The impact of mining conditions on mechanized mining efficiency

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Synopsis

A maintenance and repair contract (MARC) provides the customer a zero risk opportunity to own and operate a fleet of mechanized equipment and guarantees the life and mechanical availability of the equipment on a cost per hour basis over the life of the machine.

One of the biggest challenges to any MARC contract is a change in the severity of the mining conditions. This has a two-pronged effect: one, the life of the components of the machines can be significantly reduced, causing components to fail prematurely. This increases the dealer cost of the contract to an amount higher than the guaranteed amount. Secondly, the customer will be affected by severe conditions underground by the loss of efficiency and ultimately productivity, which drives up the cost per ton of the operation. A negative spin-off of poor mining conditions is an increase in accident damage on mechanized machines. Therefore an increase in severity impacts on the machine cost per hour (affecting the dealer) and productivity decreases and increase in accident damage (affecting the customer) result in a lose-lose situation for both parties.

A severity index has been developed, strongly based on the Caterpillar Underground site severity index which looks at the impact of mining conditions on component life and 'derates' the life of the component accordingly. Although this is not new to the mining industry, the 'buy-in' from the customer and subsequent team-based approach by mining, engineering and the supplier to improve the severity is ground-breaking. This promotes a partnership approach to improving productivity whereby poor maintenance by the supplier or poor mining conditions result in penalties to the MARC contract. Most importantly, and an area that has turned out to be the biggest win-win of this exercise, is that on a monthly basis each MARC site is audited by a team comprising accountable mine personnel, ventilation, operator trainers and dealer personnel in a detailed, measurable audit that identifies and highlights areas that will result in productivity losses. Corrective action is put in place that can not only reduce the MARC rate over time, but also significantly improve productivity on the mine site.

Mining severity

Advances in technology in mining have resulted in general improvements in mining conditions, especially in the fields of ventilation, mechanized mining equipment and drilling and blasting techniques. Unfortunately, many of the operating mines are designed around less efficient technologies such as handheld drilling resulting in irregular tunnel dimensions, uneven footwall conditions and poor fragmentation in drawpoints. Despite improvements over the past few years, many mining methods require operating in areas where established workshops are located far away from the production environment.

Mining severity can be described as any conditions underground that may result in a reduction in safe working conditions, decrease in productivity or reduction in machine life. By addressing these issues and improving the availability and utilization of the mechanized mining equipment, there can be significant improvements in productivity and ultimately a reduction in overall cost per ton.

Accident damage caused as a result of mining conditions and operator in efficiency is an often controversial and relationship damaging spin-off in any MARC contract. For example, an early life failure on a component such as an axle could be attributed to operating in extreme conditions, or could be as a result of product defect or poor maintenance practice. Therefore in order to minimize confrontation, all areas affecting on accident damage are covered in the severity audit.

Some common conditions affecting on poor equipment performance are as follows:

- *Workshops*—size, location, tooling, lighting, drainage, contamination control
- *Ventilation*—cooling, visibility, operator efficiency
- *Haulages*—dimensions, clearance, obstructions, footwall, drainage, water, gradients
- *Haul distance*—drawpoint to tip, ramp tramming
- *Maintenance practice*—planning, mechanical skills, servicing on time, fluid analysis

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- *Operator efficiency*—training, motivation, salary, incentives.

One of the challenges in determining mining severity is the divergence between engineering, mining and suppliers. Clearly suppliers and engineering departments understand the relevance of timely and regular planned maintenance on the machines, whereas disparity between a supplier and engineering occurs in underground transport and cage and shaft delays. Mining and engineering departments have been incompatible since the dawn of mining. Production at all costs from mining personnel clashes with scheduled maintenance of machines, while shaft schedules often obstruct critical men and material transport for optimizing production. Fortunately, through teamwork and communication many of these obstacles can be overcome with the overriding intent to produce a ton of ore at the lowest possible cost. This should be the principal focus in implementing a severity audit process in a mining operation.

The key issues above affect in different ways the major components of a machine and this relationship between general severity factors and explicit factors affecting specific parts of the machine are discussed in more detail in the following sections.

Calculation of a MARC rate

Before analysing the calculation of a MARC rate, it is necessary to determine why a mining customer would outsource the management of mechanized equipment to an original equipment manufacturer (OEM). In essence the MARC contract offers a zero-risk option for customers whereby an OEM will guarantee the maintenance and repair rate on an hourly basis over the life of the machine. Generally measured in hours, the MARC contract in an underground environment can run from 27000–30000 hours. A guaranteed hourly rate enables the customer to track cash flows on mechanized equipment (often a significant contributor to overall mining operational costs) over the equipment life. From an OEM perspective, guaranteeing the cost per hour and ultimately carrying all the risk of early life component failures, the trade-off is a captured parts market share on the contracts and, depending upon performance, increased machine market share. In terms of a typical MARC contract, the overall billed revenue of a MARC contract for a single machine could be in the region 3.5:1, maintenance cost: initial capital purchase.

The determination of a MARC rate is a structured process, with two major factors affecting on the overall rate. Firstly software is used to build up a price file for the specific machine from base principles using individual part numbers.

In order to provide the most benefit to the customer, all major components are priced according to world class benchmarks before failure. This ratio is 80% of all components failing before failure, 20% after failure. In other words the OEM will guarantee that 80% of all components will be changed out at end of life before failure, with the remaining 20% after failure repairs. The advantage to the customer of this ratio is that the cost of a before failure repair is typically 60–70% of an after failure repair as Figure 2 indicates.

In terms of a \$50 000 engine, a before failure saving incorporated into the MARC rate would indicate significant savings over the life of the MARC contract. In this case, two engines would indicate a saving of \$20000–\$30000 over a 30 000 hour period, or \$1 per hour. Taking the transmission, torque converter, final drives and engine into account, this could relate into a cost per hour saving of upwards of \$6–10 per hour. The challenge for the OEM is to ensure that this ratio is maintained, as anything less than achieving the 80% target will result in additional costs against the contract for the OEM account. Compared this to the overall revenue, this could constitute an additional 23% of costs attributable to the OEM, whereby machine costs exceeding revenue earned result in a loss situation.

The second focus of building a MARC rate is to identify the planned component life and severity the machine will go through during its life. The component life calculation is estimated from historical data, experience from similar operations and CAT data sheets. Once a component life is estimated, this forms an essential part of the MARC rate. An incorrect estimation at this stage can result in huge cost overruns and large liability for the OEM. For example, a rear axle planned to last 8 000 hours between change-outs will require one change out in 15 000 hours. Therefore a budget of \$20 000 would be inserted into the cost build-up, which is a before failure change-out. If the component life lasts only 6 000 hours, then this will result in two axle change outs as opposed to a single change-out, or an additional \$20 000 unbudgeted, resulting in \$1.33 per hour. To amplify this potential loss situation, if the axle lasts 6 000 hours and experiences a catastrophic failure, then the repair cost could be doubled, equating to \$2.60 per hour.

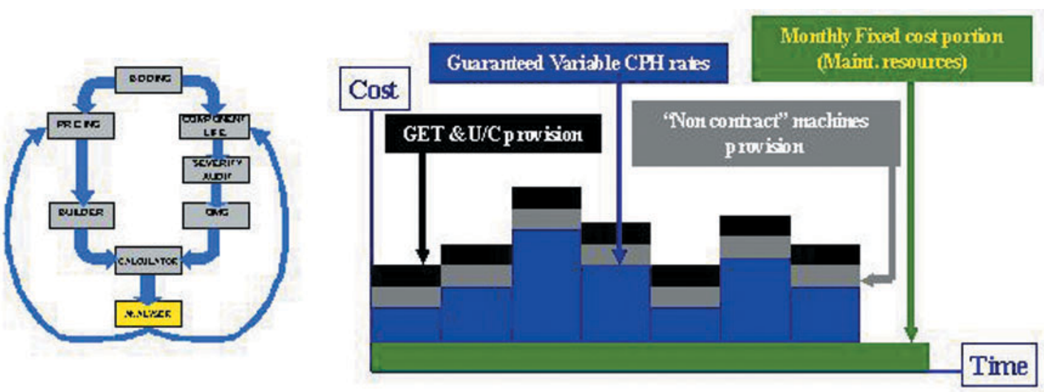


Figure 1—MARC rate build process

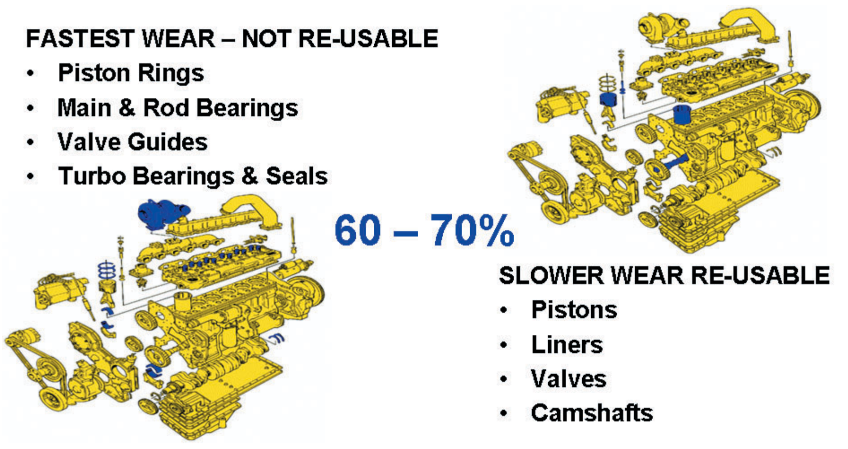


Figure 2—Predictive component failure

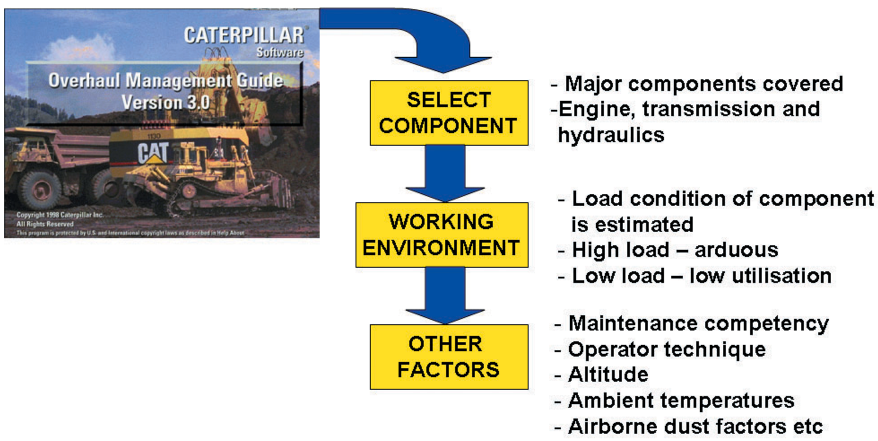


Figure 3—Component life forecasting tool

While these amounts may appear insignificant in isolation, fleets of 30–40 machines poorly managed, where components fail prematurely can result in deficits against initial budget of up to $1.5 million or more. This liability is heightened on larger surface machines and larger fleets. If, as discussed, the strategic aim of a MARC contract is to offer a guaranteed hourly rate over the machine life, the reputation and balance sheet of the OEM can be seriously affected

So, how do we accurately predict component life? Tools for predicting the severity of the mining conditions are used up front to determine whether the historical component life will be attained. (See Figure 3.)

Time taken up front to determine accurate rates is all too often neglected or subsidized to win new business, a mistake that will live with the OEM for the extent of the MARC contract.

In the case of a greenfield operation, estimating severity remains a theoretical exercise, whereas in an existing or brownfield operation this can be determined more accurately. Unfortunately mining is dynamic and, depending upon commodity prices and cut-off grades, often dictates moving into previously mined areas as do certain mining methods, cut and fill, VCR, etc. As in opencast mining, the longer the contract extends the greater the depth of the operation and usually the distance away from the workshops, and this is normally not taken into account when calculating a MARC rate.

While MARC rates are calculated on a cost per hour basis, these operational costs can be transformed into a productivity measure, such as cost per ton. This cost per ton measure, as will be proved later on in this paper, is significantly affected by factors such as payload (linked to fragmentation), operator efficiency and cycle times as opposed to the more frequently measured factors such as oil consumption, up-front capital cost and MARC repair rates. In an attempt to prove this, the last section in this paper looks at a sensitivity analysis on a typical underground haul profile. These productivity measures discussed above are all linked to mine severity and therefore the identification and rectifying of some of the mine severity factors will result in better productivity. With OEMs being paid on machine utilization, in other words engine operating hours, it is in the interests of all partners to improve the productivity. The increase in machine operating hours, providing that the machine is used within design parameters, offers additional turnover on the OEM MARC contract and an exponential increase in terms of tons of rock moved.

Severity audit—a measurement tool

Severity audits are not a recent invention. Original equipment manufacturers have long recognized the link between extreme mining conditions and lower productivity. In most cases, particularly in Africa, there is a resistance to recognition of the production capability of the machine versus the capital outlay of the equipment. This is partly due to the fact that there are very few instances where machines are operated to design parameters in terms of tons per hour capability and also a misunderstanding of the link and subsequent efficiency improvements between cost and productivity. It is the responsibility of any OEM to try to assist the mine in improving the uptime, or availability and reliability (mean time between failure and mean time to repair) of the machine as part of the contractual conditions of any MARC contract. The logical path to this, however, is very often less travelled and this is for the OEM to assist in identifying and mitigating the risks in obstacles outside of the repair and maintenance arena to improving productivity.

The severity audit tool is a natural progression of this and this is where the value add of this whole process comes into play. The audit is separated into three main areas:

- Workshops
- General operating factors
- Component operating factors.

General operating factors are the ambient mining conditions affecting the overall potential to reduce productivity, whereas component operating factors look at specific mining severity that has an impact on the major components of the machines, namely:

- Engine
- Torque converter/transmission
- Axles, differentials, final drives, frame, brakes
- Hydraulic system.

The process followed by the severity audit is shown in Figure 4.

Selecting an audit team

If the ultimate aim of the severity review is to strengthen a partnership between OEM and customer, then the audit team should be representative of all stakeholders. The mix of the team will determine the buy-in with the audit and this is the critical issue. A typical team will be made up of the following:

- Independent team leader
- OEM—fleet manager, supervisor/foreman, operator trainer
- Customer—engineer, underground manager, shift boss.

The function of the independent auditor is as an arbitrator on contentious issues and to maintain consistency between contracts and audit periods. The buy-in from the OEM in understanding the impact the maintenance practice has on component life and the customer between engineering and mining is value add. The feedback session after the audit where the scores are collated is used as a means to set action plans to rectify some of the critical areas before the next audit.

Audit report—LHD and trucks

The severity questionnaire is an important part of the process; in order to ensure consistency the results must be measurable and consistent both between mining current operations and subsequent studies. This measurability is critical especially when the results affect the bottom line.

Figure 5 lists a sample of questions, with easily measurable answers that require proven answers. In the scaled scorecard a low score indicates a conformation to world class standard, while a high score signifies a definite impact on component life. High scores of 8 or more indicate areas that contribute strongly towards a derated component life. Negative numbers relate to areas whereby the OEM is penalized for poor maintenance practice.

A total of 79 questions per working area results in a large scoring matrix, depending upon the size of the mine being audited. This scoring matrix forms the basis of the results calculation.

The scorecard (Figure 6) is from a recent severity audit. The Mine Area indicates separate areas where machines are operating and would have to be measured against all 79 questions. Item 1 indicates that the maximum derate points allowed by this section is 50 points. Any score higher than this defaults to 50 points. In this case areas with points of 90—100 require a significant amount of effort to bring the workshop conditions back in line. The audit maximum of 50 indicates that an absence of any workshop in a specific mining area will have a finite impact on component severity. The challenge from a customer perspective is to focus on the high numbers, in this case highlighted in yellow to reduce this significantly.

Subsequent sections will be audited and scored in the same way. This score sheet is checked and verified by the audit team and signed off. Any disputes at this stage are arbitrated by the independent auditor.

The score summary, extracted from the scoring matrix highlights the overall derate for the mine being audited.

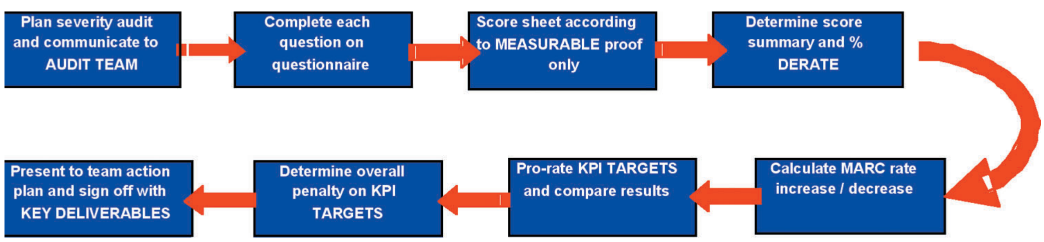


Figure 4—Severity audit implementation process

Severity Audit criteria and scores - LHD'S

1. Workshops	
1.1 CONCRETE FLOORING	
The workshop has a solid concrete floor with drainage built to equipment specifications	
Level concrete floor over full workshop area, with drainage meets all specifications	0
Level concrete floor over full workshop area but only drainage in pit/ramp area	2
Damaged concrete flooring with standing water	4
No concrete floor, but firm footwall and no standing water	6
No concrete, thick mud, no drainage	8
1.2 INGRESS / EGRESS / ESCAPE ROUTES	
The workshop has more than one entry/exit point for ease of machine maneuvering and safety in case of an underground fire	
Separate equipment workshop ingress and egress available, both well marked and lit up	0
Separate equipment workshop ingress and egress available but entrance/exit areas not clearly marked or poor lighting	2
Single access only, no alternative escape route available and machines must reverse out of workshops	4
Single cubby work area, no actual workshop available	8
1.3 PIT/RAMP	
The workshop consists of a pit or ramp that is suitable for the size of machines being worked on	
Pit/ramp is solidly constructed, with good access onto the pit/ramp, adequate lighting and easy access into and out of the pit. Pit has good drainage for removal of debris and oil. Adequate clearance above pit for removal of major components	0
Pit/ramp is solidly constructed with good access, inadequate drainage or means to clear debris from the pit,	2
Clearance to hanging wall too low to remove large components efficiently	4
No pit/ramp in place, no means of working under machine	8

Figure 5—Severity audit questionnaire—workshops

	DESCRIPTION	MAX POINTS	Mine area 2000L LEVEL North	2100L LEVEL North	2500 LEVEL North	2500 LEVEL South	3000 LEVEL South	3000 LEVEL NORTH	3000 LEVEL 3360	1500 LEVEL North	
1	WORKSHOPS 1	50	47	50	50	50	50	50	43	50	2
		Total	47	64	53	106	104	96	43	110	
1.1	Concrete flooring		0	0	0	8	8	8	0	8	
1.2	Means of egress & ingress		2	2	2	4	4	4	2	4	
1.3	Pit or ramp		0	8	4	8	8	4	4	8	
1.4	Number of units per pit/ramp		0	0	0	4	4	0	0	4	
1.5	Oil dispensing facility (contamination free)		8	8	8	8	8	8	8	8	
1.6	Overhead lifting equipment (certified) where required		2	4	4	8	8	8	4	8	
1.7	Adequate lightning in working areas		0	0	0	8	8	4	1	8	
1.8	Pressurized water and separate wash bay		4	4	0	4	4	4	0	4	
1.9	Compressed air available		0	0	1	4	4	4	1	4	
1.10	Lock up facilities for tooling, spares and documents		1	8	1	8	8	8	1	8	
1.11	Electricity to handle welding equipment and electrical tools		2	2	1	4	4	4	2	4	
1.12	Underground communications to workshop		2	2	2	4	4	4	0	4	
1.13	Fuel dispensing equipment (contamination free)		4	4	8	8	8	8	0	8	
1.14	Noise level signage		2	2	2	4	2	4	0	2	
1.15	Suitable tools available		-2	-2	-2	-2	-2	-2	-2	4	
1.16	Workshop equipment available		2	2	2	4	4	2	2	4	
1.17	Welding bay (fully equipped)		4	4	4	4	4	4	4	4	
1.18	Workshop ventilation/ambiant temperature conditions		4	4	4	4	4	8	4	4	
1.19	Gas cylinder storage		4	4	4	4	4	4	4	4	
1.2	Waste oil management		8	8	8	8	8	8	8	8	

Figure 6—Score sheet for workshops section

In Figure 7, the first two rows highlight the scores achieved in the overall general operating conditions. The maximum score is averaged across the mining areas to a maximum of 5% for each category.

Maximum scores in each of the component operating conditions are as follows:

- ➤ Engine 20%
- ➤ Transmission / torque converter 20%
- ➤ Axle, diffs, final drives, frames 40%
- ➤ Hydraulic system 10%.

This, added to general operating conditions (5%) and workshop conditions (5%) makes up the total scoring system.

General operating conditions affect all component operating areas as can be seen from Figure 7. The result relates to a total derate of 25% on the overall audit. The results sheet in Figure 8 is fairly complex and looks at a number of measurable key performance indicators (KPIs) defined by contractual targets on the MARC site. These are jointly agreed upon and measured as part of the audit.

The final section analyses the impact of severity on the overall MARC rate as well as the impact on KPIs and subsequent penalties against the OEM for not achieving adjusted contractual targets.

In the matrix in Figure 8, numbered icons highlight some of the salient points. These are discussed in more detail below.

SCORE SUMMARY FOR LHD'S AND DUMP TRUCKS

GENERAL OPERATING CONDITIONS	GENERAL
WORKSHOPS	5%
GENERAL OPERATING FACTORS	5%
TOTAL	10%

COMPONENT OPERATING CONDITIONS	COMPONENT	GENERAL	TOTAL
ENGINE OPERATING FACTORS	8%	10%	18%
TORQUE CONVERTER / TRANSMISSION OPERATING FACTORS	16%	10%	26%
AXLE, DIFFERENTIALS, FINAL DRIVES, FRAMES, BRAKES	26%	10%	36%
HYDRAULIC SYSTEM OPERATING FACTORS	10%	10%	20%
	AVERAGE REDUCTION IN LIFE		25%

Figure 7—Scoring summary per component

MARC RATE ADJUSTMENT CALCULATION

1

	US$/hr
Existing MARC rate	30.00
Derate percentage	24.75%
MARC rate change (%)	14.75%
New MARC rate	34.43

2

DERATE PERCENTAGE	MARC ADJUST
-30.0%	-30.0%
-20.0%	-20.0%
-10.0%	-10.0%
0.0%	0.0%
10.0%	5.0%
20.0%	10.0%
30.0%	20.0%
40.0%	30.0%

Penalty calculation

KPI / KPA	BASE TARGET	3 DERATE FACTOR	4 WEIGHT %	5 ADJUSTED TARGET	6 ACTUAL ACHIEVED	7 % ACHIEVED	8 PENALTY/ BONUS	9 WEIGHTED PENALTY/BONUS
AVAILABILITY	85%	25%	30%	64%	90%	40.8%	28%	8.4%
OIL CONSUMPTION	2.5	25%	10%	3.12	2.5	20%	2%	0.2%
MTBF	45	25%	30%	33.84	110	225%	20%	6.0%
MTTR	4	25%	30%	4.99	6	-20%	-2%	-0.6%
							Penalty	0.0%

BONUS / PENALTY RATE TABLES

AVAILABILITY

DEVIATION %	PENALTY
0%	0%
1%	1%
2%	2%
3%	4%
4%	6%
5%	8%
6%	10%
7%	12%
8%	14%
9%	16%
10%	18%
15%	20%
20%	22%
25%	24%
30%	26%
35%	28%

OIL CONS. / MTBF / MTTR

DEVIATION %	PENALTY /
0%	1%
11%	2%
21%	4%
31%	6%
41%	8%
51%	10%
61%	12%
71%	14%
81%	16%
91%	18%
100%	20%

Figure 8—Final derate, KPI and penalty tables

Machine Life	30,000
Derate %	19%
Baseline %	0%

				COMPONENT DERATE @ 19%			COMPONENT BASELINE LCC		
Comp code	Engine	Budget (US$) per change out	Component Life budget	Comp life decrease	Change-outs over life	Cost	Comp life decrease	Change-outs over life	Cost
1000	Engine	0.00	15,000.00	12195	2	-	15000	2	-
1052	Turbocharger	3700.00	12,000.00	9756	3	11,100	12000	2	7,400
1062	Muffler	0.00	15,000.00	12195	2	-	15000	2	-
1100	Cylinder Head Assembly	0.00	7,500.00	6097.5	4	-	7500	4	-
1250	Fuelsystem	0.00	2,500.00	2032.5	14	-	2500	12	-
1254	Fuel Injection Valve/nozzle	10708.00	12,000.00	9756	3	32,124	12000	2	21,416
1256	Fuel Transfer Pump	0.00	2,500.00	2032.5	14	-	2500	12	-
1350	Cooling System	0.00	2,500.00	2032.5	14	-	2500	12	-
1353	Radiator	0.00	15,000.00	12195	2	-	15000	2	-
1355	Thermostat/Water Temperature Regulator	600.00	4,001.00	3252.813	9	5,400	4001	7	4,200
1357	V-Belt(S)	395.00	4,000.00	3252	9	3,555	4000	7	2,765
1361	Water Pump	2458.00	12,000.00	9756	3	7,374	12000	2	4,916
1400	Electric System	0.00	5,000.00	4065	7	-	5000	6	-
1401	Battery	324.00	4,000.00	3252	9	2,916	4000	7	2,268
1405	Alternator	2276.00	4,000.00	3252	9	20,484	4000	7	15,932
1453	Electric Starting Motor	2011.00	4,000.00	3252	9	18,099	4000	7	14,077

Figure 9—LCC component cost derate table

- ➤ The score summary in the top left-hand corner brings in the derate percentage from the score summary sheet. This is compared to the MARC rate adjustment matrix (highlighted by the arrow) and then extrapolated to the exact percentage increase. For example, a derate percentage of 24.8% equates to a MARC rate increase percentage of 14.75%.
- ➤ The critical table in this calculation links the derate percentage to the MARC rate adjustment column. This is a scientific exercise based upon the cost build (or life cycle cost, LCC) of the major components over the life of the machine. As discussed earlier, LCCs are built from part numbers and each part is afforded a component life. Therefore it is easy to calculate the value of all parts and components used over the machine life. If the overall cost is understood, then the derate percentage calculates that the percentage life of the component is reduced due to mining conditions and therefore costs will increase. The tablein Figure 9attempts to highlight this.

  In Figure 9, only the main engine headings have been calculated. The component derate percentage of 19% will result in a reduction in component life as per the budgeted parts costs on the contract. Measured against the baseline (in the far right column) the number of component change-outs and the overall cost are indicated.

  By summarizing this for all major components depending upon the derate percentages, a new MARC rate can be calculated. (Figure 10.)

  By running a number of scenarios, the MARC adjustment (Figure 8) table was put together for ease of audit reconciliation.
- ➤ The KPIs are listed and measured as per the contractual targets. These are considered essential indicators of machine reliability and performance.
- ➤ The derate factor of 25% (scaled up from 24.75%) reduces the targets to a new target. This implies that an increase in mining severity may indicate a tougher target to meet original contractual targets. Therefore in this case, availability has been derated from 85% contractual target to 64%. Calculation is 85%–(85% x 25%)
- ➤ The weighting indicates the importance of the KPI in terms machine reliability. The weighting and KPIs are negotiated by the team members and form an important part of the partnership dynamics.
- ➤ The adjusted target is the measure to which the penalties are calculated from.
- ➤ Actual performance indicates the monthly performance achieved by the MARC site and is a good measure of OEM performance despite severity conditions.
- ➤ The percentage achieved column compares actual with target (actual / target) % and using the penalty tables determines whether any penalties on the KPIs need to be included.
- ➤ These penalty percentages are multiplied by the weighting to finally determine the penalty.

In this example the machines performed above KPI adjusted targets and therefore attracted no penalty.

LHD—MARC rate adjustment	
Engine	101 052.00
Power train	181 510.59
Drive train	122 099.47
Hydraulics	57 522.05
Implements	317 973.17
Machine	213 253.88
Total	993 411.16
Cost per hour	**33.11**

Figure 10—Final MARC rate adjustment on overall LCC rate

Impact of site severity on machine productivity

The first part of this paper identified a method of determining the severity of the mining conditions when compared to component life. This increase in severity does not take into account the improvements in productivity that can be achieved as working conditions improve.

This section analyses the relationship between mining conditions and productivity improvements. In order to ascertain how severity affects the productivity of a machine, Caterpillar software was used to determine a number of real-life scenarios found in most underground mining environments. From this a sensitivity analysis was carried out to determine an increase/decrease in productivity due to severity.

Major areas looked at were as follows:

- *Tramming distances*—excess of 300 metres (round trip)
- *Bucket fill factors*—< 90%
- *Tunnel dimension, roadway conditions*—measured by limiting loader speed
- *Operator efficiency*—measured in utilized time per hour.

A typical underground mining operation set-up, drawpoint to tip arrangement was used as an example. A 10 t capacity underground loader was used, with the following parameters:

Machine type:	10 t capacity front end loader	
Target availability:	85%	
Load time:	20 seconds	
Hours per annum:	8760 (equates to 24 x 7 operation	
Haul road profile:	Drawpoint to crosscut	25 metres
	Cross-cut	100 metres
	Cross-cut to tip	25 metres
	Total haul (one way)	150 metres
	Total cycle	**300 metres**
Material:	Loose density = 1 900 kg/m^3	
	Bank density = 2 700 kg/m^3	
Cycle time:	Load with exchange	0.50 minutes
	Haul (loaded)	0.73 minutes
	Dump and maneuver	0.30 minutes
	Return (empty)	0.73 minutes
	Total cycle time	**2.26 minutes**
Fill factor:	95% of overall SAE rated capacity	
Operator efficiency:	83% (calculated as operating 50 minutes in every hour, or 20 hours per day)	
Production per hour:	159 tons per hour (based upon above assumption)	

This set-up above lists a good underground set-up, good underfoot conditions with attainable underground speeds of 10 km/h in drawpoints and cross-cuts. This equates to the machine able to operate at all times in second/third gear.

From the theoretical analysis, production studies as part of the results from the severity audits can be input into the same model (assuming that the haul distances are modelled on the actual underground conditions).

The following example takes the above haul profile, machine and availability profiles and actual underground utilization figures to determine the current production output.

Cycle time	Load with exchange	0.70 minutes[1]
	Haul (loaded)	1.25 minutes
	Dump and maneuver	0.30 minutes

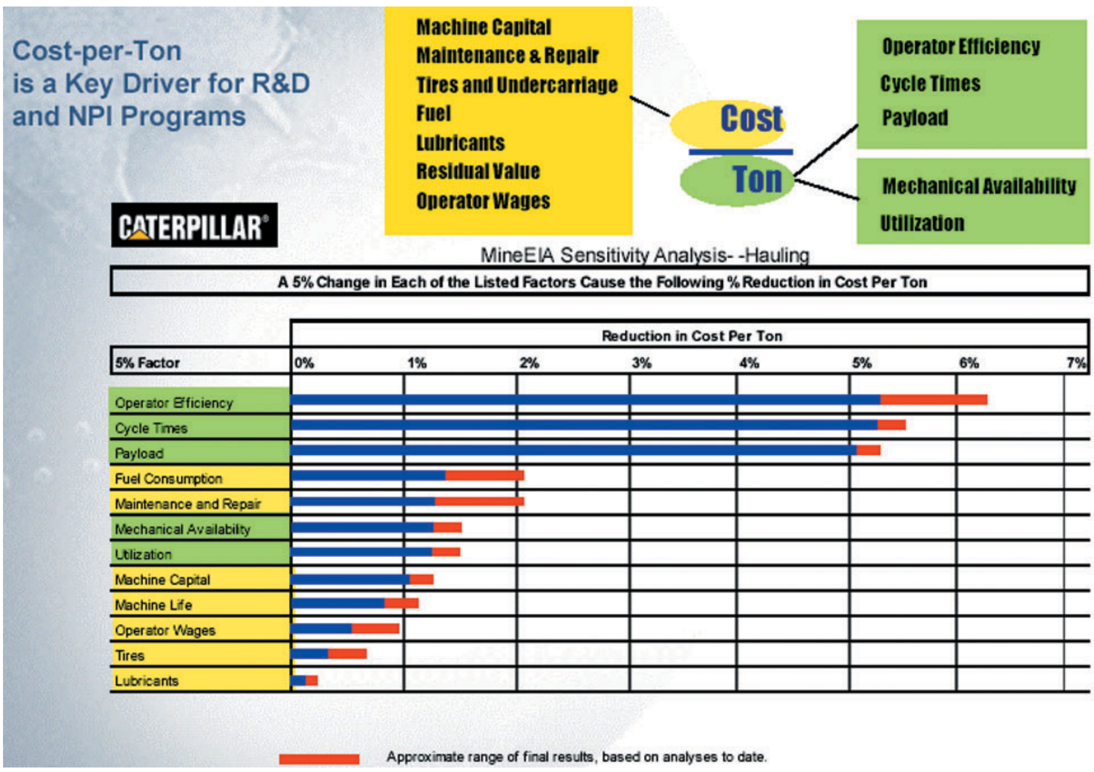


Figure 11—Cost per ton relationship on productivity improvement

	Return (empty)	1.25 minutes
	Total cycle time	3.50 minutes
Fill factor:	95% of overall SAE rated capacity	
Operator efficiency:	67% (calculated as operating 40 minutes in every hour, or 16 hours utilization per day)	
Production per hour:	83 tons per hour (based upon above assumptions)	

[1]Increased load time due to poor fragmentation

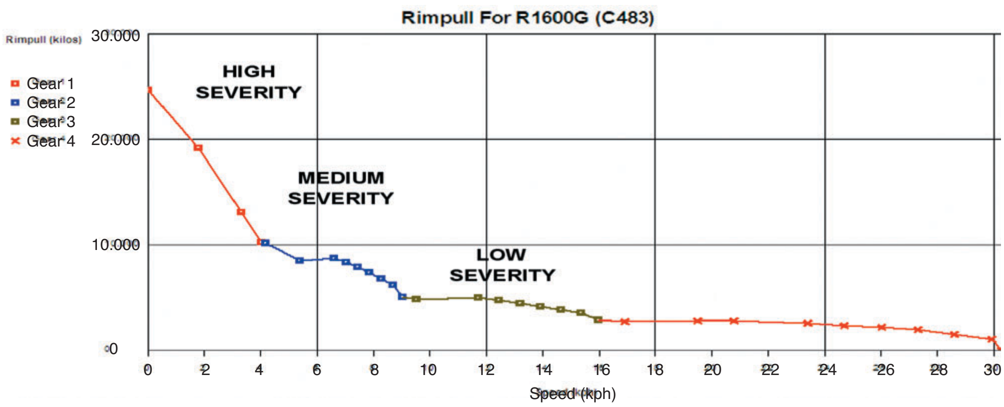
In this example, the productivity has almost halved by changing the roadways to realistic underground conditions and changing utilization from 20 hours to 16 hours per 24 hour period. By careful collaboration, these areas are simple to look at and rectify, thus significantly increasing the efficiency of the operation. This example indicates that one loader can mine the same tonnage in this operation that would normally require two loaders working solely due to mining condition.

Sensitivity analysis

By taking the base case productivity scenario of 159 tons per hour, the following section identifies areas of severity and the subsequent impact on productivity. Through hundreds of production studies, a generic scorecard has been produced by Caterpillar that examines the relationship between costs and tonnages. What this exercise will show is that the often fanatical focus on input costs such as machine pricing, repair rate, and oil consumption, all too often neglects the productivity measures such as operator efficiency and cycle times (affected by road conditions) that have a major impact on productivity improvement. (Figure 11.)

This section examines the sensitivity of a number of input conditions on productivity using the same parameters as the base case example. Parameters looked at are

- Poor roadway conditions (affecting cycle time)
- Operator efficiency
- Mechanical availability.



Severity	Maximum Gear	Cycle time (mins)	Payload capacity	Operator efficiency	Tonnes annually	Annual loader cost ($US)	Cost per ton ($US)	% increase cost/t
Base case	3rd - 10 km/hr	2.26	95%	83%	1,378,674	$ 309,009	0.22	
Moderate severity	2nd - 8 km/hr	3.29	95%	83%	716,327	$ 309,009	0.43	92%
High severity	1st - 4 km/hr	5.52	95%	83%	571,433	$ 309,009	0.54	141%

Figure 12—Cost per ton v s.haulage conditions

Severity	Utilisation per 24 hours	Operator efficiency	Cycle time (mins)	Payload capacity	Tonnes annually	Annual loader cost ($US)	Cost per ton ($US)	% increase cost/t
Base case	20	83%	2.26	95%	1,378,674	$ 309,009	0.22	
Moderate severity	19	78%	2.26	95%	1,295,621	$ 309,009	0.24	6%
High severity	18	73%	2.26	95%	1,212,568	$ 309,009	0.25	7%

Figure 13—Cost per ton v s.operator efficiency

Severity	Available % per 24 hours	Cycle time (mins)	Payload capacity	Tonnes annually	Annual loader cost ($US)	Cost per ton ($US)	% increase cost/t
Base case	85%	2.26	95%	1,378,674	$ 283,608	0.206	
Moderate severity	80%	2.26	95%	1,297,575	$ 270,109	0.208	1%
High severity	75%	2.26	95%	1,216,417	$ 270,114	0.222	8%

Figure 14—Cost per ton v s.mechanical availability

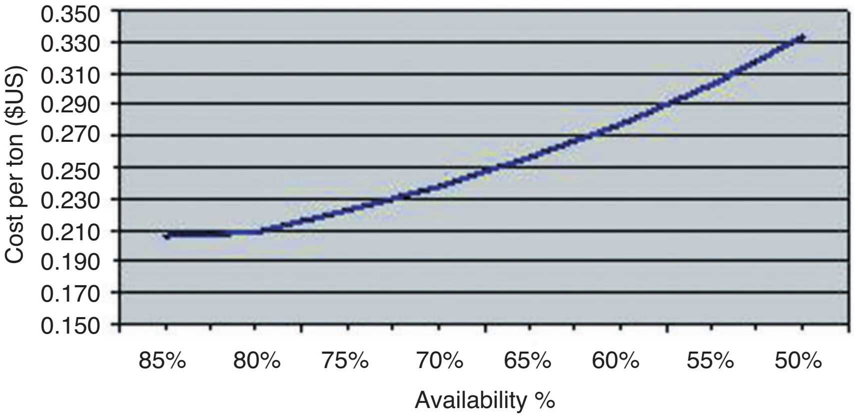


Figure 15–Impact of poor availability on cost per ton

In each of the following examples (Figures 12 to 14.), the tonnage moved during the year is calculated by one loader and compared to a cost per ton. Assume that the overall operating cost of the loader is $50 per hour.

Roadway conditions

As can be seen in Figure 12, cost per ton is doubled due to roadway conditions. Commonly machines operate in first gear due to road conditions. Areas for improvement in roadways are relatively straightforward and involve operator discipline (clearing rocks), good development drilling and blasting (footwall conditions) and good road maintenance (drainage, fines for road repairs, lighting).

Operator efficiency

Operator efficiency is affected by shift change times, operators taking time to carry out daily checks and congestion in loading areas with personnel, other units and poor ventilation and lighting. Once again, as part of a partnership approach focus on 'hot-seat' change-outs, reduction in preshift check times (auto-greasing systems, dual fuel tanks) and operator motivation all contribute to improving operator production time. (Figure 13.)

Mechanical availability

As can be seen in Figure 14, availability has approximately 1% decrease in overall cost per ton for a 5% change in availability. However, it is clear as the Figure 15 shows that this relationship becomes severe as availability declines.

Conclusion

There is no doubt that undertaking a MARC contract requires an 'eyes wide open' approach. Managed correctly, with buy-in from a customer who understands that the risk of failure is carried primarily by the OEM, it will result in higher rewards.

The most successful MARC contracts have been managed using a transparent, open-book partnership approach measuring common key performance indicators linked to the partnerships common goals.

Severity in underground mining conditions plays a major role in determining the extent of this win-win. Through teamwork and by using a scientific, documented process, targeted improvements in underground mining conditions will lead to the ultimate objective in the partnership, lowering the cost per ton of ore produced.

Success to date has been achieved by adopting an open-book approach, with a recommended action plan to reduce mining severity and thus MARC rates. Monitoring of productivity improvements through cost per ton analysis will be the ultimate driver of the success of this model.

Acknowledgements

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All productivity analysis, LCC calculations and proprietary software remain the exclusive property of Caterpillar Inc.

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