METODOLOGIA E TÉCNICAS EXPERIMENTAIS

COMPUTER SIMULATION OF STABILITY AND CONTROL OF TRACTOR-TRAILED IMPLEMENT COMBINATIONS UNDER DIFFERENT OPERATING CONDITIONS(1)

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ABSTRACT

The mechanics of a tractor-trailer system moving up and down sloping ground under different operating conditions was theoretically simulated. A computer program was developed to analyze the system to predict the effect of both the trailer loading weight and the slope angle on the tractor stability, traction ability, and drawbar loading. The program was used to analyze a tractor-trailer system moving at uniform motion up and downhill. The results of this analysis showed that the tractor becomes unstable when towing a 3750 kg trailer uphill at 28° slope angle. Insufficient traction occurred at slope angles ranging from 15° to 18° corresponding to trailer weight of 3750 to 750 kg. The parallel component of drawbar pull reached a maximum value of 17318 N when the trailer was pushing the tractor downhill at 30° slope angle. The normal component (normal to the tractive surface) showed similar maximum values for both uphill and downhill motions of the system. The use of computer analysis in this study provided a significant improvement in predicting the effect of different parameters on stability and control of tractor-trailer combination on sloping ground.

Key words: Tractor-trailer, Stability, Traction, Sloping ground, Drawbar.

RESUMO

SIMULAÇÃO COMPUTACIONAL DA ESTABILIDADE E CONTROLE DE COMBINAÇÕES TRATOR-CARRETA SOB DIFERENTES CONDIÇÕES DE OPERAÇÃO

A mecânica do sistema trator-carreta movendo-se encosta acima e abaixo, sob diferentes condições de operação, foi simulada teoricamente. Foi desenvolvido um programa de computador para analisar o sistema visando prever o efeito do peso da carga da carreta e do ângulo da pendente na estabilidade do trator, na capacidade de tração e no carregamento da barra de tração. O programa computacional foi usado para analisar o sistema trator-carreta em deslocamento uniforme encosta acima e abaixo. Os resultados dessa análise mostraram que o trator se torna instável quando traciona uma carreta de 3.750 kg subindo uma encosta com 28º de declividade. Tração insuficiente ocorre quando os ângulos de inclinação variam de 15º a 18º, com pesos na carreta, respectivamente, de 3.750 a 750 kg. A componente paralela da força na barra de tração atingiu valor máximo de 17.318 N quando a carreta estava empurrando um trator encosta abaixo em uma ladeira com 30º de inclinação. A componente normal (normal à superfície de tração) apresentou valores máximos semelhantes, tanto nos deslocamentos do sistema encosta acima como encosta abaixo. O uso da análise computacional neste estudo trouxe melhoria significativa na previsão do efeito de diferentes parâmetros na estabilidade e no controle da combinação trator-carreta em terrenos inclinados.

Palavras-chave: trator-carreta, estabilidade, tração, terrenos inclinados, barra de tração.

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I. INTRODUCTION

The tractor has already been displaced in some of its previous tasks by self-propelled machines, either totally or partially. There are powerful arguments why the next task on this list will be transport. Often, the debate about transport requirements in agriculture and the role of the conventional tractor has attracted much interest recently. In many review papers, the authors have drawn attention to the growing requirements for more efficient transport and the pressure towards operating tractors at high speeds. Studies of tractor usage patterns are notoriously difficult to assess because of the wide differences in farms, but one feature that they continually highlight is the large percentage of time spent on transport and related tasks. In many countries, the tractor tasks in agriculture have become very important in recent years. The vehicles used for the largest percentage of transport are tractor-trailer combinations. But the dynamic performance of the tractor-trailer combination differs from the tractor alone and often accidents are caused because the tractor-trailer combinations became unstable by towing the trailer (ZHANG and TRAAO, 1991).

Tractor rollover incidents continue to be the major source of fatal and serious farm work injury (NATIONAL SAFETY COUNCIL, 2001; LIU and AYERS, 1999). Tractor stability and the reduction of injuries related to tractor rollovers were areas addressed by many researchers (PURSCHWITZ, 1992; MURPHY et al., 1993; MURPHY et al., 1996; GOLDENHAR and SCHULTE, 1996; YODER and MURPHY, 2000). SPENCER (1978) developed a theoretical model for predicting the condition of overturning stability and control loss of two-wheel drive tractor with towed implements. He showed that the minimum safe operating slope of a loaded silage trailer is 27% at a path angle of 15 degrees from the straight line up the sloping ground. Mitchell et al. (1972) developed a mathematical model for predicting rearward overturning behavior of a tractor for any set of initial conditions of angle of tip and angular velocity about the rear axle. They designed a control system based on stability criteria determined from the simulations. Their control system prevented rearward overturning in several tests on 0- and 11-degree slopes. SAGI et al. (1972) in a theoretical study of the combination of a wheeled tractor and a double-axle trailer concluded that loading the rear wheels by filling them with water, or by attaching additional weights to them will improve the tractor's braking capacity by moving the center of gravity backwards or lowering it. TAYLOR and KANE (1976) studied the effects of drawbar properties on the behavior of articulated vehicles. They found that drawbar flexibility can give rise to instability of the trailer.

The purpose of this study was to develop a computer program to predict and study the effect of trailer loading weight and slope angle of a tractor-trailer system moving up or down on a sloping ground on the following parameters; drawbar load, stability, and traction ability under different operating conditions.

2. METHODOLOGY

2.1. Nomenclature

W_1= weight of tractor.

W_2= weight of trailer.

N_1= soil reaction against the trailer wheels.

N_2= soil reaction against the rear wheels of the tractor.

N_3= soil reaction against the front wheels of the tractor.

R_1= rolling resistance of the trailer wheels.

R_2= rolling resistance of the rear wheels of the tractor.

R_3= rolling resistance of the front wheels of the tractor.

Py= normal component of the drawbar pull to the tractive surface.

Px= parallel component of the drawbar pull.

F = total of net traction forces developed by rear wheels of tractor.

F_2= braking force on the rear wheels of the tractor.

F_3= braking force on the front wheels of the tractor.

R_A= air resistance.

$I_{1(2)}$= the moment of inertia of the entire tractor (trailer) about a transverse axis through

the center of gravity

$\alpha_{1(2)}$= the angular acceleration of the entire tractor (trailer).

$I_{r(f)}$= the moment of inertia of the wheels about the center of the rear (front) axle.

I_{wt} = the moment of inertia of the trailer about the center of the trailer axle.

$\alpha_{f(r)}$= angular acceleration of the front wheels (rear wheels).

α_{wt} = angular acceleration of the trailer wheels.

a_h = the acceleration of the center of gravity in the direction of motion (w.r.t. earth).

a_v = the acceleration of the center of gravity in the direction normal to the tractive surface.

β = angle of the uphill grade relative to horizontal.

c = coefficient of rolling resistance.

μ = traction coefficient.

y_1= height of the center of gravity of trailer above the ground.

y_2= height of the tractor hitch point above the ground.

y_3= height of the center of gravity of tractor above the ground.

y_4= height of the air resistance.

x_1= distance of center of gravity of trailer forward of the axle of the trailer.

x_2= distance of axle of trailer rearward of the hitch point.

x_3= distance of hitch point rearward of the rear axle of the tractor.

x_4= distance of center of gravity of tractor forward of the rear axle of the tractor.

x_5= wheel base of the tractor.

$R_{f(r)}$= radius of the front (rear) wheels of the tractor.

R_t= radius of the trailer wheels.

2.2. Theory

General Equilibrium Equations

A rear wheel drive tractor in combination with a single axle trailer was considered in this study (Figure 1). The analysis was based on the following assumptions:

1- line of action of the drawbar pull, P, located midway between the traction wheels and parallel to the direction of motion.

2- line of action of the normal soil reaction passes through the center of wheels.

3- lines of action of the traction forces and rolling resistances are tangent to the wheels.

The equations of motion are:

For Tractor

Summation of forces parallel to the direction of motion gives:

$$F - R_2 - R_3 - W_1 \sin b - (W_1 / g)\, a_h - Px - R_A = 0 \quad (1)$$

Likewise, summation of forces in the direction normal to the tractive surface gives:

$$N_2 + N_3 - W_1 \cos b - (W_1 / g)\, a_v - Py = 0 \qquad (2)$$

Also, summation of moments about the point of intersection of all forces at the rear wheel-soil interface

$$Px(y_2) + Py(x_3) + N_3(x_5) + W_1 \sin b\,(y_3) + (W_1 / g)\, a_h(y_3) + R_A\,(y_4) + I_r\, a_r + I_f\, a_f$$

$$- W_1 \cos b\,(x_4) - (W_1 / g)\, a_v\,(x_4) - I_1\, a_1 = 0 \qquad (3)$$

For The Trailer

Summation of forces parallel and in the direction normal to the tractive surface gives:

$$Px - (W_2 / g)\, a_h - W_2 \sin b - R_1 = 0 \qquad (4)$$

$$N_1 + Py - (W_2 / g)\, a_v - W_2 \cos b = 0 \qquad (5)$$

Summation of moments about the point of intersection of all forces at the rear wheel-soil interface gives:

$$(W_2 / g)\, a_v\,(x_1) + W_2 \cos b\,(x_1) + Px\,(y_2) + I_2\, a_2 - Py\,(x_2) - W_2 \sin b\,(y_1) - I_{wt}\, a_{wt}$$

$$- (W_2 / g)\, a_h\,(y_1) = 0 \qquad (6)$$

A computer program was developed to use the solution of the equations for checking the effect of trailer loading and coefficient of rolling resistance on the traction force, tractor stability and drawbar loading for different slope angles uphill and downhill, i.e. for slope angle from -30° to +30°. The following is a description of the procedure used in the program.

2.3. Structure of the program

Figure 2 shows the relationship among main calculation modules in the program. The main functions of these modules are described as follows:

DATA INPUT: It is a starting module which help users to establish an input data file (interactive mode) or specify an existing data file (batch mode) that contains all information of the system (x_1, x_2, x_3, x_4, x_5, y_1, y_2, y_3, I_{wt}, I_f, I_r, R_t, R_f, R_r, W_1, W_2, m, c), and to determine the name of output file.

CALCULATIONS: It is a calculation module to carry out analysis. The program was written to provide the research worker with various options, depending on the type of test to be carried out. The program is menu-based and, at this stage of a test, the operator may select from the following:

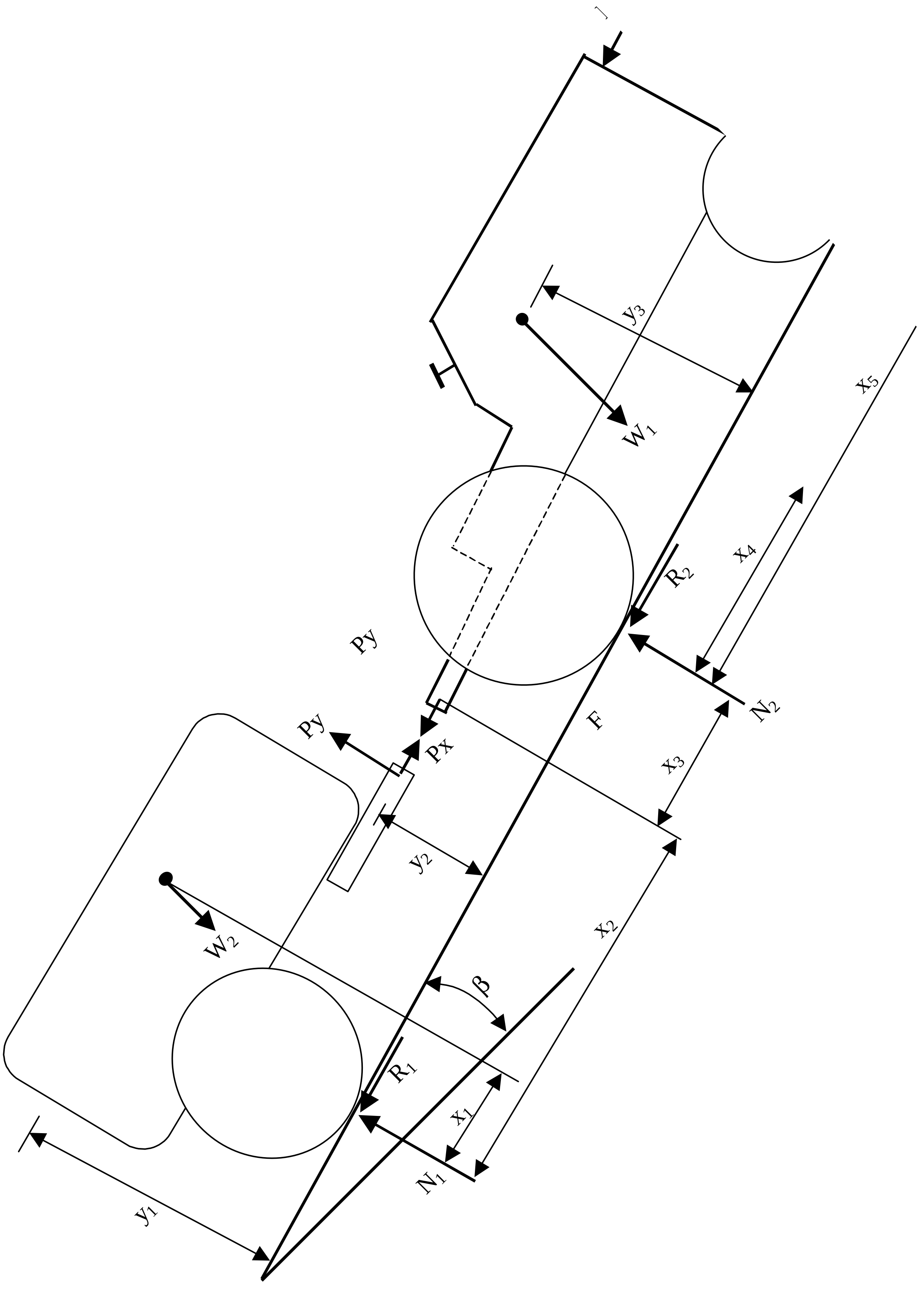

Figure 1. Schematic representation of forces acting on tractor-trailer system.

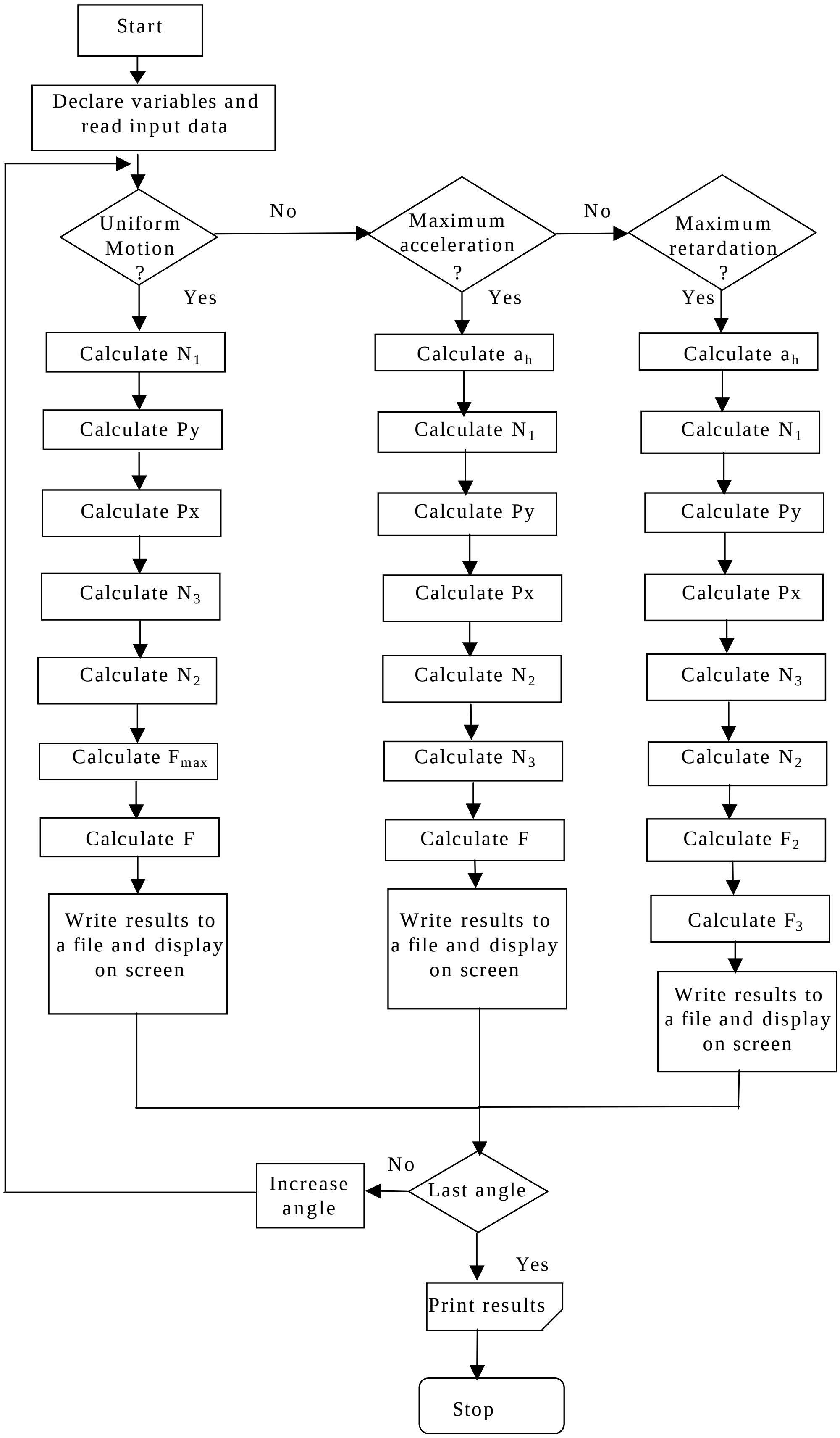

Figure 2. Flow chart of the program developed in this study.

(a) Steady state conditions (uniform motion).

(b) Forward motion with maximum acceleration.

(c) Forward motion with maximum retardation (full braking).

The analysis and equations of motion for each case are given below:

(a) *Uniform Forward Motion with No Acceleration*

When there is no acceleration inertia force and couples are omitted. Neglecting air resistance and substituting $R_1= cN_1$, $R_2= cN_2$, $R_3= cN_3$ in the previous six equations, then solving for N_1, Px, Py, N_3, N_2 and F yields the following results:

$N_1= [\ W_2 (\cos b\ (x_2 - x_1) + \sin\beta\ (y_1 - y_2))\ ]\ /\ (x_2 + cy_2)$

$Px= cN_1 + W_2 \sin\beta$

$Py= W_2 \cos\beta - N_1$

$N_3= [\ (W_1 x_4 - W_2 x_3)\cos\beta - (W_1 y_3 + W_2 y_2)\sin\beta + N_1 (x_3 - cy_1)\ ]\ /\ x_5$

$N_2= (W_1 + W_2)\cos\beta - (N_1 + N_3)$

$F_{max}= \mu\ N_2$

$F = c(N_1 + N_2 + N_3) + (W_1 + W_2)\sin\beta$

(b) *Forward Motion with Maximum Acceleration*

In this case, the acceleration is parallel to the direction of motion and traction force developed by the rear wheels has its maximum value ($F = F_{max} = ìN_2$).

Neglecting air resistance and substituting $R_1= cN_1$, $R_2= cN_2$, $R_3= cN_3$, $á_f= a_h / R_f$, $á_r= a_h / R_r$, and $á_{wt}= a_h / R_t$ in the previous six equations, then solving for N_1, Px, Py, N_3, N_2, F, and a_h yields the following results:

$a_h= (k_1 + k_2 + k_3)\ /\ (k_4 + k_5 + k_6)$

where

$k_1= W_2\cos\beta\ [x_5(c / \mu) + x_5(x_2 - x_1)\ /\ (cy_2 + x_2) - (x_3 + x_5) - (cy_2 - x_3)(x_2 - x_1)\ /\ (cy_2 + x_2)]$

$k_2= W_2\sin\beta\ [(x_5 / \mu) + x_5(y_1 - y_2)\ /\ (cy_2 + x_2) - (y_1 - y_2)(cy_2 - x_3)\ /\ (cy_2 + x_2) - y_2]$

$k_3= W_1\cos\beta\ [((c / \mu) + x_4 - x_5)(x_5)] + W_1\sin\beta\ [(x_5 / ì) - y_3]$

$k_4= (W_2 / g)\ [y_2 + (cy_2 - x_3)(y_1 - y_2)\ /\ (cy_2 + x_2)] - x_5(W_1 + W_2)\ /\ \mu g$

$k_5= -x_5\ [(I_{wt} / R_t) + (W_2 / g)(y_1 - y_2)]\ /\ (cy_2 + x_2) + W_1 y_3\ /\ g$

$k_6= (I_{wt} / R_t)(cy_2 - x_3)\ /\ (cy_2 + x_2) + (I_r / R_r) + (I_f / R_f)$

$N_1= [W_2 (\cos\beta\ (x_2 - x_1) + \sin\beta\ (y_1 - y_2)) + a_h((I_t / R_t) + (W_2 / g)(y_1 - y_2))\ ]\ /\ (x_2 + cy_2)$

$Px= cN_1 + (W_2 / g)a_h + W_2 \sin\beta$

$Py= W_2 \cos\beta - N_1$

$N_2= [c \cos\beta + \sin\beta + a_h / g](W_1 + W_2)\ /\ \mu$

$N_3= (W_1 + W_2) \cos\beta - (N_1 + N_2)$

$F= \mu N_2$

(c) *Forward Motion with Maximum Retardation (Full Braking)*

Trailer has no brakes and the tractor must take over the whole braking effort. Lines of action of braking force on the front (F_3) and rear (F_2) wheels are tangent to the wheels at the points of interaction with the ground. Neglecting air resistance and substituting $R_1= cN_1$, $R_2= cN_2$, $R_3= cN_3$, $\alpha_f= a_h / R_f$, $\alpha_r= a_h / R_r$, and $á_{wt}= a_h / R_t$ in the previous six equations, then solving for N_1, Px, Py, N_3, N_2, F_2, F_3, and a_h yields the following results:

$a_h = [W_2\{\sin\beta\ (y_1 - y_2) + \cos\beta\ (x_2 - x_1)\} - (W_1 + W_2)(cy_2 + x_2)(\cos\beta\ (\mu + c) + \sin\beta)\ /\ \mu]\ /$

$[(W_2 / g)(y_1 - y_2) + (I_{wt} / R_t) - (W_1 + W_2)(x_2 + cy_2)\ /\ \mu g]$

$N_1= \{(W_1 + W_2) \cos\beta\ (\mu + c) + \sin\beta\ (W_1 + W_2) - a_h(W_1 + W_2) / g\}\ /\ \mu$

$Px = (W_2 / g)a_h - cN_1 - W_2 \sin\beta$

$Py = W_2 \cos\beta - N_1$

$N_3 = [W_1 \cos\beta\ (x_3) + N_1(x_3 - cy_2) + a_h\{(W_1 / g)y_3 + (W_2 / g)y_2 + (I_f / R_f) + (I_r / R_r)\} - W_2\ y_2 \sin\beta - W_2\ x_3 \cos\beta - W_1\ y_3 \sin\beta]\ /\ x_5$

$N_2 = (W_1 + W_2) \cos\beta - (N_1 + N_3)$

$F_2 = \mu\ N_2$

$F_3 = \mu\ N_3$

Slope angle is varied in several equal steps. The result of calculations from each step can be written to an output file and displayed on screen.

PRINT: It is a post-processing module to print out the results of the analysis.

2.4. Sample results of the program

The computer program was used to predict the effect of trailer loading weight and the slope angle on the tractor stability, traction ability, and drawbar loading of a tractor-trailer system moving at uniform forward motion up and downhill.

The sizes and types of tractor and trailer chosen are typical of a combination used in all farming systems in many countries.

The data used for analysis were obtained from a specification of a 80 kW tractor and 3.75 t capacity single axle trailer. The tractor was assumed to move on unplowed dry clay soil with an average traction coefficient of (m = 0.55) and the coefficient of rolling resistance was assumed to be 0.05. The following are some important specifications of the tractor and trailer:

- mass of the tractor (W_1 / g) = 4000 kg

- mass of the trailer (W_2 / g) = 3750 kg (fully loaded trailer)

- distance of center of gravity of tractor forward of the rear axle of the tractor (x_4) = 0.739 m

- height of the center of gravity of tractor above the ground (y_3) = 0.841 m

- distance of center of gravity of trailer forward of the axle of the trailer (x_1) = 0.80 m

- height of the center of gravity of trailer above the ground (y_1) = 1.541 m

- wheel base of the tractor (x_5) = 2.083 m

- distance of hitch point rearward of the rear axle of the tractor (x_3) =0.775 m

- distance of axle of trailer rearward of the hitch point (x_2) = 4.70 m

- height of the tractor hitch point above the ground (y_2) = 0.464 m

2.5. Field experiments

Field experiments were conducted using the above tractor-trailer combination to compare the predicted parallel component of the drawbar pull (Px) with the measured force values. The influence of slope angle (uphill) and trailer mass upon parallel component of the drawbar pull were investigated experimentally in a series of field tests. Force was measured using a force transducer mounted on the hitch point and consisting of load cells to measure parallel component of the drawbar pull.

Signal conditioners with second order low pass filters adjusted at 100 Hz were connected on each load cells. A custom application created under the LabView v5.0 environment (National Instruments Inc.) monitored input signals, displayed, and saved the results in data files. The results reported for these tests include values of parallel component of the drawbar pull (Px) at the different slope angles and trailer mass. For each case, three test replicates were used and the average force values were used for comparison with the force predictions.

3. DISCUSSION

This section provides a discussion of the computer analysis results for the specific combination of tractor and trailer and operating conditions explained in the previous section.

a) Uphill motion

Figures 3 through 7 show the effect of the trailer loading on the tractor stability, traction force, and drawbar loading for different slope angles uphill.

The stability of the tractor is determined by the value of the soil reaction on the front wheels N_3, which predict whether the tractor is stable ($N_3 > 0$) or unstable ($N_3 < 0$) and tend to turn over backwards.

Figure 3 shows that increasing the slope angle decreases the value of N_3, because the distribution of the tractor weight will be more on the rear wheels and less on the front wheels (i.e. less stability). Also as the trailer load increases, the value of N_3 decreases due to weight transfer and it reaches the lowest value at full loading capacity (W_2 = 3750 kg). At this loading the tractor becomes unstable at 28° slope angle.

The traction force can be determined by the value F from Figure 4. The figure shows that an increase in slope angle causes an increase in traction force requirement. The increase in traction force compensates the increase in the parallel component of tractor and trailer weight. The increase in the trailer loading causes an increase in the traction requirement to obtain sufficient pull of the new trailer loading.

The required traction force is limited by the traction ability of tractor which is represented by F_{max}. Figure 5 shows that F_{max} increases with slope angle and trailer loading. But this increase does not cover the increase in traction force requirement in certain slope angle causing insufficient traction (rear wheel slipping). The slope angle at which the tractor stops climbing ranges between 15 and 18 degrees for corresponding trailer weight of 3750 and 750 kg, respectively.

The parallel component of the drawbar pull (Px) increases with the increase in slope angle and trailer loading (Figure 6). This is due to the parallel component of the trailer weight, which must be compensated by the drawbar pull. At 15°, this force reaches a maximum value of 10837 N when the trailer weight is 3750 kg.

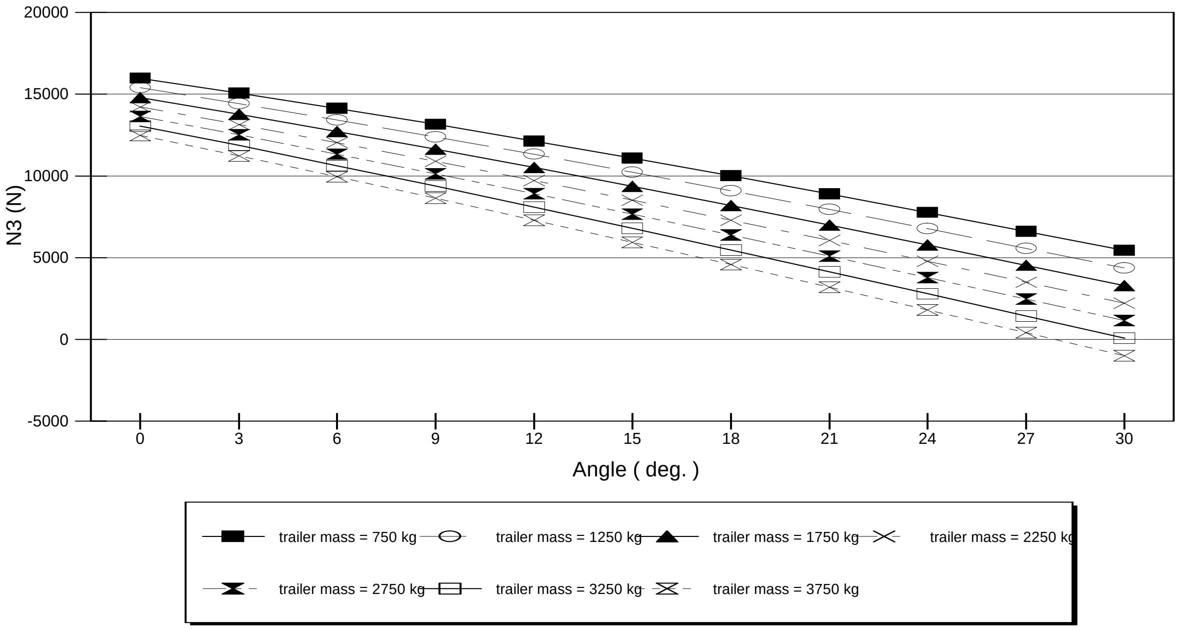

Figure 3. Soil reaction against the front wheels of tractor (N_3) vs. the slope of the road (uphill) at different total mass of the trailer.

The normal component of drawbar pull (Py) on the other hand decreased slightly with the increase in slope angle at small trailer loads, but at higher rates for larger trailer loading (Figure 7). The decrease in Py is related primarily to the decrease in the normal component of the trailer weight with the increase in slope angle and secondarily to the increase in the parallel component which counteracts the moment of the normal component of the trailer weight. Higher trailer loads cause additional moment resulting in an additional increase in the normal component of the drawbar load and reaches a maximum of 10303 N when the trailer is fully loaded (3750 kg).

b) Downhill motion

Figure 8 shows that the soil reaction against the front wheels (N_3) increases as the slope angle increases due to the weight transfer from the rear axle to the front axle. Even though increasing the weight on the trailer decreases the normal soil reaction against the front wheels due to the weight shift from the front axle to the rear axle which decreases the stability, N_3 is always positive in the downhill motion meaning that the tractor-trailer system is always stable. The maximum traction force that the traction wheels can develop is dependent on the normal soil reaction against the rear wheels of the tractor.

The maximum traction force decreases as the slope angle increases due to the weight shift from the rear wheels to the front wheels of the tractor, and also because the pull requirement of the tractor to the trailer decreases and even becomes negative. But as the trailer weight increases, the normal load on the drawbar increases and the normal soil reaction on the rear wheels increases due to the weight transfer from the front wheels to the rear wheel of the tractor, thus increasing the traction force (Figure 9).

The actual traction force is shown in Figure 10. At slight slopes from 0 to 3 degrees, the traction force is driving the tractor-trailer system and it is indicated by the positive sign. But at steeper slopes the parallel component of the weight of the tractor and the trailer increases. So the tractor-trailer system moves down by the action of its weight.

Increasing the weight on the trailer at slight slopes increases the load on the drawbar and hence the traction force requirement increases. But at steeper slopes, increasing the weight on the trailer increases the driving effect of the parallel component of the weight.

Figures 11 and 12 show the effect of slope angle and trailer weight on the drawbar pull for the tractor-trailer system. Figure 11 shows that as the slope angle increases the parallel component of pull decreases. The positive values mean that the tractor is pulling the trailer. The negative values mean that the trailer is pushing the tractor downhill due to the increase in the parallel component of the trailer weight. While at zero value both the tractor and the trailer are moving by their own weight and this happens at about three degrees of slope angle as explained before.

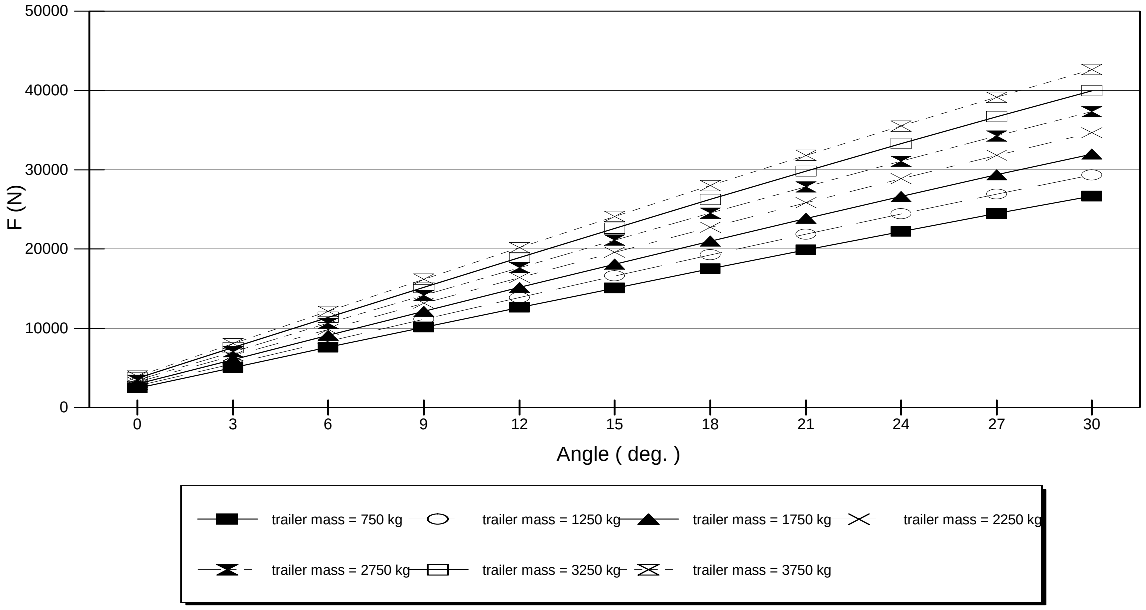

Figure 4. Traction force (F) vs. the slope of the road (uphill) at different total mass of the trailer.

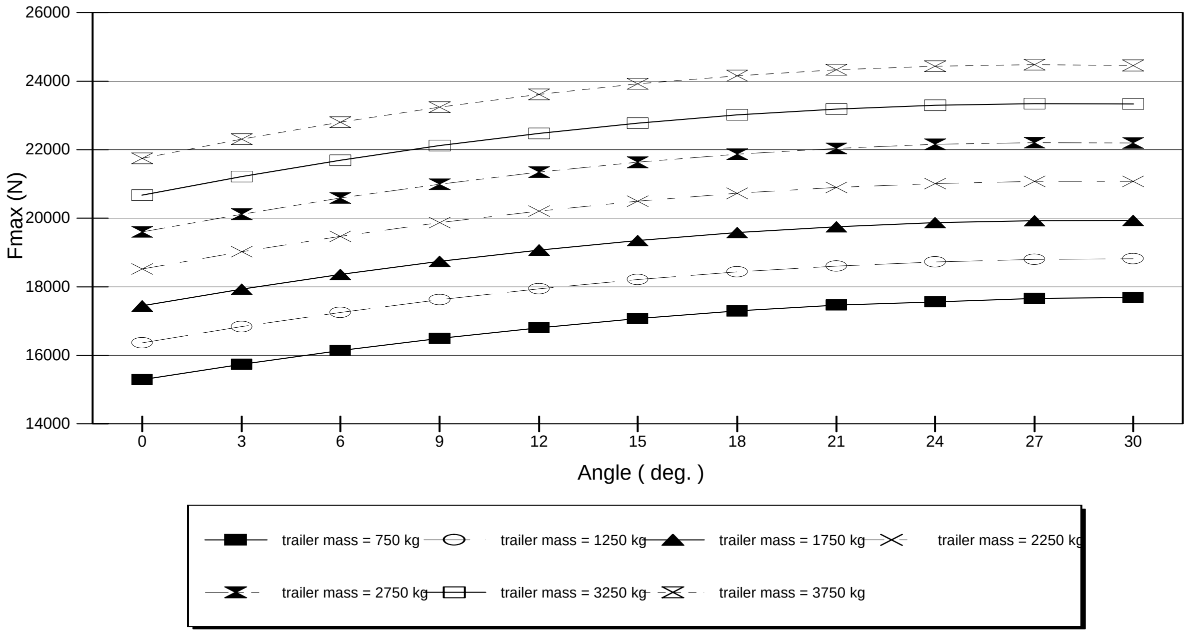

Figure 5. Maximum traction force (F_{max}) vs. the slope of the road (uphill) at different total mass of the trailer.

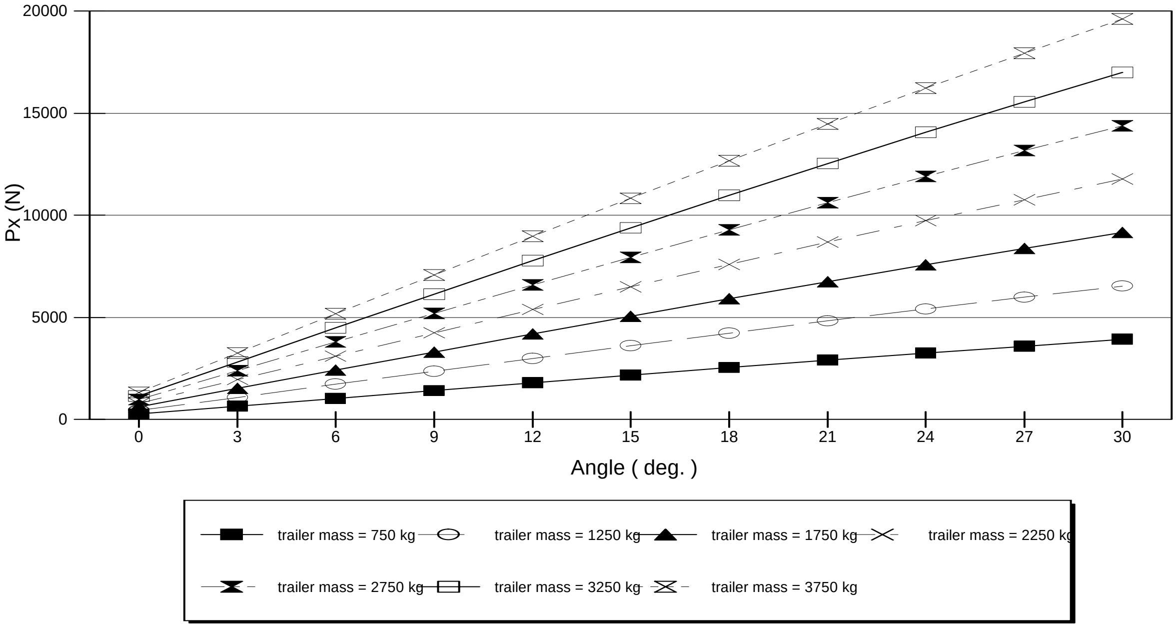

Figure 6. Parallel component of the drawbar pull (Px) vs. the slope of the road (uphill) at different total mass of the trailer.

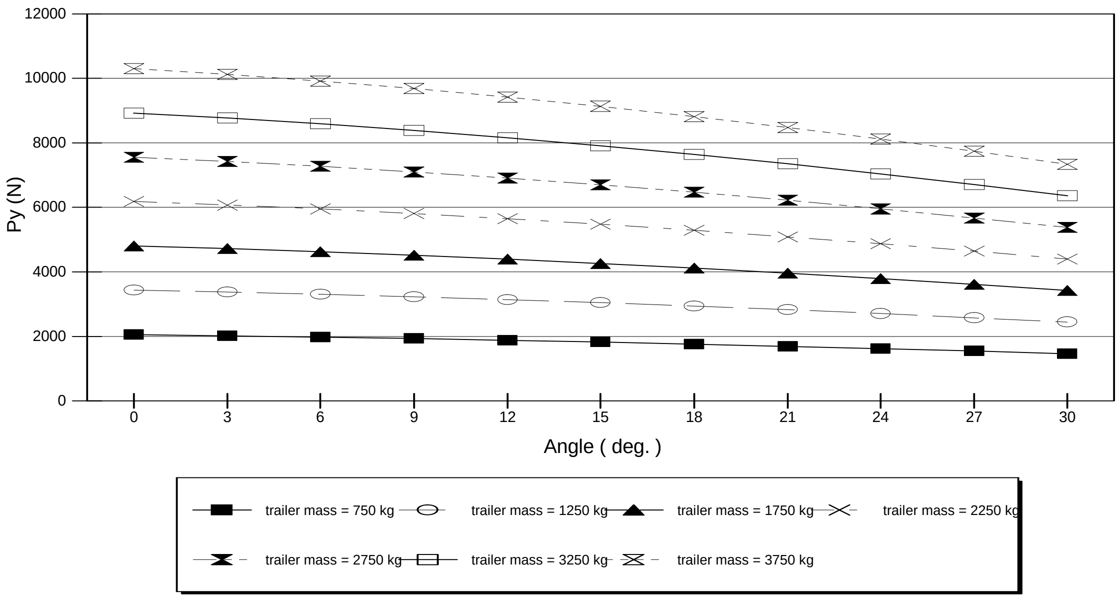

Figure 7. Normal component of the drawbar pull (Py) vs. the slope of the road (uphill) at different total mass of the trailer.

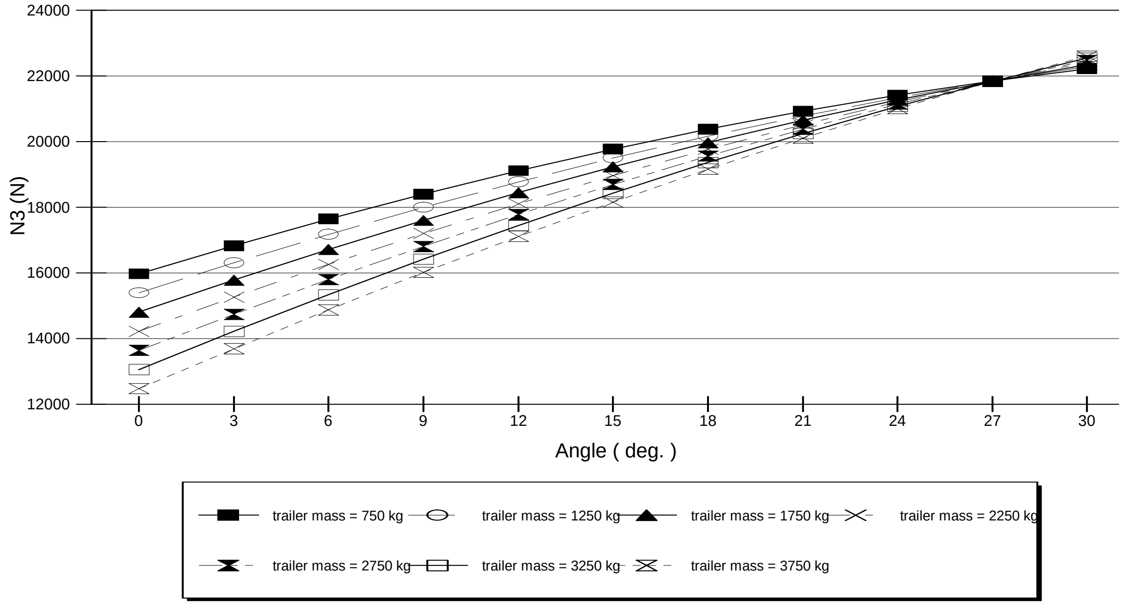

Figure 8. Soil reaction against the front wheels (N_3) vs. the slope of the road (downhill) at different total mass of the trailer.

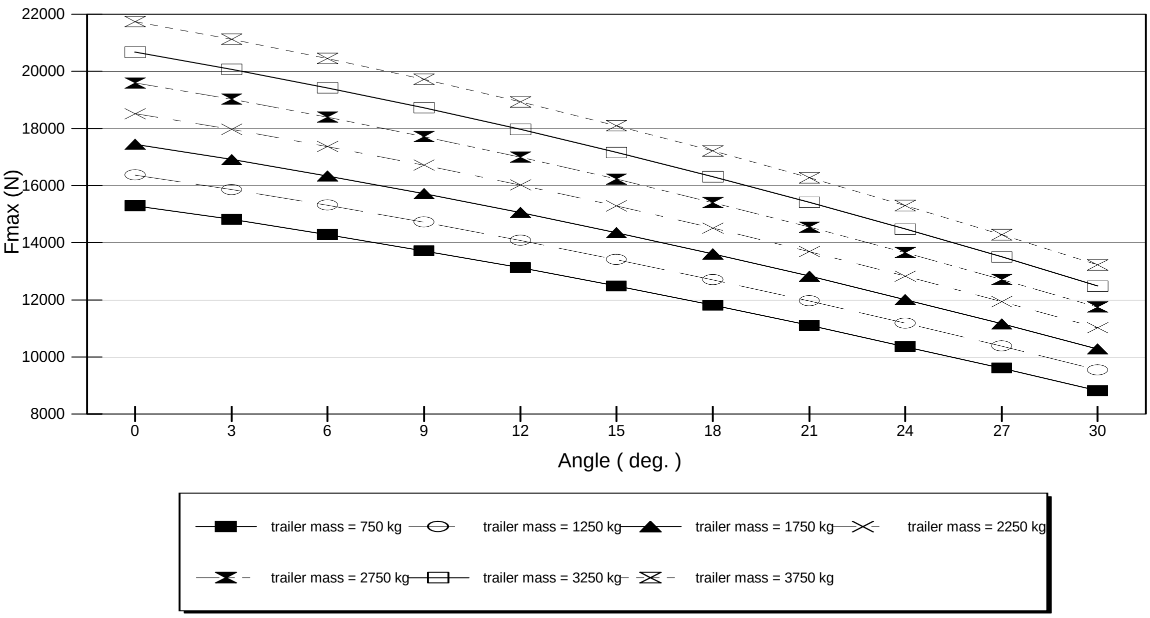

Figure 9. Maximum traction force (F_{max}) vs. the slope of the road (downhill) at different total mass of the trailer.

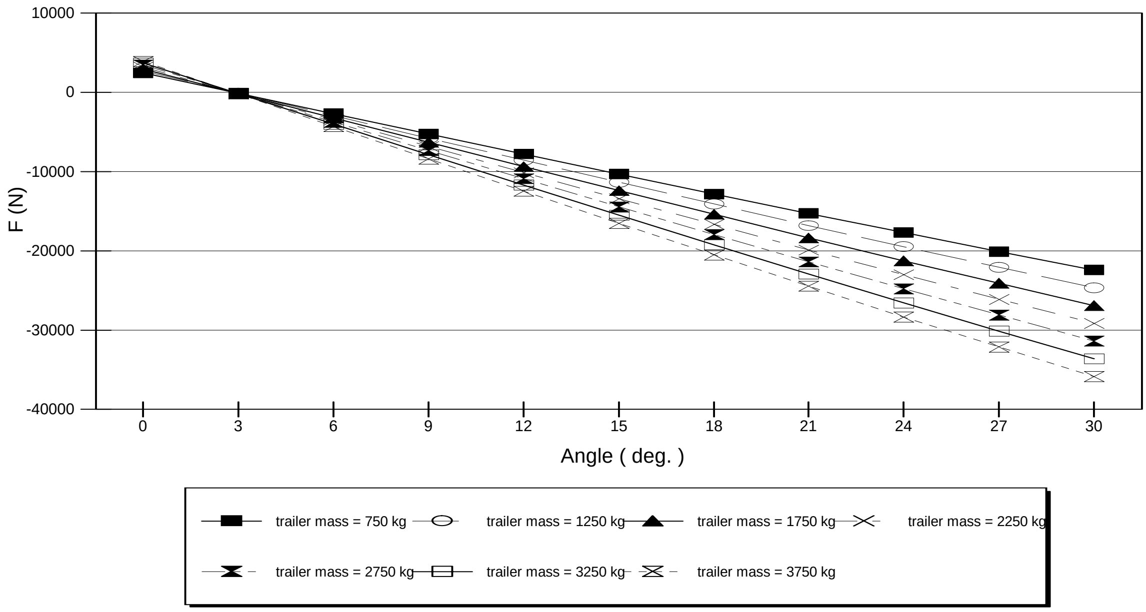

Figure 10. Traction force (F) vs. the slope of the road (downhill) at different total mass of the trailer.

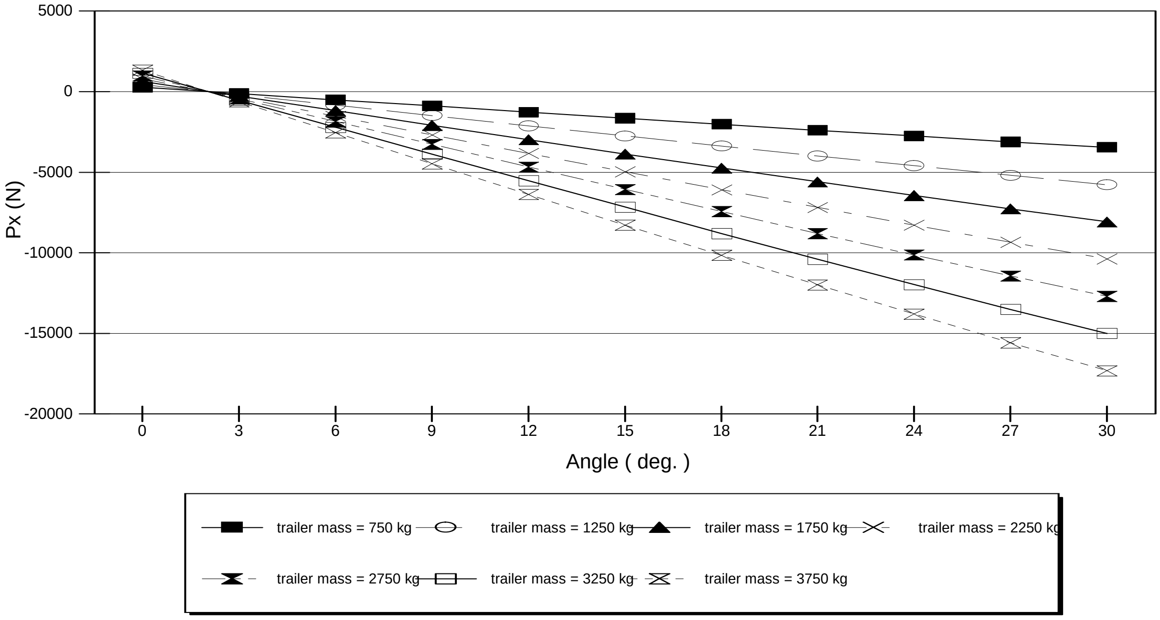

Figure 11. Parallel component of the drawbar pull (Px) vs. the slope of the road (downhill) at different total mass of the trailer.

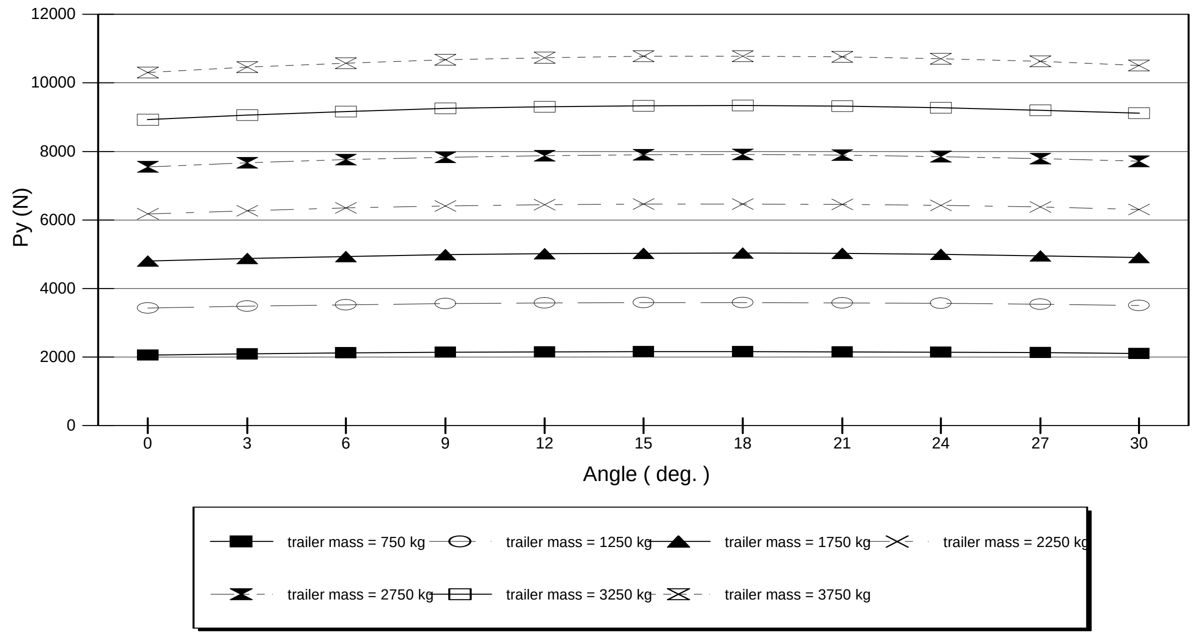

Figure 12. Normal component of the drawbar pull (Py) vs. the slope of the road (downhill) at different total mass of the trailer.

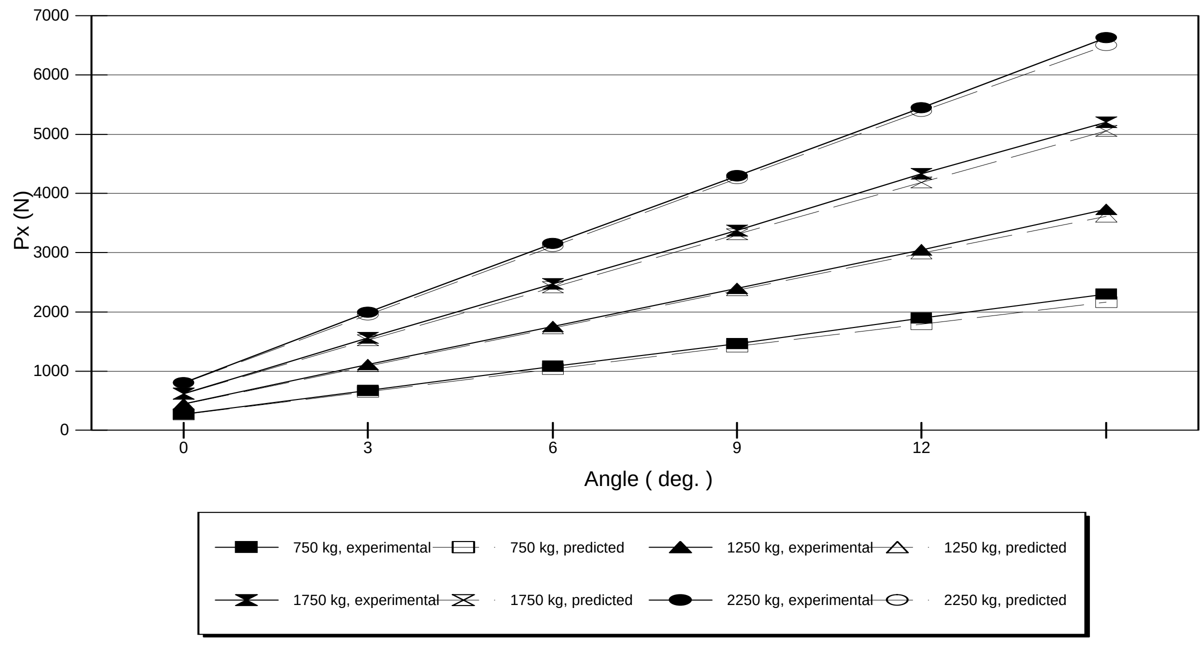

Figure 13. Measured and predicted parallel component of the drawbar pull (Px) vs. the slope of the road (uphill) at different total mass of the trailer.

At low slope angles (less than three degrees), increasing the weight on the trailer increases the parallel component of pull because the tractor is pulling the trailer. At steeper slopes (more than three degrees), increasing the weight on the trailer increases the pushing of trailer to the tractor which reach a maximum of 17318 N.

Figure 12 shows that the normal component of pull increases as the slope angle and trailer weight increases due to the increase of trailer weight shift to the front. The value of this force reaches a maximum of 10781 N.

As shown in Figure 13, the relationships between both the predicted and measured parallel component of the drawbar pull (Px) at the different slope angles (uphill) and trailer mass are similar. A comparison of the parallel component of the drawbar pull shows that the computer program predicted the force relatively accurately; in general, the predicted values tending to be lower than the measured. The relative error between the computer program and field tests values ranged from 0.4 % to 5 %.

4. CONCLUSIONS

The use of computer analysis in this study provides a significant improvement in predicting the effect of trailer loading weight and the slope angle on the tractor stability, traction ability, and drawbar loading. The following conclusions were drawn for uphill and downhill motions of a tractor-trailer system moving at uniform motion and specific operating conditions based on the computer analysis results obtained from this study:

a) Uphill

1. The higher the slope angle and trailer weight the lower is the stability. The tractor-trailer system considered in this study became unstable at a slope angle of 28° for a trailer mass of 3.750 kg.

2. Insufficient rear wheel traction occurred when the maximum traction force developed by the tractor rear wheels was less than the required traction force. This situation happened at slope angles ranging from 15 to 18 degrees at all trailer mass ranging from 3750 to 750 kg.

b) Downhill

1. The stability of the tractor decreased as the weight of the trailer increased, and increased as the slope angle increased. However, the system is always stable for the ranges of trailer loading considered in this work.

2. The maximum traction force decreased as the slope angle increased, and increased as the weight on the trailer increased.

3. The traction force drives the tractor-trailer system at slight slope from 0 to 3 degrees, while at steeper slopes the tractor-trailer system moves down by the action of its own weight.

REFERENCES

GOLDENHAR, L.M.; SCHULTE, P.A. Methodological issues for intervention research in occupational health and safety. **American Journal of Industrial Medicine**, New York, v. 29, p. 289-294, 1996.

LIU, J.; AYERS, P. Off-road vehicle rollover and field testing of stability index**. Journal of Agricultural Safety and Health**, Washington, v. 5, p. 59-71, 1999.

MURPHY, D.J.; KIERNAN, N.E.; CHAPMAN, L.J. An occupational health and safety intervention research agenda for production agriculture: does safety education work? **American Journal of Industrial Medicine**, New York, v. 29, p. 392-396, 1996.

MURPHY, D.J.; PURSCHWITZ, M.; MAHONEY, B.S.; HOSKIN, A.F. A proposed classification code for farm and agricultural injuries. **American Journal of Public Health**, New York, v. 83, p. 736-738, 1993.

MITCHELL, B.W.; ZACHARIAH, G.L.; LILJEDAHL, J.B. Prediction and control of tractor stability to prevent rearward overturning. **Transactions of the ASAE**, , v. 15, p. 838-844, 1972.

NATIONAL SAFETY COUNCIL. **Accident Facts** - 2001 Edition. Chicago: National Safety Council, 2001.

PURSCHWITZ, M.A. Farm and Agricultural Injury Statistics. In: D.J. MURPHY. **Safety and Health for Production Agriculture**. St. Joseph, MI.: ASAE, 1992. Chapter 3, p.253. (Textbook n.º 5)

SAGI, R.; ORLOWSKI, S.; NIR, D. Theoretical study of braking capacity of a tractor-trailer system. **Transactions of the ASAE**, St. Joseph, v.15, p. 845-848, 1972.

SPENCER, H. B. Stability and control of two-wheel drive tractors and machinery on sloping ground. **Journal of Agricultural Engineering Research**, London, v.23, p.169-188, 1978.

TAYLOR, D.L; KANE, T.R. Effect of drawbar properties on the behavior of articulated vehicles. ASME, 1976. (Paper no. 76)

YODER, A.M.; MURPHY, D.J. Evaluation of the farm and agricultural injury classification code and follow-up questionnaire. **Journal of Agricultural Safety and Health**, Washington, v. 6, p. 71-80, 2000.

ZHANG, S.H.; TRAAO, H. Study of the dynamic performance of tractor-trailer combinations for farm use. **Memories of the Faculty of Agriculture Hokkaido University**, Hokkaido, v. 17, p. 399-450, 1991.