Safety Science 49 (2011) 1252–1261

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Predicting the performance of cost-effective rollover protective structure designs ☆,☆☆

J.R. Harris [a,*], G.L. Winn [b], P.D. Ayers [c], E.A. McKenzie Jr. [a]

[a] National Institute for Occupational Safety and Health, 1095 Willowdale Road, MS G800, Morgantown, WV 26505, United States
[b] Department of Industrial and Management Systems Engineering, College of Engineering and Mineral Resources, West Virginia University, P.O. Box 6070, Morgantown, WV 26506-6107, United States
[c] Biosystems Engineering and Environmental Science, University of Tennessee, 2506 E.J. Chapman Road, Knoxville, TN 37996, United States

ARTICLE INFO

Article history:
Received 6 July 2010
Received in revised form 4 November 2010
Accepted 15 April 2011
Available online 17 May 2011

Keywords:
Tractor
Tractor overturn
Tractor rollovers
ROPS
Finite element analysis

ABSTRACT

Agricultural tractor overturns kill more than 100 workers each year in the United States. Rollover protective structures (ROPS) can prevent most of these deaths but can be expensive in retrofit applications. Cost-effective ROPS (CROPS) have been designed and built at the National Institute for Occupational Safety and Health but performance must be evaluated. This study: (1) evaluated CROPS performance, (2) developed a simulation model for probabilistic CROPS evaluation, and (3) evaluated exemplar prototype CROPS performance via simulation of testing requirements. The CROPS prototype evaluated in this study was a Ford-3000 CROPS prototype design. Simulations based on ROPS performance standard SAE J2194 (Society of Automotive Engineers) identified scenarios where the Ford-3000 CROPS might fail. No failure scenarios were identified during simulation of ROPS performance testing to Occupational Safety and Health Administration (OSHA) test procedures and performance requirements. Despite passing experimental SAE J2194 testing, computer simulations found scenarios where the Ford-3000 CROPS prototype design might fail. Re-design of the Ford-3000 concept is necessary before field implementation.

1. Introduction

1.1. Magnitude of the problem

The agriculture/forestry/fishing/hunting (A/F/F/H) industry sector continues to be one of riskiest industries in the United States. In 2003, the A/F/F/H industry sector had the highest rate of fatal occupational injuries of any sector (US Department of Labor, 2003). Many of the deaths within the A/F/F/H sector are specifically tied to agriculture; many agriculture occupational fatalities involve tractors and tractor overturns. Data for agricultural production from 1992–1998 show the largest source of identifiable fatal injury was the tractor (Hard et al., 2002). When these same data are evaluated by injury event, more than one quarter of all agricultural production deaths (1051) were attributed to "overturning vehicle/machine" for the time period 1992–1998. From 1992–2002, an average of 125 fatalities per year were attributed to tractor overturns (Myers et al., 2008).

A highly effective engineering control already exists to prevent almost all fatalities due to tractor overturn, the rollover protective structure (ROPS) and a seatbelt. OSHA has required ROPS on all tractors (with very limited exceptions) manufactured since 1976. In fact it has been cited that ROPS, when properly used with a seatbelt, typically prevent fatal injury in 99% of overturns (Hallman, 2005). ROPS systems have been commercially available for several decades now in the United States, but this intervention has not saturated the tractor fleet. In 2001, ROPS usage in the United States was estimated at 50% (Myers, 2003). Myers indicated that ROPS usage needs to exceed 75% before significant reductions in rollover fatalities will be realized. More recently, ROPS usage in the United States was estimated at 59% for 2006 (NASS, 2008).

1.2. Regulations and consensus standards

A Society of Automotive Engineers (SAE) industry consensus standard, SAE J2194, provides a test for evaluating the performance of ROPS. Through this test the ROPS is exposed to four sequential loads: longitudinal, first vertical crush, transverse, and second vertical crush. Longitudinal refers to loads in line with the long axis of the tractor. Transverse refers to loads in line with the short axis of the tractor (and perpendicular to the longitudinal axis). As will be

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☆☆ The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.
* Corresponding author. Tel.: +1 304 285 6120; fax: +1 304 285 6047.
E-mail address: JHarris@cdc.gov (J.R. Harris).

0925-7535/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.ssci.2011.04.011

explained in the Methods section, all loads are based upon the reference mass of the tractor. The same ROPS is used for each of the sequential loads, and the occupant clearance zone is observed for intrusion by the ROPS or exposure to a "virtual" ground plane. Exposure to a virtual ground plane is evaluated to ensure that if the tractor rolled in the direction of the load being applied, the ground would not enter the occupant clearance zone.

The OSHA test procedures and performance requirements in 29 CFR 1928.52 are similar to SAE J2194 in many regards (US Department of Labor, Occupational Safety and Health Administration). Both outline longitudinal and transverse tests. However, the OSHA regulations do not have a vertical crush test. In addition, the clearance volume to be protected has different dimensions from SAE J2194 and required energy levels during longitudinal and transverse tests are different as discussed in the Methods section. OSHA regulations define an agricultural tractor, in part, as a "wheel-type vehicle of more than 20 engine horsepower".

1.3. Past research efforts

ROPS performance research has a long history in the United States. This research dates back to at least 1952 when Osborne Maybrier of Kentucky applied for a United States patent on a "safety guard for a tractor operator" (Maybrier, 1952). More recently, Johnson and Ayers (1994) were among the first researchers to systematically consider ROPS designs for multiple "pre-ROPS" tractors. A pre-ROPS tractor is a tractor design typically developed before 1970 when ROPS were options for tractors, and tractor axle housings were not intentionally designed to support potential ROPS loading. Johnson and Ayers investigated a popular pre-ROPS tractor to evaluate the ability of the axle housing to support a ROPS design. They determined through both static and overturn testing that the particular tractor model investigated (name kept confidential in paper) could support a ROPS for loadings necessary to pass ASAE S519 (equivalent to SAE J2194).

In 2005, Harris, Cantis, McKenzie, Etherton, and Ronaghi presented a paper and results at the annual National Institute for Farm Safety (NIFS) meeting describing progress on attempts to design and commercialize cost-effective rollover protective structures (CROPS) (Harris et al., 2005). The aim of the CROPS concept is to increase the percentage of tractors in the United States with ROPS installed by lowering the economic barrier to retrofitting older tractors with ROPS. Harris et al. provided performance data and plans for a prototype CROPS that one ROPS manufacturer estimated could be manufactured and sold for \$290 (2005 United States Dollars [USD]). The same manufacturer estimated the highest shipping cost for the 48 contiguous states to be \$193 (2005 USD). Typical ROPS costs (including installation) were estimated at \$1000. Cost savings were realized in the design through a weld-free construction of common structural elements and fasteners. A CROPS design for a Ford tractor is shown in Fig. 1.

The CROPS concept is one potential solution to the problem of retrofitting the large fleet of existing US tractors without ROPS. Owusu-Edusei and Biddle (2007) estimated that installing CROPS on all tractors which needed them could save 192 lives over a 20-years period. Previous research has shown that CROPS can be developed that pass the testing procedures outlined in consensus standards (Harris et al., 2005). However, each test represents a single evaluation of the CROPS system, and additional evaluation is necessary to ascertain the influence of dimension and strength variation on CROPS performance. This paper describes our evaluation of CROPS performance through development of a CROPS probabilistic simulation model and examination of exemplar CROPS prototype performance via simulation of testing requirements.

Fig. 1. Ford CROPS prototype.

2. Methods

The current study evaluated the reliability of a CROPS design to meet static testing requirements of SAE J2194 and OSHA regulations as found in 29CFR1928.52. The particular CROPS design evaluated was a Ford-3000 prototype. Reliability was assessed through probabilistic design simulation (PDS) methods utilizing finite element analysis (FEA), response surface methods, and Monte Carlo simulations considering variations in material and geometry input parameters for the Ford-3000 prototype. The basic steps in this study were: (1) perform SAE J2194 experimental static test, (2) develop FEA model based upon SAE J2194 experimental static test data, (3) perform screening tests to identify important prototype factors influencing energy absorption in CROPS within expected variations, (4) utilize design of experiments methods (including central composite design, CCD) to identify important factors and estimate response surface, and (5) perform Monte Carlo simulations on response surface to estimate reliability of design.

2.1. Ford-3000 CROPS design

Fig. 2 shows the conceptual drawing of an early Ford-3000 CROPS design prototype. The Ford-3000 tractor line was manufactured from 1965–1975. A standard tractor weighed approximately 3700 lb. [1678 kg] and had 47 engine horsepower [35 kW]. The axle housing configuration was rectangular in cross-section. The primary elements of the CROPS design for the Ford-3000 include the 2″ × 3″ × 1/4″ [51 mm × 76 mm × 6 mm] tubing utilized for the uprights and crossbar and the 3/8″ [10 mm] thick plate used to fabricate attachment plates and gussets. Fasteners include 5/8″ [16 mm] and 3/4″ [19 mm] grade 5 or 8 bolts.

2.2. SAE J2194 experimental tests

NIOSH researchers conducted all SAE J2194 static testing in the NIOSH High Bay Laboratory in Morgantown, West Virginia. Components of the test facility include: test bed, hydraulic power supply, hydraulic actuators, hydraulic control equipment, data acquisition equipment, reaction frame, and overhead bridge crane.