Modeling a Pothole Impact of an Agricultural Tractor Using HVE and SIMON

Ciro Ramirez, PhD, PE, CSHO and R. Joe Thornhill, PhD, PE, CSHO
Thornhill, Ramirez & Associates, Inc.

Abstract:

This paper presents an HVE study of the dynamics of a cabbed agricultural tractor pulling a large rotary shredder when impacting a deep pothole. The study was conducted using the SIMON physics module as part of an effort to quantify the way in which a tractor operator could be ejected from the tractor cab, possibly resulting in serious injuries from the shredder. The HVE radial spring tire model was used to predict tractor bounce as it encountered the hole at a variety of attack offsets and two different speeds. Unique vehicle features modeled for this study included agricultural tires and a rigid, unsprung front axle mounted on a pivot and angle limiting stops. A follow-up study was conducted by combining the SIMON soft soil model and field measurements to estimate the coasting distance of the tractor and shredder at the incident site if engine fuel flow is stopped.

Introduction:

Agricultural tractors are designed to provide high tractive force at low speeds over unpaved surfaces, with a secondary design feature being auxiliary power take-off (PTO) capability to drive implements such as rotary shredders/mowers and augers. Tractor designs do not typically include sprung suspensions, with operator comfort provided by seat suspensions instead. Agricultural tractors are intended for off-road use and are susceptible to overturning due to their high center of gravity. The lack of a sprung suspension can also cause violent tractor motions when encountering large bumps or potholes. The tractor dynamics study described in this paper was conducted to predict the motions caused by striking a large pothole while towing a rotary shredder. The resulting displacement and acceleration at the operator's position were also studied in order to evaluate the likelihood of an unrestrained operator being ejected from the cab in such an event. These results were used in the analysis of an accident in which the operator was ejected through the rear window of the cab and severely injured when he was struck by the shredder.

Tractor and Shredder Vehicle Models:

Figure 1 shows the tractor and shredder geometry. The unit modeled was equipped with an enclosed cab with an integral rollover protective structure (ROPS). The tractor was equipped with solid front and rear axles, unsprung, with the front axle pivoted and equipped with rigid stops. Front tires on the tractor were pneumatic, unlugged, 11.00-16 agricultural tires, while the rear tires were a 18.4-34 lugged design, and were not liquid-filled. The shredder was equipped with six solid tires mounted on hydraulically operated axles which could be adjusted for mowing height.

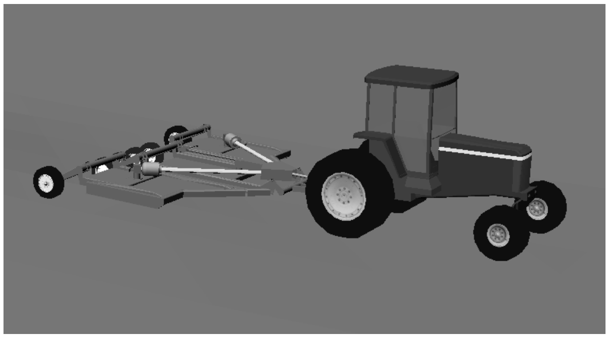

Figure 1. Tractor and shredder model geometry.

Tractor center of gravity location and weight were determined by weighing the incident unit and an exemplar in horizontal and tilted orientations. The HVE model of the tractor was based on a generic, class 2 truck model, with body geometry created from measurements using Rhinoceros® 4 modeling software. Engine power was based on published specifications, but transmission ratios were calculated from measurements of ground speed and engine RPM in each gear considered. The geometry of the pivoted front axle was determined using basic measurements and geometric analysis of a photograph of the pivot (Figure 2(a) and 2(b)).

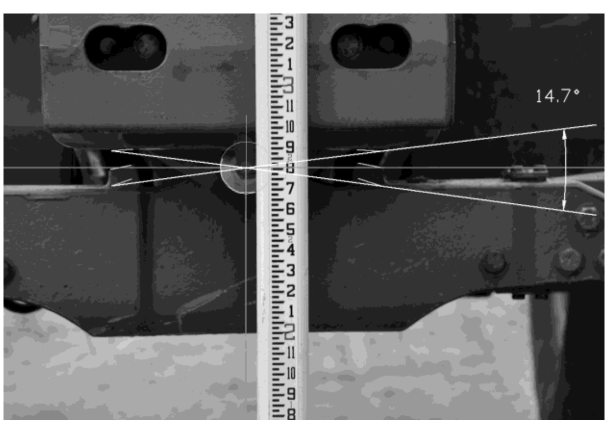

Figure 2(a). Geometry of pivoted front axle and axle stops.

Because dramatic front wheel motions were expected when the tractor encountered the pothole, it was important to model the front axle swing. HVE allows for solid axles, but does not provide a pivoted axle option. In order to simulate this motion, the pivot was approximated by two narrowly spaced suspension springs. Figure 2(c) illustrates this approximation. Although the axle suspension should be very stiff when the front tires are compressed equally, it should offer little resistance to pivoting until the stops are encountered. Preliminary runs showed that a spring spacing of 4 inches, combined with a spring rate of 10,000 lb/in (ride rate at wheel), allowed axle motions to mimic those of a free-swinging axle, and would result in an equivalent wheel force of only 700 lb when contacting the suspension stops. In order to modify the vehicle model with these suspension characteristics, it was necessary to edit the limit values for the spring spacing and rate, as well as the maximum jounce stop stiffness, in the *language.rsc* file.

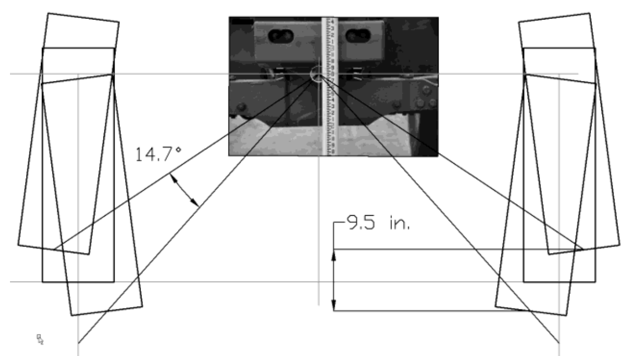

Figure 2(b). Wheel motion due to pivoted front axle.

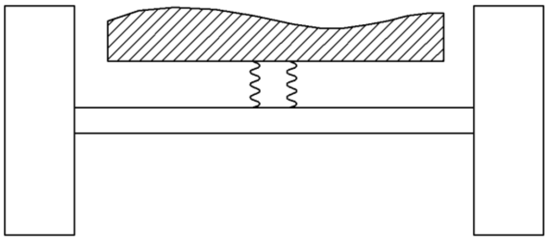

Figure 2(c). Approximation to pivoted axle using closely spaced springs.

One of the parameters of greatest interest in this study was the pitching motions of the tractor after encountering the pothole. Because of the rigid suspension, this response would be dominated by the tire compressive stiffness. Compressive stiffness for front and rear tires were determined using measurements and models described by Brassart, et al. [1] and Lines and Murphy [2]. Although these models were created primarily for non-rolling tires, the combination of low ground speed and the impact conditions being simulated, rather than ride quality, indicated that non-rolling stiffness values would be appropriate. The Lines and Murphy regression equation used for the front tires was:

$$K = 172 - 1.77d_{rim} + 5.6a + 0.34bd_{rim}p$$

where:

K = tire stiffness (kN/m)
d_{rim} = rim diameter (in)
b = tire section width (in)
a = tire age (years)
p = inflation pressure (bar)

For the measured tire pressure of 30 psi, this equation yielded a compressive stiffness value for the front tires of 1783 lb_f/in. For the rear tires, compressive stiffness was interpolated from measurements tabulated by Brassart, et al. for similar tires, yielding a value of 2627 lb_f/in. Because the pothole modeled in this study was deep enough to result in significant non-vertical impact forces on the tire, the HVE radial tire model was used for all tractor tires during impact simulations. No pothole impacts were anticipated for the shredder, so estimated stiffness values and point contact models were considered adequate for these tires. Only the outer two tires were modeled for the shredder.

Terrain Model:

The terrain model for this study was created in Rhinoceros® 4 using survey data obtained by a licensed surveyor at the incident site, as well as scene photographs. The terrain model is shown in Figure 3. The terrain slopes slightly downhill in the direction the tractor was moving just prior to the impact. The model includes a simulated pothole which was re-created from scene photographs. The tractor operator may have been unable to detect this pothole due to the presence of tall grass and the high mowing speed he was using. The location and approximate dimensions of the pothole were determined from scene photographs and witness testimony, as the pothole had been filled in before the site was examined. A cross-section of the pothole is shown in Figure 4. The simulated pothole was created with a spherical bottom and a small fillet radius at the ground surface. The HVE Michigan Unploughed Sod material was used for the ground surface in the study. As discussed below, a secondary study for coast-down used the HVE soft soil model to simulate drag.

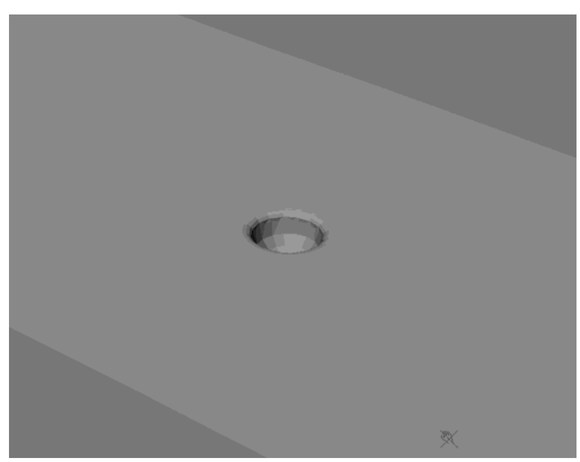

Figure 3. Terrain with pothole.

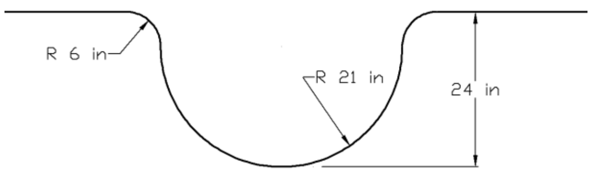

Figure 4. Cross-section of pothole.

Event Parameters:

Because the shredder was driven from a power take-off with specified RPM requirements and scene evidence indicated which gear was engaged at the time of the incident, the ground speed of the tractor when it encountered the pothole could be estimated. No steering input or braking was included, and throttle position was fixed throughout the event because the tractor was equipped with a fixed hand throttle. The primary variable in the hole impact study was the lateral position of the tractor as it approached the pothole. The operator's testimony indicated that the right front wheel of the tractor struck the pothole, so the alignment of the centerline of the right front wheel was shifted across the width of the pothole over a series of runs. The runs were conducted for a ground speed of 7.25 mph as the wheel reached the pothole, and were repeated for a ground speed of 6 mph. Finally, the effect of tractor weight was studied by repeating all runs for a different weight (10,000 lb vs. 13,465 lb). In addition to tractor dynamics at the center of gravity, the motions input to the operator's body by the tractor seat were of interest, so accelerations were output at the location of the seat. Scene evidence indicated that the tractor exited the pothole with a counterclockwise yaw rotation, so results which correctly predicted this orientation and yielded tractor motions which were consistent with a rearward ejection were of greatest interest.

Results:

The study results showed that the motions of the tractor after encountering the pothole were very sensitive to lateral alignment with the pothole, and were less sensitive to ground speed. Tractor weight was found to have only a modest effect, with responses qualitatively very similar for the two weights studied, but with a lighter tractor experiencing greater peak accelerations. Runs in which the right front wheel approached aligned near the center of the hole resulted in complete loss of forward momentum and even rebound rearward out of the pothole (Figures 5(a)-5(c)). This response was due to significant wheel drop before contacting the far side of the pothole. The response did not meet the requirements discussed above, and would likely result in significant front axle damage, which was not observed.

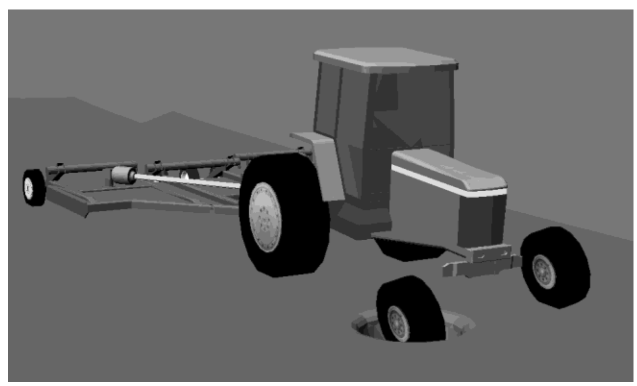

Figure 5(a). Tractor entering pothole, RF wheel aligned 1.9 inches right of pothole centerline. Speed 7.25 mph, tractor weight 10,000 lb. Note axle swing.

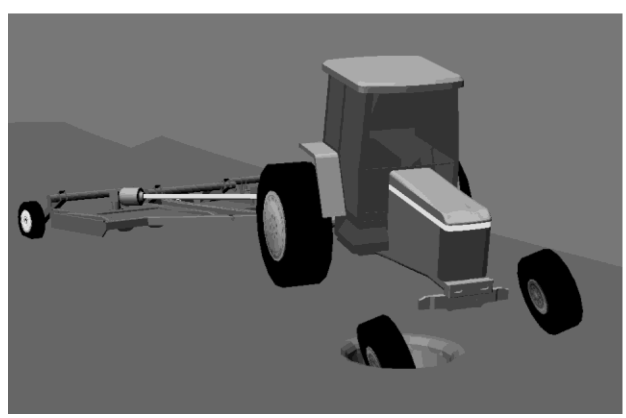

Figure 5(b). Tractor rebound and CW yaw rotation.

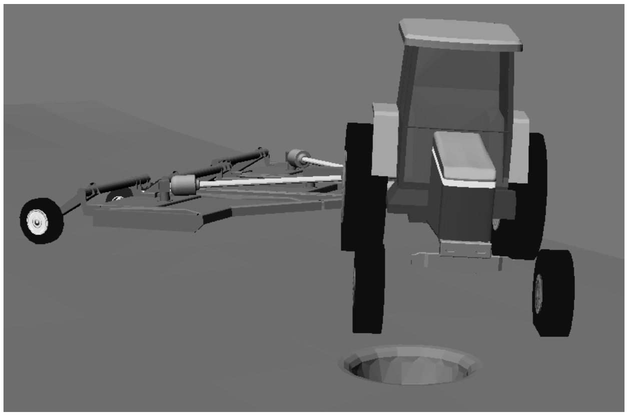

Figure 5(c). Tractor post-impact orientation with CW yaw.

Tractor motions for wheel alignments near the left side of the pothole included significant pitch-up of the front of the tractor, followed by strong roll motions during entry and exit of the right rear tire (Figures 6(a)-6(c)). Runs for alignments near the left side of the pothole also resulted in significant clockwise yaw, and so did not satisfy the post-impact requirements.

Runs for wheel alignments to the right of the pothole centerline resulted in strong pitch-up motion of the front, followed by a counterclockwise yaw rotation. Rear wheel impact with the pothole resulted in strong roll motions, accompanied by pitch-down of the front of the tractor. These motions are illustrated in Figures 7(a)-7(c). Pitch-up for some of the runs in this group was severe enough to approach the rearward rollover threshold of the tractor. The counterclockwise yaw rotation which resulted from runs involving wheel impact to the right of the pothole centerline satisfied the requirement for post-impact tractor alignment, and the combination of strong pitch and roll motions were judged to agree with the occupant kinematics needed for rearward ejection. Pitch-down as the front wheel entered the pothole, followed by rapid longitudinal deceleration when the wheel impacted the far side, would cause the operator to move forward in the cab, and the strong pitch-up following front wheel impact with the far side of the pothole would cause the steering wheel and dash of the tractor to move rearward into his body. These motions are consistent with the operator’s testimony and cab damage

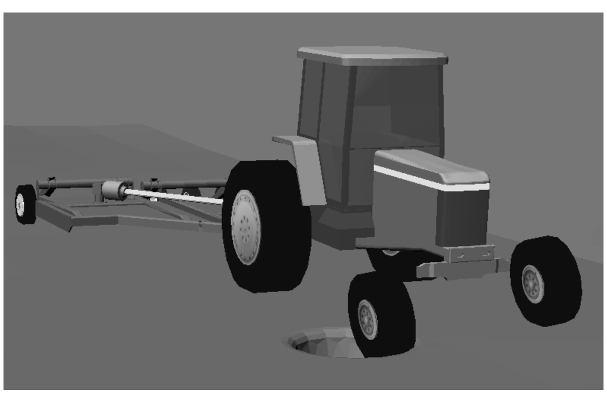

Figure 6(a). Tractor entering pothole, RF wheel aligned 13.1 inches left of pothole centerline. Speed 7.25 mph, tractor weight 10,000 lb.

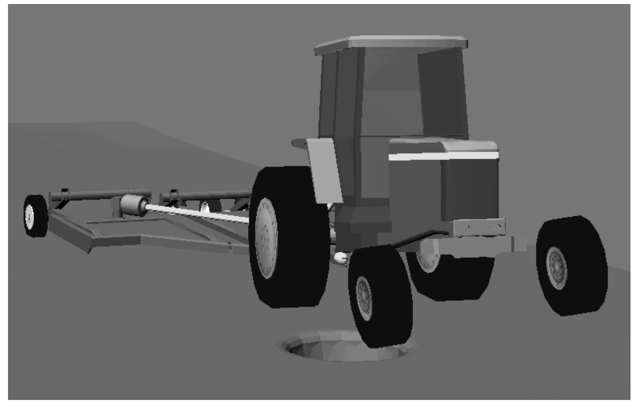

Figure 6(b). Tractor pitch-up and CW yaw rotation.

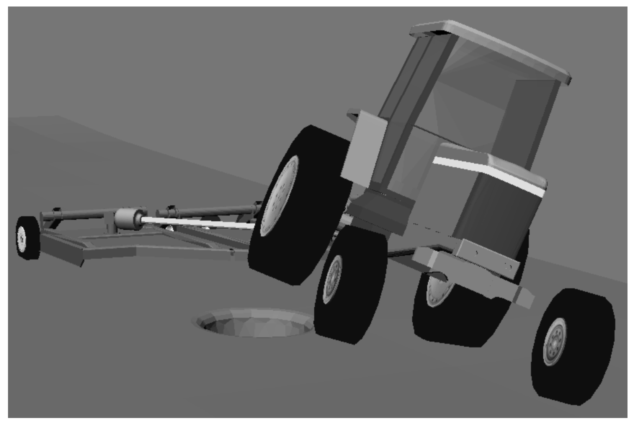

Figure 6(c). Tractor roll following rear wheel impact.

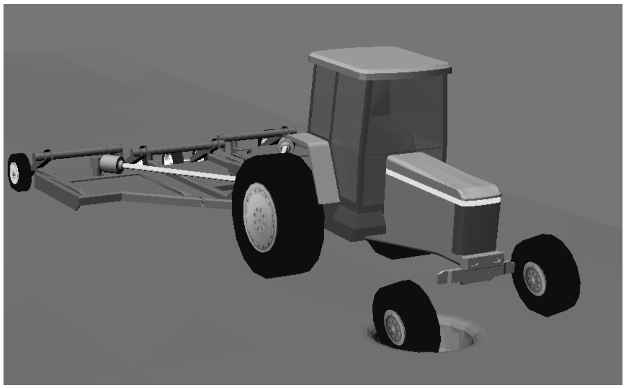

Figure 7(a). Tractor entering pothole, RF wheel aligned 10.9 inches right of pothole centerline. Speed 7.25 mph, tractor weight 10,000 lb.

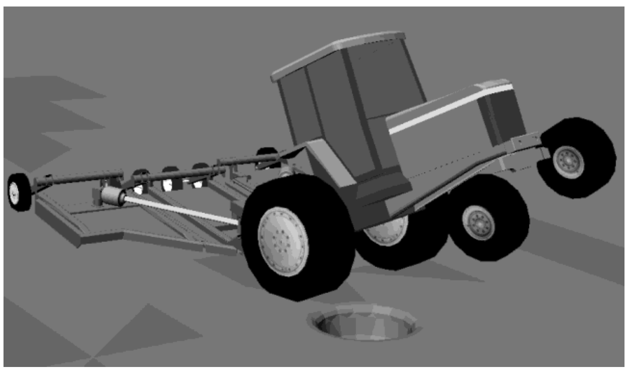

Figure 7(b). Tractor pitch-up and CCW yaw rotation.

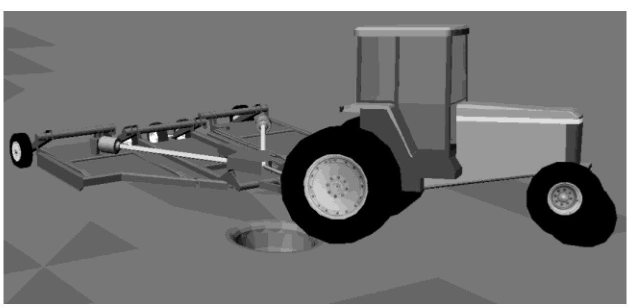

Figure 7(c). Tractor pitch-down, roll, and CCW yaw.

observed for this incident. The impact between the operator's body and the front of the cab would propel him rearward, while roll of the top of the cab to the left following rear wheel impact would result in ejection from the cab near the right rear of the cab. The results of this study were used in conducting further biomechanical analysis which confirmed these observations. A plot of accelerations at the operator's seat for a run in this group is shown in Figure 8. Front wheel impact with the edge of the pothole occurred at approximately 0.7 seconds, and rear wheel impact with the edge of the pothole occurred at approximately 2.4 seconds. Other peaks in the forward acceleration trace are due to bouncing motions of the tractor.

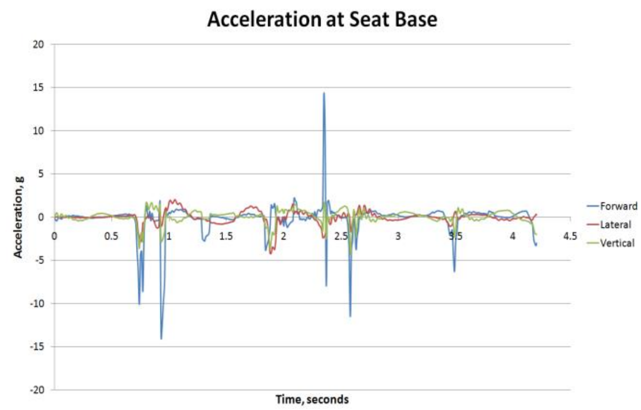

Figure 8. Accelerations at operator seat. RF wheel aligned 7.9 inches right of pothole centerline. Speed 7.25 mph, tractor weight 10,000 lb.

The effects of tractor speed and weight for the same alignment as in Figure 8 are shown in Table 1. As mentioned earlier, these effects are less dramatic than the effect of wheel alignment to the pothole. The peak negative accelerations, which are related to the initial front wheel impact and pitch-up motion, with subsequent rearward acceleration of the occupant's body, are more consistent than the peak positive accelerations, which are primarily related to tractor pitch-down motion resulting from rear wheel impact with the pothole.

	6 mph	**7.25 mph**
10,000 lb tractor	4.7g / -10.63g	14.23g / -13.89g
13,465 lb tractor	1.7g / -8.06g	9.1g / -9.1 g

Table 1. Effect of tractor weight and approach speed on peak positive and negative longitudinal acceleration at base of operator's seat. RF wheel aligned 7.9 inches right of pothole centerline.

Coast-down Study:

The study described above was conducted to permit assessment of the ejection of an unrestrained operator from the cab of a tractor. Some tractors incorporate a seat switch which can be used to shut off the engine of a tractor if an operator is not present. In order to evaluate the likelihood of protecting an operator from injury or death due to contact with the towed shredder if the engine is stopped in this manner, a coast-down study was conducted. Coasting distance in gear was measured with the tractor and shredder under a variety of conditions, and adjusted to obtain an estimate of the coasting distance at the incident site at one ground speed, 7.25 mph. Because of the substantial angular momentum of the rotating shredder blades, which are coupled directly to the tractor's drivetrain through the PTO, this coast distance can be significant even at the low ground speeds used for mowing. The coast distance in this instance was estimated to be 30.5 feet, based on a speed at engine shutdown of 7.25 mph. The distance that the tractor/shredder would travel after an operator exited the seat would be extended because seat switch shutoff systems include a delay to prevent spurious engine shutoff due to vibration and seat bounce. With a 2 second delay, the total distance traveled with an initial ground speed of 7.25 mph would be extended to 51.8 feet. This distance is great enough to make protection of an operator from injury in this type of incident impractical.

A ground speed of 7.25 mph while operating a towed shredder is generally considered to be quite high. In order to evaluate the effect of lower mowing speeds on coasting distance of a tractor/shredder combination, the HVE SIMON model was used with a soft soil tire-terrain model. Because the radial spring tire model and the soft soil model cannot be used together, these runs did not include contact with the simulated pothole. The available vehicle information did not include a reliable estimate of the drive train inertia including the reflected inertia of the shredder through the PTO. In order to perform this study based on actual measurements, the drive train inertia of the tractor was adjusted until the coast-down distance from 7.25 mph matched the estimate from coast-down measurements. This model was then run for lower starting speeds in order to determine the corresponding coast-down distances. The results for a 10,000 lb tractor are shown in Table 2(a) and 2(b); results were essentially identical when the same procedure was used with a 13,465 lb tractor. Although lower ground speeds significantly decrease the coast-down distance, adding the distance traveled by the tractor during a 2 second switch delay extends the total distance traveled significantly. Based on these results, it is unlikely that the use of a seat switch to shut off the engine would prevent injury from the shredder if the operator is ejected rearward. These results reinforce the importance of using restraints when operating a tractor pulling a shredder, as is also required when operating tractors equipped with ROPS.

Ground Speed	Coast-down Distance
3.5 mph	8.3 ft
5 mph	16.4 ft
6 mph	22.5 ft
7.25 mph	30.5 ft

Table 2(a). Coast-down distances for different ground speeds, 10,000 lb tractor.

Ground Speed	Total Distance
3.5 mph	18.6 ft
5 mph	31.1 ft
6 mph	40.1 ft
7.25 mph	51.8 ft

Table 2(b). Total distance traveled for different ground speeds, 10,000 lb tractor, 2 sec. delay.

Summary:

The results of the HVE studies presented here show that unrestrained operators of agricultural tractors can be ejected rearward if the tractor encounters a pothole, due to the violent tractor motions that result. Although such an event is extremely dangerous under any circumstances, the risk of death or serious injury is increased dramatically when the tractor is towing a large implement such as a shredder. The studies also show that seat switches for sensing operator presence are not an effective substitute for the use of seat belts or other operator restraints when operating tractors.

Several improvements could be made in this type of analysis with new or improved HVE features. The modeling of the pivoted solid front axle would be simplified if this type of axle was directly supported, and pivot points which are not collinear with the centers of the front wheels are desirable to best model axle motion. Although accelerations were reported for the operator's seat, it is desirable to directly output position and velocity at the location of accelerometers, in order to simplify subsequent biomechanical analysis. Finally, the ability to simultaneously use the radial tire model and the soft soil model would permit full simulation of coast-down events following a pothole impact.

References:

1. Brassart, François P., Malcolm E. Wright, and Bernard Drouin, "Non-Rolling Agricultural Drive Tire Mechanical Models," SAE Paper 952130, Society of Automotive Engineers, 1995.
2. Lines, J. A. and K. Murphy, "The stiffness of agricultural tractor tires," Journal of Terramechanics 28(1): 49-64. ISTVS, Hoboken, NJ, 1991.

Contact:

Ciro Ramirez, Ph.D., P.E., CSHO and R. Joe Thornhill, Ph.D., P.E., CSHO are forensic engineers with Thornhill, Ramirez & Associates, Inc. in Leander, Texas. They provide consulting services in the areas of vehicular accident reconstruction and forensic analysis of accidents involving machinery. They may be reached at info@trengineer.com.