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HSE CONTRACT RESEARCH REPORT No. 44/1992

ROPS TEST CRITERIA FOR 40 km/h AGRICULTURAL AND FORESTRY TRACTORS

ROPS TEST PROCEDURES FOR TRACTORS WITH MASS BELOW 600 kg AND TRACK WIDTH BELOW 1150 mm

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Silsoe Research Institute, Wrest Park,
Silsoe, Bedford

Price £20.00

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Proposals to increase the maximum design speed of agricultural and forestry tractors from 32 km/h to 40 km/h have raised concern that the ROPS test energies defined in current EEC directives may not be adequate at higher speeds. The review has been based on a study of 160 overturning accident reports compiled by HSE inspectors in the period 1979 to 1985. The data showed that 58% of overturns occurred at speeds below 10 km/h, including the majority of multiple roll overturns. It has been possible to calculate only the energy absorbed by ROPS in the lateral direction from the available data. In 95% of overturns the energy absorbed laterally by the ROPS was less than the test energy despite speeds at overturn being over 40 km/h in some cases. The effect of forward speed on energy absorbed in the longitudinal and vertical directions has been estimated by examination of the respective deflections. Correlations with speed are very low in all directions. The evidence suggests that no change to the existing ROPS test codes is necessary if the maximum design speed is raised to 40 km/h.

ROPS test criteria for 40 km/h agricultural and forestry tractors

B B Harral

1. Objectives

Tractors used in agriculture are being produced with higher maximum design speeds (up to 50 km/h). In addition suspension systems for seats, cabs and the tractor itself are becoming increasingly sophisticated and resulting in a higher quality ride for the driver. Current proposals in Europe are to amend the European Tractors Directives for maximum design speeds, from 32 km/h to 40 km/h. It is reasonable to expect that, in the future, tractors will be driven on highways and in the field at higher speeds. HSE are concerned that the ROPS fitted to these tractors may not withstand the energies likely to be imposed on them in an overturn situation. There is a need to review the test energy criteria laid down in the various strength tests for ROPS fitted to tractors with design speeds in excess of 32 km/h, to ensure that they are realistic.

2. ROPS test codes

The current EEC directives governing the testing of ROPS and FOPS on agricultural and forestry tractors are 77/536/EEC (dynamic) and 79/622/EEC (static) [amendments 82/953/EEC and 88/413/EEC]. These apply to tractors weighing more than 600 kg which have a track width of more than 1150 mm. The codes lay down test energy criteria which are based on studies of tractor overturning accidents, ROPS behaviour in overturning tests and mathematical simulations.

Tractor speed is not explicitly addressed by the directives but was implicitly included by the use of data from a large range of tractor overturning accidents. Type approval is currently limited to tractors with a maximum design speed of 32 km/h by EEC directive 74/150/EEC (amendment 82/890/EEC).

3. Previous Work

The two common methods of investigating tractor overturning stability and ROPS strength are either to analyse tractor overturning accident data or to use computer based simulation models. Schnieder and Baker[1], Chisholm and Seward[2], and Owen and Hunter[3] are examples of accident data studies in the US and UK. The study by Owen and Hunter is largely concerned with stability on slopes. Only the study by Schnieder and Baker includes the effect of forward speed, and they found that 50% of overturning accidents in the US occurred at less than 8 km/h. Their survey included 60% of tricycle type tractors, which are inherently less stable than wide-front types. The survey by Chisholm and Seward describes a method of calculating ROPS energy in accidents and is particularly useful in the context of the present work.

Various mathematical models and computer simulations have been devised, some two-dimensional and some three-dimensional. Chisholm[4] provides a description and assessment of those developed before 1977, and Kyeong and Rehkugler[5] have written a more recent review. However, as far as can be ascertained, there are no readily available simulation models that include both ROPS damage and forward speed.

4. Overturning accident reports

The lack of a suitable computer simulation program has meant that the effect of forward speed on ROPS damage must be assessed from data given in overturning accident reports. Full reports produced by HSE inspectors prior to 1986 are required to give the necessary detail.

A study has been made of 160 reports describing overturning accidents in England and Wales involving agricultural and forestry tractors from the period 1979 to 1985. The data in these reports are many and varied but for the purposes of this study only quantities relating to speed and ROPS damage have been extracted. These are:

(i) Tractor mass
(ii) Tractor speed at overturn
(iii) Degree of overturn
(iv) Direction of overturn
(v) ROPS type and approval number
(vi) ROPS deflections; lateral, longitudinal and vertical.

5. Results and discussion

5.1 General results

The accidents described in the HSE reports of overturning tractors included 11 Road Traffic Accidents and 12 cases where no ROPS was fitted. Although tractors are designed to travel no faster than 32 km/h on public roads, the reports included a significant number of instances in which the inspector estimated the forward speed at overturn to be in excess of 40 km/h. This was generally in cases where a tractor has run away downhill before overturning. These incidents are particularly useful for providing data on the effects of speed on ROPS damage and energy absorbed. The distribution of numbers of tractors overturning at increasing estimated forward speed is shown in Fig.1. It is clear that the majority, 58%, overturn at speeds below 10 km/h. This is in close agreement with Schnieder and Baker's findings in the US, despite the difference in tractor type; all those in the UK reports were of the wide-front variety, while 60% of those in the US survey were of the tricycle type. Thus, the majority of overturns occur at speeds well below those attainable by modern tractors. This suggests that higher design speeds will not result in more accidents or a greater proportion of high speed accidents.

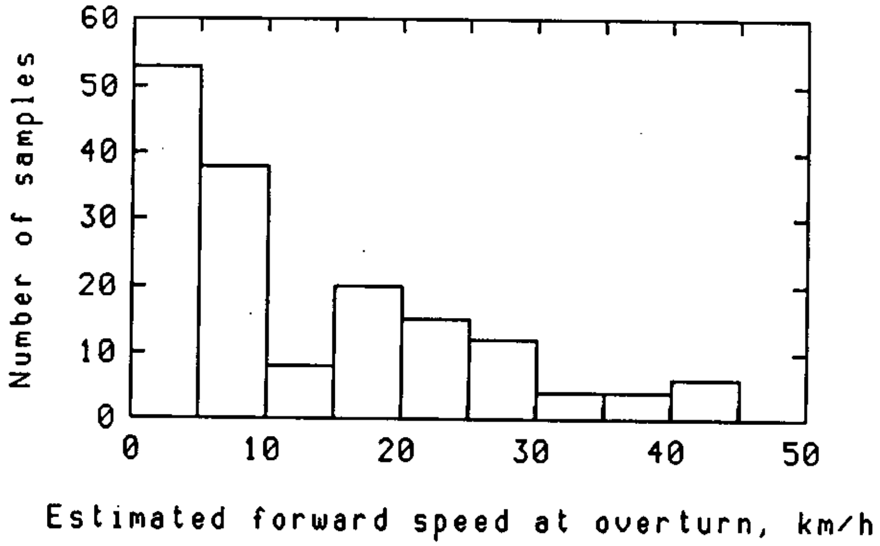

Fig.1 Distribution of estimated forward speeds at overturn in tractor overturning accidents

The accidents shown in Fig.1 are replotted in Fig.2 to show the degree of overturn. It emerges from Fig.2 that the high speed overturns do not result in multiple rolls, as might be supposed. Multiple roll behaviour can be very serious in terms of ROPS damage, because of the possibility of further damage being sustained at each roll. It seems likely that the multiple rolls, which occur most frequently at slow speeds, are mainly a result of the terrain on which the overturn takes place. The driver is proceeding slowly because of a dangerously steep slope but once stability is lost kinetic energy increases very rapidly.

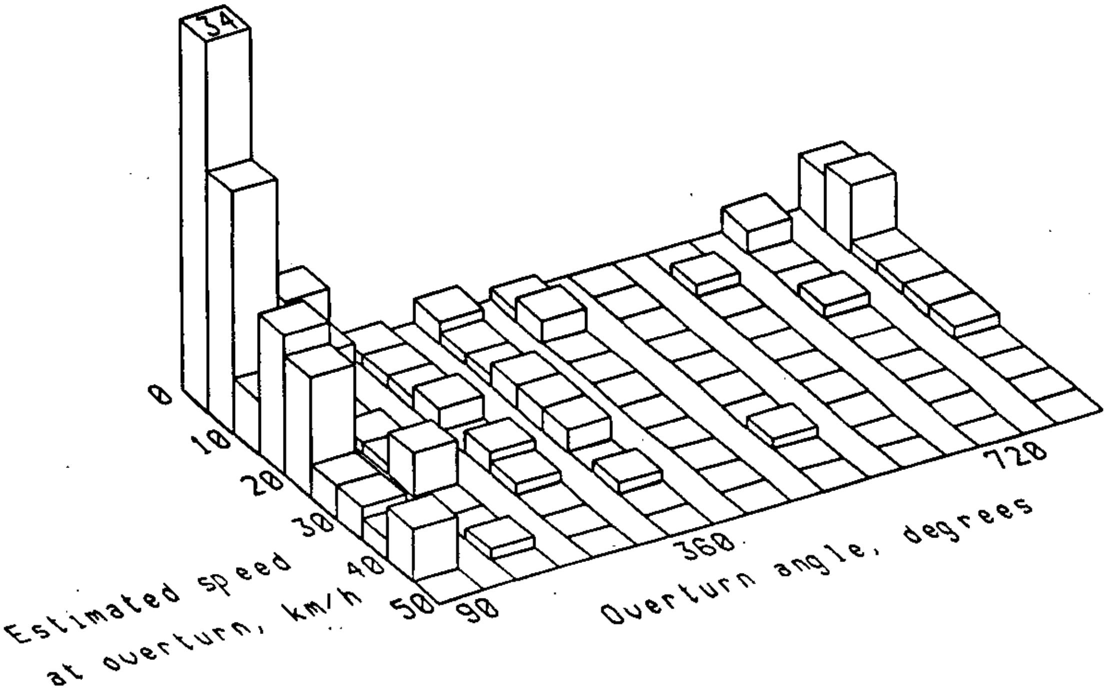

Fig.2 Distributions of tractor overturn angles and estimated forward speed at overturn

The accident reports reveal several important points to be borne in mind when considering the questions of speed.

(i) 85% of the overturns examined were side overturns.

(ii) Only 60% of the overturns resulted in measurable ROPS deflections in any direction.

(iii) Only 30% of overturns resulted in measurable longitudinal ROPS deflections; the direction associated with forward motion.

(iv) Only 31% of overturns resulted in measurable vertical ROPS deflections.

5.2 Energy absorbed by ROPS

A method of calculating the energy absorbed by the ROPS in an overturn was described by Chisholm and Seward[2]. It applies only where there is measurable permanent deflection, these are in any event the cases of most interest. The method uses the energy input and elastic and plastic deflections measured during the ROPS acceptance tests.

Where permanent ROPS deflections were recorded by the HSE accident inspectors, the relevant ROPS approval test data were obtained. Essential to the accident energy calculation is the ROPS elastic deflection, since this absorbs a significant proportion of the energy in the approval test. Unfortunately, elastic deflections are recorded in the lateral test only. Hence, ROPS energy can only be calculated for the lateral direction. Energy is not a vector but the term "lateral energy" will be used to denote energy absorbed in lateral deflection. The ratio between the lateral energy absorbed by the ROPS in the overturn and the lateral energy absorbed in testing is shown in Fig.3. plotted against cumulative probability. Lateral test energy is taken from directive 79/622/EEC to be:

$$\text{Energy(Joules)} = 1.75 \times \text{Tractor mass(kg)}$$

Fig.3. shows that in more then 95% of overturns the energy ratio is less than unity and the test is more severe than the accident. This agrees well with the results presented by Chisholm and Seward[2] from their study of 281 accidents in the UK between 1968 and 1975. A similar log-normal distribution is also apparent but in only 45% of overturns was the energy less than half that in the test as opposed to the 83% reported by Chisholm and Seward. The reason for this is not clear.

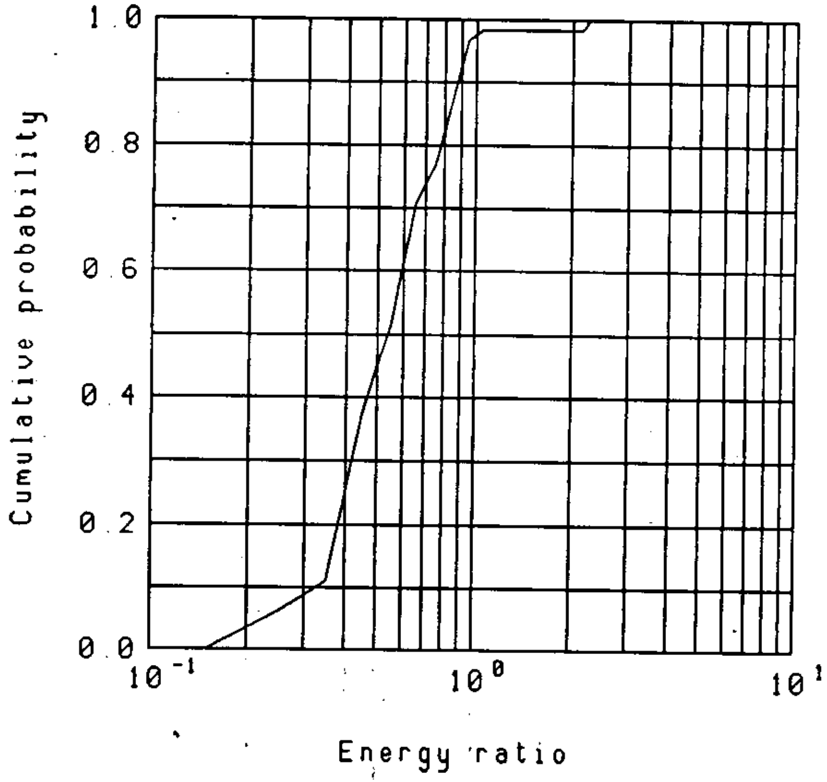

Fig.3 Ratio of energy absorbed in ROPS lateral test to energy absorbed in overturn

Data extracted from accident reports also enables the total kinetic and potential energy of the tractor to be calculated at overturn. Kinetic energy is calculated from the tractor mass and velocity at overturn, while potential energy is calculated from the tractor mass and the height of the centre of gravity from the ground. The height of the centre of gravity is found from the regression equations given by Chisholm[4] relating tractor geometry to mass. Fig.4. shows the number of overturning accidents and the percentage of the total energy absorbed by the ROPS in the lateral direction. In more than 90% of overturns less than 20% of the total energy is absorbed by the ROPS laterally, and the maximum absorbed is only 35%. The remainder of the energy is dissipated in two ways, damage to the tractor and longitudinal and vertical damage to the ROPS. There is no evidence from accident reports that anything other than a small proportion of this energy is absorbed by the ROPS in longitudinal and vertical deflection, but ample evidence that a great deal of energy is absorbed in the destruction of wheels, axles and the tractor body.

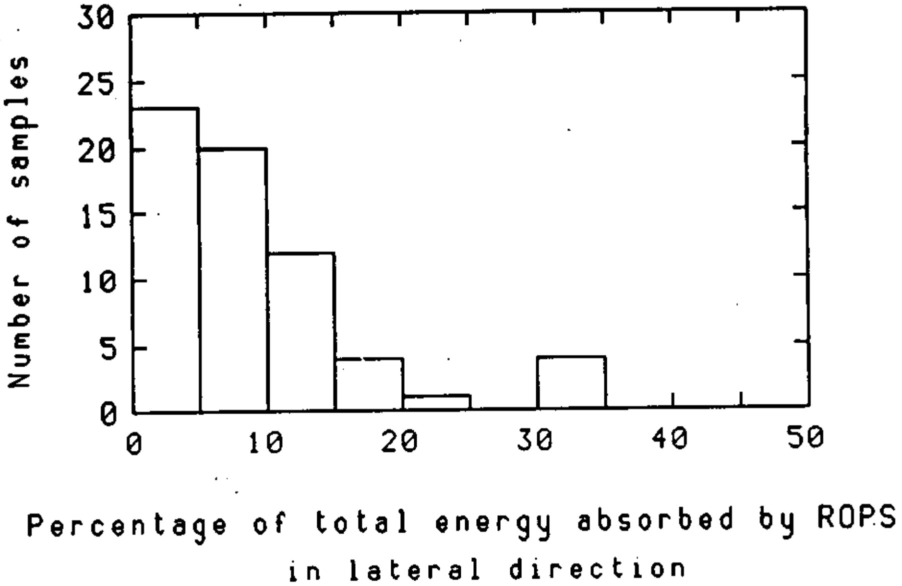

Fig.4 Proportion of total kinetic and potential energy absorbed by ROPS in lateral direction during overturn

As has already been stated in 5.1, in only 30% of overturns is there any permanent longitudinal deflection and in only 31% is there any permanent vertical deflection. It should be noted that deflections in a particular direction do not necessarily mean loading in that direction; for example, because of the design of cab structures, a vertical deflection can result from either longitudinal or lateral loading.

5.3 Effect of speed on lateral ROPS energy

Fig. 5 shows the specific lateral energy absorbed by the ROPS plotted against estimated speed at overturn. The regression line has a slope of 0.0033 and a correlation coefficient of 0.12, which implies that increasing the forward speed from 32 km/h to 40 km/h would increase the lateral energy by 2.4%. This is an insignificant amount, which could not justify any change to the side loading energy in ROPS approval tests, particularly when viewed against the low correlation, the fact that 95% of ROPS absorb less lateral energy when overturning than in the test, and also that almost 60% of overturns occur at less than 10 km/h and will probably continue to do so.

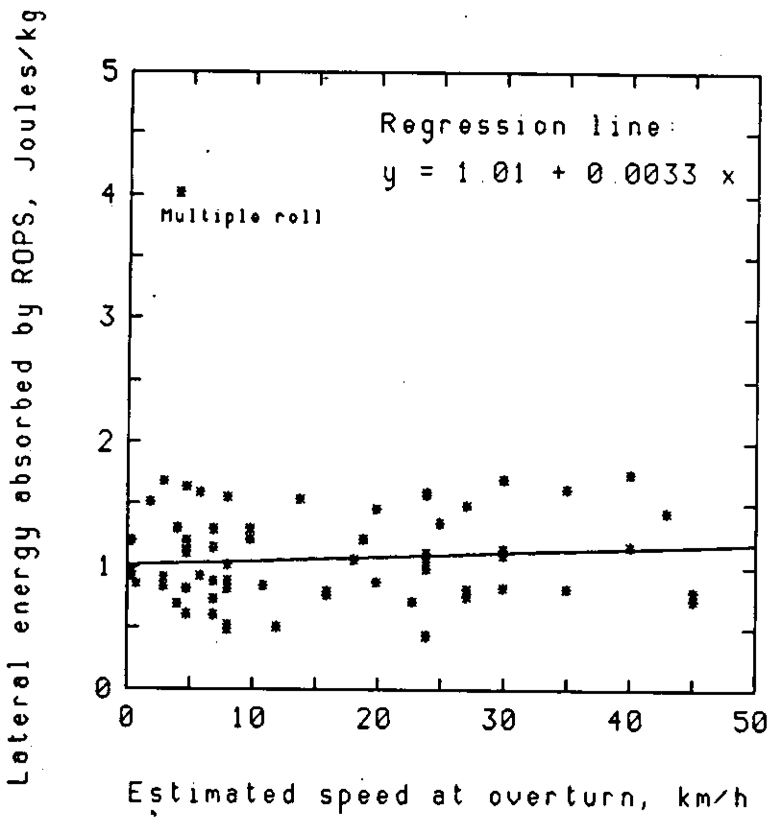

Fig.5 Variation of lateral energy absorbed by ROPS with estimated speed at overturn

5.4 Effect of speed on longitudinal and vertical ROPS energy

There are insufficient data to calculate longitudinal and vertical ROPS energy, as already mentioned. Therefore, assessing the effect of speed must rely on weighing what data there are in the light of the results for the lateral direction.

Table 1 gives the ROPS maximum permanent longitudinal and vertical deflections, as given in the accident report, listed in ascending order of estimated forward speed at overturn. Out of 54 overturns listed, 48 are side overturns. The deflections depend on ROPS design and do not by themselves indicate energy absorbed but despite this, if there is a strong effect of forward speed it would show in a trend of increasing deflections. An increase in forward speed from 20 km/h to 40 km/h represents an increase in kinetic energy that must be dissipated of 300%.

Fitting regression lines to the forward speed and deflection data in Table 1 gives low correlations, 0.24 in the case of longitudinal deflection and 0.04 in the case of vertical deflection.

Table 1

ROPS longitudinal and vertical deflections

Estimated forward speed at overturn - km/h	Maximum ROPS deflections, mm		Estimated forward speed at overturn - km/h	Maximum ROPS deflections, mm	
	Longitudinal	Vertical		Longitudinal	Vertical
0.5	25	0	16.0	0	2
0.5	40	25	16.0	6	4
0.5*R	30	33	18.0*F	50	16
1.0	7	40	18.0	10	50
1.0	20	20	20.0	3	23
2.0F	50	30	20.0	13	6
2.8	6	0	24.0	0	10
3.0R	50	0	24.0F	10	5
4.0*	300	300	24.0	0	97
5.0	6	3	24.0*	50	50
5.0	0	150	24.0	30	45
5.0*	0	20	24.0	65	88
6.0	28	0	25.0	69	54
6.0*	0	40	25.0	10	7
6.0	114	51	27.0	30	30
7.0*	46	18	27.0*	5	10
7.0	4	0	27.0	25	0
8.0	0	10	28.0	0	38
8.0	20	10	30.0	90	100
8.0	0	10	30.0	120	0
8.0	30	60	32.0	27	0
8.0	0	10	35.0	10	0
10.0	0	12	35.0	100	20
10.0*	0	40	40.0F	100	100
10.0	50	3	43.0	0	20
11.0	22	0	45.0	10	5
12.0	10	5	45.0	0	2

* Multiple roll

R - Rear overturn

F - Front overturn

6. Conclusions

Computer simulation software designed to study the effect of forward speed on energy absorbed by ROPS is not available. The conclusions are therefore based on the study and analysis of data in 160 reports of tractor overturns prepared by HSE inspectors between 1979 and 1985.

It has been possible to calculate only the energy absorbed by ROPS in the lateral direction from the available data, not in the longitudinal or vertical directions. The effect of forward speed on energy absorbed by ROPS in the longitudinal and vertical directions has been estimated by examination of the respective deflections given in the accident reports. Correlation between energy or deflections and speed is very low in all directions; 0.12 between lateral energy and speed, 0.04 between longitudinal deflection and speed, and 0.24 between vertical deflection and speed.

The evidence suggests that no change to the existing ROPS test codes is necessary if the European Tractor Directives are amended to increase design speeds from 32 km/h to 40 km/h.

Acknowledgements

My thanks to C J Hampson of Test Group, Silsoe Research Institute, for his work extracting essential ROPS test data from test reports. Thanks also to Richard Culpin, HSE Nottingham, for providing tractor accident data, and Anne Coan, HSE Bootle, for tracing the ROPS approval numbers and finding the test reports.

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ROPS TEST PROCEDURES FOR TRACTORS WITH MASS BELOW 600 kg AND TRACK WIDTH BELOW 1150 mm

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A test code for the Roll Over Protection Structure (ROPS) on small tractors with mass less than 600 kg and track width less than 1150 mm may become necessary because of their increasing use. As neither accident nor test data exist energies absorbed by the ROPS in side and rear overturns down a bank were predicted using a dynamic simulation model. Geometric and inertial data from four small tractors were measured but component stiffnesses and vehicle/soil contact parameters were calculated or estimated from large tractor data.

Predicted energies were highly variable and depended on subtle variations in vehicle dynamics and vehicle/ground interactions. Including the driver's mass can theoretically make a considerable difference but in practice it depends on the driver's actions during the overturn. The results suggest that the ratios between static test energy and tractor mass in the lateral and longitudinal directions should be the same as those used for large tractors. In the vertical direction the same ratio of load to mass as used for large tractors is recommended.

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ROPS test procedures for tractors with mass below 600 kg and track width below 1150 mm

B B Harral

1. Object of the work

To establish and prepare draft dynamic and static strength test procedures for operator roll over protection structures fitted to agricultural/forestry tractors which have a track width of less than 1150 mm and weigh less than 600 kg. And consider the suitability of the test procedures for other light weight vehicles (excluding two-wheeled motorcycles) used in agriculture. The result will assist the UK in discussions in Europe with regard to complementing existing EEC directives and possibly the Mobile Machinery Directive.

2. ROPS test codes

The current directives covering the testing of ROPS and FOPS on agricultural and forestry tractors are 77/536/EEC (dynamic) and 79/622/EEC (static) [amendments 82/953/EEC and 88/413/EEC]. These apply to tractors weighing more than 600 kg which have a track width of more than 1150 mm. The directives lay down test energy criteria which are based on studies of tractor and ROPS behaviour in overturning tests and mathematical simulation.

Also relevant to the present work is directive 87/402/EEC for testing ROPS on narrow-track wheeled agricultural and forestry tractors with track width less than 1150 mm and mass between 600 kg and 3000 kg.

3. Previous work

The ROPS test procedures for tractors above 600 kg which have a track width greater than 1150 mm were arrived at after an extensive study of data from mathematical simulations of tractor overturns and data calculated from real accidents. Chisholm[1], and Kyeong and Rehkugler[2] have described and reviewed the simulation models. A detailed comparison of results from all the sources and their incorporation into ROPS test procedures is given by Boyer, Chisholm and Schwanghart[3].

It is clear from the above work that computer simulation using mathematical models is the most satisfactory method for investigating overturning accident parameters. Most simulation models have been verified against experiments. These show that despite the unpredictable variation in real accidents, the simulations can give reasonably accurate predictions of overturning motion and ROPS energy if all the tractor and terrain parameters are known. A wide range of accident types and conditions can be studied without the need for destructive tests.

Many of the simulation models developed for large tractors are potentially suitable for small tractors although their predictions may not have been verified against experiments with small tractors. Recently a simulation program, SIMMOST, has been developed and tested by Rehkugler and Bartlett[4] for small ride-on grass mowers to study the onset of instability. Unfortunately it is not suitable for roll angles greater than about 45° and hence is not suitable for overturn. Of the other models, only Chisholm's two-dimensional overturn simulation program[1] is readily accessible. Two particular factors give confidence in the program's performance; First, it has been verified against experimental overturns, and second, it has predicted a ratio between lateral ROPS energy and tractor mass of 1.8, very close to the 1.75 adopted for the EEC ROPS static test codes.

4. Accident data

Accident data involving small tractors was provided by HSE, Nottingham, covering the years 1986-1991. Data from the following Activity/Workplace classes were given:

- Agriculture
- Construction
- Disciplined services
- Education services
- Health services
- Other services
- Manufacturing
- Transport and storage
- Other

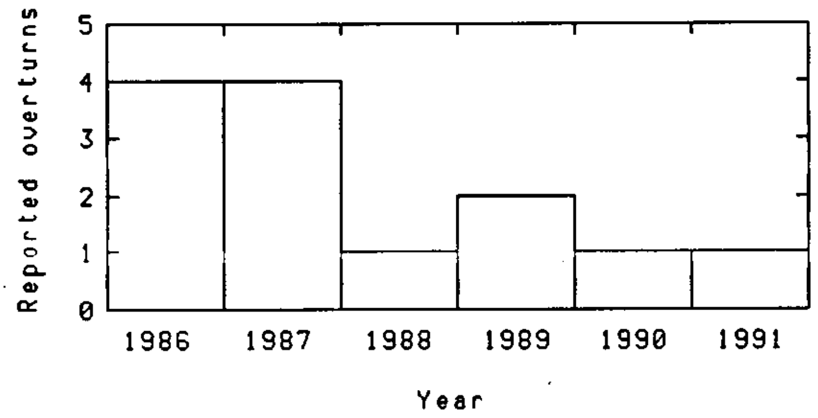


Fig.1 Reported overturns involving agricultural and industrial tractors with mass less than 600 kg and track width less than 1150 mm

The data shown in Fig.1 are very meagre, totalling thirteen incidents only. Articles in the popular press have suggested a higher accident rate, 23 serious accidents involving All Terrain Vehicles (ATV's) in the last three years, including four deaths[5,6]. The only statistics found for the USA, where ATV's are especially popular, are those given by a roll cage manufacturer[7]. These give 1500 fatalities in accidents involving ATV's since 1970, and 100,000 people injured each year. In Germany the number of people injured in accidents involving small tractors under 600 kg used in agriculture, forestry, horticulture and maintenance of public grounds, is apparently negligible[8].

Apart from the broad statistics given above there appears to be no detailed data on accidents involving small tractors, such as terrain, type of vehicle, speed, type of overturn, injuries sustained, etc.

5. Simulation

The overturn simulation program written by Chisholm paid particular attention to the contact between the tractor parts, wheels, ROPS, etc. and the ground which is very important to energy absorption and dissipation. As such it requires a large number of terrain and vehicle parameters to be defined. One of the features of the program that simplifies data input, is that it includes equations relating many of the vehicle parameters to the tractor mass. These have been derived from measured data. A typical value for a dimension or a component stiffness can be defined simply by specifying the tractor mass.

The program models sideways overturn on two types of terrain; either overturn on a uniform slope or overturn down a bank. Overturn down a bank is generally more serious and this has been taken as the standard case.

5.1 Small tractor data

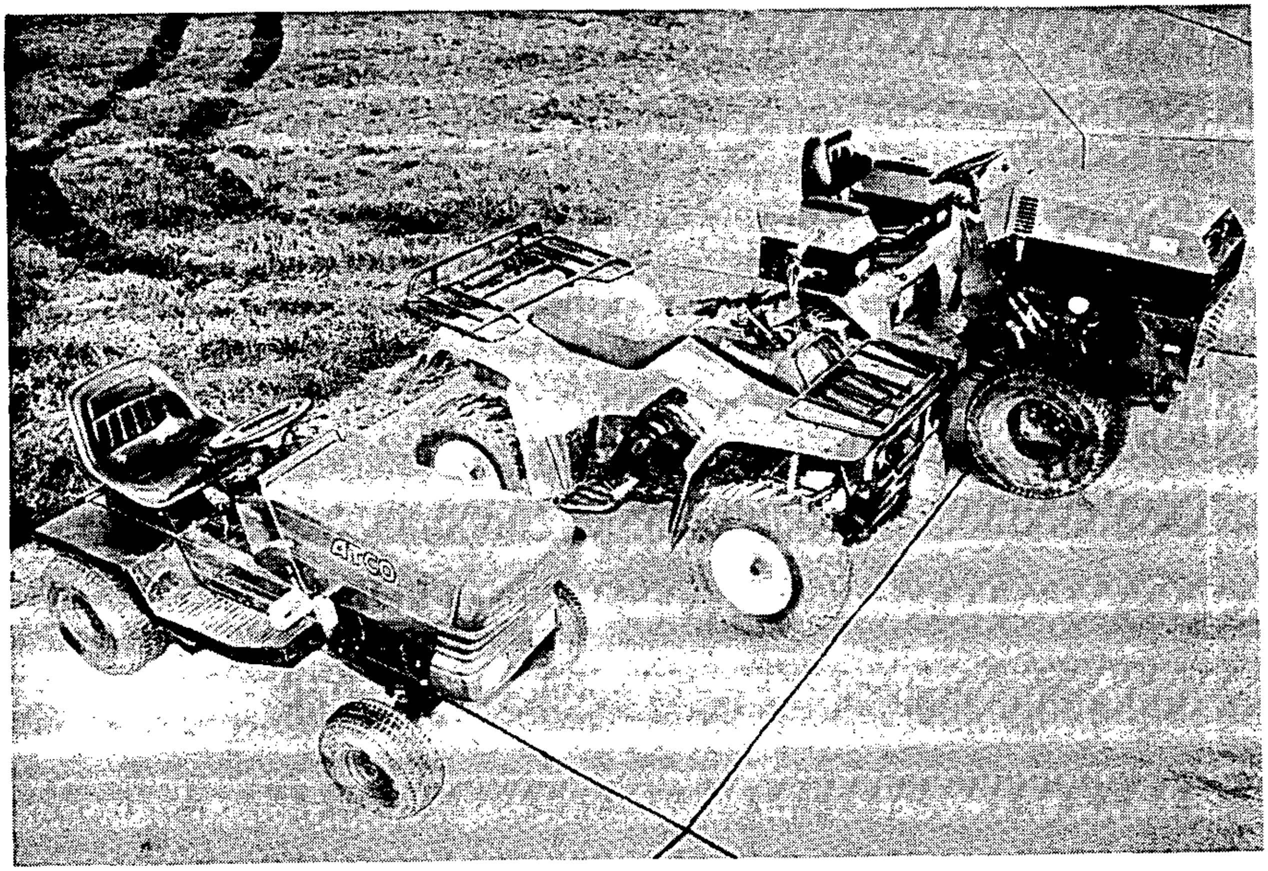


Fig.2 Examples of small tractors with mass below 600 kg and track width below 1150 mm. Left to right: ATCO 1236; Kawasaki ATV; Ransomes TURFTRAK 4

Some typical small tractors with track widths below 1150 mm and weights below 600 kg are shown in Fig.2. To make the simulations as accurate as possible, parameters from four tractors have been measured, including the three shown in Fig.2. The values are given in Table 1. As there has not been time to measure all the data required, some parameters, such as tyre stiffness, have been estimated from other sources, while others such as ROPS stiffness have been calculated by the program from the tractor mass. Table 2 gives these values. The MF1010 tractor, although just above the mass limit for small tractors, has been included to provide more simulation results at the transition from small to large. The Kawasaki ATV differs from the other models in having front and rear suspensions.

Table 1

Measured tractor parameters

Tractor	ATCO 1236	Kawasaki ATV KLF300-C2	Ransomes TURFTRAK 4	MF 1010
Mass:				
Mfrs spec, kg	-	253	572	659
Measured, kg	205	270	625	790
Track width:				
Rear, mm	650	845	1090	920
Front, mm	750	845	1090	1030
Wheel base, mm	1200	1195	1110	1410
Rear tyres:				
Size/Type	18x8.5-8	24x10-11	Turf Track	29x12.00-15
Overall dia, mm	430	550	590	710
Overall width, mm	170	230	305	280
Rim dia, mm	234	308	330	420
Front tyres:				
Size/Type	15x6.00-6	24x8-11	Turf Track	21x8.00-10
Overall dia, mm	350	550	590	490
Overall width, mm	125	170	305	180
Rim dia, mm	173	308	330	284
C of G position#:				
z_r, mm	535	610	636	659
z_f, mm	665	585	474	751
h, mm	381	482	456	510
Roll M of I, kgm^2	-	26.8	-	120
Roll R of G, m	-	0.31	-	0.39
Seat position#:				
h, mm	650	800	780	960
z_r, mm	0	300	0	150
ROPS (where fitted)#:				
Height, mm	-	-	-	2350
Width, mm	-	-	-	1000
Towing point height#, mm	290	280	320	270

h = distance from ground; z_r = distance from rear axle; z_f = distance from front axle

Table 2

Calculated and estimated tractor parameters

Tractor	ATCO 1236	Kawasaki ATV KLF300-C2	Ransomes TURFTRAK 4	MF 1010
Tractor:				
Effective rear mass$^+$, kg	114	132	267	421
Roll M of I, kgm^2	12.8	26.8	76.6	120.0
Roll R of G, m	0.25	0.31	0.35	0.39
Rear tyre:				
Vertical stiffness, kN/m	180	16*	180	180
Vertical damping, kNs/m	0.61	0.61	0.61	0.61
Lateral stiffness, kN/m	100	100	100	100
Lateral damping, kNs/m	0.5	0.5	0.5	0.5
Rear wheel rim:				
Lateral stiffness, kN/m	14.1	16.4	33.1	52.3
Lateral damping, kNs/m	1.14	1.32	2.67	4.21
Lateral collapse force, kN	2.04	2.38	4.80	7.58
Rim deflection limit, m	0.2	0.2	0.2	0.2
ROPS:				
Height$^\#$, m	1.85, 2.04	2.00, 2.19	1.98, 2.17	2.16, 2.35
Width, m	1.0, 1.2	1.0, 1.2	1.0, 1.2	1.0, 1.2
Vertical stiffness, kN/m	40.2	53.0	122.6	154.9
Vertical collapse force, kN	4.02	5.30	12.26	15.49
Lateral stiffness, kN/m	20.1	26.5	61.3	77.5
Lateral collapse force, kN	2.01	2.65	6.13	7.75
Effective impact areas:				
ROPS, m^2	0.020	0.022	0.030	0.032
Tyre, m^2	0.013	0.020	0.024	0.032
Rim, m^2	0.013	0.020	0.024	0.032

$^+$ effective rear mass = $(z_f/(z_f+z_r))$ x measured mass[1]

* tyre+suspension stiffness

$^\#$ distance from ground (1.20 m and 1.39 m above seat)

5.2 Terrain data

The bank geometry and soil parameters are largely as defined by Chisholm in his overturning simulations of large tractors. The outline of the bank is shown in Fig.3. Values for the tyre/soil friction coefficients and the ROPS/soil penetration resistance are difficult to measure and in the absence of any evidence to the contrary have been assumed to be the same as for the large tractors. The values used in the simulations are given in Table 3.

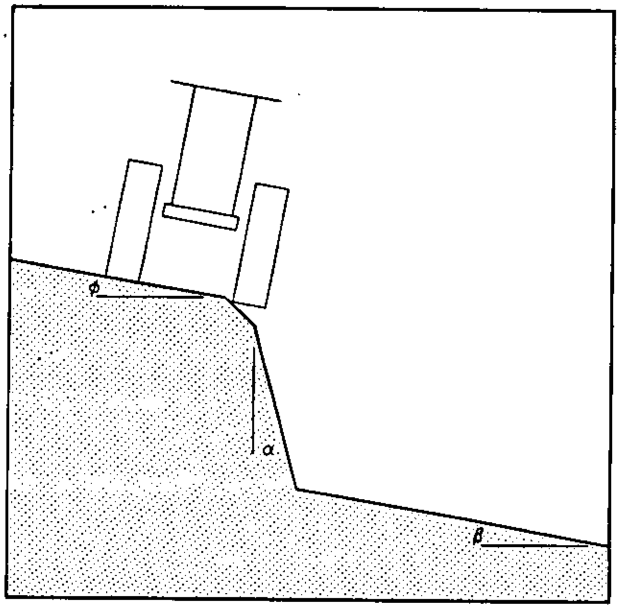


Fig.3 Bank parameters in sideways overturning simulation

Table 3

Bank geometry and soil parameters

Bank height, m		2.25
Bank angle ϕ, degrees		0.0
Bank angle α, degrees		0.0, 7.5, 15.0, 22.5, 30.0, 37.5
Bank angle β, degrees		0.0
Limiting coefficient of soil friction		0.5
Soil cone indices, kN/m^2:	at surface	120
	at 76mm	1032
	at 152mm	1944
	at 229mm	2856
Tractor heading angle, degrees		6.0
Tractor forward speed, m/s		1.5

6. Results and discussion

6.1 General results

Simulations of the four tractors overturning down a bank have been made. The variable parameters have been the bank angle, α, in steps of 7.5° from 0° to 37.5°, the ROPS height, 1.2 m and 1.39 m from the seat height, and the ROPS width, 1.0 m and 1.2 m. A typical overturn is shown in Fig.4, which shows the outline of the tractor at 0.05 s intervals and also time histories of the coordinates of the centre of gravity, θ_g, X_g and Y_g. In this instance the tractor has come to rest on its side. However, the simulations reflect the very variable outcome in real tractor overturns with quite small changes in conditions, as described in accident reports. In a few cases the simulation predicts the tractor overturning down the bank and then righting itself at the bottom, Fig.5 shows an example, but whether this occurs in reality is not known.

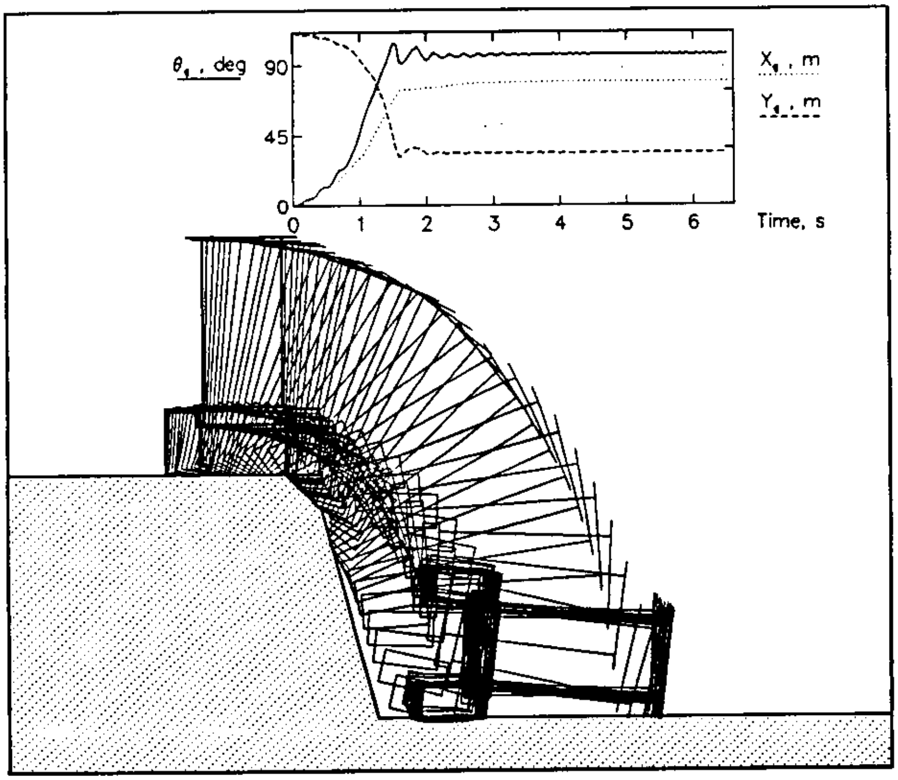


Fig.4 Simulated sideways overturn of TURFTRAK tractor down a 2.25 m high bank, α = 15°, showing tractor outlines at 0.05 s intervals and time-histories of tractor rotation, θ_g, and position of centre of gravity, X_g and Y_g

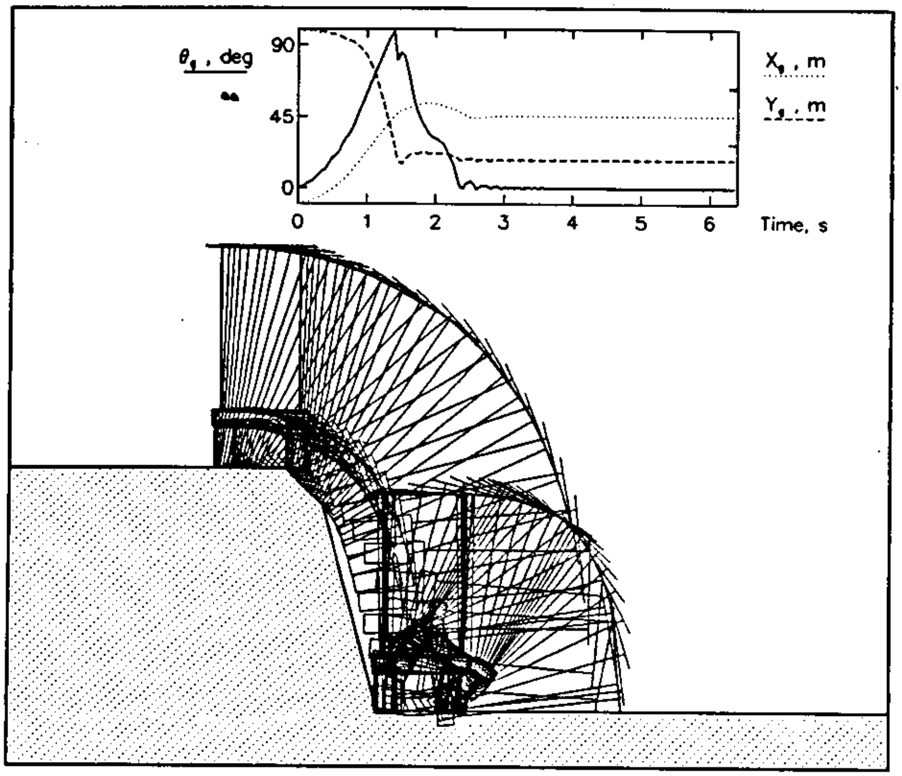
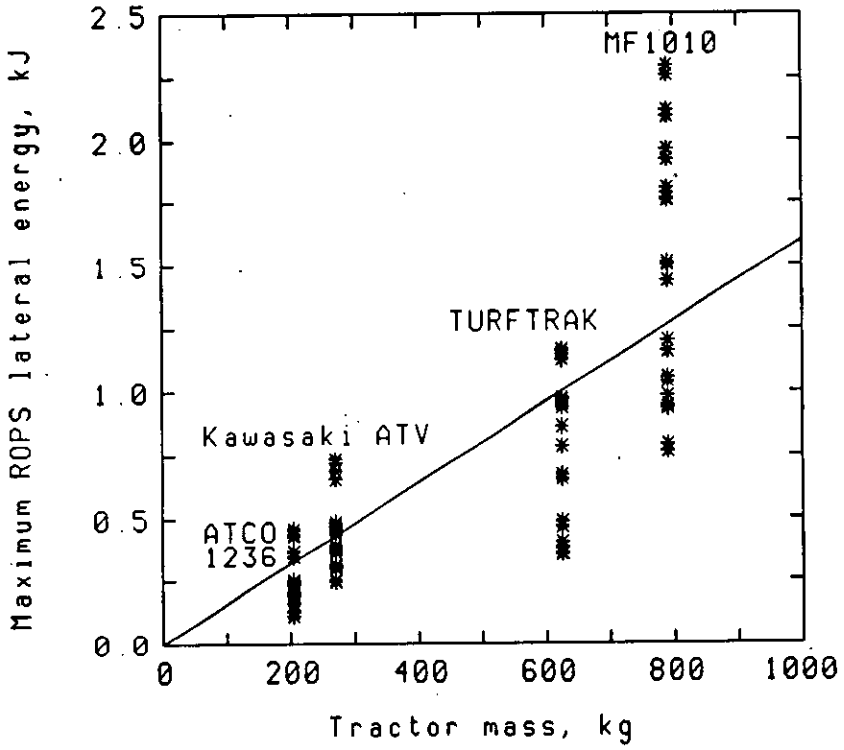


Fig.5 Simulated sideways overturn of ATCO 1236 tractor down 2.25 m high bank, α = 15°, showing tractor returning to an upright final position

6.2 Lateral ROPS energy

The maximum lateral energy absorbed by the ROPS as predicted by each of the ninety-six simulations is plotted in Fig.6 against tractor mass. These simulations do not include the mass of a driver which is discussed in Section 6.3. As expected, Fig.6 shows a wide variation in absorbed energy, depending on subtle variations in vehicle dynamics.



Regression line: Slope=1.60 Joules/kg Corr.coeff=0.93

Fig.6 Maximum lateral energy absorbed by ROPS in sideways overturn down a bank, predicted from simulations at six bank angles and based on measured data from small tractors

The slope of the regression line through the origin is 1.60 Joules/kg with correlation coefficient 0.93. This is less than the 1.75 Joules/kg specified by the static test codes for standard and narrow tractors weighing more than 600 kg, and implies a stepped transition between the two ranges. Assuming the same ratio of 50% between static and pendulum test energies that is used in the large tractor codes is used here, the lateral test energy levels would be:

Pendulum test:	Energy (Joules)	= 3.20 x mass (kg)
Static test:	Energy (Joules)	= 1.60 x mass (kg)

6.3 Effect of a driver on lateral ROPS energy

A tractor driver who may weigh 75 kg will constitute a significant proportion of the total mass on a small tractor, 26% in the case of the ATCO 1236 and 11% in the case of the TURFTRAK. Apart from increasing the total mass, the driver may also significantly change the position of the centre of gravity and the moment of inertia. While all these factors can be taken into account by calculation, the most unpredictable aspect of adding a driver is his movement during an overturn. A driver will instinctively lean away from the direction of overturn and those who do not attempt to jump will be thrown one way or another, however firmly they may try to brace themselves and grip the steering wheel.

An indication of what difference a driver might make is given in Figs.7(a) and (b) which show a simulated overturn of the ATCO 1236 with and without a driver. Estimated parameters for the driver are: mass 75 kg, roll moment of inertia 10 kg/m^2, and centre of gravity 0.1 m above seat centre. The driver is assumed to remain fixed relative to the tractor coordinates throughout the overturn. The tractor rotation at all bank angles is greater when the driver is present, because the overall centre of gravity is higher (0.48 m compared with 0.38 m). The overall roll moment of inertia is also higher (30.2 kg/m^2 compared with 12.8 kg/m^2) and the consequence is that the lateral energy absorbed by the ROPS is between two and six times higher when the driver is present compared with the energy when the driver is not present. However, these are extreme results and must be viewed with caution, this is the smallest of the four tractors and the driver is not a rigid body nor is he rigidly attached to the tractor.

If the ROPS lateral energy is increased to allow for the presence of a driver then the stepped transition in test energies between small and large tractors at 600 kg tractor mass, referred to in 6.2, can be avoided. Increasing the small tractor value of 1.60 Joules/kg, calculated from driverless overturns, by 10% will align the two ranges. The lateral test energy levels would then be:

Pendulum test:	Energy (Joules)	=	3.50 x mass (kg)
Static test:	Energy (Joules)	=	1.75 x mass (kg)

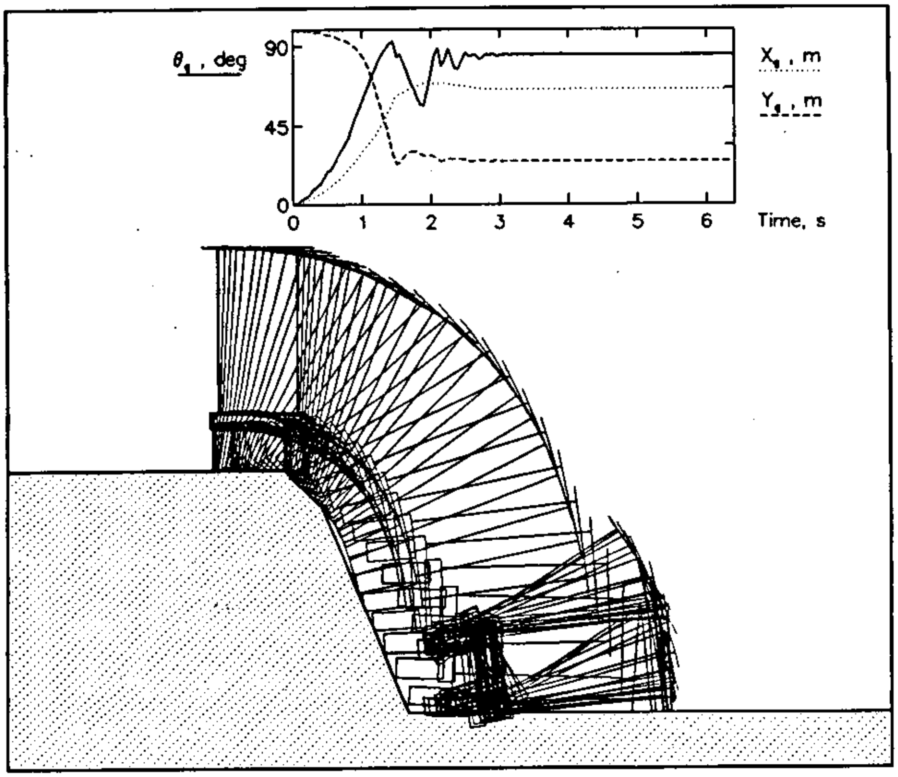


Fig.7(a) ATCO 1236 tractor without driver. Simulated sideways overturn down a 2.25 m high bank, α = 22.5°. Maximum ROPS lateral energy = 0.11 kJ

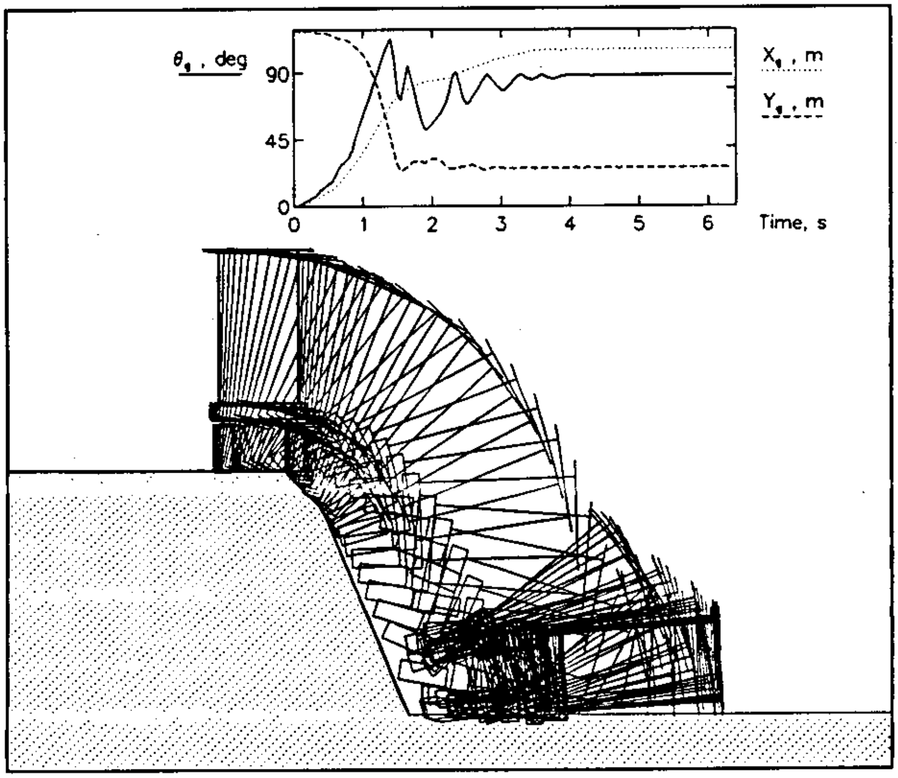


Fig.7(b) ATCO 1236 tractor with driver. Simulated sideways overturn down a 2.25 m high bank, α = 22.5°. Maximum ROPS lateral energy = 0.64 kJ

6.4 Lateral ROPS deflections

The ROPS stiffness and collapse force data used in the simulation, Table 2, give ROPS deflections which are realistic and allow a safe zone of clearance within the structure. The maximum deflection was predicted in a simulation of the TURFTRAK overturning sideways down a 2.25 m high bank, $\alpha = 0°$; Maximum lateral deflection (elastic + plastic) was 195 mm (permanent = 56 mm) and maximum vertical deflection was 43 mm.

6.5 Longitudinal ROPS energy

ROPS damage longitudinally may be due either to rear overturning (rearing), forward overturning, or the longitudinal loading component in a sideways overturn. In practice, rear overturning is uncommon but can be caused by unusual loading or ballasting conditions. Rearward load from towing a heavy trailer or climbing a steep slope will normally lead to rearward slip before instability occurs. If a tractor is heavily ballasted at the rear by an implement this will normally touch the ground first, the combination will slew and what started as a rear overturn will become a side overturn. The most likely cause of a rear overturn in which the rear of the cab absorbs most energy is to fall backwards down a bank.

Most studies have concentrated on rearing since this is the most amenable to analysis, and all the work has involved tractors of 1500 to 5000 kg mass. Boyer, Chisholm and Schwanghart[3] have reviewed and compared many of the energy formulae derived from tests and simulations of tractor rearing. A typical expression is:

$$E = 0.004908\ m^{1.7516}$$

where:

m is the ballasted mass, kg

E is the pendulum test energy, Joules

If this expression is applied to the small tractors the ratio of energy to mass is very small, even for the largest of the small tractors. The ratio for the TURFTRAK (including a 75 kg driver) is 0.67 Joules/kg, while the ratio for the ATCO 1236 is only 0.34 Joules/kg, both well below the figure of 2.33 Joules/kg given in the codes for pendulum tests on standard tractors (static test energy is assumed to be 60% of pendulum test energy). While it is possible to use these figures in a code, they may be inadequate for the other forms of longitudinal loading and they do not give a ratio between lateral and longitudinal energies that is consistent with the large tractor codes. Longitudinal energy in the large tractor code is 80% of lateral energy and intuitively the same would be expected for small tractors. This applies particularly to the longitudinal component in a side overturn.

An approximate dynamic simulation of a tractor falling backwards down a bank has been carried out using an adaptation of Chisholm's simulation program. This gives ROPS longitudinal energy values up to 6 Joules/kg depending on tractor size, bank angle and height, and tyre/soil friction characteristics. Fig.8 shows the effect of bank height and bank angle on the maximum specific energy absorbed by the ROPS in a rear overturn (specific energy is energy divided by tractor mass).

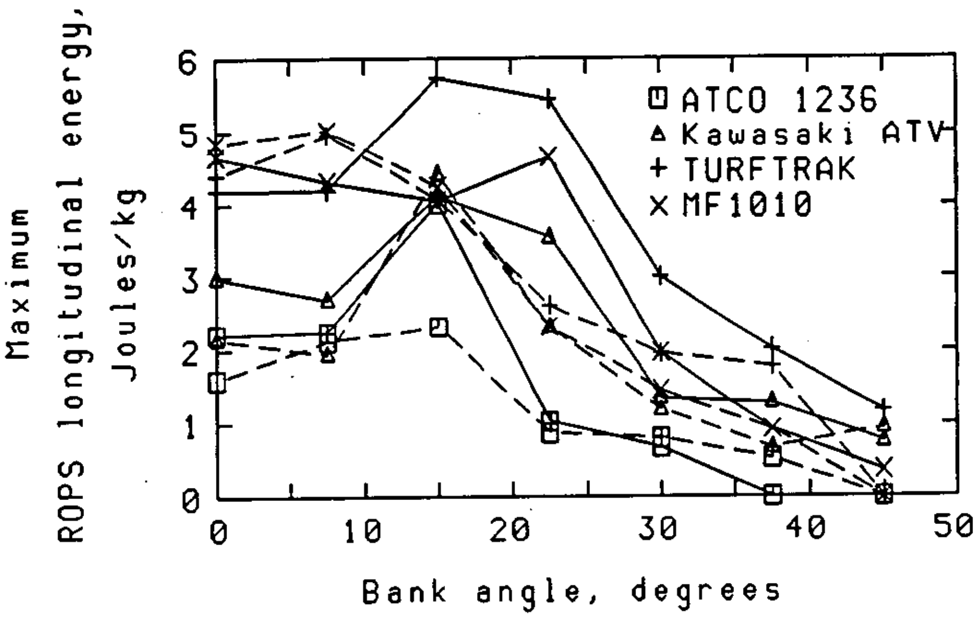


Fig.8 The effect of bank angle α, and bank height on the maximum specific energy absorbed by the ROPS longitudinally in a simulated rear overturn down a bank; bank height -- 1.75 m, — 2.25 m

As α increases (i.e as the bank becomes less steep) the trend is for the specific energy to decrease until a point is reached at about 45° when the tractor no longer overturns. The average specific energy from all bank angles is 2.63 Joules/kg, but for bank angles of 30° and above is 1.25 Joules/kg. Further work is required to reach a definite conclusion as to which energy level should be used for ROPS testing. In the absence of more data it seems appropriate to recommend that the longitudinal static test energy level is maintained at 80% of the lateral test energy level, this would cover overturns down banks of 30° and above. The longitudinal energy levels would then be:

Pendulum test:	Energy (Joules) = 2.33 x mass (kg)
Static test:	Energy (Joules) = 1.40 x mass (kg)

6.6 Vertical ROPS loading

The arguments for a vertical test in which a force equal to twice the tractor weight is applied, are given by Boyer, Chisholm and Schwanghart[3]. In the absence of any information to the contrary and to maintain some uniformity between small and large tractor tests, it is suggested that the same procedure is used for the ROPS on small tractors.

7. Conclusions

The ROPS energy levels encountered in overturns of small tractors with mass less than 600 kg and track width less than 1150 mm have been examined. Accident data are not available so the energies absorbed by the ROPS have been predicted using a computer based dynamic simulation model. Measured geometric and inertial data from four small tractors has been used in simulations of a tractor overturning down a bank. Predicted energies are highly variable and depend on subtle variations in vehicle dynamics and ground contact behaviour. Including the mass of a driver may make a considerable difference to the results, particularly from the smallest tractors, but in practice it depends very much on the actions of the driver during the overturn. The results suggest that the ratios between static test energy and tractor mass in the lateral and longitudinal directions should be about 90% of those used for large tractors. However, to avoid a stepped transition at 600 kg, a 10% allowance for the presence of a driver is recommended to align the two ranges. In the vertical direction the same ratio of load to mass as used for large tractors is recommended. The test energies and loads will then be:

Lateral	Pendulum test:	Energy (Joules) = 3.50 x tractor mass (kg)
	Static test:	Energy (Joules) = 1.75 x tractor mass (kg)
Longitudinal	Pendulum test:	Energy (Joules) = 2.33 x tractor mass (kg)
	Static test:	Energy (Joules) = 1.40 x tractor mass (kg)
Vertical	Crush test:	Load (N) = 20 x tractor mass (kg)

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