EFFECTIVENESS OF AUTOMATED MACHINE GUIDENCE TECHNOLOGY IN PRODUCTIVITY IMPROVEMENT: CASE STUDY

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Abstract: Automated machine guidance (AMG) systems are a relatively new solution to enhance the precision and improve the productivity of heavy civil operations. These systems process 3D computer models of the earthwork together with the spatial information of the end-effector of the machine, and display the relative location of the end-effector and design levels in real-time for the operator. This paper presents a case study of two large earthmoving projects to compare the performance of equipped bulldozers and excavators with non-equipped machines under similar conditions. The studied operations were summer reclamation and highway excavation for bulldozers and excavators, respectively. The results show that the automated machine guidance technology improved the productivity by 6% to 34% for bulldozers and 19% to 23% for excavators. The variation in improvement rates for bulldozers were due to different site conditions, because unstable soil conditions negatively affect the operation regardless of using automated machine guidance system. In addition to productivity improvement, application of automated machine guidance could reduce the need for surveying; the surveyor team was present 21% to 30% of the working hours for conventional operation of excavators whereas this figure was only 5% for the equipped machines.

1 INTRODUCTION

Construction is often regarded as a traditional industry that is slow to adopt productivity improvements. Historical data demonstrates that the productivity rate in US construction industry remained relatively unchanged from the 1960s to 2009 (Eastman et al. 2011). This performance is well below the increase rate of other non-farm industries. A recent study, however, showed that this inferior performance is not valid for the entire construction industry, because a considerable portion of construction operations have been moved into manufacturing setting and the productivity of off-site operations is higher than that for on-site activities (Eastman et al. 2011; Eastman and Sacks 2008).

Despite all criticisms, earthwork operations are among the pioneers of adopting new technologies to improve productivity and accuracy (Navon 2005). Earthmoving operations depend on heavy equipment, and technical advancement in various features of these machines could improve their performance and help them remain economically viable (Tatum et al. 2006). Some of the areas of improvement include efficient engines with lower fuel consumption and emissions, lower service and maintenance costs, better electrohydraulic systems, and integrated monitoring and control systems.

In addition to the evolution of the machines, a number of add-ons have been developed to enhance the performance of the operations. On-board diagnostic system (OBD), automated machine guidance (AMG) technology, weight sensors, and rear-view cameras are among the main new add-on products. AMG
technology is one of the major advancements that gives the machine operator real-time visual information about the location of the end-effector with respect to the design level, such as the location of grader’s or bulldozer’s blade, excavator’s bucket, or screed of pavers. AMG systems mostly use high accuracy GPS systems, such as real-time kinematic (RTK) GPS, to localize the end-effector. Since these antennas capture data under harsh condition (such as jittering), the signals are filtered for better results. Then, the system emulates the movement of the machine in a virtual environment which also contains the geographical data of the design. The whole process is visualized in a graphical user interface (GUI) in real-time. For example, Figure 1.a shows a dual GPS antenna system installed on the blade of a bulldozer and Figure 1.b depicts a typical graphical view of the operation displayed in the cabin. This way, the operator is able to guide the machine with more confidence than in the conventional approach; it also requires less staking and related interruptions during the operation, because these heavy machines sometimes knock down the stakes during operation (Barrett 2008; Han et al. 2006; Han et al. 2005). Moreover, application of an AMG system could reduce the possibility of rework. These products have become popular in the last decade and several companies fabricate a wide range of product lines for different machines, varying from a simple 1D depth estimation device to a full 3D AMG system.

AMG technology has been the subject of some research projects, such as the evaluation of accuracy of GPS-based systems for road pavement (Peyret et al. 2000) and excavation operations (Bernold 2002; Huang and Bernold 1997). In addition to accuracy, the effectiveness of AMG devices is a key factor in improving productivity. For instance, project planners and cost estimators need to adjust their productivity estimations based on the rates that could be achieved through the use of AMG systems (Han et al. 2005). It is also important for the decision makers to be able to estimate the payback rate of these relatively expensive systems before purchase. Therefore, a few research efforts used simulation methodology to compare the performance of the conventional earthmoving with GPS-based operation (Shehata et al. 2012; Han et al. 2008; Han et al. 2006; Han et al. 2005). In addition to simulation, some of the machine control companies provide case studies about the productivity improvement of their products. These case studies, however, are mainly carried out to promote the product and may not adhere to the basics of scientific approach. Therefore, there is a need for an independent scientific field study to evaluate the performance of the AMG technologies regardless of their make. The outcome could be useful for construction planners and decision makers, as well as for comparison with future studies.

This paper explores the productivity benefits achieved through the use of GPS-based AMG systems on bulldozers and excavators. This study examines the productivity rates in conventional and AMG-based operations, as well as the required surveyor time in both methods.

Two types of automated machine guidance devices are investigated in this research: 3D dual antenna grade control for bulldozers and 3D pose estimation system for excavators. The first system uses two RTK GPS antennas installed on both sides of a dozer’s blade (see Figure 1.a) to calculate location (x, y, z) and angles (pitch, yaw, roll) of the blade. It is also possible to implement this system using only one GPS receiver which has lower accuracy compared to dual GPS. Then the system processes the 3D locational data together with the 3D CAD model of the design profiles and displays them together in a monitor installed in the cabin for the operator. These systems usually have the options to show virtual plan and side view of the operation (see Figure 1.b).
The 3D solution for excavators is more complicated than for bulldozers, because extreme working conditions prevent tracking the end-effector using a GPS antenna. There are a variety of products for excavators in which the high-end solution (full 3D) uses a combination of two RTK GPS antennas installed on the cabin for localization of the machine and estimation of the yaw angle of the boom, and a series of angle sensors attached on the arm, stick, and the bucket to monitor the pose of the articulated arm (See Figure 2.a). The samples studied in this research were equipped with this type of 3D system.
A practical approach to evaluate the effectiveness of these automated machine guidance technologies is to compare the performance of equipped with non-equipped machines under relatively similar working conditions. The job conditions include the same location, same type of soil, same skill level of operators, and the same machine capacity. In addition, the job quantities should be large enough to capture the effectiveness of the system over the long term, which would provide satisfactory comparison data.

2 CASE STUDIES

Two large earthmoving operations were selected for this field survey, and both operations were carried out by a large construction company. There were two main reasons to choose these two cases: First, the contractor used same capacity machines for the same work zones, and some of the plants were operated conventionally while the rest of the machines were equipped with AMG devices. This provided the opportunity to compare their productivity rates. Second, this company uses an effective monitoring system to track the required data for productivity measurement, including working hours, operation locations, and work quantities of each machine, with high accuracy.

2.1 Bulldozer Study

A summer reclamation project in Northern Alberta, Canada, was studied to assess the performance of a 3D grade control system for bulldozers. This project included reclaiming land that was previously used for mining operations. This land had to be restored to its natural contours and pre-mining site condition. The bulldozer production rates were tracked based on time and material being placed. The total volume of earth material moved to the designed grade for the months of June and July 2013 was 181,950 bank cubic meters. The total bulldozer time allocated to the placement of cover-soil materials was 822 hours for the bulldozers without automated machine guidance and 561 hours for the equipped machines. The specified cover material included sub-soil, low-sodic soils, topsoil, and muskeg material with lifts of 70 cm, 50 cm, 30 cm, and 50 cm, respectively. Materials were hauled by off-highway dump trucks to the cover soil placement areas. Then the bulldozers spread out the dumped stockpiles to the required placement thickness and design grades.

Summer reclamation is not as efficient as reclamation in cold months due to large settlements on the placement area. Thawing of the frozen ground in the summer season causes these settlements, which result in unstable ground condition. Therefore, lightweight bulldozers would be more useful during summer reclamation as heavy bulldozers could float over the unstable material.

The average length of the earth-fill sections for this case study was 45 meters, which was an inefficient length. This was mainly due to the fact that haul trucks were not able to move the dump material over the areas where cover-soils were being placed. Nine Caterpillar D6Ts and two Caterpillar D8Ts were used during this case study. Four bulldozers were equipped with AMG including three CAT D6T bulldozers and one CAT D8T. The data was collected using transaction reports, surveying data, and site supervision notes. The transaction report is the company’s internal form of tracking hours assigned to each specific cost code to track time allocated to each task. Working hours of all bulldozers, even those without AMG systems, were tracked using mobile hour recorders. This method provides accurate machine hours. The construction supervisors tracked the work zone of each bulldozer. Onsite project coordinators compiled these records at the end of each day to ensure the acceptable productivity was achieved for each task and for each machine. An accurate survey of the work area of each bulldozer was completed after large sections of work were inspected and approved by a client representative. This inspection/approval procedure followed every two days on average, and the bulldozer would typically wait for an approval before starting work on a new zone. The bulldozer assigned to a specific area would not be moved until the completion of the cover soil in that particular zone, as a way to minimize downtime due to bulldozer relocation. These monitoring processes provide working hours, specific working areas, and approved bank volume of material associated with each bulldozer. These measurements allow for tracking the productivity of each bulldozer based on the actual work volumes with little interpolations required for production estimation of each machine. Figure 3 presents the average of production rates with regards to each month, material type, and bulldozer type.
Application of AMG systems on three CAT D6Ts resulted in 30% increase in average productivity in June subsoil placement. The productivity improvement for the equipped CAT D8T, however, was only 6% in the same operation. The much lower productivity improvement for the CAT D8T compared to CAT D6Ts was due to placement conditions. The D8T had floating issues on the placement areas, causing non-value added (NVA) hours which diminished the overall productivity improvement of the automated machine guidance system. The productivity improvement for CAT D6Ts was significant; because the smaller bulldozer causes less ground pressure than a D8T (Caterpillar 2014), the D6Ts experienced less downtime and operated on the placement more efficiently.

June Topsoil placement was done using only CAT D6T bulldozers and the results demonstrate an overall productivity increase of 34%. July muskeg placement was also performed by CAT D6T bulldozers due to material conditions. Muskeg is an unstable type of earth material and related earthwork should be performed by skilled operators with lightweight equipment. As presented in Figure 3, the productivity of CAT D6T bulldozers in placing Muskeg was lower than any other cover soils. The overall productivity increase in placing muskeg with AMG was about 28%. July Topsoil placement was completed using both CAT D6T and CAT D8T bulldozers. There is a substantial difference between the productivity rates of topsoil placement in June and July for CAT D6Ts; rainfall at the end of June saturated the soil and therefore diminished the performance in July. Summer reclamation is highly weather dependent; for example, extreme precipitation could slow down the operation. The improvement rate for the equipped CAT D6T bulldozers in July Topsoil placement was about 28% which was lower than 34% improvement in June, but this figure was still higher than the 20% improvement for the equipped CAT D8T.
These results demonstrate that the productivity improvement rate obtained by the use of automated machine guidance technology is not constant in every scenario. This value also depends on the working situation, namely soil condition, and the AMG systems for bulldozers are more effective in suitable working conditions.

2.2 Excavator Study

This part of the study compared the productivity rates of similar excavators, equipped with a 3D AMG system and without such technology, in a large highway twinning job in the province of Ontario, Canada. This project included large volumes of excavation to accommodate the large cuts and fills of this highway design. The collected data covers the period of June – July 2013, when a total of 101,686 bank cubic meters of earth material were excavated. Total working excavator hours are broken down to 337 hours of conventional operation and 436 hours using AMG technology. In this project, excavators worked on the benches above the material to be excavated while the dump trucks were on the bottom of the other side of the bench being loaded. This case study excluded rock excavation which required extra operation, resulting in much lower productivity rates than the soil excavation. Seven excavators were assigned to the earth excavation task, and two were equipped with a full 3D automated machine guidance system. The machines working on earth excavation included three CAT 345DLs, one CAT 345D, two CAT 336Es, and one LinkBelt LBX700. The LinkBelt LBX700 is similar in size and power to a CAT 345. One CAT 345DL and one CAT 336E were equipped with AMG technology.

The data collection process was similar to that described above for the bulldozers, included tracking of machine hours, work areas, and detailed surveying data of each machine’s work zone to measure excavation quantities. Data recording units installed in all working equipment (even equipment without AMG) recorded working hours. The work zones specific to each machine were tracked by site supervisors and the excavation quantities were jointly measured and approved by the surveyors of the contractor and client. In addition to these three types of data, the time allocated for surveyors guiding the operators of the equipment was also tracked.

Figure 4 presents the compiled productivity rates; the operation with the use of AMG outperformed the conventional approach. The average productivity improvement rate was about 23% for the CAT 345 excavator compared to other non-equipped similar excavators while 19% productivity improvement was observed with the CAT 336 excavator compared to other non-equipped CAT 336.

![Production Rates of Excavators](image_url)

**Figure 4: Graphical presentation of excavator productivity rates**

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The productivity improvement rates for the excavators were less variable than the bulldozers, possibly due to the stationary operation of excavators. Because of the nature of their function, excavators are less susceptible to the negative effects of unstable ground.

In addition to the productivity improvement, application of AMG system on an excavator results in more savings due to the reduced surveying time. Contractor’s surveyors must carry out some grade checks to ensure that the excavation correctly proceeds based on the designed grades. However, a conventionally operated excavator requires more frequent supervision and grade checks, because it requires some visual stakes during the excavation. Moreover, during conventional operations, some visual markers disappear or are knocked down and must be reset. Figure 5 presents allocated surveyor hours versus total working hours of each of seven excavators during the time of study. Surveyors helped the operators of the AMG-equipped excavators in only 5% of the operation time while this value varies from 21% to 30% of time for conventionally operated machines. It should be mentioned that the utilization of survey time in the conventional approach also depends on the number of excavators performing work. A job with a few excavators might require greater surveyor time per excavator, as the surveyors need to spend the time among few work zones.

![Equipment hours vs. surveyor team hours for different excavators](image)

<table>
<thead>
<tr>
<th></th>
<th>Survey</th>
<th>Excavator</th>
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<tbody>
<tr>
<td>2008 CAT 345DL (Machine Control)</td>
<td>12.2</td>
<td>221.5</td>
</tr>
<tr>
<td>2011 CAT 336E (Machine Control)</td>
<td>9.8</td>
<td>214</td>
</tr>
<tr>
<td>2008 CAT 345DL</td>
<td>57.6</td>
<td>192</td>
</tr>
<tr>
<td>2008 CAT 345DL</td>
<td>14.2</td>
<td>49</td>
</tr>
<tr>
<td>2010 CAT 345D</td>
<td>6.6</td>
<td>32</td>
</tr>
<tr>
<td>2007 LinkBelt LBX700</td>
<td>3.5</td>
<td>16</td>
</tr>
<tr>
<td>2011 CAT 336E</td>
<td>10.1</td>
<td>48</td>
</tr>
</tbody>
</table>

Figure 5: Equipment working hours vs. surveyor hours for all seven studied excavators

The survey times allocated to cover-soil placement areas in the bulldozer case study were not tracked, but the use of grade control systems for bulldozers could reduce the need for this labour-intensive task as well (Han et al. 2006; Han et al. 2005). Another important factor in effectiveness of GPS-based automated machine guidance systems is the GPS signal loss, which was not studied in this research, but it could be problematic in areas with natural obstacles (such as trees and narrow valleys) or human-made obstacles (such as urban canyons) (Meguro et al. 2009).
3 DISCUSSION

The results from these case studies demonstrate that the use of AMG systems increases productivity between 6% and 34% for bulldozers and between 19% and 23% for excavators. This field study revealed that the productivity improvement for bulldozers depends on site conditions. The findings of this study could be compared with the outcome of the simulation-based studies on the use of GPS-based machine control technology in earthmoving projects. Table 1 provides these results.

<table>
<thead>
<tr>
<th>Study</th>
<th>Methodology</th>
<th>Results</th>
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<tbody>
<tr>
<td>Han et al. 2006</td>
<td>Discrete event simulation</td>
<td>Two different GPS-based earthmoving scenarios were analyzed and the productivity improvement rates over the conventional system were 21.74% in short haul and 5.67% in long haul distance</td>
</tr>
<tr>
<td>Han et al. 2008</td>
<td>Discrete event simulation</td>
<td>Productivity improvement depends on site conditions. Two models were analyzed with 34.36% and 16.38% productivity improvement rates for the GPS-based system</td>
</tr>
<tr>
<td>Shehata et al. 2012</td>
<td>Discrete event simulation</td>
<td>Time saving of 18.57% and productivity improvement of 41.47% for the GPS-based operation</td>
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4 ECONOMIC ANALYSIS

The productivity improvement rates are useful during the scheduling and planning of major heavy civil construction projects. To help exemplify the noticeable benefits of the implementation of AMG systems, a simple scenario is presented. This case examines operating costs and payback based on increased productivity for a D8 bulldozer. Operating costs for the machine and the operator were obtained using OPSS 127 (Ontario Ministry of Transportation 2014) and Statistics Canada (2014), respectively. Based on these sources, the hourly rate of a D8 bulldozer is 243.5 CAD (= $218.8 for machine + $24.68 for the operator). An initial investment of $60,000 Canadian is considered for the 3D automated machine guidance system. It was assumed that the bulldozer has an average productivity of 165 bank cubic meters per hour and the productivity improvement rates of 20%, 25%, and 30% were used in this analysis. As presented in Figure 6, the operation cost of a machine with an AMG will be lower than an unequipped bulldozer after a certain point. For example, in the case of 25% productivity improvement, the initial investment will pay for itself after 203,000 cubic meters of earthmoving, and the subsequent operations would have a larger profit margin than the conventional operation.
CONCLUSION

This research project investigated the effectiveness of machine control technology on bulldozers and excavators using systematically collected data from two large earthmoving projects. The results demonstrated overall increases in productivity by using AMG technology in both types of equipment. The rate of productivity improvement, however, is not consistent in all cases and depends on the site conditions, more specifically soil condition. The observed productivity improvement rates for bulldozers varied from 6% to 34% in different conditions and the improvement rate varied from 19% to 23% for excavators. In addition, the required survey time for excavators was also tracked, and showed considerable reduction for equipment with AMG. The equipped excavators required surveyors only 5% of the time, while this value was 21% to 30% of the time for the conventionally-operated excavators.

References