Remote control of an agricultural tractor in SAE field upset tests

T.J. Lutz and G.T. Homce

National Institute for Occupational Safety and Health,
Pittsburgh Research Laboratory, P.O. Box 18070,
Pittsburgh, Pennsylvania 15236-0070, USA
E-mail: tcl9@cdc.gov E-mail: gdh3@cdc.gov

Abstract: Research by the National Institute for Occupational Safety and Health (NIOSH), Division of Safety Research in Morgantown, West Virginia is addressing the problem of injuries due to agricultural tractor rollovers, and improvements to rollover protective structures (ROPS). As part of this research, the NIOSH, Pittsburgh Research Laboratory modified a Ford model 4600 agricultural tractor for remote control operation, and used this tractor to conduct SAE field upset tests. Modifications to the tractor involved installing a protective framework, electrical actuators for fuel, brake, clutch, and steering controls, and a radio link for remote operation. The tractor has been used to complete over 30 total side and back upset tests, with no failures of the remote control system. These tests have allowed NIOSH researchers to study the performance of currently available ROPS, use this information for the development of improved ROPS designs, and test a NIOSH-developed prototype automatically deploying ROPS.

Keywords: ROPS; tractor; tractor safety; rollover; remote control; agricultural safety; overturn; field upset test; SAE J2194.

Reference to this paper should be made as follows: Lutz, T.J. and Homce, G.T. (2004) 'Remote control of an agricultural tractor in SAE field upset tests', *Int. J. Vehicle Design*, Vol. 34, No. 3, pp.286–296.

Biographical notes: Timothy J. Lutz received a Bachelor of Science degree in mechanical engineering in 1983 from The Pennsylvania State University. He worked as an Engineer for Westinghouse Electric Corporation from 1983 to 1990 on various nuclear waste projects and US Navy ship component designs. From 1990 to 1997 he was employed by the US Bureau of Mines at the Pittsburgh Research Centre conducting research in remotely controlled mining equipment. Lutz is currently a Mechanical Engineer for the National Institute for Occupational Safety and Health (NIOSH) at the Pittsburgh Research Laboratory. His research focuses on improving agricultural equipment safety and noise reduction in mining equipment. Lutz is a Registered Professional Engineer.

Gerald T. Homce received a Bachelor of Science degree in Mining Engineering in 1981 and a Master of Science degree in Mining Engineering with a minor in Electrical Engineering in 1983, from The Pennsylvania State University. He worked as an Engineering Trainee for the Republic Steel Corporation while attending Penn State and was later employed as the Supervisory Mining Engineer for underground operations of Myco-Sci, Inc., Worthington, Pennsylvania. From 1985 to 1997 he was employed by the US Bureau of Mines at the Pittsburgh Research Centre, conducting research into the safety and efficiency of mine electrical systems. Homce is currently an Electrical Engineer for the National Institute for Occupational Safety and Health (NIOSH) at the Pittsburgh Research Laboratory. His research focuses on preventing occupational electrical injuries, and improving agricultural equipment safety. Homce is a registered Professional Engineer and a licensed Mine Foreman.

1 Introduction

The work described in this report involved modifying a standard Ford model (Mention of any company, brand name or product does not constitute endorsement by NIOSH) 4600 tractor for remote control operation, to safely conduct field upset tests (full scale rear rollovers and side rollovers) conforming to SAE standards [1]. The tests are part of agricultural safety research, focusing on rollover protective structures (ROPS), being conducted by the National Institute for Occupational Safety and Health (NIOSH), Division of Safety Research in Morgantown, West Virginia.

Tractor rollovers are the number one cause of agricultural occupational fatalities, causing dozens of deaths each year [2]. Research by NIOSH is addressing this problem with several coordinated efforts. One is the design and development of an automatically deploying ROPS to allow use where conventional fixed ROPS are not practical [3]. Another is the development of fabrication plans for owner/operator construction of simple, low cost fixed ROPS that meets SAE requirements [4]. These tasks require full-scale rollover testing, which dictates unmanned operation of an agricultural tractor. As a key element of this research, personnel from the NIOSH, Pittsburgh Research Laboratory modified a tractor for remote operation, established a rollover test site, and conducted field upset tests.

2 General requirements

Several general requirements and constraints were identified early in this project, guiding design and development of the remote control tractor. Several important points are listed below:

- The tractor must be capable of the manoeuvres necessary for the tests specified in ANSI/SAE J2194, specifically, guidance during approach of rollover ramps and pits at speeds up to 10 mph (16 km/h).
- The tractor should not be tethered by control or power leads. This requires on board battery power of tractor control actuators, and a radio link to the remote operator.
- The tractor must be equipped with an integral 'reinforcing frame' to protect vulnerable parts and structures during rollovers.
- All modifications must be sufficiently rugged to withstand the mechanical stress associated with repeated rollovers.
- Total cost for the conversion should be kept below approximately $10,000 US for parts and supplies.
- Tractor controls that should be equipped for remote operation are fuel supply, engine starting, throttle position, clutch engagement, braking, and steering.

- Remote control of gear selection is unnecessary for rollover testing. Gear selection can be done manually prior to proceeding under remote control.
- The remote control system must have failsafe features incorporated where appropriate, to minimise the hazards from a loss of control or other malfunctions.

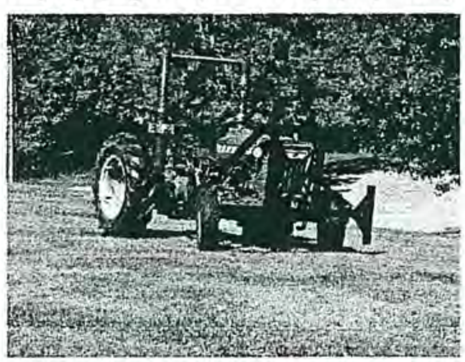
3 General modifications to original tractor components

The 1975 standard model 4600 Ford tractor used in this work is powered by a 201 cu in (3294 cc) three cylinder diesel engine, has a wheel base of 84.5 in (2146 mm), weighs approximately 4480 lbs (2032 kg) dry in stock configuration, and has a minimum track width of 67.5 in (1715 mm). The tractor does however, have front axle and steering components that Ford manuals identify as those found on a Ford model 4100 tractor (either as special order original equipment or from some previous retrofit).

If the tractor should become completely inverted during a rollover, the original equipment structures and body panels surrounding the engine and radiator would likely be damaged. To avoid this, a reinforcing framework was designed and installed. Attachment points for the framework are existing threaded and through holes low on the main tractor castings. It extends above and forward of the tractor hood. It is constructed primarily of 3 in × 3 in × 0.25 in wall (7.6 cm × 7.6 cm × 0.6 cm wall) square tubing, using a design that alters the tractor's external dimensions as little as possible. The framework also provides mounting points for the clutch and brake actuators as well as two control system batteries. After initial testing, an additional removable section of frame was added to protect the front axle assembly during side rollovers. The protective framework can be seen in Figure 1.

The original 16 gallon (60.5 l) fuel tank was removed, making space available under the cowling behind the engine for a radio receiver, electrical equipment associated with remote control system actuators, and a one gallon fuel tank. The small size of the replacement fuel tank along with rerouting of the vent line reduces the chance of a significant fuel spill during rollovers. The original exhaust system, which extended well above the tractor's hood line, was replaced with an automotive muffler and rerouted downward to avoid damage.

Figure 1 Reinforcing framework on tractor (ROPS visible in this photo is an early prototype of an automatically deploying ROPS, shown in deployed position)



4 System design and component selection

Control parameters were determined by simple measurement procedures. The forces required to disengage the clutch (at the foot pedal), apply the brakes (at the foot pedals), change the throttle position, change the fuel shutoff position, and the torque needed to rotate the steering wheel, were determined with a spring scale. The travel limits associated with each function were measured directly. Table 1 lists the measured values.

Selection of actuators was based on the requirements in Table 1 as well as size, input power requirements, operation rates, and suitability for tasks. Duff-Norton Mini-Pac actuators were selected for operation of the clutch and brakes. These employ a rugged electric motor-powered jack screw providing 100 lbs (445 N) of force while drawing 3 amps at 24 V dc. They are available with sufficient stroke for both functions, and feature enclosed integral limit switches, simplifying control circuitry design. A speed of 1.13 in/s (2.87 cm/s) was selected for clutch pedal actuation, allowing engagement in all gears on level terrain without engine stall. Figures 2 and 3 show the actuators installed on the tractor.

Table 1 Tractor control parameters

Function	*Force*	*Stroke*
Clutch	43 lbs (191 N)	6 in minimum, 7 in maximum (15.2–17.8 cm)
Brakes (left and right combined)	40 lbs (178 N)	3 in (7.6 cm)
Throttle	4 lbs (18 N)	1.75 in (4.4 cm)
Fuel shutoff	4 lbs (18 N)	1.25 in (3.2 cm)
Steering (with engine running)	30 in lbs (3.4 Nm)	4 turns lock to lock

Figure 2 Cutch actuator (Structure in foreground is part of the reinforcing framework installed on the tractor)

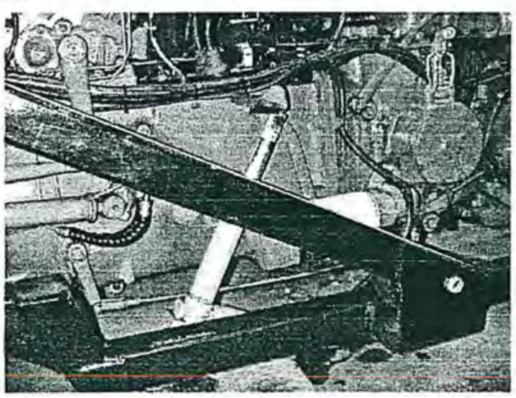


Figure 3 Brake actuator

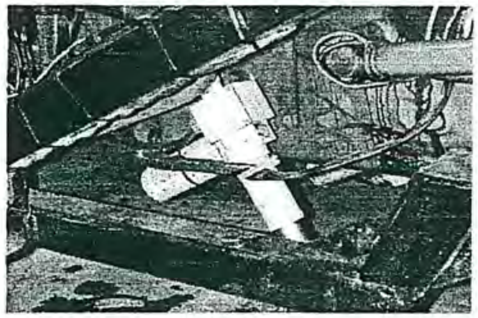
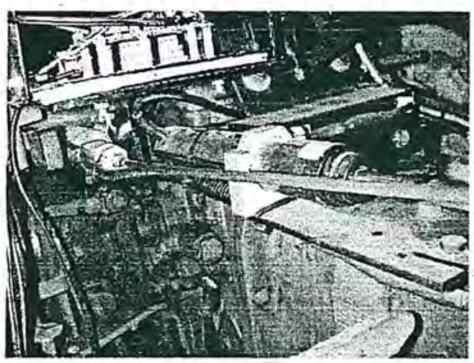


Figure 4 Throttle and fuel shutoff actuators (Foreground and background respectively)



Fuel shutoff is controlled by a Trombetta 24 V dc solenoid that is actuated and latched by engine starter engagement. Throttle position is controlled by an ADDCO 24 V dc linear actuator capable of multiple discrete settings. Four possible throttle positions, idle, maximum rpm, and two intermediate steps, can be set independently through an electronic control module. One important feature for both the throttle and fuel shutoff actuators is positive return to a safe condition when un-powered. When power is removed from these units, under normal operation or under emergency stop conditions, springs return the throttle to idle position and shut off fuel to the engine. Figure 4 shows the fuel shutoff and throttle actuators.

Steering control proved the most challenging of any individual remote function on the tractor. Basic requirements include the following:

- steering control resolution on the order of a few degrees
- rotation range capable of maximum steering gear limits
- response speed adequate for tractor speeds up to 10 mph (16 km/h)
- a drive system that enables easy conversion back to manual control
- rugged construction to withstand repeated rollover testing

Several methods were initially considered, including hydraulic or electric actuators linked directly to the steering gear, or an electric motor driving the steering column shaft. Ultimately, an electric positioning motor coupled to the steering shaft through sprockets and a chain was chosen. This approach is the most practical, since it leaves the original power-assisted steering system intact and is compatible with the power and control sources used for other remote functions on the tractor. In simplest terms, the remote operator steers the tractor by turning a knob on a radio transmitter, requesting a steering wheel position. An on-board radio receiver causes a corresponding rotation of a steering drive motor coupled to the steering wheel shaft on the tractor (radio transmitter and receiver are described later in this report).

The specific system used on the tractor includes an API DM-2205i-AE microprocessor-based controller, powering an API three-stack NEMA 34 stepper motor with a Micron 10:1 planetary gear head, coupled to the steering shaft through a 0.5 in (1.3 cm) roller chain. The system can generate the necessary torque, and allows wide flexibility in position, speed, and range control. The system is also less expensive than many alternatives. A few important specifications of the steering control are shown below:

- The controller is software programmable and can access multiple programs from memory.
- The controller has an analogue input compatible with the 0–10 V dc steering control signal available from the on-board radio control receiver (radio system to be described later in report).
- The controller accepts 24–74 V dc main input power, 36 V dc nominal is used.
- Torque available at the gear head output is 130 in lbs (14.7 Nm) (limited by 36 V dc input).
- Maximum rotation speed at the gear head output is 0.4 rps (limited by 36 V dc input).
- Rotation resolution at gear head output is 0.8% of full rotation range, e.g. 8.4° for three revolutions full range (limited by analogue control input).
- The chain drive uses a 1:1 ratio (0.5:1 to 2:1 available with sprocket changes).

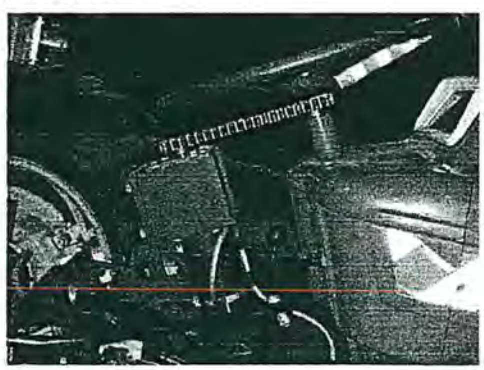
The motor/gear head assembly is mounted between the operator's seat and the shift control levers, with the drive chain running to a sprocket on the steering wheel shaft as shown in Figure 5. The location does not interfere with manual operation of controls, or vertical seat travel. To supply 36 V dc to the motor controller, an additional 12 V battery was placed in series with the 24 V dc source used for other actuators. Switches near the motor allow the user to select one of several steering programs preloaded into the controller memory, or disable the motor power completely for manual steering.

The motor and controller are an open loop system, that is, there is no feedback to the controller of actual motor position. This reduces complexity, but does require proper initialisation each time the system is powered up. For remote operation, before any on-board systems are energized, the steering control switch is set to 'remote', the steering program is pre-selected (via a rotary switch), and the steering wheel on the tractor is manually aligned straight ahead. The transmitter is energized first, with the steering control knob centred (corresponding to 5 V dc output at the receiver). The tractor main power system is then energized. At this point, a delay relay isolates the steering motor from the controller for several seconds to allow the radio link to synchronise, the controller to initialise, and the 5 V dc steering control signal to stabilise. The initial condition resulting from this sequence is the steering referenced to straight ahead for an analogue input of 5 V dc to the controller, ½ full travel to the left for 0 V dc, and ½ full travel to the right for 10 V dc. This relationship will be maintained unless the motor is mechanically stalled.

The programs for the steering control are assembled in a companion PC software package, APImate, and uploaded to the motor controller. They are short code sequences that initialise basic controller settings, execute loops that monitor changes in the 0–10 V dc analogue input and send motion commands to the motor based on these changes. For work thus far, two programs have been used. One gives a full range of 1½ steering wheel revolutions, and the other three full revolutions. Because control resolution is based on full rotation range, the 1½ revolution program gives more precise control and better operator 'feel' for the steering, and so is used for the overturn tests where accurate steering is important. The three revolution program offers less accurate control, but is more suitable for slow speed/short radius cornering.

A few other points about the steering system should be noted. Since the operator has only visual feedback for tractor control, the steering wheel spoke aligned to 12 o' clock for straight travel has been marked for high visibility (Figure 5). This simple feature provides a fast, continuous, and very effective update of steering gear position for the operator, visible at distances of several hundred feet. For a drive system of the type used here, if the load exceeds available torque, the motor simply stalls. This does not harm the motor under normal conditions, and is an advantage since it eliminates the danger of damaging drive components if unusual steering resistance is met. Such resistance can occur when the steering gear is not initially centred properly and is subsequently driven to the stops, or if the steering drive is activated without the tractor engine running to provide power steering. One drawback to the system is the tendency of the microprocessor-based controller to remember each change in the analogue control voltage and execute the corresponding steering moves in sequence. This means that an inadvertent over shoot in rotation of the steering control knob by the operator will likely cause a brief oversteer at the tractor. Although undesirable, the effects of over steering can be minimised through practice.

Figure 5 Steering system drive unit



Selection of a radio-link system for control was guided by actuator requirements as well as operational and safety issues. The required features included the following:

- a total of at least four on/off signals to manage the clutch, brake, and four throttle positions
- a proportional analogue signal for the steering controller
- a manual emergency stop and failsafe operation for loss of signal
- radio frequency interference tolerance and a minimum range of 1000 ft (305 m)
- suitability for rugged field use.

The radio system selected is a Futaba VSD-2001. Operating at 900 MHz spread spectrum with up to 1 W radio frequency output, it has six discrete on/off channels, one analogue channel (supplying an adjustable 0–10 V dc signal at the receiver), and a range of one mile. The system uses a 16 bit ID code for security, with over 65,000 discrete codes available, and features loss of signal failsafe operation, with all receiver relays opening and the analogue signal going to 0 V dc within 500 ms of detecting a corrupt signal. The transmitter is a compact handheld unit with rechargeable batteries. The receiver, powered by 24 V dc available on the tractor, is mounted on shock isolators with the antenna protruding through the hood of the tractor. Figure 6 shows the system components.

On board control circuitry uses signals supplied from the radio system receiver to drive power relays controlling the various actuators (except for the controller used to drive the steering motor). Circuit design provides for failsafe operation where possible, such as using the un-powered state of a relay to translate to the least hazardous condition for a given function. More specifically, the system is designed to shut off the engine and apply the brakes under emergency conditions. This occurs if the manual emergency stop is applied, or if there is a loss of communication between the remote control transmitter and tractor for any reason. Additionally, the throttle is returned to idle any time the clutch is disengaged or the brakes are applied. All control circuitry is housed in a weather resistant enclosure mounted on shock isolators under the cowl just behind the engine compartment. The control circuitry enclosure and circuitry are shown in Figure 7.

Figure 6 Radio system

Figure 7 Onboard control circuitry (Protective enclosure shown open, and rear section of tractor hood cowling removed for photo)

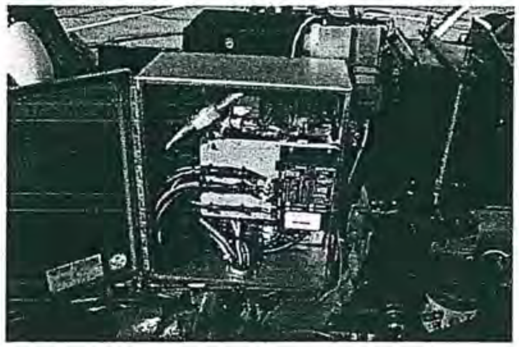


Table 2 Modification costs

Component or materials	*Cost* ($ US)
Clutch and brake actuators	700
Throttle control	500
Fuel shutoff solenoid	200
Steering system	2,300
Radio system	1,800
Batteries	600
Electrical parts	600
Steel fabrication materials	1,000
Misc. (fuel tank, exhaust system, etc.)	400
Total	8,100

Four sealed lead acid batteries are installed on the tractor. One is used only for engine starting, but if necessary, can subsequently be electrically isolated from the tractor and used for powering instrumentation. Two are wired in series to supply 24 V dc for all actuators except the steering system, which requires the fourth battery to be added in series for 36 V dc. Each battery is maintained by a dedicated on board charger, with all chargers powered by a single 120 Vac shoreline when the tractor is not in use. There is a master disconnect switch for the 24 V dc actuator power system, a chassis ground disconnect switch for the starter battery, and a keyed switch for the starter circuit.

5 Cost and time for tractor modifications

An approximate maximum of $10,000 US was available for all parts and materials for the tractor modifications. The use of simple designs and readily available components allowed this target to be met. Table 2 gives a breakdown of costs for parts and materials. The modifications were completed by a team of engineers and technicians at the NIOSH, Pittsburgh Research Laboratory, requiring an estimated 1250 total hours.

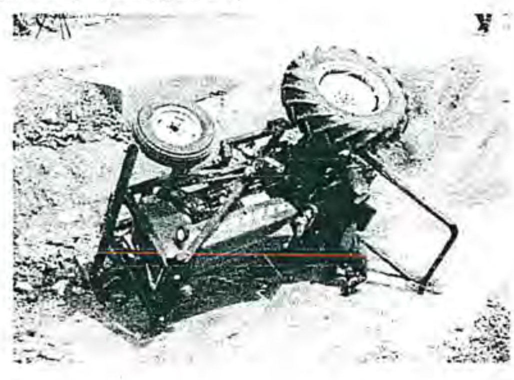
6 Performance in SAE field upset tests

As of this writing, over 30 field upset tests have been performed with the modified tractor. In general, the tractor has performed well, meeting all SAE upset test specifications. The remote control systems installed on the tractor, after minor initial revisions and replacement of a defective steering motor controller, have operated without failure.

Rear upset tests were generally routine, with the tractor tipping rearward while attempting to engage a steep slope, and ultimately stopped by the ROPS. One exception to this was a test where, due to a problem with the test site surface, the tractor while tipping rearward continued past a vertical position, rotating 180° and coming to rest in a completely inverted position. Although the final impact with the test surface was severe, the tractor and on board remote control equipment were undamaged.

Side upset tests have had unanticipated complications. In general terms, the SAE standard configuration for these tests calls for one side of the tractor, travelling at least 10 mph (16 km/h), to climb an 18 in (460 mm) high ramp while the opposite side simultaneously drops abruptly into a pit a minimum of 45 in (1145 mm) deep, inducing a sideward upset to the pit side. In actual practice, this arrangement causes the tractor to become partially airborne, falling into the pit, and absorbing most of the resulting impact with the front corner and rear wheel (pit side) of the tractor. As a result, the first test done at the specified speed caused severe damage to front axle and steering gear components. To prevent such damage, an extension was added to the tractor's reinforcing framework to guard the front axle. Immediately following the initial front impact during a side upset, the next ground contact occurs when the rear wheel comes to rest on the pit floor. In several tests, 3–4 of the 5 width-adjustment lugs on the pit side rear wheel were broken. With the relatively small inconvenience and cost of replacing the broken lugs however, this is considered acceptable damage for the side upset tests. Another side upset problem involves cumulative damage occurring to the front axle on the ramp side of the tractor. The repeated 10 mph (16 km/h) engagement of the sloping ramp is causing progressive distortion of the front axle upward and rearward, affecting the camber and caster of the front wheel on that side. Ultimately, this will require replacement of several axle components. Figure 8 shows the tractor after a side upset test.

Figure 8 Tractor immediately after a side upset test (Visible in the photo is an anthropometric mannequin on board during the test)



7 Summary

A Ford model 4600 agricultural tractor was modified for unmanned operation at the NIOSH, Pittsburgh Research Laboratory, in order to perform SAE field upset tests. The modifications involved using various types of electrical linear actuators for fuel, brake, and clutch control, a microprocessor-controlled positioning motor for steering, and a radio system for communication from a remote operator. The tractor was also equipped with a reinforcing framework to minimise damage from the rollover tests. The modifications required approximately 1250 h for design and installation, and $8,100 US for parts and supplies. The tractor has been used to complete over 30 total side and rear upset tests, with no failures of the remote control systems. The tests are part of agricultural safety research, focusing on reducing tractor rollover injuries, being conducted by the NIOSH, Division of Safety Research in Morgantown, West Virginia. Data obtained during these tests has been used to develop and refine designs for fabrication plans for owner/operator construction of simple, low cost fixed ROPS that meets SAE requirements. In addition, these tests have been used to refine a NIOSH-developed prototype automatically deploying ROPS system. Two tractor manufacturers have expressed interest in possible commercialisation of this system. Use of these improved ROPS technologies would be expected to reduce the number of agricultural tractor rollover injuries.

References

1 ANSI/SAE Standard No. J2194, December 1987 (formerly also identified as ASAE Standard No. S519).

2 Myers, J.R. and Snyder, K.A. (1993) 'Roll-over protective structure use and the cost of retrofitting tractors in the united states', *Journal of Agricultural Safety and Health*, Vol. 1, No. 3, pp.185–197.

3 Powers, J.R., Harris, J.R., Etherton, J.R., Snyder, K.A., Ronaghyi, M. and Newbraugh, B.H. (2001) 'Performance of an automatically deploying ROPS on ASAE tests', *Journal of Agricultural Safety and Health*, Vol. 7, No. 1, pp.51–61.

4 Harris, J.R., McKenzie Jr., E.A., Etherton, J.R. and Cantis, D.M. (2002) 'Designing cost-effective rollover protective structures (CROPS) at NIOSH', *Proceedings of the National Institute for Farm Safety (NIFS) Annual Conference*, June 2002, Ponte Vedra, Florida.