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ORIGINAL RESEARCH ARTICLE

ROLLOVER STABILITY MODELS FOR THREE-WHEELED VEHICLE DESIGN

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ABSTRACT

The current commercial three-wheeled vehicles (TWVs) in the market are rollover unstable, with adverse effects on life and property. This places limitation on their speed and usage, even though they are fuel efficient, cheap and generate about 33% of green gases per rider when compared with four-wheeled vehicles.This work derived mathematical models for the analysis of the stability of the three-wheeled vehicle (TWV). Based on these models, the test method for rollover stability was adopted. Rollover test was carried out on a TWV on Nigerian road. The results showed that the vehicle is unstable with respect to rollover stability. The test procedure if adopted and legislated upon, would significantly enhance safety of life and property of the population. Moreover, the speed and usage of the vehicle for both private and commercial purposes will be enhanced.

1.0 Introduction

The tricycle, called trike or three-wheeler, is a three-wheeled vehicle (TWV). In African and Asian countries, they are used mainly for commercial purposes (Gawade et al., 2004) as shown in Figure 1.

Figure 1: Three-wheeled vehicle (TWV)

The vehicle is safer when compared with commercial motorcycle, and cheaper and able to manoeuvre through heavy traffic in urban environments when compared with four-wheeled vehicles. It is fuel efficient and generates about 33% of green gases per rider when compared with cars and jeeps as a result of weight difference (Goodarzi et al., 2015). All this have accentuated its usage.

However, there are some safety problems associated with the usage of these TWVs. They are more accident prone when compared to four wheeled vehicles. The stakeholders of three-wheeled vehicles attested to it that the vehicle can tip-over when negotiating a bend, even though their maximum speed is about 60km/h. This places some limitations on their usage.

The development of the TWV was based on the old scooter motorcycles without much stability considerations. The upright sitting positions of occupants result in high centre of gravity (Mukherjee et al., 2007). Considering also that the vehicle is narrow and cannot lean inwards when negotiating a bend to counter the effect of centrifugal force, there are bound to be instability problems (Berote et al., 2008; Dardaine et al., 2008). Consequently, there are challenges posed by the TWV especially in the area of safety of life and property, due to this instability. However, Huston et al. (1982) and Valkenburgh et al. (1982) asserted that it is possible to engineer a TWV that can be safe as the four-wheeled ones. Therefore, the aim of this study is to generate mathematical models and to investigate the rollover stability of TWV, in order to enhance safety of life and property on the roads.

2. Materials and Methods

2.1 Rollover Stability Model under Static Condition

Figure 2 shows the static model for TWV on a banked road for the determination of rollover stability factor and height of centre of gravity h. Where θ is the angle of inclination of the vehicle to the horizontal plane. The basic assumptions of the model are: load distribution is symmetrical about x- axis when on horizontal plane and the effect of depression of tyre due to load transfer is negligible.

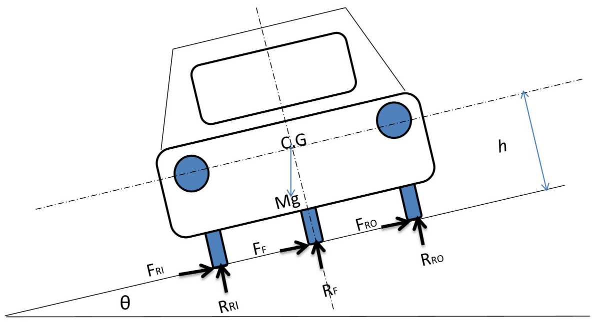

Figure 2: Three-wheeled vehicle on a banked road

The governing equations are derived by vertical and horizontal resolution of forces about the plane of motion:

$$F_{RI} + F_F + F_{RO} = mg\sin\theta \qquad (1)$$

$$R_{RI} + R_F + R_{RO} = mg\cos\theta \qquad (2)$$

$$F_F = \frac{L_2}{w_B} mg\sin\theta \qquad (3)$$

$$R_F = \frac{L_2}{W_B} mg\cos\theta \qquad (4)$$

$$F_{RI} + F_{RO} = \frac{L_1}{w_B} mg\sin\theta \qquad (5)$$

$$R_{RI} + R_{RO} = \frac{L_1}{w_B} mg\cos\theta \qquad (6)$$

Where W_B is wheelbase and W_T is the wheel-track

Taking moment about centre of gravity:

$$h(F_{RI} + F_F + F_{RO}) = \frac{W_T}{2}(R_{RI} - R_{RO}) \qquad (7)$$

Substituting equation (1) and (6) in (7) to eliminate RRO:

$$h(mg\sin\theta) = \frac{W_T}{2}(R_{RI} - (- R_{RI} + \frac{L_1}{w_B} mg\cos\theta) \quad (8)$$

Rearranging equation (8):

$$R_{RI} = \frac{L_1}{2W_B} mg\cos\theta + \frac{h}{W_T} mg\sin\theta \quad (9)$$

Similarly, substituting equation (1) and (6) in (7) to eliminate RRI:

$$h(mg\sin\theta) = \frac{W_T}{2}(- R_{RO} + (- R_{RO} + \frac{L_1}{w_B} mg\cos\theta) \quad (10)$$

Rearranging equation (23):

$$R_{RO} = \frac{L_1}{2W_B} mg\cos\theta - \frac{h}{W_T} mg\sin\theta \quad (11)$$

If the vehicle does not slide or is blocked from sliding as θ is increased, at limit of rollover, RRO will become zero, therefore equation (11) becomes:

$$\frac{L_1}{2W_B} mg\cos\theta = \frac{h}{W_T} mg\sin\theta \quad (12)$$

Or:

$$\frac{L_1}{2W_B}\cos\theta = \frac{h}{W_T}\sin\theta \quad (13)$$

Therefore, the Static Stability Factor (SSF) for the three wheeled vehicle is defined as:

$$\tan\theta = \frac{l_1}{W_B}\frac{W_T}{2h} \quad (14)$$

The equation is basically the same as that of Huston et al., (1982) only that a different methodology of derivation was adopted.

Rearranging equation (14), where h is height of centre of gravity of the vehicle:

$$h = \frac{L_1}{W_B} \text{ x } \frac{W_{TE}}{2\tan\theta} \quad (15)$$

Equation (15) can be used to determine the height of centre of gravity h for a TWV, using rollover angle, since other parametric values can be accessed or determined.

2.2 Rollover Stability Model under Dynamic Condition

Figure 3 shows the model of three wheeled vehicles moving in circle of radius R. The basic assumptions of the model are: that the vehicle is moving in horizontal plane with constant tangential velocity V, the effect of aerodynamic drag force is not significant, load distribution is symmetrical about x-axis and the effect of depression of tyre due to load transfer is negligible. Mathematical models were developed from the model to determine dynamic behaviour of TWV as it affects the Rollover Stability, using force and torque equations.

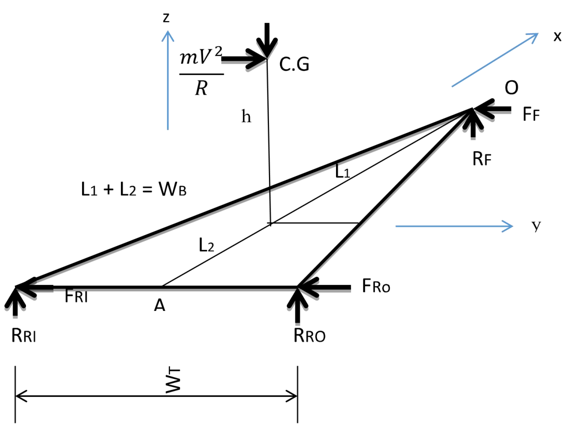

Figure 3: Rollover dynamic stability model

The centrifugal force acting at the centre of gravity (C.G) of the vehicle in the direction of y-axis is balanced by lateral frictional resistance from the three wheels ($F_{RI} + F_F + F_{RO}$) if there is no slide, while the rear wheels reactions due to the weight of the vehicle is given as $\frac{L_1}{W_B}(mg)$.

Therefore, the force equations are:

$$\frac{mV^2}{R} = F_{RI} + F_F + F_{RO} \quad (16)$$

$$R_{RO} + R_{RI} = \frac{L_1}{W_B}(mg) \quad (17)$$

Taking moment about centre line A-O (along x-axis) to eliminate R_F the equation becomes:

$$\frac{mV^2}{R}h = \frac{W_T}{2}(R_{RO} - R_{RI}) \quad (18)$$

Substituting equation (17) in (18):

$$\frac{mV^2}{R}h = \frac{W_T}{2}\frac{L_1}{W_B}mg - R_{RI}W_T \quad (19)$$

At the limit of rollover stability the reaction at inner wheel will be zero (RRI = 0), therefore:

$$\frac{mV^2}{R}h = \frac{W_T}{2}\frac{L_1}{W_B}mg \quad (20)$$

Where V is now the critical or rollover velocity (V_R) and a is the centrifugal acceleration

$$\frac{V_R^2}{R} = a = \frac{W_T}{2h}\frac{L_1}{W_B}g \quad (21)$$

Rearranging Equation (6):

$$\frac{a}{g} = \frac{W_T}{2h}\frac{L_1}{W_B} \quad (22)$$

Equation (22), which is dimensionless, is the dynamic stability factor. The equation is basically the same as that: static stability factor for TWV as seen in Equation (14); and Valkenburgh et al., (1982), except for the methodology of derivation.

The lateral friction coefficient (μ) is in the opposite direction to dynamic stability factor. If the dynamic stability factor is less than the lateral friction coefficient, such that:

$$\frac{a}{g} = \frac{W_T}{2h}\frac{L_1}{W_B} < \mu \quad (23)$$

then vehicle will rollover since the lateral friction force will stop the vehicle from sliding, which is not what is desirable in vehicle design. It is easier to handle sliding challenges under emergency situation than rollover (Huston, et al., 1982).

If however, the dynamic stability factor is greater than the lateral friction coefficient, then the vehicle will slide before rollover based on Equation (24), which is the desirable option in vehicle design.

$$\frac{a}{g} = \frac{W_T}{2h}\frac{L_1}{W_B} > \mu \quad (24)$$

The rollover velocity (V_R) is defined in Equation (25) based on Equation (21):

$$V_R = \left(\frac{W_T}{h}\frac{L_1}{W_B}gR\right)^{\frac{1}{2}} \quad (25)$$

The other dynamic reactions that may be incorporated into the basic Equation (22) are: dynamic reactions due to acceleration and deceleration (Huston, et al., 1982) aerodynamic reactions due to drag force (Sachdeva and Kamiyo, 2015; Rajamani, 2012); gyroscopic couple and Coriolis force. These reactions put together will change the value of L_1 to L_{1A}. Since other factors are constant, the final equation becomes:

$$\frac{a}{g} = \frac{W_T}{2h}\frac{L_{1A}}{W_B} \quad (26)$$

2.3 Test Method for Rollover Stability Determination of TWV

There are various test methods for rollover stability. The following are some of the standard methods for vehicle testing: The tilting test, constant cycle test, slowly increasing steer (SIS), NHTSA (National Highway Traffic Safety Administration's) J-turn and Road edge recovery (PER). For the purpose of testing the vehicle for stability, tilting test method is adopted based on Equations (14) and (15). Moreover, it is less involving and easy to implement in a developing country. 0.8 is taken as minimum rollover stability factor or 39° minimum tilting angles (Mukherjee et al., 2007).

Briscoe Garage UNILAG Service Centre was used for the test with fairly flat horizontal surface. Items used for the test were: TWV, Long jack, Protractor with attached pendulum, Camera and Engineering Tape. The vehicle was placed on the floor of the Garage with attached protractor and a pendulum at the back of vehicle. The vehicle was jacked up from left or right until it reached the rollover point as shown in the Figure 4.

All necessary readings were taken. Other values that involved loads were obtained through analysis (Swearingen, 1962), since it will be very involving to obtain standard human weights with average centre of gravity.

Dimensions taken from the vehicles were: Wheelbase, wheel-track, horizontal distance from the ground centre of front axle driver back support, horizontal distance from the ground centre of front axle to the passenger back support, vertical distance from the to the top of driver seat and vertical distance from the ground to the top of passenger seat.

For the purpose of this work, 72kg average weight for an adult was adopted based on the random survey that was carried out at Ogun State Property and Investment Cooperation (OPIC) Estate Agbara, Nigeria for one hundred adults.

Shown in Figure 4 is the picture of the vehicle during the tilting test.

Figure 4: Tilting of TWV to Rollover Angle

3. Results and Discussion

3.1 Rollover Tilting Test Results

The Rollover dynamic stability factor determination was based on angle of tilt, which is $\tan\theta$ (Equation 14). Table 1 shows the values of rollover angles that were obtained through the tilting test that was carried out at Briscoe Garage UNILAG Service Centre with the centre gravity of humans taken into consideration (Swearingen, 1962) for a TWV on Nigerian roads.

Table 1: Rollover stability report

Item	Occupants A	Rollover Angle Actual B	Rollover Angle Minimum Standard c	Variance a - b D	Compliant (C) / Non-compliant (NC) e
1	0	390	390	00	C
2	1 = Driver	340	390	-50	NC
3	2 = Driver + 1 Passenger	340	390	-50	NC
4	3 = Driver + 2 Passengers	300	390	-90	NC
5	4 = Driver + 3 Passengers	280	390	-110	NC

Figure 5 shows the TWV rollover stability simulations.

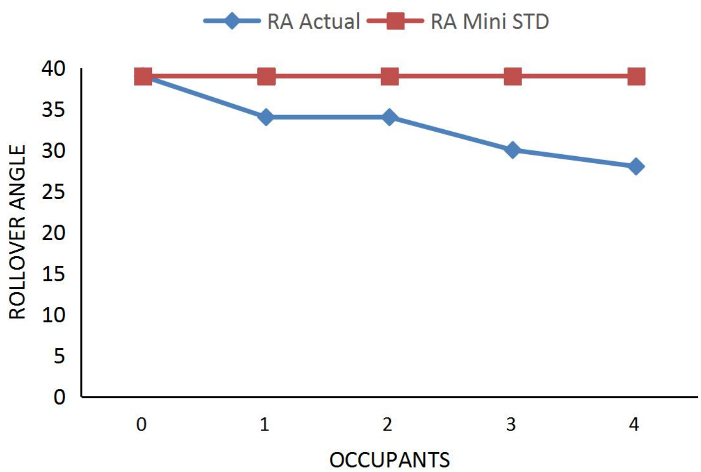

Figure 5: Rollover stability angle versus occupants

From Table 1 and Figure 5, it can be deduced that the vehicle itself without any occupant is rollover stable. With the driver alone, the vehicle became unstable. The reason is quite obvious. The weight of the driver shifted more load to the front wheel than the rear. This reduced the value of L1 and also increased the overall height of C.G. since centre C.G. of vehicle is lower than that of the driver. The two factors combined together brought down the value of rollover stability below the minimum required based on Equation (14). The result is in line with that of literature (Mukherjee et al., 2007; Karanam et al., 2012). However, with the first passenger at rear seat, more loads were transferred to the rear wheels than the front wheel because of the position of C. G. of the vehicle (Karanam et al., 2012). One would have expected rollover stability to increase but the height of C. G. of the passenger nullified the effect of increase in stability. Moreover, with more passengers, the effect of the height of C. G. of passengers took over since there were no more backward movements. This made the vehicle to become more and more rollover unstable. Therefore, the non-compliance of the vehicle, in terms of rollover stability is mainly due to the high C. G. of occupants. It can be deduced from the variances that the vehicle itself is rollover stable and it will suffer rollover instability with one occupant and above.

From equations (14) and (22) it can be seen that the factors that affect rollover stability are: wheel-track (WT), horizontal distance from centre of front wheel to the C. G. of vehicle (L1), height of C. G. (h) and wheelbase (WB). Deceleration will transfer more load to the front wheel thereby increasing rollover instability and should be taken into account in vehicle design stability. Outward cambering of rear wheels will increase rollover stability since wheel-tract is increased (Ihueze and Ebisike, 2018). In case of the redesign of the vehicle, the effect cambering of the wheels should be taken into consideration, including suspension, and roll resistance.

There are other factors such as steering compliance, gyroscopic couple due to road bumps, Coriolis force due to curvilinear motion, etc. that could impact negatively on lateral stability. All these factors should be taken into consideration in a major modification of the vehicle at the initial stage of its design to be rollover stability compliant based on Equation (26), so that newer models of the vehicle will be rollover stable.

4. Conclusions

This study came up with mathematical models and tilting test method for the determination of the rollover stability of TWVs and for the design and regulation of the vehicle in developing countries, in order to enhance safety of life and property.

The test method was used in the determination of the rollover stability of one of the commonest TWV on the Nigerian road. The vehicle was found to be rollover unstable with one occupant and above. However, this instability could be minimised on the current TWV by increase in the wheel-track of the vehicle relatively to wheelbase and lowering seat heights of the occupants. The ultimate solution lies in redesigning of the vehicle to take care of the problem.

The TWST currently being used by developing countries is not too safe in terms of rollover stability due basically to the high centre of gravity of occupants. Therefore, the following recommendations are made to ensure its rollover stability:

That the Rollover Stability Factor should not be less than 0.8 which amounts to 390 rollover angle, taken into consideration all the loadings through redesign and modifications.

Developing countries should at least adopt the Tilting method of vehicle testing for the design, regulation and importation of TWV.

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