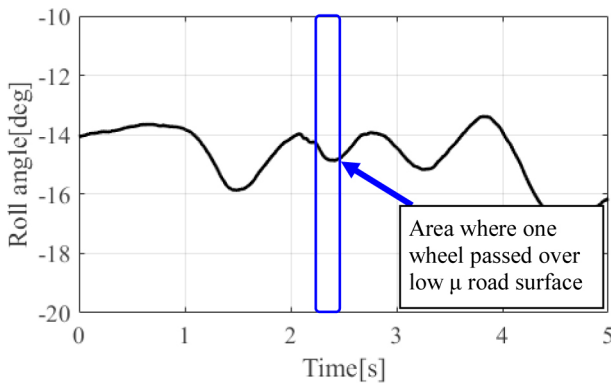


Fig. 5. Roll Angle Measurement Data at Left Turn

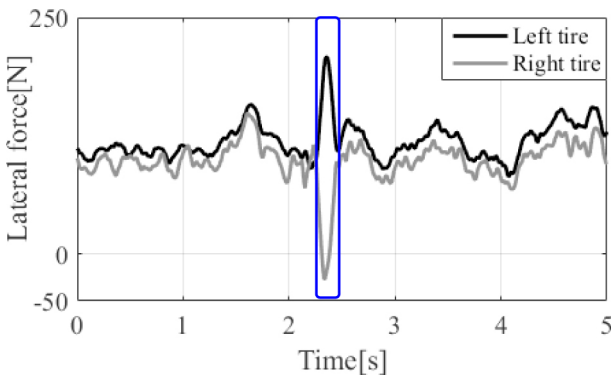


Fig. 6. Tire Lateral Force Measurement Data

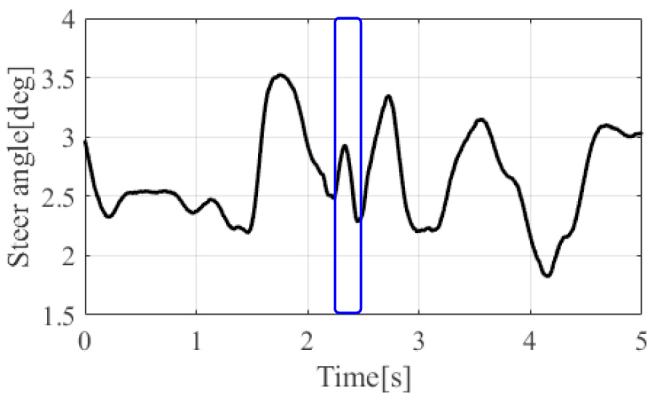


Fig. 7. Steer Angle Measurement Data

SIMULATION

Simulation Model

There is a limit to the number of items that can be measured using the actual vehicle, so this phenomenon was investigated further by using a simulation. A simulation model of the same vehicle used in the actual measurement test was created for this investigation. The analysis software that was used was SimMechanics. The simulation model of the vehicle was composed of 20 rigid bodies, 18 revolute joints, and two prismatic joints for the left and right front suspension. In addition, non-linear springs and dampers were established for the left and right front forks and the rear suspension, while torsion springs corresponding to rubber bushings were established in rear arm and engine rotation axis. The rider was coupled to the main frame as a rigid body. The main frame of the vehicle possesses six degrees-of-freedom as a reference point, but the other portions of the

simulation model, the rotation of the left and right front wheels and of the rear wheel, the rotation of the front lean mechanism, the elasticity of the left and right front suspension, the rotation of the handle bars, the rotation of the rear arm, and the rotation of the engine all possess 15 degrees-of-freedom. The Magic Formula model was used as the tire model. Each rigid element has mass property, moment of inertia, and coordinates at connecting points, and the springs and dampers have the values for the physical properties. Figs. 8, 9 and 10 show the simulation model in more detail.

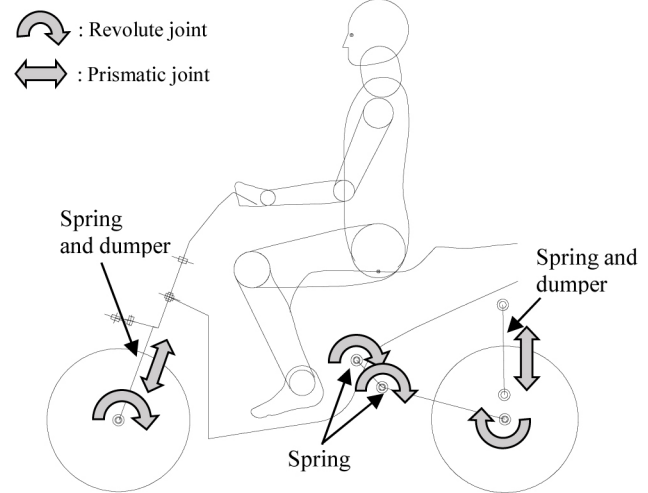


Fig. 8. LMWV Simulation Model

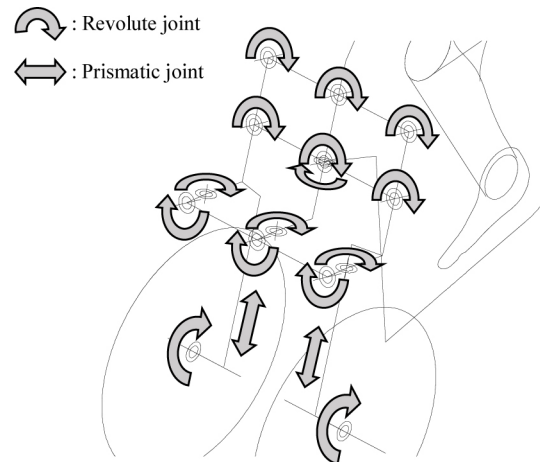


Fig. 9. Lean Mechanism of the Simulation Model

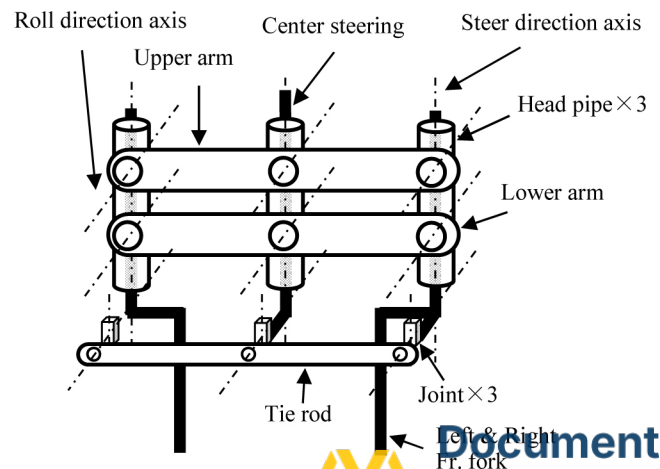


Fig. 10. Detailed Drawing of the Lean Mechanism