STABILITY CHARACTERISTICS OF THREE AND FOUR WHEELED VEHICLES

Simulations Of Three And Four Wheeled Vehicles

FNC 5352/19708R Issue 1

S Challener, K Chan & G Lock

Frazer-Nash Consultancy Ltd
Stonebridge Business Park
Dorking
Surrey
RH4 1HJ

DOCUMENT INFORMATION

Project :	Stability Characteristics Of Three And Four Wheeled Vehicles		
Report Title :	Simulations Of Three And Four Wheeled Vehicles		
Client :	Health And Safety Executive		
Client Ref. :	Contract No. 4034/R36.078		
Classification :	None		
Report No. :	FNC 5352/19708R		
Issue No. :	1	**Compiled By :**	K. Chan, S. Challener
Date :	May 2000		& G Lock
		Approved By :	A J Vibert

DISTRIBUTION

Copy	Recipient	Organisation
1	G. Male	HSE - Bootle
2 - 3	M Hirons	HSE - Sheffield
4	5352 – File	FNC

Originating Office: FRAZER-NASH CONSULTANCY LIMITED
Stonebridge House, Dorking Business Park, Dorking, Surrey RH4 1HJ, UK
T: +44 (0)1306 885050 F: +44 (0)1306 886464 E: info@fnc.co.uk W: www.fnc.co.uk

SUMMARY

The incidence of rollover of forklift trucks and dumpers has caused concern within the Health and Safety Executive for some time. In particular a number of deaths and injuries have occurred when a driver tries to 'escape' as his vehicle rolls. Whilst much research has been conducted on the base line stability of industrial and agricultural machinery, none has considered the rate at which such vehicles roll.

Frazer-Nash Consultancy has been commissioned to produce a technique for estimating the rate of roll for forklift trucks and dumpers. The study was conducted in three main phases. Initially a comprehensive literature search was conducted to unearth any relevant research. The knowledge gained from the search assisted in the production of an analysis technique, which can be used to predict the forward speed at which a given vehicle will roll, the rate at which it will roll and consequently the time taken for the complete event.

The technique was developed using an advanced programming language (IDL) and was based on a true dynamic, real time simulation. Where possible this methodology was simplified and compiled in the form of an Excel spreadsheet. Initially it was envisaged that the Excel version would be a very rough 'guestimate' of the dynamic assessment, though repeated tests have shown that the spreadsheet version provides excellent results with rollover times consistently within 5% of the IDL version.

Several variants of forklift trucks and dumpers have been assessed and their results presented. Finally a parametric study has been conducted which considers the variation of geometrical and mechanical parameters and the effects these changes have on the vehicle performance.

CONTENTS

1. INTRODUCTION 1

2. LITERATURE SEARCH 2
   - 2.1 INTRODUCTION 2
   - 2.2 REVIEW OFTRUCK MANUFACTURERS 2
   - 2.3 COEFFICIENT OF FRICTION 2
   - 2.4 OPERATING CONDITIONS 3

3. ASSUMPTIONS 4
   - 3.1 INTRODUCTION 4
   - 3.2 STEADY STATE 4
   - 3.3 WORST CONDITIONS 4
   - 3.4 APPLIED FORCES 4
   - 3.5 RIGID BODY 4
   - 3.6 BUMP STOPS 5
   - 3.7 REAR AXLE PIVOT 5
   - 3.8 STEERING 5
   - 3.9 CENTRE OF GRAVITY 5
   - 3.10 ROLL INERTIA 5
   - 3.11 CO-ORDINATE SYSTEM 6

4. TECHNICAL APPROACH 7
   - 4.1 PIVOT LINE DEFINITION 8

5. PROGRAMMING 10
   - 5.1 INTRODUCTION 10
   - 5.2 PROGRAMME DEVELOPMENT 10

6. SIMULATION RESULTS 12
   - 6.1 INTRODUCTION 12
   - 6.2 DEFINITIONS 12
   - 6.3 BASIC THREE WHEELED TRUCK 13
   - 6.4 THREE WHEELED TRUCK WITH BUMP STOPS 14
   - 6.5 BASIC FOUR WHEELED TRUCK 16

6.6 FOUR WHEELED TRUCK WITH REAR PIVOTING AXLE 18

6.7 DUMPER TRUCK WITH PIVOT STEER 19

7. PARAMETRIC STUDIES 21

7.1 STUDIES 1 AND 2 21

7.2 STUDY 3 24

8. CONCLUSIONS AND RECOMMENDATIONS 26

8.1 CONCLUSIONS 26

8.2 RECOMMENDATIONS 26

9. REFERENCES 27

Appendix A - Suppliers & Manufacturers A1-A2

Appendix B - Detailed Calculations B1

Appendix C - Results of parametric study using truck simulations C1-C15

1. INTRODUCTION

The Health and Safety Executive (HSE) has been concerned for many years with the number of deaths or injuries resulting from the roll over of industrial and agricultural machinery. Of particular concern are forklift and dumper trucks, which are known to roll over on a regular basis. The frequency of such incidents in the USA is highlighted in Reference 1.

The trade off between commercial, practical requirements and safety issues has resulted in a multitude of vehicles that can roll over relatively easily in the hands of an untrained operator or in an emergency avoidance manoeuvre. We now have the situation where there are many vehicles in every day operation, which are only safe because of the skill of the operator.

Whilst work has been conducted on the base-line stability of such vehicles, little is known about the time taken for these vehicles to roll over. This is of particular importance when one considers the driver's reactions and response. As a consequence the HSE wish to establish a technique for predicting the time taken for a vehicle to roll, once instability occurs. Results from such a technique could subsequently be used to predict drivers' reactions and ultimately lead to the safer design and / or operation of such vehicles.

Frazer-Nash Consultancy Limited (FNC) has been contracted by the Health and Safety Executive (HSE) to conduct a study into the stability and roll characteristics of 3 and 4 wheeled forklift trucks and pivot steer dumpers. The work has been conducted under contract No. 4034/R36.078.

The objectives of the study are to:

1. Obtain an in-depth understanding of the problems involved.
2. Produce an analytical method of assessing lateral stability and time to roll for the following variants:

	3 – Wheeled Vehicles	4 - Wheeled Vehicles
Front Steering	✓	✓
Rear Steering	✓	✓
Articulated Steering		✓

3. Present results, both in terms of stability and rate of roll, and identify the sensitivity of the results to changes in mechanical and geometrical properties.

2. LITERATURE SEARCH

2.1 INTRODUCTION

As a means of gathering information and knowledge on the stability of industrial and agricultural vehicles a comprehensive literature search was conducted. This involved searching the databases and libraries of over twenty institutions. Searches were conducted via subscription databases, library searches and via the internet.

The relevant articles and papers found are listed as References 2 to 43 in Section 9, together with their source.

2.2 REVIEW OF TRUCK MANUFACTURERS

A comprehensive search was made of all UK manufacturers and suppliers of forklift trucks and dumpers. A list of suppliers and manufacturers is contained in Appendix A. FNC obtained technical brochures and sales documentation from all the listed companies.

In addition, a letter was sent to each of these companies requesting information on the frequency of rollovers. Unfortunately the response from this survey was poor with no valuable information being provided by any source. The authors can only conclude that manufacturers and suppliers are not aware of the rollover incidents of trucks, that they fear they may prejudice themselves by supplying such data or that they keep no records of such incidents.

A visit was also made to the British Industrial Truck Association, which was keen to help and supplied some valuable information. Unfortunately they could not provide any definitive data on rollover incidents. They did recognise the magnitude of the problem and were addressing the issue with operating guides, videos and driver training.

2.3 COEFFICIENT OF FRICTION

As part of this exercise an investigation was made into the coefficient of friction likely to occur between truck tyres and the ground.

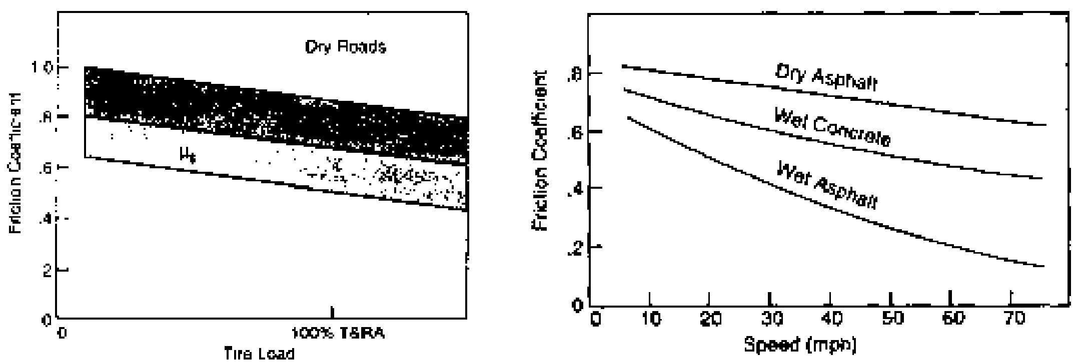

Figure 1 – Coefficients of Friction

Figure 1 presents coefficients of friction from Reference 2. In the left-hand graph the μ_p (dark shading) refers to peak friction and the μ_s (light shading) refers to sliding friction. The figure demonstrates the broad range of friction coefficients possible and how friction reduces with increasing tyre load. The right hand graph presents typical coefficients of friction for various surfaces and demonstrates how friction reduces with increased speed.

2.4 OPERATING CONDITIONS

The operating conditions seen by industrial trucks and dumpers range from smooth tarmac to rutted muddy ground. It is recognised that surface roughness can have a significant effect on the roll stability of trucks and often is considered to be a significant contributor to rollover accidents. Unfortunately it is outside the scope of this report to consider these effects and the simulations discussed in this report assume smooth ground.

3. ASSUMPTIONS

3.1 INTRODUCTION

This study has investigated the stability of forklift and dumper trucks in terms of their lateral overturning stability. Forward or backward overturning when driving up or down a slope is not included.

3.2 STEADY STATE

It has been assumed that a constant angular velocity of forward motion is maintained during the sideways roll. This implies that a constant forward speed is maintained at the front outside wheel around a fixed turning centre with a constant radius of turn. The rollover time is the time from initial wheel lift to the truck lying on its side, any initial 'ramping up' effects are ignored. Where the truck is on a slope it is assumed that the slope remains constant. No transient forces (such as those generated on rough ground) are considered to act on the truck.

3.3 WORST CONDITIONS

The assumption is made that the worst conditions for any particular configuration are applied. Any slope is taken to be in the worst position relative to the overturning axis (pivot line).

3.4 APPLIED FORCES

The only forces that have been considered during this study are steady state 'centrifugal' force due to cornering and the force due to gravity. These both act through the centre of gravity of the vehicle. The centrifugal force acts along a radius through the centre of gravity from the centre of the turn and acts in a direction parallel to the ground, which may be sloping. The force due to gravity always acts vertically downwards.

These forces apply overturning or restoring moments about an overturning axis (referred to as pivot line in the simulation). The centrifugal force always produces an overturning moment whereas gravity will initially apply a restoring moment. When the truck begins to roll, this restoring moment is reduced, until the gravity force is vertically above the line of roll, after which point the gravity force generates an overturning moment increasing the speed of the rolling process.

The effect of a slope is to reduce the restoring force provided by gravity and adding a component in the direction of the centrifugal force. The result is therefore to reduce the 'effective' stability of the truck. In the simulations the slope is always assumed to reduce stability i.e. the turn is at the bottom of the slope.

3.5 RIGID BODY

The analysis has assumed that the fork lift trucks behave as a rigid body with no suspension motion or structural deformation. The types of truck covered by this study do not generally have any suspension system. The assumption of rigid body behaviour ignoring this compliance is considered to be acceptable for forklift trucks whereas the compliance of the tyres is considered significant and is modelled for dumper trucks.

3.6 BUMP STOPS

Three wheeled trucks, which have a single rear wheel, have bump stops where the chassis would come into contact with the ground during rolling. The effect of these bump stops, which limit the extent to which the truck can overturn about the single wheel, has been taken into account during the analysis. The way that the behaviour of these stops has been modelled is to assume that a new roll axis is established when the bump stop hits the ground and the overturning changes from being about the single back wheel to being about the bump stop. The angular momentum of the rolling motion is maintained as this transition takes place

3.7 REAR AXLE PIVOT

A rear axle pivot can be found in some four wheeled trucks to increase comfort of ride. This pivot is assumed to be located directly above the centre of the rear axle. It is at a fixed height above ground and has a restricted range of rotation (referred as rear axle pivot range in the simulation). The restricted range is due to a physical limit on the rotation of the pivot. These trucks are assumed to have no bump stops (as defined above).

3.8 STEERING

For the four wheeled trucks Ackerman steering geometry has been assumed. For the dumper trucks it has been assumed that both front and rear axles lie on imaginary lines which pass through the centre of turn (See Figure 5).

3.9 CENTRE OF GRAVITY

All truck types except the dumper truck are assumed to consist of a single unit with its centre of gravity (truck mass plus cargo) remaining in the same position relative to the front axle during all manoeuvres.

The centre of gravity (CG) for the pivot steer dumper trucks is assumed act as one mass (equivalent to dumper mass plus cargo) positioned relative to the front axle. The perpendicular distance from the axle is maintained through out the simulation. Since the front and the back sections are effectively separate masses this assumption could impose second order errors during a tight turn. However the assumption is considered wholly valid commensurate with the detail of the assessment.

3.10 ROLL INERTIA

The roll inertia of the truck (about its CG) is required as an input to the simulations. The truck (with or without load) was assumed to be a rectangular block and the roll inertia was found using the mass and an estimated radius of gyration K.

i.e. roll inertia of truck about CG = $M \times K^2$

where M is the mass of the truck,
K is the estimated radius of gyration of the truck.

However, in the simulation algorithm, the roll inertia about the roll axis is re-calculated for each axis using the following equation:

roll inertia of truck about roll axis = $I + M \times R^2$

where M is the mass of the truck,
I is the roll inertia of the truck about its CG,
R is the perpendicular distance between the CG and the roll axis.

If the mass, the relative position and the roll inertia of individual components are known, the roll inertia of the complete truck about its CG will be the sum of the individual roll inertias plus the sum of the individual masses times the square of their distance from the CG of the truck.

i.e. roll inertia of truck about CG = $\Sigma (m \times k^2 + m \times r^2)$

where m is the mass of individual component,
k is the radius of gyration of individual component,
r is the distance of CG of individual component from CG of truck,
$m \times k^2$ is the roll inertia of individual component.

3.11 CO-ORDINATE SYSTEM

To aid the mathematics of the analysis a vector notation has been adopted in which all the dynamic components and properties of the trucks (such as CG position, pivot line position, forces and velocities) are represented by vectors. The changes to these parameters are evaluated using vector manipulation algorithms. To simplify the evaluation of these parameters, the Cartesian co-ordinate system is set square to the plane of the slope. Therefore the inclination of the turning surface only affects the weight vector. The co-ordinate system is assumed to be fixed on the truck with the front outside wheel as the origin of the co-ordinate system. The consistent notation used is:

X Parallel to the ground radially away from the centre of turn
Y Parallel to the ground in the forward direction
Z Perpendicular to the ground upwards

4. TECHNICAL APPROACH

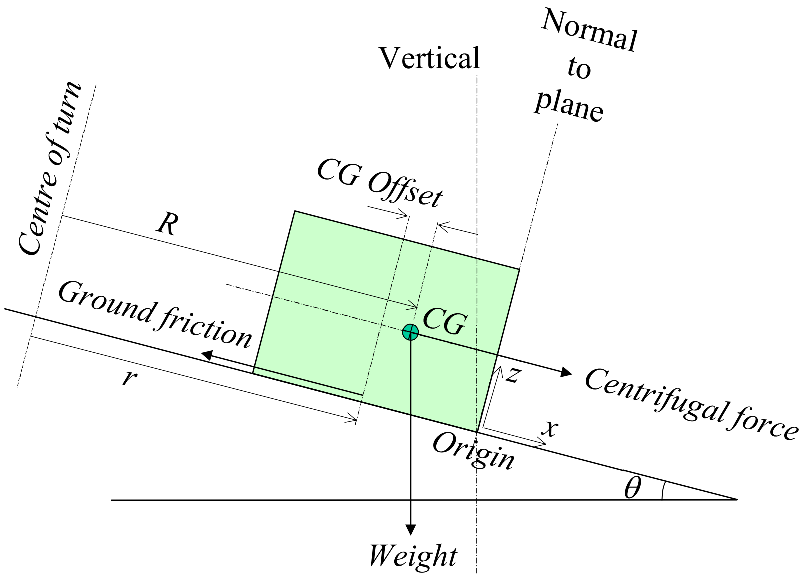

Figure 2 – Rear View of Truck Turning a Corner on a Slope

This section provides an overview of the technical approach. Details of the theory are presented in Appendix B. When a truck turns a corner (refer to Figure 2), the inertial force (referred as centrifugal force in this document) will try to push the truck away from the centre of turn. This force acts on the centre of gravity (CG) of the truck. Frictional force between the wheels of the truck and the ground serves as the centripetal force required to maintain the radius of turn. These two forces form a turning moment which will act to roll the truck over its outside edge. This outside edge is usually the line joining the front and rear wheels farthest away from the centre of turn. This line is the overturning axis (referred as the pivot line in the simulation).

Besides the turning moment of the centrifugal force, the weight of the truck also forms a turning moment about the pivot line, but in the opposite direction. The sum of these two turning moments determines the stability and the rate of roll of the truck. However, when the ground friction is insufficient to counter the centrifugal force the truck will skid and slide sideways.

All the truck types investigated were treated as a point mass rolling about a pivot line. The turning moment of any force is the product of the force and the perpendicular distance from the pivot line. This distance is the moment arm of the force. For a truck of the simplest form, the pivot line remains the same throughout the duration of the roll. However, if the truck has bump stops or a rear pivoting axle, the pivot line will change partway through the roll process. This changes the moment arms of the weight and the centrifugal force, resulting in an abrupt change in the total turning moment and the roll acceleration. It is therefore possible that the roll could be halted and further rolling of the truck prevented.

During the change of the pivot line, several changes take place. These include the moment arms of the forces, the roll acceleration and the direction of roll. Using the principle of conservation of angular momentum in the new roll direction, the roll velocity about the new pivot line can be calculated.

Since all the dimensions of the truck and the description of the turn are known initially, position vectors of the CG and the centre of turn, the pivot lines and moment arms can be calculated. These vectors and the initial turning velocity define the centrifugal force. The total turning moment about the pivot line and hence the roll acceleration can then be calculated.

Using numerical integration, the angle of roll, the new position vectors, roll velocity and acceleration in each time interval can be evaluated. As a result, the complete time history of the roll process is obtained.

4.1 PIVOT LINE DEFINITION

Different truck configurations will roll about different pivot lines. For simple three or four wheeled trucks, the pivot line is simply the line joining the ground contacts of the front and rear wheels farthest away from the centre of turn. In the case of three wheeled trucks (or four wheelers with a narrow rear track width) which have bump stops at the rear, the bump stop hitting the ground will create a different ground contact and form a new pivot line (refer to Figure 3).

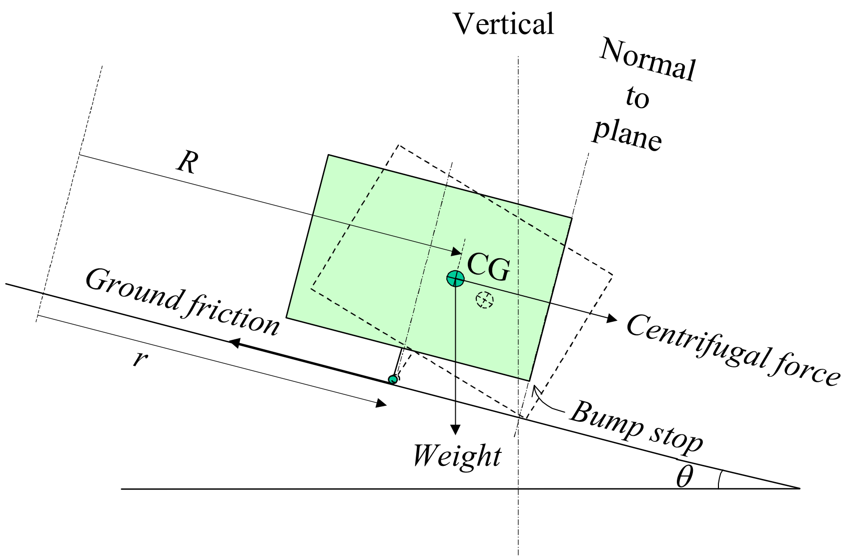

Figure 3 - Rear View of a Three Wheeled Truck with Bump Stops

The situation becomes more complex for a truck with a rear pivoting axle (referring to Figure 4). The pivoting axle increases comfort of ride when driving over rough ground because it allows the rear axle to roll relative to the front axle. The CG can now roll about a pivot line joining the rear axle pivot (point D) with the front wheel (point O). This is the first pivot line until the limited rotation of the rear pivot is exhausted, then the pivot line shifts to the line joining the front and rear outside wheels (line OC) and the truck behaves like a standard four wheeled vehicle. Therefore, depending on the position of the CG relative to the initial pivot line, one of the axles starts to roll earlier than the other.

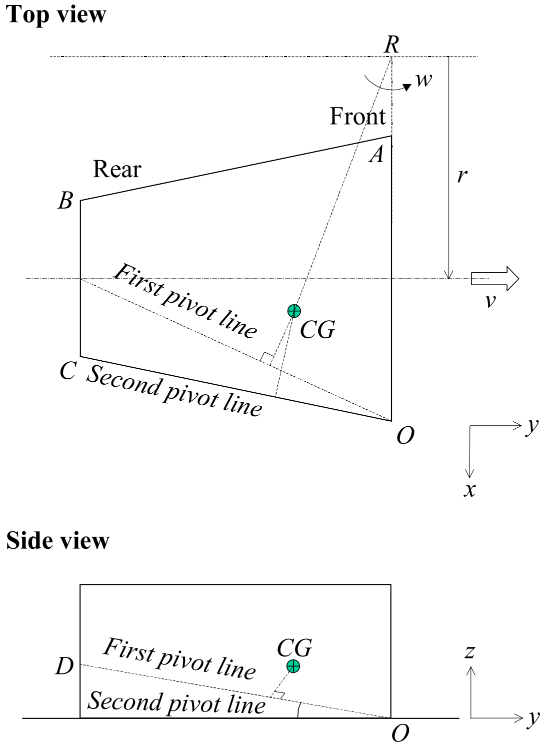

Figure 4 - Views of a Four Wheeled Truck with Rear Pivoting Axle

For a dumper truck (Figure 5) with an articulated steering pivot (point B), there is only one pivot line (line OD), the line joining the ground contacts of the front and rear outside wheels. Since the angle of articulation (ζ) is assumed to be maintained during roll, the pivot line remains unchanged during the whole roll process. The pivot line does however change relative to the CG position as the angle of articulation, and hence the turning radius changes.

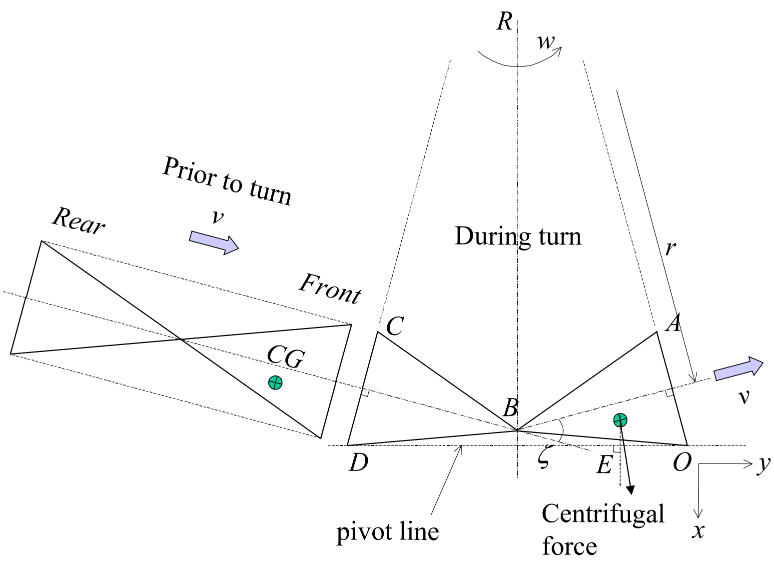

Figure 5 - Top View of a Dumper Truck Turning a Corner

5. PROGRAMMING

5.1 INTRODUCTION

The objective at the commencement of this project was to produce a detailed transient simulation of the event. If possible a ‘down-tuned’ Excel spreadsheet was to be produced that would possibly give indicative answers. As will be described in this section FNC have exceeded the latter requirement.

5.2 PROGRAMME DEVELOPMENT

The theory developed during the study was initially incorporated into a comprehensive program, written using the Interactive Data Language (IDL) programming system. The IDL program includes a full dynamic time integration of the roll process. A single IDL program is used for the analysis of all truck types including dumper trucks. The roll angle increment is calculated over a small time step of 10ms and integrated to give the time history of roll.

The Excel program, which is being supplied to HSE as part of the study, uses a simpler integration method based on increments of roll angle. The time increment is calculated over a small roll angle and summed over 90 degrees of roll. This difference is solely due to the limitations of Excel. Separate spreadsheets are used for forklift and dumper trucks respectively. Tests have shown that the Excel spreadsheet gives results that are within 5 to 10% of the more exact results predicted by the full integration method used in the IDL program. This accuracy far exceeds the project requirement and FNC’s expectation at the commencement of the project.

Both programs have easy to use user interfaces (Figure 6).

Analysis on the rate of roll of a truck (3 or 4 wheels) turning on a slope

Date: 1 Feb 2000 **Author: Kin Chan** **Version no: 1.4** **Calculation: roltm1_3.mcd**

Note: **Roll over behaviour of a four wheels truck with bump stops**

The vehicle will roll over completely

Input Section

Enter 1 for truck with rear pivoting axle, 2 for truck with bump stops

Truck type (1 - pivoting axle, 2 - bump stop)	2
mass of vehicle (kg)	2870
roll inertia (about CG) of vehicle (kgm2)	225
height of CG from ground (m)	0.47
CG from front of vehicle (m)	0.625
lateral offset of CG from centre line (m)	0.007
front track width (m)	0.906
rear track width (m)	0.175
wheel base (m)	1.229
rear axle pivot not installed	0.4
rear axle pivot not installed	20
bump stop width (m)	0.906
bump stop height (m)	0.1
angle of slope (0 to 30 degrees)	5
turning velocity of vehicle (m/sec)	6
radius of turn of vehicle (min. 1m)	3.5
coefficient of friction	1.2

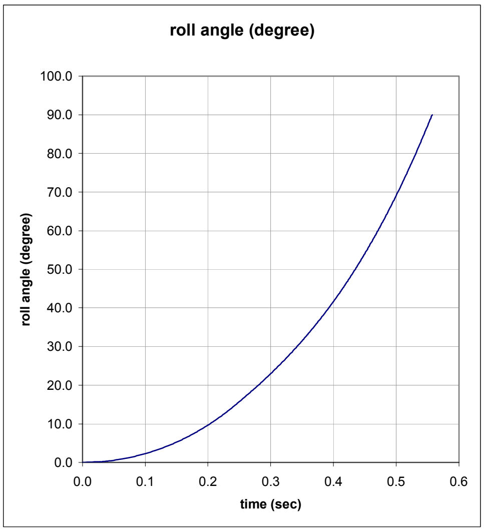

Figure 6 - User Interface in the Excel program

Checks on some of the input parameters have been incorporated in the Excel version. These checks ensure the inputs are within pre-set limits and that dimensions are compatible. Any infringement will be reported and the analysis delayed. Time histories of roll acceleration and velocity are displayed in the second sheet of the spreadsheet.

6. SIMULATION RESULTS

6.1 INTRODUCTION

Examples of the following configurations are presented in this section:

1. Basic three wheeled truck
2. Three wheeled truck with bump stops
3. Basic four wheeled truck
4. Four wheeled truck with rear pivoting axle
5. Dumper truck with pivot steer

6.2 DEFINITIONS

The following are the definitions of the input parameters used in the simulation:

- **Mass of vehicle** – total mass of the truck, the driver and any load it is carrying (kg).
- **Roll inertia** (about CG) of vehicle – roll inertia of the total mass about its CG (kgm^2).
- **Height of CG from ground** – height of the CG of the total mass when vehicle is standing on level ground, positive upward (m).
- **CG from front of vehicle** – the perpendicular displacement of the CG from the front axle, positive toward the rear of the vehicle (m).
- **Lateral offset of CG** – the perpendicular distance of the CG from the central axis of the vehicle, positive in the direction of the centrifugal force (m).
- **Front track width** – the distance between the ground contact patches of the front wheels (m).
- **Rear track width** – the distance between the ground contact patches of the rear wheels (m).
- **Wheel base** – the distance between the ground contact patches of the front and rear wheels (m).
- **Height of rear axle pivot** - the height of the axle pivot when vehicle is standing on level ground, positive upward (m).
- **Rear axle pivot range** – the end to end rotation range of the axle pivot (degrees).
- **Bump stop width** – the total separation between the bump stops (m).
- **Bump stop height** – the height of the bump stops when vehicle is standing on level ground, positive upward (m).
- **Angle of slope** – the angle between the slope and horizontal (degrees).
- **Velocity of vehicle** – the velocity of the front wheel farthest away from the centre of turn, positive when driving forward (m/sec).
- **Radius of turn** - mean turning radius at front wheels before roll (m).
- **Roll angle** – the angle the lateral axis of the truck makes with the slope surface (degree).
- **Roll acceleration** – the rate of change of the roll velocity.

6.3 BASIC THREE WHEELED TRUCK

For a basic three wheeled, or a four wheeled truck with a narrow rear track width, the assessment methodology is the same. The following input settings (representing the latter), for the simulation (Excel version), produces time histories of roll angle and acceleration as shown in Figures 7 and 8.

Parameter	Input
Mass of vehicle	2870kg
Roll inertia (about CG) of vehicle	$225kgm^2$
Height of CG from ground	0.47m
CG from front of vehicle	0.625m
Lateral offset of CG from centre line	0.007m
Front track width	0.906m
Rear track width	0.175m
Wheel base	1.229m
Angle of slope	5°
Forward velocity of vehicle	6m/sec
Radius of turn of vehicle	3.5m

Table 1 - Simulation Input for a Four Wheeled Truck with a Narrow Rear Track

This data is based on the data supplied in Reference 43 and is taken from an actual vehicle, with the exception of roll inertia that has been estimated. In the table above and ensuing results, a 5 degree slope and a speed faster than the minimum required to cause a rollover has been assumed.

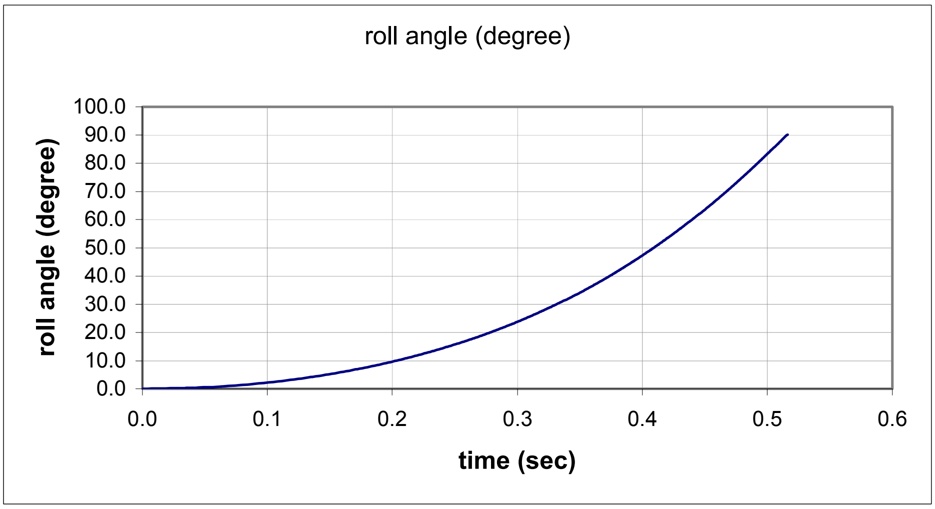

Figure 7 - Time History of Roll Angle of a Basic Three Wheeled Truck

As explained earlier, the CG moves closer to the pivot line once the truck starts rolling. The turning moment of the weight reduces, resulting in a rise in the total turning moment in the direction of the roll. This gradually increases the roll acceleration and velocity. Once the CG moves above and beyond the pivot line, the turning moment of the weight goes in the direction of the roll and the acceleration increases further. However, the height of the CG starts to decrease from this point, hence the moment arm of the centrifugal force and its turning moment decrease accordingly. Just before the truck hits the ground, the drop in CG height becomes significant enough to cause a slight reduction in roll acceleration (Figure 8).

The roll process takes 0.516sec to complete and has a maximum roll acceleration of 23.9rad/sec^2.

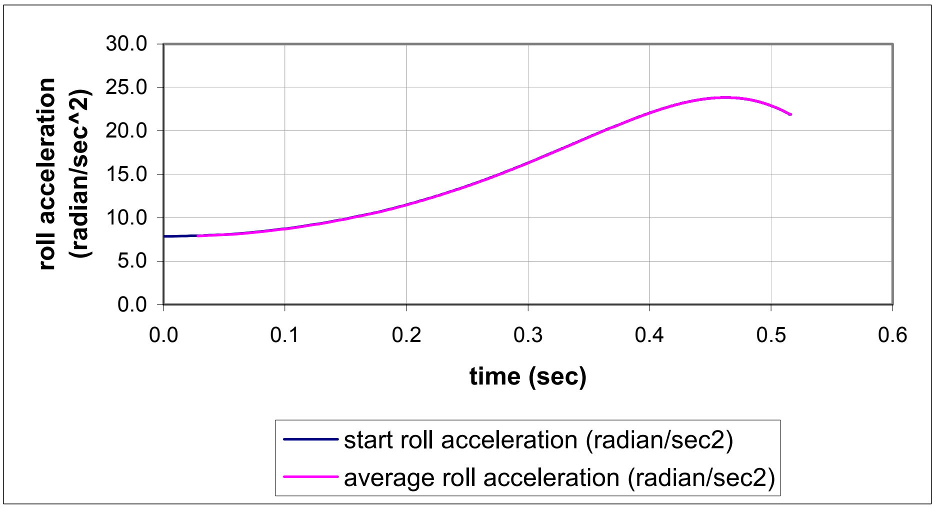

Figure 8 - Time History of Roll Accelerations of a Basic Four Wheeled Truck with a Narrow Rear Track

6.4 THREE WHEELED TRUCK WITH BUMP STOPS

For a three wheeled truck of the above input settings (Table 1) with bump stops of width 0.906m and height 0.1m, the simulation (Excel version) produces time histories of roll angle and acceleration as shown in Figures 9 and 10.

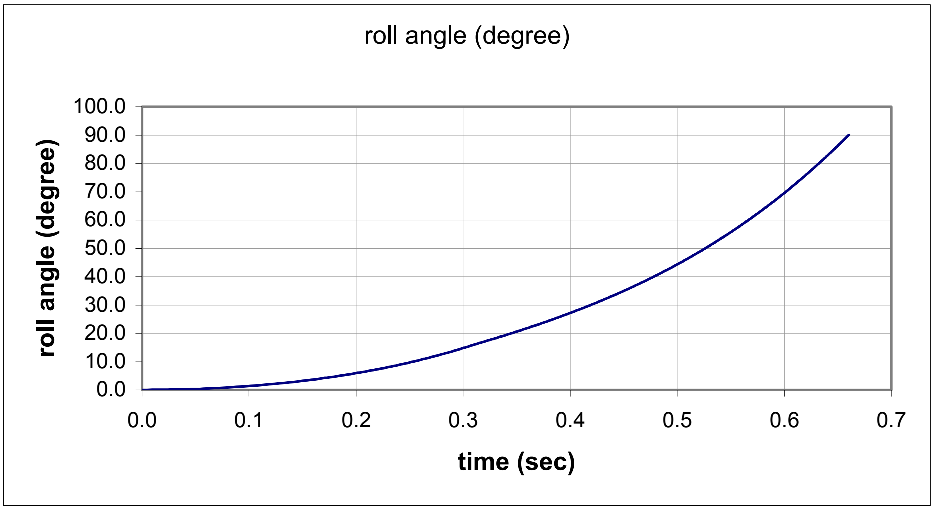

Figure 9 - Time History of Roll Angle of a Three Wheeled Truck with Bump Stops

The main differences compared to the previous configuration are the lengthened total rollover time (0.661sec compare to 0.516sec) and the sharp fall in roll acceleration when one of the bump stops hits the ground (at around 0.3sec in Figure 10).

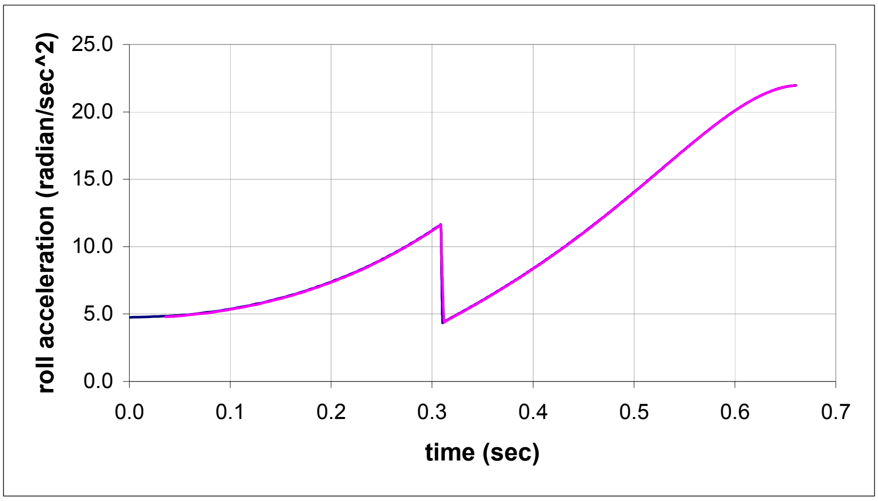

Figure 10 - Time History of Roll Accelerations of a Three Wheeled Truck with Bump Stops

For the case when the bump stop only slows down the roll rate but is not sufficient to stop the roll (an example set of data is shown in Table 2), the results indicate a slow rate of roll for the first second. However, the truck will pick up its roll rate again in very short notice (see Figure 12). In the following example, the total rollover time is 1.7 sec and the maximum roll acceleration is 16.6 rad/sec.

Parameter	Input
Mass of vehicle	2870kg
Roll inertia (about CG) of vehicle	225kgm^2
Height of CG from ground	0.47m
CG from front of vehicle	0.625m
Lateral offset of CG from centre line	0.007m
Front track width	0.906m
Rear track width	0.175m
Wheel base	1.229m
Bump stop width	1.15m
Bump stop height	0.05m
Angle of slope	5°
Forward velocity of vehicle	5m/sec
Radius of turn of vehicle	3.5m

Table 2 - Simulation Input for a Three Wheeled Truck with Bump Stops

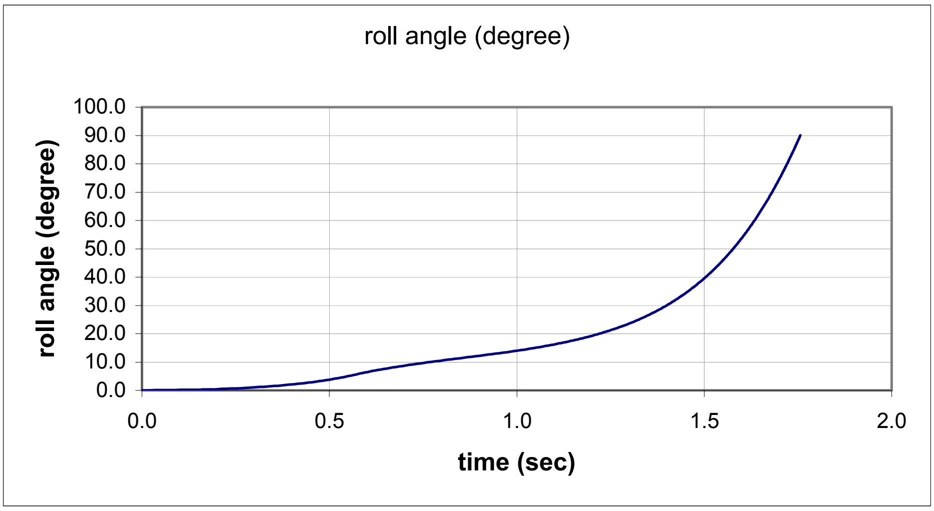

Figure 11 - Time History of Roll Angle of a Three Wheeled Truck with Bump Stops (low roll rate)

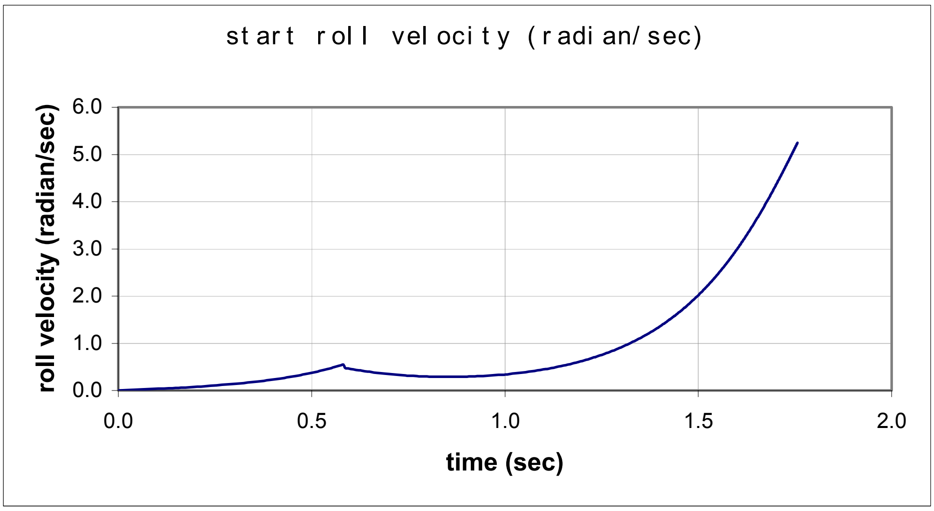

Figure 12 - Time History of Roll Velocity of a Three Wheeled Truck with Bump Stops (low roll rate)

6.5 BASIC FOUR WHEELED TRUCK

For a four wheeled truck of the following input settings (Table 3), the simulation (Excel version) produces time histories of roll angle and acceleration as shown in Figures 13 and 14.

Parameter	Input
Mass of vehicle	2870kg
Roll inertia (about CG) of vehicle	225kgm^2
Height of CG from ground	0.47m
CG from front of vehicle	0.625m
Lateral offset of CG from centre line	0.007m

Front track width	0.906m
Rear track width	0.906m
Wheel base	1.229m
Angle of slope	5□
Forward velocity of vehicle	6m/sec
Radius of turn of vehicle	3.5m

Table 3 - Simulation Input for a Basic Four Wheeled Truck

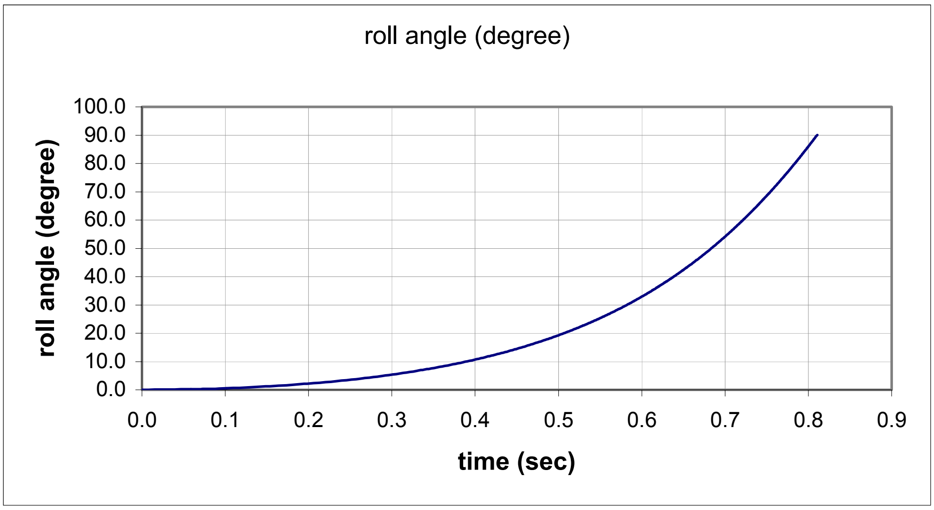

Figure 13 - Time History of Roll Angle of a Basic Four Wheeled Truck

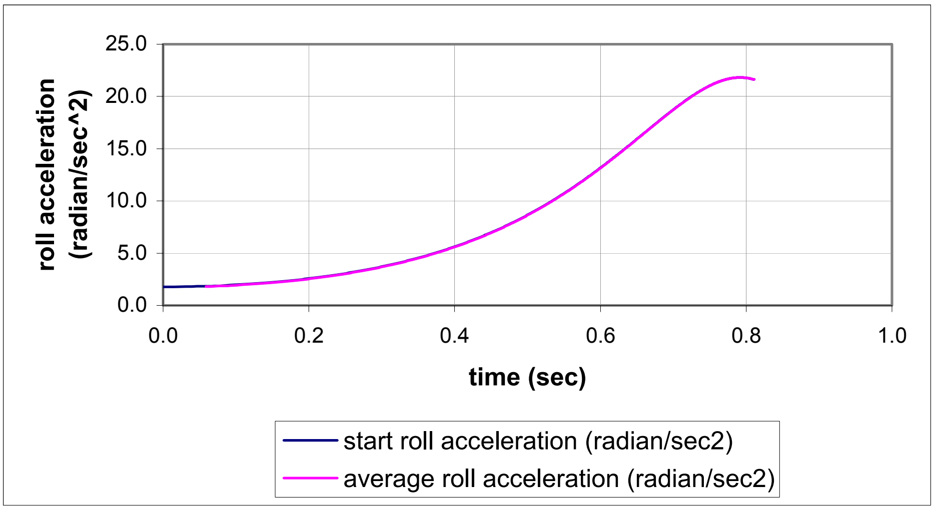

Figure 14 - Time History of Roll Angle of a Basic Four Wheeled Truck

The general features of Figures 13 and 14 above are similar to the basic three wheel assessment (Figures 7 and 8). It is interesting to note that the change in rear axle configuration has increased the roll time from approximately 0.5 seconds to 0.8 seconds, a 60% increase.

6.6 FOUR WHEELED TRUCK WITH REAR PIVOTING AXLE

The assessment has been conducted here for notionally the same vehicle but with a pivoting rear axle.

Parameter	Input
Mass of vehicle	2870kg
Roll inertia (about CG) of vehicle	225kgm^2
Height of CG from ground	0.47m
CG from front of vehicle	0.625m
Lateral offset of CG from centre line	0.007m
Front track width	0.906m
Rear track width	0.906m
Wheel base	1.229m
Height of rear axle pivot	0.4m
Rear axle pivot range	20□
Angle of slope	5□
Forward velocity of vehicle	6m/sec
Radius of turn of vehicle	3.5m

Table 4 - Simulation Input for a Four Wheeled Truck with Rear Pivoting Axle

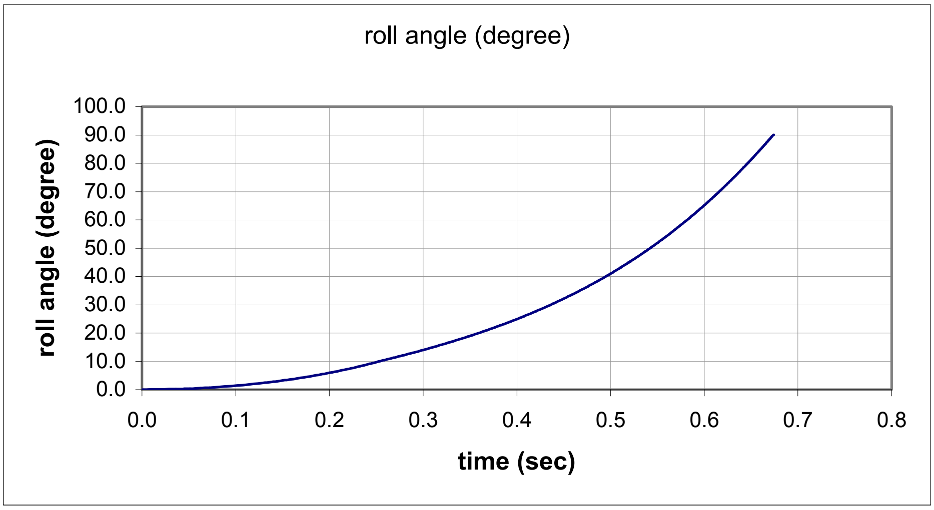

Figure 15 - Time History of Roll Angle of a Four Wheeled Truck with Rear Pivoting Axle

Again the response curves are similar to those of the three wheeled truck with bump stops. Roll times are slightly longer than for a three wheeled truck with bump stops but slightly shorter than for a 'basic' four wheeled truck. The differences between the pivoting rear axle assessment (Figures 15 and 16) and the basic truck will depend on the height assumed for the rear axle pivot.

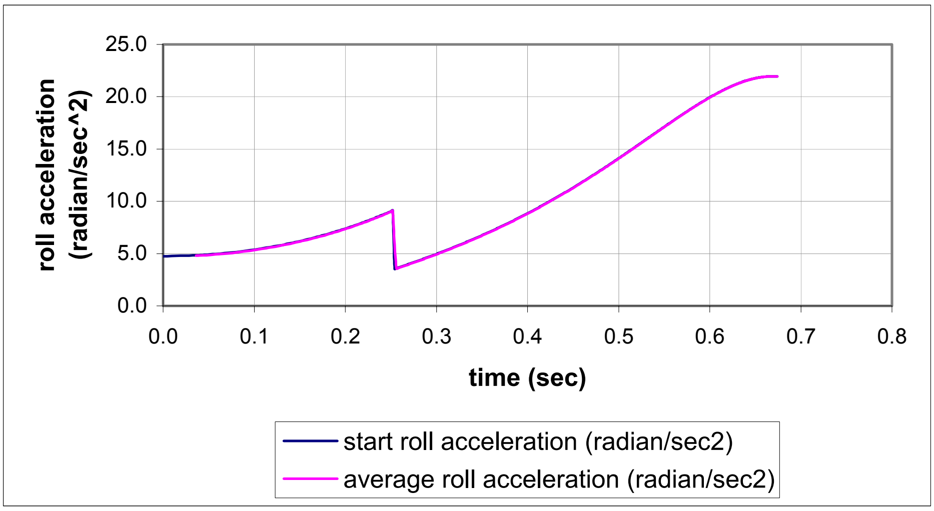

Figure 16 - Time History of Roll Accelerations of a Four Wheeled Truck with Rear Pivoting Axle

6.7 DUMPER TRUCK WITH PIVOT STEER

For a dumper truck of the following input settings (Table 5), the simulation (Excel version) produces time histories of roll angle and acceleration as shown in Figures 17 and 18.

Parameter	Input
Mass of vehicle	2870kg
Roll inertia (about CG) of vehicle	225kgm^2
Height of CG from ground	0.47m
CG from front of vehicle	0.4m
Lateral offset of CG from centre line	0.007m
Tracks width	0.906m
Wheel base	1.229m
Length of front section	0.615m
Angle of slope	5□
Forward velocity of vehicle	6m/sec
Radius of turn of vehicle	3.5m
Tyre Stiffness	1e5 N/m

Table 5 - Simulation Input for a Dumper Truck

As would be expected the form of the results is similar to that of the forklift trucks. However a significant reduction in roll times has been noticed for tight turns and this is attributed to the outboard shift in Centre of Gravity as the pivot articulates.

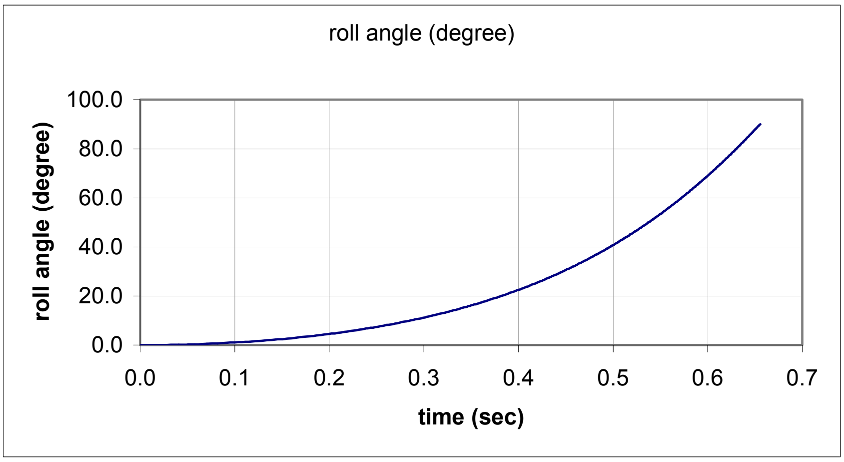

Figure 17 - Time History of Roll Angle of a Dumper Truck

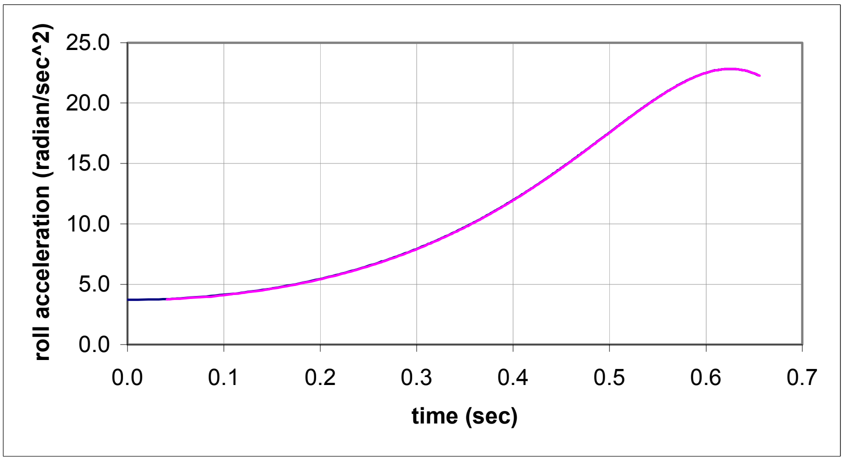

Figure 18 - Time history of Roll Accelerations of a Dumper Truck

7. PARAMETRIC STUDIES

To assess the influence of each parameter for the four truck types and demonstrate the capability of the truck simulation as a design and evaluation tool, three parametric studies were conducted. Studies 1 and 2 highlight the relative significant of the trucks' physical and operational attributes while study 3 compares the turning stability of a three wheeled truck with and without cargo.

7.1 STUDIES 1 AND 2

The time to rollover (Study 1) and the critical speed (Study 2) and their percentage changes are tabulated when each of the parameters are changed in turn. The results of study 1 are illustrated in Figures 19 to 23 below and the data can be found in Tables C1 to C5 in Appendix C. Tables C6 to C10 in Appendix C provide data on study 2 which considers the change in critical speed as opposed to roll time.

In these studies, the total time of rollover is the time for the truck to roll 90 degrees onto its side. The critical speed refers to the speed of travel of the truck necessary to cause rollover.

In the tables, the nominal values of the parameters were chosen in the belief that these are the common operational conditions. Therefore, this parametric comparison only represents the relative behaviour around these conditions. To conduct the comparison, each parameter was changed by ±10% from the nominal value to assess the percentage change in rollover time or critical speed. Care has to be taken when interpreting the results. Since the nominal values of CG offset and slope angle are relatively small, 10% changes from these nominal values will be too small to cause any noticeable change in total roll time or critical speed. If the nominal value of CG offset is much bigger, the roll performance of the truck will be more sensitive to 10% change of CG offset.

In this section, only the results of the first study are discussed. In the graphs below, a positive percentage change of rollover time indicates an increase in stability and vice versa. A common trend can be observed for all truck types. Rollover times increase when:

- Mass of truck decreases
- Roll inertia increases
- The CG is in a lower position
- The CG is closer to the front of truck (3 wheeled vehicles and 4 wheeled vehicles with a narrow track width only)
- The CG is closer to the centre of turn
- Front track width is increased
- The slope is less inclined
- The radius of turn increases

The result also shows clearly that the turning velocity has the most significant impact on the stability of the truck types. In all cases, the mass, the roll inertia and the slope angle play a lesser part in the stability of the trucks.

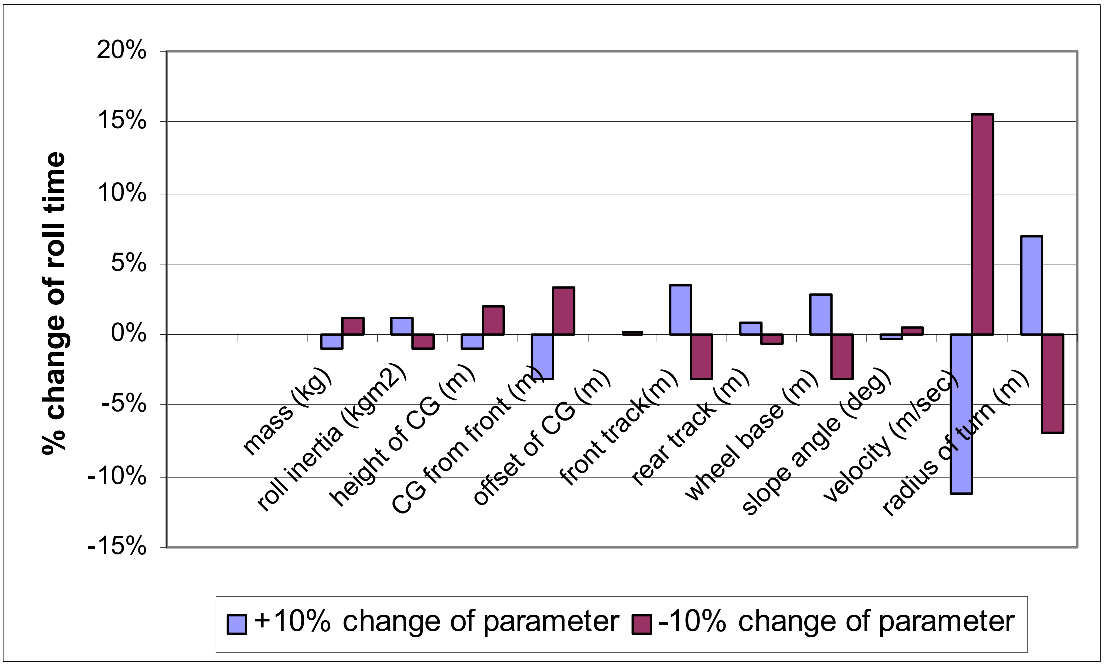

Figure19 - Parametric Comparison of a Basic Three Wheeled Truck (Table C1)

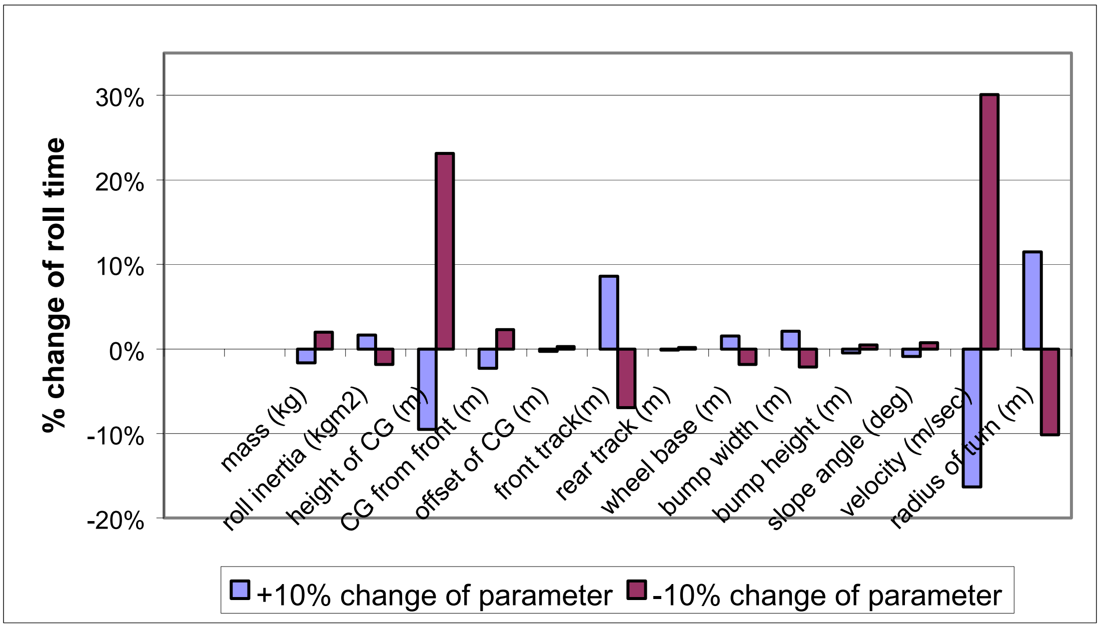

Figure 20 - Parametric Comparison of a Three Wheeled Truck with Bump Stops (Table C2)

The addition of bump stops, whilst making the vehicle more stable in certain instances, reveals that the time to roll is more sensitive to CG height and front track width as well as velocity and radius of turn.

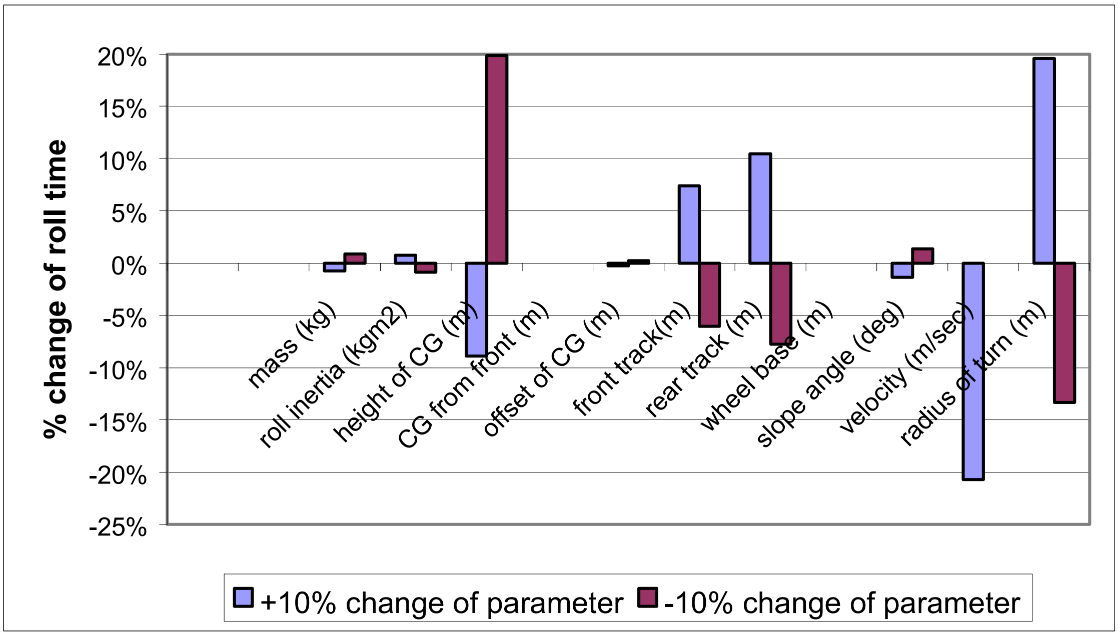

Figure 21 - Parametric Comparison of a Basic Four Wheeled Truck (Table C3)

The results of the basic four wheeled truck are very similar to the three wheeled truck with bump stops. The roll time is sensitive to turning velocity and radius as well as CG height and rear track width.

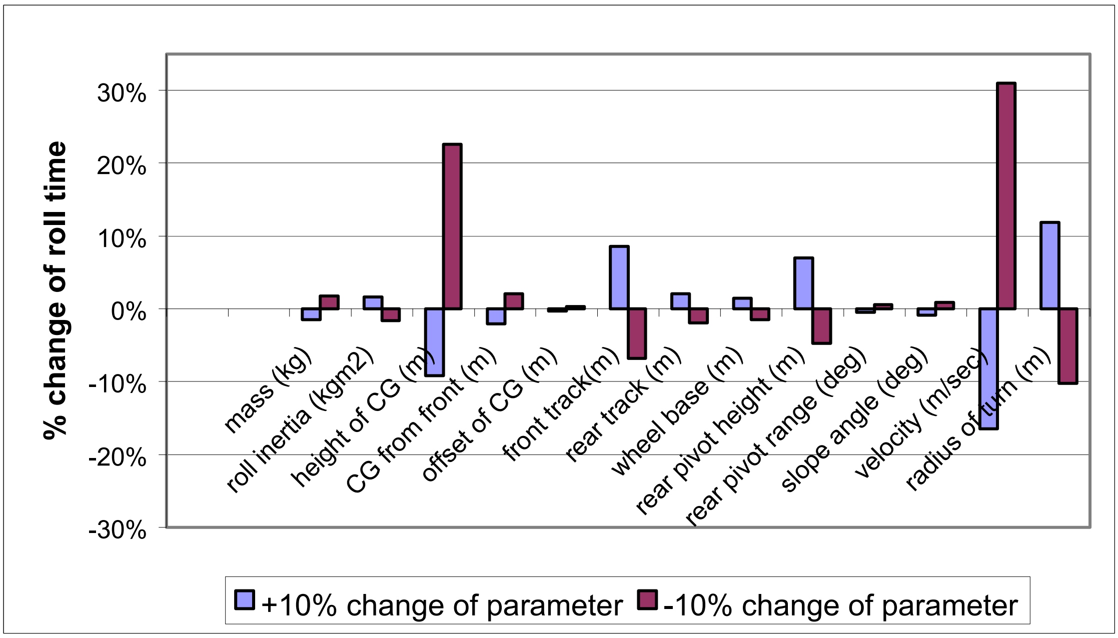

Figure 22 - Parametric Comparison of a Four Wheeled Truck with Rear Pivoting Axle (Table C4)

The results of the pivoting rear axle (Figure 22) are more akin to the three wheeled vehicle with bump stops (Figure 20). However, the roll time is also sensitivity to rear axle pivot height.

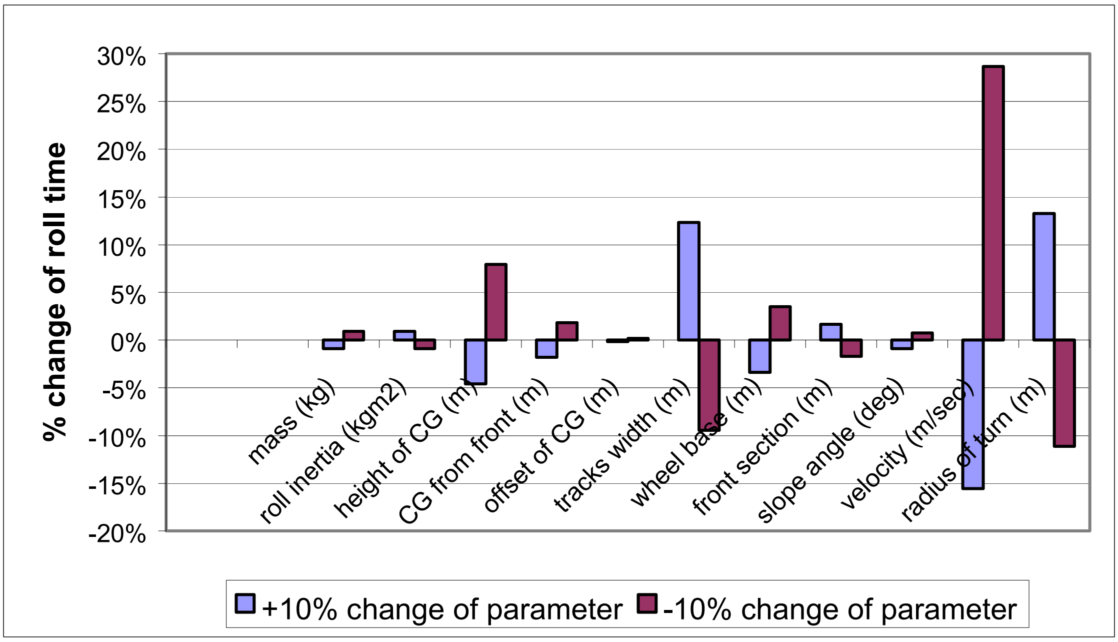

Figure 23 - Parametric Comparison of a Dumper Truck (Table C5)

For the dumper truck, the roll time is sensitive to turning velocity as well as radius and tracks width.

7.2 STUDY 3

The truck models produced will be a good design and evaluation tool. A simulation exercise has been conducted to illustrate this capacity. The total time of roll and the critical velocity of a forklift truck with the following dimensions has been found with and without cargo.

Parameter	Input
Mass of vehicle	2865kg
Load when applied	1500kg
Roll inertia (about CG) of vehicle (without load)	225kgm^2
Roll inertia (about CG) of vehicle (with load)	475kgm^2
Height of CG from ground	0.470m
CG from front of vehicle (without load)	0.653m
CG from front of vehicle (with load)	0.143m
Lateral offset of CG from centre line	0.007m
Front track width	0.910m
Rear track width	0.168m
Wheel base	1.230m
Bump stop width	1.0m
Bump stop height	0.090m
Angle of slope	5°
Forward velocity of vehicle	6m/sec
Radius of turn of vehicle	3.5m

Table 6 - Simulation Input for a Forklift Truck

In this study, the fork of the truck is assumed to be in the lowered position and the height and offset of the CG are assumed to be unchanged before and after loading. This is acceptable since the height of the CG of the load is similar to that of the truck when the fork is at a low position. The load is also assumed to be firmly attached to the fork such that relative motion between the cargo and the vehicle is prevented during the roll history.

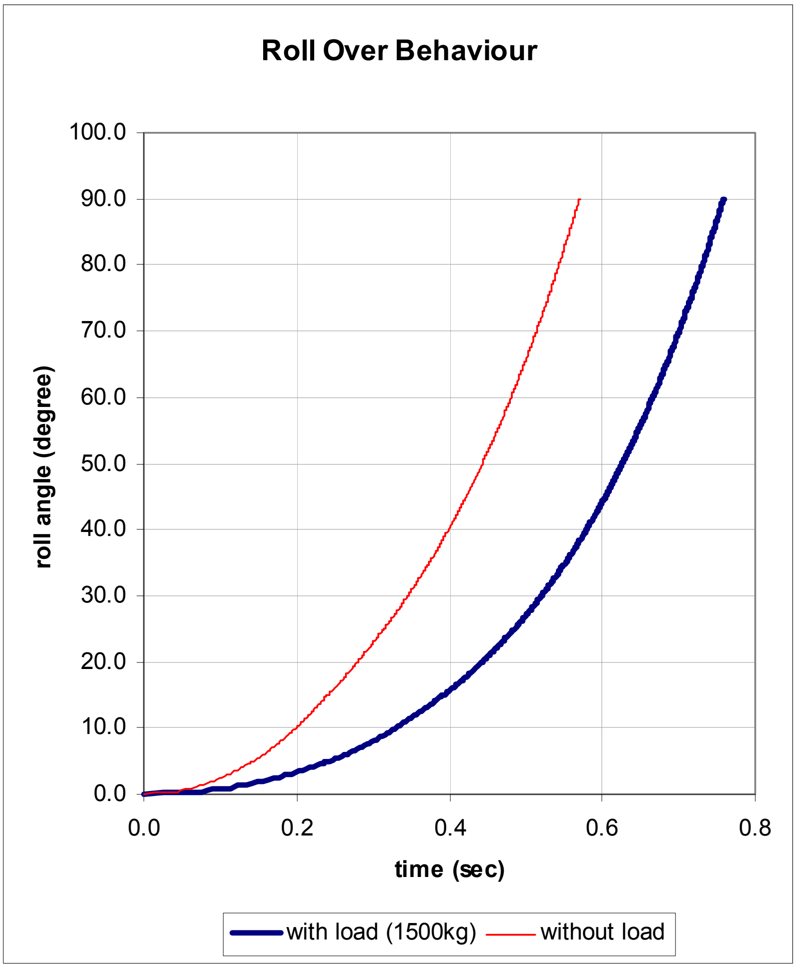

Figure 24 - Time Histories of Roll Angle of a Forklift Truck with and without front loading

Significant increases in total roll time (refer to Figure 24) and critical speed have been predicted for the loaded truck. The total roll time increases from 0.57s to 0.76s while the critical velocity increases from 3.8m/s to 5.1m/s. This apparent improvement in stability is the result of the increase in roll inertia and the forward shift of the CG with negligible rise in CG height.

The forward shift of the CG increases the moment arm (and the stabilising moment) of the total weight from the roll axis. This is true only for a three wheeled truck with the roll axis at an angle to the side of the truck. However, the situation will change considerably if the load is raised. With a load comparable to the weight of the truck, an elevation of the load will raise the CG height of the loaded truck a comparable amount and create an increased rolling moment.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The study into the rollover of forklift trucks and dumpers has resulted in the development of a novel assessment tool which can predict both the onset of instability and the time taken for the vehicle to roll over.

Salient conclusions are given below:

- An in-depth study of the problems associated with truck and dumper rollover has been conducted.
- Feedback on truck and dumper rollovers from industry was very disappointing.
- Analytical models to predict the onset of instability and the resulting rate of roll have been produced. The Excel spreadsheet performs extremely well compared to the detailed transient assessment conducted in IDL. It was not envisaged that a spreadsheet could perform this well at the outset of the project.
- Results for a range of trucks have been presented and a parametric study into the influence of specific design parameters on roll stability and times has been conducted.
- From the limited input data, rollovers where predicted to take between 0.8 and 1.8 seconds.
- Three parametric studies have been carried out. These studies highlight the influence of physical dimensions and environmental characteristics on the roll behaviour of the trucks. It has been demonstrated that the models will provide a useful tool for assessment of truck design and definition of operation envelope.

8.2 RECOMMENDATIONS

The work now requires validation and it is envisaged that some practical testing will be required.

The assessment methodology could be further developed to incorporate tyre stiffness and suspension geometry. The four wheeled truck model could then be adapted to model the rollover of All Terrain Vehicles (ATV's) or any other type of vehicle.

When the assessment tool has been verified; the results need to be assessed in the light of human responses and ergonomic design. Is it, for example, advantageous for a truck to roll so quickly that the driver has no time to escape the vehicle and is, as a consequence, protected by the roll cage? Or, conversely, is it advantageous for a truck to roll slowly so that an experienced driver has time to conduct a manoeuvre that would halt the roll and bring the vehicle back to a stable situation (space permitting)?

9. REFERENCES

1. McCARTHY RL, TAYLOR RK, KOST G, ROBINSON JN, WOOD CT***Comparative Analysis of indusrial lift truck (forklift) accidents.*** ASME (Paper), 1990, No. 1990, p.8p

2. THOMAS D GILLESPIE '***Fundamentals of Vehicle Dynamics'***. Published by the Society of Automotive Engineers, Inc.

3. WILSON JA ***Instabilities – the neglected failure mode.*** ASME (Paper), 1998, p.4p

4. VARIOUS ***Proceedings of the 13th IAVSD Symposium on the Dynamics of Vehicles on Roads and Tracks.*** Vehicle System Dynamics, 1994, Vol 23

5. ANTOUN RJ, HACKERT PB, OLEARY MC, SITCHEN A ***Simulating vehicle dynamic handling.*** Automotive Engineering, Oct 1986, Vol 94, no.10, p.72

6. CHANG CN, DING DH ***Theoretical stability analyses of the cornering behaviour of three and four-wheel vehicles.*** International Journal of vehicle design, 1994, Vol 15, No. 3-5, pp301-317

7. LOVAT G, MISTROT P, DONATI P, BOULANGER P, SCHULER B ***Simulation of the dynamic characteristics of a forklift truck travelling over an obstacle.*** Heavy vehicle systems, 1997, Vol 4, no. 2-4, pp 183-203

8. METZ LD ***Dynamics of four-wheel steer of highway vehicles.*** SAE Special Publications, 1993, no. 950

9. TALBOLT TF, APPLETON JH ***Dump truck stability.*** ASME (Paper), 1986, p.4p

10. ACKERMANN J, BUNTE T ***Automatic car steering control bridges over the driver reaction time.*** Kybernetika, 1997, Vol 33, No. 1, pp.61-74

11. HEENAN K ***A survey of stability assessment methods for mobile machinery.*** HSE Laboratory, HSE registry file: SME/919/59/1997

12. MALE GE ***Safety of construction Plan – A Survey of standards and accidents associated with earth moving machinery.*** HSE Specialist Inspector Reports, SIR No. 53

13. BSI ***Safety of industrial trucks***. BS EN 1726-1:1999

14. BSI ***Safety of industrial trucks.*** BS EN 1759:1999

15. BSI ***Earth-moving machinery – Safety.*** BS EN 474-1:1995

16. BSI ***Earth-moving machinery – Safety.*** BS EN 474-6:1997

17. BSI ***Counterbalanced lift trucks – Stability – Basic tests***. BS 3726:1978

18. ***Mechanical Stability and Driver Visibility of Construction Site Dumpers:*** Results of Processed Survey Data.

19. K HEENAN I.ENG, FIMINE, ***Health & Safety Laboratory***, May 1995

20. *An investigation into the Static Instability of a WINGET 4S3000 Site Dumper Truck*

21. R. WDE ALLEN AND THEODORE J. ROSENTHAL ***A Computer Simulation Analysis of Safety Critical Manoeuvres for Assessing Ground Vehicle Dynamic Stability Systems*** Technology Inc.

22. ANDRZEJ G. NALECZ, ZHENGYU LU AND KENNETH ***An Investigation into Dynamic Measures of Vehicle Rollover Propensity*** L. d'Entremont, Univ. of Missouri-Columbia

23. C. B. WINKLER, S. E. BOGARD AND K. E. CAMPBELL, Univ. of Michigan Transportation Research Institute ***Repeatability of the Tilt-Table Test Method***

24. C. YEH, N. H. LEE, T. Y. LIN AND D. K. HO, NATIONAL TSING HUA University, Taiwan ***Handling Analysis of Automobiles Travelling in Jack-Up Attitude Edge***

25. S. TOUSI, A. K. BAJAJ AND W. SOEDEL ***Finite Disturbance Directional Stability of Vehicles with Human Pilot Considering Nonlinear Cornering Behaviour,*** Vehicle System Dynamics, 20 (1991), pp.21-55

26. C. B. WINKLER, S. M. KARAMIHAS AND S. E. BOGARD, Univ. of Michigan ***Transportation Research Institute Roll-Stability Performance of Heavy-Vehicle Suspensions***

27. E. ESMAILZADEH AND H. BATENI, SHARIF ***Optimal Active Vehicle Suspensions with Full State Feedback Control .*** Univ. of Technology

28. G. E. MALE, HSE, ***Safety of Construction Plant – A survey of Standards and Accidents Associated with Earth Moving Machinery*** Feb 1998

29. HEALTH & SAFETY AT WORK SPECIAL REPORT – ***Implementing the New Rules on Work Equipment*** Issue 41, June 1999

30. GARY J. LOCK, FNC ***Understanding HGV Rollover***

31. K. E. CLEMINSON AND G. J. LOCK , FNC ***Investigations into the Rollover of Road Tanker Vehicles***

32. The Mechanics of Heavy Vehicles – Chapter 19 ***Mechanics of the Rollover Process*** 24th – 27th June 1992

33. Bsi EN 1459 : 1998 *Safety of Industrial Trucks* – ***Self-Propelled Variable Reach Trucks***

34. HEALTH & SAFETY AT WORK ***– Lift Trucks***

35. HEALTH & SAFETY AT WORK – ***Work Equipment***

36. PUWER 98 – Regulations 25-30 Part III: ***Mobile Work Equipment***

37. SITE DUMPER ASSOCIATION - ***Stability Standard for Site Dumpers***

38. BITA – ***Stability Awareness Guidance for Powered Industrial and Rough Terrain Lift Trucks***, 3rd Ed. March 1996

39. BITA – ***Do's & Don'ts for Users of Industrial and Rough Terrain Lift trucks***, 6th Ed. July 1997

40. BITA – ***Operator's Safety Code for Powered Industrial Trucks***, 16th Ed. June 1998

41. BITA – Guidance Note GN27 (August 1987): ***Operator Warnings on Truck Tipovers***

42. BITA – Guidance Note GN45 (January 1994): ***Double Deep Stacking & Stability Tests & Rating***

43. O CRICHTON AND D ALLINSON Health & Safety Laboratory ***Estimates of the Dynamic Lateral Stability Envelope for a Lansing Linde E15C Forklift Truck.*** FE/96/010.

APPENDIX A – SUPPLIERS & MANUFACTURERS

Atlet Limited, Jefferson Way, Thame Industrial Estate, Thame, Oxon. OX9 3SP

Barlow Handling Ltd, Maidenhead Business Campus, Maidenhead, Berkshire. SL6 3QN

Boss Group Ltd, Grovebury Road, Leighton Buzzard, Bedfordshire. LU7 8SR

BT Rolatruc Ltd, Stirling Road, Slough, Berkshire. SL1 4SY

CESAB Ltd, Unit 6, Bevan Way, Smethwick, Warley, West Midlands. B66 1BZ

Clark Material Handling Europe, PO Box 4106, Solihull, West Midlands. B91 3WE

Crown Lift Trucks Ltd, Fishponds Road, Wokingham, Berkshire. RG11 2JT

Fiat OM Industrial Trucks Ltd, Road Five, Winsford Industrial Estate, Winsford, Cheshire. CW7 3RB

Grant Handling Ltd, Unit 10, Hewitts Industrial Estate, Elmbridge Road, Cranleigh, Surrey. GU6 8LW

Hamech Ltd, Cufaude Lane, Bramley, Basingstoke, Hants. RG26 5DW

Hyster Europe Ltd, Berk House, Basing View, Basingstoke, Hants. RG21 2HQ

JCB Materials Handling Ltd, Rocester, Staffordshire. ST14 5JP

Jungheinrich (GB) Ltd, Southmoor Road, Wythenshawe, Manchester. M23 9DU

Kalmar UK Ltd, Siskin Drive, Coventry. CV3 4FJ

Kelvin Engineering (Basingstoke) Ltd, London Road, Hatch, Nr. Basingstoke, Hants. RG24 0JF

Lansing Linde Ltd, Kingsclere Road, Basingstoke, Hants, RG21 4XJ

Lex Komatsu Ltd, Logistics House, Horsley Road, Kingsthorpe, Northampton. NN2 6LB

Manitou (Site Lift) Ltd, Ebblake Industrial Estate, Wimborne, Dorset. BH21 6AY

Mitsubishi Caterpillar Forklift Europe BV, 29 Rue de Pré-Bois, PO Box 535, 1215 Geneva 15 Switzerland

Moffett Engineering Ltd, Listraor, Clontibret, County Monaghan, Ireland

Narrow Aisle Ltd, Market Bridge, Tipton, West Midlands. DY4 7AH

Nissan Motor (GB) Ltd, The Rivers Office Park, Denham Way, Maple Cross, Rickmansworth Herts. WD3 2YS

Still Materials Handling Ltd, The Old Steelwork, Millfields Road, Bilston, West Midlands. WV14 0QR

Toyota Industrial Equipment (UK) Ltd, Gelderd Road, Gildersome, Morley, Leeds. LS27 7JX

Wilmat Handling Company Ltd, Wilmat House, 43 Steward Street, Birmingham. B18 7AE

Yale Europe Materials Handling Ltd, St David's Court, Union Street, Wolverhampton, West Midlands. WV1 3JE

Thwaites Ltd, Leamington Spa, Warwickshire. CV32 7NQ

Benford Ltd, PO Box 26, The Cape, Warwick. CV32 5DR

Ausa (UK) Ltd, Unit 1 Alma Industrial Estate, Regent Street, Rochdale. OL12 0HQ

Mortimer Manufacturing Ltd, Burley Road, Cottesmore, Oakham, Leicester, LE15 7BN

Winget Ltd, PO Box 41, Edgefold Industrial Estate, Plodder Lane, Bolton, Lancs BL4 0LS

Industrial Bodies and Associations

Site Dumper Association

Construction Plant-Hire Association

British Industrial Truck Association

APPENDIX B – DETAILED CALCULATIONS

APPENDIX C - RESULTS OF PARAMETRIC STUDY USING TRUCK SIMULATIONS (PC VERSION).

Study 1 – Investigation into the change of rollover time

In this study, each parameter is changed in turn by ±10% to assess the percentage change in total time of roll. The nominal values of dimensions are estimated from actual vehicle. The results are presented graphically in the main body of the report.

Basic three wheeled truck

Parameter	Nominal Value	% Change	Total Time of Roll (sec) (Norm: 0.516s)	% Change of Rollover Time
mass of vehicle (kg)	2870	10	0.511	-0.97%
		-10	0.522	1.16%
roll inertia (about CG) of vehicle (kgm^2)	225	10	0.522	1.16%
		-10	0.511	-0.97%
height of CG from ground (m)	0.47	10	0.511	-0.97%
		-10	0.526	1.94%
CG from front of vehicle (m)	0.625	10	0.500	-3.10%
		-10	0.533	3.29%
lateral offset of CG from centre line (m)	0.007	10	0.516	0.00%
		-10	0.517	0.19%
front track width (m)	0.906	10	0.534	3.49%
		-10	0.500	-3.10%
rear track width (m)	0.175	10	0.520	0.78%
		-10	0.513	-0.58%
wheel base (m)	1.229	10	0.531	2.91%
		-10	0.500	-3.10%
angle of slope (0 to 30 degrees)	5	10	0.514	-0.39%
		-10	0.519	0.58%
turning velocity of vehicle (m/sec)	6	10	0.458	-11.24%
		-10	0.596	15.50%
radius of turn of vehicle (min. 1m)	3.5	10	0.552	6.98%
		-10	0.480	-6.98%

Table C1 - Parametric Study of a Basic Three Wheeled Truck

Three wheeled truck with bump stops

Parameter	Nominal Value	% Change	Total Time of Roll (sec) (Norm: 0.661s)	% Change of Rollover Time
mass of vehicle (kg)	2870	10	0.650	-1.66%
		-10	0.674	1.97%
roll inertia (about CG) of vehicle (kgm^2)	225	10	0.672	1.66%
		-10	0.649	-1.82%
height of CG from ground (m)	0.47	10	0.598	-9.53%
		-10	0.814	23.15%
CG from front of vehicle (m)	0.625	10	0.646	-2.27%
		-10	0.676	2.27%
lateral offset of CG from centre line (m)	0.007	10	0.659	-0.30%
		-10	0.663	0.30%
front track width (m)	0.906	10	0.718	8.62%
		-10	0.615	-6.96%
rear track width (m)	0.175	10	0.660	-0.15%
		-10	0.662	0.15%
wheel base (m)	1.229	10	0.671	1.51%
		-10	0.649	-1.82%
bump stop width (m)	0.906	10	0.675	2.12%
		-10	0.647	-2.12%
bump stop height (m)	0.1	10	0.658	-0.45%
		-10	0.664	0.45%
angle of slope (0 to 30 degrees)	5	10	0.655	-0.91%
		-10	0.666	0.76%
turning velocity of vehicle (m/sec)	6	10	0.553	-16.34%
		-10	0.860	30.11%
radius of turn of vehicle (min. 1m)	3.5	10	0.737	11.50%
		-10	0.594	-10.14%

Table C2 - Parametric Study of a Three Wheeled Truck with Bump Stops

Basic four wheeled truck

Parameter	Nominal Value	% Change	Total Time of Roll (sec) (Norm: 0.811s)	% Change of Rollover Time
mass of vehicle (kg)	2870	10	0.805	-0.74%
		-10	0.818	0.86%
roll inertia (about CG) of vehicle (kgm^2)	225	10	0.817	0.74%
		-10	0.804	-0.86%
height of CG from ground (m)	0.47	10	0.739	-8.88%
		-10	0.972	19.85%
CG from front of vehicle (m)	0.625	10	0.811	0.00%
		-10	0.811	0.00%
lateral offset of CG from centre line (m)	0.007	10	0.809	-0.25%
		-10	0.813	0.25%
front track width (m)	0.906	10	0.871	7.40%
		-10	0.762	-6.04%
rear track width (m)	0.906	10	0.896	10.48%
		-10	0.748	-7.77%
wheel base (m)	1.229	10	0.811	0.00%
		-10	0.811	0.00%
angle of slope (0 to 30 degrees)	5	10	0.800	-1.36%
		-10	0.822	1.36%
turning velocity of vehicle (m/sec)	6	10	0.643	-20.72%
		-10	Stable	VALUE!
radius of turn of vehicle (min. 1m)	3.5	10	0.970	19.61%
		-10	0.703	-13.32%

Table C3 - Parametric Study of a Basic Four Wheeled Truck

Four wheeled truck with rear pivoting axle

Parameter	Nominal Value	% Change	Total Time of Roll (sec) (Norm: 0.674s)	% Change of Rollover Time
mass of vehicle (kg)	2870	10	0.664	-1.48%
		-10	0.686	1.78%
roll inertia (about CG) of vehicle (kgm^2)	225	10	0.685	1.63%
		-10	0.663	-1.63%
height of CG from ground (m)	0.47	10	0.612	-9.20%
		-10	0.826	22.55%
CG from front of vehicle (m)	0.625	10	0.660	-2.08%
		-10	0.688	2.08%
lateral offset of CG from centre line (m)	0.007	10	0.672	-0.30%
		-10	0.676	0.30%
front track width (m)	0.906	10	0.732	8.61%
		-10	0.628	-6.82%
rear track width (m)	0.906	10	0.688	2.08%
		-10	0.661	-1.93%
wheel base (m)	1.229	10	0.684	1.48%
		-10	0.664	-1.48%
height of rear axle pivot (m)	0.4	10	0.721	6.97%
		-10	0.642	-4.75%
rear axle pivot range (0 to 180 degrees)	20	10	0.671	-0.45%
		-10	0.678	0.59%
angle of slope (0 to 30 degrees)	5	10	0.668	-0.89%
		-10	0.680	0.89%
turning velocity of vehicle (m/sec)	6	10	0.563	-16.47%
		-10	0.883	31.01%
radius of turn of vehicle (min. 1m)	3.5	10	0.754	11.87%
		-10	0.605	-10.24%

Table C4 - Parametric Study of a Four Wheeled Truck with Rear Pivoting Axle

Four wheeled dumper truck with pivot steer

Parameter	Nominal Value	% Change	Total Time of Roll (sec) (Norm: 0.656s)	% Change of Rollover Time
mass of vehicle (kg)	2870	10	0.650	-0.91%
		-10	0.662	0.91%
roll inertia (about CG) of vehicle (kgm^2)	225	10	0.662	0.91%
		-10	0.650	-0.91%
height of CG from ground (m)	0.47	10	0.626	-4.57%
		-10	0.708	7.93%
CG from front of vehicle (m)	0.4	10	0.644	-1.83%
		-10	0.668	1.83%
lateral offset of CG from centre line (m)	0.007	10	0.655	-0.15%
		-10	0.657	0.15%
tracks width (m)	0.906	10	0.737	12.35%
		-10	0.594	-9.45%
wheel base (m)	1.229	10	0.634	-3.35%
		-10	0.679	3.51%
length of front section (max. 2/3 wheel base)	0.615	10	0.667	1.68%
		-10	0.645	-1.68%
angle of slope (0 to 30 degrees)	5	10	0.650	-0.91%
		-10	0.661	0.76%
turning velocity of vehicle (m/sec)	6	10	0.554	-15.55%
		-10	0.844	28.66%
radius of turn of vehicle (min. 1m)	3.5	10	0.743	13.26%
		-10	0.583	-11.13%

Table C5 - Parametric Study of a Four Wheeled Dumper Truck with Pivot Steer

Study 2 – Investigation into the change in critical speed

In this study, each parameter is changed in turn by ±10% to assess the percentage change in critical speed. The critical speed is the turning speed of the truck when it becomes unstable, i.e. the truck is going to turn over completely. Tabulated and graphical results are presented below.

Basic three wheeled truck

Parameter	Nominal Value	% Change	Critical Speed (m/sec) (Norm: 3.9m/sec)	% Change of Critical Speed
mass of vehicle (kg)	2870	10	3.90	0.00%
		-10	3.90	0.00%
roll inertia (about CG) of vehicle (kgm^2)	225	10	3.90	0.00%
		-10	3.90	0.00%
height of CG from ground (m)	0.47	10	3.70	-5.13%
		-10	4.20	7.69%
CG from front of vehicle (m)	0.625	10	3.80	-2.56%
		-10	4.10	5.13%
lateral offset of CG from centre line (m)	0.007	10	3.90	0.00%
		-10	3.90	0.00%
front track width (m)	0.906	10	4.10	5.13%
		-10	3.70	-5.13%
rear track width (m)	0.175	10	4.00	2.56%
		-10	3.90	0.00%
wheel base (m)	1.229	10	4.10	5.13%
		-10	3.70	-5.13%
angle of slope (0 to 30 degrees)	5	10	3.90	0.00%
		-10	4.00	2.56%
radius of turn of vehicle (min. 1m)	3.5	10	4.10	5.13%
		-10	3.70	-5.13%

Table C6 - Critical Speed Parametric Study of a Basic Three Wheeled Truck

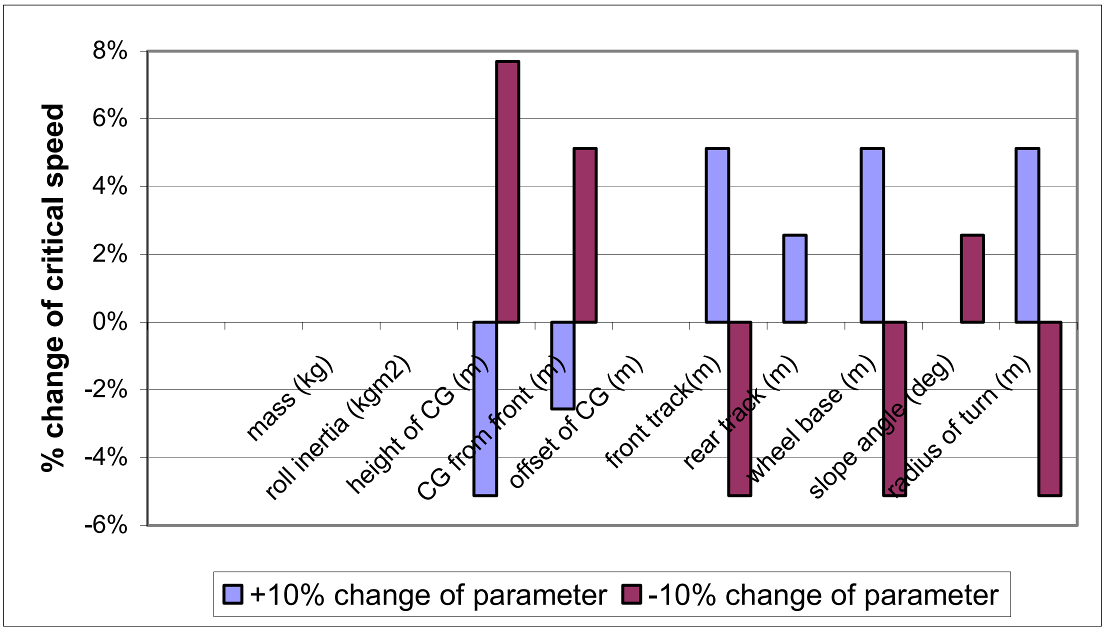

Figure C1 - Parametric Comparison of a Basic Three Wheeled Truck

Observation: stability is more sensitive to CG height

Three wheeled truck with bump stops

Parameter	Nominal Value	% Change	Critical Speed (m/sec) (Norm: 5.0m/sec)	% Change of Critical Speed
mass of vehicle (kg)	2870	10	5.00	0.00%
		-10	5.00	0.00%
roll inertia (about CG) of vehicle (kgm^2)	225	10	5.00	0.00%
		-10	5.00	0.00%
height of CG from ground (m)	0.47	10	4.50	-10.00%
		-10	5.60	12.00%
CG from front of vehicle (m)	0.625	10	4.90	-2.00%
		-10	5.10	2.00%
lateral offset of CG from centre line (m)	0.007	10	5.00	0.00%
		-10	5.00	0.00%
front track width (m)	0.906	10	5.20	4.00%
		-10	4.70	-6.00%
rear track width (m)	0.175	10	5.00	0.00%
		-10	5.00	0.00%
wheel base (m)	1.229	10	5.00	0.00%
		-10	4.90	-2.00%
bump stop width (m)	0.906	10	5.000	0.00%
		-10	5.000	0.00%
bump stop height (m)	0.1	10	5.000	0.00%
		-10	5.000	0.00%
angle of slope (0 to 30 degrees)	5	10	4.90	-2.00%
		-10	5.00	0.00%
radius of turn of vehicle (min. 1m)	3.5	10	5.20	4.00%
		-10	4.70	-6.00%

Table C7 - Critical Speed Parametric Study of a Three Wheeled Truck with Bump Stops

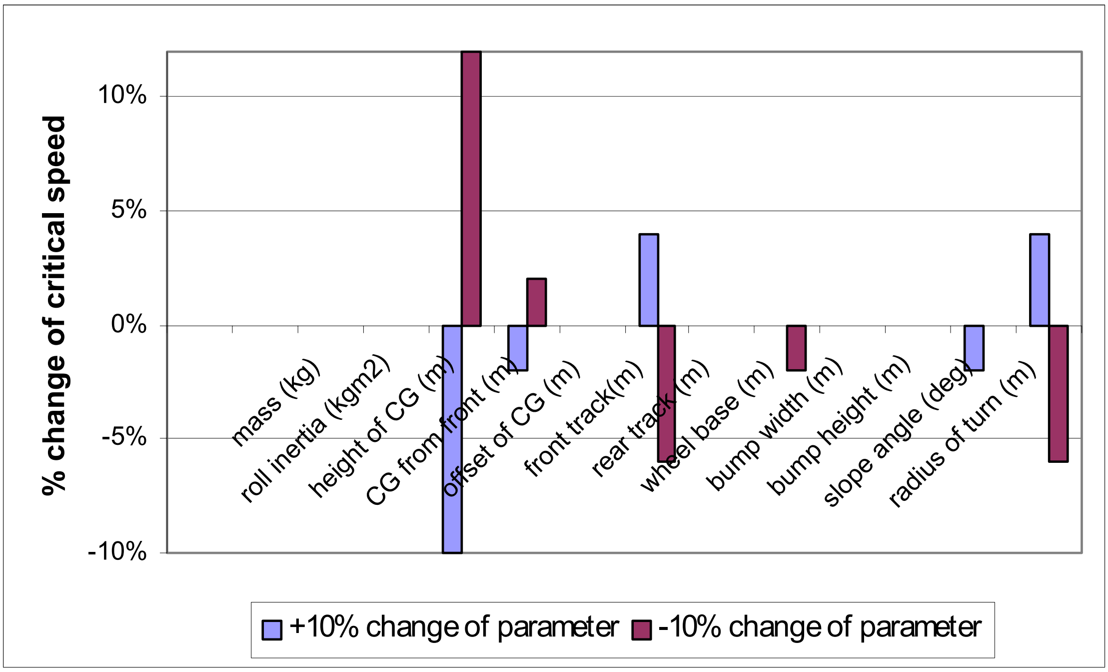

Figure C2 -Parametric Comparison of a Three Wheeled Truck with Bump Stops

Observation: more stable than a basic 3 wheeled truck, however, stability is more sensitive to CG height

Basic four wheeled truck

Parameter	Nominal Value	% Change	Critical Speed (m/sec) (Norm: 5.5m/sec)	% Change of Critical Speed
mass of vehicle (kg)	2870	10	5.50	0.00%
		-10	5.50	0.00%
roll inertia (about CG) of vehicle (kgm^2)	225	10	5.50	0.00%
		-10	5.50	0.00%
height of CG from ground (m)	0.47	10	5.20	-5.45%
		-10	5.80	5.45%
CG from front of vehicle (m)	0.625	10	5.50	0.00%
		-10	5.50	0.00%
lateral offset of CG from centre line (m)	0.007	10	5.50	0.00%
		-10	5.50	0.00%
front track width (m)	0.906	10	5.60	1.82%
		-10	5.30	-3.64%
rear track width (m)	0.906	10	5.60	1.82%
		-10	5.30	-3.64%
wheel base (m)	1.229	10	5.50	0.00%
		-10	5.50	0.00%
angle of slope (0 to 30 degrees)	5	10	5.60	1.82%
		-10	5.50	0.00%
radius of turn of vehicle (min. 1m)	3.5	10	5.70	3.64%
		-10	5.20	-5.45%

Table C8 - Critical Speed Parametric Study of a Basic Four Wheeled Truck

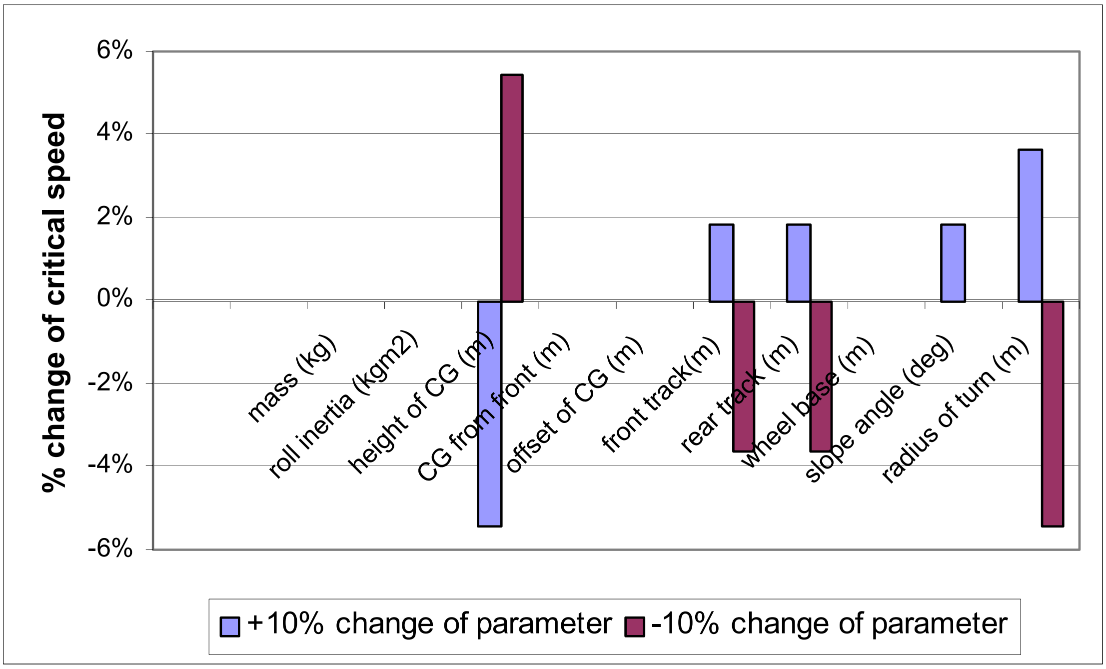

Figure C3 - Parametric Comparison of a Basic Four Wheeled Truck

Observation: stability is more sensitive to CG height.

Four wheeled truck with rear pivoting axle

Parameter	Nominal Value	% Change	Critical Speed (m/sec) (Norm: 5.0m/sec)	% Change of Critical Speed
mass of vehicle (kg)	2870	10	5.00	0.00%
		-10	5.00	0.00%
roll inertia (about CG) of vehicle (kgm^2)	225	10	5.00	0.00%
		-10	5.00	0.00%
height of CG from ground (m)	0.47	10	4.50	-10.00%
		-10	5.60	12.00%
CG from front of vehicle (m)	0.625	10	4.90	-2.00%
		-10	5.10	2.00%
lateral offset of CG from centre line (m)	0.007	10	5.00	0.00%
		-10	5.00	0.00%
front track width (m)	0.906	10	5.20	4.00%
		-10	4.70	-6.00%
rear track width (m)	0.175	10	5.00	0.00%
		-10	5.00	0.00%
wheel base (m)	1.229	10	5.00	0.00%
		-10	4.90	-2.00%
height of rear axle pivot (m)	0.4	10	5.200	4.00%
		-10	4.700	-6.00%
rear axle pivot range (0 to 180 degrees)	20	10	5.000	0.00%
		-10	5.000	0.00%
angle of slope (0 to 30 degrees)	5	10	4.90	-2.00%
		-10	5.00	0.00%
radius of turn of vehicle (min. 1m)	3.5	10	5.20	4.00%
		-10	4.70	-6.00%

Table C9 - Critical Speed Parametric Study of a Four Wheeled Truck with Rear Pivoting Axle

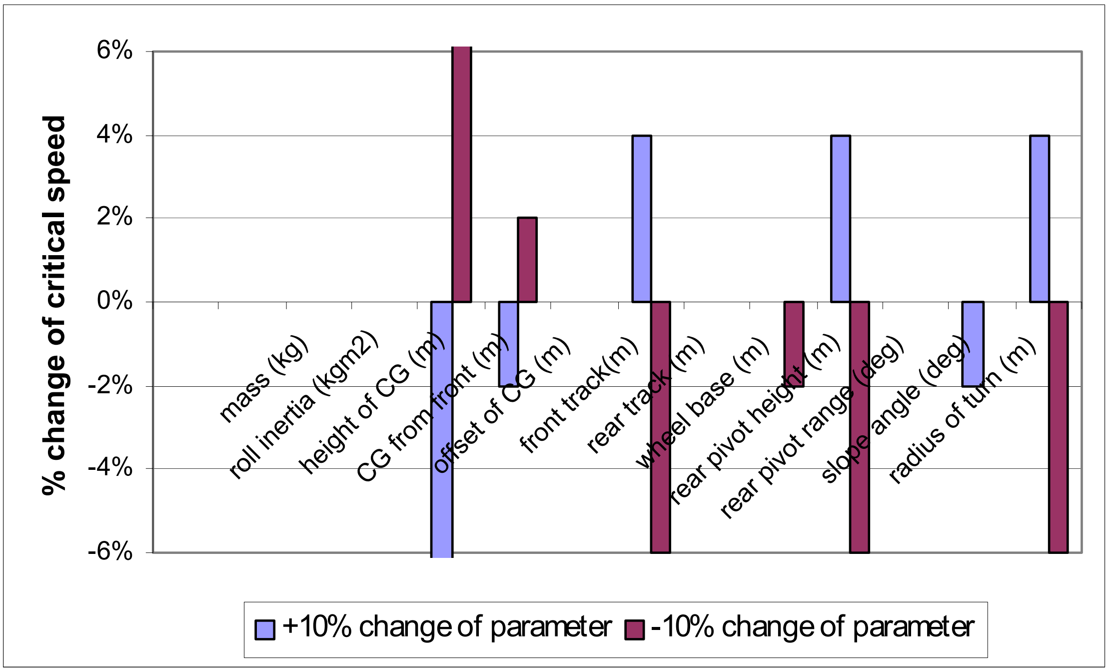

Figure C4 - Parametric Comparison of a Four Wheeled Truck with Rear Pivoting Axle

Observation: stability is more sensitive to CG height.

Four wheeled dumper truck with pivot steer

Parameter	Nominal Value	% Change	Critical Speed (m/sec) (Norm: 5.0m/sec)	% Change of Critical Speed
mass of vehicle (kg)	2870	10	5.000	0.00%
		-10	5.000	0.00%
roll inertia (about CG) of vehicle (kgm^2)	225	10	5.000	0.00%
		-10	5.000	0.00%
height of CG from ground (m)	0.47	10	4.700	-6.00%
		-10	5.300	6.00%
CG from front of vehicle (m)	0.4	10	4.900	-2.00%
		-10	5.000	0.00%
lateral offset of CG from centre line (m)	0.007	10	5.000	0.00%
		-10	5.000	0.00%
tracks width (m)	0.906	10	5.300	6.00%
		-10	4.600	-8.00%
wheel base (m)	1.229	10	4.800	-4.00%
		-10	5.100	2.00%
length of front section (max. 2/3 wheel base)	0.615	10	5.000	0.00%
		-10	4.900	-2.00%
angle of slope (0 to 30 degrees)	5	10	4.900	-2.00%
		-10	5.000	0.00%
radius of turn of vehicle (min. 1m)	3.5	10	5.300	6.00%
		-10	4.600	-8.00%

Table C10 - Critical Speed Parametric Study of a Four Wheeled Dumper Truck with Pivot Steer

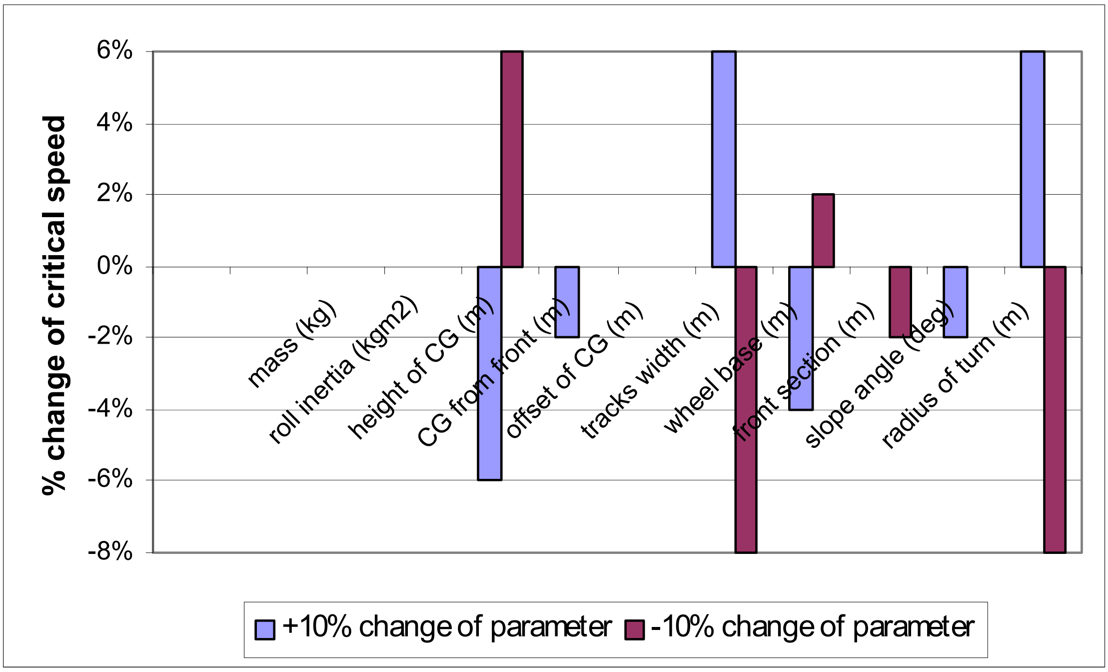

Figure C5 - Parametric Comparison of a Four Wheeled Dumper Truck with Pivot Steer

Observation: stability is more sensitive to CG height as well as tracks width and radius of turn.