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Foldable rollover protective structures: Universal lift-assist design

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Abstract

The numbers of agricultural tractor rollover fatalities occurring with foldable rollover protective structures (FROPS) in their lowered position are significant. Raising and lowering the FROPS is a time consuming and strenuous process, and operators often leave the FROPS in the folded-down position providing no protection during a rollover. The purpose of this project is to design, manufacture, and test a lift-assist mechanism to raise and lower the FROPS from the operator's seat. The lift-assist design is based on the FROPS actuation forces, FROPS and tractor dimensions, and ergonomics engineering standards [SAE J898/ISO 6682 and SAE J1814]. The design considered can be retrofitted and will not modify or compromise the FROPS structure. A universal lift-assist lever design has been constructed and successfully tested for three FROPS of different sizes meeting appropriate ergonomics engineering standards. The operator actuation forces were less than the 75 N allowable maximum, and within the zones of comfort and reach for the operator. The lift-assist design uses an energy absorbing torsional spring to accommodate heavier FROPS designs.

Keywords

Folding; Actuation force; Torsion spring; Handle force

Introduction and literature review

A rollover protective structure (ROPS) is a mechanical structure which absorbs a portion of the impact energy generated by the mass of the agricultural tractor (as defined by SAE J2194) during a rollover accident (SAE, 2009). ROPS decrease the possibility of severe human injuries by providing a clearance zone to protect the operator within the ROPS envelope. It is well known that tractor rollovers are the leading cause of agricultural fatalities in the USA (NIOSH, 2008), and an agricultural tractor fitted with a ROPS and seatbelt virtually eliminates those fatalities if they are used properly. Foldable ROPS are becoming popular and are often used in agriculture where low trees, overhead obstructions, and limited access storage promote their usage. Myers (2015), formerly a NIOSH safety engineer, indicated that overhead obstructions limit the use of ROPS. The adaptation of a foldable ROPS has been used as a solution to tree limb obstruction and they are now considered the state of the art in operator protection. If a foldable ROPS is not offered, an operator can possible remove the ROPS to operate in low clearance situations, providing no rollover protection. Thus, manufacturers have an incentive to provide the foldable ROPS as an option. For this reason, foldable ROPS are more commonly used and are prevalent in the agricultural tractor community (Myers, 2015).

According to a typical ROPS manual (Wright, 2014) the statement - "If ROPS is a folding ROPS, ROPS should be in the upright position and pinned when operating the machine." Unfortunately, this does not always happen. Foldable ROPS can be difficult to fold up and down, so they are frequently left folded down during operation. Instruction from the OSHA website (OSHA, 2013) indicates that foldable ROPS may be temporarily lowered but they must be returned to the raised position when the vertical clearance allows it's use.

A problem exists when the ROPS are left folded down. Hill (2017) found that in all cases evaluated, folded ROPS did not provide the adequate operator clearance zone to meet the appropriate engineering standards. An unreferenced survey conducted by European Commission members showed that in tractor rollover accidents, 40% of fatalities and serious injuries happened when the ROPS was in inoperative (folded) position (Hoy, 2009). Pessina, Facchinetti, and Giordano (2016) reported that 30% of the tractor rollover fatalities in Italy from 2008 to 2014 resulted from ROPS in the folded down position.

OECD Code 7 define the maximum rear-mounted foldable ROPS actuation forces (OECD, 2017). The forces by operator to actuate (i.e. raise and lower) foldable ROPS has been identified as being up to 100 N in the comfort zone to 50 N with a forward leaning of the body in the accessible zone. But the OECD Code 7 does not address the fundamental problem of the operator leaving the operator's seat to raise and lower the ROPS. Engineering control designs are needed to allow the folding operation from the tractor seat, within the applicable ergonomic standards. This requires; 1) an understanding of foldable ROPS actuation forces and angles, ergonomic standards and allowable operator forces and movements, and 2) if needed, the application of mechanical lift-assist mechanisms to reduce actuation forces. This lift-assist mechanism needs to have a stored energy component, which does not compromise the ROPS performance. One factor to consider in designing a foldable ROPS lift-assist design that is retrofitted to existing ROPS is that integrity of the ROPS cannot be compromised. Modifications of the ROPS, such as drilling, welding and mounting of structures can affect the ROPS performance and must be avoided as it would require retesting of the ROPS. Mounting of lift-assist devices (gas springs, extension springs) requires rigid attachment to the ROPS which can affect the ROPS performance and nullify the ROPS certification. A lift-assist design with a non-contact attachment when the ROPS is in the upright position, specifically a torsion spring, which can be attached without brackets or drilling holes holds promise.

An initial patent for foldable ROPS design was developed by White (1979). Azzarello (1987) describes a design to use the three-point hitch to provide hydraulic power to lift a folded ROPS. Ludwig (1990) described a lift lever attached to a foldable ROPS, but it could not be operated from the vehicle seat and still meet the ergonomic standard requirements.

Alternative options for manually foldable ROPS exist, including: 1) automatically deployable ROPS (Ballesteros, Arana, Perez de Ezcurdia, & Alfaro, 2015; Powers et al., 2001), 2) powered FROPS (Ayers et al., 2012), 3) a telescopic ROPS (Sheehan, 1992), 4) a hydraulic gas cylinder powered FROPS (Panek & Kolli, 1998), and 5) a spring assembly powered FROPS (Bartel & Nebel, 2014). These options have promise for future ROPS designs, but they are expensive and impractical to retrofit on the existing foldable ROPS currently in operation as they modify the ROPS.

The force (or torque) to lift a ROPS is dependent on the mass of the ROPS folding section, its centre of gravity, and friction at the pivot location. Khorsandi, Ayers, Jackson, and Wilkerson (2016) found that although actuation speed did not substantially affect the actuation force, there was a significant difference between initial and continuous actuation forces. Accurate measurement of the mass and location of the centre of gravity of the foldable ROPS section are needed. A program was generated to determine these weights and locations based on ROPS dimensions (width, length, tube section and thickness) and anticipated pivot friction (Ayers, Khorsandi, Wang, & Araujo, 2018; Khorsandi & Ayers, 2018).

A FROPS lift-assist design needs to meet the ergonomic requirements for seated off-road equipment operators. SAE J898/ISO 6682 e Control locations for off-road work machines (SAE, 1994), and SAE J1814 - Operator controls e off-road machines (SAE, 2003) define the required control locations and actuation forces allowable for off-road operators. Maximum lever actuation forces allowed in SAE J1814 range from 75 to 100 N, for infrequently operated controls within the zone of comfort and reach, and depending on the direction of travel. Initial lift-assist designs for FROPS actuation were described by Ayers et al. (2018) and Froula, Brummitt, and Gilliam (2016). Ayers et al. (2018) describes the benefit of using a lift-assist torsion spring for reducing the FROPS actuation forces. This torsion spring was not integrated into the foldable ROPS stop and was not accompanied by a lift assist lever. The lift-assist torsion springs were attached to the FROPS pivot pin. Froula et al. (2016) presented a lift-assist lever design specifically for a FROPS for an Exmark lawn mower (Exmark, Beatrice, NE, USA). The lever was designed to raise and lower the FROPS from the operator seat but was designed for a specific FROPS orientation. Neither the lift-assist torsion spring or lift-assist lever engage the foldable ROPS when in the upright protective position and thus do not compromise the integrity of the ROPS. Although progress has been made to assist tractor operators in raising and lowering FROPS, still a simple universal manual lift-assist design with integrated torsion spring that can be retro-fitted on existing FROPS is needed.

1.1. Objective

The specific goal of this project was to develop and evaluate a universal retrofit mechanical lift-assist lever for foldable ROPS that can be operated from the tractor seat and meets appropriate ergonomic standards. Three FROPS models were tested to evaluate the design. The following specific tasks are identified.

1. Determine the actuation forces and angles for three foldable ROPS of various sizes.

2. Based on the actuation forces and location of the foldable ROPS with respect to the seat reference point, design and develop a universal retrofit mechanical lift-assist lever and torsion spring operable from the tractor seat for the various size FROPS.

3. Evaluate the mechanical lift-assist lever to determine the forces and movement required by the operator to meet appropriate ergonomic standards for the various size FROPS.

Material and Methods

2.1. FROPS force and dimension measurements

The three FROPS utilized in this study are shown in Table 1. They consist of one lawn mower ROPS (Exmark) and two agricultural tractor ROPS (FEMCO (FEMCO Inc., McPherson, KS, USA) and John Deere (Deere and Company, Moline, IL, USA). The width of the ROPS ranged from 51 to 76 mm, with thick- nesses ranging from 2.9 to 4.6 mm. The maximum vehicle operating mass for the three FROPS ranged from 713 to 4009 kg, providing a substantial range of actuation forces.

Measurements of the vertical, longitudinal and lateral (outside) distances from the seat index point (SIP) to the FROPS pivot bolt were conducted to better understand the range of the required lift-assist lever dimensions (Table 1). Based on discussions with FROPS operators it was disclosed that the FROPS does not need to be folded down completely to operate the equipment when under overhead obstructions. No referenced study was found that identified the vertical clearance required for operators. However, this preliminary study revealed that FROPS folded to approximately 600 mm above the seat index point (SIP) was the lowest position in which sufficient vertical clearance was provided to these operators to drive comfortably. Thus, the FROPS angle (referenced at 0o with the upper section of the FROPS horizontal) at which the top of the FROPS was <600 mm above the SIP was deter- mined (Table 1) and this was used in this study as the lowering limit angle. As additional information is gathered regarding the vertical clearance needed by operators with FROPS, the results of this study can be modified to account for these findings.

2.2. FROPS actuation force measurements

Actuation force measurements were conducted for the three FROPS using a digital force gage (M&A Instruments HF-500 (M&A Instruments Inc., Arcadia, CA, USA) and digital pro- tractor (Fowler mini-Mag (Fowler High Precision, Newton, MA, USA) similar to the method described by Pessina et al. (2016) (Fig. 1). The actuation forces were measured in 10-degree increments at the top of the FROPS while lifting from 10 to 80o, with the FROPS moving through the angle point. So, this was a continuous motion (dynamic) force, not an initiation force or a static force. A lifting force measurement of 0 N indicated that the FROPS was nearly balanced.

2.3. FROPS lift-assist design

The FROPS lift-assist design consists of two parts. The first is the FROPS lift-assist lever which is actuated by the operator and is used to raise and lower the FROPS. This lever must meet the location and force requirements described in SAE J898/ISO 6682 (SAE, 1994) and SAE J1814 (SAE, 2003). The universal lift- assist design utilizes two circular disks with mounting holes that can be rotated and fixed to position the lever handle at the operator zone of comfort (Fig. 2). The two rows of holes on the two disks (detailed in Fig. 3) provide rotation increments of 5o to more accurately position the handle with respect to the operator. The disks are bolted together when the desired angle is obtained. In addition, the lower lever arm length is adjustable with arm stops that can be positioned to allow the lever arm movement to slide the handle to the desired position (Fig. 2). The adjustable lever arm can also be slid down to lower the arm when the FROPS is in the lowered position to provide clearance from any vertical obstructions using adjustable slide arm stops. Also, when the FROPS is in the upright position, the lever arm can slide back so that it does not interfere with the movements of the operator. The FROPS interaction at the top of the upper lever arm allows for adjustable pegs to accommodate FROPS widths from 51 to 127 mm. The installed lift-assist lever is shown attached to the FROPS in Figs. 4 and 5. The FROPS lift-assist lever is attached to the FROPS by an extended pivot bolt (Fig. 4). The extended pivot bolt is the same diameter and grade as the original bolt but is about 76 mm longer to mount the lever. Analysis of bolt forces by Froula et al. (2016) and discussion with the ROPS manufacturers indicated this bolt extension and limited interaction with the FROPS does not impact the structural integrity. The attachment of the lever to the pivot bolt is performed using a collar screwed onto the pivot bolt, and a sleeve inserted in the upper lever arm. The collar is attached to the pivot bolt after the original nut is used to mount the pivot bolt to the FROPS. The journal bearing between the collar and the sleeve provides minimal friction (Fig. 4).

The second part of the FROPS lift-assist design is the lift- assist stop and integrated torsion spring (when needed). As the FROPS does not need to be lowered below 600 mm above the SIP, a FROPS stop bracket can be used to used stop the FROPS at the appropriate angle. If the actuation forces on the lift-assist lever are below 75 N, the minimum for infrequent and the torsion spring location, the torsion spring size (N m deg-1) and engagement points can be determined. Torsion spring rates (torque/angle) is dependent on material, wire diameter, coil diameter, number of active coils. Proper design is needed to assure the material remains in the elastic range under the applied torque and does not fail (reach the yield stress).

The innovation of the torsion spring lift-assist design is:

1. It does not require a power source and can be implemented manually.
2. It can be retrofitted to existing foldable ROPS design, using a pivot bolt extension.
3. It is simple and relatively low cost.
4. Guidelines can be developed to choose the proper torsion spring design based on ROPS mass dimensions.
5. It can be implemented into a lift-assist design that can be operated from the tractor seat.

It is important to note that the universal lift-assist lever, stop bracket, and torsion spring bracket are reversible, and can be mounted on either side of the ROPS. If needed for heavy ROPS, two levers and torsion spring brackets can be used and mounted on both sides.

Results and discussion

The FROPS lift-assist lever was constructed and initially evaluated with the Exmark and FEMCO FROPS. The disk rotation and lower lever arm extension are described in Table 2. For the lift-assist lever tests a new force and angle data acquisition system was used. The FROPS angle measurements were collected using a G-NSDOG1–006 MEMS-SERIES (Measurement Specialities Inc., Hampton, VA, USA) single axis inclinometer. Lift-assist handle force measurements were collected using an Omegadyne Inc. Model LC105–50 (Omegadyne Inc., Sunbury, OH, USA) load cell. The data from both sensors was acquired using a Campbell Scientific Inc. CRX23 Micrologger (Campbell Scientific Inc., Logan, UT, USA) at a rate of 5 Hz. Data for both the lift-assist handle force and FROPS angle were collected simultaneously while raising the FROPS from the lower limit angle to full upright position.

Figures 7 and 8 show the handle actuation forces during FROPS raising for the Exmark and FEMCO ROPS, respectively. The measured forces were less than the 75 N limit stated in SAE J1814 for infrequent control operation (SAE, 1994). Figures 9 and 10 show the location of the handle path for the respective ROPS during actuation within the operator reach zones described by SAE J898/ISO 6682 (SAE, 2003). Figures 9 and 10 show the cross-sections of the volumes presented in SAE J898/ISO 6682 at the lateral distance from the SIP that includes the handle path. In Fig. 10 the handle path travels in both the zone of comfort and the zone of reach. As stated in SAE J1814 the 75 N force limit is for both zones (SAE, 1994).

The handle actuation force and angle measurements were also conducted for the Deere FROPS (Fig. 11). Note that the actuation forces when raising from 10 to 30o were greater than the 75 N minimum as required by SAE J1814. The FROPS lift-assist torsion springs and brackets were developed for the Deere FROPS to lower the operator actuation forces. Along with the disk rotation and lower lever arm extension, the torsion spring design and engagement angle are described in Table 2. The actuation force was measured at the lift-assist lever handle while using the lift-assist torsion spring as the FROPS was raised. Figure 11 shows the actuation forces during Deere FROPS actuation with the torsion spring. The measured forces were reduced considerable and less than the 75 N limit stated in SAE J1814. Figure 12 shows the location of the handle path during actuation within the zones described by SAE J898/ISO 6682. The handle path is also within the operator reach zone defined by ISO 26322–1 and ISO 26322–2 (ISO, 2008; ISO, 2010).

For the three FROPS tested, the universal lift-assist design (lever and torsion-spring integrated stop bracket) was able to meet ergonomic engineering standards [SAE J898/ISO 6682 and SAE J1814]. The lift-assist handle operated in both the zones of reach and comfort, and at less than the 75 N maximum allowable.

Conclusion

A universal retrofit mechanical lift-assist lever for foldable ROPS that can be operated from the tractor seat was developed and tested. Three FROPS models were tested to evaluate the design. Due to the high handle actuation forces, a torsion spring and bracket was developed for the heaviest ROPS. The lift assist lever is adjustable to allow the handle to be placed and operated within the operator's zone of comfort or reach. For the three FROPS tested, the universal lift-assist design (lever and torsion spring-integrated stop bracket) was able to meet ergonomics engineering standards [SAE J898/ISO 6682 and SAE J1814]. The lift-assist handle operated in the zone of reach and comfort, and at less than the 75 N maximum allowable actuation force.

The design of the lift-assist lever does not preclude the need for the FROPS to be fixed in the upright position using a safety bolt or locking pin. Until a better design is available, the safety bolt needs to be manually removed each time the FROPS is lowered. For these 3 FROPS the safety bolt location is within the reach zone.

This paper describes the design and testing of the universal lift-assist lever for foldable ROPS and the integration of a torsion spring to reduce the operator handle forces. The next step would be to conduct repeated fatigue testing to evaluate the components reliability under typical operation.

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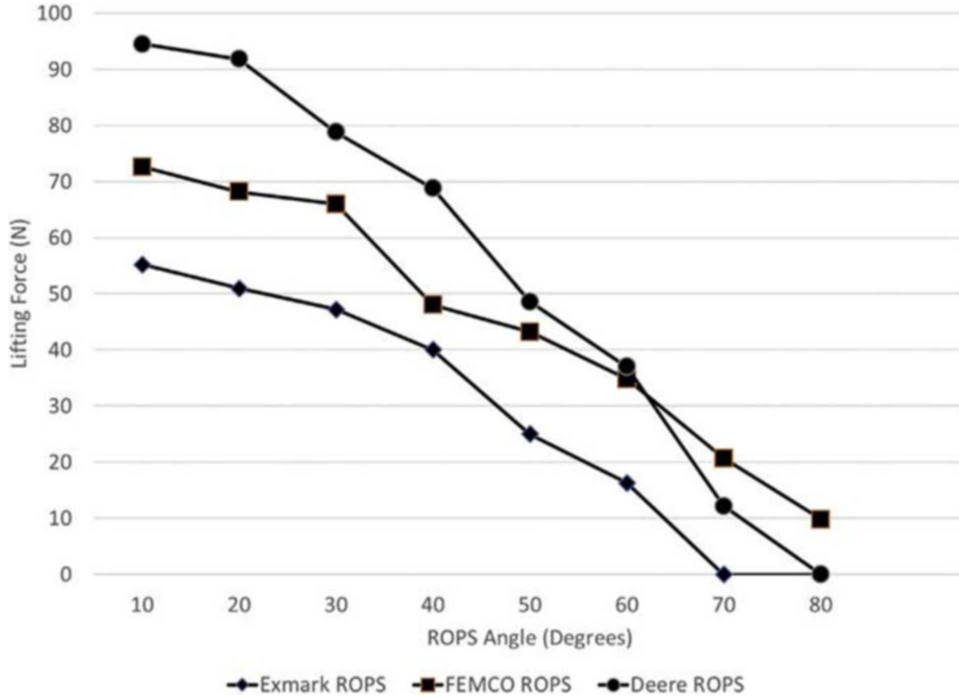

Fig. 1.
e Actuation force measurements for the three FROPS evaluated.

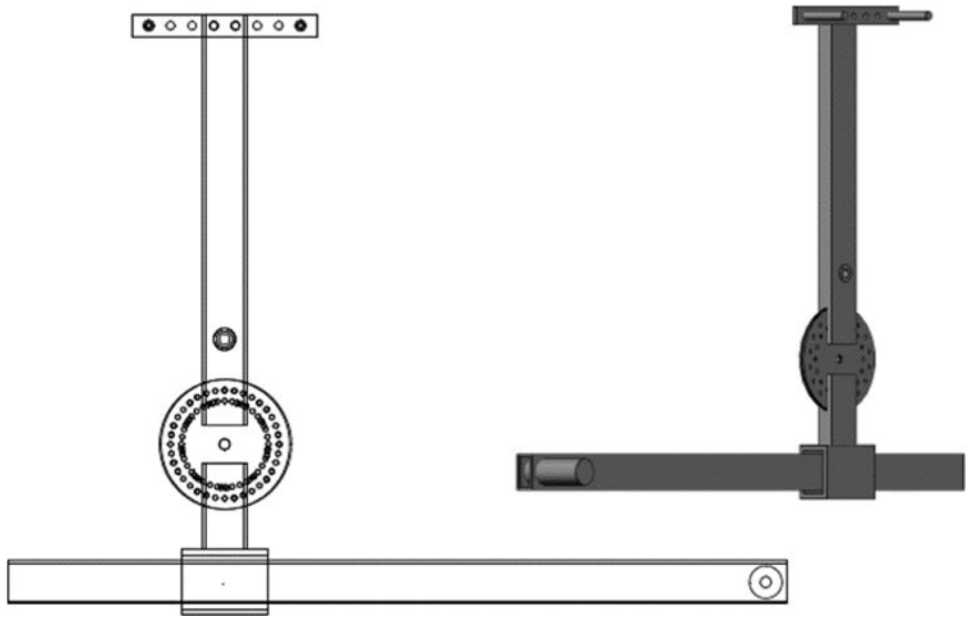

Fig. 2.
e Universal FROPS lift-assist lever.

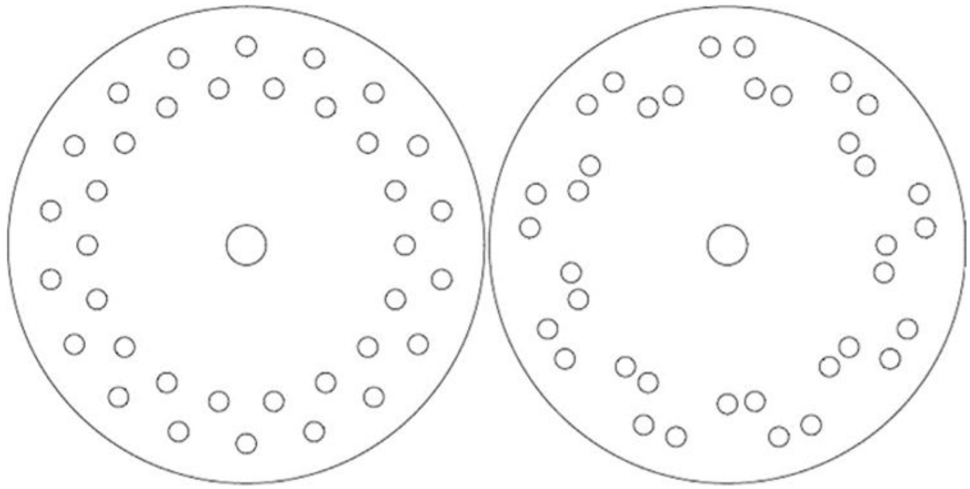

Fig. 3.
e Universal FROPS lift-assist lever disks.

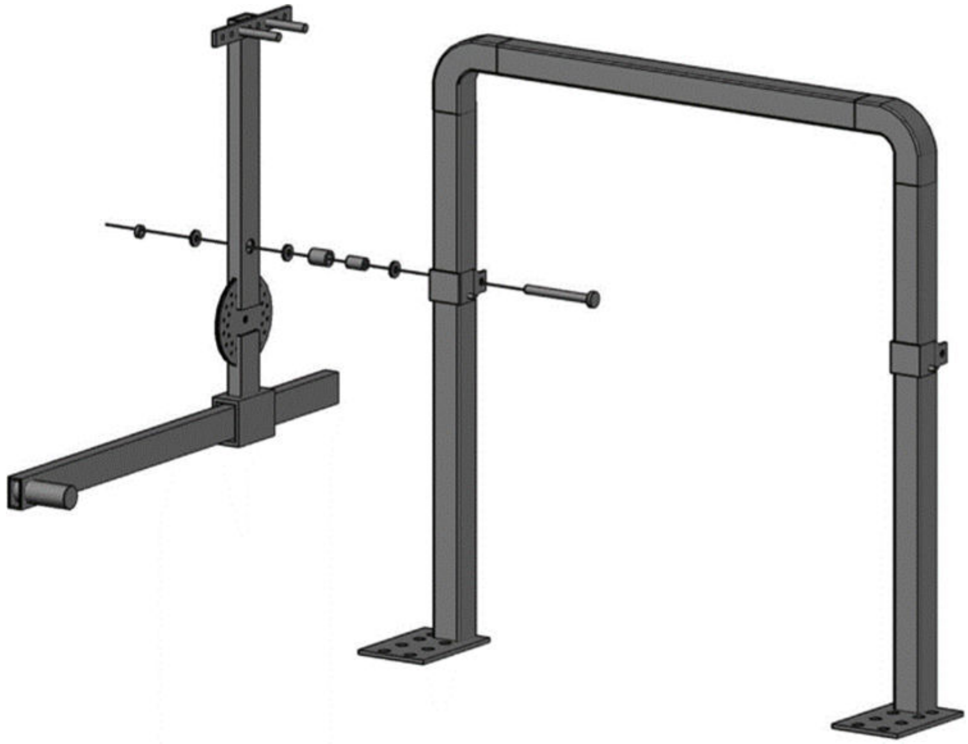

Fig. 4.
e Universal FROPS lift-assist lever attachment.

Fig. 5.
e Mounted FROPS lift-assist lever.

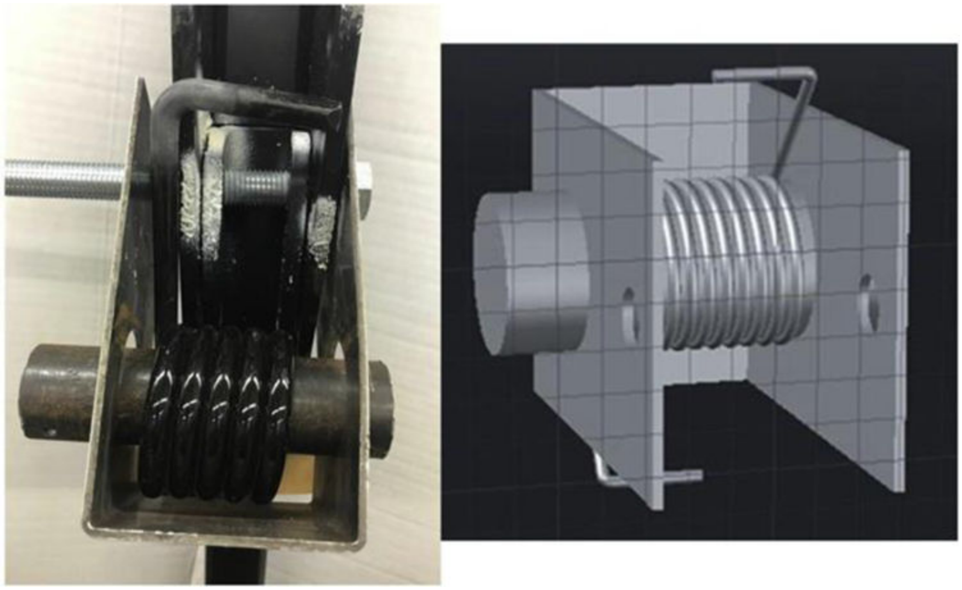

Fig. 6.
e Picture and graphical illustration of FROPS lift-assist torsion spring and stop bracket.

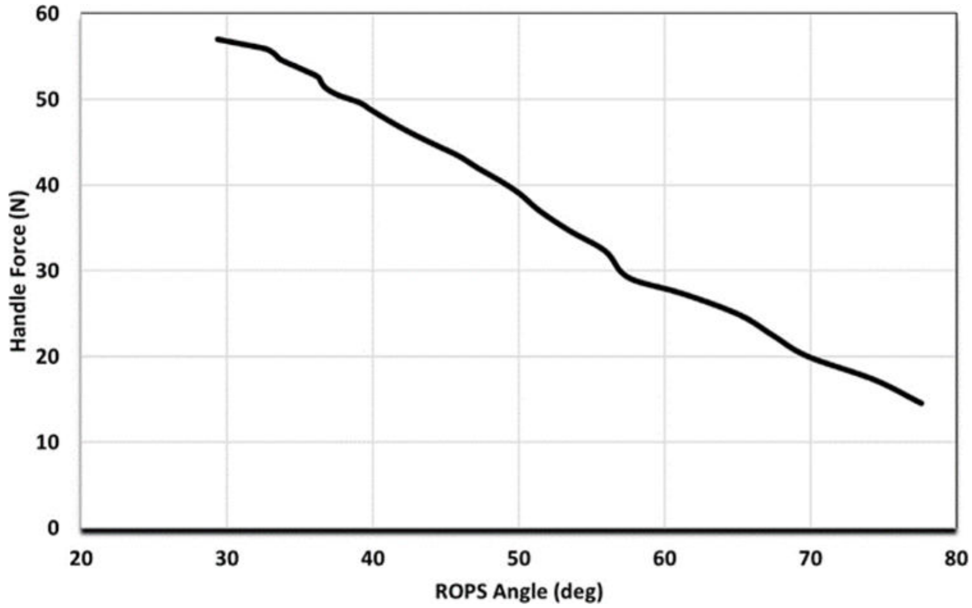

Fig. 7.

e Exmark lift-assist handle actuation forces.

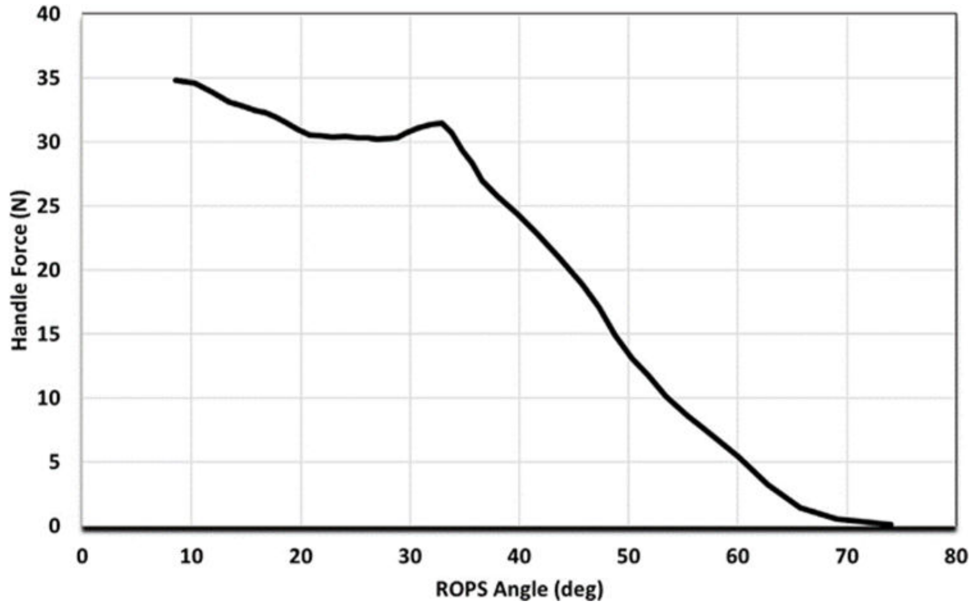

Fig. 8.
e FEMCO lift-assist handle actuation forces.

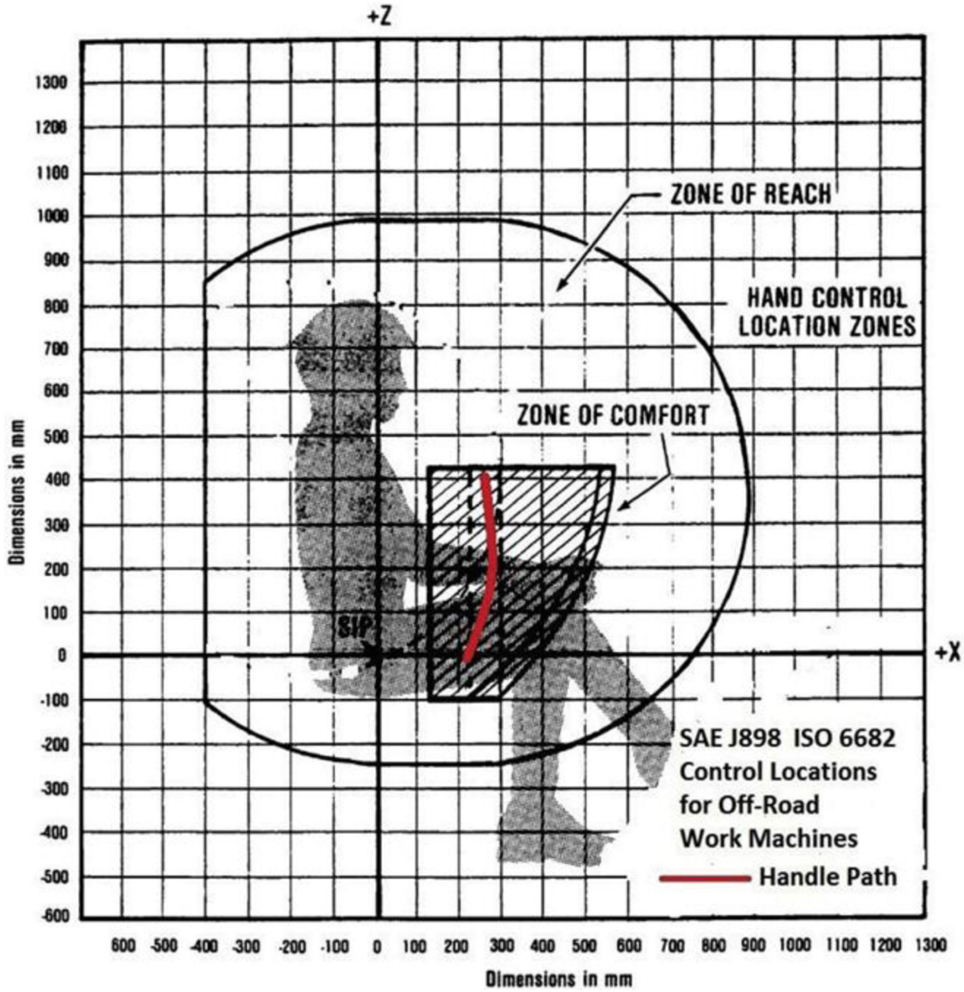

Fig. 9.
e Exmark lift-assist handle path.

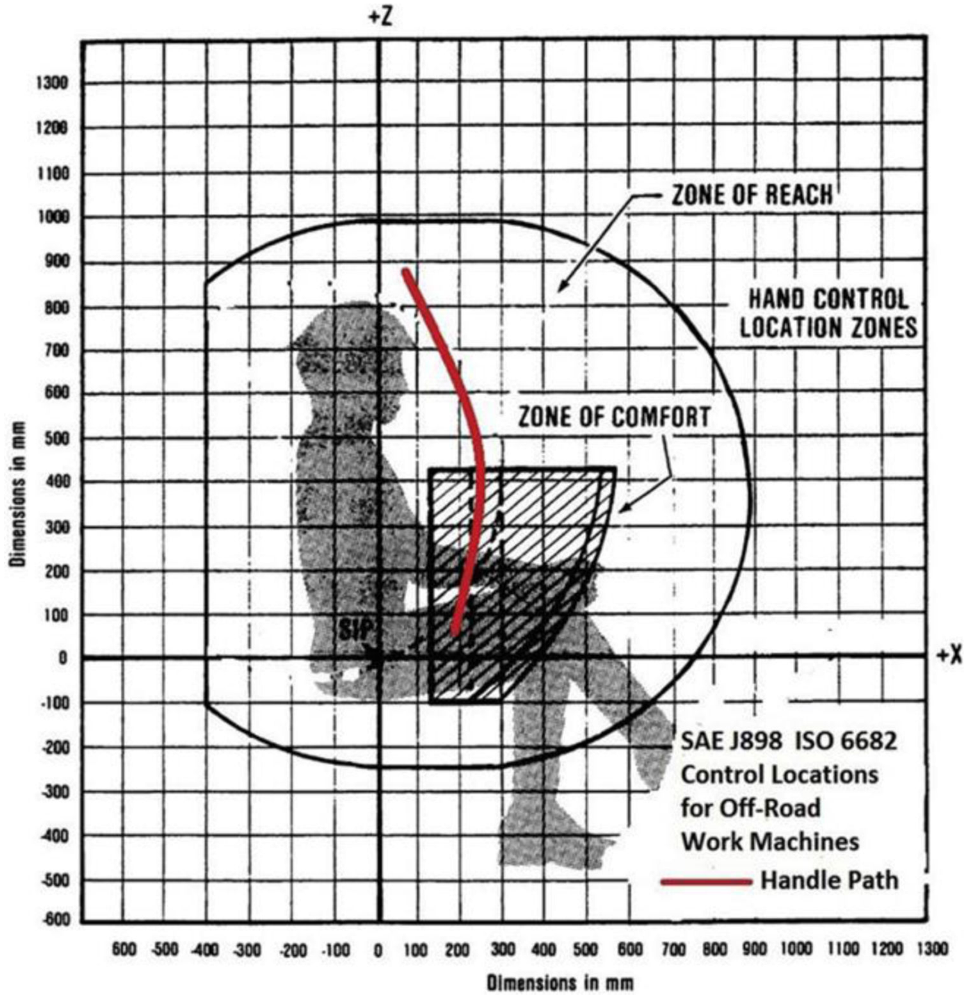

Fig. 10.

e FEMCO lift-assist handle path.

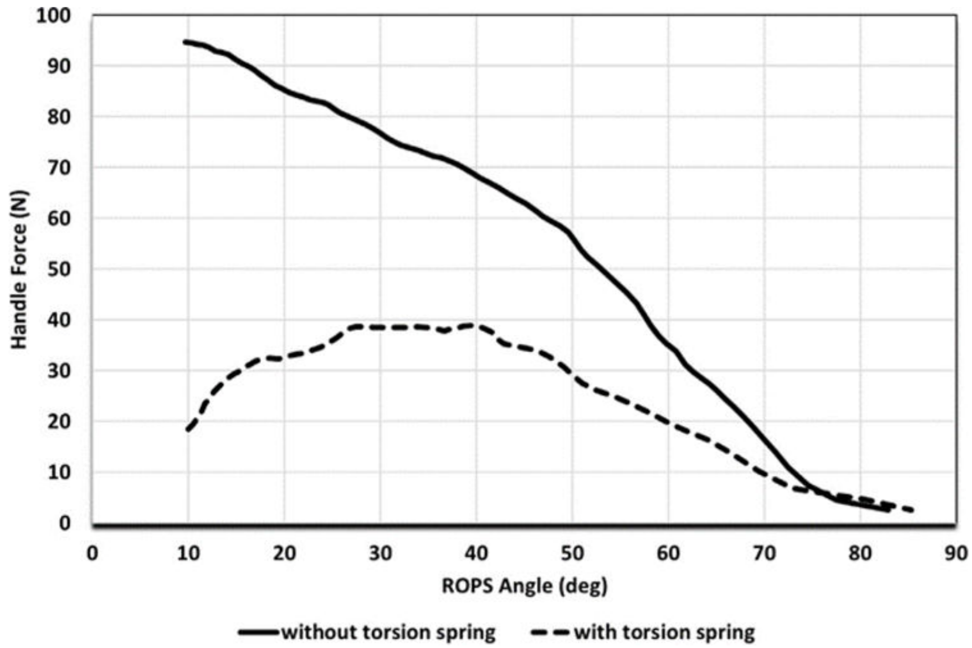

Fig. 11.

e Deere lift-assist handle actuation forces.

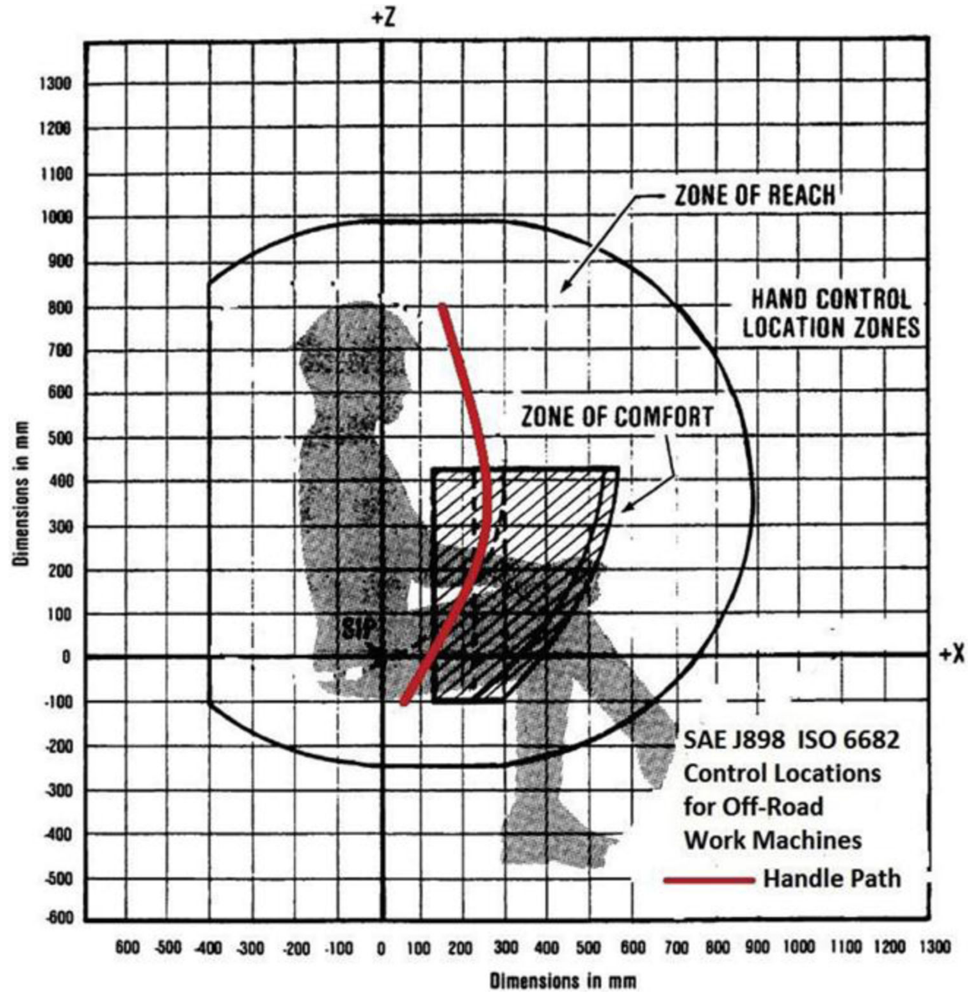

Fig. 12.
e Deere lift-assist handle path.

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Table 1.

The three ROPS utilised for the lift-assist designs.

ROPS Manufacturer	Model	Max vehicle mass (kg)	Standard	Post size (width-depth-thickness) (mm)	Vertical SIP-pivot (mm)	Longitudinal SIP-pivot (mm)	Outside Lateral SIP-pivot (mm)	Outside ROPS width (mm)	ROPS angle at 600 mm above SIP (degrees)
Exmark	109e6908	713	OSHA 1928	51 e 51e2.9	330	−200	415	830	30
FEMCO	301013466	1092	OSHA 1928	51 e 51e4.4	670	−480	410	820	10
Deere	S el 0095 544	4009	SAE J2194	51 e 76e4.6	660	−500	455	910	11

Table 2.

FROPS lift-assist lever designs.

	Lever				Torsion Spring			
	Disk Angle (°)	**Arm Ext (mm)**	**Max force (N)**	**Angle (°)**	**Wire Dia (mm)**	**Coils (#)**	**Inside Dia (mm)**	**Engage Angle (°)**
Exmark	10	320	57	30	e	e	e	e
FEMCO	0	590	35	10	e	e	e	e
Deere	−10	570	95	10	e	e	e	e
Deere with torsion spring	−10	570	39	30e40	9.5	5	46	75