Estimating Potential Cost Savings from Implementing an Innovative TBM Guidance Automation System

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ABSTRACT

It is vitally important to evaluate costs, benefits and risks associated with adopting new method or technology prior to field implementation. The present research proposes a framework for estimating potential cost savings by implementing new method or technology in the field in terms of (1) productivity-dependent crew cost; (2) time-dependent indirect cost; and (3) time-independent indirect cost in the current practice that can be removed. In regards to system reliability, the proposed framework guides the identification of possible breakdown event categories and the evaluation of probabilities and consequences for each category of event. A case study is presented in the context of developing an innovative TBM guidance automation system in tunnel construction. Potential cost saving resulting from implementing the new automation system for a 1,000-meter-long drainage tunnel project in Edmonton, Alberta is estimated to be \$ 424k, which outweighs the additional cost associated with system reliability (about \$ 34k) by about 12.5 times.

INTRODUCTION

Productivity improvement research focuses on the evaluation of the field productivity related to the workforce by applying regression, correlation, and other statistical analyses on field-collected data (Park et al. 2005, Jergeas 2009). The research endeavors have been resorted to advanced artificial intelligent algorithms (such as neural networks) or tracking and positioning technologies [e.g. radio frequency identification (RFID) and global positioning system (GPS)] for more sophisticated productivity analysis. Nonetheless, the objectives of such applied research remain much the same as the work sampling technique or the Method Productivity Delay Model, which were formalized in 1970s for measuring productivity, identifying productivity-undermining factors, and proposing recommendations on productivity improvement. Innovations in computing, automation and integration in terms of sensors, simulation, building information modeling (BIM), cloud computing, and robotics in the construction engineering and management domain hold great promises to make game-changing differences to the practical field. However, implementation of innovative solutions from research to streamline construction processes and enhance field productivity still remains a challenge (Balaguer et al. 2008).

The present research proposes a framework for estimating immediate cost savings which is potentially materialized by applying an innovative method in the construction field in contrast with the current practice. The differences in application cost between new and existing methods are categorized into three parts, namely: (1) productivity-dependent crew cost (direct cost charged by construction duration); (2) time-dependent indirect cost (field overhead charged by project duration); and (3) time-independent indirect cost in the current practice that can be removed as a result of implementing the new method. Cost savings from the three parts are estimated based on method productivities of new and existing methods, respectively.

In addition, it is advisable to factor in additional costs in connection with adopting new technology (including system reliability, crew training, and learning curve etc.) In terms of system reliability, the proposed framework guides the identification of possible breakdown event categories, together with the evaluation of the probability and the consequence for each category of event. A Monte Carlo simulation approach can be applied to determine the additional cost based on simulated system breakdown time periods in statistical terms (e.g. 80% percentile is used to describe the conservative estimate of additional cost). The additional cost includes the fitting crew's cost to check and fix the system plus the direct and indirect costs incurred in the field due to the construction operation shutdown.

A case study of evaluating the proposed framework for estimating cost savings is presented in the context of implementing an innovative tunnel boring machine (TBM) guidance automation system in tunnel construction, which is called the Virtual Laser Target Board (VLTB) for TBM Guidance (Shen and Lu 2012). In the following sections, the tunnel construction method together with the two alternative TBM guidance systems are described first before presenting the detailed case study of estimating cost savings as a result of adopting the new system.

CURRENT PRACTICE OF LASER GUIDANCE IN TUNNELING

To ensure quality of the as-built tunnel, the TBM must be guided along its as-designed alignment. In the current practice, a laser station and a laser target board are used to guide the TBM, as shown in Figures 1 and 2. The laser station shoots a straight laser beam, which is calibrated to stay parallel to the as-designed tunnel alignment, onto the target board mounted on the rear end of the TBM. Based on the position of the laser projection spot on the target board, the TBM operator can infer current position and deviations of the TBM.

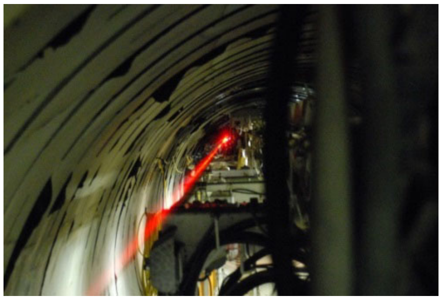


Figure 1. Guidance laser beam.


Figure 2. Laser target board.

Establishing the laser station and maintaining its accuracy are not only extremely time-consuming, but also require the expertise of a tunnel survey crew. Shutdowns of tunneling construction due to *Routine survey* and *Relocation survey* are required to calibrate the laser station:

- **Routine survey**: In every 10 m the TBM advances, there is on average 1.5-hour shutdown for the survey crew to check the accuracy of the laser alignment.
- **Relocation survey**: In every 200 m the TBM advances, there is on average 5-hour shutdown for the survey crew to relocate the laser station. Due to dispersion and refraction of the laser beam and line of sight issues, the typical maximum application distance for the laser system is about 200 m. Thus, it is necessary to relocate the laser station as tunneling operations advance so as to ensure its accuracy and reliability.

TUNNELING GUIDED BY VIRTUAL LASER TARGET BOARD

Different from the traditional laser guidance system, the VLTB TBM guidance system integrates four main functions: (1) TBM tracking automation through surveying-computing integration; (2) wireless data communication enabled by ZigBee-based wireless sensor networks; (3) VLTB tablet program for TBM guidance; and (4) near real-time visualization of tunnel construction in a 3D environment.

The VLTB hardware consists of one robotic total station, one rugged tablet computer, a limited quantity of prisms installed at the rear end of the TBM, and ZigBee nodes for wireless communications between the total station and the tablet. The robotic total station (Figure 3) is controlled by an in-house developed computer program to automatically track and survey the positions of these prisms (Figure 4).

The VLTB system can automatically measure the positions of the prisms and calculate the deviations and orientation angles of the TBM by applying point-to-angle algorithms, without the need of using any gauges such as levelers, gyroscopes, inclinometers and compasses (Shen and Lu 2012). The operator can monitor these parameters of TBM position and orientation directly on the tablet in near real time. When a misalignment error is detected by VLTB, straightforward correction information on TBM steering control can be immediately provided for the operator to take action just in time.

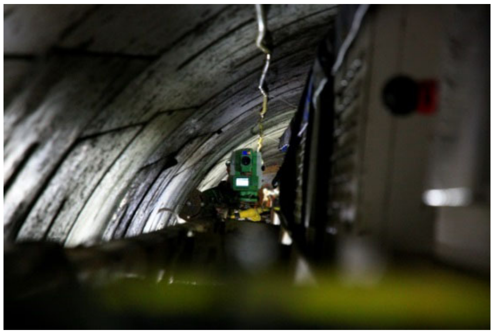


Figure 3. Robotic total station.

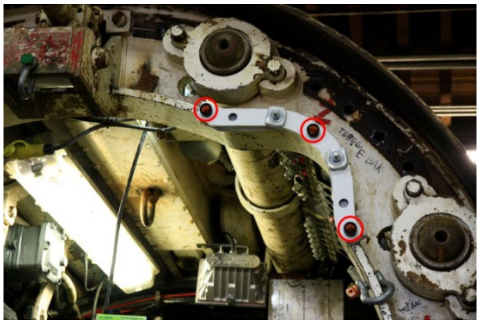


Figure 4. Three tracking prisms.

The VLTB system is designed to perform automatic calibration, thus eliminating the need for once-every-10-meter *Routine survey* in connection with implementing the traditional laser guidance system. In addition, the *Relocation survey* during implementing the VLTB technology can be achieved much faster in comparison with the traditional laser solution: in every 200 m the TBM advances, there is on average 2-hour shutdown for the survey crew to relocate the robotic total station, in contrast with at least 5 hours shutdown required for relocating the laser station in current practice. Note the typical maximum application distance for VLTB of about 200 m is imposed by the laser technology, which is utilized by the robotic total station to automatically track and survey prisms installed on the TBM.

COST SAVING MODEL: CONTRASTING NEW VS. CURRENT METHODS

In this section, a case study of evaluating productivity and cost performances on tunnel construction by implementing the two alternative TBM guidance systems is presented to illustrate the proposed model for estimating cost savings. To build a 1,000-meter-long tunnel, the total project time and direct construction cost are estimated for the traditional laser system and the proposed automation system, respectively. The cost savings from implementing a new method in contrast with current practice can be attributed to three parts:

Part 1: Direct cost saving resulting from improving productivity of construction method.

Only the costs of productivity-dependent resources in the construction crew are factored in; while the costs of productivity-independent resources in the crew should be excluded. In the tunnel application, the labor resource cost is productivity dependent; as productivity improvement will increase the hourly production output hence reduce the direct cost per unit of construction. On the other hand, *the TBM's cost is accounted by the partner company in terms of $ per meter of tunnel built, instead of $ per hour of construction use*. Thus, TBM's cost is productivity-independent and hence ignored in determining the cost savings in this case study. As mentioned earlier, a tunnel crew and a survey crew are involved in this tunnel project. Typically, the tunnel crew consists of one Tunnel Supervisor (indirect cost), one Tunnel Forman, one TBM operator, one crane operator, two Level II tunnel laborers and four Level I tunnel laborers. The tunnel crew works 8 hours/shift, 1 shift a day, 5 days a week. The survey crew consists of three surveyors and works on the site by appointment only (Shen and Lu 2012).

The labor hourly rates used for estimating the cost savings are given in Table 1; those rates are estimated based on the standard union rates as of Alberta 2013 and do not represent the actual rates of the partner company; they only serve the purpose of illustrating cost saving quantification. In addition, the professional surveyor's hourly rate is assumed to be $77.3 per hour; 3-surveyor crew is applied for routine survey, relocation survey and post-construction as-built survey in applying the traditional laser guidance solution; while only 2-surveyor crew is required for relocation survey in applying the VLTB system.

Table 1. Labor hourly rates for tunneling crew used in evaluating cost saving.

Quantity in Crew	Job	Hourly Rate
1	Tunnel Forman I	$52.05
1	TBM Operator	$65.44
1	Crane Truck Operator	$46.57
2	Tunnel Laborer II	$94.59
4	Tunnel Laborer I	$183.42
	Total	$442.07

The productivity improvement by introducing an automated tunnel alignment survey solution such as VLTB to guide the TBM operations is estimated to be at least 10% by experienced tunneling experts. The timeliness, accuracy and transparency in providing as-built tunnel information potentially boost the crew's morale and confidence in assuring quality of construction while eliminating unnecessary delays to construction cycles.

In the current case study of 8 ft drainage tunnel construction by using the TBM and the crew in the City of Edmonton, the ideal production rate under normal working conditions is determined as 1.6 hours per meter advanced (i.e. 5 meters per 8 hours shift). According to historical data, the efficiency factor achievable in the field by use of the traditional laser guidance system ranges from 70% to 80%, with the most likely value being 75%. Thus, the efficiency factor applicable to qualify the ideal production rate is defined as a triangular distribution TRIANGULAR [70%, 75%, 80%]. Depending on other critical factors such as geotechnical conditions encountered, mechanical conditions of the TBM, and experience and competency level of the TBM operator, the productivity improvement is estimated as three-point values of efficiency increment and the corresponding triangular distribution is defined as TRIANGULAR [10%, 15%, 20%].

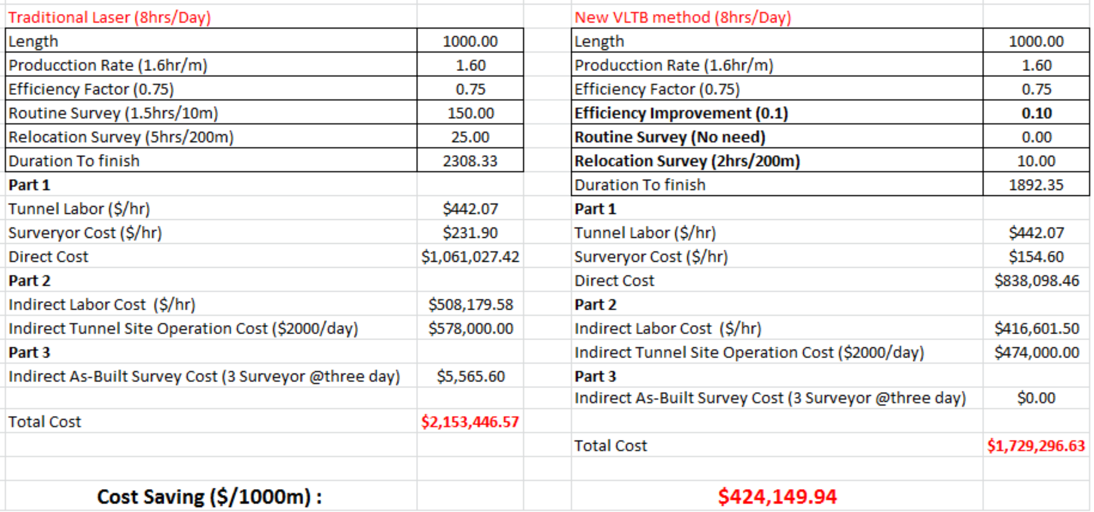
Part 2: Time-dependent indirect cost saving as a result of improved productivity and shortened project duration.

The project management is stationed in the site office and consists of one tunnel supervisor, one project manager, and one field engineer. The average hourly rate is estimated to be $73.38 per hour. For the project management team, the total hourly rate is $220.15 per hour. The field-specific overhead is assumed to be $2,000 per day to cover trailer office, utilities, material handling (crane/storage/muck train /ventilation).

Part 3: Cost saving due to eliminating time-independent additional cost.

Apart from productivity improvement in tunneling construction, the VLTB system is also capable of performing as-built tunnel invert surveys automatically as construction operations unfold, at no extra cost. In current practice, as-built invert survey is conducted by the survey crew after construction is completed. For the same 1,000 m tunnel above, it takes 3 full working days (24 hours) for the survey crew to measure as-built invert. In this case study, the labor cost for mapping out as-built tunnel alignment after the tunnel is completed is taken as “Part 3” cost saving.

For 1,000 m straight tunnel construction, the application of the proposed framework for quantifying cost saving from implementing VLTB in contrast with the traditional laser guidance system is demonstrated in Figure 5. Note the efficiency factor is sampled as 75% while the efficiency boost is sampled as 10% from respective triangular distributions. The total cost, which summarizes cost components of Part 1, Part 2, and Part 3, is estimated to be $ 2,153,446.57 and $ 1,729,296.63 for implementing the traditional laser guidance system and the VLTB new method, respectively. Thus, the potential cost saving ($ per 1 km straight drainage tunnel in Edmonton, Alberta) is determined as the difference, namely: $ 424,149.94.



Traditional Laser (8hrs/Day)		New VLTB method (8hrs/Day)	
Length	1000.00	Length	1000.00
Producction Rate (1.6hr/m)	1.60	Producction Rate (1.6hr/m)	1.60
Efficiency Factor (0.75)	0.75	Efficiency Factor (0.75)	0.75
Routine Survey (1.5hrs/10m)	150.00	**Efficiency Improvement (0.1)**	**0.10**
Relocation Survey (5hrs/200m)	25.00	**Routine Survey (No need)**	0.00
Duration To finish	2308.33	**Relocation Survey (2hrs/200m)**	10.00
Part 1		Duration To finish	1892.35
Tunnel Labor ($/hr)	$442.07	**Part 1**	
Surveryor Cost ($/hr)	$231.90	Tunnel Labor ($/hr)	$442.07
Direct Cost	$1,061,027.42	Surveryor Cost ($/hr)	$154.60
Part 2		Direct Cost	$838,098.46
Indirect Labor Cost ($/hr)	$508,179.58	**Part 2**	
Indirect Tunnel Site Operation Cost ($2000/day)	$578,000.00	Indirect Labor Cost ($/hr)	$416,601.50
Part 3		Indirect Tunnel Site Operation Cost ($2000/day)	$474,000.00
Indirect As-Built Survey Cost (3 Surveyor @three day)	$5,565.60	**Part 3**	
		Indirect As-Built Survey Cost (3 Surveyor @three day)	$0.00
Total Cost	**$2,153,446.57**		
		Total Cost	**$1,729,296.63**
Cost Saving ($/1000m) :		**$424,149.94**	

Figure 5. Application demo of the cost saving estimating framework for 1km tunnel construction.

By performing Monte Carlo simulation to randomly sample the efficiency factor and the efficiency increment from the respective triangular distributions the cost saving estimate can be further characterized in terms of mean, standard deviation, and percentiles. For the current case study, the mean is determined as $ 519,640, the standard deviation as $70,842, the maximum as $722,654, and the minimum as $328,913. The 20th percentile of $455,531 can be interpreted as the *conservative* estimate of cost saving on 1-km tunnel construction by implementing the new VLTB technology, which can be interpreted as: with 80% likelihood, the potential cost saving will be no less than $455,531 by implementing the VLTB technology to constructing 1-km drainage tunnel in contrast with the current practice of using the traditional laser guidance system. It is noteworthy the project duration in terms of the working hours for the case project can be shortened by about 20-25% if the VLTB system is utilized. For instance, the duration to finish 1-km tunnel is 2308 hours and 1892 hours for applying the traditional laser guidance solution and the new VLTB solution, respectively based on one sampled simulation run (Figure 5).

ADDITIONAL COST IN ADOPTING NEW METHOD

Additional costs are associated with introducing a new method to substitute for an existing one, including costs incurred in association with training, learning curve, system reliability and other contingency factors (*unknown unknowns*). Such additional costs should be balanced against the benefit of adopting the new method in order to arrive at the net cost saving.

In the current case study, the VLTB system is intended to function continuously and automatically as tunnel construction advances, thus cost factors such as crew training and learning curve can be ignored. The TBM should not advance without the guidance of the VLTB system, and whenever the VLTB breaks down, the tunnel construction should halt. As such, the system reliability and risks of likely breakdowns need to be analyzed. The costs associated with system reliability in the current case study are addressed in the following section.

The main component of the VLTB system is a Leica® Robotic Total Station which is commonly applied as highly reliable and precise survey instrument. The on-board battery lasts at least 6 hours, and a high-volume extra battery is also available which lasts at least 10 hours. Note the system requires 10 minutes re-setup after battery change. Thus, robotic total station breakdown could happen at a very low possibility and thus is not considered in estimating the additional costs of adopting the new technology.

However, due to the extremely narrow survey window in the tunnel field, the line of sight between the robotic total station and the prisms on the TBM can be unavailable within the 200 m automatic working range (relocation survey). Once the line of sight is blocked, the VLTB automation functionality will not perform properly. The TBM operator will be immediately notified of the problem, and then a fitting crew (two surveyors) will be called in to check the system and provide TBM guidance support. The following categories of likely system breakdown events are identified, with probability and fitting crew time required estimated:

- Routine check: temporary obstruction of the line of sight by tunneling crew and/or tools. 6.25%~15 min
- Minor adjustment: line of sight is blocked by expansion ring of TBM, etc. Need to adjust the position of total station on the fixed holding bracket. 2.5%~30 min
- Major adjustment: line of sight is blocked by the trailing gantry behind TBM, need to relocate the holding bracket of the total station. 0.625%~60 min
- Relocation adjustment: line of sight is blocked by tunnel liner already installed; need to establish new reference points and relocate holding bracket. 0.3125%~120 min

It is noteworthy that with 90.31% probability, the VLTB system would function normally without experiencing any system breakdown. For the 1-km case project, the total system breakdown time is estimated to be on average 29.39 hrs with standard deviation being 7.07 hrs. The 80% percentile value of 31.60 hrs is selected to calculate the expected additional cost of implementing the VLTB system due to system reliability in 1-km tunnel construction: $154.60 per hr (2-surveyor crew hourly rate) X 31.60 hr = $4,855.36; plus tunneling production loss due to system breakdown $ 912.12 per hr X 31.60 hr = $28,826.15 (including Tunneling crew $442.07 per hr; project management cost $220.15 per hr; field overhead/indirect cost $250 per hr). Thus, the total additional cost resulting from VLTB system breakdown is estimated as $4,855.36 + $28,826.15 = $33,711.51. In short, the total potential cost saving (about $ 424k) resulting from implementing VLTB far outweighs the additional cost associated with system reliability (about $ 34k) by about 12.5 times.

CONCLUSION

It is vitally important to evaluate costs, benefits and risks associated with adopting new method or technology prior to changing current practice in the construction field. This research proposes a framework for estimating cost savings in terms of: (1) productivity-dependent crew cost; (2) time-dependent indirect cost; and (3) time-independent indirect cost in the current practice that can be removed. It is advisable that additional costs in connection with adopting new technology be estimated (e.g. system reliability, crew training, and learning curve etc.) In terms of system reliability, the proposed framework guides the identification of possible breakdown event categories and the evaluation of probabilities and consequences. A Monte Carlo simulation approach can be applied to determine the additional cost in statistical terms based on simulated system breakdown time periods. A case study of estimating cost savings from implementing an innovative TBM guidance system in tunnel construction is presented; the main finding is as follows: for a 1,000-meter-long drainage tunnel project in Canada is estimated to be about $ 424k, which far outweighs the additional cost associated with the system reliability (about $ 34k) by about 12.5 times.

REFERENCES

Balaguer, C., and Abderrahim, M. (2008). “Trends in robotics and automation in construction.” *Robotics and Automation in Construction*, 1-20.

Jergeas, G. (2009). “Improving construction productivity on Alberta oil and gas capital projects.” *Report Submitted to Alberta Finance and Enterprise*, Calgary, Alberta, Canada.

Park, H., Thomas, S., and Tucker, R. (2005). “Benchmarking of construction productivity.” *J. Constr. Eng. Manage.*, ASCE, 131(7), 772-778.

Shen, X., and Lu, M. (2012). “Development of virtual laser target board for tunnel boring machine guidance control.” Proceedings of the International Conference on *Computing In Civil Engineering, ASCE*, Clearwater Beach, Florida, 413-420.