Evaluation of a Commercial Tractor Safety Monitoring System Using a Reverse Engineering Procedure

C. Casazza, R. Martelli, V. Rondelli

ABSTRACT. There is a high rate of work-related deaths in agriculture. In Italy, despite the obligatory installation of ROPS, fatal accidents involving tractors represent more than 40% of work-related deaths in agriculture. As death is often due to an overturn that the driver is incapable of predicting, driver assistance devices that can signal critical stability conditions have been studied and marketed to prevent accidents. These devices measure the working parameters of the tractor through sensors and elaborate the values using an algorithm that, taking into account the geometric characteristics of the tractor, provides a risk index based on models elaborated on a theoretical basis. This research aimed to verify one of these stability indexes in the field, using a commercial driver assistance device to monitor five tractors on the University of Bologna experimental farm. The setup of the device involved determining the coordinates of the center of gravity of the tractor and the implement mounted on the tractor. The analysis of the stability index, limited to events with a significant risk level, revealed a clear separation into two groups: events with high values of roll or pitch and low speeds, typical of a tractor when working, and events with low values of roll and pitch and high steering angle and forward speed, typical of travel on the road. The equation for calculating the critical speed when turning provided a significant contribution only for events that were typical of travel rather than field work, suggesting a diversified calculation approach according to the work phase.

Keywords. Overturn recognition, Rollover, Stability index, Tractor safety.

Agriculture is one of the most hazardous occupational sectors in Italy, as indicated by the number and rate of work-related deaths. According to the Italian Workers’ Compensation Authority (INAIL, 2009), an average of 143 workers died in agricultural production each year in 2000-2008, corresponding to an annual fatality rate of 15 deaths per 100,000 workers (authors’ elaboration based on statistics and data of Italian National Institute of Statistics; ISTAT, 2016). Although the installation of rollover protective structures (ROPS) on tractors is obligatory in Europe, one of the main causes of these work-related deaths is tractor use; indeed, 44.7% of total agricultural fatalities in 2000-2010 were due to
tractors (authors’ elaboration based on INAIL surveillance system). Even if no specific statistics exist on how fatal accidents involving tractors occurred, the main risks are side and rear overturns (Mayrhofer et al., 2014), particularly a side rollovers, often when driving on steep slopes and sometimes associated with abrupt maneuvers (Arana et al., 2010).

Goldberg and Parthasarathy (1989) studied the abilities of tractor drivers in dangerous situations and concluded that drivers are often incapable of predicting an overturn, and that once a tractor reaches its critical overturn angle, driver response times are too long to allow corrective action. In any case, informed driver intervention is still more effective in preventing tractor overturns than active electronic or mechanical intervention (Sommer et al., 2006). It therefore appears to be extremely important to install sensors and a display on the tractor that can point out impending risk conditions and warn the driver to take corrective action to improve the tractor stability.

The analytical mechanics of farm tractors have been widely studied since the 1950s with the aim of developing mathematical models for predicting rear and side overturns (Kumar et al., 2013). Studies can be found in the literature on the design and evaluation of systems applied to tractors for stability measurement and driver alerts (Freeland, 1990; Greene and Trent, 2002; Nichol, 2005; Spencer and Owen, 1981). These studies are based mainly on mathematical models of stability that have been widely studied and validated (Ahmadi, 2013; Mitchell et al., 1972; Murphy et al., 1985; Ochoa-Lleras et al., 2015).

The stability conditions of a vehicle can be evaluated from a static (i.e., exceeding a critical angle for side or rear overturn) or dynamic point of view. Because determination of a stability index based on static conditions is simple and reliable, this process is considered a first step in the evaluation of vehicle stability. The evaluation of stability from a dynamic point of view is obviously more realistic but also more complex and must take into account different factors, including tractor speed, turning radius, and the wide variety of implements that can be coupled to the tractor. To do this, it is necessary to equip the vehicle with devices that incorporate sensors, such as accelerometers and gyroscopes, that measure the dynamic parameters of the tractor (e.g., tractor speed, pitch, roll, and yaw rate). Technological advances have put inexpensive sensors on the market that can measure these parameters, and a number of studies have shown that they can successfully monitor tractor stability. Sommer et al. (2006) developed a micro-electromechanical system (MEMS) sensor package and a pendulum overturn model to alert the driver of side overturn risk and provide an active intervention to prevent rear overturn. Blanco-Roldán et al. (2012) designed a device, called INCLISAFE, that incorporates a stability index developed by Liu and Ayers (1998) that considers both static and dynamic stability and emits a warning signal when the vehicle stability decreases. Exploiting the wide diffusion of mobile devices, Liu and Koc (2013, 2015) evaluated a software application for rollover detection and emergency reporting that was developed for smartphones and tablet computers. The sensors installed in these devices could verify the monitoring of vehicle stability and alert emergency services when a rollover accident occurs.

The aim of this research was to consider the geometric parameters (center of gravity, mass, track width, and wheelbase) and motion parameters (steering angle rate, speed, and roll and pitch angles) of different tractor-implement combinations to evaluate the performance of a commercial stability index device in real working conditions.
Material and Methods

The study of tractor stability in working conditions in the field was conducted using a commercial safety and driver assistance device that alerts the driver to a risk of overturning. The device is composed of inexpensive MEMS sensors including a biaxial accelerometer (MXD2020, MEMSIC, Inc., Andover, Mass.) used as an inclinometer, a triaxial accelerometer (AIS328DQ, STMicroelectronics, Geneva, Switzerland) to validate the inclinometer’s indications and confirm a tractor overturn, a gyroscope (ENC-03R, Murata Electronics, Kyoto, Japan) to measure the steering angle rate, GPS (SLE-1613, Knctek Co., Seoul, Korea) for localization of the tractor, GSM/GPSR (GC864-QUAD V2 Compact, Telit, London, UK) for data transmission, and CC2500 transceivers (Texas Instruments, Dallas, Tex.) installed on the implements coupled to the tractor to allow automatic recognition.

The data recorded by the sensors are sent to an internal microprocessor that uses an algorithm formulated by the manufacturer for calculation of a stability index as a function of the registered parameters and geometric characteristics of the tractor and any coupled implement. The device requires an installation and setup phase by the manufacturer for calibration based on the tractor’s geometric characteristics. The track width, wheelbase, and mass on each wheel in horizontal and tilted positions are determined in this phase to calculate the coordinates of the tractor’s center of gravity. The height of the center of gravity ($z_{cg}$) is obtained from comparison of the tractor’s geometric parameters when horizontal and when tilted laterally at an angle of approximately 12°, evaluating the shift of the projection of the center of gravity on the horizontal plane (eq. 1 and fig. 1):

$$z_{cg} = \frac{1}{\sin \alpha} \left[ x_{cg} \cos \alpha - w' \left(1 - \frac{m'}{m}\right) \right]$$  \hspace{1cm} (1)

where $w$ is the track width (m), $\alpha$ is the inclination angle (deg), $x_{cg}$ is the x-axis of the tractor center of gravity when horizontal (m), $w' = w \cos \alpha$, $m'$ is the mass that rests on the right-hand wheels when tilted (kg), and $m$ is the total mass of the tractor (kg).

Figure 1. Positions of the tractor in the determination of the center of gravity.
For all the implements mounted to the tractor, the coordinates of the center of gravity were determined by weighing the tractor-implement system in the two positions (horizontal and tilted) and making a comparison with the data relating to the tractor alone. In the case of a towed implement, its center of gravity was not determined, as its contribution to the position of the center of gravity of the tractor-implement system was considered negligible.

When monitoring the stability conditions of the tractor or tractor-implement system, if the risk threshold set in the commercial device is exceeded, the driver is alerted with a visual signal that appears on an LCD monitor installed in the cab. The measured parameters (forward speed, pitch and roll angles, steering angle rate, tractor position) and the risk index value ($IR_{device}$) are also recorded in an on-line database for evaluation and subsequent elaboration independent of the risk index value. The safety system therefore includes hardware, software, and an integrated information system for localization of the machinery. After a preliminary evaluation of the commercial device in the laboratory and in controlled field conditions (Casazza et al., 2015), warning devices were installed on five tractors at the University of Bologna experimental farm and monitored during the 2013 crop season in two different working conditions: the hilly area of Ozzano (44° 25’ 19” N, 11° 28’ 33” E, 140 m a.s.l.) and the plain at Cadriano (44° 33’ 36” N, 11° 24’ 57” E, 25 m a.s.l.). The operational parameters of the tractors coupled to 14 implements were evaluated (table 1). To allow automatic recognition of the implement coupled to the tractors, a transceiver was mounted on each implement (fig. 2).

The working parameters measured by the warning device and downloaded from the dedicated website were subjected to a reverse engineering procedure to elaborate an algorithm defining a risk index ($IR_A$) that was capable of replicating the risk index of the device ($IR_{device}$) that resulted from the unknown algorithm elaborated by the manufacturer.

A multistep approach was adopted in the reverse engineering procedure. In the first step, events associated with a single parameter (e.g., forward speed, steering angle rate, pitch and roll angle) of high value were analyzed. In the second step, events with a contribution of two parameters were considered, followed by three parameters, and finally all parameters. This approach allowed different algorithms to be hypothesized and therefore calculated different risk indexes. By comparing $IR_{device}$ with the calculated risk indexes, it was possible to select the proposed $IR_A$. Given the large number of data obtained, results are presented only for the hilly area, where the contribution of roll and pitch was greater.

## Results and Discussion

Evaluation of the data using the reverse engineering procedure allowed the hypothesis

<table>
<thead>
<tr>
<th>Tractor ID</th>
<th>Model</th>
<th>Power (kW)</th>
<th>Test Area</th>
<th>Implements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Landini Landpower 135</td>
<td>107</td>
<td>Hill</td>
<td>Rotary harrow 1, round baler 1, liquid manure spreader, grubber</td>
</tr>
<tr>
<td>2</td>
<td>Fiatagri 100/90 DT</td>
<td>74</td>
<td>Hill</td>
<td>Round baler 1, liquid manure spreader, rotary mower</td>
</tr>
<tr>
<td>3</td>
<td>New Holland T7</td>
<td>200</td>
<td>Hill and plain</td>
<td>Plow, harrow, rotary harrow 2, subsoiler</td>
</tr>
<tr>
<td>4</td>
<td>John Deere 6620</td>
<td>103</td>
<td>Plain</td>
<td>Rotary harrow 1, subsoiler, round baler 2, rotary harrow 2, harrow</td>
</tr>
<tr>
<td>5</td>
<td>New Holland TN85DA</td>
<td>63</td>
<td>Plain</td>
<td>Mower conditioner, tedder, sprayer, flail mower</td>
</tr>
</tbody>
</table>
that, in the definition of $IR_{device}$, the values of roll angle, pitch angle, and tractor speed in the turning phase ($IR_{roll}$, $IR_{pitch}$, and $IR_{steer}$, respectively) are considered separately, and the highest value of the three is used for the definition of the overall risk index (eq. 2):

$$IR_A = \max[IR_{roll}, IR_{pitch}, IR_{steer}]$$

(eq. 2)

$IR_{roll}$ (eq. 3) is the risk index that takes into account the value of roll angle ($\theta$). It was hypothesized that the critical value of roll angle ($\theta_{crit}$) refers to a condition of static equilibrium based on a stability triangle that has the rear track width for base and the tractor

![Stability triangle of the tractor.](image)
wheelbase for height (eq. 4 and fig. 3):

\[
IR_{\text{roll}} = \frac{\theta}{\theta_{\text{crit}}} \times 100
\]  \hspace{1cm} (3)

\[
\theta_{\text{crit}} = \arctan \frac{w}{2z_{cg}} \left(1 - \frac{y_{cg}}{l}\right)
\]  \hspace{1cm} (4)

where \(\theta\) is the roll angle (deg), \(\theta_{\text{crit}}\) is the critical value of roll angle (deg), \(w\) is the track width (m), \(l\) is the wheelbase (m), \(z_{cg}\) is the height of the center of gravity (m), and \(y_{cg}\) is the projection on the horizontal plane of the distance between the center of gravity and the rear axle (m).

The critical roll angle \((\theta_{\text{crit}})\) depends on the ratio between the height of the center of gravity and the segment on the horizontal plane (fig. 3) parallel to the rear axle passing through the center of gravity and limited by the sides of the stability triangle. Regarding the tractor-implement system, the center of gravity was calculated considering the two masses in the case of an implement mounted on the tractor, or just the center of gravity of the tractor in the case of a towed implement.

\(IR_{\text{pitch}}\) (eq. 5) is the risk index referred to the pitch angle \((\varphi)\). It takes into account the critical value of the pitch angle \((\varphi_{\text{crit}})\) defined by equations 6 and 7 for uphill and downhill conditions, respectively:

\[
IR_{\text{pitch}} = \frac{\varphi}{\varphi_{\text{crit}}} \times 100
\]  \hspace{1cm} (5)

\[
\varphi_{\text{crit \_up}} = \arctan \frac{y_{cg}}{z_{cg}}
\]  \hspace{1cm} (6)

\[
\varphi_{\text{crit \_down}} = \arctan \frac{l - y_{cg}}{z_{cg}}
\]  \hspace{1cm} (7)

To define the risk index correlated to the steering angle rate (eq. 8), it was hypothesized that the effect of forward speed is considered only in the turning phase and is limited to cases in which two constraints are met: \(\omega \geq 60\ \text{deg s}^{-1}\) and \(v \geq 25\ \text{km h}^{-1}\), where \(\omega\) is the steering angle rate (deg s\(^{-1}\)), and \(v\) is the forward speed (km h\(^{-1}\)):

\[
IR_{\text{steer}} = \frac{v}{v_{\text{crit}}} \times 100
\]  \hspace{1cm} (8)

The critical speed calculated on the basis of the equilibrium of the centrifugal force and weight force in the turning phase is expressed by equation 9, hypothesizing that the tractor follows a steady-state circular turn (McDonagh, 2014):

\[
v_{\text{crit}} = \sqrt{gr_wR}
\]  \hspace{1cm} \frac{1}{r_c}
\]  \hspace{1cm} (9)
where $v$ is the forward speed of the tractor in the turning phase (km h$^{-1}$), $v_{crit}$ is the forward speed critical value (km h$^{-1}$), $r_c$ is the centrifugal force arm (m), $r_w$ is the weight force arm (m), and $R$ is the radius of curvature (m).

To evaluate the correspondence between the estimated risk index ($IR_{i,t}$) and $IR_{device}$, events with risk index values greater than or equal to 75 were compared. Four cases of tractor-implement coupling were studied. These were considered representative, as in two cases the same tractor was coupled to two different towed implements, in two cases the same towed implement was coupled to two different tractors, and the last case was an implement fully mounted on the tractor (fig. 4). Each event had corresponding values of pitch and roll angle, with the latter expressed as an absolute value due to the practically symmetric position of the center of gravity of the tractor-implement system. In figure 4, events are shown in blue when the steering angle rate is $\geq 60$ deg s$^{-1}$ and in red when below this value, specifying the maximum value measured.

The graphs show that the distributions of events for the two risk indexes are practically superimposed. The independence of the three parameters (pitch, roll, and steering angle rate) can be observed, as there are no cases in which there is a simultaneous contribution of two of the parameters. The thresholds of roll and pitch above which the events reach risk index values greater than 75 are also evident. There is a clear distinction between the alarm signals when working, with lower forward speeds ($<15.4$ km h$^{-1}$) and high values of roll and pitch, and when traveling, with speeds $>25$ km h$^{-1}$, steering angle rate $>60$ deg s$^{-1}$, and low values of roll angle, typical of road travel.

The contribution of the setup phase of the warning device on the tractor, involving determination of the center of gravity, is evident by comparison of figures 4b and 4c, which refer to the same implement coupled to two tractors with very different centers of gravity. Indeed, despite performing the same operation, tractor 1 produced many more signals than tractor 2 due to lateral tilting. Moreover, these signals are at much lower values of roll angle due to the greater distance of the projection of the center of gravity from the base of the stability triangle, which determined a much lower $\theta_{crit}$. This is also supported by the events for tractor 1 when coupled to a liquid manure spreader, for which there is an equally low threshold of roll angle (fig. 4a).

An interesting case is that of the plow mounted on tractor 3 (fig. 4d), in which events with a risk index greater than 75 can be related to longitudinal tilting and not lateral tilting. The $IR_{i,t}$ algorithm takes into account that the plow is fully tractor-mounted, causing a retraction of the center of gravity of the tractor-implement system with positive effects on the static stability due to the higher value of the critical angle of side overturn, as is clear in equation 4. Consequently, although cases were registered with roll angles close to 20° for the tractor-implement system, there are no risk index values greater than 75.

To evaluate the contribution of the turning phase in the algorithm of the commercial device, events with $IR_{steer}$ (eq. 8) greater than 75 were selected, ignoring the hypothesis of the constraints imposed on the forward speed and steering angle rate ($v \geq 25$ km h$^{-1}$ and $\omega \geq 60$ deg s$^{-1}$). Figure 5 shows the values of steering angle rate and forward speed for events with $IR_{steer}$ greater than 75. It can be noted that the forward speeds are always higher than 23 km h$^{-1}$, typical of a tractor in transit and not working. These events also had low values of roll angle, and this confirms the hypothesis that the tractors were traveling. It can therefore be considered that the formula for calculation of the critical speed (eq. 9) is more suited to calculating the risk level for a tractor in transit rather than in normal field operations.
Figure 4. Events with risk index levels ≥75 (IR_{device} left and IR_{a} right): (a) tractor 1 and liquid manure spreader, (b) tractor 1 and round baler 1, (c) tractor 2 and round baler 1, and (d) tractor 3 and plow.
Figure 5. Events registered by the commercial device with $HR_{over} \geq 75$ not considering the constraints on forward speed and steering angle rate ($v \geq 25$ km h$^{-1}$ and $\omega\geq 60$ deg s$^{-1}$): (a) tractor 1 and liquid manure spreader, (b) tractor 1 and round baler, (c) tractor 2 and round baler, and (d) tractor 3 and plow.
Conclusions

The reverse engineering analysis hypothesized an algorithm for calculation of the stability index based on the separate contributions of lateral tilting, longitudinal tilting, and steering angle rate. As expected, the commercial device uses a simplified approach based on a static or steady-state evaluation for determination of the risk level. This is consistent with the aim of the device, which is not to warn the driver during an overturn but rather to rectify repeated incorrect driver behavior and modify an unsafe working method.

From the analysis of the data related to events that were considered hazardous, a clear separation into two groups emerged: events with high values of roll or pitch angle and low speeds, typical of a tractor when working, and events with low values of roll and pitch and high steering angle rate and forward speed (>23 km h⁻¹), typical of travel on the road. It might therefore be useful to introduce two different indexes according to whether the vehicle is working or in transit, and it would be worthwhile, when working, to also consider the contribution of turning at the low speeds characteristic of this work phase, maintaining the current formula for calculating the critical speed only for travel, when speeds are higher. This approach would be consistent with data related to rollover accidents, according to the authors’ elaboration based on the INAIL surveillance system, which demonstrated that as many rollover fatalities occur during field work as occur during travel. An added value of the device can be attributed to the setup phase on the tractor, which involves determining the coordinates of the center of gravity using a procedure that is onerous to perform but important for the evaluation of the stability conditions, as shown by the results.

Future research will involve the cooperation of experienced tractor drivers to set a device alert threshold to avoid an excess of signals that might otherwise be ignored.

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