ECONOMICS OF GPS-ENABLED NAVIGATION TECHNOLOGIES

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ABSTRACT

To address the economic feasibility of global positioning system (GPS) enabled navigation technologies including automated guidance and lightbar, a linear programming model was formulated using data from Midwestern U.S. Corn Belt farms. Five scenarios were compared: (i) a baseline scenario with foam, disk or other visual marker reference, (ii) lightbar navigation with basic GPS availability (+/-3 dm accuracy), (iii) lightbar with satellite subscription correction GPS (+/-1 dm), (iv) automated guidance with satellite subscription (+/-1 dm), and (v) automated guidance with a base station real time kinematic (RTK) GPS (+/-1 cm). Results indicate that RTK automated guidance becomes the most profitable alternative when farm size can be increased while maintaining the same equipment set. Results also indicate that relative profitability ranking is sensitive to years to depreciate the technology.

Keywords: automated guidance, automated steering, lightbar, GPS navigation, linear programming, machinery management

INTRODUCTION

Global positioning system (GPS) enabled navigation technologies (NT) such as lightbars (LB) and automated guidance systems (AG) are commercially available, promising more efficient field operations. Benefits that the agricultural industry claim include 1) reduction in overlap, 2) increased speed of field operations, 3) workday expansion, 4) greater flexibility in hiring labor and 5) appropriate placement of spatially sensitive inputs. GPS location information also allows other technologies such as automated sprayer boom controls and georeferenced yield monitor data. GPS NT are an example of an embodied technology (Griffin et al., 2004) that increases efficiency without requiring additional management skill as opposed to information intensive precision agriculture technologies such as yield monitors and variable rate applications. GPS NT allows field operations to be completed in a timely manner thus improving yields and increasing area farmed with a given equipment set. GPS NT have been used for spatially sensitive practices such as controlled trafficking in compaction prone soils, side-dress nitrogen, and input placement in strip till systems. GPS NT benefits on compacted soils have been evaluated with at least one study (Watson & Lowenberg-DeBoer, 2003) and the economic feasibility of LBs has been reported (Griffin et al., 2005; Lowenberg-DeBoer, 1999; Medlin & Lowenberg-DeBoer, 2000). The bulk of the pertinent literature is engineering (Abidine et al, 2004; Ehrl et al., 2003; Grisso and Alley, 2002; Mann et al., 2003; Stoll, 2003; Stombaugh and Shearer, 2001; Tillett et al., 2003) with only a few studies of whole-farm economic impacts (Griffin et al., 2005).

A linear programming (LP) model was formulated using PCLP Version 5, Beta Test Version software (Dobbins et al., 2001). The model has been used since 1968 in conjunction with the Top Farmer Crop Workshop at Purdue University and was chosen to conduct this research because more than 7,000 farmers have relied upon, trusted, and inputted their own information over 25,000 times, validating the model (Candler et al., 1970; Doster, 2002; McCarl et al., 1977).

This study focused on GPS NT in single equipment set farms. Disk, foam, or other visual markers (VM) NT serve as the base for comparison. With VM NT, the operator gauges markings left by previous passes, causing fatigue, human error, and overlap estimated at 10% of the equipment width (Watson and Lowenberg-DeBoer, 2003). LBs and AG make use of an initial pass or other predetermined line, i.e. the A-B line, to return to equally spaced parallel passes. LBs use GPS to provide a visual electronic indicator that the equipment operator uses to manually adjust the equipment, lessoning fatigue and human error. AG automatically steers equipment along these passes offering increased accuracy and lessoned fatigue.

Commercial applicators are adopting GPS NT to make custom applications of fertilizer, pesticides and other crop inputs. Eighty-two percent of U.S. custom applicators use LBs for ground based applications, while 22% uses AG (Whipker & Akridge, 2007). GPS guidance has become standard practice on U.S. aerial applicators.

METHODS

This study used linear programming (LP) to determine optimal solutions to contribution margins and “shadow values” for factors of production. LP is a mathematical tool for optimizing an objective function (Dantzig, 1949) such as maximizing contribution margin with respect to a set of whole-farm constraints on land, labor, and capital under a given weather regime (Boehlje and Eidman, 1982). Contribution margin is total crop sales revenue minus total direct costs, and can be considered returns to resources or fixed costs such as land, labor, and machinery. A shadow value is an estimate of the marginal value of a scarce resource and represents the change in contribution margin by using the last unit of resource. The base for comparison was a representative sized Midwestern U.S. Corn Belt farm with a single equipment set (e.g. one planter and one harvester) using VM technology for swathing. The base was modified in a series of LP runs to model the NT scenarios.

Five scenarios were compared: (i) a baseline foam, disk, or other VM (10% overlap), (ii) addition of LB with basic GPS availability (+/-3 dm accuracy), (iii) addition of LB with satellite subscription (+/-1 dm), (iv) addition of AG with satellite subscription (+/-1 dm), and (v) addition of AG with a base station real time kinematic (RTK) GPS (+/-1 cm). It is assumed VM NT costs are incurred in all scenarios plus any GPS NT costs, i.e. disk markers are installed on the planter.

The Mathematical Linear Programming Model

The optimization problem was specified as a linear programming model in the standard summation notation and written as in Boehlje and Eidman (1982, p. 404-405) as:

$$Max\ \Pi = \sum_{j=1}^{n} c_j X_j \qquad \text{eq. 1}$$

subject to:

$$\sum_{j=1}^{n} a_{ij} X_j \leq b_i \text{ for } i = 1 \ldots m \qquad \text{eq. 2}$$

$$X_j \geq 0 \text{ for } j = 1 \ldots n \qquad \text{eq. 3}$$

where:

X_j = the level of the jth production process or activity,

c_j = the per unit return to the unpaid resources (b_i's) for the jth activity,

a_{ij} = the amount of the ith resource required per unit of the jth activity,

b_i = the amount of the ith resource available.

Each LP run within a NT scenario changed information relative to adding or changing the extent the GPS NT was used. LP objective value results indicate 1) timeliness benefit from adding GPS NT and 2) benefit of increasing farm size without changing equipment sets and still remain timely. Shadow values were examined to ascertain if the change violated timeliness criteria (i.e., if planting or harvesting became untimely) by considering the magnitude of and the number of time periods with a shadow value. Increases in the number of time periods with relatively large shadow values indicate compromised timeliness and the scenario were rejected as not a solution a rational farmer would accept. Time periods are generally one week in length during field operation periods.

Hypothetical Model Farm Scenario

The 1,214 ha baseline farm has three tractors, but only two have GPS-enabled NT. Field operations were based on conventional tillage production systems reported in Cain (2006). Field operations benefiting from GPS NT include the 7.3 m chisel plow, the 12.8 m field cultivator, 9.8 m tandem disk, 9.1 m grain drill and 18.3 m planter. Skip and overlap are reduced with the chisel, cultivator, and disk. Although planter skip, overlap, and planting speed are not impacted by NT, GPS-enabled planting operations were included to model farmer behavior based on their desire for straight and parallel rows. This combination of tractor and tillage equipment was chosen because of potential overlap reduction benefits. A chisel is a primary tillage implement that minimizes soil inversion while preserving crop residue. A field cultivator is a secondary tillage implement that incorporates crop residue. A disk is a primary tillage implement that incorporates crop residue while stirring the soil. GPS NT is specific to two tractors, i.e., the farm has two individual GPS NT systems. With VM NT, tractors and implements could be used 12 hrs day^{-1}, and increased to 13 and 15 hrs day^{-1} for LB and AG, respectively. The farm has two each of the chisel, disk and field cultivator and one 24-row planter and one combine (370 hp) with a 12-row corn head on 0.76 m row spacing and 9.1 m soybean head. The conventional tillage farm is disked, chisel plowed, and field cultivated prior to planting corn and disked and field cultivated prior to planting soybean. Equipment working rate is ha hr^{-1} worked taking into account speed, size, and field efficiency (Schnitkey, 2000) (Table 1 and Table 2). The planter working rate was a constant 12.9 ha hr^{-1} regardless of GPS NT.

Table 1. Implement size, field efficiency and working rates without GPS NT.

Implement	Width (m)	Field efficiency (%)	Working Rate (ha hr^{-1})
Disc	9.8	80	6.6
Chisel plow	7.3	85	5.3
Field cultivator	12.8	85	11.4
Boom sprayer	36.6	55	36.4
Drill (soybean)	9.1	70	6.4
Planter (corn)	18.3	70	12.9
Harvester (corn)	9.1	85	4.8
Harvester (soybean)	9.1	85	4.8

Table 2. Working rates and overlaps for field operations benefiting from GPS NT.

	9.3 m tandem disk		7.3 m chisel plow		12.8 m field cultivator	
GPS NT	WR (ha hr^{-1})	Overlap (m)	WR (ha hr^{-1})	Overlap (m)	WR (ha hr^{-1})	Overlap (m)
VM NT	6.86	0.98	5.23	0.73	11.33	1.28
3 dm LB	7.41	0.3	5.57	0.3	12.29	0.3
1 dm LB	7.55	0.1	5.71	0.1	12.50	0.1
1 dm AG	7.55	0.1	5.71	0.1	12.50	0.1
1 cm AG	7.60	0.05	5.76	0.05	12.53	0.05

WR= working rate

For LP models, not only were the absolute values important but also the ratios. LP models are typically used for long term planning horizons and not for a single year, therefore prices and yields representative across several years were chosen. Corn and soybean prices were \$0.197 kg^{-1} and \$0.456 kg^{-1}, respectively, for a price ratio of 2.48. Corn and soybean base yields were expected to be 11.80 Mg ha^{-1} and 3.97 Mg ha^{-1}, respectively, when planted and harvested in the optimal time periods. Per hectare variable costs were $ 963.71 USD and $ 481.86 USD for corn and soybean, respectively. Yield and variable cost ratios are 0.31 and 0.50 for corn and soybean, respectively.

Table 3. Change in number of time periods with shadow value compared to base farm.

Resource	Increase WR	Increase Equipment Hours	Increase Farm Size
3dm LB			
Tractor	0	0	-1
Planter	0	0	0
Drill	0	0	1
Harvester	0	0	0
1 dm LB			
Tractor	0	0	0
Planter	-1	0	0
Drill	-1	0	0
Harvester	0	0	-1
1 dm AG			
Tractor	0	4	-1
Planter	-1	0	1
Drill	-1	1	0
Harvester	0	-1	-1
RTK AG			
Tractor	0	4	0
Planter	0	0	1
Drill	0	1	0
Harvester	0	-1	-1

Analysis

Benefits of GPS NT systems were studied by incrementally changing the model to reflect effects of NT on working rates, workday, equipment availability and area farmed in a timely manner. Changes to the model were cumulative. Each change was added to the model using parameters from the previous step. This was done by initially changing the working rate, then increasing the number of hrs day^{-1} that unpaid labor worked, then increasing equipment use hrs. Unpaid labor is family labor not paid hourly but compensated from net farm income. With VM NT, 10% overlap is assumed, the level of advertised GPS accuracy was assigned to be the overlap for GPS NT, and 0.05 m overlap for RTK-AG (Table 1), affecting working rate calculations. Finally, farm size was increased to bring planter capacity utilization in the last time period to a level similar to the base, conditional upon other operations not being adversely affected, i.e., harvester capacity (Table 2). Timeliness was measured by the hrs of planting for each time period. A farm remains timely if planting is completed by a base hrs period^{-1}.

LP Results

Initial LP runs were made with no GPS NT. In the base, a contribution margin of $1,452,173 farm^{-1} was realized (Table 4). Adding a LB with 3 dm accuracy increased the contribution margin by $34,530 (Table 4) or US$28.44 ha^{-1} just from increasing working rates of the chisel and field cultivator. When the hrs day^{-1} that equipment was used increased from 12 to 13 hrs day^{-1}, the contribution margin increased by $49,478 over the base farm or $40.16 ha^{-1} (Table 5). The next higher level NT was a satellite subscription GPS signal used with the LB or AG to give 1 dm accuracy, yielded an increase of $36,773 (Table 4) or US$30.29 ha^{-1} (Table 5) above base when only working rates were changed. When equipment time changed to 13 and 15 hrs day^{-1} for 1 dm LB and AG, contribution margin increased by $51,513 or $42.43 ha^{-1}. RTK-AG, the highest level of technology tested, increased the contribution margin by $37,364 or $30.78 ha^{-1} for the farm just from increasing timeliness, i.e., reducing yield penalties by increasing working rate. Increasing the number of hours that implements are used increased the contribution margin an additional $57,802 (Table 4) or $47.61 ha^{-1} (Table 5).

The shadow value on land changed as GPS NT benefits were added. The shadow value is the amount the farmer would be willing to pay for one additional unit of resource or in this case one ha of land. Without GPS NT, the shadow value on land was US$438 ha^{-1} (Table 3). As NT were added, the shadow value on land increased. When the working rate increased, the shadow value increased to approximately $980 for all GPS NT, or a difference of $541 to $543 (Table 4). The shadow values in both LB NT were unchanged while AG NT increased to $1,106 ha^{-1} when time constraints were relaxed. When additional acres were added to make the farm as timely as the base, all land shadow values reverted back down to levels similar, albeit lower, to the base. This decrease in land shadow value results from a constant harvester capacity with increased equipment set utilization, subsequently reducing the value of the next unit of land. The additional value due to GPS NT could make the difference between a successful land rental bid and being left behind in the competitive U.S. Corn Belt market for farmland.

Table 4. Change in returns, shadow values, and planter capacity utilization.

GPS NT	Increased Working Rate	Increase Equipment Hours	Increase Farm Size	
Contribution Margin (US$ farm-1) (Base = $1,452,173) [after land costs]				
3 dm LB	34,530	49,478	196,619	[128,619]
1 dm LB	36,773	51,513	219,799	[143,299]
1 dm AG	36,773	57,802	387,360	[251,360]
RTK AG	37,364	57,802	389,062	[253,062]
Shadow Value on Land (US$ ha-1) (Base=$438)				
3 dm LB	541	543	37	
1 dm LB	542	545	-10	
1 dm AG	542	668	336	
RTK AG	543	668	337	

Economic Analyses

A partial budget was created from LP results. Annualized costs were calculated using a 10 year useful life, 8% discount rate and no salvage value for GPS NT. For example, the annualized costs of RTK-AG were $5.19 ha^{-1} assuming a $35,000 initial investment (Table 5). Annual subscription fees for 1 dm DGPS correction were assumed to be $1,500, up from the $800 fee used in Griffin et al. (2005) while the 3 dm accuracy had no annual fee. It was assumed that conventional VM NT were still present, therefore the fixed costs of VM were not deducted from the costs of GPS NT. Annualized ha^{-1} GPS NT costs were subtracted from returns to the respective GPS NT (Table 5). When farm size was not expanded, the 1 dm AG NT was most profitable, followed by RTK AG, 1 DM LB, 3 DM LB and VM. All GPS NT were more profitable than VM in all cases. When full benefits of GPS NT were made by expanding farm size, RTK AG became the most profitable GPS NT. Economic ranking differs from those presented in Griffin et al. (2005) due to differences in crop prices and GPS NT cost ratios.

Sensitivity of Differing Years to Depreciate

It is sometimes unclear whether precision agriculture technologies such as GPS NT are to be depreciated similar to the associated field machinery or depreciated over a shorter horizon used for computer technology. A sensitivity analysis was conducted to determine the relative ranking of the five NT alternatives over a range of years to depreciate the technology. In all cases, all four GPS NT dominated VM NT.

Table 5. GPS navigation technology costs and returns relative to visual markers.

	3 dm LB	1 dm LB	1 dm AG	RTK AG
Potential farm size expansion by adding GPS NT (Base farm size 1,214 ha)				
Change in farm size (ha)	162	182	324	324
Navigation Technology (NT) Costs (US$)				
Initial investment US$	3,000	5,000	18,000	35,000
Annualized cost farm $^{-1}$	540	900	3,240	6,300
Annual subscription fee	0	1,500	1,500	0
Total annual cost farm^{-1}	540	2,400	4,740	6,300
Total annual cost ha^{-1}	0.44	1.98	3.90	5.19
Total annual cost ha^{-1} with added ha	0.39	1.72	3.08	4.10
Returns to fixed costs above base (US$ ha^{-1})				
Returns (no added land)	40.76	42.43	47.61	47.61
Returns (added land)	93.47	102.65	163.43	164.54
Returns to fixed costs minus GPS NT above base (US$ ha^{-1})				
Returns (no added land)	40.31	40.46	43.71	42.42
Returns (added land)	93.08	100.93	160.35	160.44

In the event that the GPS NT must be paid the first year and without the opportunity for expanded farm size, the 3 dm LB scenario was the most profitable followed by 1 DM LB, 1 DM AG, and RTK AG (Table 6). When farm size was able to change, the 1 dm AG dominated followed by 1 dm LB, RTK AGG, and 3 DM LB. This quick payback period may be one reason that LB was so readily adopted by both agricultural service providers and farmers.

It is more realistic that GPS NT will be given a time period greater than one year to show a positive payback. Computer equipment is typically depreciated over a three year period. In the case of a three year depreciation schedule, the 1 dm AG dominated the 3 dm and 1 dm LB and RTK alternatives. The same relative rankings exist for the three year, five year and seven year deprecation schedules.

Although a 10-year deprecation schedule may be too long, it seems to be used by most studies. The 1 dm AG was the most profitable when farm size was held constant followed by RTK AG, 1 DM LB, and 3 dm LB. When farm size could expand, RTK AG dominated 1 dm AG, 1 dm LB and 3 dm LB.

CONCLUSION

Results of this study suggest that GPS NT is promising for farmers who can devote at least one tractor to field operations that typically overlap. Making complete use of GPS NT by expanding farm size is important to profitability potential. Under current price to cost ratios, AG dominated LB which dominated VM NT. RTK AG becomes the most profitable option when farm size is allowed to adjust. Other studies suggest that RTK-AG is profitable when spatially sensitive practices like controlled traffic and strip tillage show substantial yield benefits.

Table 6. Sensitivity analysis of years to depreciate GPS NT costs to returns to fixed costs

	3 dm LB	1 dm LB	1 dm AG	1 cm AG
	Depreciated over 1 year			
Returns (no added land) (US$ ha^{-1})	38.09	36.75	30.36	16.48
Returns (expanded acreage) (US$ ha^{-1})	91.12	97.71	149.82	139.96
	Depreciated over 3 years			
Returns (no added land) (US$ ha^{-1})	39.73	39.49	40.25	35.70
Returns (expanded acreage) (US$ ha^{-1})	92.57	100.09	157.62	155.13
	Depreciated over 5 years			
Returns (no added land) (US$ ha^{-1})	40.06	40.04	42.23	39.54
Returns (expanded acreage) (US$ ha^{-1})	92.86	100.57	159.18	158.17
	Depreciated over 7 years			
Returns (no added land) (US$ ha^{-1})	40.21	40.28	43.07	41.19
Returns (expanded acreage) (US$ ha^{-1})	92.99	100.78	159.85	159.47
	Depreciated over 10 years			
Returns (no added land) (US$ ha^{-1})	40.31	40.46	43.71	42.42
Returns (expanded acreage) (US$ ha^{-1})	93.08	100.93	160.35	160.44

Based on research and interactions with farmers, these results can be extended to better understand AG benefits for planting and input application. Since row crop planters do not overlap, only increases in speed affect working rates. However it is difficult to increase planter speed without disrupting seed placement and causing yield penalties. Farmers often comment that they conduct planting operations as fast as possible irregardless of GPS NT. Benefits of GPS NT for planting depend on greater accuracy, e.g. controlled trafficking, strip till agronomics, etc. At present, very little data exists on yield response to reduced compaction or appropriate placement of inputs in the row. Although pesticide and fertilizer applications benefit from increased speed and reduced overlap, large proportions of U.S. Corn Belt inputs are applied commercially rather than by the farmer.

As with other technologies, the fixed costs of GPS NT are declining over time but the annual subscription fees have increased. If this trend continues, there will be a relative incentive to adopt RTK-GPS over DGPS signals requiring subscription services. Current annual subscription fees of $1,500 are similar to the breakeven fees calculated between common adoption decisions.

Intangible benefits of GPS NT were not modeled. In some cases, farm operators who have neck or shoulder discomfort may be able to farm a few additional years. Some evidence suggests farm operators' social lives are improved with the automation of steering and has allowed quality time in the cab of the farm equipment with their partner. Another benefit that was not modeled is equipment draft during tillage operations. In production practices that includes bedding the soil, a pull or draft to one side occurs when one side of the implement is in soil that has not been tilled and the other end of the implement is in freshly worked soil. With GPS NT, “race tracking” or row-skip can be accomplished such that each end of the implement is either in freshly worked or untilled soil; thus reducing stress to the equipment operator and the equipment.

Another benefit of GPS NT is that without the need for visual markers, wider equipment such as planters, bedders, and sprayers may be feasible in some areas. In certain cases, some VM technology such as disc row markers for 24-row equipment may be more expensive than GPS NT and therefore simplifying the analysis.

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