A new path shape for tractor driving simulator

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**Written for presentation at the
CSAE/SCGR 2005 Meeting
Winnipeg, Manitoba
June 26 - 29, 2005**

Abstract
Evaluation of new technologies in agricultural machinery guidance is very important and can help producers to choose the right equipment for their applications. Researchers at the Department of Biosystems Engineering at the University of Manitoba have taken the initiative of using a tractor driving simulator for this purpose. Modifications are underway in order to enhance the fidelity of the simulator. One of the necessary modifications is to the driving path. Presently, the driving path is a continuous repetition of a complex trigonometric function which has been chosen without reference to any field experiments. The objective of this study was to develop a new path geometry based on real-field driving behavior of a tractor operator. An RTK-GPS used to record the exact location of a tractor while the operator used a Differential Global Positioning System (DGPS)-based guidance system (light-bar) to drive along parallel passes in the field. Then, polynomial and spline curve fittings were performed to the field data to approximate the driving pattern. Spline curve fitting was more successful than polynomial fitting because it had significantly less fitting error as compared to polynomial fitting (4% versus 14-24%) and its results can be used for further study of steering behavior. Polynomial curve fitting results were used to build a random path to be used in a tractor driving simulator. Guidelines for future use of results and further analysis of the present data are presented. **Keywords:** driving simulator, guidance systems, curve fitting, polynomials, splines.

INTRODUCTION

Guidance of agricultural machinery has received the attention of agricultural engineers since the 1920s. However, in the last few decades, great increases in tractor power, implement size, working speeds, and complexity of operation of agricultural implements have made the operator's work of making steering adjustments and simultaneous monitoring of the implements' performance much harder (Wilson 2000). Consequently, there is an increasing need for innovative research in this area. Buick and Lange (1998) compared three different guidance systems including a foam marker system and two GPS based guidance systems. Ehsani et al. (2002) evaluated the accuracy of several Differential GPS (DGPS)-based guidance-aid systems and pointed out that there is not enough literature published on testing these systems under field conditions. In recent work here at the University of Manitoba, a driving simulator has been used for ergonomic evaluation of new GPS-based guidance aids for agricultural vehicles (Ima and Mann 2004).

Driving simulators have had numerous applications in areas other than agriculture; study of accidents (Alexander et al. 2002), study of effect of sleepiness on driving behavior (Verster et al. 2004), and study of new highway designs (Laurie et al. 2004) are just a few examples. There have also been a few cases of driving simulators being used in areas related to agriculture. For example, The Ohio Supercomputer Center (2004) developed a tractor driving simulator that used virtual simulation. The key advantage of this driving simulator was that it subjected the driver to a dangerous situation in order to conduct an evaluation.

One of the concerns with driving simulators is the geometry of the desired path that the human subject should follow during experiments. Currently, the driving simulator at the Department of Biosystems Engineering, the University of Manitoba, uses a pseudo-random function generated by a sum of six sinusoids (Ima and Mann 2004). This specific geometry has certain drawbacks. Firstly, it is not realistic; the desired path that a tractor has to follow to cover an entire field is usually either a series of parallel adjacent passes or of contour lines. However, due to unavoidable driving errors, the actual path would be somewhat different but it would not necessarily be a sinusoid. Secondly, it is not completely unpredictable and after a while the subject learns the pattern, which will affect the results. Actually, previous studies have shown that drivers are able to memorize quite complicated patterns and road networks when driving in a simulator (Aginsky et al. 1997). Furthermore, it is evident that monotonous path geometry can have great effects on driver fatigue and performance in simulated driving (Thiffault and Bergeron 2003).

The objective of this study was to develop a new path shape, for use in a tractor driving simulator, based on the real-field driving behavior of a tractor operator. This new path shape should be as close to the real-field driving pattern as possible so that, after implementing it in the simulator, the subject 'drives' the same pattern as he would do when driving in the real-field situation. We used a series of field data of accurate tractor position when driving in parallel paths. Using polynomial and spline curve fitting techniques, we were able to build such a path. Spline curve fitting was more successful because of its significantly less fitting error and continuous derivatives which can be used when studying driver's steering behavior. The recommended path should be tested in the simulator for its adequacy. One approach could be to compare the steering behavior of the subject when driving in the simulator with the in-field situation; if we can achieve the same steering behavior with the simulator as in the field, that will be a strong indication that the new path is 'realistic'.

MATERIALS AND METHODS

Field experiments

The data used in this study were collected in a series of field experiments that aimed at comparing the overall accuracy of the latest versions of seven commercially available DGPS-based guidance systems while following a straight line (parallel swathing). The tests were performed in late summer and early fall of 2001 in an 8-ha (20-acre) wheat field in central Ohio. In order to have a fair comparison several measures were taken; all the guidance systems were tested on the same day, the order of the guidance systems for each day was randomly selected, the same driver and tractor (John Deere 4640) were used for all tests, and the swath width was 12.19 meters (40 ft) in all experiments. Also, the latest available versions of firmware were installed in all guidance systems and all system configurations and settings were set based on the manufacturers' recommendations. To determine the exact location of the tractor in the field, a Real Time Kinematic (RTK) GPS was used (Ehsani et al. 2002).

Analysis of data

Data files contain position of the tractor, in State Plane Coordinate System (abbreviated as SPCS), as the driver was driving parallel passes using different guidance systems. A selected set of this data is shown in Figure 1. Line A-B is the first pass, after which the driver made nine parallel passes using a light-bar guidance system. For each pass, we first found the regression line for the data points. Then, we calculated the vertical distance between data points and the regression line; this distance is the deviation from the desired straight path that the tractor should ideally follow and is hereafter referred to as "driving error". Finally, we plotted the driving error values against the position of tractor along the path. An example of such a plot is shown in Fig. 2. Then, we divided the entire pass into several sections and performed polynomial curve fitting for each section using 2nd-, 3rd-, and 4th-order polynomials. We also carried out spline curve fitting using a single spline for the entire length of each pass. All data analysis was done using Matlab (Mathworks Inc.)
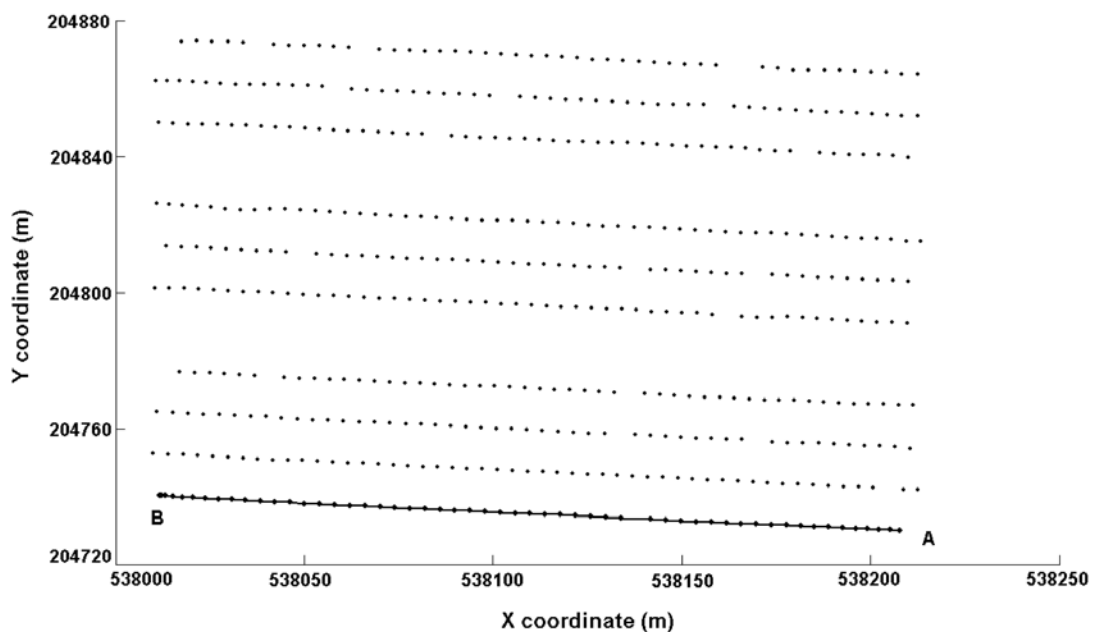

Fig. 1. An example of driving path data provided by RTK-DGPS measurement of tractor location.

In order to have an estimate of "goodness of fit" for different fitting methods, Root Mean Square (RMS) of curve fitting error was calculated using the following equation:

$$RMS = \sqrt{\frac{\sum_{i=1}^{N}(y_i - Y_i)^2}{N}} \qquad (1)$$

Where: (refer to Fig. 2)

N the number of data points in a specific section

y_i the actual ordinate of the ith data point; that is the ith value of driving error

Y_i ordinate of fitted curve at the ith point

Polynomials A function p defined for all real numbers x by

$$p(x) = a_N\, x^N + a_{N-1}\, x^{N-1} + \cdots + a_1\, x + a_0 \qquad (2)$$

where N is a non-negative integer and a_0, a_1, ..., a_N are fixed real numbers, is called a polynomial; if $a_N \neq 0$, then $p(x)$ has degree N or, in other words, it is an N th order polynomial (Lancaster and Šalkauskas 1986).

Splines Given a strictly increasing sequence of real numbers, x_1, x_2, ..., x_n, a spline function $S(x)$ of degree m with the knots $x_1, x_2, ..., x_n$ is a function defined on the entire real line having the following two properties:

I.   In each interval (x_i, x_{i+1}) for $i = 0, 1, ..., n$ (where $x_0 = -\infty$ and $x_{n+1} = \infty$), $S(x)$ is given by some polynomial of degree m or less.

II. $S(x)$ and its derivatives of order $1, 2, ..., m-1$ are continuous everywhere.

Thus, a spline function is a piecewise-polynomial function satisfying certain conditions regarding continuity of function and its derivatives (Greville 1969).

This specific characteristic of splines of having continuous derivatives is of great importance in this study because this allows us, as we will see later on, to find the steering behavior of the driver by twice differentiating the resulting spline. Actually, polynomials have long been the functions most widely used to approximate other functions, mainly because they have the simplest mathematical properties (Lancaster and Šalkauskas 1986). However, a polynomial of high degree fitted to a fairly large number of given data points tends to exhibit more severe undulations than a spline involving a comparable number of parameters (Greville 1969).

RESULTS AND DISCUSSION

Recommended path

Figure 2 shows best-fit polynomials of 2nd degree for each section of a specific pass. Also, for each of the passes, spline curve fittings were carried out using a single spline of 5th degree; an example of spline curve fitting is presented in Fig. 3. The number of polynomial pieces for each case of spline fitting was selected so that the best possible fit would be achieved. In fact, for each pass, we started with a 30-piece spline, and then we increased the number of pieces and looked if there was any improvement in the fit. The number of pieces was incremented until there was no apparent improvement between two successive fits. The spline shown in Fig. 3, for example, is a 41-piece spline. As mentioned previously, we used 5th degree

splines; therefore, the spline shown in Fig. 3 has 41 pieces, each of which can be expressed by an equation in the following form:

$$y = a_5 x^5 + a_4 x^4 + a_3 x^3 + a_2 x^2 + a_1 x^1 + a_0 \tag{3}$$

The coefficients and breakpoints for the specific spline of Fig. 3 are presented in Table 1. For example, according to this table, between $x = 37.02$ to $x = 41.08$ the following equation is valid:

$$y = (5.34 \times 10^{-4})(x - 37.02)^5 + (-3.25 \times 10^{-3})(x - 37.02)^4 + (-2.83 \times 10^{-2})(x - 37.02)^3$$
$$+ (-2.93 \times 10^{-2})(x - 37.02)^2 + (2.99)(x - 37.02) + 16.2 \tag{4}$$

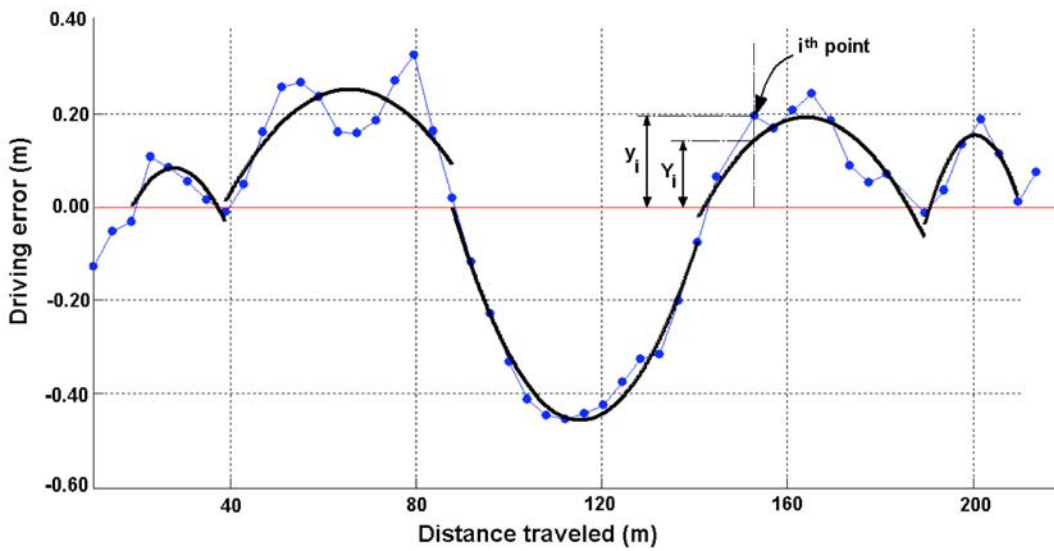which, when simplified, will be in the form of Eq. 3.

Fig. 2. An example of driving error data points (solid circles) and a 2nd order polynomial curve fitting to these points.
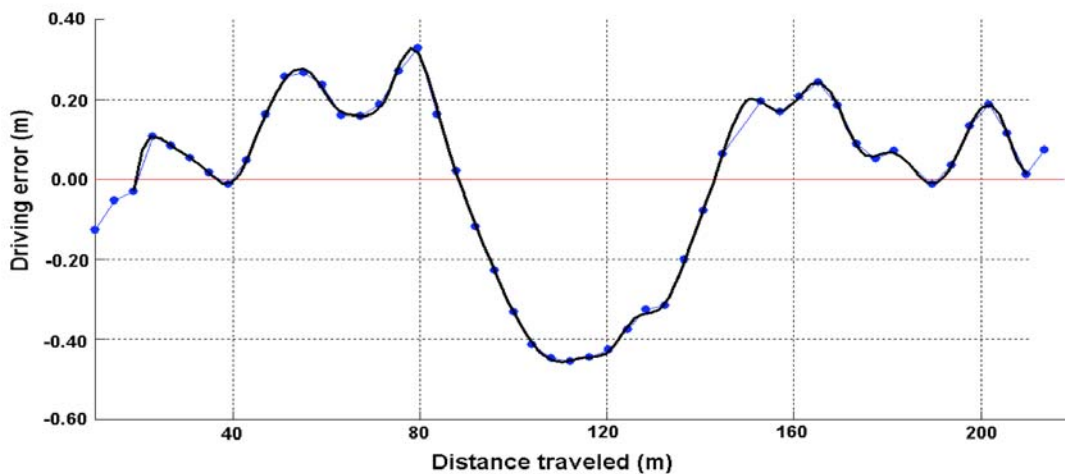

Fig. 3. Spline curve fitting to driving error data points.

Table 1. Coefficients and breakpoints for the spline of Fig. 3. In each domain, the equation $y(x) = \sum_{i=0}^{5} C_i \times (x - L)^i$ **should be used to calculate the magnitude of the spline. In this equation ,** L **is the lower bound of domain, an example is given in the text.**

	C_5	C_4	C_3	C_2	C_1	C_0
8.68 - 20.82	1.42E-04	-8.08E-03	1.76E-01	-1.84E+00	8.47E+00	-3.08E+00
20.82 - 24.86	1.25E-04	5.09E-04	-7.51E-03	-3.40E-02	-7.67E-01	5.47E+00
24.86 - 28.91	-3.80E-04	3.03E-03	2.11E-02	7.27E-03	-1.11E+00	1.59E+00
28.91 - 32.96	3.15E-04	-4.66E-03	7.96E-03	3.10E-01	2.83E-01	-9.77E-01
32.96 - 37.02	-2.45E-04	1.72E-03	-1.58E-02	1.57E-01	2.37E+00	4.87E+00
37.02 - 41.08	5.34E-04	-3.25E-03	-2.83E-02	-2.93E-02	2.99E+00	1.62E+01
41.08 - 45.14	-7.95E-04	7.57E-03	6.74E-03	-3.39E-01	1.21E+00	2.57E+01
45.14 - 49.19	9.75E-04	-8.57E-03	-1.39E-03	-3.97E-02	-2.57E-01	2.67E+01
49.19 - 53.26	-1.12E-03	1.12E-02	2.00E-02	-2.52E-01	-1.62E+00	2.36E+01
53.26 - 57.34	9.23E-04	-1.16E-02	1.64E-02	3.48E-01	-1.20E+00	1.60E+01
57.34 - 61.44	-4.33E-04	7.19E-03	-1.99E-02	1.38E-02	5.82E-01	1.59E+01
61.44 - 65.54	-4.48E-04	-1.67E-03	2.54E-02	1.96E-01	1.06E+00	1.87E+01
65.54 - 69.65	1.61E-03	-1.09E-02	-7.75E-02	3.05E-02	2.86E+00	2.71E+01
69.65 - 73.75	-1.89E-03	2.21E-02	1.51E-02	-9.11E-01	-1.54E+00	3.28E+01
73.75 - 77.83	1.12E-03	-1.66E-02	6.03E-02	2.03E-01	-4.81E+00	1.63E+01
77.83 - 81.90	-4.25E-04	6.18E-03	-2.50E-02	3.93E-02	-3.12E+00	7.78E-01
81.90 - 85.95	1.85E-04	-2.46E-03	5.25E-03	6.15E-02	-2.96E+00	-1.17E+01
85.95 - 90.01	-3.38E-05	1.30E-03	-4.11E-03	6.65E-03	-2.60E+00	-2.28E+01
90.01 - 94.07	-1.42E-04	6.17E-04	1.15E-02	6.27E-02	-2.45E+00	-3.32E+01
94.07 - 98.12	2.05E-04	-2.25E-03	-1.81E-03	1.69E-01	-1.40E+00	-4.13E+01
98.12 - 102.18	-1.76E-04	1.90E-03	-4.68E-03	6.09E-02	-4.44E-01	-4.47E+01
102.18 - 106.25	1.85E-04	-1.68E-03	-2.88E-03	7.39E-02	8.83E-02	-4.55E+01
106.25 - 110.32	-1.41E-04	2.08E-03	4.16E-04	-3.51E-03	3.47E-01	-4.44E+01
110.32 - 114.38	-1.96E-04	-7.79E-04	1.10E-02	1.14E-01	7.07E-01	-4.26E+01
114.38 - 118.45	8.78E-04	-4.77E-03	-3.41E-02	3.91E-02	1.70E+00	-3.75E+01
118.45 - 122.52	-1.42E-03	1.31E-02	3.36E-02	-2.59E-01	2.46E-01	-3.26E+01
122.52 - 126.60	1.31E-03	-1.59E-02	1.02E-02	4.91E-01	1.39E+00	-3.16E+01
126.60 - 131.50	-6.96E-04	1.07E-02	-3.28E-02	-8.87E-02	3.39E+00	-2.00E+01
131-50 - 136.40	3.46E-04	-6.38E-03	9.25E-03	1.47E-01	3.17E+00	-5.23E+00
136.40 - 141.31	7.98E-05	2.10E-03	-3.27E-02	-2.29E-01	3.28E+00	1.22E+01
141.31 - 146.21	-3.76E-04	4.06E-03	2.78E-02	-3.12E-01	-1.05E-01	2.04E+01
146.21 - 151.11	2.01E-04	-5.14E-03	1.73E-02	2.41E-01	-3.25E-01	1.70E+01
151.11 - 155.20	1.97E-04	-2.09E-04	-3.52E-02	-9.51E-03	1.44E+00	2.08E+01
155.20 - 159.29	-1.67E-04	3.83E-03	-5.58E-03	-3.27E-01	-1.86E-01	2.43E+01
159.29 - 163.36	-9.91E-05	4.14E-04	2.90E-02	-1.26E-01	-2.33E+00	1.86E+01
163.36 - 168.24	-8.64E-05	-1.60E-03	1.94E-02	2.03E-01	-1.94E+00	8.95E+00
168.24 - 173.11	4.73E-04	-3.71E-03	-3.26E-02	1.56E-01	4.37E-01	5.43E+00
173.11 - 177.97	-5.48E-04	7.81E-03	7.27E-03	-3.02E-01	-7.43E-01	6.71E+00
177.97 - 182.82	2.38E-04	-5.51E-03	2.96E-02	2.81E-01	-1.11E+00	-3.12E-01
182.82 - 187.66	-5.90E-05	2.73E-04	-2.11E-02	2.07E-01	1.86E+00	1.91E+00
187.66 - 199.67	2.35E-04	-1.16E-03	-2.97E-02	-1.28E-01	2.34E+00	1.34E+01

Coefficients of all polynomials were saved in arrays and a Matlab code was written to generate random paths using these coefficients. Such paths can be used in the driving simulator as the actual path that the driver should follow. Unlike the current path shape used in the driving simulator, these paths are unpredictable and also they are more realistic because they are based on field data.

Our literature review was not able to locate any previous research on driving pattern of a tractor operator. Therefore, we were not able to compare our results with any previously published work.

Comparison of different fitting methods

Using Eq. 1, the RMS of curve fitting error for different methods of curve fitting was calculated; the average of RMS values of fitting error for 2nd-, 3rd-, and 4th-order polynomial fittings were 44, 33, and 25 mm respectively while it was 7 mm for the spline fitting method; spline fitting error was significantly less than polynomial fitting errors different $(p = 0.01)$.

Polynomial curve fitting results were not very promising. In some cases in which there were not enough data points, 4th order polynomial curve fitting result was strange and not acceptable. That is because each polynomial of degree N can be fully defined by knowing the coordinates of $N + 1$ of its points; therefore if we try a 4th order polynomial curve fitting when there are less than 5 data points in that specific section, we are actually trying to solve an under-defined problem which has infinite number of solutions and the result will not be reliable. Spline curve fitting, on the other hand, showed none of these shortcomings; it had the lowest fitting error and no erratic behavior. Plus, as mentioned previously, splines have continuous derivatives over the entire length, and this characteristic of splines can be used to study steering behavior.

Future work

The first derivative of the actual driving path gives the slope of this path, and the second derivative gives the change of this slope which is directly proportional to steering wheel corrections of the driver. In Fig. 4, second derivative of the spline shown in Fig. 3 is presented. The ordinate is the rate of change of slope of actual driving path (here, the spline of Fig. 3) and is in units of degrees per meter. This change in slope is directly proportional to steering adjustments. These graphs can be used to compare different guidance systems because the more the number of steering corrections, the more the workload on the driver and fatigue. They can also be used as a fidelity test for the simulator; if the steering pattern of the subjects in the driving simulator is close to those obtained from field tests, we will be more certain of the appropriateness of the recommended path.
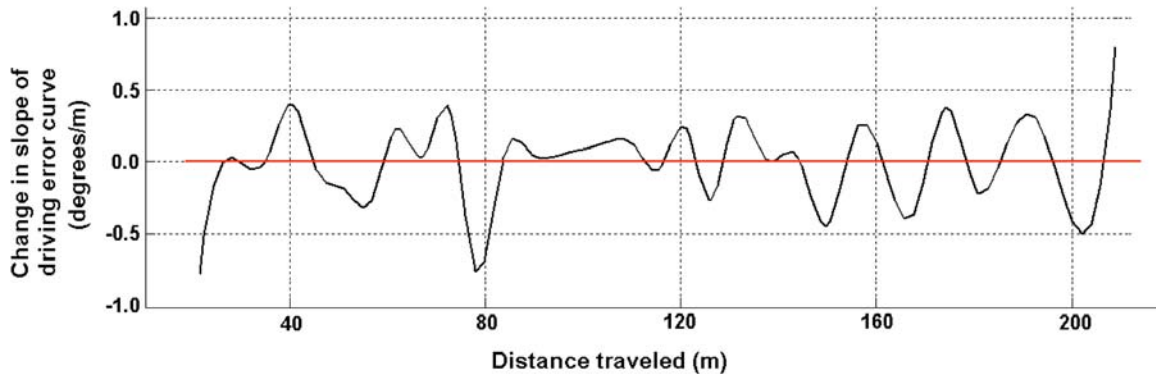

Fig. 4. An example plot of driver's steering behavior. This plot shows changes in slope (second derivative) of actual driving path which is directly proportional to steering adjustments.

CONCLUSIONS

The objective of this study was to develop a new path shape for the tractor driving simulator based on real-field driving behavior of a tractor operator. Field experiments were performed with the tractor operator with the goal of driving along parallel straight passes using GPS guidance systems. We used mathematical curve fitting methods to approximate the tractor operator's driving behavior. The spline curve fitting method was more successful than polynomial curve fitting. It had significantly less fitting error and also it can be used as a tool for further study of such parameters as steering behavior.

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