FINAL REPORT SRC PROJ. USQ1S.

HITCH DESIGN AND DYNAMIC STABILITY OF INFIELD HAULOUTS

DECEMBER 1990

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1 INTRODUCTION

This report is submitted to the Sugar Research and Development Council as a summary of the findings generated under the project USQ1S, "Hitch Design and Dynamic Stability of Haulouts".

An interim report (July 1990) detailed the early stage of this project.

The rationale behind this project was given in the Detailed Research Proposal which is included as appendix 2.

Within this report is detailed the findings of an industry survey, a summary of the literature review and the results from the stability analysis. Included under these headings are the reasons why the particular method of analysis was used and the bearing the industry survey had on this approach.

Finally the findings are presented in a manner suitable for presenting as recommendations to the intended end users of the report.

2 INDUSTRY SURVEY

To quantify the stability problems faced by the operators of larger capacity haulouts a trip covering most of the sugar growing areas was undertaken. This trip was for a two week period during September of 1990 covering the Sugar growing areas from Mossman to Childers. During this time operators, owners and manufacturers were consulted regarding their stability problems and the project Engineer was able to watch different units operating to get some firsthand idea of the problems involved. The feedback obtained from this trip was combined with that gained during the industry liaison involved in a previous project DDI1S "Development of a Large Capacity Haulout Bin" to give some framework to the analysis of the stability problem.

A significant number of the larger haulout unit operators surveyed reported one or more aspect of instability with their units. For some, they perceived their problems as minor, however others saw their stability problems as a major limiting factor in their operation. The actual instability took many different forms and was said to be contributed to by many different factors, some real, others imagined.

By far the most common form of instability encountered was a low-speed turn-over, brought about by a combination of slope and critical tractor-trailer parameters. One of the contractors in North Queensland spoken to had rolled a particular type of haulout bin six times. Most operators have experienced at least one situation where the haulout has rolled over - sometimes the tractor rolls with the bin but more frequently just the bin rolls. It seems unusual that there has not been more serious injuries as a result of these accidents - the incidents are just dismissed as an accepted part of the haulout process. Although the problem is industry wide there appears to be some variety of bins that are particularly unstable. These bins are limited to operating on terrain that does not have steep gradients. Where they are taken into areas with such undulating country the infield efficiency is reduced by the slower speeds necessary to prohibit roll-over. Drains and headlands have been highlighted as places where roll-overs are most likely to occur. Operator error is often blamed for this type of accident. This error, however could sometimes be more correctly defined as an uncertainty on the part of the operator as to the safe operating limits of the unit which undoubtedly vary from unit to unit. A number of the contractors spoken to had areas within their contract where they were not comfortable using their large capacity haulouts and would prefer to use a smaller unit (generally a roll-on/roll-off unit).

As a response to the roll-over problem some manufacturers have put the roll pivot of hitch relatively high. Various bin parameters are blamed for these roll-overs, including a trailer centre of gravity that is both too high and too far forward, excessive tyre 'wallow' and side-wall flex and hitch design. It was noted by many people that tandem axle units are more stable than single axle units - although there is still a large amount of industry resistance to tandem axles because of lack of mobility, tyre scrubbing and the associated stool damage. In terms of hitch design there is conjecture about the effect of the different geometrical parameters of the hitch on the unit stability. More than one manufacturer related that there is a certain angle which one can turn the unit through when the front of the unit 'dives' downward. One farmer encountered who had built his own bin said the hardest part of the bin was the hitch design - the hitch was assembled and disassembled numerous times until it proved to be a stable unit. Whereas soft tyres are desirable to counter stool damage and soil compaction it seems they are a large contributor to unit instability. Some people have changed to higher ply tyres in an attempt to lessen the sway that soft sidewalls seem to induce.

The other type of instability that occurs with the units is the dynamic instability or, put in a more simple manner, the lack of control over a moving unit. This is generally put down to hitch design (particularly the distance from the pitch axis to the yaw axis) and also tyre properties i.e. similar to those mentioned above. One group of haulout drivers in the industry told of two bins with identical hitches but different levels of stability - therefore one must be careful not to limit the scope of any analysis by not adequately considering all associated parameters.

Another facet of the dynamic tractor control problem is the distance that the hitch is mounted in front of the rear axle. There are different opinions on (and indeed different effects of) the effect of mounting the hitch at varying distances in front of the axle. This was highlighted as a critical and sensitive parameter on a number of occasions. According to some a hitch point in excess of 40 mm in front of the rear axle will cause loss of directional control of the tractor.

3 LITERATURE SEARCH RESULTS

During the course of the project numerous papers where looked at and reviewed as to their applicability to the problem. Below is an attempt to provide a brief synopsis of the relevant papers and present any useful conclusions / recommendations.

Definition of some of the terms used in the paper

C.G.	Centre of Gravity
Yaw:	The rotation of a vehicle around its vertical axis.
Pitch:	The rotation of a vehicle around its lateral axis, the lateral axis is that axis across the vehicle, e.g. along an axle of the vehicle.
Roll:	The rotation of the vehicle along its longitudinal axis, i.e the axis in its direction of motion.
Lateral Instability:	Describes the uncontrolled movement of the vehicle in the lateral direction. This may take the form of sideways divergence from its path or a swaying motion in the plane of the travelling surface - it involves rotation about the yaw-axis.

Papers Reviewed

[1] *Zeng, Dechao; Zhu, Yongchua; Zhoi, Yiming, "Mathematical model for sideways overturning performance of tractor and trailer combinations." Journal of Terramechanics v 26 n 3-4 1989 p 193 - 200, 1989*

This paper and two other similar papers by the same authors in less well known publications were probably the most rigourous mathematical treatment of the tractor-trailer dynamic roll-over problem. Their most complicated analysis contained 25 degrees of freedom - which is quite imposing. Stability for the unit was defined in terms of critical roll angles with an "energy symmetry method" employed to ascertain the forces, motions and acceleration during the roll-over process. This was done using a fortran computer program. Although the papers mentioned an analysis of the effect of varying operational and constructional parameters none of these results where published in any of the papers which was somewhat disappointing. Due to the intense mathematical nature of the papers this avenue was not pursued any further.

[2] *J.C. Huston, D.B. Johnson, "Basic Analytical Results for Lateral Stability of Car/Trailer systems." SAE Trans., Vol. 91, pp. 13-22, 1982.*

In this paper Johnstone and Huston examine two classical solutions for car/trailer stability and find them to be deficient in adequately describing the dynamics of the solution. They consequently develop a method of determining the lateral stability which involves solving the equations of motion in three-degrees of freedom (lateral velocity of the combination, yaw rate of the tractor and rate of change of the angle between the tractor and trailer). The equations are reduced to a form where they can be solved, giving solutions in the form $V= A.e^{\lambda t}$,(V - a degree of freedom, A - system constant, t -time and the λ values are called the system eigenvalues). The values of λ determine the system stability.

[3] *D.B. Johnson, J.C. Huston and T.A Gray, "The Influence of Drawbar Flexibility and Roll Steer on the Stability of Articulated Vehicles." SAE Trans., Vol. 88, pp. 690-698, 1979.*
J.C. Huston, D.B. Johnson, " Relative Significance of Parameters Affecting Lateral Stability of Articulated Recreational Vehicles." SAE Trans., Vol. 88, pp. 699-707, 1980.

These two papers examine the influence of drawbar stiffness and roll freedom of the power unit and trailer on the results of a lateral stability analysis. They conclude that both these variables can effect the stability of the unit particularly the roll freedom of the two units. However these papers are not of particularly great relevance to the lateral stability analysis we eventually ended up using. The nature of the hitch connecting tractors and haulout bins is such that there is no drawbar stiffness involved i.e the trailer can roll independently of the tractor. The effect that roll steer has on the critical velocity (defined as that velocity which causes the real part of the system eigenvalue in the analysis goes positive) is interesting but there is no way of determining the necessary roll steer coefficients if we wanted to use this approach. We are on the whole more interested in the effect of different variables on the stability trend rather than an exact critical velocity. Also because the front axle of our tractor is considered centrally pivoted this concept does not apply to the front axle. The effect of low pressure tyres (such as those found on the rear of a tractor) in a roll steer situated is unquantified. While not being particularly useful set of papers one comment made is worth noting "If all possible parameters and degrees of freedom where included in a mathematical model of an articulated recreational vehicle, analysis becomes particularly difficult, and the hope of reaching any general conclusions becomes very remote. The determination of reasonable values of parameters is in itself a formidable task. On the other hand if significant parameters or degrees of freedom are omitted from the model, serious errors can result and invalid conclusions can be drawn.

[4] *D.B. Johnson and J.C. Huston, "Comparison of the behaviour of Articulated Recreational Vehicles with Either Fixed or Position Control of Steering." SAE Trans., Vol. 89, pp. 989-998, 1980.*

This paper examines the effect of adding position control of steering, rather than the usually assumed fixed steering angle, to a lateral stability analysis. A critical speed based on an eigenvalue analysis technique is used as the stability metric. The paper concluded that the influence of adding position control steering to the system (which possibly is closer to reality than the fixed steering assumption) is dependent upon the characteristics of the articulated vehicle.

[5] *R.T. Klein and H. T. Szostak, "Determination of Trailer Stability Through Simple Analytical Methods and Test Procedures." SAE Trans., Vol. 88, pp. 978-988, 1980.*
R. T. Klein and H. T. Szostak, "Development of Maximum allowable Hitch Load Boundaries for Trailer Towing." SAE Trans., Vol. 89, pp. 999-1005, 1980.

These papers define static stability in terms of an understeer gradient, K, which can be defined as a factor which effects the steering angle necessary to maintain a fixed radius turn at a nominated speed. When K is negative the vehicle is experiencing oversteer, i.e the given steering angle input produces a sharper turn than that which would occur in a static situation. This produces unsafe car/trailer directional control.

In the first of these papers the effect of different amounts of trailer load transferred to the rear axle of the car is looked at. However these hitches are a standard car type towing arrangement and so do not accurately relate to the hitches used in conjunction with haulout units. If this type of hitch is employed the weight transferred from the front to the rear axle of the tractor must be watched carefully to insure against oversteer and the associated instability.

The second of these papers looks at dynamic stability in terms of damping of the unit i.e how quickly does the unit stop oscillating after being subjected to some external input. Factors that improve damping (and hence stability) are noted to be increased hitch to axle distance, increased tyre stiffness, lower speeds, decreased trailer moment inertia and decreased trailer to car weight ratios. Interestingly it is necessary to have a minimum percentage of the weight transferred from the trailer to the car to ensure a large enough damping ratio. bearing in mind of course the need to hedge against oversteer.

[6] *A Deltenre and M. F Destain, "Dynamic behaviour of an agricultural tractor and its trailer." Agricultural engineering. Proceedings of the 11th international congress on agricultural engineering [CIGR], Dublin, Ireland, 4-8 September 1989 .pp 2841-2849. 1989*

This paper is primarily concerned with the tractor/trailer combinations ride vibration and the subsequent effect on the drivers well-being, hence there is really no relevance of this paper to the work at hand.

[7] *G. M. Owen, "Trailed Equipment on Slopes: Problems and Solutions.", The Agricultural Engineer, .pp. 124-127, Winter 1987.*

This paper is concerned with simple modification to tractor hitch to allow roll freedom for the trailer. This lessens the likelihood of tractor and operator damage in the event of a trailer roll-over. The hitch described, however is very primitive compared with those in use in haulout step and would only involve a retrograde step.

[8] *H. B. Spencer, "Stability and control of two wheel drive tractors and Machinery on sloping ground.", J agric Engng Res. Vol. 23, pp. 169-188, 1978.*
A. G. H. Hunter, " Vehicle design for stability on slopes.", The Agricultural Engineer, pp. 115-120, Winter 1989.

These papers describes stability of tractor combinations (with trailers etc) in terms of Polar diagrams which show control loss and stability boundaries for varying slope and heading angles. Instability is defined as when one of the wheel reactions normal to the ground becomes zero (situation with potential for a roll-over). Control loss is defined as when wheel-ground interaction forces are inadequate to counter longitudinal/lateral forces and the wheels slip. Their theoretical analysis was substantiated by full scale and scale-model tests. An interesting point was there observance that stability loss was often preceded (i.e more likely to happen) by loss of control of the vehicle.

[9] *D. A. Crolla and F. Hales, "Lateral stability of tractor and trailer combinations.", Journal of Terramechanics, vol16, pp. 1-22, Mar 1979.*
D. A. Crolla, "The ride and handling of tractor and trailer combinations." The Agricultural Engineer, pp. 111-115, Winter 1979.

Crolla and Hales performed an analysis of stability using a method similar to that of Huston and Johnstone. They expressed the lateral motions of the combination in terms of four degrees of freedom (tractor longitudinal,tractor lateral, tractor yaw and trailer yaw). These equations where solved with standard computer routines to give the system 'eigenvalues' and 'eigenvectors'. Lateral instability is then predicted when the real part of the eigenvector becomes positive

These papers draw one interesting conclusion:- "Although the more detailed studies showed some advantage could be gained by minor hitch modifications, the scope for significant improvement appears to lie in changing the configuration of the system to resemble an off-road version of an articulated lorry."

The other relevant conclusions they came to can be summarized as:
1. Increasing the weight transferred from the trailer to the tractor increases system stability.
2. Increasing the hitch distance behind the rear tractor axle decreases system stability.

[10] *McMullan et al, "The behaviour of tractor drive tyres at low inflation pressures when reacting high side forces."J agric Engng Res. Vol. 39 pp. 221-229, 1988.*

This paper looked (in passing) at the effect of lateral tyre defelection on stability. It is referred to in the static analysis section of this report.

The last and most pertinent paper to be reviewed is recorded at the beginning of the dynamic analysis section, as it forms the basis for the analysis.

From the industry survey and literature search it becomes apparent that there are two dimensions to the stability analysis. The most critical form of instability is the lower speed roll-over problem. This is addressed with a static stability analysis using a computer program written for the express purpose of studying the effect of parameter changes on the unit stability.

The other form of instability is the lateral dynamic stability problem. This is addressed with an analysis performed drawing on a program written for one of the papers reviewed.

4 Static Stability Analysis

DEFINITION OF TERMS USED IN STATIC STABILITY ANALYSIS

PARAMETER	Term	Value
MASS OF TRACTOR	MT	5700 kg
MASS OF TRAILER	MS	12500 kg
DISTANCE FROM CENTRELINE OF TRACTOR TO WHEEL CENTRE	j	0.85 m
HEIGHT TO TRACTOR C.G	n	1.0 m
HEIGHT TO BOTTOM HITCH ATTACHMENT	c	0.5 m
HEIGHT TO TOP HITCH ATTACHMENT	b	0.8 m
DISTANCE FROM CENTRELINE OF TRACTOR TO VERT. HITCH ATTACHMENT	k	0.35 m
DISTANCE FROM FRONT TRACTOR AXLE TO C.G	i	1.8 m
DISTANCE FROM REAR TRACTOR AXLE TO C.G	h	0.8 m
DISTANCE OF HITCH IN FRONT OF REAR AXLE	m	0.025 m
HEIGHT TO TRAILER C.G.	a	1.5 m
DISTANCE FROM TRAILER CENTRELINE TO WHEEL CENTRE	d	0.85 m
DISTANCE FROM HITCH TO TRAILER AXLE	f	6.0 m
DISTANCE FROM HITCH TO TRAILER CG	e	4.0 m
DISTANCE FROM YAW PIVOT TO TRACTOR AXLE	l	0.8 m
ANGLE BETWEEN TRACTOR AND TRAILER	phi	60°
CROSS SLOPE	pheta	20°
DOWN SLOPE	beta	20°

NOTE: These statistics where compiled to represent an 'average' two-wheel drive tractor (approx. 100 KW) and a twelve and a half tonne gross weight haulout on a single axle. The tractor data was drawn from John Deere, Ford, Massey Ferguson and Belarus.

The critical slopes where determined by running the program with a nominal set of parameters varying the three angles to determine a combination of angles that would always be close to unstable.

Assumptions made :

*The surface had a Cone Index (CI) of 2000 Kpa. This was used in the Gee-Clough relationships which related the tractor rolling resistance to vertical force. CI=2000 Kpa approximates a hard surface (e.g road, headland, heavily compacted soil).

*The front axle of the tractor was pivoted.

*The effect of the tractor differential ensured that the driving force at each of the wheels was the same, similarly it was assumed the retarding force applied by the rear tyres was the same for both tyres.

*The analysis assumed a forward motion with no accelerations.

*Rolling resistance of the tractor rear wheels was neglible compared to their driving force.

*The tractor and trailer where considered as unsprung rigid masses - which if anything will tend to make the units appear more stable than they are. This is not a problem though as we are more interested in the effect of parameter changes rather on the stability trend, rather than a definitive set of parameters for stability.

*There was no roll stiffness between tractor and trailer.

Weights (i.e. Tractor and Trailer weights converted into the local axis system, both the tractor and trailer have body-centered co-ordinate systems)

$$WSX=WS*(SIN(\theta)*COS(\beta))$$

$$WSY=WS*(SIN(\beta))$$

$$WSZ=WS*(COS(\beta)*COS(\theta))$$

$$WTX=WT*(-SIN(\phi)*SIN(\beta)+COS(\phi)*SIN(\theta)*COS(\beta))$$

$$WTY=WT*(SIN(\phi)*SIN(\theta)*COS(\beta)+COS(\phi)*SIN(\beta))$$

$$WTZ=WT*(COS(\theta)*COS(\beta))$$

Trailer Equations

Σ Lateral Forces = 0

$$TLA_{5+6} -WSX -2.HLA = 0 \qquad (1)$$

Σ Longitudinal Forces = 0

$$TLO_{5+6}-WSY -2.HLO = 0 \qquad (2)$$

$$TLO_{5+6} = TV_{5+6}.0.067 \text{ (From Gee-Clough Relationships)} \qquad (3)$$

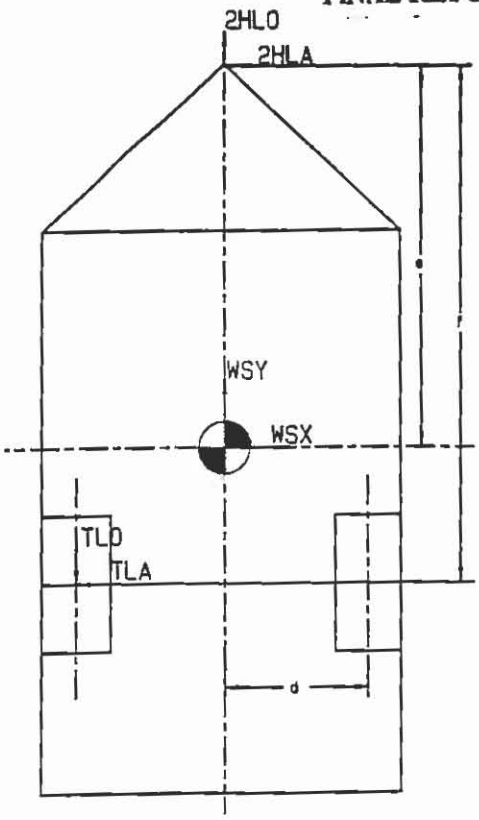


Figure 1 Trailer plan view

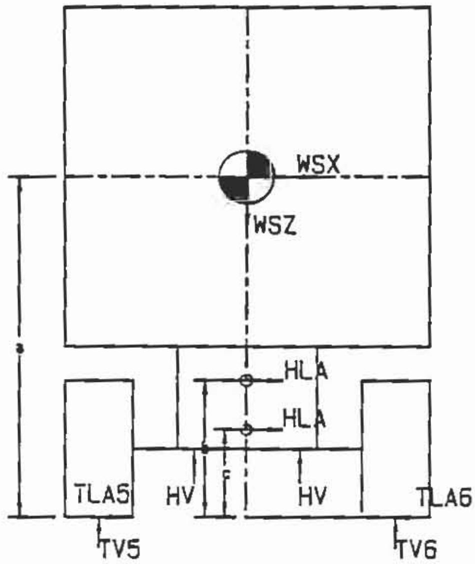
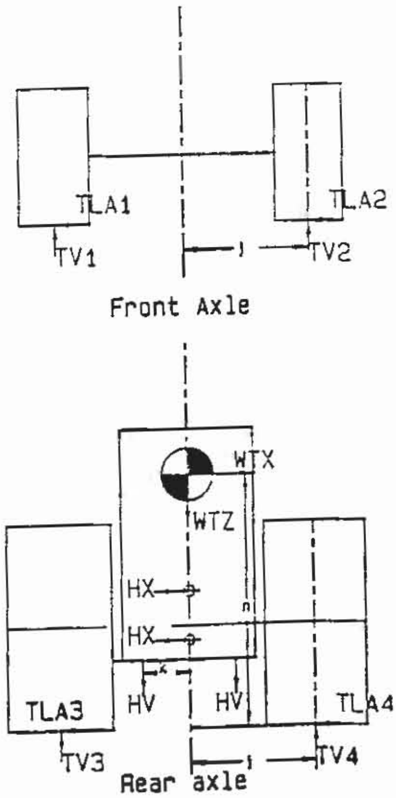


Figure 2 trailer end view



N.B HX is a combination of HLO & HLA
Vertical forces act a dist. m in front of rear axle

Figure 3 Tractor end views

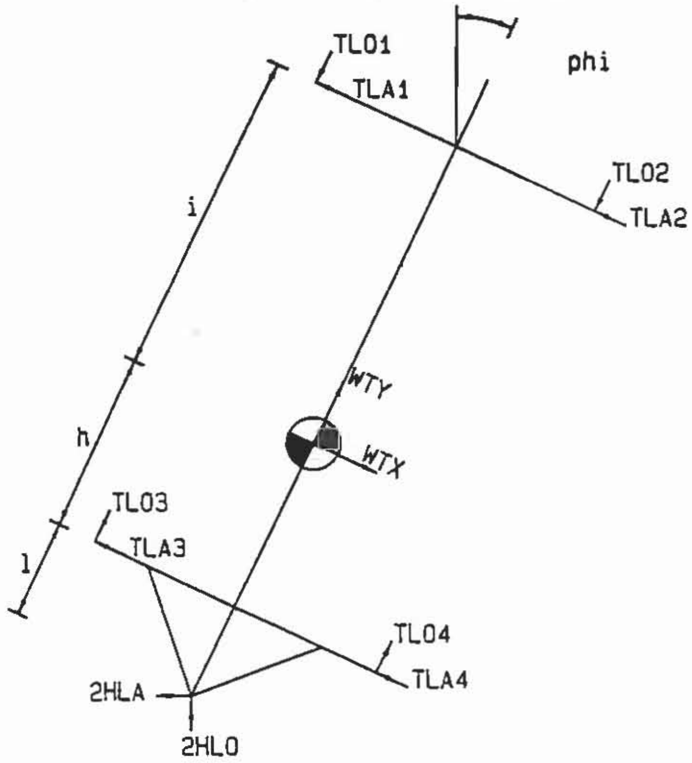


Figure 4 Plan View of tractor

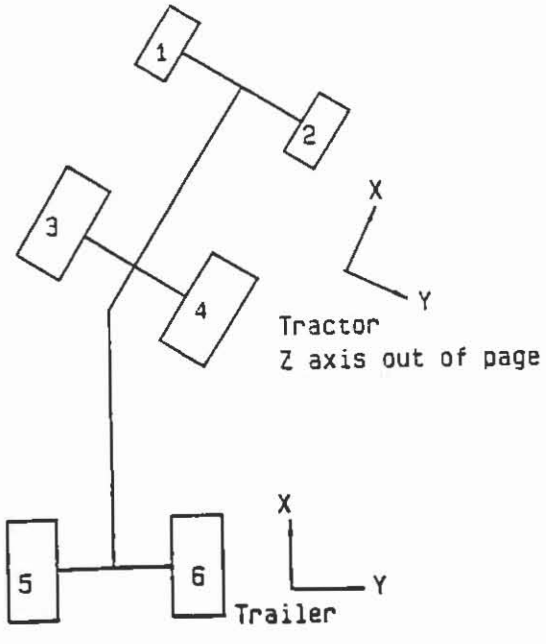


Figure 5 Co-ordinate system and numbering

Σ Vertical forces = 0

$$TV_{5+6} + 2.HV - WSZ = 0 \tag{4}$$

Σ Moments around rear axle (pitch axis) = 0

$$WSZ.(f-e) - 2.HV.(f+m+l) = 0 \tag{5}$$

Σ Moments around hitch (pitch axis) = 0

$$WSZ.(e+l+m) - TV_{5+6}.(f+l+m) = 0 \tag{6}$$

Σ Moments around wheel 6 (roll axis) = 0

$$WSX.a + HLA.(b+c) + HV.2.d + TV_5.2.d - WSZ.d = 0 \tag{7}$$

Σ Moments around wheel 6 (yaw axis) = 0

$$WSY.d + HLO.2.d + HLA.2.f + WSX.d - TLO_5.2.d = 0 \tag{8}$$

Combining equations (7), (8) and (3) we get equation (17) viz.

$$HLA = \frac{0.065.WSZ.d - WSX.(0.065.a + d) - HV.2.d.0.065 - WSY.d - HLO.2.d}{(2f + 0.065.(b+c))}$$

Tractor Equations

Σ Longitudinal Forces = 0

$$TLO_{1+2} + HLO.2.\,Cos\phi + HLA.2.Sin\phi - TLO_{3+4} - WTY = 0 \tag{9}$$

$TLO_{1+2} = 0.065.TV_{1+2}$ (From Gee-Clough relationships) (10)

Σ Lateral Forces = 0

$$TLA1+2+3+4 + 2.(HLA.Cos\phi - HLO.Sin\phi) - WTX = 0 \tag{11}$$

Σ Moments around wheel 4 (roll axis) = 0

$$TV_{1+3}.2j - (HLA.Cos\phi - HLO.Sin\phi).(b+c) + WTX.n - WTZ.j - HV.2.j = 0 \tag{12}$$

Σ Moments around rear axle (pitch axis) = 0

$$(HLO.Cos\phi + HLA.Sin\phi).(b+c) - HV.2.m + TV_{1+2}.(i+h) - WTZ.h - WTY.n = 0 \quad (13)$$

Σ Moments around rear axle (pitch axis) = 0

$$(HLO.Cos\phi + HLA.Sin\phi).(b+c) + HV.2.(i+h-m) - TV_{3+4}.(i+h) + WTZ.i - WTY.n = 0 \quad (14)$$

Σ Moments around centre of rear axle (yaw axis) = 0

$$2.TLA_1.(i+h) - 2.(HLA.Cos\phi - HLO.Sin\phi).l - WTX.h = 0 \quad (15)$$

Σ Moments around front pivot (yaw axis) = 0

$$TLA_{3+4}.(i+h) - WTX.i + 2.(HLA.Cos\phi - HLO.Sin\phi).(h+i+l) = 0 \quad (16)$$

These equations are used in the gwbasic program "tractsim" which is included in appendix 3.

This analysis was kept purely static for simplicity purposes. Even so, as with the rigid body assumption, it is likely that introducing dynamic terms would have merely emphasised the effects, and not changed the overall trend.

With this analysis it is possible that control loss may have occurred in some cases (i.e wheel reactions overcoming frictional forces) before stability loss. However this is not of great concern because of decision to study trends rather than absolutes.

The hitch was considered to connect to the tractor beneath the rear axle or thereabouts and this was where the vertical weight from the trailer was assumed to be transferred. Because the hitch was pivoted about the yaw axis at a distance l behind the rear wheels the lateral and longitudinal forces acting from the trailer onto the tractor where assumed to operate at that point. This forces where assumed to act through two points (i.e. the trailer attached to the hitch turning axis through two members) however in practice this has the same effect as just one central hitch point.

The results are presented in graphical form in figures 1 to 5. The values presented are TV4, TV5 and TLA3+4. TV4 and TV5 represent the vertical reaction at the critical tractor and trailer wheels respectively. Using the approach of Spencer [8] we define stability loss as "when the normal to ground reaction of one of the machine's wheels becomes zero" (i.e TV4 or TV5 = 0). From this we reason that a decline in the value of TV4 or TV5 towards zero is indicative of a decrease in unit stability. TLA3+4 is the net sideways force on the rear tractor tyres. Although the exact effect of this parameter is not known we will assume increasing the value of TV3+4 increases the likelihood of a roll-over. This assumption is based on the conclusions of McMullan et al [10], viz. "Substantial lateral tyre deflection, such as may occur when tyres at low inflation pressure are subjected to large side loads, may have significant effect on the roll stability of the vehicle."

Looking at figure 6 we can see that an increase in the height to C.G. of the trailer causes, as would be expected, a decrease in trailer stability.

Figure 7 shows that as the wheel track of the unit increases the trailer becomes less likely to tip over. The gains of increasing the wheel track of the trailer are greater at the lower values (i.e increasing d from 0.7 to 0.8 has a more stabilizing effect than increasing the wheel track from 1.4 to 1.5 metres)

Figure 8 shows increasing the distance from the tractor rear axle to the trailer C.G, while the distance to the trailer axle remains constant increase the trailer stability but decreases the tractor stability. This is because it involves weight being taken off the tractor rear axle and placed onto the trailer axle.

Increasing the hitch height with respect to the trailer C.G. increases trailer static stability but decreases tractor stability. This is presented in figure 9. In cases where changing a parameter effects the tractor and trailer in opposite ways, the question must be asked which is the critical unit. In most cases the trailer is the unit that will turn over, hence the increase in stability should be sought with the trailer, possible at the expense of some tractor stability.

The final static graph shows us the effect of increasing the distance from tractor axle to hitch (yaw pivot) on the lateral tractor tyre forces. Increasing this distance (l) increases the lateral forces. It is possible that these lateral forces combine with other forces to cause tractor tyre deflection and a consequent dive of the trailer hitch at certain angles of turn.

Varying the distance m i.e. the distance of the hitch (pitch pivot) in front of the tractor had liitle effect on sytem stability.

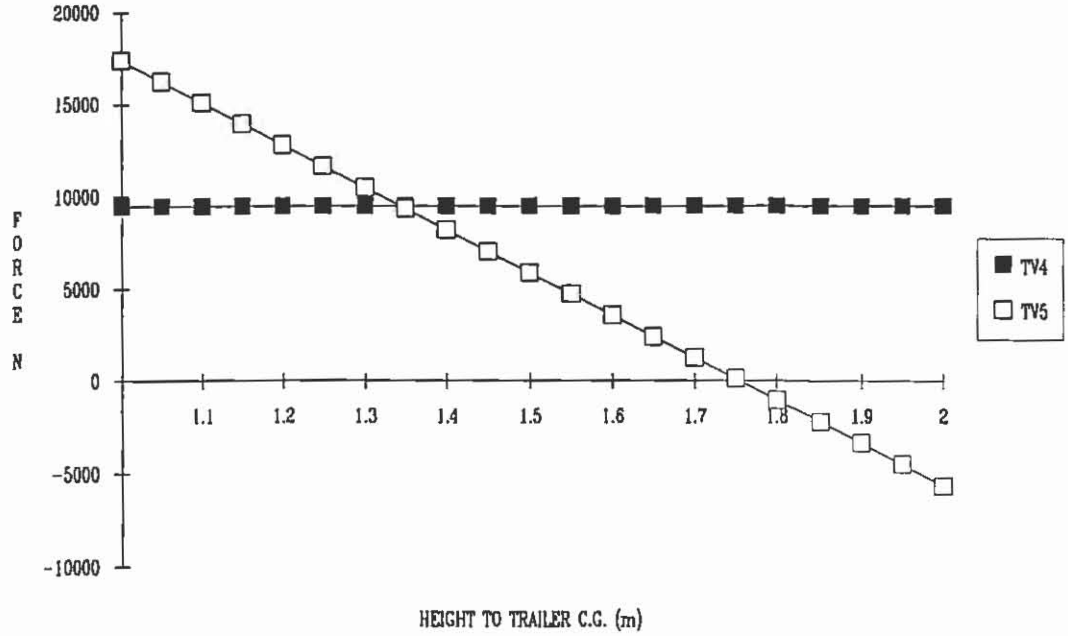


Figure 6

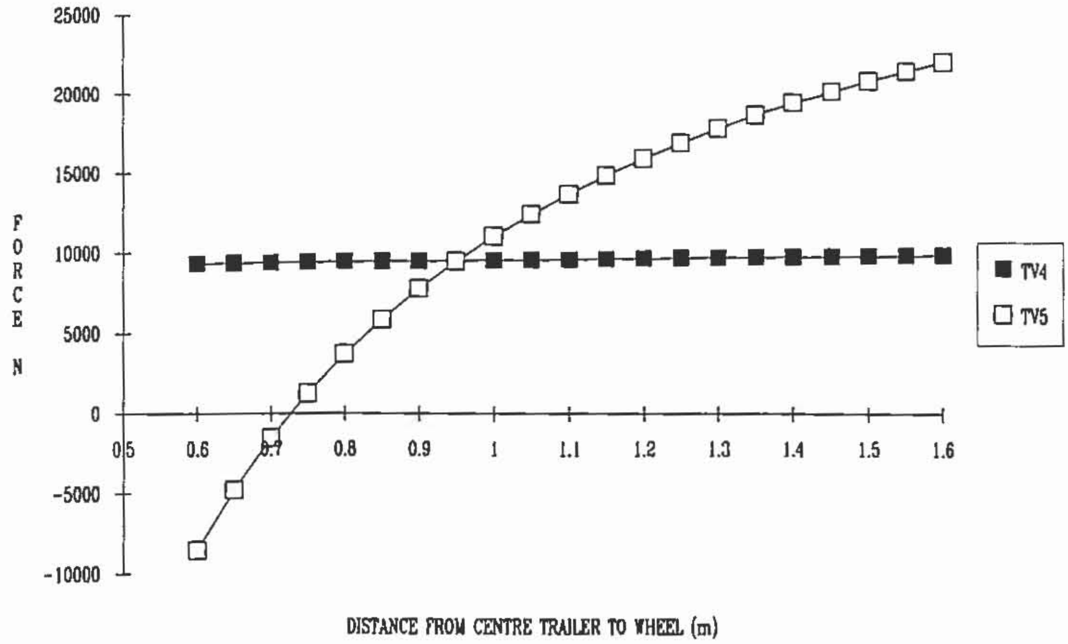


Figure 7

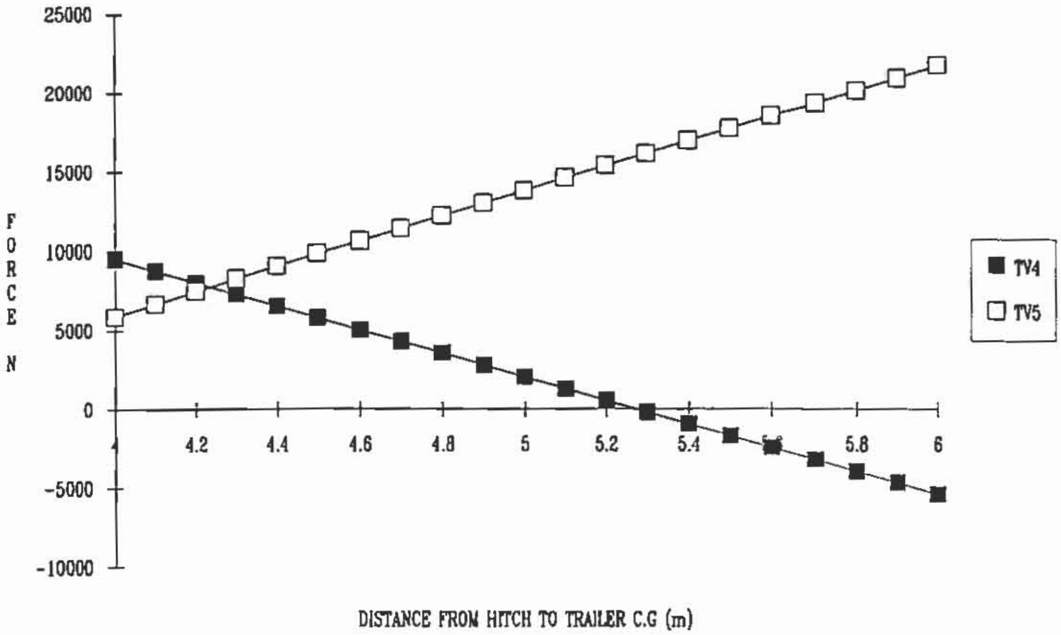


Figure 8

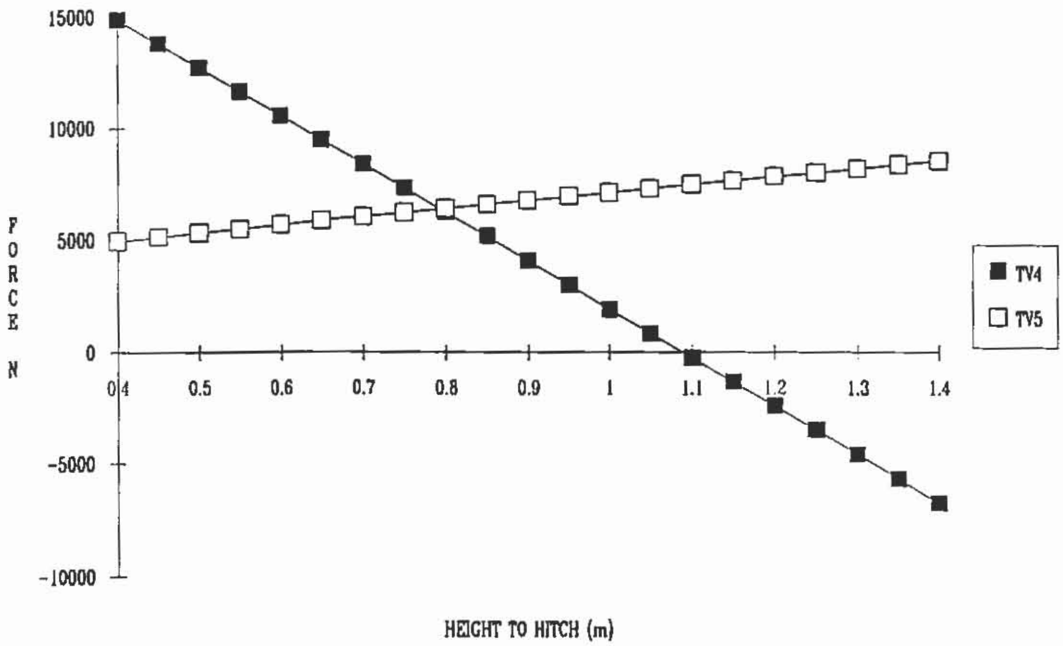
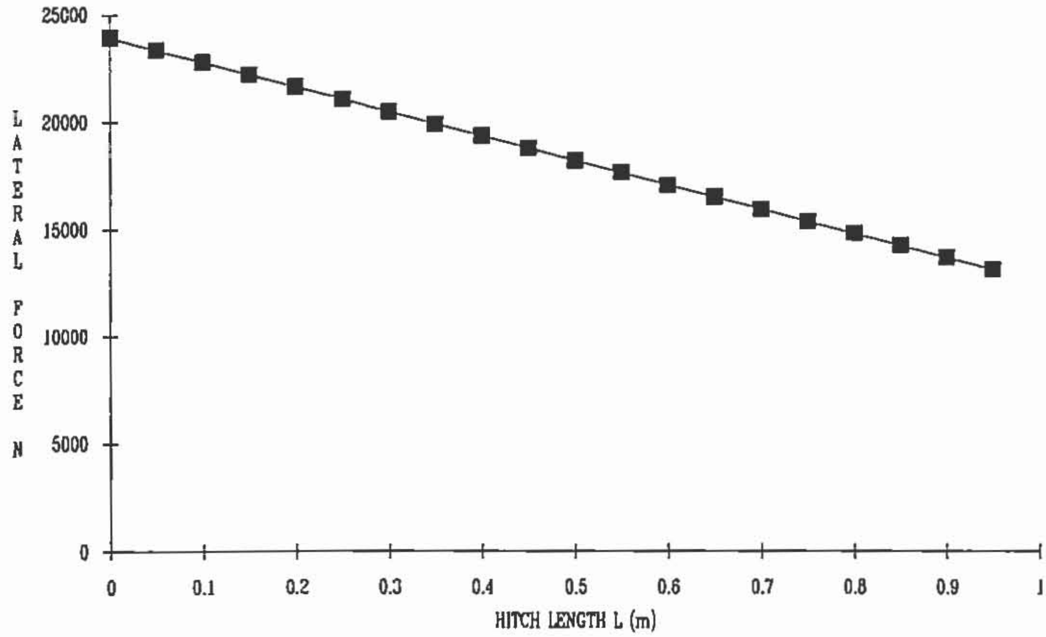


Figure 9



25000
20000
15000
10000
5000
0
LATERAL FORCE N
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
HITCH LENGTH L (m)

Figure 10

5 Dynamic Stability Analysis

The paper our dynamic stability analysis was based around is reviewed here as a precursor to the analysis.

Liansuo Xie and Paul W Claar II. "Simulation of Agricultural tractor-trailer system stability." SAE Technical Paper Series, no. 851530, 16p, 1985.

This is the most recent paper that the literature search could locate concerning tractor trailer lateral stability and it appeared to be the most comprehensive and suitable to our type of application.

The tractor/trailer combination was viewed as having three-degrees of freedom, sideslip, yaw of the tractor and swing of the trailer relative to the tractor. Tractor-trailer roll was omitted as a degree of freedom from the analysis, however the change in vertical loading of the tyres in turning was taken in to account by approximation. Both tractor and trailer were considered as unsprung rigid bodies and planar motion was assumed. Lateral tyre forces where expressed as a function of heading angle and critical tyre dimensions. Using these assumptions the equations governing the motion of the tractor trailer combination where written.

The governing equations of motion where linearized to reduce the complexity of the system (and hence necessary computing effort). The linearized equations of motion where then reduced to a set of six first order differential equations and modified into an eigenvalue problem, in the form as used by Crolla and Hales [4] and Huston and Johnstone [5].

It is easiest to quote from the Xie and Claars paper to explain the method of determining the stability of the system from the eigenvalues. "The computed eigenvalues are the natural frequencies for the vehicle system. If all the eigenvalues have negative real components the system is stable, whereas if one or more of the eigenvalues has positive real components the vehicle system is unstable. If the eigenvalues have non-zero imaginary components, the system oscillates because damping exists. The magnitude of the real part of the eigenvalue indicates the effective damping for an oscillatory root or a measure of the system response to a disturbance from its initial static conditions."

The analysis

Upon deciding that this was a suitable analysis to use to determine the effect of changing different parameters on system stability, we were able to contact Professor Claar via the international computer net. He kindly provided us with a copy of the program used with his analysis which fortunately was compatible with the U.C.S.Q Pyramid computer.

Minor modifications where made to the program to enable easier data input and analysis. A provision was also included in the program such that the vertical weight transfer point from the tractor to the trailer could be separated from the longitudinal/lateral connection points. (This to recognize that most haulouts have their hitch roll and yaw axes separated from the pitch hitch axis) For simplicity purposes one of his routines was substituted with an identical routine from the U.C.S.Q 's NAG library.

The results are presented graphically in figures 11 to 16. The eigenvalues indicated are actually the real parts of the eigenvalues. The combination chosen for the analysis was Xie and Claars "A" trailer , a 12.5 tonne single axle unit which could easily be an eight tonne capacity haulout, and the JD4020 tractor. The tractor is possibly slightly smaller than that which might pull this size haulout. Xie and Claar presented the full range of parameters for these units so it was convenient to stick with this combination.

Parameter Variation.

The parameters that where deemed to be variable in the design process were varied in the analysis to see what effect they would have on the stability of the unit. It can be noted in the figures that separate graphs are drawn for the oscillatory (non-zero imaginary components of the eigenvalues) and exponential (imaginary components equal to zero) real parts of the eigenvalues. This is done more for clarity then anything else. In terms of stability we are concerned with the magnitude of the real part of the eigenvalue (recorded on the graph as eigenvalues) regardless whether the roots are oscillatory or exponential. The more negative the value the greater the stability.

Figure 11 shows the effect of varying the distance c i.e distance between the hitch lateral pivot and tractor C.G. The unit stability increases as the lateral pivot comes closer towards the rear axle of the tractor.

It is a hard to draw concrete conclusions from figure 12 which looks at the effect of changing the d/s ratio (distance of trailer C.G. to hitch / distance of trailer axle to hitch). Xie and Claar conclude that moving the trailer C.G. forward reduces system stability, however this conflicts with the conclusions of Crolla and Hales [9].

Figure 13 shows that increasing the height to hitch (h2) increases the system stability although the stability gains are not large.

As one would expect lowering the C.G of the trailer (h3 - height to C.G) increases the stability of the unit. As with the varying of height to hitch, however the gains in stability appear to be small. This is shown in figure 14.

Figure 15 looks at varying the distance FHD (distance from lateral to pitch pivots) which we introduced into the system of equations. The variance of this parameter has little effect on the system stability as quantified by this type of analysis.

On the whole this analysis did not point to great improvements to dynamic lateral stability by the variance of tractor/trailer parameters. Perhaps this is not suprising when we look at the conclusion drawn by Crolla and Hales [9] which was mentioned previously - "Although the more detailed studies showed some advantage could be gained by minor hitch modifications, the scope for significant improvement appears to lie in changing the configuration of the system to resemble an off-road version of an articulated lorry."

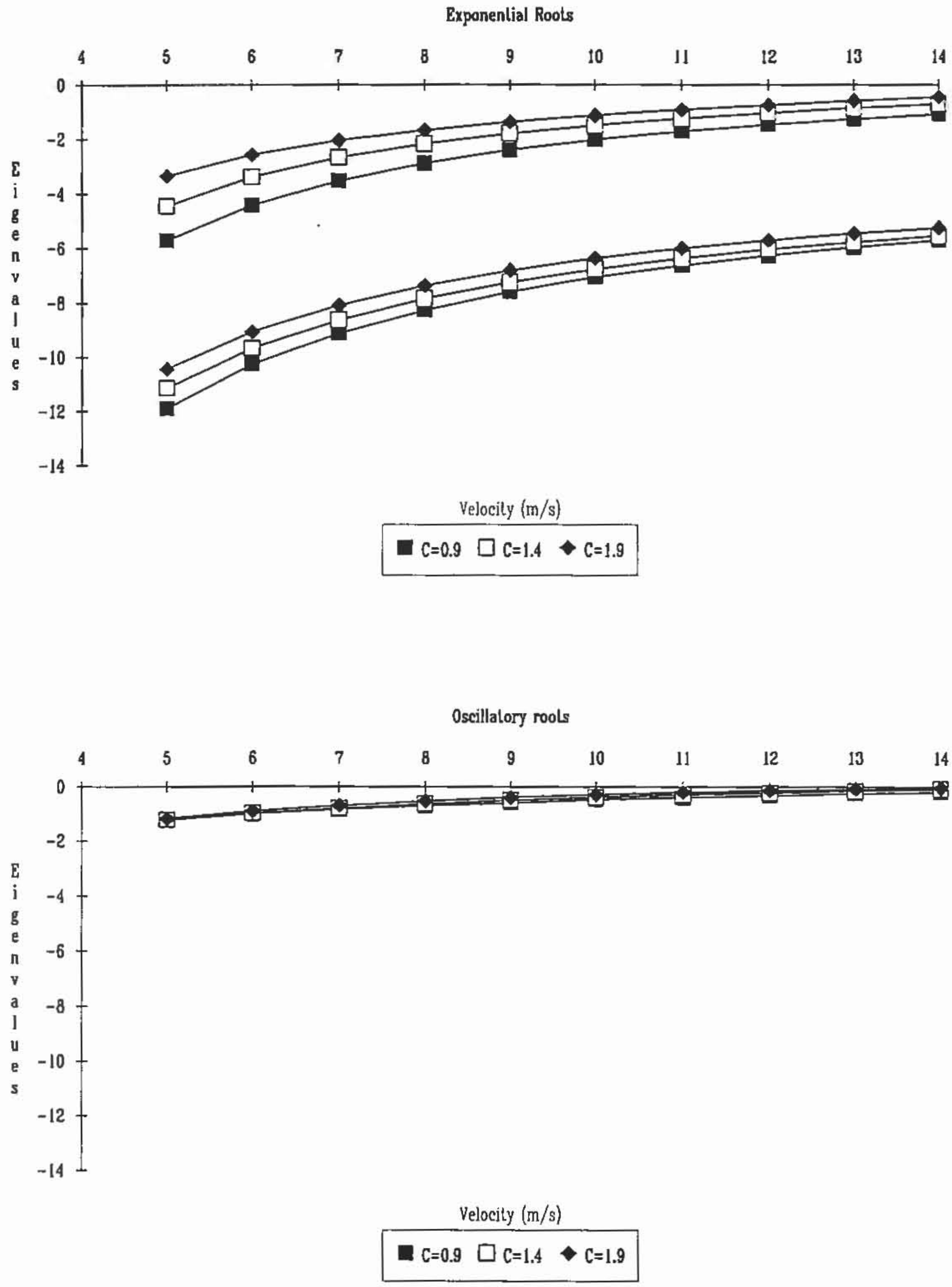

Exponential Roots
4
5
6
7
8
9
10
11
12
13
14
0
-2
-4
-6
-8
-10
-12
-14
Eigenvalues
Velocity (m/s)
C=0.9
C=1.4
C=1.9
Oscillatory roots
4
5
6
7
8
9
10
11
12
13
14
0
-2
-4
-6
-8
-10
-12
-14
Eigenvalues
Velocity (m/s)
C=0.9
C=1.4
C=1.9

Figure 11

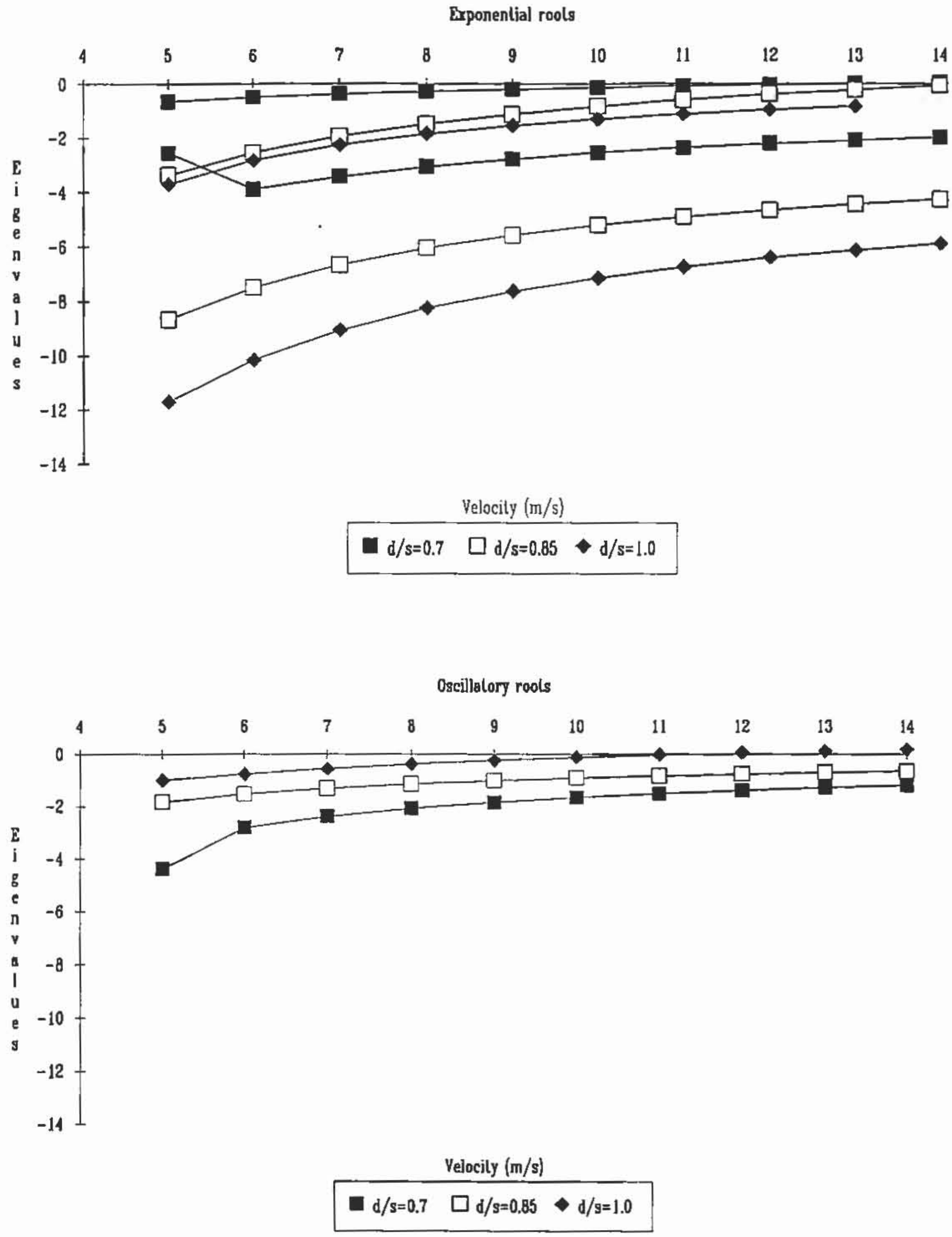
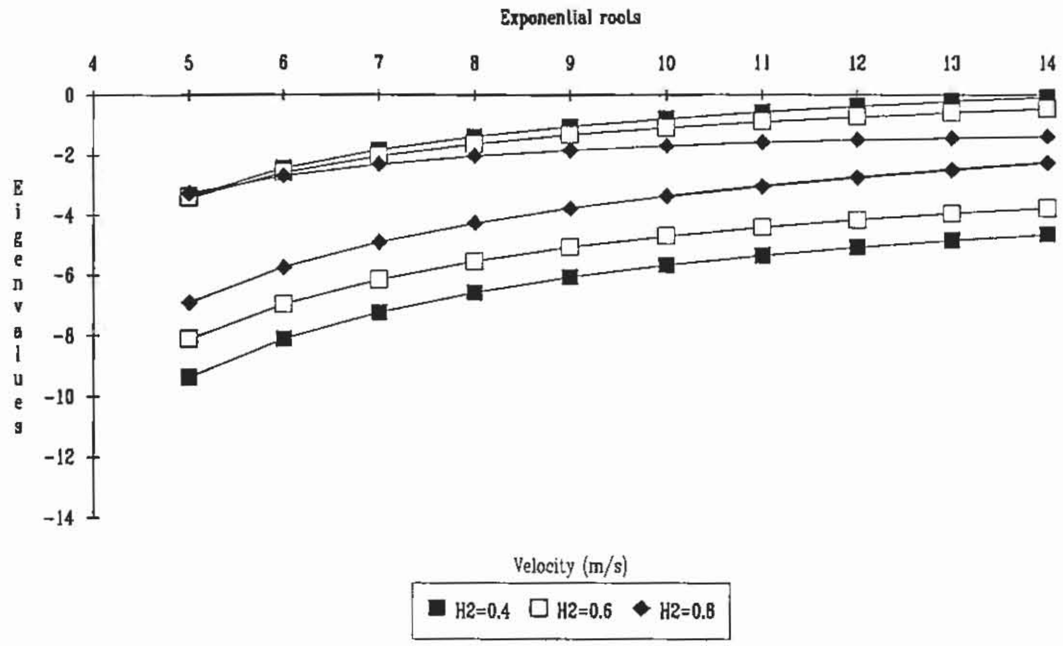

Exponential roots
4 5 6 7 8 9 10 11 12 13 14
0 -2 -4 -6 -8 -10 -12 -14
Eigenvalues
Velocity (m/s)
d/s=0.7 d/s=0.85 d/s=1.0
Oscillatory roots
4 5 6 7 8 9 10 11 12 13 14
0 -2 -4 -6 -8 -10 -12 -14
Eigenvalues
Velocity (m/s)
d/s=0.7 d/s=0.85 d/s=1.0

Figure 12



Exponential roots
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5
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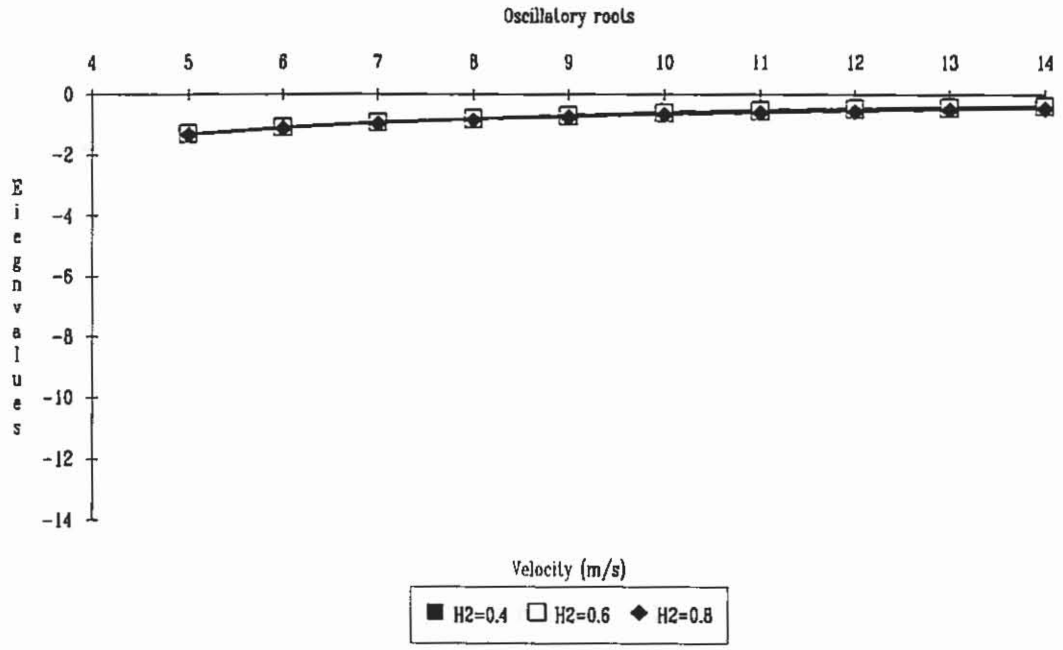
8
9
10
11
12
13
14
0
-2
-4
-6
-8
-10
-12
-14
Eigenvalues
Velocity (m/s)
H2=0.4
H2=0.6
H2=0.8



Oscillatory roots
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7
8
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11
12
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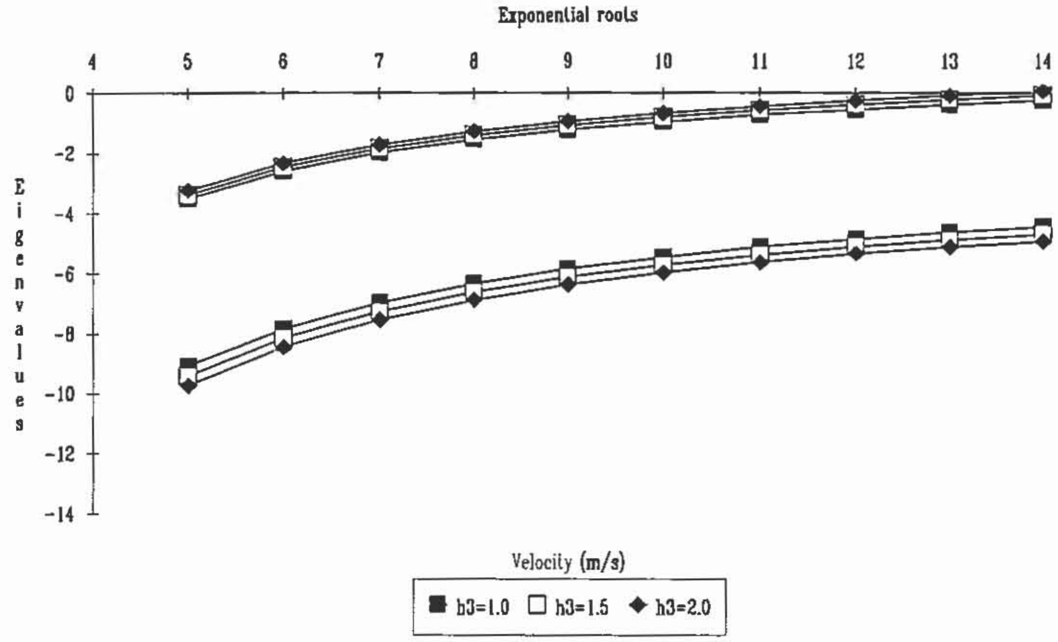
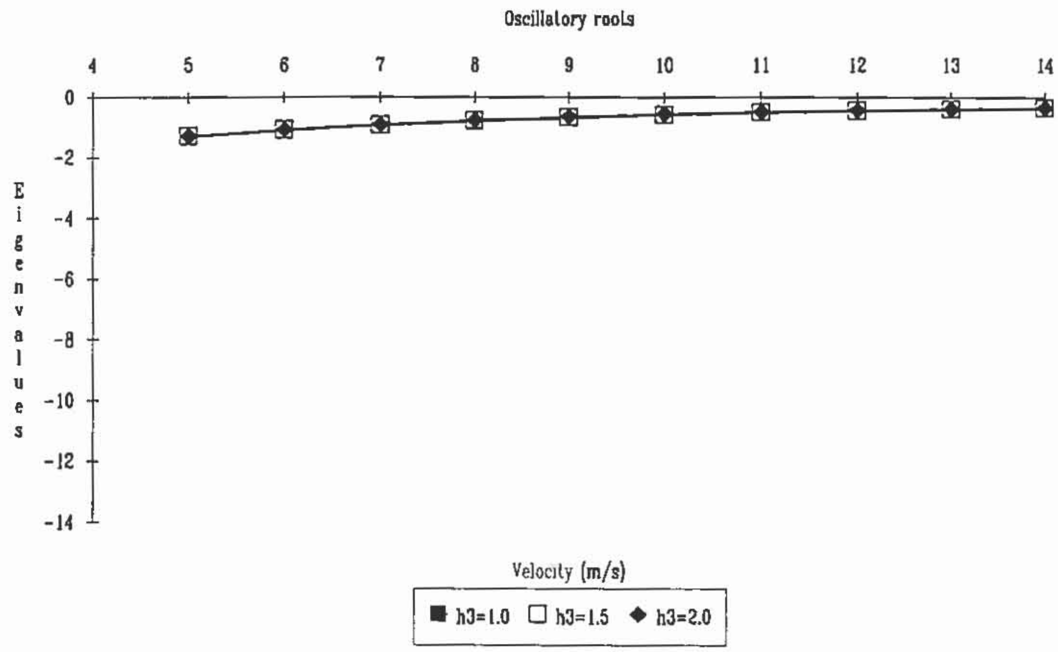
14
0
-2
-4
-6
-8
-10
-12
-14
Eiegnvalues
Velocity (m/s)
H2=0.4
H2=0.6
H2=0.8

Figure 13


Exponential roots
4
5
6
7
8
9
10
11
12
13
14
0
-2
-4
-6
-8
-10
-12
-14
Eigenvalues
Velocity (m/s)
h3=1.0
h3=1.5
h3=2.0


Oscillatory roots
4
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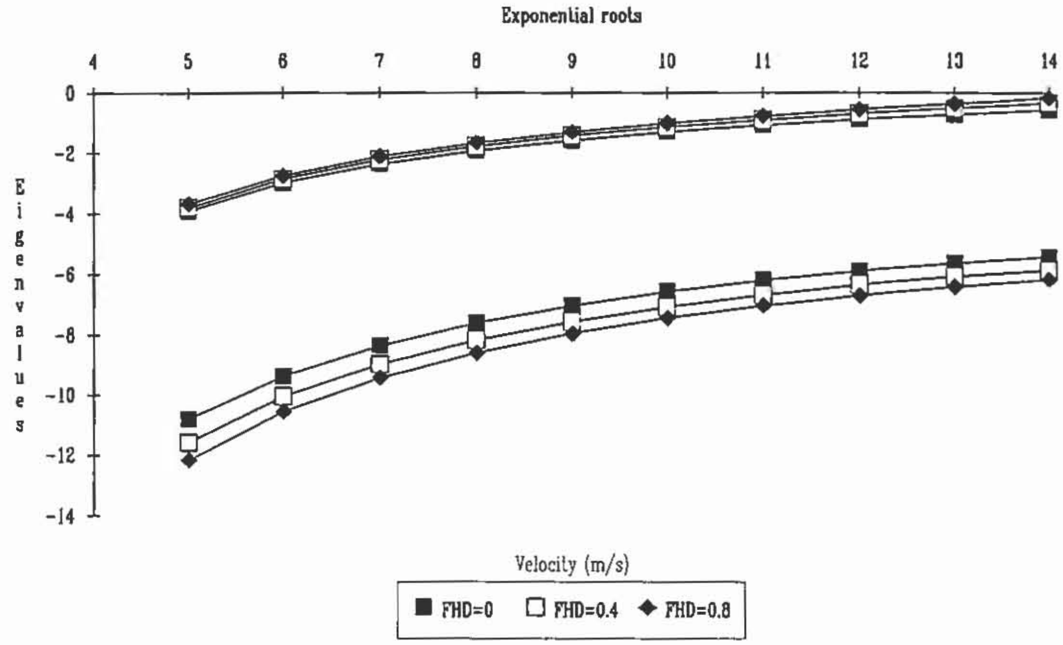
11
12
13
14
0
-2
-4
-6
-8
-10
-12
-14
Eigenvalues
Velocity (m/s)
h3=1.0
h3=1.5
h3=2.0

Figure 14


Exponential roots
4
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6
7
8
9
10
11
12
13
14
0
-2
-4
-6
-8
-10
-12
-14
Eigenvalues
Velocity (m/s)
FHD=0
FHD=0.4
FHD=0.8

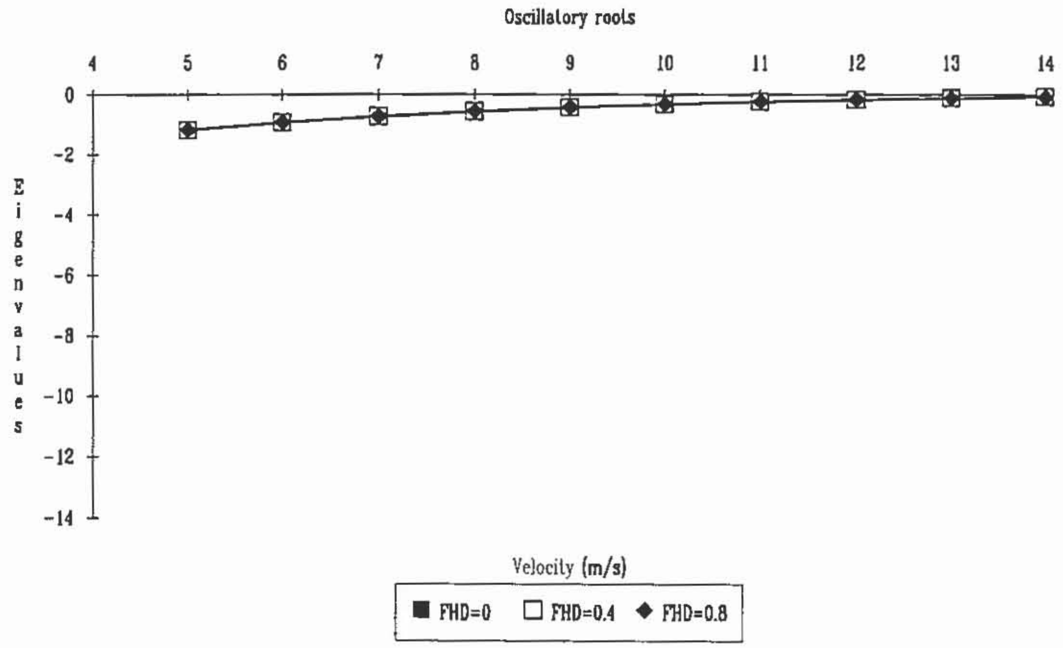
Oscillatory roots
4
5
6
7
8
9
10
11
12
13
14
0
-2
-4
-6
-8
-10
-12
-14
Eigenvalues
Velocity (m/s)
FHD=0
FHD=0.4
FHD=0.8

Figure 15

6 Relevant Industry conclusions

(From analyses and literature survey)

To improve roll-over stability of tractor-trailer combinations

1. Use tyres with greater wall stiffness.

2. Keep trailer weight as low as possible.

3. Use maximum possible vehicle width.

4. Keep trailer centre of gravity as close to trailer axle as possible.

5. For trailer stability use highest feasible hitch (i.e roll axis of hitch).

6. For increased tractor stability keep hitch (yaw pivot) as close to rear axle as possible.

To improve lateral dynamic stability of unit.

1. Put hitch as close to rear axle as possible.

2. Keep the hitch point high.

3. Use tyres with relatively stiff sidewalls.

4. Keep C.G. of trailer as low as feasible.

7 CRITICAL APPRAISAL OF RESULTS

The static stability analysis yielded results which confirmed logical thinking on the subject. Unfortunately the dynamic analysis did not yield as concrete solutions as the static analysis. Neither analysis gave useful results on the effect of placing the hitch attachment point (viz the pitch axis of the hitch) in front of the tractor axle - a factor which was highlighted as critical by some operators. It is possible that this effect is related to oversteer instability as discussed by Klein and Szostak [5].

The ideal analysis for this type of problem would be a complete simulation of the tractor-trailer combination taking into account degrees of freedom in all planes. This would encompass both static and dynamic stability problems. This is the type of analysis however that involves copious amounts of time and expertise. Even after such a simulation is developed to be relevant the model must be benchmarked against real tractor/trailer combination which is again a time consuming and expensive operation.

It would have made a fitting finale to this project to use the recommendations to design an appropriate hitch, however due to time constraints this was not possible.

APPENDIX 1 TRACTSIM BASIC PROGRAM

```
10 CLS
20 OPEN "C:\APPS\BASIC\EXCEL\OUT.XLS" FOR OUTPUT AS #1
30 'FRANKS STATIC TRACTOR-TRAILER COMBINATION ANALYSER
40 '
50 '
60 'INPUT VARIABLES
70 '
80 MT=5700 'MASS OF TRACTOR
90 MS=12500 'MASS OF TRAILER
100 J=.85 'DISTANCE FROM CENTRELINE OF TRACTOR TO WHEEL CENTRE
110 N=1! 'HEIGHT TO TRACTOR C.G
120 C=.5 'HEIGHT TO BOTTOM HITCH ATTACHMENT
130 B=.8 'HEIGHT TO TOP HITCH ATTACHMENT
140 K=.35 'DISTANCE FROM CENTRELINE OF TRACTOR TO VERT. HITCH ATTACHMEN
150 I=1.8 'DISTANCE FROM FRONT TRACTOR AXLE TO C.G
160 H=.8 'DISTANCE FROM REAR TRACTOR AXLE TO C.G
170 M=.025 'DISTANCE OF HITCH IN FRONT OF REAR AXLE
180 A=1.5 'HEIGHT TO TRAILER C.G.
190 D=.85 'DISTANCE FROM TRAILER CENTRELINE TO WHEEL CENTRE
200 F=6! 'DISTANCE FROM HITCH TO TRAILER AXLE
210 E=4! 'DISTANCE FROM HITCH TO TRAILER CG
200 F=6! 'DISTANCE FROM HITCH TO TRAILER AXLE
210 E=4! 'DISTANCE FROM HITCH TO TRAILER CG
220 L=.8 'DISTANCE FROM YAW PIVOT TO TRACTOR AXLE
230 '
240 ' TRACTOR/TRAILER WEIGHT CALCULATIONS
250 '
260 A2=60 'phi (turning angle)          THESE ARE THE CRITICAL
270 A1=20 'beta (cross slope)          ANGLES USED TO DETERMINE
280 A3=20 'pheta (down slope)           INSTABILITY
290 PI=3.141592654#
300 PHI=A2*PI/180
310 BET=A3*PI/180
320 PHE=A1*PI/180
330 PRINT #1,"L","TV4","TV5","TLA34"
340 FOR L=0 TO 1! STEP .05
360 WS=MS*9.810001 'WEIGHT OF TRAILER
370 WT=MT*9.810001 'WEIGHT OF TRACTOR
380 WSX=WS*(SIN(PHE)*COS(BET))
390 WSY=WS*(SIN(BET))
400 WSZ=WS*(COS(BET)*COS(PHE))
410 WTX=WT*(-SIN(PHI)*SIN(BET)+COS(PHI)*SIN(PHE)*COS(BET))
420 WTY=WT*(SIN(PHI)*SIN(PHE)*COS(BET)+COS(PHI)*SIN(BET))
430 WTZ=WT*(COS(PHE)*COS(BET))
440 '
450 '
460 ' TRAILER EQUATIONS
470 '
480 TV56=WSZ*(E+L+M)/(F+L+M)
490 TLO56=TV56*.065
```

```
500 HLO=(TLO56-WSY)/2
510 HV=(WSZ-TV56)/2
520 HLA=(.065*WSZ*D-WSX*(.065*A+D)-HV*2*D*.065-WSY*D-
HLO*2*D)/(2*F+.065*(B+C))
530 HX=2*(HLA*COS(PHI)-HLO*SIN(PHI))
540 TV5=(WSZ*D-WSX*A-HLA*(B+C)-HV*2*D)/2/D
550 TV6=TV56-TV5
560 TLO5=.065*TV5
570 TLO6=TLO56-TLO5
580 '
590 'TRACTOR EQUATIONS
600 '
610 TV12=(WTZ*H+WTY*N+HV*2*M-(HLA*SIN(PHI)+HLO*COS(PHI))*(B+C))/(I+H)
620 TV1=TV12/2
630 TV2=TV12/2
640 TV13=(WTZ*J+HV*2*J-WTX*N+(HLA*COS(PHI)-HLO*SIN(PHI))*(B+C))/2/J
650 TV3=TV13-TV1
660 TVT=WTZ+HV*2
670 TV4=TVT-TV1-TV2-TV3
680 TLO12=.067*TV12
690 TLO1=TLO12/2
700 TLO2=TLO1
710 TLO34=TLO12+HLO*2*COS(PHI)+HLA*2*SIN(PHI)-WTY
720 TLO3=TLO34/2
730 TLO4=TLO3
740 TLA14=HX+WTX
750 TLA1=(WTX*H+HX*L)/2/(I+H)
760 TLA2=TLA1
770 TLA34=TLA14-TLA1*2
780 '
790 'OUTPUT
800 '
810 PRINT #1,L,TV4,TV5,TLA34
820 NEXT L
830 CLOSE
840 END
```

APPENDIX 2 PROJECT RATIONALE

ATTACHMENT B

DETAILED RESEARCH PROPOSAL

OBJECTIVES

During a tour of the sugar industry in 1989 associated with SRC project DDI1S, "Development of a large capacity haulout bin" two problem areas outside the scope of the project where identified. After discussions with different manufacturers and users of haulout bins it became obvious that there was a need for a comprehensive analysis of hitch design and the dynamic stability of tractor-haulout combinations.

The objectives of this proposal are:

1. To carry out a comprehensive examination of the dynamic stability of tractor-haulout combinations to determine and catalogue contributing factors and methods of eliminating instability.

2. To perform an engineering analysis of haulout hitch geometry with the view to establishing guidelines for the design of stable and functional hitches.

STAFF AND FACILITIES

F Pearce, BE (With Dist) — Principal Researcher

The principal researcher graduated from the UCSQ in 1988 with a degree in Agricultural Engineering, specialising in agricultural machinery. He has since been employed as the Project Engineer for the SRC funded project DDI1S - "Development of a Large Capacity Haulout Bin". During this time a comprehensive insight has been gained into the cane transport industry and particularly the associated stability problems.

Facilities of the School of Engineering UCSQ are available, including:

Office and secretarial support.
Access to CAD and FEA facilities and associated hardware.
Access to mainframe computer for modelling.
Resident professional and technical expertise.

BACKGROUND

Dynamic instability of Haulout Bins is a problem that has long been recognized within the industry, but little has ever been done from a technical perspective to address the issue. Instability of the units takes several different forms, which can be broadly categorized as:

1). Lateral oscillatory motion in transit.

2). The propensity for the bin to tip over during turning.

3). The haulout unit "driving" the tractor, leading to loss of directional stability.

The potential for injury from these phenomenon is in itself a compelling reason for an analysis to be performed. One particular operator in the North Queensland region told of a trailer-haulout combination he was using that had been tipped over six times in its working life.

The problem of instability is dependent on various factors including tyre properties, weight distribution within the bin, hitch location and geometry and driver ability.

Main roads legislation limiting the allowable axle loads for haulout units has been the source of much concern in the industry in recent years. A method of increasing the quantity of cane carried is to employ a weight transfer hitch, which transfers weight from the trailer axle to the tractor axles. To ensure stability of this hitch it is important to achieve the correct sequence of axes as well the correct overall geometry of the hitch.

Currently most manufacturers employ a trial and error method for hitch design. This involves manufacturing a hitch and then performing successive modifications on the hitch until the hitch is stable enough for use. No rational design process is available to reduce the guess work. Once a hitch that works is introduced into the industry it is often copied (with varying degrees of success) by other manufacturers. There are still a number of bins working in the industry that have doubtful stability owing to a less than optimized hitch.

A significant contribution could be made to haulout design if a proper engineering analysis and design was undertaken. With the current industry rationalization taking place there are significant advantages to be made by increasing the size of transport equipment. If the gross weight of the unit exceeds 16 tonnes, (regardless of the configuration of the haulout) there is a need for a weight transfer hitch.

As well as helping the unit to comply with MRD legislation, the weight transfer hitch is a significant contributor to the wet-weather mobility of the unit. With the trend towards continuous crushing as a further step in streamlining the industry, it is important that reliable wet weather transport is available.

This project will provide the fitting final touch to the previous associated project, SRC project DDI1S, "Development of a large capacity haulout bin".

METHODOLOGY

The project is expected to run full time for six months, addressing the two objectives concurrently during this period.

I. To carry out a comprehensive examination of the dynamic stability of tractor-haulout combinations to determine and catalogue contributing factors and methods of eliminating instability.

There has been a considerable amount of research undertaken into tractor-trailer stability. Consequently the logical first step into this objective is a detailed literature search.

The next step in the process hinges on the results of the literature search. If there is sufficient documented work covering all the parameters involved with haulout stability, the next step will involve the application of the work done. If possible the computer model the research was based upon will be obtained and used to establish a basis for stability.

If sufficient research is not located the necessary dynamic analysis will be performed and a computer model, simulating the dynamic stability will be written and applied.

II. To perform an engineering analysis of haulout hitch geometry with the view to establishing guidelines for the design of stable and functional hitches.

The first step in this objective is to perform a thorough collection of the associated parameters involved with the design. This would involve contacting manufacturers of both bins and tractors, primarily by written correspondence, to ascertain the limits which any hitch must fall within.

With this information and the hitch loads collected as part of the previous project, a detailed design would then be undertaken applying three-dimensional vector mechanics to the system.

The accompanying GANTT CHART shows the proposed time allotted to each task.

ASSOCIATED ACTIVITY

The following are publications relating to the proposal

Pearce, F. , Harris, H. D. & Bennet A. H. (1989). Measuring Hitch Loads on an Infield Haulout Bin. Paper submitted for A.S.S.C.T Annual conference 1990.

Xie, L. & Claar, P. W. (1986). Simulation of Agricultural Tractor-Trailer System Stability. SAE Trans., Vol. 95, pp. 744-757

Klein, R. H. & Szostak, H. T. (1980). Determination of Trailer Stability Through Simple Analytical Methods and Test Procedures. SAE Trans., Vol. 88, pp. 708-714.

Crolla, D. A. & Hales, F. D. (1979). The Lateral Stability of Tractor Trailer Combinations. J. Terramechanics 16(1): 1-22.

Poole, H. G. (1977). The Technical and Economic Significance of Weight Transfer Tractor Transport Systems. The Harold Poole Group Company publication.