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Manual GPS guidance system for agricultural vehicles

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Abstract

In this paper, the performance of a manual GPS guidance system to assist farming operations is evaluated. The distribution of granular fertilizer was simulated in order to discretize areas with excessive application of fertilizers and areas with fertilizer application rates below the intended rate. The path of travel followed by a tractor with the manual GPS guidance system was analysed and compared with a commercial parallel tracking system and without guidance assistance. In addition, the analysis evaluated how the use of manual GPS guidance systems improves the performance of field operations that require large distances between passes. Under the experimental conditions used, the best results were obtained using a commercial parallel tracking system but, for our purposes, small differences were observed between the results obtained with the commercial system and the results obtained with the developed manual GPS guidance system, getting pass-to-pass average error values of 0.26 and 0.73 m, respectively. The results obtained with both systems were significantly better than the results obtained when no guidance assistance was used. In our trials, area with appropriate fertilizer rate was clearly increased when guidance assistance was used. Values of area with correct fertilizer rate applied ranged between 87% with commercial parallel tracking and 59% without guidance assistance. The use of the manual GPS guidance system presented in this paper has proved sufficient to obtain good results for mechanical fertilizer spreading.

Additional key words: parallel tracking; precision agriculture; spreader simulation.

Resumen

Sistema GPS de guiado manual para vehículos agrícolas

En este trabajo se ha evaluado un sistema de asistencia al guiado manual para la realización de labores agrícolas. Se simuló la distribución de fertilizante granulado con el objetivo de discretizar áreas con excesiva cantidad de fertilizante y áreas con cantidades inferiores a las previstas. Se comparó la trayectoria seguida por un tractor utilizando el sistema GPS de asistencia al guiado manual con un sistema comercial de guiado paralelo, y sin asistencia al guiado. Nuestro análisis ha permitido evaluar las mejoras que estos sistemas suponen para la realización de labores que requieran elevadas distancias entre pasadas. En nuestras condiciones, los mejores resultados se obtuvieron con un sistema comercial de guiado paralelo, si bien, considerando nuestro propósito, las diferencias fueron reducidas respecto a las obtenidas con el sistema de asistencia al guiado manual desarrollado, con valores medios de error pasada a pasada de 0,26 y 0,73 m, respectivamente. Los resultados obtenidos con ambos sistemas fueron significativamente mejores que los obtenidos cuando no se utiliza ningún sistema de asistencia. En nuestros ensayos, el área con dosis adecuadas de fertilizante se incrementó de forma clara con la utilización del sistema de asistencia al guiado manual. Los valores de superficie con dosis correctas de fertilizante aplicado oscilaron entre el 87% con el sistema comercial de guiado paralelo y el 59% sin asistencia al guiado. Los resultados obtenidos evidencian que el sistema de asistencia al guiado manual desarrollado es válido para la aplicación mecánica de fertilizantes.

Palabras clave adicionales: agricultura de precisión; guiado paralelo; simulación de fertilización mecánica.

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Abbreviations used: DGPS (differential global positioning system); GIS (geographical information system); GPS (global positioning system); PDOP (position dilution of precision); PT (parallel tracking); RMSE (root mean square error); RTK (real time kinematic); STD (standard deviation of error); TCM (terrain compensation module).

Introduction

The reform of the Common Agricultural Policy (CAP) adopted by the European Union in 2003 has introduced a system of single farm payment and has decoupled production support. Council Regulation (EC) No 1782/2003 of 29 September 2003 has introduced the concept of cross compliance. Based on this concept, farmers will receive direct payments on condition that they adopt good agricultural practices and meet the requirements established by community legislation in the areas of public, animal and plant health, and environment and animal welfare (cross compliance). In addition, growing food safely leads to the need to conveniently document production processes (traceability). With regard to documentation, considerable progress is being made to monitor equipment performance and, consequently, agricultural production processes.

Increased technological sophistication of equipment and increased field speeds require extra attention of the driver, which contributes to a decrease in guidance accuracy (Kaminaka *et al*., 1981). Moreover, with the gradual increase in equipment widths, it becomes increasingly difficult for the operator to determine visually from the cab whether path spacing is appropriate (Wilson, 2000). Such an effect is more pronounced when field operations are performed by very wide machines and there are no visual indicators. Under such conditions, keeping the correct distance between consecutive passes without guidance assistance becomes difficult (Stoll and Kutzbach, 1999). Improving fertilizer distribution is beneficial to the environment, insofar as environmental problems caused by excessive fertilizer application rates are avoided and a more sustainable agriculture is achieved.

Widespread use of global positioning systems (GPS), such as GPS/GLONASS, has allowed for the development of many applications in a variety of areas related to agriculture and forestry, such as operating efficiency (Taylor *et al*., 2001), fleet management (Veal *et al*., 2001) or yield mapping (Shannon *et al.,* 2002).

In the field of fertilizer application, GPS systems have significantly contributed to the development of guidance systems. Farmers are striving to adapt fertilizer distribution to the requirements established by both legislation and the market. Currently, some commercial systems allow for data storage on a computer mounted on the fertilizer spreader. Such data can be further loaded into the farm management system computer program (Marquering and Scheufler, 2006).

Manual GPS guidance systems typically use a visual indicator to show where the vehicle is in relation to the intended path. The operator have to steer the equipment, but the lightbar or other indicator tells the driver when and how much to correct. The efforts of several authors have contributed to the development of manual guidance systems (Gómez and Santana, 2007) and automatic guidance systems (Bell, 2000; Harbuck *et al*., 2006). Automatic guidance systems require driving an initial pass, but the system then steers the tractor through each subsequent pass. The operator still has to steer at turnrows and around any obstacles, but passes are made without operator input. Automatic guidance reduces driver fatigue and improves machinery performance during field operations insofar as the operator can focus attention on the tasks performed (Kocher *et al*., 2000).

Among the benefits of combining fertilizer application systems with guidance systems are reduced field input costs due to more even fertilizer application and reduced fertilizer application overlaps, skips or rates below the desired rate (Thuilot *et al*., 2002; Batte and Ehsani, 2006), which affect fertilizer use efficiency. Many authors have focused on testing the performance of a number of devices, generally by evaluating guidance error, *i.e.* the deviation of the vehicle from the desired path (Taylor *et al*., 2004, Dunn *et al*., 2006). For precision agriculture, Han *et al.* (2002) have suggested that the cross-tracking error determines overlaps and skips. For parallel tracking (PT) applications, the most important measure is the error measured between subsequent passes. Ehsani *et al.* (2002) related mean error with overlaps and skips, using root mean square error (RMSE) as a measure of safety and standard deviation of error (STD) as a measure of accuracy. They generated regression lines to determine the path followed by the machine. Wu *et al.* (2005) concluded that least square regression was a suitable approach to find the best fitting line through GPS data.

In addition to GPS signal accuracy, the ergonomic design of the system becomes particularly relevant when using guidance systems. Karimi *et al*. (2006) observed that the most accurate lightbar guidance systems involved increased operator workload because the driver needed to make continuous steering adjustments. Ima and Mann (2004) suggested that the quality of the operations performed using guidance displays depended on a number of ergonomic factors, such as colour perceptibility, flash rate, display size, viewing distance and height of placement of the display in the cab. Hence, ergonomic factors must be considered in the design of the guidance display and in the placement of the display in the tractor cab.

Wilson (2000) reported two main limitations of GPS for vehicle guidance: first, the difficulty to obtain the accuracies required under adverse conditions, such as the presence of buildings or trees. Second, inherent time delay required for signal processing to determine the location, which would become more relevant at higher field speeds. Nevertheless, the author suggested that such limitations would be overcome with the technological development of new equipment. Another limitation of guidance systems is that the dynamic operation of receivers is extremely variable in time, such that variable results are obtained depending on date and time of day (Han *et al*., 2004).

In this paper, the performance of a low-cost manual GPS guidance system, developed by the Agricultural Mechanization Research Group at the University of Santiago de Compostela and integrated into a data acquisition system previously built by our research group (Amiama *et al.*, 2008a) and adapted to an agricultural tractor was evaluated. To accomplish this task, the distribution of granular fertilizer was simulated, and a comparison was made between the results obtained for the uniformity of application using low-cost manual GPS guidance system and the results obtained with a commercial manual GPS guidance system. Besides, both systems were compared with fertilizer application without guidance assistance, the traditional fertilizer application method in the study area. Essentially, the paths of travel of a vehicle equipped with both systems were compared by analyzing the expected distribution of the fertilizer rate applied in the fields and by discretizing areas with excessive application of fertilizers and areas with fertilizer application rates below the intended rate.

Material and methods

Characteristics of the equipment used

The tractor used for this study was a John Deere™ 6910S (John Deere Co., Moline, III). A Bogballe ET 3200 (Bogballe Co., Uldum, DK) trailed twin-disc fertilizer spreader was attached to the tractor during the tests (see Fig. 1). In the tests, fertilizer was not actually applied, but a theoretical or expected distribution pattern was used. By using a theoretical distribution, we removed the potential effects of a wrong spread pattern of the fertilizer spreader on our results. This approach allowed us to compare the error in guidance under the three systems of interest.

The tractor was equipped with a data acquisition system developed for harvesters by the Agricultural Mechanization Research Group at the University of Santiago de Compostela, (Amiama *et al.*, 2008a), previously adapted to an agricultural tractor. The data acquisition system was adapted by removing the sensors for capture of the parameters of harvester operation while maintaining the rest of the modules,

a) b)

Figure 1. Tractor and trailed twin-disc fertilizer spreader used in trials (a) and location of GPS antennas at the top of the cab (b).

and by adapting the software for data collection and management to the operations specific to the tractor.

An open source software application was developed in Visual Basic (Microsoft) using the MapObjects™ 2.3 ActiveX controls (Environmental Systems Research Institute, Inc.), which allowed for the visualization of the path of travel through the field on the touch-screen monitor of the computer installed in the tractor cab. Our manual GPS guidance system aims to maximize the versatility of the equipment installed in the cab, such that many applications, among which guidance, remote location, route management or record of machine activity status, can be implemented using the same hardware. In addition, equipment replication in several tractors does not involve the purchase of costly software licenses for every implemented application. In fact, the only extra cost required if compare with the system developed for harvesters, is the cost of replacing the GPS used in harvesters (C/A code GPS receiver) with a GPS that provides higher accuracy (± 300 mm accuracy, 95% of the time, is considered sufficient for the field operations tested). The GPS signal used was the free SF1 signal, which was captured with the StarFire™ iTC position receiver. The differential correction signal used was the free SF1 signal owned by Deere & Company, which offers ± 300 mm accuracy.

Position data were recorded using the StarFire™ real time kinematic (RTK) system. The system was composed of a RTK Base Station located near the fields where the tests were performed, and a vehicle StarFire™ iTC receiver. The purpose of the base station was to act as a local reference station. It transmitted correction signals to the vehicle StarFire™ iTC receiver through the RTK radio. The vehicle StarFire™ receiver interpreted the correction signal coming from the base station. The StarFire™ system provided a horizontal accuracy of about 2 cm. The position data were stored in the vehicle panel computer installed in the tractor cab. This system allowed the user to capture the actual path of the tractor for each of the system tested.

The guidance application shows in the display a shaded strip on each side of the tractor path, which reflects the treated area. The width of the strip of land shaded was defined by the user and was equivalent to the distance between passes. Thus, the driver could see on the monitor which areas had been treated and which areas had been left untreated. Additionally, a virtual path parallel to the actual path of travel was marked on the screen at a distance equivalent to the width initially defined by the user. This virtual line was used as an additional reference to the shaded path and made tractor guidance easier for the driver.

The guidance application allows for PT with any type of path (straight and curved) and is devised to conform to small, irregular shaped fields where the driver can freely choose the path of travel of the tractor. In small, irregular shaped fields, which are characterized by smaller field capacities (Amiama *et al*., 2008b), straight paths might cause a sharper decrease in the efficiencies of the field operations performed. Developed system has implemented functions as automatic screen sliding, switching of orientation viewpoint, different levels of zoom, nº available satellites and position dilution of precision (PDOP).

The tractor was also equipped with a GreenStar™ parallel tracking manual steering system that utilized three components, GreenStar display, mobile processor and StarFire™ iTC position receiver. The differential correction signal used was the SF1. Filter configurations were set based on the manufacturer's recommendations. StarFire iTC position receiver had integrated a terrain compensation module (TCM) for improved guidance performance. TCM corrects for vehicle dynamics such as roll on sideslopes, rough terrain or varying soil conditions. Before performing the tests correct information about differential global positioning system (DGPS) mounted direction, fore/aft value and height must be introduced. TCM calibrations were done with the vehicle on a hard, level surface and in a complete stop (cab not rocking), TCM was calibrated for 2D placing first the tractor in one direction and then, after the first calibration, turning the vehicle 180° to face opposite direction and repeating the calibration in this position. Figure 2 shows the displays viewed by the driver with each guidance system.

In tests performed without guidance assistance, the only visual reference used by the driver was the wheel tracks of the previous pass.

The antenna of the guidance systems was placed on top of the tractor cab, at the centre of the machine. The antenna of the RTK GPS rover unit was mounted parallel to the antenna of the guidance systems at a distance of at least 75 cm in order to reduce possible signal interference, as shown in Figure 1b.

Experimental design

Field tests were conducted on ten fields on Gayoso-Castro farm (43° 06' N, 7°27' W), in Castro de Ribeiras

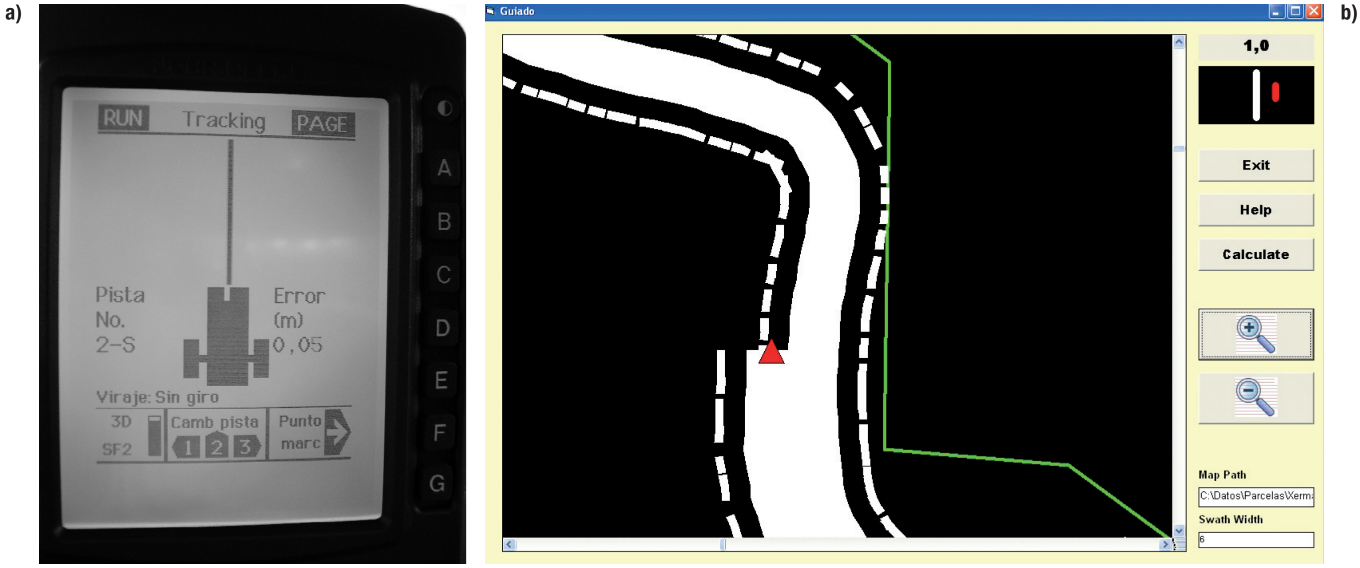

Figure 2. Display visualization for GreenStar™ Parallel Tracking system (a) and for the software application developed (b).

de Lea, 20 km north of Lugo, Spain. Site elevation was 420 m, with a level slope class (dominant slope < 4%). The experimental design involved performing parallel passes in the direction of the widest side of ten fields for the three systems considered. For all tests, swath width was 24 m and operating speed was set at 8 km h^{-1} because this is the usual speed for a fertilizer application rate of 400 kg ha^{-1}. The selected fields were flat, without overhead obstructions in the immediate test area and with a width that allowed for at least five passes. The area of the fields ranged 4.7 to 11.6 ha, and the total area of the fields was 87 ha. The tests were performed in February 2008. To reduce the effect of error from different sources, all the tests performed on a field were performed on the same date. In addition, the same driver was used for all the tests. The driver was experienced in mechanical fertilizer spreading and drove his own tractor.

Data were collected at 1 Hz frequency. For all the systems tested, the driver defined an initial straight path that was used as a reference for the following passes. The initial reference straight path was defined placing two marks in the field for driver orientation in this fist pass. The linear regression equation obtained from the RTK GPS points read at this first pass was used as a reference to compare the other swaths in each field. This will be the reference to calculate next desired paths (function of the swath width). The adjusted path will be defined by the parallel path, parallel to the reference pass, who better adjust to the RTK DGPS measurements, as shown in Figure 3. First, the driver operated the tractor without using any guidance system, such that the path from the previous test could not be used and consequently bias the test.

Data analysis

Swath uniformity

There are two key aspects in the assessment of the performance of fertilizer spreaders: accuracy of fertilizer rates and uniformity in application. Accuracy is defined as the capability of applying a fertilizer rate at a given location, and uniformity is defined as the evenly distributed application of a fertilizer rate. To

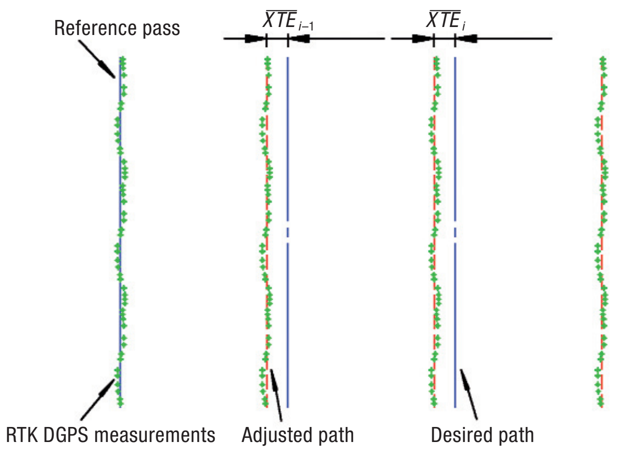

Figure 3. Layout of the test and definition of the mean cross-track error ($\overline{XTE}_i$).

achieve the greatest distribution uniformity, distance between passes must be constant.

For each pass, cross-track error (XTE) for a point *j*, is defined as the distance, measured perpendicular to the direction to the travel, between his true position, calculated from the data provided by RTK GPS, and the desired path.

Pass accuracy can be calculated with the use of two expressions: mean cross-track error ($\overline{XTE}_i$) and root mean square error (RMS_i).

$$\overline{XTE}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} XTE_{ij} \quad [1]$$

$$RMS_i = \sqrt{\frac{1}{N_i}\sum_{j=1}^{N_i}(XTE_{ij})^2} \quad [2]$$

where N_i = total number of measurement points for the *i*th pass, XTE_{ij} = the XTE at *j*th point for the *i*th pass, $\overline{XTE}_{ij}$ = the mean of the XTE for the *i*th pass, and RMS_i = the RMS error for the *i*th pass.

But these expressions translate the error from a pass to the next passes. To avoid this problem pass-to-pass accuracy must be definite. For this purpose, pass-to-pass average error (Ep_i) and pass-to-pass root mean square error (sp_i^2) were used.

$$Ep_i = (\overline{XTE}_i - \overline{XTE}_{i-1}) \quad [3]$$

$$sp_i^2 = \frac{1}{N_i}\sum_{j=1}^{N_i}(XTE_{ij} - \overline{XTE}_i)^2 \quad [4]$$

where Ep_i = the pass-to-pass average error for the *i*th pass, and sp_i^2 = the pass-to-pass root mean square error for the *i*th pass.

Following Ehsani *et al*. (2002), the curved segments and the points at the end and at the beginning of each swath were removed from the original raw data to evaluate the straight-line accuracy.

Statistical processing was performed by using the variable Ep_i, which was considered most representative of the performance of each guidance system tested.

In addition to the comparison of the three systems tested, the experimental design allowed us to determine whether the characteristics of the different fields affected the results. In principle, the shape or size of fields should not affect results when some guidance system was used. However, the shape, size and relief of a field could influence the results obtained when no guidance assistance system was used.

In order to assess the effects of field characteristics on the results, each field was considered as a block by applying a randomized block design. Such a design was used to assess whether considering fields as block factors was useful in reducing the size of experimental error. Otherwise, using a blocked design would be counterproductive insofar as it would generate weaker hypothesis tests and wider confidence intervals than a fully randomized design.

Given that the number of readings within each block could be not equivalent for the different treatments because of the different performance of the guidance systems tested and the different number of readings obtained for different blocks due to differing field shapes and areas, we worked with the mean values of readings (*xij*) by block (*j*) for each treatment (*i*) as response variable. Accordingly, the response to treatment *i* for block *j* was computed from Eq. [5].

$$Y_{ij} = \sum \frac{X_{ij}}{n_{ij}} \quad [5]$$

The assumptions of homoscedasticity, normality and independence of results are required to obtain valid results from the analysis of variance. With such a transformation, the assumption of homoscedasticity cannot be met, but a balanced design is achieved. As shown by Scheffé (1999), the assumption of homoscedasticity of the response variable can be relaxed (results are approximately valid) in balanced designs if Eq. [6] is met, as in our test.

$$\frac{\max[\mathrm{var}(Y_{ij})]}{\min[\mathrm{var}(Y_{ij})]} < 3 \quad [6]$$

If using a blocked design was not useful, a one-way experimental design with three treatments was considered and all the values of the test were used.

The Ep_i values obtained were compared according to ANOVA F-test. A Tukey's test was performed in the cases in which significant values were obtained. The SPSS computer package was used to solve the statistical tests.

Fertilizer rates applied

To analyze the uniformity of the spatial distribution of fertilizer, fertilizer application was simulated by using a geographic information system (GIS), namely the ArcMap application (ESRI, 2005), and following a procedure similar to that used by Lawrence and Yule (2007). The distribution of the fertilizer rate applied to the fields was obtained by taking as a reference the path of travel of the tractor through test fields and introducing the transverse distribution diagram of the fertilizer spreader for granular fertilizer (15-15-15). A wide range of colours was used to visually identify areas with the intended fertilizer rate, areas with excessive fertilizer rates and areas with fertilizer rates below the intended rate. The deviation range was determined for fertilizer rates above or below the intended rate. ArcMap allowed us to accurately obtain the theoretical fertilizer rates applied at every point of the field. The fertilizer rate chosen was 400 kg ha^{-1}. Deviations from that rate were considered correct for values of up to ± 10% of the intended fertilizer rate.

Results and discussion

Swath uniformity

Simple visual inspection of the paths of travel generated by the two systems allowed us to predict better performance of the fertilizer spreader in the fields where a guidance system was used than in the fields where no guidance system was used (Fig. 4). The preliminary visual analysis of results suggested that the performance obtained with the John Deere Parallel Tracking system was better than the performance obtained with the guidance system developed by our research group.

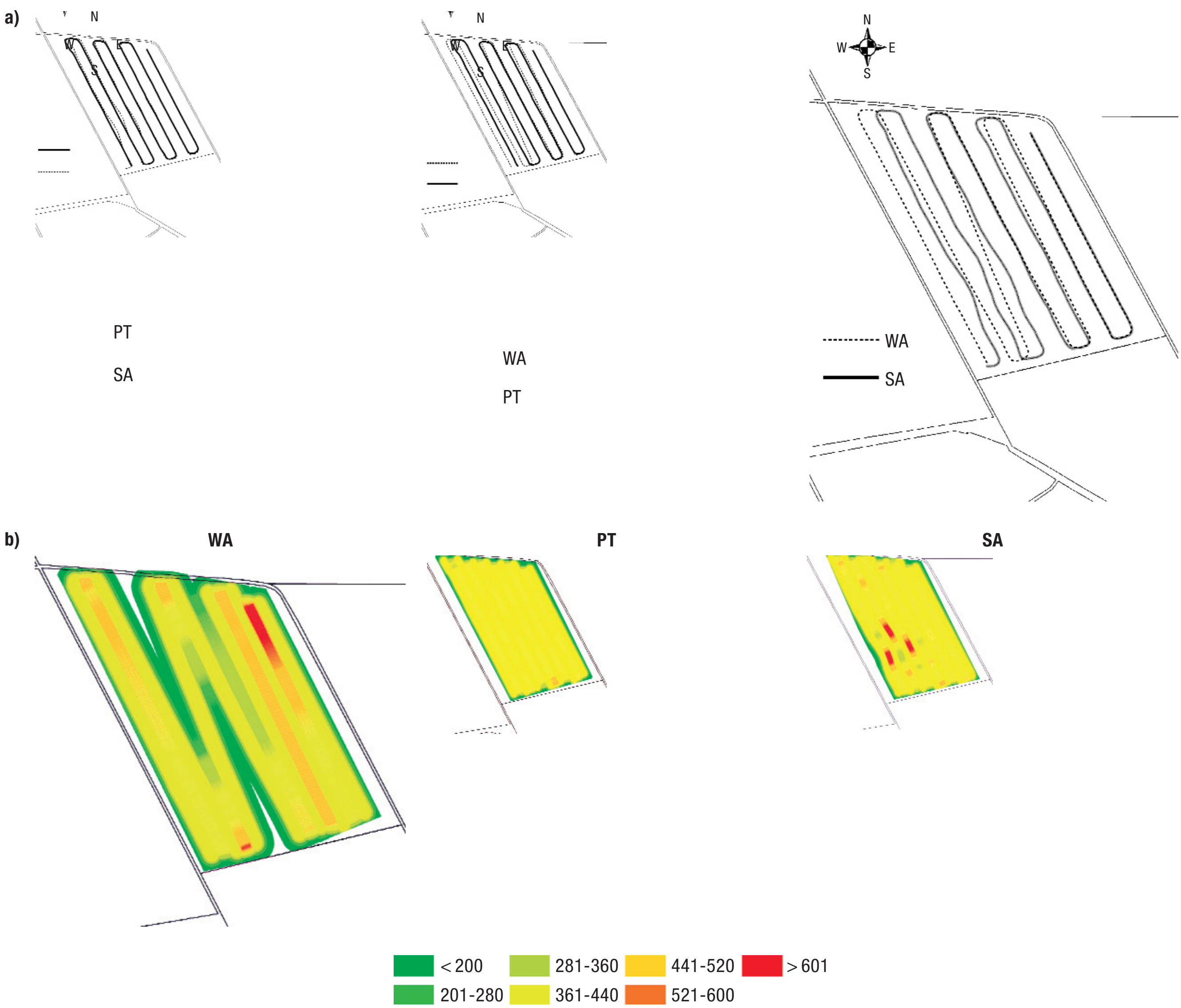

Figure 4. Comparison of paths (a) and fertilizer rates (b) for the three systems tested, PT (Parallel Tracking), SA (Software Application) and WA (Without Assistance).

As explained in previous section "*Swath uniformity*", we first assessed whether considering the field as a block factor was useful in reducing experimental error. A two-way ANOVA F-test was performed considering a block factor (field) and a treatment factor (Ep_i). The test revealed that the block factor was not significant ($p = 0.05$). Such a result could be justified by the large size, regular shape and flat relief of fields. Under different experimental conditions (narrow fields with rough relief, etc.), the field factor could largely influence the results obtained when no guidance assistance was used.

Table 1 shows the results obtained for a single treatment factor (guidance system). To determine $\overline{XTE}$ and Ep_i, the absolute values of the deviations were used.

The numerical values obtained confirmed the results shown in Figure 4. By analyzing mean cross-track error ($\overline{XTE}$) and pass-to-pass average error (Ep_i), the PT treatment yielded lower deviations between the target path and the actual path of travel obtained with other systems. In addition, the fit of the path to the regression line defined by the data points for the virtual path (parallel to the initial path) was better for the PT system, *i.e.* the paths were straighter when using PT than when using the other systems. The ANOVA F-test performed revealed differences among systems. Tukey's test did not show significant differences at 0.05 level between the two systems that used a guidance system. Yet, the results obtained for each treatment would be different at 0.01 significance level. These results are in agreement with the results reported by other authors (Stoll and Kutzbach, 1999; Wilson, 2000) and suggest that it is difficult to keep the required distance between passes with large implement widths without guidance assistance.

Table 1. Mean values (m) obtained, cumulative frequencies of Ep_i (m) and mean values of Ep_i (m) considering overlaps and skips, for each of the systems tested

	Without assistance	**Parallel tracking**	**Software application**
Mean values (m)			
$\overline{XTE}$	4.89	0.54	1.85
RMS	5.36	0.71	2.23
Ep_i	2.62[a]	0.26[b]	0.73[b]
spi_2	4.42	0.28	1.26
Cumulative frequencies of Ep_i (m)			
25%	0.80	0.07	0.25
50%	2.17	0.17	0.48
75%	3.78	0.30	0.84
100%	8.51	1.49	3.15
Mean values of Ep_i (m)			
Ep_i for overlaps	–2.60	–0.27	–0.78
Ep_i for skips	2.63	0.25	0.42

Different letters following figures in the same row suggest significantly different data ($\alpha = 0.05$).

For the differences observed between the two guidance systems, results appear to suggest that the PT system performs better than the guidance system developed by our research group. Such differences can be attributed to the following causes:

— The screen refresh was too high. Owing to such a high refresh rate, slight steering wheel movements made by the driver were quickly transferred to the screen, thus demanding great guidance effort from the driver, who tended to make steering adjustments continuously. These results are in agreement with the results reported by Ehsani *et al.* (2002) and Karimi *et al.* (2006) for tests performed with lightbar guidance systems.

— The manner in which guidance was displayed on the screen by shading a strip of land on both sides of the path of travel produced a tendency to overlap in excess because the driver focused on not leaving any area unshaded between passes rather than on following the centre of the path indicated by the line.

Figure 5 graphically represents the values of Ep_i as absolute values and shows a better performance of the PT system.

For a better interpretation of the results shown in Figure 5, Table 1 shows the values of Ep_i at different percentiles. These values reveal a better performance of the PT system, with an Ep_i value below 0.30 m for 75% of the passes. By using our guidance system, the

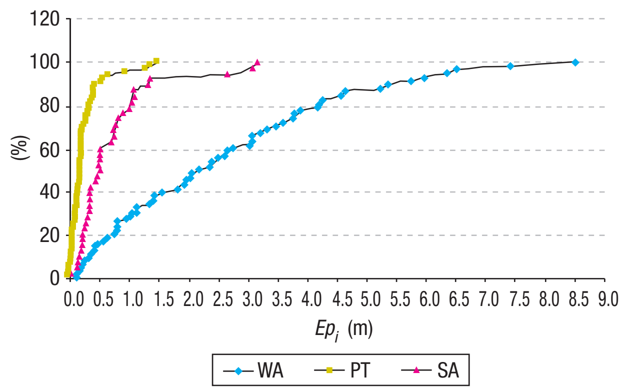

Figure 5. Comparison of pass-to-pass average errors for the three systems tested, WA (Without assistance), PT (Parallel Tracking) and SA (Software Application).

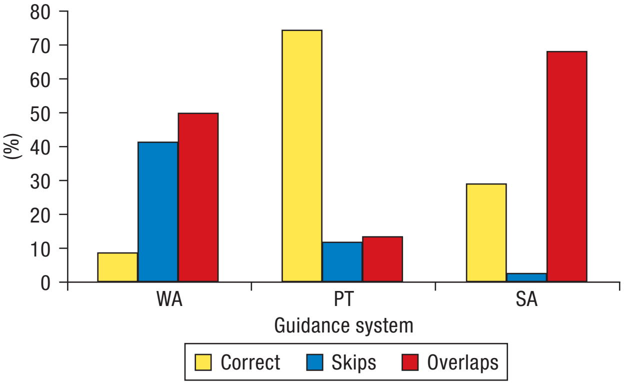

Figure 6. Comparison of paths for the three systems tested, WA (Without assistance), PT (Parallel Tracking) and SA (Software Application).

value of Ep_i at the 75th percentile amounted to 0.84. This value would be at the limit of suitability but would substantially improve fertilizer distribution without guidance assistance; the most frequent method in our locality, insofar as such a high level of accuracy was obtained only in 25% of the passes performed without guidance assistance.

Fertilizer distribution and fertilizer rates applied

Figure 6 plots the percentage of passes for which the correct distance between passes was kept against the percentage of passes with overlaps or skips. Deviations from the intended path resulted in fertilizer excess or deficit as compared to the intended fertilizer rate. Taking into consideration that the accuracy of the GPS used for guidance was ± 30 cm, the passes defined as correct were the passes performed at a distance of less than 30 cm from the desired path. For the PT guidance system, the number of correct passes prevailed over passes with overlaps or skips, which were very similar. The percentage of correct passes without guidance assistance was much lower. By using the guidance system developed by our research group, the number of correct passes increased compared to operating the applicator without any guidance. However, a very high percent passes with overlaps was observed. Passes with overlaps result in excessive fertilizer application.

Table 1 summarizes the mean values of Ep_i discriminated according to overlaps and skips. These values suggest that not using any guidance system results in larger mean errors and, consequently, in an increase in the areas with fertilizer application rates above or below the intended rate, which is in agreement with the results reported by many authors (Stoll and Kutzbach, 1999; Thuilot *et al.,* 2002; Batte and Ehsani, 2006).

Figure 4b shows the results of the simulation performed. Reddish shades suggest fertilizer rates higher than the intended rate whereas greenish shades suggest fertilizer rates below the intended rate (400 kg ha^{-1} ± 10%). The best results for uniformity of fertilizer distribution were achieved using the PT system.

Figure 7 shows the distribution of the fertilizer rates applied in the set of fields tested for each guidance system. The proportion of fertilizer rates below 350 kg ha^{-1} is justified due to the presence of field bounda-

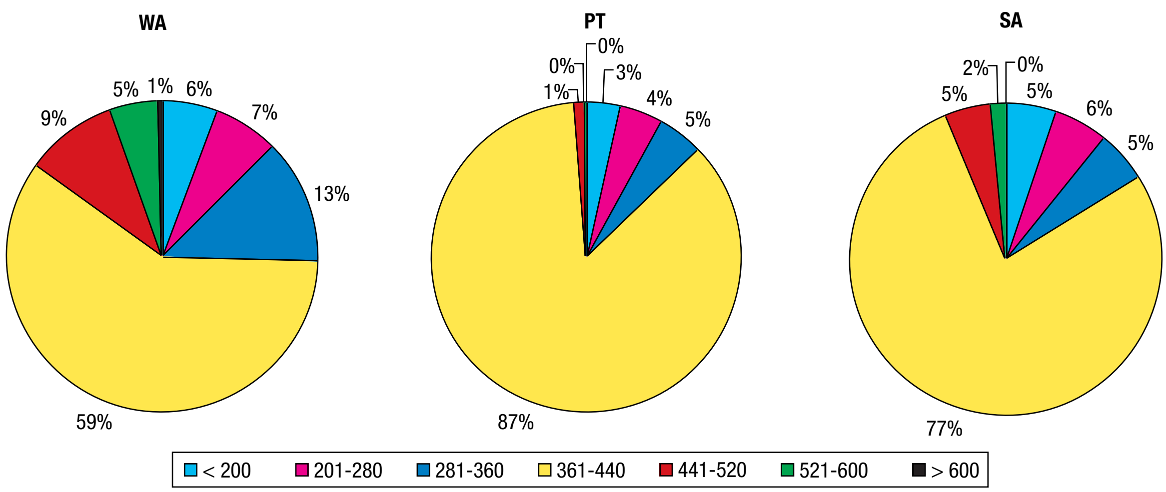

Figure 7. Percent area with correct fertilizer rates, excessive rates or rates below the intended rate for the three systems tested, WA (Without assistance), PT (Parallel Tracking) and SA (Software Application) (ranges in kg ha^{-1}).

ries, where the fertilizer rate applied is usually below 300 kg ha^{-1}.

When the PT system was used, the correct fertilizer rate was applied to 87% of the area and only 1% of the area received excessive fertilizer rates. The free SF1 differential correction signal, which is the least accurate signal offered by John Deere, proved sufficient to perform fertilizer application operations. When field operations were performed without guidance assistance, 59% of the area received the correct fertilizer rate, whereas 15% of the area received excessive rates. Intermediate results were obtained with the guidance system developed by our research group, with 7% of over fertilized area. These results demonstrate that using guidance systems considerably reduces pollution problems caused by poor fertilizer distribution because areas with excessive fertilizer rates are minimized by using guidance assistance.

Our results are in agreement with the results reported by Thuilot *et al.* (2002). Tests performed using guidance systems showed a more even fertilizer distribution and a decrease in areas with fertilizer rates higher than the intended rate, skips or fertilizer rates below the intended rate. These results match the results shown in Figure 6. In Figure 6, the guidance system developed by our research group showed the highest percentage of path with overlaps. However, the deviation observed in these areas was lower than the deviation observed when working without guidance assistance (see Table 1). Despite the lower percent of path with overlaps, the percent area affected by overlaps without guidance assistance was higher than the percent area affected with the guidance system developed because of the higher pass-to-pass deviations observed. Figure 8 provides a graphical summary of the results obtained in this study. The improvements achieved in fertilizer distribution by using guidance systems are expected to prompt a better crop response, increased economic benefits and reduced environmental impact.

The small differences found between the two guidance systems tested, with better results for the commercial guidance system, do not justify the greater investment required to purchase a commercial system, of about € 3,400, as compared to the € 1,600 investment required to replace the GPS used in harvesters (low accuracy) by a system that provides higher accuracy for tractor guidance. In addition, our solution prevents the duplication of monitors in the tractor cab, and avoids space and visibility reduction.

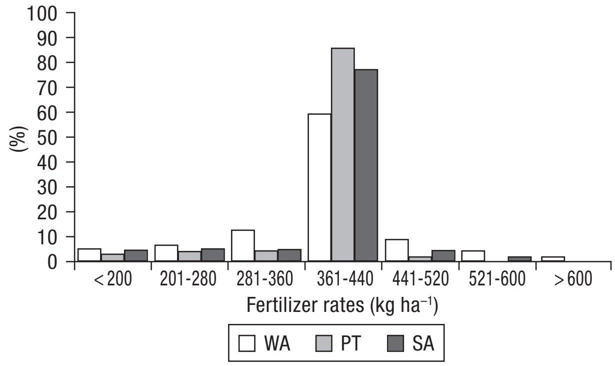

Figure 8. Percent area treated with the different ranges of fertilizer rates considered (in kg ha^{-1}), for the three systems tested, WA (Without assistance), PT (Parallel Tracking), and SA (Software Application).

Conclusions

Based on this study in which we have tested a commercial GPS guidance system, a low-cost GPS guidance system developed in this study, and fertilizer applicator operation without guidance in ten different fields, we reached the following conclusions:

— Using guidance systems for granular fertilizer distribution improved uniformity of fertilizer application. Although the improvement is higher for the PT commercial system, the differences observed between commercial PT and the software application developed by our research group were not significant.

— The free SF1 differential correction signal, which is the least accurate signal offered by John Deere, proved sufficient to perform fertilizer application operations.

— With regard to the fertilizer rates applied, the best distributions were obtained with the commercial PT system. When no guidance system was used, the areas with fertilizer application rates higher than the intended rate and the areas with rates below the intended rate tended to be equivalent. In contrast, when guidance systems were used, areas with fertilizer rates below the intended rate tended to be larger than areas with excessive fertilizer application. The use of GPS guidance systems reduces the area where excess fertilizer is applied, which contributes to a more sustainable agriculture that is more environmentally friendly. The greater investment required does not justify the better results obtained with the commercial GPS guidance system compared to the low cost system developed in this study.

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