Simulation of Tractor Accidents and Overturns

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INTRODUCTION

NUMEROUS accidental and intentional overturns of tractors occur each year in the United States and in the world. The accidental overturns frequently result in serious injury and death (Volpe 1971, Baker 1972). Each overturn provides new information on the dynamic behavior of the tractor but frequently at substantial cost in equipment and sometimes life. Simulation of tractor motion can be a powerful tool in determining tractor dynamics for a variety of situations. Davis (1973) has demonstrated the capabilities of a simulation model for defining the general 3 dimensional motion of an agricultural wheel tractor with an experimental verification using a 1/12 scale tractor model. This encourages the use of the simulation model for full size tractor overturns because the mathematical simulation model and computer program have proven performance not only mathematically but also experimentally.

A parametric study of tractor motion can be valuable in determining the influence of various input data parameters on the tractor motion during an overturn and provides a learning experience without creating a physical model of the vehicle. Among the things that can be learned are the influence of vehicle to surface relationships (traction parameters) upon tractor motion and the amount of energy in the vehicle at impact of the roll over protective structure (ROPS) with the terrain.

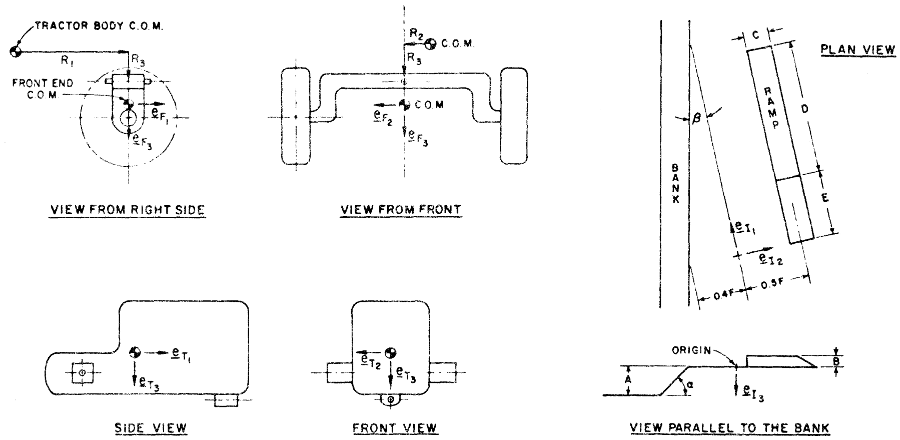

FIG. 1 Coordinate system geometry and definition of the terrain for the tractor motion simulations.

Simulation of tractor motion can give the data necessary for determining the loading on ROPS in an accidental overturn. By observing the influence of steering changes on tractor motion we can learn the proper corrective action for an impending overturn. This may further serve as a training technique for tractor operators in an interactive display of tractor motion. The simulation studies provide data for evaluation of load direction and magnitude to be applied to model ROPS structures and relate to a dynamic structural analysis as shown by Srivastava and Rehkugler (1975).

OBJECTIVES

The objectives of the research reported here were as follows:

1 Demonstrate the capability of SIMTRAC (Davis and Rehkugler 1975) to simulate the overturn described in ASAE standard S306.3 and accidental side overturns of full size tractors.

2 To evaluate the influence of surface-tire parameters on tractor overturns.

3 To evaluate the availability and validity of input data for the simulation model as it may be obtained from published literature and industrial sources.

4 To relate the simulation for full sized vehicles to documented accidental overturns (Baker 1972).

DESCRIPTION OF SIMULATIONS

Three side overturn simulations were completed with a full sized tractor of total weight of 4600 Kg, wheel base 2.57 m and tread width of 2.03 m. Simulations 1 and 2 gave the motion of the tractor as it travelled on a terrain similar to that described in Accident No. 8 by Baker (1972). this simulates tractor motion as the tractor is driven over the edge of the road and upsets. Fig. 1 illustrates the terrain for the simulations. In Simulations 1 and 2 ramp height B = 0, bank height A = 83.8 cm and bank angle a = 28.9 deg. Initial tractor velocity was 19.3 km/h, at a bearing angle of 12 deg with respect to the edge of the ditch bank. Steering is initiated at various times in this basic simulation after the left side of the tractor goes off the edge of the bank. When steering takes place the front wheels are rotated 30 deg to the right. Simulation 1 represented motion on a soil surface, and Simulation 2 consisted of motion on a concrete surface.

Simulation 3 gives tractor motion in the ASAE S306.3 side overturn test. Initial tractor velocity was 16 km/h at a bearing angle of 12 deg with respect to the top of the bank. The front wheels were maintained in the straight ahead position throughout the motion on a soil surface.

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The three simulations were selected to meet the objectives 1, 2 and 4 given previously. They also deal with tractor motion that is of practical interest in determining the manner in which a ROPS impacts with a given surface.

Input Data for SIMTRAC Simulations 1, 2, and 3

Input data for SIMTRAC may be categorized as,

1 Descriptive text
2 Initial conditions
3 Inertial data
4 Tractor geometry
5 Externally applied moments and forces
6 Tire data and surface to tire interface data
7 Operational parameters — steering
8 Terrain geometry
9 Program control—output—integration parameters

SIMTRAC (Davis and Rehkugler 1975) requires a preparation of the data in a precise format. Table 1, however, gives a more descriptive set of data for the simulations reported here so that a person may visualize the general nature of the simulations.

Data for items 1, 2, 4, 5, 7, 8 and 9 are obtained or specified without serious difficulty. Inertial data, tire data and surface to tire interface data are much more difficult to obtain. The validity, precision and accuracy of each data item was subject to careful scrutiny and interpretation.

The descriptive text (1) merely gives a general written description of the simulation. Simulation 1 is given as an example. The initial conditions (2) are given for the 3 simulations in accordance with coordinates defined in Fig. 1. Inertial data (3a) was obtained by scaling from a model tractor body as used by Davis (1973). This scaling of inertial values was done for the tractor body I_{22} on the basis of the mass ratio times the length ratio squared from prototype to model. The other values of the tractor body mass moments of inertia were assigned values based on the inertia matrix obtained by Hanford (1974) who scaled these mass moments of inertia on the basis of the geometry of the full sized tractor body. The values for the tractor body are approximately one half the values provided by Smith (1975) for a whole tractor of nearly the same size. This seems reasonable because the tractor body mass moments of inertia should be much smaller because the contributions of the rear wheels and front end are eliminated.

Mass moments of inertia for the front end and rear wheel (3b, c) were obtained in the same fashion as described for I_{22} of the tractor body. Goering and Buchele (1967) give the values of I_{22} of a rear wheel of 1250 cm·kg·sec^2 for a slightly smaller wheel. Based on the wheel dimensions, weight, the assumption of a liquid filled tire, and radial position of the mass concentration at the center of the tire a value of 2130 cm·kg·sec^2 is calculated for I_{22} of the rear wheel. This compares well with the scaled value shown in Table 1. Tractor weights (3d) and tractor geometry (4a, b, c, d) were obtained by direct measurement. Stiffness of the front end rotation stop (4d) was determined by considering the front axle to be a cantilever beam and using the deflection of the beam as a determinant of equivalent rotation of the front axle (Hanford 1974). Damping at the front end stop was scaled from the model tractor data of Davis (1973).

Tire rolling resistance data (6a, b) were obtained from Schwanghart (1968) and Krick (1973) for operation on soil and from Barger et al. (1973) for operation on concrete. Schwanghart's data was obtained for a 5.50-16.00 tire in loose soil so these rolling resistance values were used for the front wheel. The values for the rear wheel were reduced in proportion to increased diameter of the rear wheel as shown by Gill and Vanden Berg (1967) p. 390. The rolling resistance coefficients for concrete apply to 11.25-36 tires and are not significantly influenced by slip angle.

Rear and front tire damping coefficients were determined from Raney et al. (1961) by mass and geometry scaling from the tractor size used by them and the tractor modelled here. The values are in the neighborhood of values of tire damping coefficients given by Davisson (1969) as ranging from 1.8 to 35 N·sec/cm.

The tire radial force-deflection data was obtained by direct static measurement. The values given in 6e are 5 percent greater than the static values to account for dynamic effects on tire spring rates (Thompson, et al. 1972). Other researchers indicate that dynamic spring rates may be even higher (Raney et al. 1961 and Matthews and Talamo 1965).

Gross coefficient of traction-rear wheel slip data (6f) for soil was obtained from Krick (1973). The values for concrete were obtained from Gill and Vanden Berg (1967) p. 419 for a 12-28 pneumatic tire. These data values were obtained by reading from the graphical values given in each of the publications.

Lateral force coefficients versus slip angle (6g) for soil were derived from Schwanghart (1968) and Krick (1973) data at 5 percent slip. Slightly different values are given for front and rear tires because of different tire diameters. Lateral force coefficients for operation on concrete were obtained from Schwanghart (1968) for a 5.50-16 tire pressurized at 1 atmosphere. Tire size and air pressure were observed to have little effect on the lateral coefficients on a concrete surface.

Steering for the three simulations (7) was defined as required to match the overturn situation modelled. Zero steer angle was established for simulation of Accident No. 8 until 1.83 or 1.41 sec into the simulation and then changed to 30 deg right for the remainder of the time. Study of Accident No. 8 data from Baker (1972) indicates that steering may have taken place about 0.8 sec after the left wheels went off the edge of the road. In the ASAE S306.3 side overturn, steering is maintained at 0 deg for the entire time of the test.

Terrain geometry (8) was established on the basis of the data from Baker (1972) for Accident No. 8 (Simulations 1 and 2) and from ASAE S306.3 for Simulation 3. Note that rear tractor tread width is given two different values. Actual rear tire centerline to centerline tread width is needed for the Simulation 3 but for 1 and 2 this value only establishes the location of the inertial axes coordinate system relative to the edge of the road.

Program control (9) was established to give printed output for every 0.1 sec during the simulation and data for plotting a pictorial representation of the tractor was printed every 1.0 sec. The length of time simulated was limited to 4.0 sec or until the time when one of the monitored points on the tractor passed through the limiting elevation set in the program.

RESULTS OF SIMULATIONS

Simulation 1

Accident No. 8 — Soil

Simulation 1 — Positions

Simulation 1 was carried out with two variations in the basic simulation of an overturn on a roadside ditch bank. Figs. 2 and 3 show the plan and elevation views of tractor position for a bearing angle of 12 deg and steering angle of 30 deg to the right at 1.83 sec (Sim. 1a) and 1.41 sec (Sim. 1b). The four upper corners of the ROPS and the center of mass (C.O.M.) of the tractor body are plotted at various positions to give the impression of tractor orientation. Wheel centers are shown at some positions to give further insight on tractor position. The position of the right rear ROPS point is shown at 0.2 sec intervals throughout the overturn to give an indication of the tractor path. Final position of the tractor is indicated at 2.6 sec (Figs. 2 and 3) when the left rear ROPS points exceeds +83.8 cm in the e_{I_3} direction.

Figs. 2 and 3 show the tractor travelling off the level road surface onto the roadside bank initially orienting itself at a greater angle to the left. When steering occurs the tractor front end tends to skid forward until the flat area at the bottom of the bank is encountered. The tractor then swings to the right and overturns with a roll to the left. When the steering is initiated at 1.83 sec (Fig. 2) the overturn is complete 0.77 sec later at 2.6 sec. Steering at 1.41 sec (Fig. 3) produces a complete overturn 1.19 sec later at 2.6 sec. In the latter case the tractor continues to skid down the embankment for a longer period of time before the overturn is completed.

The final position of the tractor of Accident No. 8 described by Baker (1972) is approximated in the plan view of Fig. 2. The tractor is upside down with the e_{T_1} axis of the tractor at about an 80 deg angle with the top of the bank line. The final positon of the Accident No. 8 tractor is similar to Simulation 1a and 1b but certainly they are not equal in orientation. If the ROPS was removed from the simulated tractor it is expected the overturn would continue and it is possible that the continued motion of the simulated tractor would carry it to an upside down position more closely oriented with respect to the Accident No. 8 data.

Tire Forces—Fig. 4 illustrates the front and rear tire forces during the overturn simulation of Accident No. 8. Early in the overturn simulation there is a slightly periodic fluctuation in the tire forces at about 2.5 Hz indicating a low amplitude bouncing of the tractor. At 0.9 sec there is a drop in the left rear tire force as it passes over the edge of the bank. The right rear tire force rises shortly thereafter. As the tractor continues over the bank the forces on the left front and left rear tires increase as the opposite side tire forces are reduced. At 1.8 sec the forces on both left tires rise rapidly while the tire forces on the right side of the tractor go to zero. As the tractor continues to roll to the left it tends to bounce forward onto the front left tire as shown by the high forces on left front tire. The

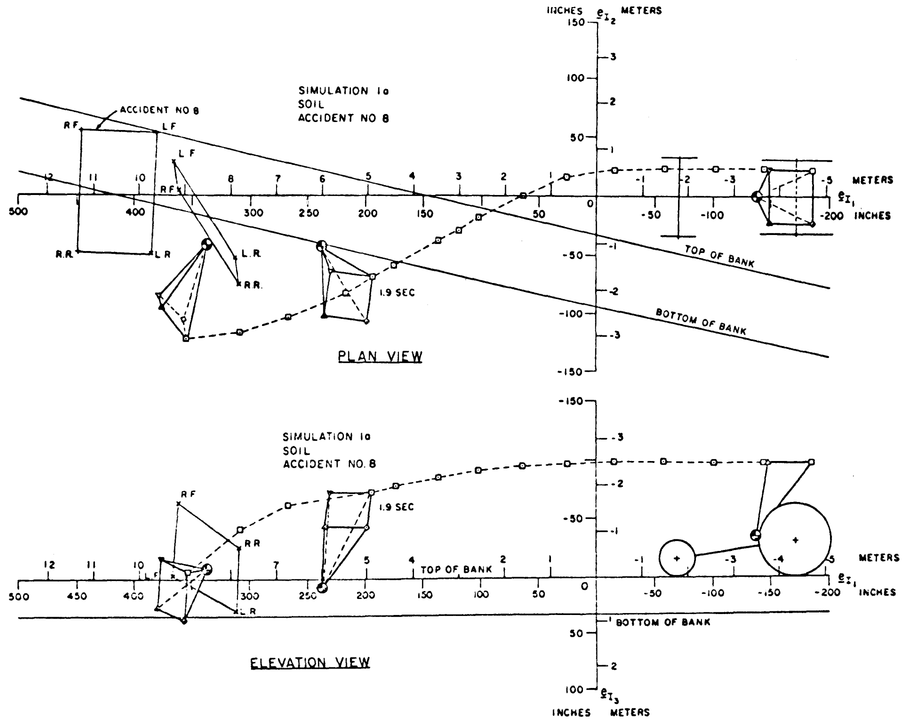

FIG. 2 Plan and elevation views of tractor positions in Accident No. 8 simulation [Sim. 1a] on soil with steering at 1.83 sec.

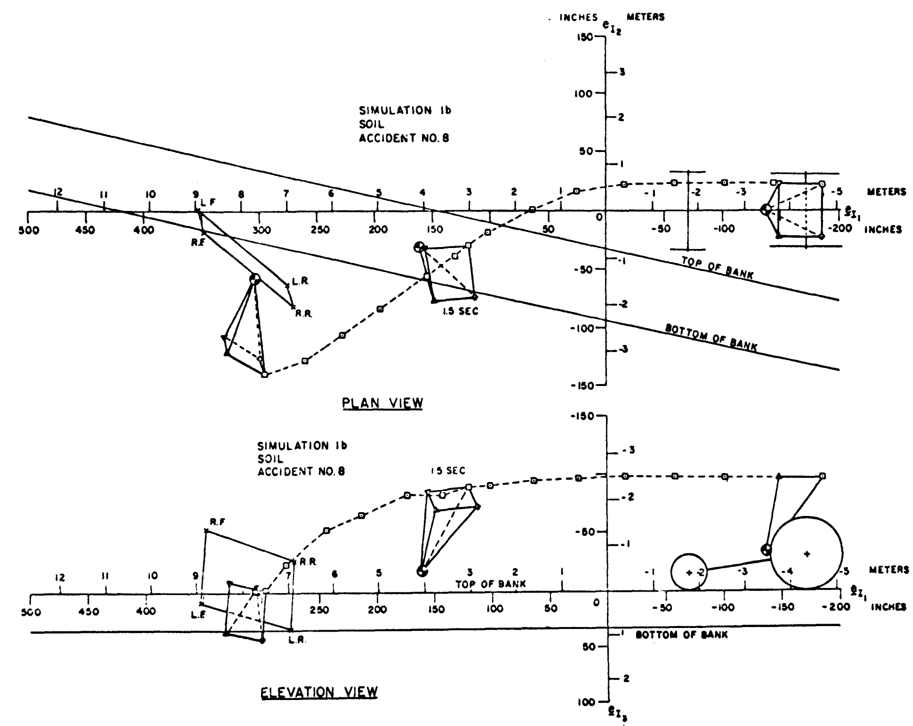

FIG. 3 Plan and elevation views of tractor positions in Accident No. 8 simulation [Sim. 1b] on soil with steering at 1.41 sec.

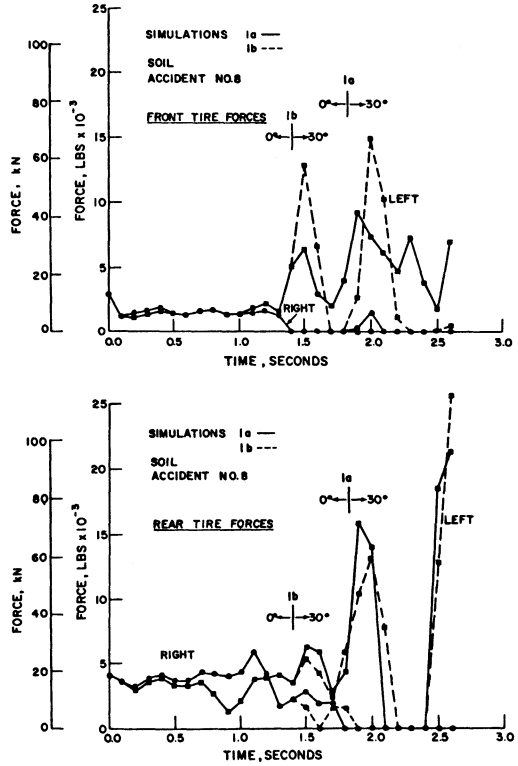

FIG. 4 Magnitude of the three vector sum of tire forces on each tire during the Accident No. 8 overturn simulation [Sim. 1a,b], on soil.

bounce is severe enough to reduce both rear tire forces to zero. Finally the tractor strikes the ground at 2.6 sec with the left rear tire, the left rear ROPS and the left front wheel. The magnitude of the force on the left rear tire indicates a severe impact with the soil at that point.

The force diagrams of Fig. 4 for Simulations 1a and 1b are somewhat different after 1.4 sec because of the different steering times. Rear tire forces are quite similar throughout both the overturns. However, the left front tire force rises quickly at 1.5 sec (Simulation 1b) just after steering occurs. A second peak occurs during the overturn period (Simulation 1b). For steering at 1.83 sec (Simulation 1a) a series of smaller magnitude left front tire force fluctuations are observed.

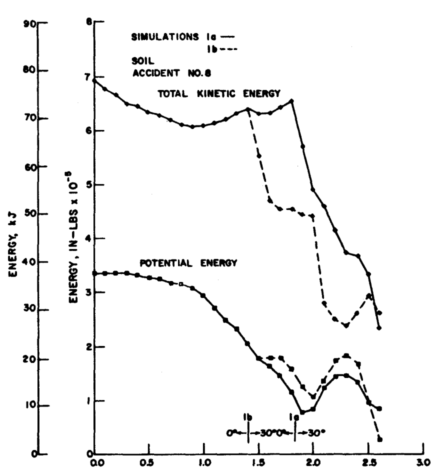

FIG. 6 Total kinetic energy and potential energy at 0.1 sec intervals for Accident No. 8 overturn simulation [Sim. 1a,b] on soil.

Energies—Figs. 5 and 6 illustrate energy values throughout the overturn. During the first second there are small reductions in translational, rotational and total kinetic energy as some of the energy is dissipated in overcoming rolling resistance. When the tractor passes over and down the bank there is a rapid loss of potential energy with some rise in kinetic energy. Just after steering there is a rapid loss in kinetic energy as the tractor skids on the soil surface. The continued skidding of all four tires and the overturn causes a rapid reduction in the total kinetic energy. A substantial loss of energy during the overturn is obvious because not only is there energy loss as measured by total kinetic energy, but the potential energy from lowering the center of mass is also being converted into kinetic energy during the overturn.

The peak in potential energy between 2.0 and 2.5 sec indicates a lifting of the center of mass as the tractor overturns. This also is mirrored in the rotational and translational kinetic energy values being reduced.

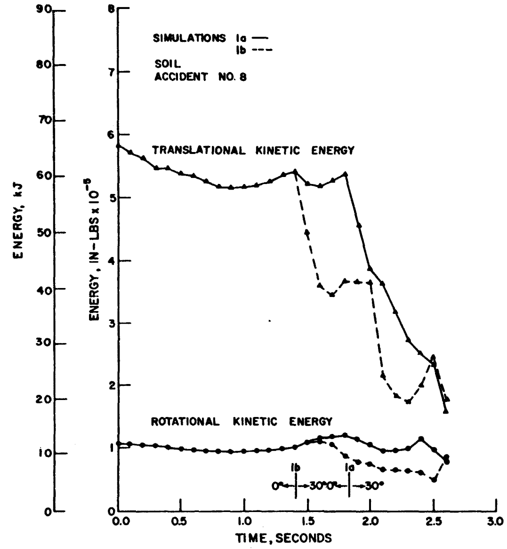

FIG. 5 Translational kinetic energy and rotational kinetic energy at 0.1 sec intervals for Accident No. 8 overturn simulation [Sim. 1a,b] on soil.

Steering at an earlier time (1.41 sec) caused significant change in the energy curves over steering at 1.83 sec. The final energy values, however, except for potential energy are quite similar. The final total kinetic energy for the two variations in steering for this overturn were approximately 33 percent (1.83 sec) and 38 percent (1.41 sec) of the original total kinetic energy. We conclude that a large portion of the kinetic energy in this system is dissipated in skidding of the tractor during the overturn.

The energy input to a tractor ROPS for the ASAE standard S306.3 pendulum test for this tractor would be 12,050 Joules impacting at a velocity of 347 cm/sec. The total kinetic energy in the tractor as observed from the simulations is 26 430 Joules (1.83 sec steering) and 29 600 Joules

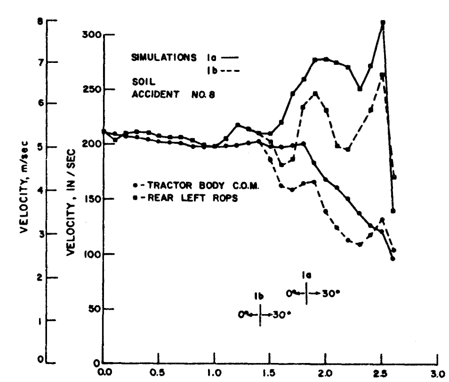

FIG. 7 Magnitude of the vector sum of the velocities of the tractor body C.O.M. and the rear left ROPS at 0.1 sec intervals during the Accident No. 8 overturn [Sim. 1a,b] on soil.

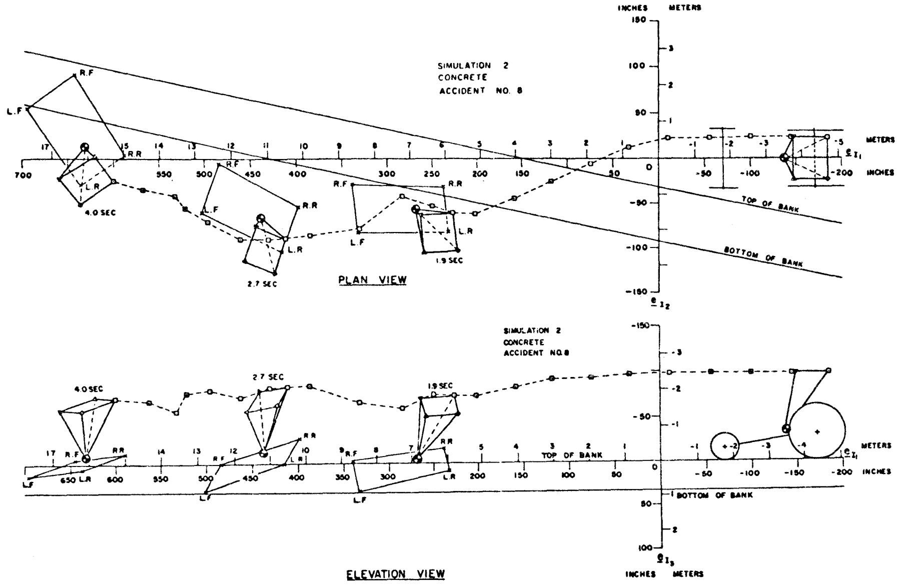

FIG. 8 Plan and elevation view of tractor positions in the motion simulation [Sim. 2] on a concrete surface.

(1.41 sec steering). Obviously because the left rear tire and left front tires contact the ground as well, the ROPS will not have to dissipate the total energy observed.

Velocities—Fig. 7 gives the magnitude of the velocity of the tractor body C.O.M. and rear left ROPS. During the overturn period after 1.4 sec there is a rapid reduction in the tractor body C.O.M. velocity which also is reflected in the drop in translational kinetic energy in Fig. 5. As the tractor overturns the rear left ROPS point reaches a high velocity but then falls sharply just before impact with the soil. Impact velocity magnitudes are 356 cm/sec (1.83 sec steering) and 437 cm/sec (1.41 sec steering). It is interesting to note that the ASAE standard S306.3 pendulum test velocity would be 348 cm/sec. The velocities components in the initial direction of travel are 216 and 229 cm/sec (tractor body C.O.M.) and 89 and 46 cm/sec (rear left ROPS) respectively for steering at 1.41 and 1.83 sec. The velocity components perpendicular to the soil surface for the rear left ROPS are 411 cm/sec (1.41 sec steering) and 330 cm/sec (1.83 sec steering).

Simulation 2

Accident No. 8 — Concrete
Simulation 2 — Positions

Simulation 2 was completed with the tractor operating on a concrete surface with the same initial conditions and steering used in Simulation 1. Tractor motion as shown in Fig. 8 was substantially different and the tractor did not overturn. (Refer also to Fig. 9 for the forces occurring at various times in the simulation to give insight into the tractor motion). The tractor angled off to the left as it proceeded over the embankment. When steering of 30 deg to the right was instituted at 1.83 sec the tractor tended to skid forward with only a slow response to the steering action. A slight roll to the left occurred but the tractor righted itself and continued to swing to the right. At approximately 2.2 sec the tractor bounced off the right rear tire and rolled to the left. It then bounced on the left rear tire at 2.5 sec with sufficient velocity to become air borne at the rear. This was followed by a second bounce on the left rear tire in the period from 2.8 to 3.2 sec, a third bounce on both rear tires at 3.4 to 3.8 sec and a final roll to the left at 4.0 sec at which time the simulation was terminated.

The tractor did not overturn in this simulation because the concrete surface did not provide sufficient lateral forces during the steering maneuver. Several partial rolls to the left were observed but there never was sufficient force or momentum to complete the overturn. After 4.0 sec of simulation time the remaining energy in the system was not sufficient to cause an overturn at a later time.

Forces—Front and rear tire forces

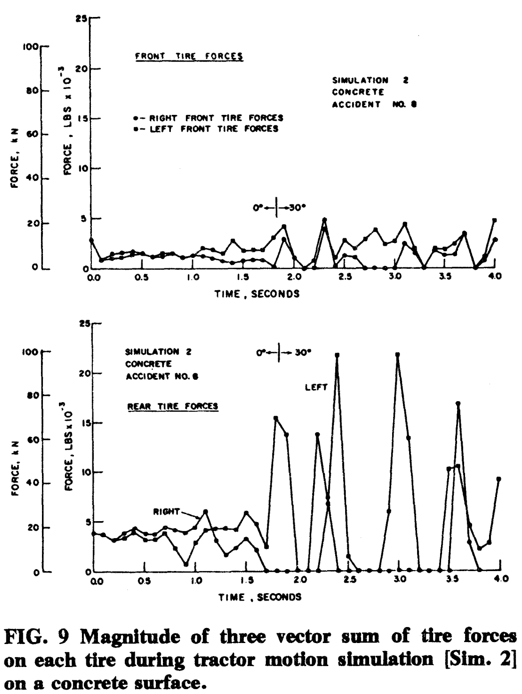

FIG. 9 Magnitude of three vector sum of tire forces on each tire during tractor motion simulation [Sim. 2] on a concrete surface.

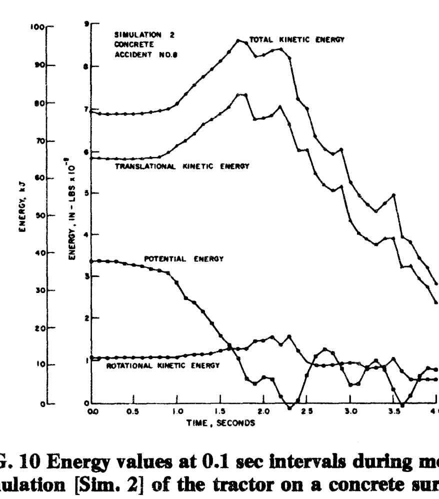

FIG. 10 Energy values at 0.1 sec intervals during motion simulation [Sim. 2] of the tractor on a concrete surface.

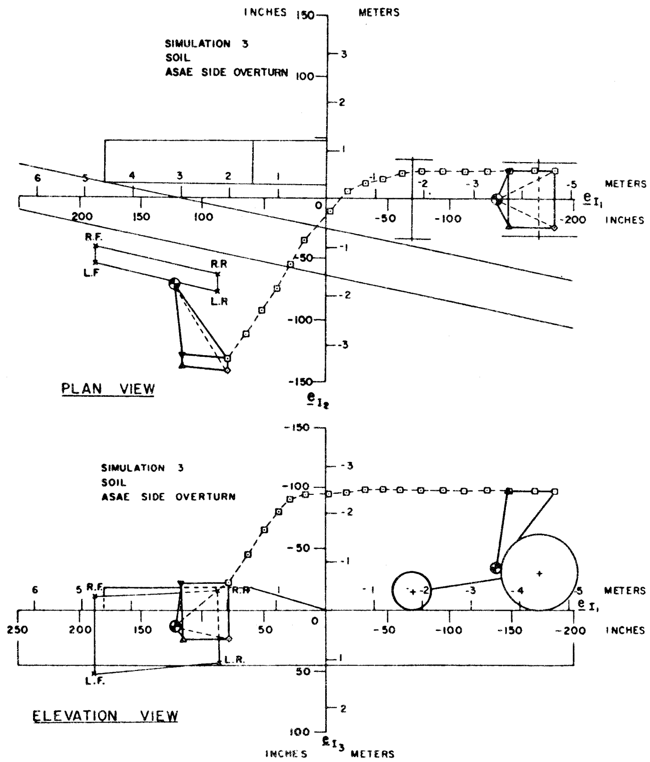

FIG. 11 Plan and elevation views of simulation tractor positions [Sim. 3] during overturn on the ASAE S306.3 standard side overturn course [Soil surface].

(Fig. 9) vary periodically with time, especially after steering to the right 30 deg at 1.83 sec. Both rolling (rotation about the e_{T_1} axis) and bouncing are apparent as measured by the variations in the left and right rear tire forces. Three bounces on the left rear tire are observed between 1.7 and 3.6 sec which gives a bounce frequency of approximately 1.6 Hz. Large forces are observed on the rear tires as a result of the bouncing movement of the tractor.

Energy—Fig. 10 illustrates the distribution of energy throughout the simulation. Beginning at 0.9 sec there is a rapid decrease in potential energy with a rise in translational energy. This continues as the tractor moves over the edge of the bank and picks up speed as it moves to a lower level. The slight rise in rotational kinetic energy in the interval 0.9 to 1.8 sec is due to increased rear wheel angular velocity. After steering at 1.83 sec, skidding, bouncing and rolling of the tractor occurs. Skidding causes a loss of translational kinetic energy and some loss of rotational kinetic energy. Bouncing and rolling produces fluctuations in potential energy. Fluctuations in rotational kinetic energy are produced by the side to side rolling of the tractor, but the gradual decline in rotational kinetic energy is a result of the reduced velocity of the tractor caused by skidding forces applied to the tires by the concrete surface. Because the tractor is not powered the kinetic energies would eventually become zero.

ASAE S306.3
Side overturn on soil
Simulation 3 — Positions

Positions—The ASAE S306.3 standard overturn course is illustrated in Fig. 11 with the tractor overturn plotted to show the motion. The tractor motion constitutes a rapid overturn to the left with the left front axle center contacting the soil at the 114 cm e_{I_3} level which stops the simulation at 1.7 sec. Continued roll to the left would bring the left side of the ROPS into contact with the soil. At the end of the simulation the e_{T_1}, axis is nearly parallel to the bank. It appears that the left front point of the ROPS would be the first ROPS point to strike the soil. The right rear ROPS path is traced at 0.1 sec intervals and shows a smooth roll to the left with increasing velocity near the end of the simulation.

Forces—Fig. 12 shows an immediate drop in both front tire forces as the left front tire drops over the edge of the bank. The front tire forces rise after that as the tractor drops down at the front end. At o.6 sec the right front tire force rises quickly as the wheel climbs the inclined ramp of the overturn test course. At the same time that the force on the left rear wheel increases there is a drop in the right rear tire force. Continued movement of the tractor brings the right rear tire onto the inclined ramp at 0.9 sec with a rapid rise in the right tire force. Somewhat later the left rear tire force increases and following a bounce when both front and rear tire forces become zero, the roll continues to the left and both the left rear and left front tire forces reach high levels.

Energy—Fig. 13 shows translational kinetic energy reaching a minimum at about 0.9 sec, just prior to the beginning of the tractor roll to the left. As soon as the overturn begins we note a rapid drop in potential energy. This continues for the rest of the overturn period from 0.9 to 1.7 sec. In the same time period translational kinetic energy increases rapidly. There is an increase in rotational kinetic energy due to the increased angular velocity of the tractor. At the end of the simulation 1.7 sec later, the total kinetic energy is about 73 440 Joules which is a significant increase over the initial kinetic energy of about 54 230 Joules.

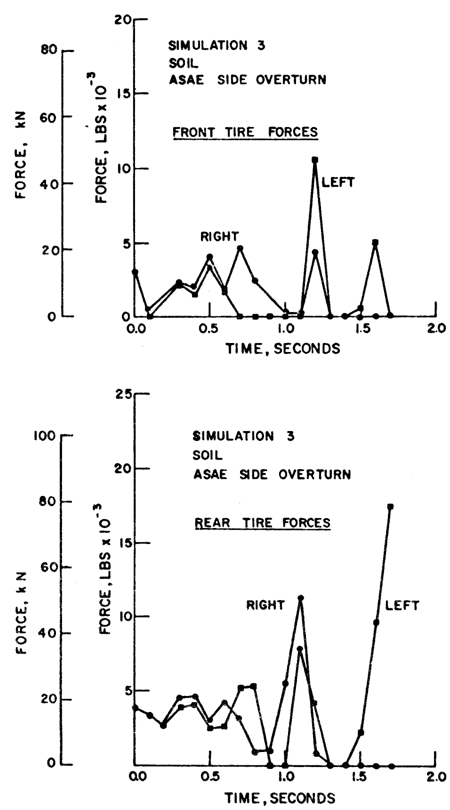

FIG. 12 Magnitude of the three vector sum of forces on each tire during the simulated ASAE overturn [Sim. 3].

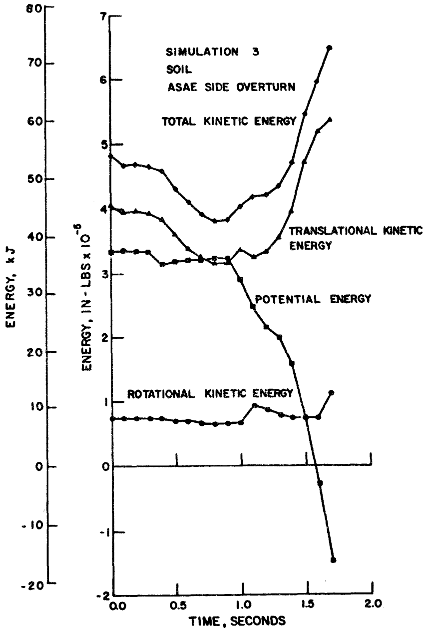

FIG. 13 Energy values at 0.1 sec intervals during the simulated ASAE tractor overturn [Sim. 3].

The energy input to the ROPS for the ASAE Standard S306.3 pendulum test would be about 12 090 Joules. Once again it appears that impact of the left rear and left front tires and wheels with the soil will dissipate a large portion of the energy in the soil.

Velocities—The velocity magnitude of the rear left ROPS and the tractor body C.O.M. increase with time throughout the overturn (Fig. 14). The tractor body C.O.M. velocity is 323 cm/sec forward, 239 cm/sec to the left and 318 cm/sec downward at 1.7 sec. The velocity components of the rear left ROPS are 300, 175 and 701 cm/sec respectively for the same directions as the tractor body C.O.M. From these component velocities we conclude that at impact the tractor will be moving forward at a velocity about 70 percent of the original forward velocity, but the approach velocity for impact perpendicular to the soil for the left rear ROPS point is much higher than the original tractor velocity.

INTERPRETATION AND COMPARISONS

Simulations 1a and 1b demonstrate some of the effects of steering at different times into the simulation of tractor overturn on a soil roadside bank. Steering at different times may have only a small influence on tractor motion if lateral steering forces are not adequate to reorient the tractor. This phenomenon is particularly demonstrated in the tractor motion simulation on a different surface such as concrete. Although all other parameters were identical except for surface characteristics, an attempt to overturn the tractor on a concrete surface for Accident No. 8 conditions resulted in only skidding, rolling and bouncing. Fig. 15 shows a comparison of left tire forces in the surface plane for the two different surfaces. Much higher forces on the left front tire were developed shortly after steering at 1.83 sec for motion on a soil surface. This helped to establish conditions for overturn of the tractor.

When a tractor turns and skids on the terrain surface, a large amount of energy is dissipated before impact occurs. This was true of both the overturn in Accident No. 8 on soil and the motion on concrete. In the case of overturn on the ASAE side overturn test, however, there was very little skidding to cause dissipation of energy. The reduced potential energy resulted in a high total kinetic energy at impact.

Data for the simulations was derived from a number of sources and should be subject to careful scrutiny before final conclusions can be reached about the simulation results. Because tire to surface interactions are critical in defining the overturn, it is important that further research be done on tire-terrain interactions for both free rolling and driven tires. Additional data should be obtained for dynamic tire spring rates to assure the use of appropriate tabular values in the simulation.

Data on mass moments of inertia of tractor components are difficult to obtain experimentally and are not readily available from published literature. The sensitivity of the overturns to mass moment of inertia values was not established here but based on elementary dynamics we would expect tractors with higher mass moments of inertia to overturn more slowly and to be less responsive to steering changes.

A comparison of the tractor final position in the field observation of Accident No. 8 (Fig. 2) with the simulated position shows some similarities. Because the simulated tractor is only roughly comparable to the actual tractor position in the accident and because the steering; and bearing angle are essentially unknown for the real accident we feel that the simulation result is a reasonable reconstruction of the original accident.

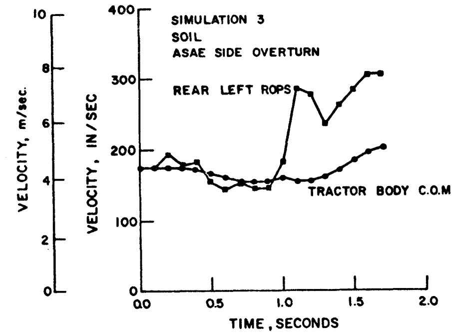

FIG. 14 Magnitude of the vector sum of the velocities of the tractor body C.O.M. and the rear left ROPS at 0.1 sec intervals [Sim. 3].

CONCLUSIONS

1 We feel that these simulations have demonstrated the capabilities of SIMTRAC to simulate both the ASAE standard S306.3 side overturn and accidental overturns of full sized agricultural wheel tractors because we are able to demonstrate a tractor behavior similar to real overturns.

2 The influence of surface-tire parameters has been demonstrated to have a significant effect on tractor overturns. For identical conditions, other than surface to tire parameters, it was shown that on soil the tractor would overturn, but on concrete the tractor would only skid, bounce and roll from side to side.

3 It was possible to obtain sufficient input data to conduct the simulations only by scaling some values that were not available directly from industrial or published literature sources. Wherever possible comparative checks were made with published values. We are confident that the errors in input data are not orders of magnitude errors but we do recognize that some values may need refinement.

4 A comparison of a simulated

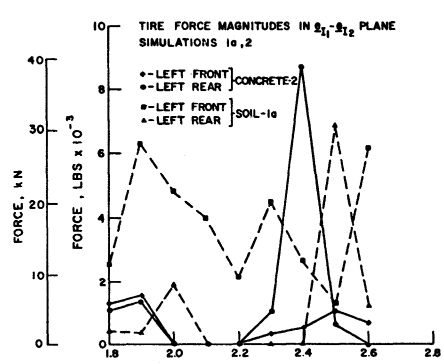

FIG. 15 Magnitude of the two vector sum of left tire forces in the plane of the surface during the time interval following steering for motion on soil [Sim. 1a] and on concrete [Sim. 2].

TABLE 1. ABBREVIATED DATA DESCRIPTION FOR A SIDE OVERTURN SIMULATION FOR A FULL SIZED TRACTOR.*

1. Descriptive Text. (Example[1])
RUN FOR AN UNPOWERED FULL SIZE TRACTOR — STEERING ANGLE ZERO DEGREES UNTIL TIME 1.83 SEC — THEN 30 DEGREES — OVERTURN ON A DITCH BANK — INITIAL VELOCITY — 12MPH 211 IN./SEC — SIMULATION OF ACCIDENT =8 WITH IMPROVED SOIL TO TIRE FORCE PARAMETERS

2. Initial Conditions — Refer to Fig. 1 for the coordinate system directions.

	e_{11}	e_{12}	e_{13}
a. Tractor body c.o.m. position-cm.	-351.5	0.0	-86.6
Tractor body c.o.m. velocity-cm/sec	447.0[3]	0.0	0.0
b. Direction cosines - Tractor body	1.0	0.0	0.0
	0.0	1.0	0.0
	0.0	0.0	1.0
c. Initial angular velocity of the tractor body - Rad/sec	0.0	0.0	0.0
	0.0	0.0	0.0
d. Initial angular position and velocity of the tractor front end relative to the tractor body - Rad and Rad/sec	0.0	0.0	

3. Inertial data

a. Mass moments of inertia - Tractor body - kg - cm - sec^2			
I_{11} I_{12} I_{13}	8751.0	0.0	-71.4
I_{21} I_{22} I_{23}	0.0	26677.0	0.0
I_{31} I_{32} I_{33}	-71.4	0.0	35252.0
b. Mass moments of inertia Front end - kg - cm - sec^2	1016.0	0.0	-108.0
	0.0	310.0	0.0
	-108.0	0.0	992.0
c. Mass moments of inertia Rear wheel - kg - cm - sec^2	1583.0	0.0	0.0
	0.0	2532.0	0.0
	0.0	0.0	1583.0
d. Weights of tractor components - kg - Tractor body	3348.0		
Front end	172.0		
Rear wheel	540.0		

4. Tractor geometry

a. Vector components in the tractor axes directions from tractor c.o.m. - cm	e_{T1}	e_{T2}	e_{T3}
Center of left rear wheel	-85.4	-78.5	11.3
Center of right rear wheel	-85.4	78.5	11.3
Hinge point for front end	171.2	0.0	18.0

b. Vector components in the front end axes directions - cm	e_{F1}	e_{F2}	e_{F3}
Hinge point to front end c.o.m	0.0	0.0	18.5
Front end c.o.m. to left front wheel turning point	2.5	-84.6	12.2
Front end c.o.m. to right front wheel turning point	2.5	84.6	12.2

c. Vector components in tractor axes directions from tractor c.o.m to point in tractor - cm	e_{T1}	e_{T2}	e_{T3}
Front right ROPS	-27.0	59.7	-158.9
Front left ROPS	-27.0	-59.7	-158.9
Rear right ROPS	-119.7	59.7	-158.9
Rear left ROPS	-119.7	-59.7	-158.9

d. General geometry and tractor characteristics

Radius rear wheel - cm	82.5
Radius front wheel - cm	40.6
Front axle length - cm	17.1
Toe in - radius	0.0078
Camber - radians	0.1856
Caster - radians	0.0825
Maximum rotation of the front end - radians	0.471
Hinge point to front end stop - cm	21.6
Stiffness of front end rotation stop - N/cm	10.5 x 10^6
Damping of front end rotation stop - N.sec/cm	506.0

5. No externally applied moments or forces.

6. Tire and tire-surface interface data

a. Rolling resistance - rear wheel	0.100 + 0.001 Θ[1,3]
(Θ = slip angle - degrees)	0.015 + 0.0001 Θ[2]
b. Rolling resistance - front wheel	0.200 + 0.002 Θ[1,3]
	0.038 + 0.0002 Θ[2]
c. Rear tire damping - N - sec/cm	18.90
d. Front tire damping - N - sec/cm	56.65

e. Tire radial force - deflection data

Force - N	Rear Tire	Deflection - cm
0.0		0.0
3456.0		1.35
6259.0		2.49
13340.0		5.08
26690.0		7.62
	Front Tire	
0.0		0.00
3923.0		1.27
5213.0		1.91
6352.0		2.54
12900.0		5.08

f. Gross coefficient of traction - rear wheel slip

C.O.T.		slip	
1,3	2	1,3	2
0.0	0.00	0.04	0.00
0.17	0.28	0.09	0.04
0.30	0.44	0.14	0.07
0.41	0.60	0.19	0.10
0.47	0.74	0.24	0.16

g. Lateral force coefficients versus slip angle - degrees

L.F.C.		Rear Tire Slip angle	
1,3	2	1,3	2
0.00	0.00	0.0	0.0
0.22	0.20	6.0	4.0
0.34	0.34	12.0	8.0
0.52	0.42	18.0	12.0
0.68	0.45	24.0	16.0
	Front Tire		
0.00	0.00	0.0	0.0
0.19	0.20	6.0	4.0
0.38	0.34	12.0	8.0
0.56	0.42	18.0	12.0
0.74	0.45	24.0	16.0

7. Operational parameters - steering

Steer angle - radians		Time - sec	
1,2	3	1,2	3
0.0	0.0	0.0	0.0
0.524	0.0	1.83	↓
0.524	0.0	4.00	4.00

8. Terrain geometry	1,2	3
Bank height - cm	83.8	114.0
Ramp height - cm	0.0	45.7
Ramp width -cm	0.0	91.4
Ramp length - m	1.02	0.305
Ramp incline length - cm	152.0	152.0
Rear tread width tractor - cm	203.0	157.0
Bank slope from horizontal - degrees	28.9	50.0
Bank bearing angle from e_{I1} axis - degrees	12.0	12.0
Elevation at which simulation stops - cm	83.8	114.0

9. Program control (see Davis and Rehkugler 1975)

*Superscript 1 = Overturn on a soil bank - Simulation 1
Superscript 2 = Overturn on a concrete bank - Simulation 2
Superscript 3 = ASAE S306.3 side overturn on soil - Simulation 3

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accidental overturn on soil with the published documentation of the accident shows similar tractor positions at the end of the overturn. Unless the conditions for the accident are fully documented it is difficult to apply the steering at the correct time and to indicate the bearing angle relative to the bank.

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