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# Assessing Perceptions and Alerts of Tractor Instability

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This paper presents ongoing results from a Tractor Driving Simulator study at Penn State University studying how tractor overturn events can be prevented. The simulator is used to expose subjects, in a controlled environment, to situations that would be unsafe to test in the field. Two sets of experiments are examined here. The first experiment consisted of a tilt perception study whose goal was to quantify the ability of subjects to remember and reproduce certain poses with pitch and roll angles. Nineteen subjects were individually exposed to a tilt angle; then, they used a controller to drive the simulator until they perceived they have reached the exposure angle; the process was repeated with 28 different poses representing combinations of pitch and roll of the tractor cabin. Overall, subjects reproduced angles with a smaller amplitude than they were exposed to, indicating that they were overestimating their tilt angles while actively controlling the cabin angle. Roll angles presented an overestimation of 8%, while pitch was accurately reproduced. There was no statistically significant difference between experienced tractor operators and non-experienced subjects, nor any significant influence of pitch angle on roll perception, or vice versa. The second experiment compared visual, haptic, and acoustic interfaces to alert a subject that they were driving at a hazardous roll angle. A screen with a bubble display—indicating the pitch and roll angles of the cabin—was enhanced with auditory (buzzers) and haptic (vibration on the steering wheel) alerts. When the simulator cab tilts over a pre-defined safety threshold, an alert was given to the operator along one or more alerting systems. The experiment collected the reaction times of the subjects to each type of alert interface to determine which one was the most effective at capturing the driver's attention.

## 1. Introduction

For the past five decades, tractor rollover has consistently been a leading cause of injuries and fatalities in the agricultural sector. Regulations that require the installation of Rollover Protection Structures (ROPS) have been implemented around the world since the 1970's (Springfeldt, 1996). However, recent statistics show the problem persists. On U.S. farms, it is still the most common cause of occupational fatalities (Myers and Hendricks, 2010). The National Institute for Occupational Safety and Health data suggests that between 1992 and 2005, 1,412 workers on farms died from tractor overturns (NIOSH, 2009). For Pennsylvania, Penn State's database of farm fatalities shows that in 2010-2014, 32 of the 141 recorded farm fatalities included vehicle rollover or overturn incidents (Görücü et al., 2015). Pessina et al. (2016), found that 56% of rollover fatalities in Italy from 2008 to 2014 occurred when no ROPS was installed, but also 19% of them occurred when a foldable ROPS was installed, but in the folded-down position at the time of the accident. The ineffective use of ROPS devices, even when they are installed, has been a rising problem since 2004 (Khorsandi et al., 2016).

Once a tractor begins an overturn it becomes mostly uncontrollable (Sommer III et al., 2006), which is why there must be an important emphasis on rollover prevention (Murphy et al., 2010). While ROPS may help mitigate the injuries resulting from a rollover incident, driver assistance devices seek to prevent the incident from occurring. As an example, Casazza et al. (2016) evaluated a commercial sensor suite for stability monitoring. Motivated by this approach, the authors developed a Tractor Driving Simulator at Penn State (Ochoa Lleras et al., 2016). This paper reviews two experiments conducted with the simulator: the first is a study of perception of tilt that helps one understand how perceptual errors can affect the operator's awareness of risk while operating on steep slopes; the second experiment was an evaluation of different alert interfaces aimed at improving the operator's awareness when driving on sloped terrain.

### 1.1 Tractor Driving Simulator

The Mechanical and Agricultural Engineering departments at Penn State developed a tractor driving simulator, as shown in Figure 1. It utilizes a parallel robot with six degrees-of-freedom, plus a custom-built mechanism for additional roll motion up to 25º. The system runs on the open source Robotic Operating System (ROS) and uses Blender for its 3-D physics simulation and rendering. A custom-built screen, 8 ft tall and 48 ft in diameter, provides a 360º immersive environment. A 2000-Watt sound system is use to recreate tractor engine noise, and a steering actuator simulates the torques required to steer the tractor. The development of the simulator is described in detail in (Ochoa Lleras et al., 2016).

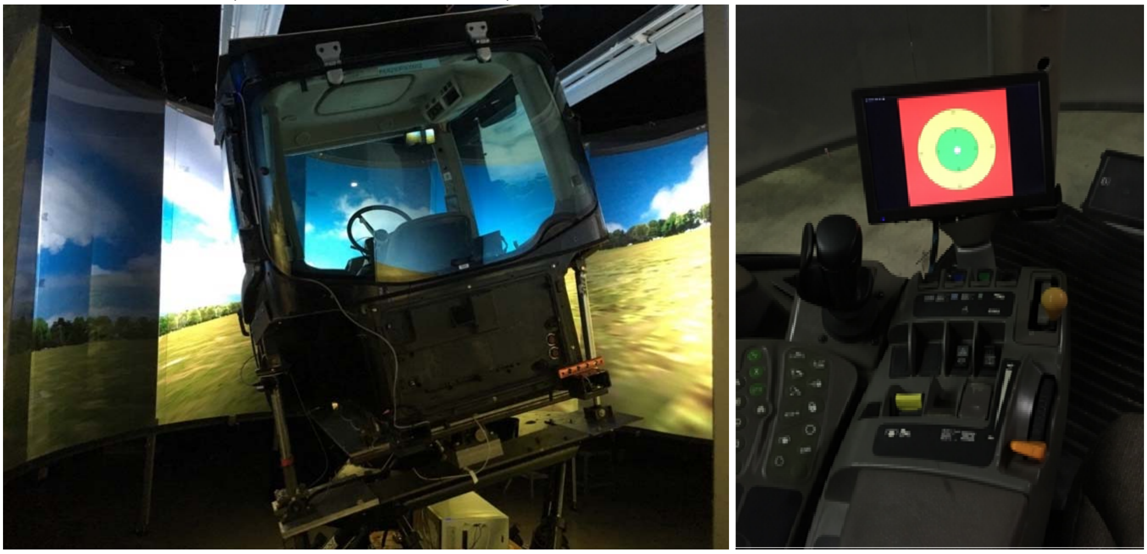

*Figure 1. The tractor driving simulator has a digital bubble-level display on the armrest instrument panel.*

## 2. Tilt Perception Study

The first experiment was designed to evaluate the operator's ability to memorize and reproduce tilt positions in roll and/or pitch. Preliminary results with four pilot subjects were published in Ochoa Lleras et al. (2016). This paper shows the results for the full study, with 19 new subjects and a slightly revised experimental procedure.

### 2.1 Procedure

The subjects sat in the tractor cabin in what they considered to be a comfortable driving position. They then followed these steps: first, starting from a level position, the platform moves the cabin to a given roll-pitch angle; it remains stationary for five seconds. This tilt angle is the one subjects are asked to remember. Then the platform returns to level. The subject then uses a video game controller to reproduce the exposure angle. When they reach what they believe is the correct roll-pitch position, they press a button to record the corresponding data point. This process is conducted with three practice angles (which are not used in the data analysis), and then for a randomized sequence of 28 set angles for the test.
During pilot testing, some subjects reported using visual aids from the surrounding screen and equipment to reproduce their tilt angles. Because of this, for the experimental tests, the cabin was externally enclosed with black-out curtains in order to focus the experiment on cues that would be available on a moving tractor in the field (vestibular signals and seat pressure on the legs and back).

### 2.2 Results

The subject pool included 11 individuals with tractor driving experience (all male) and 8 subjects with no experience (4 of them female). Their ages ranged from 19 to 69 years, with an average of 46. Figure 2 below summarizes the results for the whole experiment. The set tilt angles are shown (squares) against the average reproduced tilt for all subjects (crosses), with its corresponding one-sigma uncertainty (represented by the axes of the ellipses). Overlapping ellipses—for example, those on the bottom-right corner for set angles (17, -

15), (24, -15) and (24, -10)—show that it would be difficult for the subjects to tell these different configurations apart.

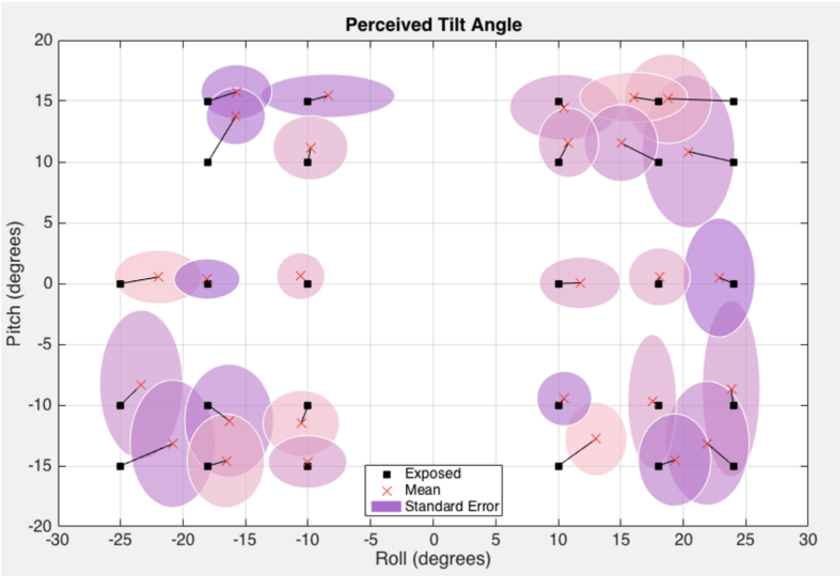


*Figure 2. Summary of reproduced tilt angles for all subjects.*

The data was analyzed through linear regressions to detect tendencies for the whole group. Figure 3 below shows regressions of the reproduced angle as a function of the set angle they were exposed to. Perfect reproduction would yield a slope of 1 and an intercept of 0 º. When the subject reproduces an angle larger than the exposure angle, this is called and over-production; it indicates that they underestimated their tilt angle while commanding the platform with the controller, and thus drove it farther from the original angle. Oppositely, an under-production is when the subject overestimated their tilt while commanding the platform, and thus took the cabin to a smaller angle. In this study, subjects appear to under-produce tilt effects in roll.

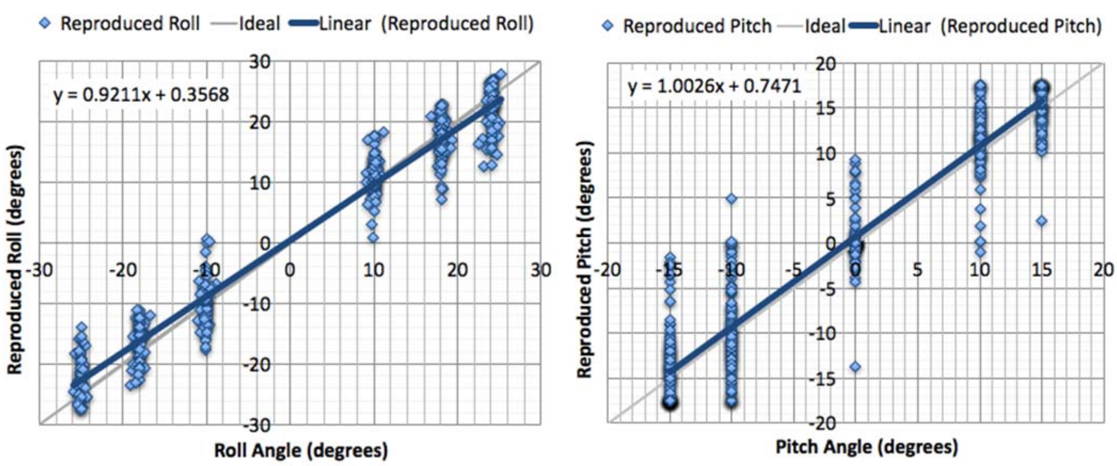


*Figure 3. Regressions show that roll was consistently under-produced, and therefore overestimated by a factor of 8 %. Pitch angles however, on average, was reproduced accurately.*

The single-variable regressions show that the group as a whole overestimated roll by about 8 %, while estimating pitch accurately. In both cases the results had small biases, below 0.8 º. It's important to note that the pitch angles used in the experiment were smaller than the roll angles. If the roll angles are split into small (under 15º) and large groups (15 º - 24 º) the slopes obtained are 1.05 and 0.91, respectively. For this reason, the differences between roll and pitch accuracy could be explained by the difference in magnitudes, rather than an inherent difference between the ability to reproduce tilt angles in the pitch and roll directions.

The two-variable regressions showed that there is no meaningful contribution of pitch angle towards roll estimation, nor a statistically significant effect of roll angle towards pitch estimation. This would suggest that accuracy of pitch and roll estimates are unrelated for this experiment.
Another issue under study was whether experienced tractor operators performed differently in the test. Figure 4 below shows that the slopes for each group were not meaningfully different from each other.

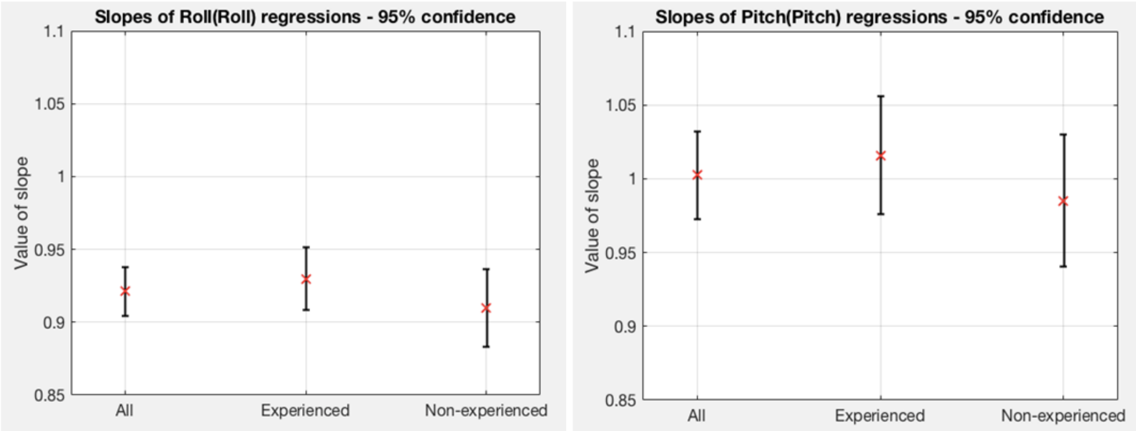


*Figure 4. No meaningful difference was detected between experienced tractor drivers and non-drivers.*

Finally, the results were controlled for fatigue, or learning throughout the experiment: the 28 angles were the same for all subjects, but were presented in a different, random order in each test. There was no significant correlation for the accuracy of the reproduced angles with the order in which they were presented.

## 3. Evaluation of Alert Interfaces

The second experiment was developed to determine what type of alert interface would be more effective at capturing the operator's attention when a hazardous situation arises. A 3-D virtual environment was developed to simulate the effect of driving a tractor on a sloped field. The subjects were asked to complete two tasks simultaneously, dividing their attention between two competing objectives: monitor the tractor's roll angle and keep an eye on the field and equipment around the tractor.
Four alert interfaces were considered. First, a digital bubble-level display that showed the current tractor tilt, plus a time history of the past 5 seconds; this display (shown in Figure 1) was marked with green, yellow and red areas to indicate the level of safety, and was kept on throughout the whole experiment. Second, an auditory alert that buzzed when a certain safety threshold was passed. Third, a haptic alert that made the steering wheel vibrate when the safety threshold was exceeded. Finally, the fourth interface was a combined system where both haptic and auditory alerts were set off simultaneously.

### 3.1 Procedure

Subjects sat in the tractor cab, holding the steering wheel as if they were driving. The screen showed a virtual field and the sound system reproduced a tractor engine sound. The tractor started moving through the field at a constant speed of 3 mph, along a succession of hills. Each hill was between 250 m and 300 m long, at a constant slope of 13º; successive hills alternated between positive roll (right side of the cabin tilting downwards) and negative roll. This recreated the effect of driving down a slanted plot of land one way, for 3 to 4 minutes, and then driving back the other way. The total length of the path was 2700 m, and took 35 minutes to complete.
While driving on the slope, the cabin would tilt farther, to 17º, three to five times per hill. In order to reduce the predictability of test, the length of the hills and the span between these 17º-roll events were chosen randomly. Additionally, a small-amplitude rocking motion was added to simulate the tractor bouncing on top of the terrain.
The subjects were instructed to keep track of two different tasks during the test. For the stability task, they were asked click a right foot-switch whenever the bubble went into the red, or any of the alerts were set off, which happened when the roll angle was above 14.5 º. For the distractor task, they were asked to click the left-foot switch whenever they saw a black sphere on the screen. Upon pressing the switch, the sphere would disappear. It would reappear at a new location, at random intervals between 6 s and 13 s, across the driver's

360-degree field of view. These two tasks simulate the competing objectives of monitoring the tractor's stability, while also devoting attention to the equipment and surrounding field while conducting field operations.

### 3.2 Results

The subject pool for the second experiment included 13 subjects with extensive tractor driving experience (all male), and 10 without any experience (one female). The ages ranged from 20 to 64 years of age, with an average of 33. Figure 5 below summarizes the most significant results of the experiment.

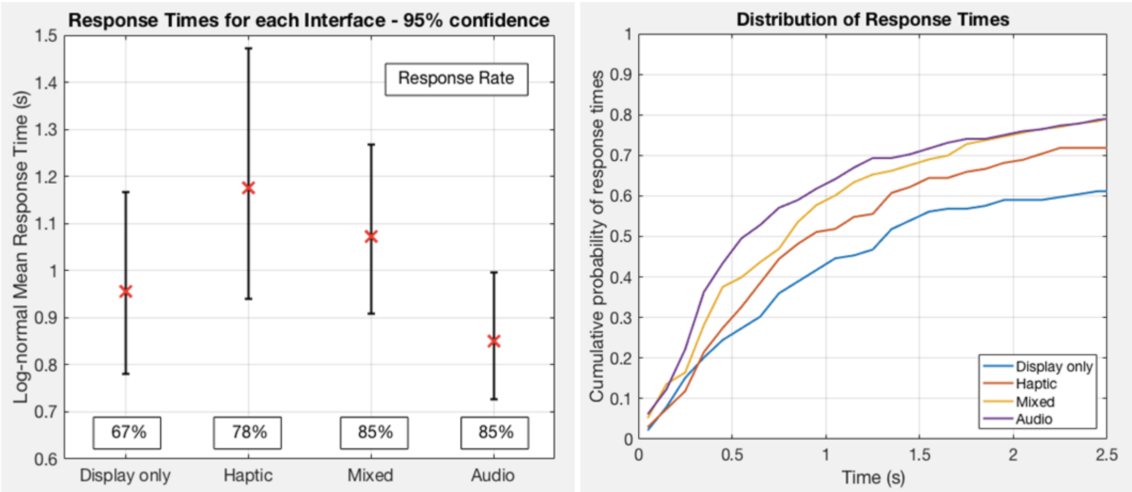


*Figure 5. The mean response times have a wide confidence interval, but the cumulative probability functions show that the auditory alert produced the largest number of effective responses in shorter time periods.*

The response times for each interface had standard deviations as large as their means. For example, the mixed alert had a mean of 0.91 s and standard deviation of 0.84 s. Therefore, the data for each interface was instead fitted with a lognormal distribution, which is commonly used for random variables that can only take positive values. The mean of the lognormal distribution suggests that the audio alert performs better than the display on its own, while the mixed and haptic alerts showed longer response times. However, the large confidence intervals make do not allow significance to be established for these results. Furthermore, the comparison assumes that the response time has a lognormal distribution, but the distribution can only be fitted over the response times, ignoring all the events where no response was obtained. In fact, none of the common statistical distributions (Weibull, gamma, stable, lognormal) appear fit the data particularly well. Hence, Figure 5 includes the response rate, which is the percentage of events that produced a response from the subjects. This shows that, while the display with no other alert produces faster responses than the haptic and mixed alerts, it also obtains a driver response only 67% of the time. That means the display is effective, but only when the operator is looking at it. Without having an additional alert to bring the operator's attention to the display, many risky situations might go unnoticed.

For this reason, the performance of each interface was evaluated with a different concept. The best interface is the one that both produces the highest number of responses in the shortest period of time. This combination can be examined by the cumulative probability function of the response time. Once the tractor has gone over the prescribed safety roll angle, these curves illustrate what percentage of those events received a response before a given time. The advantage of this metric is that it does not impose any assumptions regarding the underlying distributions of the data. The disadvantage is that it does not provide a single number that can be easily compared across interfaces. Better performance is evidenced by a curve that rises faster towards one.

The cumulative probability distributions show that displayed warnings produce quick responses; the authors, in discussing this with test subjects in post-experiment debrief, think that this is because the visual display is the only one that allows the operator to predict where the tractor roll is headed. However, requiring operator attention on the equipment around the tractor appears to limit the effectiveness of using the display on its own. Complementing the display with a haptic alert produces the smallest improvement, compared to auditory and mixed alerts. This might be because there are both mechanical and perceptual delays in transmitting the vibration to the driver: the vibration motors must speed up, the steering wheel must be accelerated into a vibration motion, and then the operator should feel the vibration and react. Meanwhile, the auditory system has no mechanical delays, and thus produces faster responses at a higher rate. Finally, the mixed system performs somewhere between the auditory and haptic alerts, showing that more stimuli does not inherently lead to faster responses. Interestingly, the results match the subjects' preferences: at the end of the test 11 subjects said the auditory alert was the most helpful, while 5 chose haptic, 5 mixed, and 2 had no preference.

## 4. Conclusions

The perceptual errors in roll occurred mostly in large roll situations, above 15º. At those angles, an under-reproduction of 9% showed that test subjects tended to overestimate their roll angle. Perceptual errors of this type would be protective while on the field, since overestimation of the roll angles stimulates more conservative driving. Pitch angles were estimated correctly, on average, but this may have been due to the smaller magnitude of pitch angles in the test. No statistically significant differences were detected between experienced tractor operators and non-operators.

The most effective alert interface as determined by driver reaction speed and effectiveness was the combination of the auditory system used with a visual “bubble” display, when compared to the haptic, mixed, and display-only interfaces. However, the distributions and large variations in the results made testing statistical hypothesis difficult. This performance metric coincided with the subjects' comments—collected after each test—where 11 of them preferred the auditory alert, while only 5 preferred the haptic and 5 the mixed system.

Ongoing experiments are examining whether using an alert system for extended periods might make the operators overly trusting of alerts, perhaps promoting unsafe driving behavior. Another question is whether constant alerts might become a nuisance for the operator, encouraging them to ignore or disconnect the device.

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