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A PRELIMINARY STUDY OF TRAMMING SPEEDS IN MULTIPLE TELE-OPERATED LOAD-HAUL-DUMP SCENARIOS USING QUEST®

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ABSTRACT

Tele-operated Load Haul Dump (LHDs) machines are becoming a common tramming solution throughout many mines at INCO Limited in Copper Cliff, Ontario, Canada. To reach maximum productivity from multiple tele-operated LHDs, the system must achive a proper balance of LHD speed in the haulage network and haulage layout geometry. A study was inititated to determine if multiple LHDs, tramming in second gear under automatic guidance, would influence the total throughput of a production process. A simulation model was used to evaluate the haulage system throughtput with the LHDs tramming in second gear while under automatic guidance. The study indicated that allowing LHDs to operate in second gear for the specificed haulage layout configuration, may not provide an increase in the system capacity. The paper concludes that further investigation of key tramming system variables should be carried out to optimize LHD speed with the haulage layout geometry.

1 INTRODUCTION

At INCO, underground mines are becoming progressively deeper to reach the vast high grade mineral deposits that lie up to two kilometers below the surface. Deeper excavations result in more complicated extraction methods and potentially increased operating costs. To overcome these drawbacks of mining deeper into the earth's crust, INCO has been developing mine haulage systems that will allow operators to control the haulage machines, from a surface location. These systems allow operators to control multiple underground machines on different levels at a mine, or even different mines throughout the company from the comfort of an office type work station.

Manually driven LHDs are operated in first gear to reduce operator fatigue and allow them to be safely controlled. Tele-operated have also been operated in first gear, and were operated at this speed because of the slow response of their steering system, and the ability of their control system to react to changing roadway conditions. Improvements in the LHD control system have allowed tele-remote LHDs to reach second gear tramming speeds.

In 2000, Mines Research at INCO Limited in Copper Cliff, Ontario, Canada initiated a study to compare the system throughput and waiting times for scenarios where LHDs were operating in first and second gear in both automatic guidance mode and under the control of a tele-operator. The results of this study will be used to assist Mines Research to determine an effective LHD automation strategy for the future.

The operation of an LHD is similar to that of a loader at a surface construction site. The operator loads material into the bucket at the loading point (drawpoint), drives (trams) to a dumping location (orepass) and dumps the material. This process is repeated over and over during the length of a shift. Tele-remote operation of this process involves the same operations as described above, but the operator is located at a surface console, instead of sitting in an operator's cabin on the machine. In tele-operation mode, the operator manipulates a set of joysticks at his console to instruct the machine to lower its bucket and pick up material (ore/rock) in the loading area. Once loading is complete, the operator then maneuvers the LHD to the beginning of the tramming path. The tramming path contains a brightly lit cable suspended from the roof of the tunnel between the loading and dumping points. This cable provides a guide for the LHD to automatically follow. Once the dumping point is reached, the LHD stops and waits for the operator to take over control of the system, and maneuver the LHD into the dumping area. After dumping, the operator moves the machine back under the lighted cable, and the automatic guidance system takes over control of the LHD for the next loading cycle. Figure 1 illustrates the control room and an LHD operating in the mine, as it was modelled in the QUEST® CAD environment.

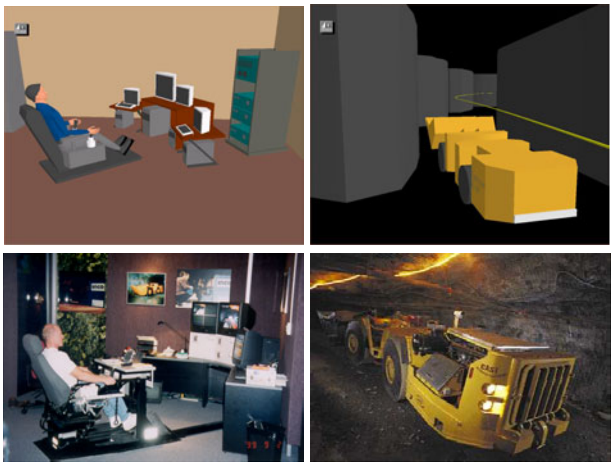

Figure 1: LHD and control room with tele-operator

2 METHODOLOGY

A model of the production tramming operation was constructed using the QUEST® discrete-event simulation software environment by Delmia Incorporated. The model was verified and validated using data from an INCO mine operating tele-remote LHDs. After the model was validated, a study was carried out to determine the LHD's productivity while operating in second gear.

LHD process parameters such as loading time, dumping time, maximum speed loaded and unloaded were input into the simulation model. These inputs were determined from conversations with operators and equipment manufacturer product catalogues. Shift logs located in a database were also analyzed to determine the number of days that at least two or three LHDs were simultaneously transporting material in the system.

The model consists of a single operator controlling the loading and dumping operations of three independent LHDs operating on three different levels at the mine. Once loading or dumping has completed, the LHD is moved to the light rope where it automatically trams to its next location. While an LHD is on the light rope, the operator is free to attend to the loading or dumping operation of any of the remaining LHDs that may be waiting for an operator. The operators work two eight-hour shifts per day, five days per week. At the beginning of each shift 30 minutes is allocated to LHD and infrastructure service.

Multiple independent replications of the model were run, with each replication simulating 80 hours of the LHDs shift time. The total tons of material hauled and the total waiting time of each LHD were recorded during each run. Figure 2 illustrates a haulage level created in the QUEST® simulation environment.

A standard for comparison was created by running the model for 80 hours of on shift time, with three LHDs operating in the system. This was used as a benchmark to which the test scenarios were compared. Presently, the model will be used to predict system behavior when the machines are running in second gear. As tele-operation technology evolves the model will be used to evaluate other systems such as automatic loading and dumping and even higher LHD tramming speeds in the haulage drifts.

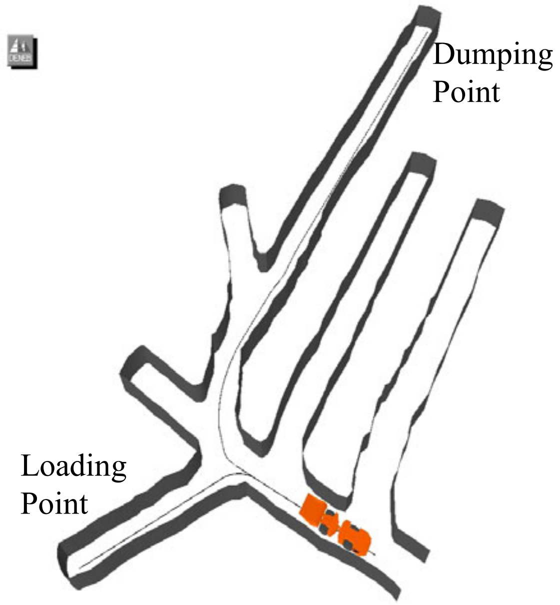

Figure 2: A haulage level as modelled in QUEST®

3 INPUT DATA AND ASSUMPTIONS

The input data for the simulation model was obtained from four areas. These included the LHD operators, Mines Engineering Department, LHD manufacturer product catalogues, and a database containing operating statistics for the LHDs.

Two-dimensional level plans for the haulage layouts were imported into the QUEST CAD environment, and the outlines of the drifts were extruded vertically to create three-dimensional drift walls, between which the LHD paths were constructed. From hard copies of the level plans, operators indicated the key areas where the LHDs were switched from automatic guidance to manual operation, loading and dumping points, and the areas where the LHDs change direction after backing out of the loading and dumping areas.

Since there were no time study data available for the LHDs working in these areas of the mine, the operating data for the LHDs were obtained from conversations with the operators and operators of similar equipment within the Mines Research group. Operators were asked to provide typical LHD loading and dumping times, as well as approximate speeds while tramming. The data was then used to create distributions that would best represent the times for the specific operations of the LHD. Any additional equipment data that was required, was retrieved from manufacturers product manuals. Table 1 indicates some of the key parameters of the simulation and their associated probability distributions.

Table 1: Key input parameters for the simulation model and their distributions

Variable Name	Distribution
Loading Time	Triangular
Dumping Time	Triangular
LHD Speeds	Constant
Bucket Factor - All LHDs	Uniform

To better represent reality, a uniform distribution was applied to the bucket factor in the model. This was determined from a bucket factor range estimated by the geologists. The bucket factor is the average tons of material hauled during each trip of the LHD. Normally a single bucket factor is used for a particular area where the LHDs are operating. In this case, a bucket factor of 10 was determined by geologists at the mine.

In most mining systems there is a considerable amount of human intervention, and this greatly increases the unpredictability of the system. To account for these extreme situations, a list of assumptions was compiled. All assumptions were discussed and verified with the operators at the mine, as well as system experts within the Mines Research. Some key assumptions are listed below.

- The speeds for each of the LHDs in first gear were determined from manufacturers specifications and discussions with the operators. Speeds in forward and reverse are assumed to be the same.
- Lunch breaks were not modelled as part of the simulation, as the operators tend to eat while the machines are tramming in automatic guidance, or waiting for the machine to be serviced.
- When there are two LHDs waiting for an operator, the operator will attend to the least utilized LHD first.
- If the shift should end before an LHD has reached its loading or dumping point, the LHD will remain in motion on the light rope until it reaches its destination. If it reaches the dump point, the operator will dump its bucket. If it reaches the loading point, it will wait until the next shift for the operator to start the loading operation.
- Time to maneuver in the loading and dumping areas is included in the loading and dumping times for the LHDs.
- The tons of ore loaded by each LHD (bucket factor) is assumed to follow the uniform probability distribution.
- Once an operator is loading or dumping an LHD, he will complete the operation before attending to another LHD in the system.

4 VERIFICATION AND VALIDATION

The model was verified using the debugging features within the QUEST software. On screen variable displays combined with the graphical displays of the elements' status, trace files, and interactive debugging provided a significant addition to the verification process. A final model walk through was performed to ensure that the model logic was correct.

Validation of the model was done using graphical and analytical techniques. The model was created to estimate the tons produced per shift and the waiting time for each LHD, with up to three LHDs operating at the same time. As no real life data was available for validating the waiting time of the LHDs, validation was performed by comparing the tons of material hauled by the LHDs during each shift. There were only five days during a month when three LHDs were operating at the same time, and it was rare if they were operating for the same length of time during each shift. Validation was performed by running the model for time periods corresponding to the actual times LHDs were operating during each shift. The production of each LHD in the model was compared to the actual production figures for that machine.

The analytical method used to validate the model was the paired-t approach (Law and Kelton 2000). The paired-t approach was used to create a single confidence interval using the data sets output from the model and the actual system. The results showed that the confidence interval created from the two data sets contained "0", indicating that statistically there is little difference in the data sets of the two systems. . The results of the paired-t validation approach are shown in Table 2, and Figure 3.

5 SIMULATION EXPERIMENT

Once validated, a benchmark for comparison was created by running the model for a simulated week or 80 hours of actual operating time, during which time all three LHDs were operating at speeds no higher than first gear. Multiple model runs were made to create an independent data sample. The speeds and the haulage distance of each of the LHDs of the benchmark are shown in Table 3.

To assess the productivity of the LHD system at higher tramming speeds, the simulation model was run for the same duration, and same number of replications as the benchmark, but with the LHDs given the ability to reach second gear speeds while under automatic guidance. Table 3 indicates the speeds associated with second gear operation.

Operating the LHDs in second gear provides an opportunity to potentially increase the production limits by allowing them to tram faster between the loading and dumping points. However, operating the equipment at higher speeds also has the potential of creating a bottleneck at the loading and dumping areas, as a single operator may not be able to manage the system of three LHDs effectively. If the operator is over utilized, this will be indicated by higher waiting times of the LHDs.

Table 2: Validation figures - Paired-t interval and 95% confidence interval

Sample Statistics (5 Independent Replications)	Tons Hauled Per Shift					
	LHD 1		LHD 2		LHD 3	
	Actual	Model	Actual	Model	Actual	Model
Mean (μ)	177	224.9	177	185.3	181	155.6
Standard Deviation (σ)	68	98.7	116	150.0	53	36.5
95% Confidence Interval	177±50.4	224.9±73.1	177±85.6	185.3±111.1	181±39.1	155.6±32.0
Paired-t Interval	[25.9,-121.5]		[37.0,-53.2]		[76.7,-25.1]	

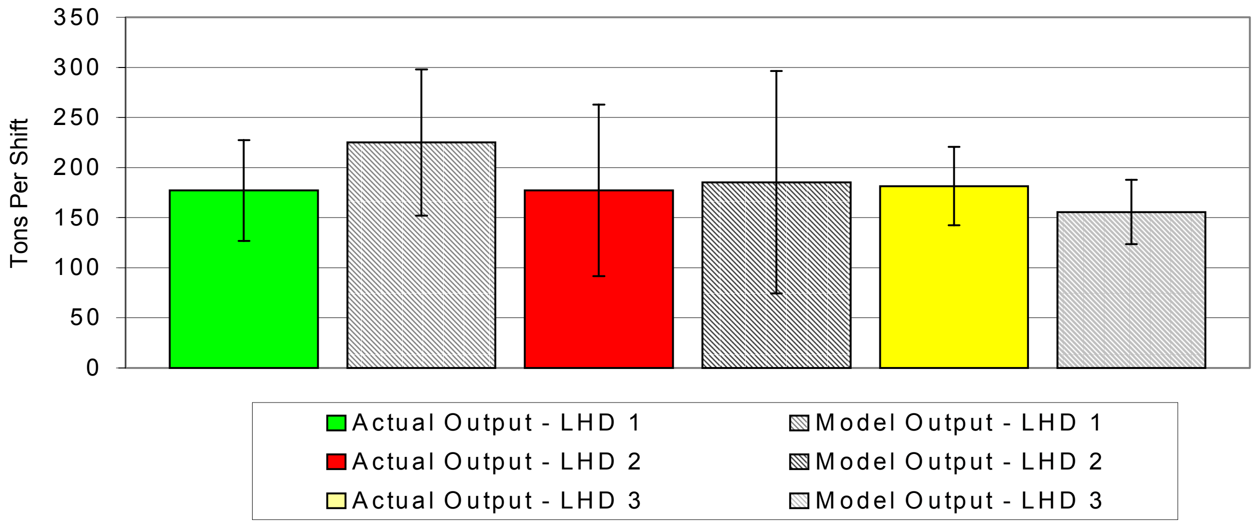

Figure 3: Model output versus actual system output - 95% confidence intervals

Table 3: Tramming distances and speeds for the benchmark system

LHD	Tramming Speed Forward and Reverse kph (mph)		One Way Tramming Distance meters (ft)
	1st Gear	2nd Gear	
LHD 1	5.6 (3.5)	10.5 (6.5)	114 (373)
LHD 2	4.7 (2.9)	8.0 (5.0)	97 (318)
LHD 3	5.0 (3.1)	9.0 (5.6)	136 (445)

6 RESULTS

The results of the study are shown in Tables 4 and 5, and Figures 4 and 5. The results indicate that an LHD system with three LHDs operating can achieve a mean throughput of approximately 1452 tons per shift while operating up to 7.5 hours per shift without interruption. The vertical lines on each bar in Figure 4 indicate the 95% confidence interval about the mean tons hauled per shift.

Tables 4 and 5 indicate that there is virtually no increase in the throughput of LHD 1 and 2 while running in second gear. The numbers also show an actual decrease in the mean production tonnage hauled by LHD 3. This is a clear indication that some of the tramming system variables have not be optimized for this particular scenario.

Table 4: 95% confidence interval for tons hauled by each LHD in the benchmark system

Sample Statistics	Tons Hauled Per Shift		
	LHD 1	LHD 2	LHD 3
Mean (μ)	487.0	495.1	469.4
St. Dev. (σ)	38.8	20.9	33.8
95% CI	487.0±34.0	495.1±18.3	469.4±29.7

It should also be noted that LHD 3 required the longest tram from the loading point to the dump area, and with a second gear speed of 5.0 kph (second fastest machine in the

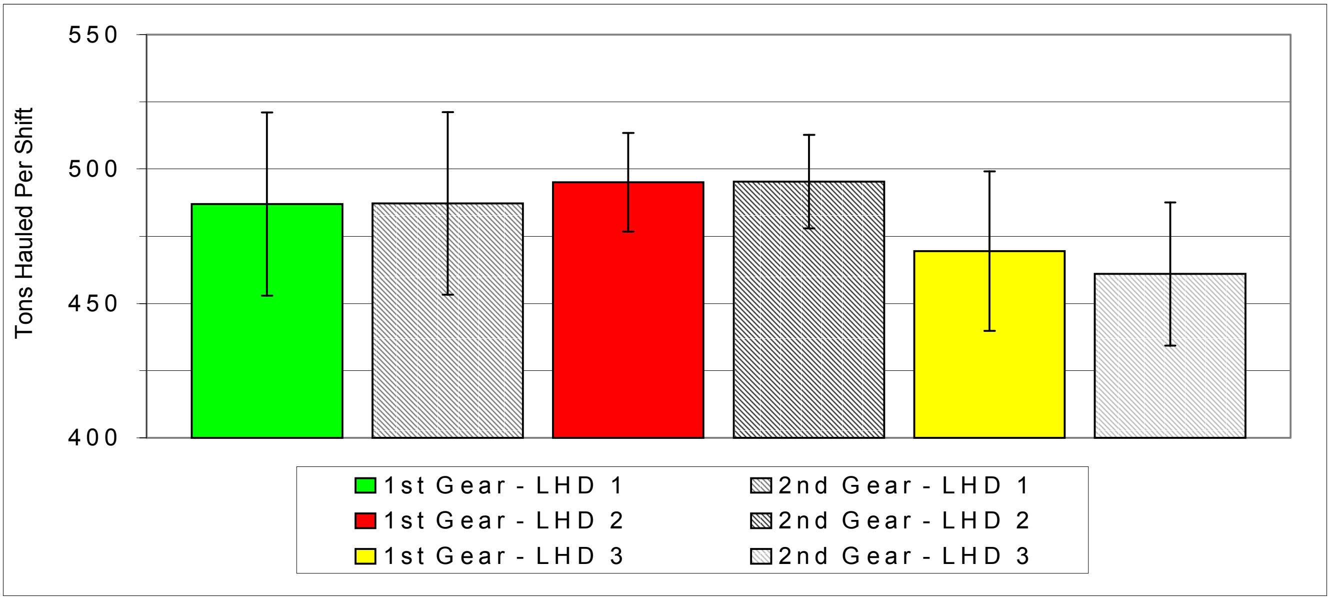

Figure 4: Tons hauled per shift 1st and 2nd gear - with 95% confidence interval

fleet), it spent the longest time in the busy tramming state. This shows that LHD 3 had the highest utilization, and therefore was the last machine to be loaded or dumped after the other lower utilized machines were attended to first.

Table 5: 95% confidence interval for tons hauled by each LHD operating in second gear

Sample Statistics	Tons Hauled Per Shift		
	LHD 1	LHD 2	LHD 3
Mean (μ)	487.2	495.3	461.0
St. Dev. (σ)	38.8	19.8	30.3
95% CI	487.2±34.0	495.3±17.4	461.0±26.6

In addition, the higher tramming rates for the LHD 1 and 2 revealed that these machines were requiring an operator attention more frequently (i.e. arriving at the end of the guidance path faster), and as a result the operator could not keep up with the demands of these LHDs.

The waiting times shown in Figure 5 and table 6 provide confirmation that all LHDs are experiencing longer waiting times while operating in second gear. Waiting time for the LHDs is an important indicator of the overall system performance. The longer the LHDs are waiting at the end of the light rope in the loading and dumping areas, the more likely the operator is over utilize, and unable to sustain the the level of performance required to keep three LHDs in a maximized productive state.

Table 6: Comparison of LHD waiting time for LHDs operating in first and second gear

	LHD Waiting Time (% of Total Operating Time)		
	LHD 1	LHD 2	LHD 3
1st Gear Operation	41.9	40.3	23.0
2nd Gear Operation	55.1	48.3	46.6
Percent Increase	32%	20%	102%

Further verification of higher waiting times and poor system productivity was seen in the model operator utilization, as operator utilization increased from approximately 90% in the benchmark to approximately 95% when the LHDs were operating in second gear.

As expected, the waiting times for each LHD increased. LHD 1's waiting time increased 32%, whereas the waiting time of LHD 2 increased 20%. The highest percent increase in waiting time occurred with LHD 3, at 102%.

In general, the increase in waiting time for each LHD is due to a combination of factors. The main factor is the length of the tram causing operator over utilization. All LHDs experienced excessive waiting times in the loading and dumping areas as a result of an operator not being ready to take over the machine functions once it reached the end of the light rope. The excessive waiting time demonstrated by the LHD 3 could also be attributed to the logic used in the model to determine which LHD is serviced first when multiple machines are waiting. The implemented logic in the model allowed the least utilized LHD to be serviced first. Since LHD 3 had the longest tram from the load area to the dump point, it spent the longest time in a utilized tramming

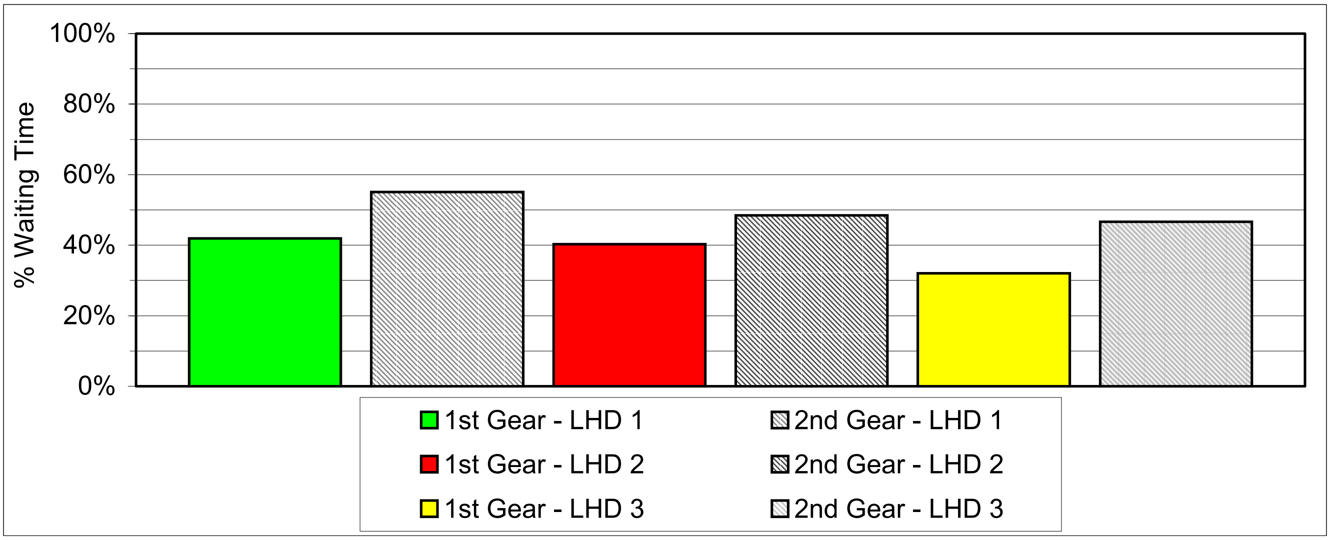

Figure 5: LHD waiting time as a percent of total operating time - 1st and 2nd gear operation

state on the light rope. This meant that once it reached its destination, it would be the last LHD to be moved off the light rope and loaded or dumped.

7 CONCLUSION

A single operator tele-remotely controlling a system of three LHDs can be very productive. This study indicates that to achieve higher productivity from a tele-remote multiple LHD system the following key parameters should be assessed.

- Tramming distance and LHD speed
- Haulage layout complexity
- Operator efficiency.

Multiple tele-remote LHDs operated at increased tramming speeds may not provide the benefits of higher production rates if the haulage system is not optimized to provide reasonable operator efficiency and reduced waiting times in the loading and dumping areas. This study has shown that higher tramming speeds can introduce longer waiting times for a system that is not designed to allow the LHDs to obtain maximum system productivity. To maximize system productivity the waiting time of each LHD must be minimized to allow the faster cycling of the machines from the loading and dump locations. Although a higher throughput can be achieved, tramming speed, tramming distance must be optimized to achieve benefits. Other factors will greatly effect the total system productivity, such as LHD and infrastructure reliability, mine delays and operator commitment. Further studies should be done to determine optimal tramming distance and system configuration.

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AUTHOR BIOGRAPHY

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