Factors in Productivity and Unit Cost for Advanced Machine Guidance

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Abstract: This paper presents an initial step in seeking to understand just how the adoption of advanced machine guidance technology, especially global positioning systems, leads to improvements in performance by the earthwork contractor. Two grading scenarios and one dozing scenario are examined based upon site observations and interviews with field personnel. Analysis demonstrated that productivity and unit cost improvements result from a reduction in surveying support, grade checking, an increase in operational efficiency, and a decrease in the number of passes. These results are in agreement with published results of benefits of 3D guidance over 2D guidance.

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Introduction

The construction industry of the twenty-first century is well positioned to progress through improvements in equipment, and methods. Mechanization is evolving into automation, as manufacturers of construction and positioning equipment work to integrate their technologies to enhance the performance of earthwork contractors.

Computer integrated construction could become the next step, as real-time positioning creates the link between all of the phases of the design-construction-inspection process. That is done by providing, to any agent, the capability to refer to the actual work, i.e., the position or trajectory of the machine relative to the design, or the results of the work relative to the design.

In the 1980s there was an effort made to have the controls of the construction equipment connected to the available positioning systems. Expense and unsatisfactory levels of accuracy inhibited the success of these efforts. During the 1990s, with the introduction of automatic total stations and global positioning system (GPS) equipment, the successful integration of surveying and machine controls at construction sites became a reality (Phair 1998; Jonasson 2000).

The measuring and guidance systems used until now have mostly been based on laser or ultrasonic technology. These systems have allowed tighter tolerances and better smoothness for the surface, a reduction in manpower, and an increase in productivity (Daoud 1999). Ultrasonic sensors never gained any real popularity on heavy earthwork equipment other than motor graders. Laser guidance technologies first presented in the form of 2D systems have now been followed by sophisticated 3D guidance systems. The Swedish National Road Authority noted an accuracy of 3/32 in. on work performed by an operator with an automated 3D laser system, while the same operator without the system achieved an accuracy only half as good (Phair 1998). This technology has gained considerable use, especially on projects requiring a very consistent grade, i.e., surfacing, fine grading, and likewise. All of these systems have the shortcoming of requiring a direct line of sight between the control station (total station) and the receiver on the guided equipment. It was not until recently that manufacturers of GPS technology have emerged with off-the-shelf systems in this field.

The idea to use GPS technology to guide construction machinery is almost as old as the GPS technology itself. Since the commercial GPS technology to guide construction machinery has only been commercially available since 1999, there still are not many users. However, there are testimonials from users that they do increase productivity (www.trimble.com/products/catalog/constr/sitevis.htm).

Regular users of 3D guided machines (GPS and laser) profess that productivity and quality are increased, rework is reduced, and a grade checker is freed up (at least for parts of the day). These sentiments should be enough to attract earthwork contractors to this advanced technology. While larger companies with greater financial resources may find the investment in machine guidance systems easy to justify, smaller companies perceive a greater risk in the venture. However, for all companies, the questions of added value and timing of the purchase are critical.

Most of the guidance or control systems available off-the-shelf today are not fully automated; instead, they give the operator guidance in either two (2D surfaces) or three dimensions (easting, northing, and elevation). For simplification, the machine guidance systems may be divided into three general categories—2D guidance needing line of sight, 3D guidance needing line of sight, and GPS guidance.

The 3D systems allow guided grading according to a predefined terrain model surface [grid or triangular irregular network (TIN)]. The use of this technology in leveling work affords a reduction in the use of stakes (maybe eventually eliminating their

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use), with their replacement by two-way computerized communication between the operator of the machine and the project data (Daoud 1999). The Mining and Earthmoving Technology System constitutes a successful example of this concept designed to service the similar needs of the mining industry (CAES 1999). These systems have the potential to augment production performance dramatically; therefore, their impact needs to be studied and documented for the benefit of potential users. This paper presents an initial step in assessing the nature of the benefits derived from the use of such advanced machine guidance technologies.

Objective

The impacts of alternative commercially available guidance technologies, especially GPS, on cost and productivity are not well documented. Therefore, earthwork contractors have only anecdotal information on which to base estimates when considering using these technologies. This paper presents an initial step to address that need through the analysis of specific earthwork operations. The primary objective was to demonstrate the critical considerations in estimating changes in cost and productivity estimates for earthwork operations. A second objective was to gain insight on how the construction methods and process might be influenced by the adoption of the new technology. Operations with motor graders and tractors (bulldozers) were examined. Insight and information were gained through consultation with vendors and contractors. Two construction sites were observed, and their scenarios were analyzed.

Methodology

As this research topic was being formulated, the opportunity presented itself to work with Trimble Navigation, Ltd. (Trimble), Redwood Valley, Calif., and one of its distributors, GeoLine Positioning Systems, Inc. Therefore, what follows is mainly based on information about Trimble's product, SiteVision GPS, and two site visits to contractors using SiteVision GPS. The site visits were to an infield restoration project at Nellis Air Force Base (AFB) in Nevada (outside Las Vegas) and to a golf course project in San Jose, Calif. The contractor, Wesley Corp., at Nellis AFB was using SiteVision GPS on a Caterpillar (CAT) 16H grader, while the contractor in San Jose, Kiewit Pacific Co., was using the system on a CAT D9R bulldozer. While the comparison based analysis that follows includes other guidance technologies, only the GPS guidance system is described as the focus of the study because of its most recent availability.

System Features

A GPS machine guidance system, in general, consists of five main components—(1) satellites; (2) GPS control stations; (3) the reference station; (4) a roving unit (on the machine); and (5) software that integrates the other components (Jonasson 2000).

The main advantage of a radio based guidance system, like GPS, over a laser based guidance system is that the base station broadcasts over an area with a radius of around 10 km, depending on the radio used. It also broadcasts omnidirectionally, without needing a direct line of sight from the reference station to the rover unit, and it broadcasts through dust and around obstructions. Also, the GPS base station can support an unlimited number of roving units within the broadcasting area.

While providing the primary advantage over laser based systems, radio technology also brings with it the main potential shortcoming of GPS. That is, the system depends on a connection to the satellites for positioning, and on the radio link (which was a problem on both sites visited) for real-time kinematics. There can be various types of interruptions for both signals, and there is still the possibility of a multipath GPS signal (the GPS signal is reflected before reaching the GPS antenna). Another shortcoming at the time of this writing, especially from the perspective of motor grader operators, is that the system does not yet offer automatic height control for the blade, like some of the more sophisticated 3D laser systems. All of these concerns should be considered when selecting a guidance system for a particular project or activity.

Calculations

The first things to consider when selecting a guidance system or method are the yields and costs of the available systems. Calculations for the main yields and costs for five different methods (conventional, ultrasonic, 2D laser, 3D laser, and GPS) were developed for a linear grading project before going on the field visits. This was done to try to sort out the items that could be impacted in a conventional estimate. After the site visits, the hypothetical project was revisited and some factors were adjusted to reflect the experience of people using guidance systems on a daily basis.

The next step was to model the two sites visited by using the conventional estimating methods for both a linear job (hypothetical project) and an area grading project. The bulldozer work observed, on the golf course project, was essentially an area grading activity, as was the infield restoration project. In addition, the golf course project activity was structured well enough to make a comparison between a conventional off-the-job productivity estimate and an estimate from the field.

The formulas used for calculating productivity for various equipment involved in the analysis can be found in standard textbooks on the subject. For easy reference, two of the five used are shown below, as presented by Schaufelberger (1999).

The regular estimate for a linear grading project is based on the following formula:

$$\text{Productivity}_{\text{Linear Grading}} = \frac{V \times W \times OF}{N} \ (\text{m}^2/\text{h}) \tag{1}$$

where V=average grading speed (km/h); W=effective grading width (m); OF=operating factor; and N=number of passes required. The formula for a conventional area estimate is very similar, and is as follows:

$$\text{Productivity}_{\text{Area Grading}} = \frac{[\text{area graded per cycle } (\text{m}^2)] \times E}{CT \times N} \ (\text{m}^2/\text{h}) \tag{2}$$

where E=operational efficiency (min/h); N=number of passes required; and CT=cycle time, determined with the following formula:

$$CT = \frac{D_F}{V_F} + \frac{D_T}{V_T} \ (\text{min}) \tag{3}$$

where D_F=distance the grader travels when moving forward (m); V_F=average forward speed of the grader (m/min); D_T=distance the grader travels when turning (m); and V_T=average turning speed of the grader (m/min). Note that Eq. (1) has an operating

Table 1. Calculations for Hourly Costs of Surveying/Positioning

Parameter	Positioning Method				
	Conventional	Ultrasonic	2D laser	3D laser	GPS
Instrument	—	—	—	—	—
Purchase price (approximate)	$34,500.00	$40,000.00	$50,000.00	$90,000.00	$100,000.00
Write-off time (years)	5.00	5.00	5.00	5.00	5.00
Cost per year[a]	$ 8,640.75	$10,018.26	$12,522.82	$22,541.08	$ 25,045.65
Cost per day[b]	$ 34.56	$ 40.07	$ 50.09	$ 90.16	$ 100.18
Cost per hour[c]	$ 4.32	$ 5.01	$ 6.26	$ 11.27	$ 12.52
Maintenance (15%) per hour	$ 0.65	$ 0.75	$ 0.94	$ 1.69	$ 1.88
Surveyors	—	—	—	—	—
Number of instrument person(s)	2.00	—	—	—	—
Number of party chief(s)	1.00	—	—	—	—
Employee cost per hour	$ 36.20	—	—	—	—
Total surveying cost per hour	$ 41.17	—	—	—	—
Equipment guidance cost per hour	—	$ 5.76	$ 7.20	$ 12.96	$ 14.40
Total cost per hour	$ 41.17	$ 5.76	$ 7.20	$ 12.96	$ 14.40

[a]Annual interest rate=8.00%.

[b]Number of days used per year=250.00 days/year.

[c]Hours worked per day=8.00 h/day.

factor that is a percent value, while Eq. (2) has operational efficiency in minutes per hour. In addition, proper unit conversions should be inserted into the calculations.

To simplify the technology comparison for the different scenarios and to protect the business concerns of the contractors, hourly rates were taken from the listing of prevailing wages in King County, Wash., effective March 2, 2000 for labor, and from the 2000 RS means heavy construction cost data (1999) for the equipment. The reader is referred to Jonasson (2000) for a tabulation of these rates. The hourly costs for each guidance method were estimated based on the approximate equipment purchasing price (ownership cost), the human-power needed to operate the equipment, and the supporting field personnel for the construction activity (Table 1).

Discussion

By interviewing project managers and operators familiar with guidance systems, it was established that the operating factor or operational efficiency and the number of passes were the two main productivity factors affected by the use of guidance systems (Jonasson 2000). The contractors stated that they still used the same amount of stakes as if they did not have a 3D guidance system, since operators of other equipment, such as scrapers, still needed them for their portions of the job. Therefore, the impact on the original staking is negligible. Instead, the impact shows up in the elimination of subsequent visits by the survey crew for stake checking and surface checking. The impact on the fixed surveying cost can be seen in Tables 2 and 3 on linear (cost per kilometer) and area (cost per hectare) grading jobs, respectively. To illustrate the impact of various options for machine guidance, yields and costs were calculated for the five major guidance options discussed earlier—conventional, ultrasonic, 2D laser, 3D laser, and GPS.

Linear Grading Problem

The following discussion of yields and costs was developed by estimating the hypothetical case of leveling a layer of crushed aggregate 0.25 m (10 in.) thick with a motor grader (CAT 140H), and its subsequent compacting. A compactor and a water truck round out the equipment fleet for this activity.

There is an estimate for fixed surveying costs for each guidance method shown in Table 2. Travel and material costs are not included in the comparison, since they should not significantly affect the outcome in showing the difference between the guidance methods. It can be surmised that the inclusion of these costs would only increase the unit cost change with the use of each higher technology (fewer return visits). The total per-kilometer costs are based on the hourly surveying cost (from Table 1, column 2) and the need for conventional surveying for the different methods. The main differences in Table 2 are shown for the 2D laser, 3D laser, and GPS methods, where there is no need for the surveying crew to check stakes. The operator has guidance even if

Table 2. Time and Fixed Surveying Costs per Kilometer

Parameter	Positioning Method				
	Conventional	Ultrasonic	2D laser	3D laser	GPS
Line and staking	4.00	4.00	4.00	4.00	4.00
Stake check	2.00	2.00	—	—	—
Surface check	2.00	2.00	2.00	—	—
Total time (h/km)	8.00	8.00	6.00	4.00	4.00
Total fixed surveying cost per kilometer using robotic total station	$329.35	$329.35	$247.01	$164.67	$164.67

Table 3. Time and Fixed Surveying Costs per Hectare

Parameter	Guidance Method				
	Conventional	Ultrasonic	2D laser	3D laser	GPS
Line and staking (h/ha)	0.75	0.75	0.75	0.75	0.75
Stake check (h/ha)	0.25	0.25	—	—	—
Surface check (h/ha)	0.25	0.25	0.25	—	—
Total time (h/ha)	1.25	1.25	1.00	0.75	0.75
Total fixed surveying cost per hectare (10,000 m^2) using robotic total station	$ 51.46	$ 51.46	$ 41.17	$ 30.88	$ 30.88
Total fixed surveying cost using robotic total station	$1,667.32	$1,667.32	$1,333.86	$1,000.39	$1,000.39

a few stakes are missing. In addition, for the 3D laser and GPS methods there is less need to check the final surface, although manufacturers encourage it.

The productivity of neither the water truck nor the compactor is affected by the guidance method. The productivity calculation for the chosen compactor [a 13-t vibrating compactor selected from RS Means Co. (2000 RS 1999)] gives a productivity of 238 m^3/h for a single machine. The number of compactors and water trucks needed to maximize the fleet productivity has to be estimated from the combination that gives the lowest overall unit cost. The water truck, a 17,700 L water trailer, was selected based on the highest productivity per hour achieved by one grader and four compactors, eliminating it as a productivity bottleneck (2000 RS 1999).

The productivity for the grader and the basis behind it are explained in more detail in the following sections for each of the different guidance methods. The estimates were refined to incorporate the broad experience of the contractor at the infield restoration project site. The reduction in the number of passes is also based on insights from the site visit. The grader operator noted that for approximately every three passes needed for the conventional method, the 3D guidance systems allowed a one pass reduction, as can be seen in Table 4.

With regard to Tables 2, 4, and 5, the data related to the conventional staking method may be explained as a guide for understanding the remaining data. The estimate for the conventional method is based on the surveying estimate of 4.00 h to stake a 1 km stretch of road, a return 2 h visit to check the stakes before finish grading, and a final 2 h check of the finished surface. The result is a fixed surveying cost estimate of $329.35 for a total duration of 8 h. The grader productivity estimate is based on two passes for spreading at 12.0 km/h, four passes for leveling at 6.9 km/h, two passes for finishing at 6.4 km/h, and finally one pass at 6.4 km/h for rework and last-minute corrections. The average speed is therefore 7.86 km/h, and the operating efficiency is estimated at 40 min/h. These estimates result in a fleet productivity of 405 m^3/h and a unit cost of $\$1.55/m^3$.

Corresponding data were generated for the remaining methods for the same scenario, with results varying due to less reliance on grade checkers to identify and confirm the target grade, increasing utility of user interfaces, and less need to relocate the measurement equipment. A more thorough explanation of the data in Tables 2, 4, and 5 is given by Jonasson (2000).

Discussion of Different Methods for Linear Grading

By comparing the five different methods, based on productivity and unit cost (Table 5), it is evident that each higher technology guidance system lowers the unit cost by significantly increasing productivity and by reducing requirements for grade checking. The tabulations show that just by reducing the requirement for one grade checker, two general laborers, and by reducing the conventional surveying needed for the project, the GPS guidance system reduces the unit cost for the activity. Fig. 1 portrays this comparison graphically.

Table 4. CAT 140H Productivity Calculations

Parameter	Positioning Method				
	Conventional	Ultrasonic	2D laser	3D laser	GPS
Effective grading width (m)	2.74	2.74	2.74	2.74	2.74
Operating efficiency (min/h)	40.00	42.00	43.00	47.00	50.00
Speed[a]	—	—	—	—	—
Spreading (km/h)	12.00	12.00	12.00	12.00	12.00
Leveling (km/h)	6.88	6.88	6.88	6.88	6.88
Finishing (km/h)	6.40	6.40	6.40	6.40	6.40
Average grading speed (km/h)	7.86	8.04	8.21	8.43	8.43
Number of passes	9.00	8.00	7.00	6.00	6.00
Productivity (m^2/h)	1,594.84	1,927.59	2,301.90	3,014.41	3,206.81
Thickness of layer (m)	0.25	0.25	0.25	0.25	0.25
Productivity (m^3/h)	405.09	489.61	584.68	765.66	814.53
Productivity (index)	100.00%	120.86%	144.33%	189.01%	201.07%
Increase from 2D to 3D laser[b]	—	—	—	30.95%	—

[a]Grader operating speeds are from Nunnally (2000).

[b]30% productivity increase from a 2D to a 3D laser guidance system noted by Phair (1998).

Table 5. Unit Cost Calculations

Parameter	Method: Conventional	Ultrasonic	2D laser	3D laser	GPS
Employees	—	—	—	—	—
Grade engineer (s)	2	2	1	1	1
General laborer	3	3	1	0	0
Total hourly employee costs[a]	$147.47	$147.47	$ 60.02	$ 32.59	$ 32.59
Hourly positioning costs	—	—	—	—	—
Conventional surveying cost[b]	—	—	—	—	—
Equipment guidance cost[b]	—	$ 5.76	$ 7.20	$ 12.96	$ 14.40
Total hourly surveying cost	—	$ 5.76	$ 7.20	$ 12.96	$ 14.40
Combination of equipment	—	—	—	—	—
Grader (s)	1	1	1	1	1
Tanker (s)[c]	1	1	1	1	1
Compactor (s)[c]	2	2	3	4	4
Total equipment cost per hour[d]	$423.28	$423.28	$535.32	$647.36	$647.36
Total hourly cost[e]	$570.75	$576.51	$602.54	$692.91	$694.35
Fleet productivity (m^3/h)[f]	$405.09	$489.61	$584.68	$765.66	$814.53
Time to complete the work (h)[g]	$ 11.29	$ 9.34	$ 7.82	$ 5.97	$ 5.61
Total fixed surveying cost[h]	$658.69	$658.69	$494.02	$329.35	$329.35
Unit cost (dollars/m^3)	$ 1.55	$ 1.32	$ 1.14	$ 0.98	$ 0.92

[a]Hourly rates from Table 1.
[b]From Table 1, conventional surveying covered in footnote h.
[c]Combination that makes the grader the bottleneck of the project.
[d]Hourly rates from Table 2.
[e]Combination of total hourly surveying cost and total fixed surveying cost.
[f]From Table 4.
[g]Quantity of work to do divided by fleet productivity.
[h]From Table 2.

Although the estimate does not support a strong distinction between the two 3D guidance systems, it does illustrate that the 3D guidance systems have an advantage over the conventional, ultrasonic, and 2D laser methods. This result is consistent with the findings of the Swedish National Road Authority, which showed a 30% increase in productivity between a 2D laser guidance system and a 3D laser guidance system (Table 4, column 5) for finish grading (Phair 1998).

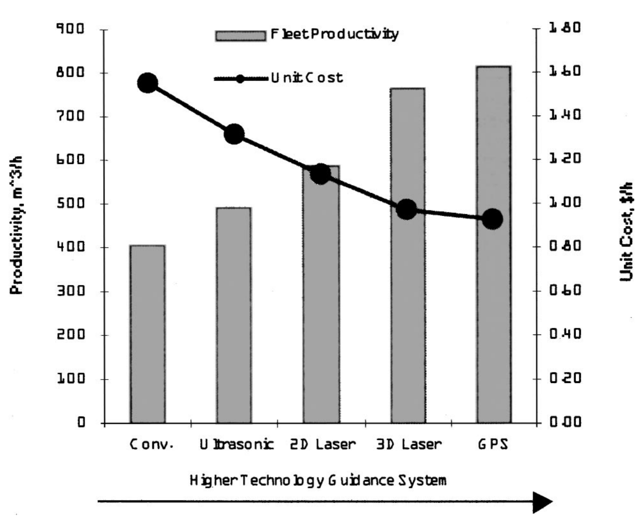

Fig. 1. Trends in productivity and unit cost for alternative guidance systems

The productivity increases shown in this example are based on assumptions for a simple grading job; therefore, caution is warranted before extrapolating these comparisons to other kinds of jobs.

Area Grading Project

The infield restoration project at Nellis AFB has been one of the beta-test sites used for SiteVision GPS for motor graders since January 2000, although it was not formally released for motor graders until May 2000. Fig. 2 shows a photograph of the motor grader, on which GPS receiver antennas can be seen mounted on masts near each end of the moldboard. There had been some initial problem with radio connections on the site, probably due to high usage of military frequencies and the close proximity of the flight control tower. The problem was overcome by using a different antenna for the radio. The part of the project that was under construction at the time of the site visit was an area approximately 1,800 by 180 m between an active runway and a taxiway. The project manager, foreman, and operator of the motor grader equipped with a GPS guidance system were interviewed. The insight obtained on this site visit was also used in refining the productivity calculations for the grader in the preceding hypothetical scenario.

Equipment on the site included a CAT 16H motor grader equipped with a GPS guidance system, a CAT 621F auger scraper, and a CAT 637E series II scraper. Supporting labor consisted of a foreman and a grade checker. Overhead, including the project manager's salary, was excluded because of the difficulty of assigning a realistic portion to the activity with only two days

Fig. 2. Caterpillar 16H with SiteVision GPS system (courtesy of Trimble Navigation, Ltd.)

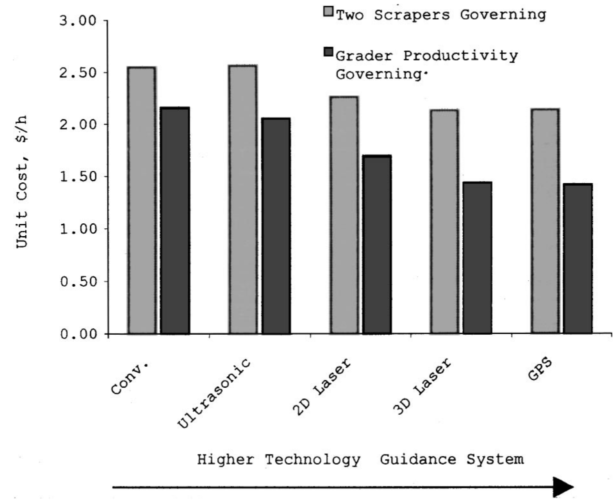

Fig. 3. Comparison of "as-is" and "optimal" scenarios for area grading job

of observation. Similar to the travel and materials cost for surveying, their impact on the cost estimates would be to increase the differences between the guidance methods, as they are usually estimated as a percentage on top of the direct cost.

Also on the site were three CAT tractors with water tanks for dust control, and another CAT motor grader equipped with an ultrasonic device to construct a 2% slope out from the existing runway edge. These machines were not dedicated solely to the cut and fill part of the project, and are therefore left out of the productivity calculations. During the site visit, there was no opportunity to do a reliable grader cycle time study. Therefore, productivity calculations were done using the same approach as applied to the linear grading project, making use of Eq. (2) and the same sources for wages, owning, and operating expenses.

The hourly cost for each guidance system and estimates for fixed surveying costs per hectare are taken from Tables 1 and 3, respectively. Productivity estimates for the motor grader are shown in Table 6. The calculations for the scrapers (both have the same capacity) give a combined productivity estimate of 372 m^3/h.

To further demonstrate that by reducing surveying and grade checking needs, the unit cost decreases with the use of higher technology guidance systems, the fleet productivity and unit cost calculations were done for the "as-is" and "optimal" scenarios. The scraper productivity governs in the as-is scenario. The optimal scenario is governed by the grader productivity. The comparison between the two scenarios can be seen in Fig. 3. Calculations were performed for the two scenarios in the same manner as depicted in Table 5. The comparison in Fig. 3 illustrates that for the optimal equipment combination, the productivity increase associated with a 3D guidance system yields a greater reduction in unit cost for the activity.

One final important observation related to design was noted during the infield project site visit. It was necessary for the project manager to adjust the design file from the designer so that the vendor's conversion software would produce a correct digital terrain model (i.e., correct "local" *x*-, *y*-, *z*-coordinates). This experience underscores the importance of alerting designers to create computer-aided designs with 3D guidance/control in mind. For field automation to be successful, designers must be aware of critical factors in the use of their design data.

Table 6. Productivity Calculations for CAT 16H (4.27 m Blade)

	Guidance Method				
Parameter	Conventional	Ultrasonic	2D laser	3D laser	GPS
Effective grading width (m)	3.20	3.20	3.20	3.20	3.20
Operating efficiency (min/h)	40.00	42.00	43.00	47.00	50.00
Speed[a]	—	—	—	—	—
Leveling (km/h)	7.36	7.36	7.36	7.36	7.36
Finishing (km/h)	6.40	6.40	6.40	6.40	6.40
Average grading speed (km/h)	6.95	7.04	6.98	6.88	6.88
Number of passes required	7.00	6.00	5.00	4.00	4.00
Cycle time (h)	0.26	0.26	0.26	0.26	0.26
Productivity (m^2/h)	4,235.32	5,256.53	6,399.32	8,622.93	9,173.33
Thickness of layer (m)	0.13	0.13	0.13	0.13	0.13
Productivity (m^3/h)	537.89	667.58	812.71	1,095.11	1,165.01
Productivity (index)	100.00%	124.11%	151.09%	203.60%	216.59%
Increase from 2D to 3D laser[b]	—	—	—	34.75%	—

[a]Grader operating speeds are from Nunnally (2000).

[b]30% productivity increase from a 2D to a 3D laser guidance system noted by Phair (1998).

Fig. 4. Caterpillar D9R equipped with SiteVision GPS

Area Cut and Fill Project

The golf course site was located in a hilly area south of Almaden Lake Park. The project called for moving more than 610,000 m^3 of soil and constructing over 1.5 km of entrance roads and parking facilities, domestic and irrigation waterlines, an artificial lake, storm drains, and drainage for the golf course. On May 25, there was an opportunity to observe a CAT D9 (bulldozer) equipped with a GPS guidance system (Fig. 4) working on hole number five. Similar to the motor grader setup, two receiver antennas can be seen in Fig. 4 mounted atop the blade ends. The project manager and bulldozer operator were helpful in answering questions related to their experience with the new technology.

The GPS systems suffered radio transmission problems, apparently due to the close proximity of a commercial radio transmission tower. Hole number five was located such that the transmission tower was between it and the base station (on top of the project office), and the contractor used a radio repeater (on the rover side of the tower) to improve transmission to the rover unit. The impact of the interrupted transmission on the overall productivity is not known.

The GPS-equipped D9 was sent to shape hole number five because it had to be completed, although it had not been staked sufficiently to guide scrapers for the rough work. The system was therefore used, with the basic stakes (centerline, and boundaries of hole), to guide the D9 in cutting and filling and shaping the area (the D9's regular task would be to handle the last 0.3 m of cut and fill, and leave the course shaped according to the design). The task involved moving material for an average distance of 105 m, which is at the upper limit for the productive use of a bulldozer, especially since the material had to be pushed up a 5% grade (Caterpillar 1998). The D9 was the only equipment used on the activity and a grade checker needed only to spend a portion of his time to assist the operator in establishing the grade.

A simple time study was performed to obtain a field estimate of productivity; for comparison, information was obtained from the project manager and operator to make an off-the-job productivity estimate by using the conventional procedures from the Caterpillar performance handbook (1998). It was hypothesized that a large difference might be indicative of the benefit of the GPS guidance system.

Estimating Production Off-the-Job

The off-the-job estimate of productivity was based on the following details: an average distance of 105 m up a 5% grade, a semi-slot dozing technique, clay-stone material of 2,825 kg/m^3 unit weight, an excellent operator, and an estimated job efficiency of 35 min/h (low efficiency due to the need for ripping). The machine was a Caterpillar D9R/9SU (with a tilt cylinder). The productivity estimate was 100 m^3/h (loose) under these conditions (maximum production of 285 m^3/h, and a cumulative correction factor of 0.35). Such estimates are typically thought to be conservative.

Estimating Production On-the-Job

A cycle time study was combined with an estimate of the average blade load (estimated to be 6.5 m^3 by the project manager) and the relevant details noted above to establish an on-the-job productivity estimate. The result was a productivity of 129 m^3/h (loose), with an average cycle time of 1.76 min. The confidence level was set at 99%. The resulting production estimate was 129 ± 14 m^3/h, therefore exceeding the off-the-job estimate by 29 ± 14 m^3/h.

The difference (29% increase) between the on-the-job estimate and the off-the-job estimate cannot be isolated to the impact of a GPS guidance system, especially given the confidence interval. In fact, the actual impact of none of the factors used to modify the off-the-job estimate could be confirmed without extensive field tests. This observation argues for a program of productivity field measurements that include 3D guidance as a factor. To be able to determine the source of productivity differences between an estimate and a field measurement, the same operator should be studied doing the same activity without the guidance system first, and then with the guidance system, and the productivity should be measured once more. This procedure would allow for a correction of the productivity using the conventional method compared to the conventional estimate. Then the productivity measured with the operator using a guidance system could be compared to that for the conventional method. Measurements from numerous operators and scenarios could result in a factor for adjusting productivity estimates if the intention is to use guidance systems on the job.

Additional Considerations in Using New Technology

Several considerations that arise in the use of the GPS guidance system were noted during the golf project site visit. Under normal circumstances, the contractor would not have used a bulldozer for the activity if the area had been more densely staked. Therefore, the main advantage of the guidance system in this situation was the added flexibility given to the contractor in utilizing his equipment and keeping the operation going without waiting for supporting services, i.e., waiting for the surveying crew to stake out the job. Elsewhere on the project site, the contractor still used stakes to the same extent as he would have done using the conventional method. The rationale is that construction machine operators will use grade stakes to visualize the overall job at hand (GPS guidance gives them on-the-spot information), not just to shape the area near each stake. The benefit of providing the operator with a TIN view option to address this reality might be worth investigation. In addition, however, the operators of other types of machines still need stakes to do the rough cut and fill.

Interestingly, for this job, the GPS guidance system was nearly *too accurate*, because it allowed the operator to build the course exactly as the design specified. For golf courses, that does not always coincide with the *intention* of the designer. The designer is looking for a ''feel-good look'' for the course that is not always easy to visualize on a computer screen, and is still counting on the operator to smooth things out in the field. The designer is therefore challenged to adjust to the new technology and try to deliver a final design, which can be used to shape the course according to the design intent. Likewise, the operator needs to be aware of the intention of the designer to accomplish a ''feel-good look'' for the golf course and not follow the guidance system blindly while shaping the surface. A benefit of the guidance only systems is that the operator can readily make these adjustments.

Sensitivity Analysis

It became evident from discussions with personnel on both sites that the only productivity parameters that can be consistently influenced are the operating factor and the number of passes. Influences on speed appeared to be negligible or nonexistent. These assertions prompted an analysis of the impact of changing these two parameters.

By looking at the formulas used to estimate productivity, it can be seen that they follow this correlation

$$\text{Productivity} \propto \frac{E \text{ or } OF}{N} \tag{4}$$

where E, OF, and N are the same variables noted in the equations described earlier. This proportionality relationship shows that productivity is in a straight-line correlation (directly proportional) with the operational efficiency, while the correlation with the number of passes is a power function. This form of the productivity formula shows how valuable it is for new technology to afford the contractor a reduction in the number of passes.

Conclusion

For each of the three scenarios investigated, there are significant positive impacts on productivity that result from using guidance systems, especially 3D guidance systems. Analysis demonstrated that productivity and unit cost improvements result from a reduction in surveying support and grade checking, an increase in operational efficiency, and a decrease in the number of passes. These results are in agreement with published results of benefits of 3D guidance over 2D guidance. Based on the unit cost results, contractors using an advanced 3D guidance system should have an advantage over competitors using conventional or 2D guidance methods. Using a 3D guidance system would be beneficial for the earthmoving contractor, and in the long run for the owner, since it increases productivity and lowers unit costs.

There are some important differences between the 3D systems. The 3D laser systems need a direct line of sight to the equipment; this is not so for the GPS guidance systems. Another difference is that the range of operation is less for the laser-based guidance systems than for the GPS guidance systems. While the results of this study demonstrate a small increase in fleet productivity and a decrease in unit cost for the GPS system versus the 3D laser system, hasty extrapolation to other scenarios is not warranted. On the other hand, in the future as more machines are outfitted with GPS, we expect fleet productivity to increase and unit cost to drop—due, in part, to decreased staking.

The positioning technologies already existing can be combined to give a variety of solutions. Actually, the choice of a particular solution will depend upon many different criteria. Most of the time, the final choice is a compromise between capabilities of fulfilling the requirements of specifications, operational constraints, and cost.

Since the completion of the research, Trimble has bought Spectra Precision, and has therefore changed the landscape on the machine control market by acquiring a leading company in laser guidance technology. This purchase may foster more innovation in merging new technologies for the benefit of the earthmoving contractor.

The use of advanced position measurement technologies for machine guidance is bringing the industry closer to the realization of the vision of computer integrated construction for earthwork projects. To facilitate each step of progress, each innovation must be thoroughly examined for its impact upon the contractor's performance and ultimately upon the broader objective of project delivery.

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