Autonomous Swarm Haulage:
The Economics of Autonomous Haulage with Small Trucks

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SUMMARY

This case study compares the economics of autonomous haulage in a mining operation that utilizes medium-sized rigid haul trucks against an operation that uses small vocational haul trucks. The economic assessment is based on a fictional, but realistic mining operation.

A base case mining operation was defined comprising a North American setting, a simple resource model, a three-phase open-pit, a site road network and processing plant. Whittle Consulting's schedule optimizer *Prober* was used to produce an optimal life-of-mine (LOM) schedule and Net Present Value (NPV). The core of the study involved a complex mining model encompassing physical movements and costings. To understand queuing and congestion behavior, physical truck and shovel movements were modelled in a discrete event simulator package, MineTwin™, based on agreed parameters including speeds and event probabilities. The results of this were then generalized for use in Prober's strategic LOM optimization. In the haul network examined, there was not a large difference in congestion and queueing behavior between small and medium sized equipment. The mining cost model used a variety of OEM, private and public sources for maintenance, fuel, capital, labor and other costs.

The base case used medium-sized equipment (31t excavator and 100t heavy rigid mining truck), manned by human drivers and with an approximate mean utilization of availability of 80%. Three subsequent cases were modelled for comparison: autonomous medium-sized equipment, manned small equipment (13t excavator and vocational 40t truck) and autonomous small equipment.

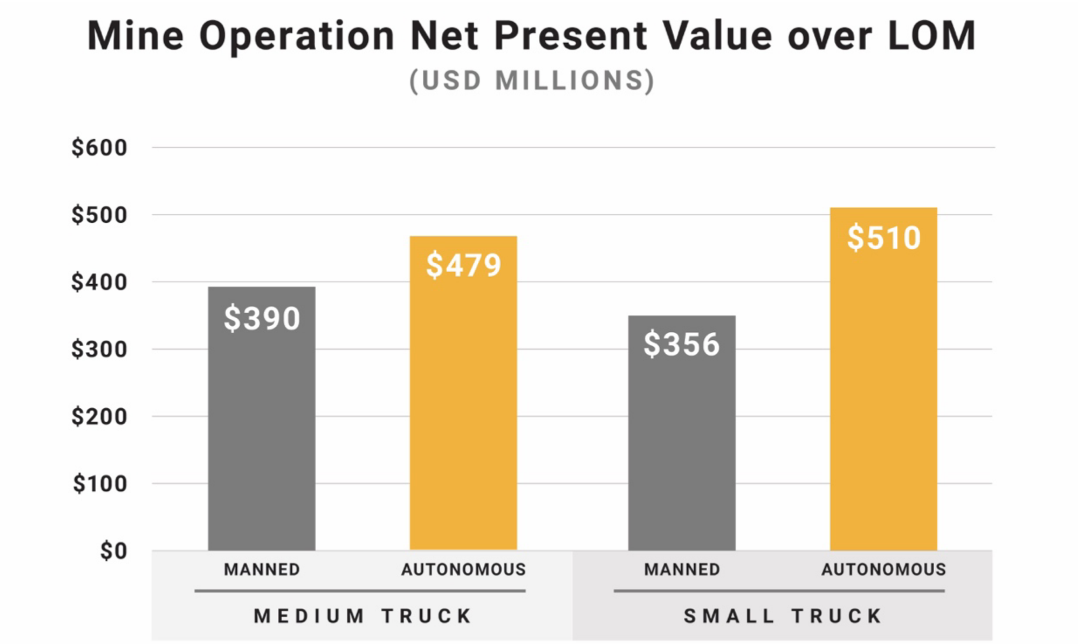

Figure 1: Comparison of the four cases analysed in this case study.

The implementation of an Autonomous Haulage System (AHS) using a medium-sized truck produces a 23% higher LOM NPV than human-driven trucks. The improvement arises from increased effective utilization of trucks and reduced labor costs, which more than offsets the incremental cost of the AHS.

The small vocational 40t trucks offer the benefit of lower capital and maintenance costs, and higher uphill speeds, at the cost of shorter vehicle life. In the human-driven case, these savings are not enough to overcome the additional labor costs driven by large increases in truck and excavator driver head counts. This finding is consistent with industry practice and experience.

The autonomous small equipment case resolves this issue by reducing headcount to a level close to the base case. The autonomous small case examined in this study increases NPV by 31% compared to human-driven medium-sized trucks and 7% compared to autonomous medium-sized trucks. The conclusion is that in addition to the increased effective utilization provided, autonomy at a low cost-per-vehicle rate is the key to unlocking the benefits of the small equipment modelled here – reduced truck capital, reduced truck maintenance and improved haul speeds. These benefits are supplementary to other potential benefits of small vocational trucks, which include electrification and short lead times.

	MINE NPV ($mm)		
TRUCK SCENARIO	MANNED	AUTONOMOUS	NPV Δ
Medium / 100-Ton Haul Trucks	$390	$479	22.8%
Small / 40-Ton Haul Trucks	$356	$510	43.2%
NPV Δ	-8.6%	+6.6%	30.9%

Figure 2: NPV differences between each pair of cases. The improvement from base case to final case is 30.9%.

About Whittle Consulting and Pronto

Whittle Consulting provides Integrated Strategic Planning to mining companies. This planning methodology considers all parts of the value chain, the entire life-of-mine and all stakeholders. It utilizes cross-functional collaboration across all elements of an organization so that an accurate model of the whole system, from resource to market, is built. This is then mathematically optimized using proprietary software *Prober* to produce a schedule. This methodology allows the full effect of any defined technology on the NPV of a mining enterprise to be calculated.

Pronto is a Silicon Valley-based technology company that provides autonomous solutions for off-road applications, initially focused on the mining and quarrying industries. Pronto offers the world's simplest AHS that is powered by artificial intelligence, hardware-light, rapidly deployable, and is scalable from smallest articulated dump trucks and quarries to the largest rigid trucks and mines. The Pronto team has been at the forefront of the most important major developments in off-road and on-road autonomy since the 2004 DARPA Grand Challenge.

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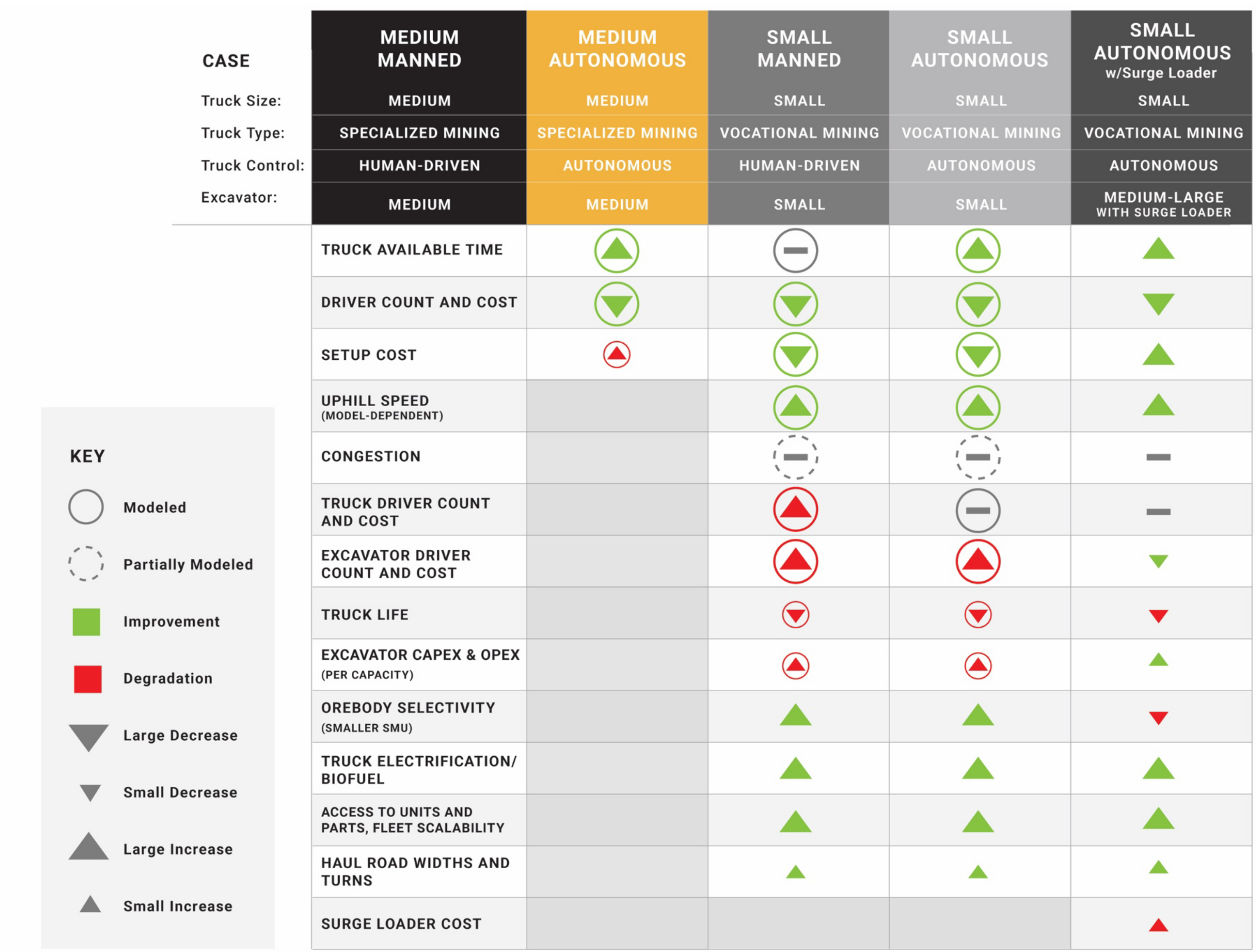

Figure 3: Summary of pros and cons of autonomous and small truck systems quantified in this case study, along with qualitative listing of other features. Includes Surge Loader option, which was not analysed.

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1 INTRODUCTION

1.1 PURPOSE

Whittle Consulting carried out an investigation to assess the full financial impact of Autonomous Haulage Systems, with a focus on transition from large to small trucks, on a hypothetical mining operation. This report summarizes the findings.

1.2 PRONTO AUTONOMOUS HAULAGE

Pronto produces an Autonomous Haulage System (AHS) engineered for a wide variety of off-road environments, from small quarries to large mines.

Pronto's origins in lightweight, low-cost, artificial intelligence-based on-road systems make Pronto's AHS ideally suited for mines operating haul trucks in the sub-150-tonne capacity range, enabling smaller operations to reap the benefits of AHS previously only available on Ultra Class trucks.

Pronto's AI-based solution uses only camera, GPS, and inertial motion sensors, eliminating brittle, expensive sensors such as lidar and radar. Critically, Pronto's system does not require a new control room or a team of remote operators - it can be entirely operated via a smartphone / tablet application. Pronto's AHS is OEM and model-agnostic and designed for rapid deployment.

Haul trucks equipped with Pronto's AHS are improving safety, reducing costs, and increasing productivity in multiple production environments today.

1.3 WHITTLE CONSULTING OPTIMIZATION METHODOLOGY

The full benefit of Pronto AHS technology cannot be assessed in isolation. Even a small change in one part of a mining operation affects, to a greater or lesser extent, the optimal operation of all other parts of the enterprise (cut-off grades, stockpiling, plant settings etc.). Therefore, a whole-system approach is required to fully estimate the effect of such an implementation. The approach must also take into account the time-value of money; the most common approach is to discount future cash flows to produce a Net Present Value (NPV) that can be directly compared between different cases.

Whittle Consulting's enterprise optimization methodology is used for this purpose.

1.3.1 Whittle Consulting

Whittle Consulting are specialists in Integrated Strategic Planning for the mining industry. A team of highly experienced industry specialists, they are dedicated to adding value to mining businesses.

With technical expertise in a range of disciplines including geology, mining engineering, metallurgy, research, mathematics, computing, finance, operational/ financial modelling and analysis, Whittle Consulting has a thorough appreciation of practical, organizational and contextual reality of mining operations. As experts in embracing and harnessing complexity, Whittle Consulting is not bound by traditional thinking. By challenging existing paradigms and conventional wisdom, the real potential of a mining business is revealed.

Since 1999, Whittle Consulting has conducted over 180 Whittle Enterprise Optimization studies around the world. These have repeatedly demonstrated that the comprehensive application of Whittle Integrated Strategic Planning and the concepts from the highly regarded Money Mining & Sustainability Seminar improves the economics of a mining project or operation by 15%, and in many cases substantially more. These results are achieved even when conventional mining optimization has been completed prior.

Whittle Consulting operates worldwide and is represented in Australia, United States of America, Canada and Indonesia.

1.3.2 Modelling

The whole mining operation from Resource to Market is modelled. While the pit and phase shapes are created in Geovia Whittle, a software package from Dassault Systèmes, the rest of the enterprise is modelled using Prober, a proprietary optimization algorithm that optimizes for NPV. The role of the Prober-user is to *describe* the mining system mathematically and then let the optimizer produce the best mining and processing schedule. This is in opposition to *telling* the software how to schedule a mining system, as in a traditional approach.

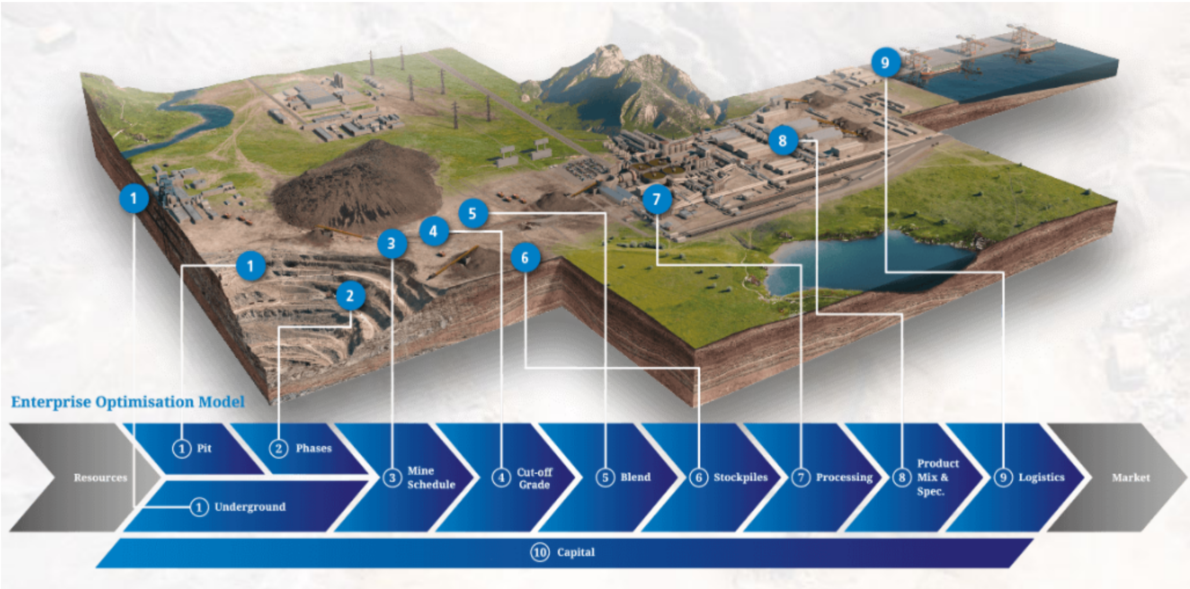

Figure 4: Whittle Consulting Enterprise Optimization process.

A full Whittle Consulting optimization may include iteration between pit design in Geovia Whittle and rest-of-system optimization in Prober.

1.4 Amalgama Simulation and MineTwin™

Amalgama Simulation are specialists in creating simulation models and decision support software tools for various industries, including mining and metallurgy. A simulation model is a detailed system representation that allows users to take experimentation and scenario analysis from the real world to the risk-free world of models. Amalgama Simulation has successfully implemented over 35 commercial simulation projects for mining companies around the world.

This study uses a detailed Truck and Shovel time usage model to appropriately model the complexities of small-medium truck and shovel interactions, especially wait times. This is based on a detailed discrete-event model created using MineTwin™ Simulation software that is used for simulating and planning mining operations.

See *Case Study Report – Truck and Shovel Modelling* [1] for a description of the modelling methodology, including the roles of Amalgama and MineTwin™. The document also references a report[2] with additional details on simulation settings.

1.5 Global Mining Guidelines (GMG) Time Classification

The GMG group publish a document *A Standardized Time Classification Framework for Mobile Equipment in Surface Mining*[3] that specifies standard terminology for time usage models. This breaks time usage into Productive time (PT), Non-Productive (NP), Operating Delay (OD), Standby (SB), Downtime (DT) and Unscheduled Time (UT). Effective Utilization is Working Time (PT + NP) divided by Scheduled Time (PT + NP + OD + SB + DT). These terms are used in the MineTwin™ and Prober models and reported throughout this document.

1.6 Glossary

LOM	Life Of Mine
MineTwin™	Detailed discrete event simulation software used to model equipment movements in a mine.
NPV	Net Present Value. The net value in dollars of the mine over its life, considering future cash flows discounted at a certain rate.
Prober	Whittle Consulting schedule optimization software
Vocational Truck	A mass-market heavy duty truck. May be a mining-specific version of a road truck model, but not a specialized mining truck.
Wait Time	Used in this report as a generic term for both truck wait (queuing) and excavator wait (hang time).

[1] N Redwood. *Case Study Report – Truck and Shovel Modelling*, (2023)
[2] A Malykhanov, JB Vosloo. *Pronto.AI Small Autonomous Trucks for Mining - Simulation Study Report*, (2023)
[3] Global Mining Guidelines Group, 13 July 2020.

2 MODEL AND CASES

All mining operations are different and any benefits from using autonomous haulage will vary from case to case. Rather than attempting to assess autonomous haulage against a large range of mines, this report assesses autonomous haulage against a single mining operation to provide an indication of the magnitude of financial benefit.

The model used in this study consists of a fictional ore body 'Marvin', a detailed truck and shovel model derived from the discrete event simulation built in MineTwin™, a very simple processing model and a set of financial parameters that were deemed representative of the prevailing financial conditions at the time of publishing.

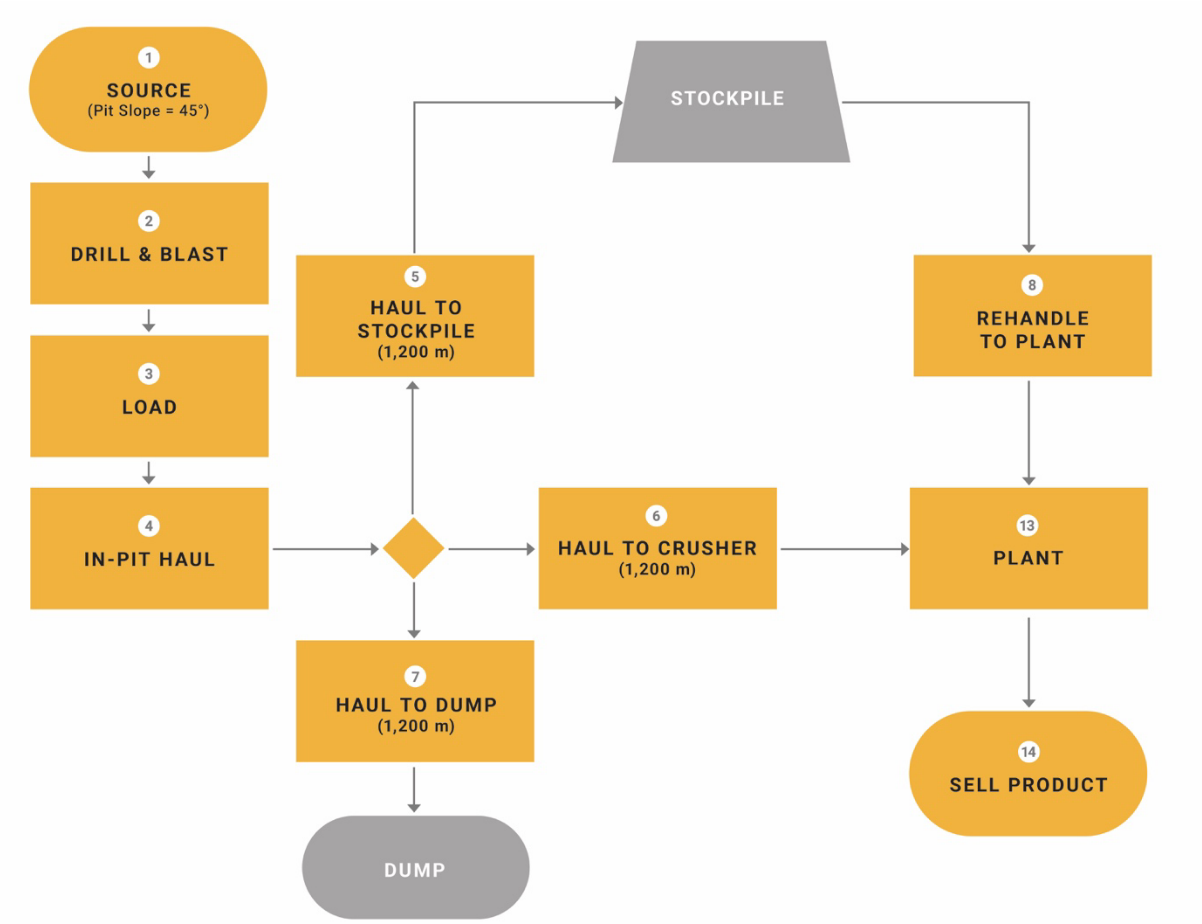

Figure 5: Simplified flow diagram. See Appendix B – Model Diagram: for a complete diagram.

2.1 CASES

Four cases are examined to understand the effect of autonomy and small vs medium-sized equipment on the mine. Each combination of these two binary choices is modelled.

Case 1 is the base case, as the most common approach taken in high labor cost countries at the time of publication. AHS is deployed in cases two and four.

Table 1: Equipment and truck control for the four cases selected.

	1	2	3	4
Truck Control	Manned	Autonomous	Manned	Autonomous
Equipment	Medium	Medium	Small	Small
Excavator	Generic Excavator	Generic Excavator	Generic Excavator	Generic Excavator
Bucket	31 t	31 t	13 t	13 t
Truck	Heavy Rigid ~100t	Heavy Rigid ~100t	Vocational 40t	Vocational 40t
Payload	99 t	99 t	40 t	40 t

2.2 Global Settings

All currency figures are quoted in US dollars (USD). A discount rate of 8% is used to account for the time value of money. The period length for schedule optimization is one year.

The enterprise is a greenfield operation. Capital of $1.0B is required. Mining may begin in the first year of operation, however the Plant is not available until the second year.

2.3 Ore Body

The ore body used is an adaptation of the Marvin ore body. This is a realistic copper-gold ore body created over a decade ago by geologist Norm Hanson for use in case studies. The version of Marvin used in the case study has gold removed so becomes a copper-only deposit; copper grade generally increases at deeper elevations. The model used has a block size of X 20 m by Y 20 m by Z 16 m.

A single open pit with three phases was sized using the Geovia Whittle software package. In each case the Skin Analysis technique was used to choose the shell with the highest expected NPV.

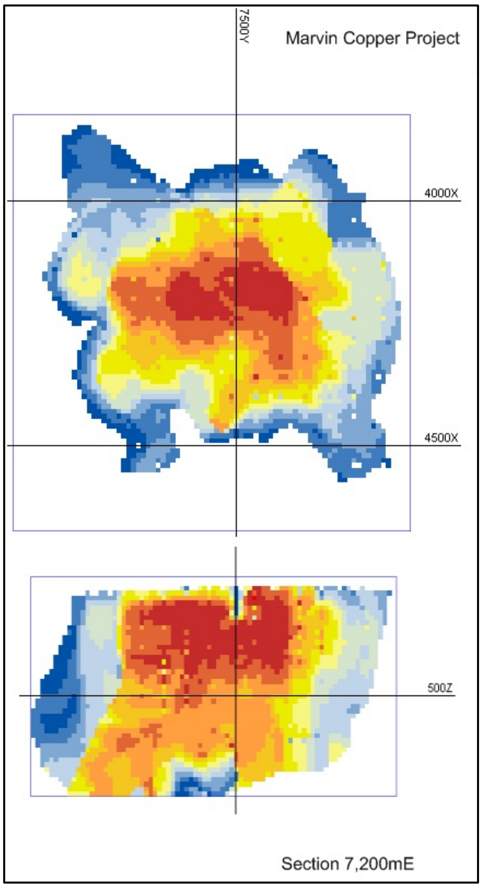

Figure 6: Cross section of ore body, coloured by grade.

2.4 Mining Model

For a trucking case study, the mining model is the focus of the analysis.

Physical parameters such as truck speeds, and cost parameters, were drawn from a variety of sources including OEM data, active mines and published data.

A key feature of this case study is an additional piece of software, MineTwin™, which is used to model the truck and shovel physical behavior based on agreed parameters (speeds etc). The results of this are then generalized for use in Prober's strategic LOM optimization.

2.4.1 Mining Cost Model

The MineTwin™ model was not used for costings, only for physical behavior. A detailed Prober mining cost model was built for strategic optimization. This calculates variable, period and capital costs for trucks and shovels, along with drill, blast and overhead costs.

Variable truck and shovel costs are incurred on a cost-per-operating-hour basis. These consist of diesel usage, electricity usage, Ground Engaging Tools (GET), buckets, bodies & ropes, oils and greases and periodic servicing. Periodic replacement of trucks and shovels is amortized over equipment life as another variable cost against operating hours. No distinction is drawn in cost rates between different activities occurring in each operating hour; this level of detail would be advised in an operating mine with available data, however, is unnecessary for this case study, which is strategic in nature.

Labor period costs scale with the number of excavators and trucks deployed. A small additional maintenance period cost is allowed; however most maintenance costs are modelled as variable costs per operating hour.

See Appendix D – Mining Cost Model for full details.

2.4.1.1 Excavators

Table 2 shows that the small 13t excavator is more expensive on most metrics than the medium sized 31t excavator. The latter has 2.4 times the bucket size of the former (with both assumed to have the same load cycle duration), but only incurs 1.8 times the cost per hour utilized. The 31t model is 3 times the capital cost of the 13t model but also has twice the operating life. Both excavators have the same driver requirements per unit, which advantages the larger model.

Table 2: Excavator cost parameters

Excavator		Generic 31t Excavator	Generic 13t Excavator
Excavator Shovel Capacity		31	13
Total Excavator Variable Cost	**$/hutilized**	**334**	**181**
Diesel	$/hutilized	50	21
Price	$/L	0.5	0.5
Consumption	L/h	100	42
Total Consumables and Maintenance	$/hutilized	239	130
Consumable and Parts	$/h	171	89
Maintenance Labor Cost	$/h	68	41
Maintenance Labor Rate	hLabor/hutilized	1.5	0.9
Maintenance Labor Cost Rate	$/hLabor	45.0	45.0
Periodic replacement capex as variable cost	$/hutilized	45	30
Total Excavator Period Cost per Year	US$M/y	$2M + $0.34M * nExc	$2M + $0.34M * nExc
Labor	US$M/unit/y	0.336	0.336
Labor Cost Per Unit	US$k/unit/y	336	336
Operator Cost per year	US$k/y	80	80
Allowance for G&A		20%	20%
Shift coverage		3.5	3.5
Maintenance Overheads	US$M	2.0	2.0
Total Excavator Capital Costs			
Cost per Excavator	US$M/unit	2.70	0.9
Operating life	h/unit	60,000	30,000.0
Cost per hour capacity	$/h	45	30

2.4.1.2 Trucks

Table 3 shows that cost parameters are more favorable for the small vocational 40t trucks than the 100t mining trucks. The 100t mining truck payload is 2.5x that of the vocational 40t truck, while variable costs are 2.76x and capital cost per truck hour 3.6x higher in the manned case. This includes some conservative assumptions on small truck life and capital cost; life is assumed to be just 15,000h, substantially less than that of a medium sized mining truck.

Diesel cost per tonne moved is assumed to not differ between the small and medium truck cases.

Autonomy changes labor cost structure and adds a small capital cost.

Table 3: Truck cost parameters

Truck		Heavy Rigid 100t	Vocational 40t
Payload		99	40
Total Truck Variable Cost per hour utilized	**$/hutilized**	**143**	**52**
Total Consumables and Maintenance	$/hutilized	95	38
Consumable and Parts	$/h	59	10
Maintenance Labor Cost	$/h	36	28
Maintenance Labor Rate	hLabor/hutilized	0.81	0.63
Maintenance Labor Cost Rate	$/hLabor	45.0	45.0
Periodic replacement capex as variable cost			
When Manned	$/hutilized	48	13
When Autonomous	$/hutilized	52	20
Total Truck Variable Cost per tonne			
Diesel flat haul 1200m	$/t	0.025	0.025
Diesel In-pit haul	$/t/mbelow	0.00072	0.00072
Total Truck Period Cost per Year			
When Manned	US$M/y	$3.0M + $0.34M * nTruck	$3.0M + $0.34M * nTruck
When Autonomous	US$M/y	$4.3M + $0.11M * nTruck	$4.3M + $0.11M * nTruck
Labor			
Manned - Number Operators per Truck	#/Truck	3.5	3.5
Autonomous - Number Operators Control Room	#	14.0	14.0
Autonomous Number Operators per Truck	#/Truck	0.35	0.35
Operator Cost pa	US$k	80.0	80.0
Allowance for G&A		20%	20%
Maintenance Overheads	US$M	3.0	3.0
Autonomy	US$M/Truck/y	0.075	0.075
Total Truck Capital Costs			
Cost per Truck - Manned	US$M/unit	1.2	0.2
Cost per Truck - Autonomous	US$M/unit	1.3	0.3
Operating life before replaced	h/unit	25,000	15,000
Cost per hour capacity - Manned	$/h	48	13
Cost per hour capacity - Autonomous	$/h	52	20

2.4.1.3 Fleet Sizing

The Prober model is set up to choose the size of both the truck and shovel fleets. The fleets are modelled first as a small base fleet, which is large enough to fill the plant each year from the stockpile at the end of the mine life. Additional to this, a main truck fleet and main excavator fleet containing the bulk of the trucks and excavators is sized by Prober. This is modelled as a capital cost to purchase additional hours of capacity; these cost rates are shown in Table 2 and Table 3. (While this means a non-integer number of pieces of equipment may be purchased, the overall error introduced by this is not material.)

Additional Period costs are also incurred when the fleet is scaled up.

2.4.2 Detailed Truck & Shovel Modelling of Physical Movements

The effects of truck and shovel interactions and congestion on scheduling were important in this case study, due to the comparison between different-sized equipment and the change in availability assumptions brought about by autonomy. For this reason, a detailed Truck and Shovel model of the physical equipment movements is at the core of the study. The MineTwin™ model was built to simulate trucks and shovels moving around the open pit haul network, interacting with material blocks and other equipment and subject to probabilistic events. The results of the MineTwin™ model were analyzed for insights, then generalized for use in the LOM integrated strategic optimization in Prober.

The truck and shovel modelling approach used is documented fully in *Case Study Report – Truck and Shovel Modelling*. In that report, only manned medium-sized trucks and shovels are modelled, whereas this study reruns the simulations with small equipment and autonomous systems.

One of the key benefits of the small truck chosen is fast uphill loaded speeds; 15 km/h compared to 11 km/h for the medium truck. Empty downhill speeds also increase from 15 km/h to 20 km/h. See Appendix A – Truck and Shovel Parameters Input To MineTwin™ for full details.

The output of the MineTwin™ modeling is summarized in Figure 7. The small-truck cases have shorter cycle times owing to increased truck speed. The autonomous cases also have shorter cycle time than their counterparts, when downtime associated with vehicle manning is considered.

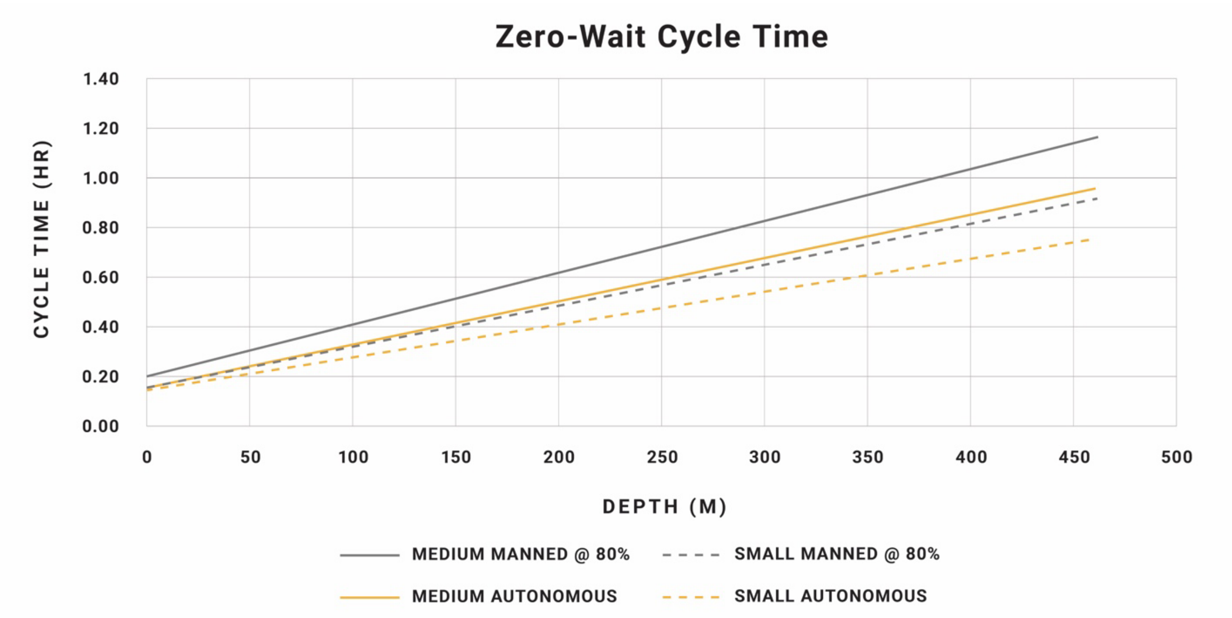

Figure 7: The cycle time derived from MineTwin™ results for each of the four cases. Note that this excludes queuing, which is handled separately. However, it includes downtime, standby and failure; this is why the autonomous cases have substantially shorter cycle times.

2.4.2.1 Truck & Shovel Wait Time Interdependence

Truck wait time is dependent on the presence of available shovels in the system; there is an inverse relationship between truck wait time and shovel wait time. This mechanism is described in detail in the companion *Case Study Report – Truck and Shovel Modelling*, which demonstrates that the mechanism works effectively.

In this Prober model, the truck and shovel wait time is derived from the MineTwin™ results for each of the four cases, and then implemented as a decision for each portion of material mined in the LOM schedule. Prober chooses a point on the curve in Figure 8, which allows it to dynamically decide whether to deploy more trucks to reduce excavator wait time, or vice versa. This decision may differ over the LOM plan and at different mining depths.

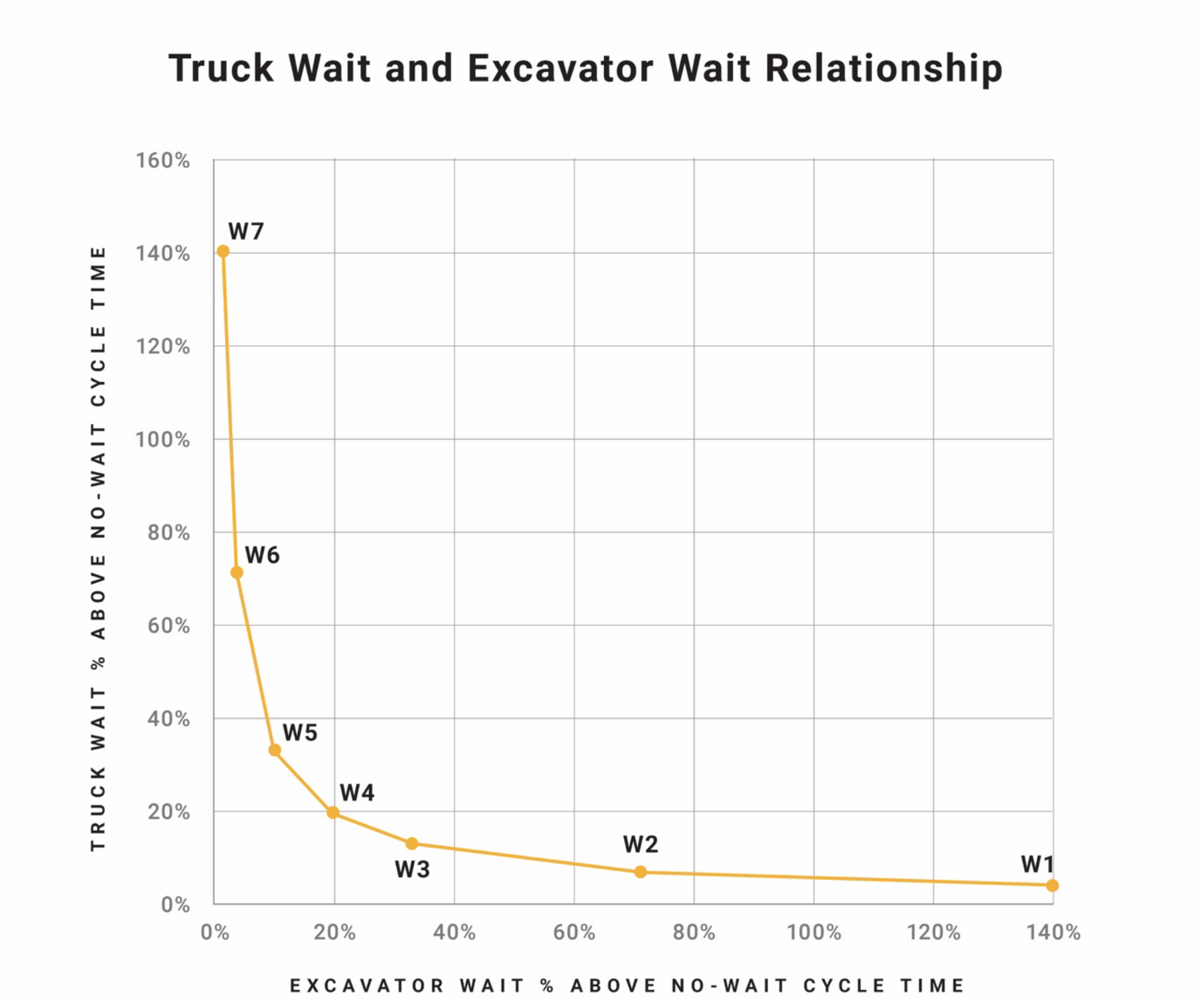

Figure 8: Seven points are chosen on the truck-wait vs excavator-wait curve, to allow Prober to approximate the relationship. For each portion of material mined, Prober must choose one point on this curve. The regression analysis found that this curve does not vary with depth. The curve shown is for manned medium equipment; it differs a little for small and autonomous equipment.

2.4.2.2 Time Usage Constraints

Two mining constraints are implemented: a truck time limit and an excavator time limit. These are both implemented as the number of hours in a year multiplied by the number of pieces of equipment; in GMG terminology this is Calendar Time. Prober essentially chooses the amount of Scheduled Time. All downtime, standby, delays, non-productive and productive time within the Scheduled Time are calculated dynamically from material masses.

In both truck and shovel fleets, Prober optimizes the available time capacity of the fleet by purchasing fleet capacity at the beginning of the LOM.

2.5 Processing Model

As plant processing is not the focus of this case study, a simplistic model is used. Only primary (Fresh) ore can be processed. The plant is modelled as a simple recovery of 82% of copper to product. There is a variable processing cost of $6/t, a period cost of $40M/y, a capital cost of $800M and a maximum throughput of 20 Mt/y.

2.6 Effects Not Modelled

This case study incorporates some but not all of the potential benefits and downsides of small trucks and autonomy.

Table 4: Effects of truck size and autonomy below are noted qualitatively, rather than being quantified in this study.

Feature	**Comment**
Small excavators and trucks provide ore selectivity benefit	The benefits of ore selectivity are well understood and have been modelled in other Whittle Consulting case studies.[4] [5] Dilution is reduced and the application of grade control at a finer resolution (lower SMU) allows increased processed grades through the bulk of the mine life through a process termed 'Metal Exchange'.
Surge loaders	An alternative to a large fleet of small excavators in the small truck case. This allows medium-large excavators, which have some scale-based benefits, to be paired with small trucks. However, surge loaders lose any ore selectivity benefit.
Fleet scalability	Small mass-market trucks are common and easily purchased with short lead times, allowing fleet to be scaled up and down over shorter time frames.
Small truck electrification	Electrification is a key step towards decarbonization and development of small mass-market electric trucks is further advanced than electrification of medium-large trucks.
(Partial) Congestion arising from large numbers of trucks and shovels	This study only partially accounts for the truck and shovel congestion that may occur in a mining operation and uses only a simple road network. Real truck and shovel movement data would be required to better account for congestion.
Pit re-optimization for smaller fleet	Pit designs would be re-optimized for small trucks and small shovels. This would reduce the minimum mining width and potentially reduce haul road width.
Mining-limited case	A case in which the excavator or truck fleet is heavily constrained would show a greater benefit from autonomy, due to larger effective utilization rates.

[4] Redwood N. *Application of Enterprise Optimisation Considering Grade Engineering® Strategies* (2016) (https://www.whittleconsulting.com.au/wp-content/uploads/2023/04/Application_of_Enterprise_Optimisation_with_Grade_Engineering_Strategies.pdf)
[5] Redwood N. *Whittle Consulting ShovelSense™ Economic Assessment* (2018) (https://www.whittleconsulting.com.au/wp-content/uploads/2023/04/Whittle-Consulting-ShovelSense-Economic-Assessment.pdf)

3 Results

NPV is the primary measure to compare between the cases. The table below shows that autonomy improves NPV, whether small or medium equipment is used. The highest NPV is achieved in the Autonomous Small equipment case, while the lowest is the Manned Small equipment case. Autonomy is vital to unlock the benefits of the small equipment case.

Table 5: Summary of physical and financial movements for each case. Numbers greyed where the same as previous case. See Appendix F – Result Discounted Cash Comparison for additional detail.

		1	2	3	4
		Manned Medium Truck	Autonomous Medium Truck	Manned Small Truck	Autonomous Small Truck
Mining					
Mass	Mt	752	752	752	752
Excavators Purchased	#	7	7	15	14
Excavator Personnel	#	25	25	53	49
Excavator Time Used	kh	669	535	1,304	1,160
Productive Time	%	47.4%	59.3%	54.4%	61.2%
Wait For Truck	%	27.2%	14.0%	19.3%	11.8%
Downtime + Standby + Operating Delay	%	25.4%	26.8%	26.2%	27.0%
Trucks Purchased	#	36	31	87	67
Truck Personnel	#	126	25	305	38
Truck Time Used	kh	3,814	3,135	7,748	6,328
Productive Time	%	70.3%	85.8%	71.5%	87.6%
Wait For Excavator	%	8.7%	9.1%	7.6%	6.9%
Downtime + Standby + Operating Delay	%	20.9%	5.1%	20.9%	5.5%
Mining Costs	*Disc. $M*	*994*	*918*	*1016*	*887*
Excavator Costs	*Disc. $M*	*204*	*183*	*222*	*210*
Initial Capital	*Disc. $M*	*63*	*61*	*59*	*57*
Operating	*Disc. $M*	*140*	*122*	*163*	*152*
Trucking Costs	*Disc. $M*	*495*	*432*	*496*	*381*
Initial Capital	*Disc. $M*	*39*	*36*	*16*	*18*
Operating	*Disc. $M*	*456*	*396*	*480*	*362*
Other Mining Costs	*Disc. $M*	*295*	*303*	*299*	*297*
Ore					
Mass	Mt	400	401	401	401
Mean Cu Grade	%	0.294%	0.294%	0.294%	0.294%
Processing Costs	*Disc. $M*	*$2,437*	*$2,437*	*$2,437*	*$2,437*
Initial Capital	*Disc. $M*	*$926*	*$926*	*$926*	*$926*
Operating	*Disc. $M*	*$1,511*	*$1,511*	*$1,511*	*$1,511*
Product					
Cu	kt	967	967	967	967
Revenue	*Disc. $M*	*$3,820*	*$3,834*	*$3,809*	*$3,834*
NPV	*Disc. $M*	***$390***	***$479***	***$356***	***$510***

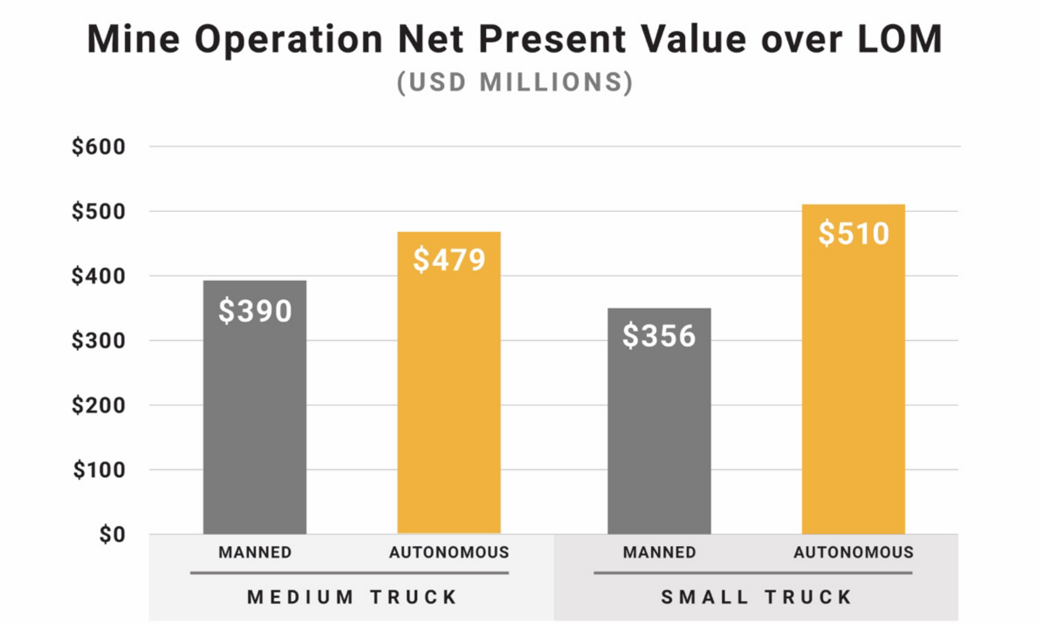

Figure 9: Comparison of LOM NPV for the four cases examined.

The difference in Effective Utilization between manned and autonomous cases can be seen in the Truck Downtime + Standby + Operating Delay figures in Table 5, which are 20% in manned cases and only 5% in autonomous cases.

It was hypothesized that the detailed truck and shovel modelling in MineTwin™ might find that large numbers of small trucks would have more congestion problems than fewer medium-sized trucks. However, for the pit phases and road network here, this was not found to be the case. As seen in Table 5, small equipment cases three and four have lower truck and excavator wait fractions than their medium equipment counterparts. The primary factor that affects this is the greater haul speed, especially uphill, of small trucks. There was not found to be any difference between queuing behavior in the MineTwin™ model. It is likely that certain phase and road design and orchestration considerations must be met in order to assure that large numbers of small trucks and excavators do not suffer congestion problems; these are assumed to be in place in this case study.

3.1 Base Schedule Case 1

The base schedule using manned medium trucks (100t heavy rigid truck) produces a schedule with a LOM of 19 years and an NPV of $390M. Mining costs over the LOM are $994M discounted, of which approximately half ($495M) is trucking, 20% ($104M) is excavator costs and the remaining 30% are other mining costs such as drill and blast.

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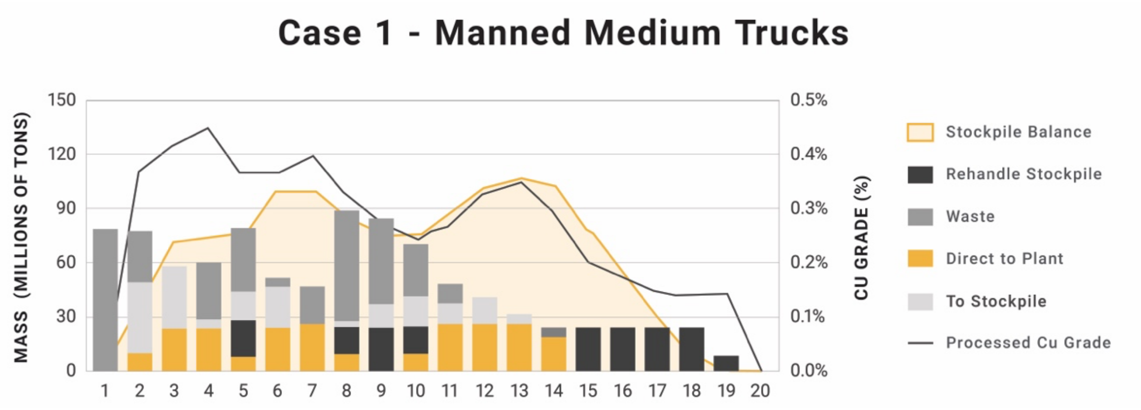


Figure 10: LOM material movements for Case 1.

Waste strip begins in period 1 and mining continues at around 70 Mt/y until period 5, providing the plant with feed around 0.4% copper through to period 7. Stockpile is rehandled for plant feed through the majority of periods 8-10 before the bulk of phase 3 ore is processed periods 11-14. The plant is filled from stockpiles from period 15 until closure in period 19.

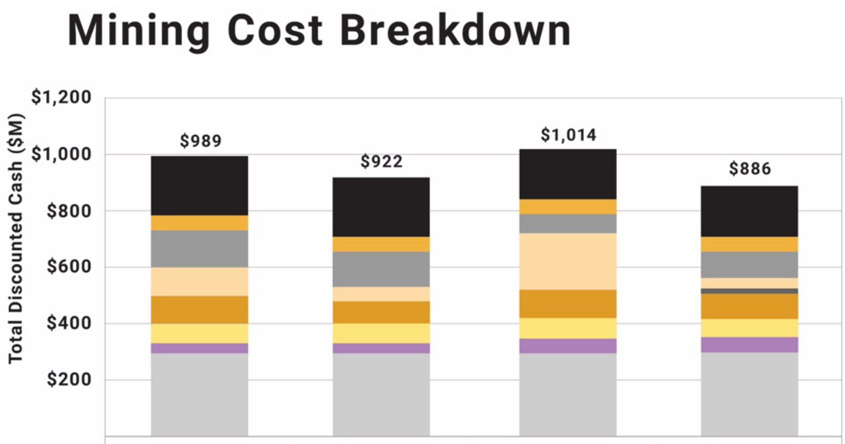
The dynamic truck and shovel wait time optimization chooses a balance that has low truck wait time of 9% and high excavator wait of 27%. This is a cost optimization – Prober finds it better to incur more excavator wait time than truck wait time, particularly as the pit becomes deeper and haul distances become longer. See Appendix E – Result Charts: Truck Wait % above Zero-Wait Cycle Time.

3.2 Autonomous Case 2

This case lifts NPV by $89M compared to the base case. This consists of a $75M mining cost saving and a $14M increase in discounted revenue.

The material movement chart is similar to the base case; see Appendix E – Result Charts, however the fleet balance and costs change and revenue is brought forward slightly.

Figure 11 shows that the mining cost reductions in Case 2 arise primarily from reduced truck labor. Firstly, the greater utilization enabled by autonomy allows the optimal truck fleet size to reduce from 36 to 31 trucks. Together with autonomy, this leads to a large reduction in personnel from 126 to 25, with truck labor cost reduced from discounted $98M to $18M over the LOM. Greater truck utilization also means the same-sized excavator fleet spends less time waiting for trucks – from 27% to 14%. This reduces scheduled excavator time over the LOM from 669,000 h to 535,000 h and therefore reduces maintenance costs.



	MANNED MEDIUM TRUCK	AUTONOMOUS MEDIUM TRUCK	MANNED SMALL TRUCK	AUTONOMOUS SMALL TRUCK
Truck Maintenance	$208	$208	$174	$177
Truck Consumables	$58	$59	$57	$59
Truck Capital Incl. Replacement	$130	$135	$67	$96
Truck Labor	$98	$18	$198	$24
Autonomy Ongoing Cost	-	$12	-	$25
Shovel Consumables + Maintenance	$96	$79	$97	$89
Shovel Capital Incl. Replacement	$74	$71	$75	$73
Shovel Labor	$30	$31	$47	$46
Drill + Blast + Other Mining	$295	$309	$299	$297

Figure 11: Discounted LOM mining costs for the four cases, split into main categories. For charts of mining cost by year for all four cases, see Appendix E – Result Charts: Mining Costs (not discounted) over LOM.

3.3 Small Truck Case 3

NPV drops $34M compared to the base case in this case; although there are several cost and schedule benefits from smaller equipment, this is overwhelmed by increased labor costs.

With small trucks and excavators, the number of trucks increases from 36 to 87 and the number of truck personnel from 126 to 305. The number of excavators increases from 7 to 15 and excavator personnel from 25 to 53, compared with the base medium case. As per Figure 11, this increases the discounted LOM trucking labor cost by $100M and excavator labor cost by $17M.

There are savings to trucking capital (including replacement) and trucking maintenance, as the small vocational trucks are mass-market and relatively cheap to buy and maintain as a result. Higher truck speeds also mean that fewer operating hours are required to move each tonne of rock.

Prober scheduling dampens the effect of the higher labor costs, to some extent. Labor costs are determined by truck numbers, so Prober buys as few as possible and then lowers the truck wait percentage further than the base case to 7.6%. This increases material movement output from the limited truck fleet, though at the cost of increased excavator wait times. Mining is completed in period 15 rather than period 14 as a result; this incurs extra period costs, though these are highly discounted. Discounted revenue also decreases a little (for the same copper mass produced), as essentially lesser mining capacity means that higher grade ore cannot be accessed as quickly, so revenues are delayed.

3.4 AUTONOMOUS SMALL TRUCK CASE 4

This case records the best NPV of $510M, a $120M (31%) increase over the base case and a $31M (6.6%) increase over the Autonomous Medium Truck Case 2. It has all the advantages of small trucks used in Case 3 – lower maintenance and capital costs and increased haul speeds – without the high labor cost disadvantage. It also has the advantages of increased truck utilization from autonomy.

In cost terms, autonomous small equipment in this case study yields a reduction compared to manned medium equipment in all of truck capital (including replacement), truck maintenance and truck labor. Refer to Table 5.

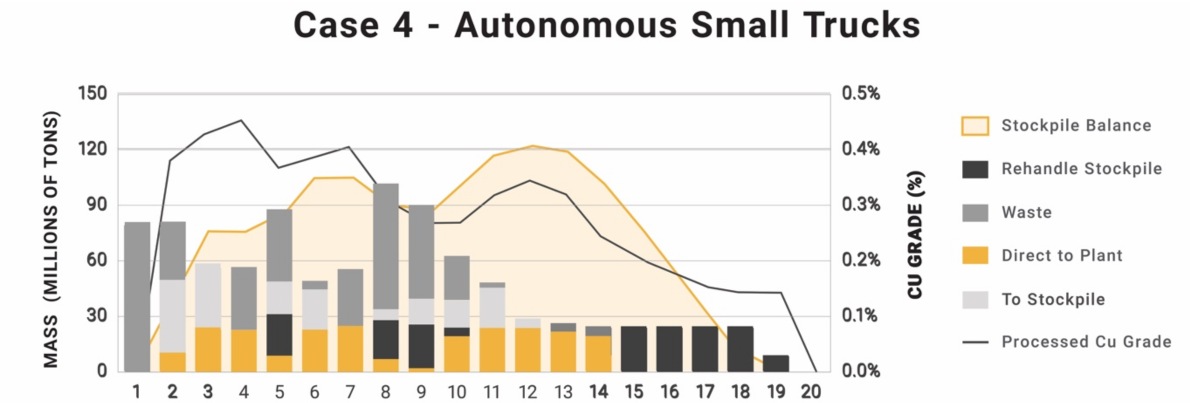


Figure 12: LOM material movements for Case 4.

As with other runs, Prober accentuates the advantages (and mitigates disadvantages) provided in the run parameters. In this case, effective mining capacity is essentially cheaper than other cases, which means it is optimal to increase mass moved in early periods to access high-grade ore. Discounted revenue increases a little (for the same copper mass produced) compared to the base case, largely from phase 3 ore, and mining ends almost one period earlier, saving period cost.

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4 CONCLUSIONS

Based on the parameters used, AHS-equipped small trucks offer an NPV improvement of 31% to the fictional, but realistic, mining operation modelled in this study.

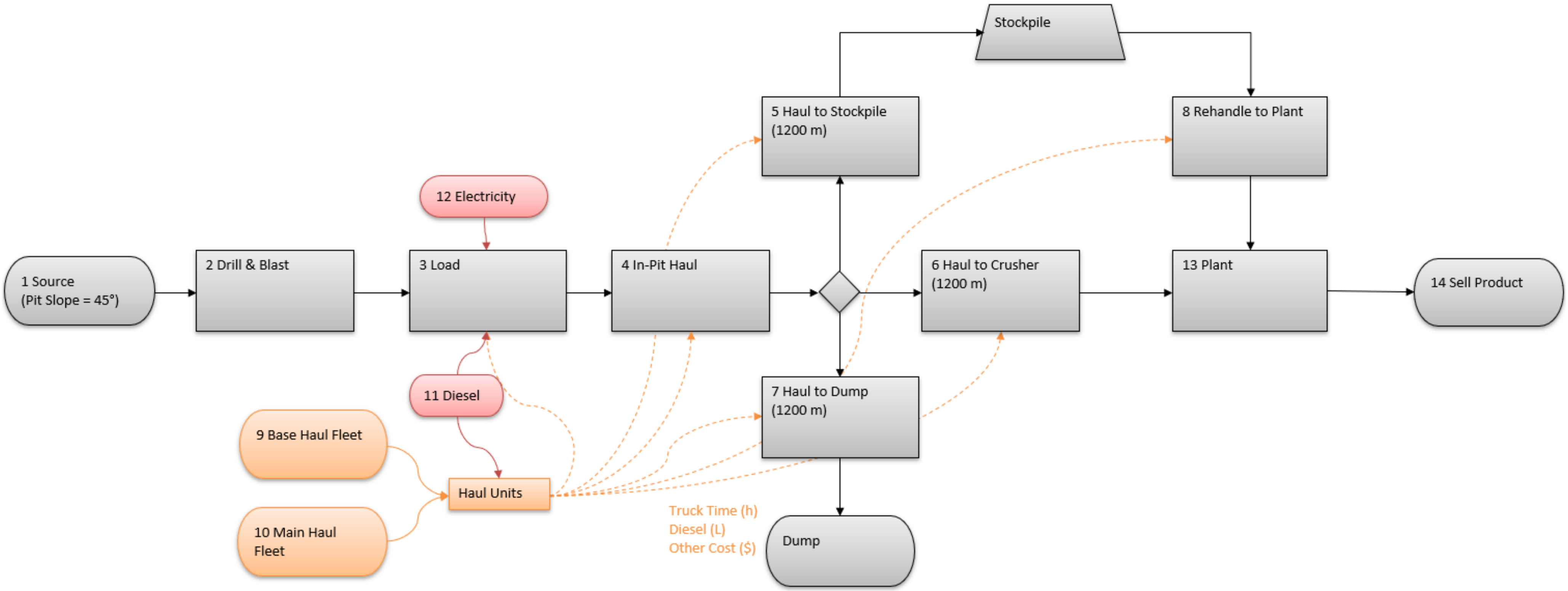
1. In the North American setting for this study, an autonomous trucking system using medium-sized equipment (31t excavator and 100t heavy rigid mining truck) produces a better LOM NPV than manned equipment. The uplift was 23% in the mine tested. The improvement arises from increased effective utilization and reduced labor costs.
2. Small vocational rigid body mining trucks offer the benefit of low capital and maintenance costs (despite shorter vehicle life) and higher uphill speeds. They also offer potential benefits in ore selectivity (with small excavators), improved scalability and easier electrification, though these are not quantified here.
3. In the North American setting for this study, manned small mining trucks cause a large drop in mine NPV compared with medium sized trucks. While they offer the cost benefits listed above, the large increase in truck and excavator driver head count causes a large increase in labor costs.
4. The key to unlock small equipment benefits in high labor cost environments is autonomy at a low cost-per-vehicle rate. The autonomous small equipment case examined in this study increased mine NPV by 31% compared to manned medium equipment and 7% compared to autonomous medium equipment. This NPV uplift arises from increased effective utilization, reduced truck capital, reduced truck maintenance and reduced truck labor, at the cost of increased excavator labor.
5. In the MineTwin™ simulation of the three-phase pit and haul network used in this case study, there was not a significant difference in congestion/queuing behavior between medium equipment and larger fleets of small equipment.

5 Appendices

5.1 APPENDIX A – TRUCK AND SHOVEL PARAMETERS INPUT TO MINETWIN™

Case		**Medium**	**Small**
Excavator			
Excavator Model		Generic Excavator	Generic Excavator
Excavator Shovel Capacity	t	31	13
Excavator Shovel Capacity	lcm	12	5
MineTwin™ settings			
Loading cycle duration	s	30	30
Relocation speed	km/h	15	30
Truck			
Truck Model		Heavy Rigid 100t	Vocational 40t
Payload	t	99	40
Dumping Duration	s	97	97
MineTwin™ settings			
Truck speed			
Empty uphill	km/h	20	20
Empty flat	km/h	50	50
Empty downhill	km/h	15	20
Loaded uphill	km/h	11	15
Loaded flat	km/h	45	45
Loaded downhill	km/h	15	20
Planned Maintenance Event Name			
Tire change		8 h every 6000 h	2h every 4500h
Minor service 1		4 h every 250 h	8h every 500h
Medium Service 1		8 h every 1400 h	8h every 1500h
Medium Service 2			
Major Service 1		8 h every 2800 h	4h every 4000h
Major Service 2		8 h every 6000 h	8h every 6000h
Downtime fraction		2.72%	2.41%
Event Name	Which scenarios?		
Meal break	Manned only	0.35 h every 12 h	0.35 h every 12 h
Shift Change	Manned only	0.165 h every 12 h	0.165 h every 12 h
Weekly Safety Meeting	Manned only	0.5 h every 168 h	0.5 h every 168 h
Man Safety	Manned only	0.1 h every 24 h	0.1 h every 24 h
Absenteeism	Manned only	12 h every 171 h	12 h every 171 h
Failure	Manned and Autonomous	0.05 h every 24 h	0.05 h every 24 h
Standby Operational Issues	Manned and Autonomous	0.05 h every 24 h	0.05 h every 24 h
Refuelling	Manned and Autonomous	0.02 h every 24 h	0.02 h every 24 h

5.2 Appendix B – Model Diagram: All Cases



5.3 APPENDIX C – GENERALIZATION OF MINETWIN™ RESULTS

MineTwin Case			Medium Manned @80%	Medium Autonomous	Small v2 Manned @80%	Small v2 Autonomous
Truck Control			Manned	Autonomous	Manned	Autonomous
Truck Nominal UofA Time - MineTwin model is the source of truth on this.			80%	95%	80%	95%
Excavator Model			Generic 31t Excavator	Generic 31t Excavator	Generic 13t Excavator	Generic 13t Excavator
Truck Model			Heavy Rigid 100t	Heavy Rigid 100t	Vocational 40t	Vocational 40t
Capacity			99	99	40	40
	Procedure Applied					
EXCAVATOR BEHAVIOUR CHARACTERISTICS						
NO WAIT (TE0)						
Total Excavator Cycle Time - On-bench, No-Wait, No Unavail (MineTwin)		h/cycle	0.04418	0.04281	0.03871	0.03837
[Operating Delay] Idle	PitMining	h/cycle	0.00060	0.00060	0.00055	0.00054
[Non-Productive Time] Moving	PitMining	h/cycle	0.00002	0.00003	0.00000	0.00000
[Non-Productive Time] Waiting for excavating	InPitWaitTime	h/cycle	0.00186	0.00049	0.00039	0.00005
[Productive Time] Excavating	PitMining	h/cycle	0.04170	0.04170	0.03777	0.03777
TRUCK BEHAVIOUR CHARACTERISTICS						
NO WAIT (Tt0)						
Truck Time Usage (no wait)						
Constant Cycle Component		h/t	0.001920	0.001579	0.004498	0.003689
Truck Time Usage - Constant at surface. with unavailability		h/cycle	0.1901	0.1563	0.1799	0.1476
[Operating Delay] Idle	HaulToPlant/Dump/Stk	h/cycle	0.0017	0.0021	0.0015	0.0013
[Non-Productive Time] Move to Loading	HaulToPlant/Dump/Stk	h/cycle	0.0348	0.0353	0.0338	0.0340
[Non-Productive Time] Wait For Loading	InPitWaitTime	h/cycle	0.0000	0.0000	0.0000	0.0000
[Productive Time] Loading	PitMining	h/cycle	0.0417	0.0417	0.0378	0.0378
[Productive Time] Move to unloading	HaulToPlant/Dump/Stk	h/cycle	0.0419	0.0424	0.0399	0.0401
[Non-Productive Time] Wait for unloading		h/cycle	0.0000	0.0000	0.0000	0.0000
[Productive Time] Unloading	HaulToPlant/Dump/Stk	h/cycle	0.0270	0.0270	0.0269	0.0269
[Operating Standby] Failure	HaulToPlant/Dump/Stk	h/cycle	0.0355	0.0006	0.0328	0.0006
[Operating Delay] Refueling	HaulToPlant/Dump/Stk	h/cycle	0.0006	0.0002	0.0006	0.0001
[Non-Productive Time] Move to idle	HaulToPlant/Dump/Stk	h/cycle	0.0002	0.0002	0.0002	0.0002
[Downtime] Moving to maintenance		h/cycle	0.0000	0.0000	0.0000	0.0000
[Downtime] Maintenance	HaulToPlant/Dump/Stk	h/cycle	0.0068	0.0070	0.0065	0.0066
Maintenance Raw	HaulToPlant/Dump/Stk	h/cycle	0.0030	0.0030	0.0028	0.0029
Maintenance Factor	HaulToPlant/Dump/Stk	h/cycle	2.3000	2.3000	2.3000	2.3000
Total Excluding Unavailability		h/cycle	0.1459	0.1465	0.1390	0.1389
Total Ex-Pit		h/cycle	0.1484	0.1147	0.1421	0.1098

Depth-based Cycle Component		h/t/mbelow	0.0000213	0.0000173	0.0000394	0.0000325
Truck Time Usage - Gradient - all-inclusive		h/cycle/mbelow	0.0021040	0.0017166	0.0015755	0.0013007
[Operating Delay] Idle	PitMining	h/cycle/mbelow	0.0000101	0.0000033	0.0000062	0.0000093
[Non-Productive Time] Move to Loading	PitMining	h/cycle/mbelow	0.0006913	0.0006903	0.0005291	0.0005288
[Productive Time] Loading		h/cycle/mbelow	0.0000000	0.0000000	0.0000000	0.0000000
[Productive Time] Move to unloading	PitMining	h/cycle/mbelow	0.0009395	0.0009383	0.0006976	0.0006971
[Non-Productive Time] Wait for unloading		h/cycle/mbelow	0.0000000	0.0000000	0.0000000	0.0000000
[Productive Time] Unloading		h/cycle/mbelow	0.0000000	0.0000000	0.0000000	0.0000000
[Operating Standby] Failure	PitMining	h/cycle/mbelow	0.0003812	0.0000066	0.0002881	0.0000050
[Operating Delay] Refueling	PitMining	h/cycle/mbelow	0.0000067	0.0000017	0.0000055	0.0000012
[Non-Productive Time] Move to idle		h/cycle/mbelow	0.0000000	0.0000000	0.0000000	0.0000000
[Downtime] Moving to maintenance		h/cycle/mbelow	0.0000000	0.0000000	0.0000000	0.0000000
[Downtime] Maintenance	PitMining	h/cycle/mbelow	0.0000753	0.0000764	0.0000490	0.0000594
Maintenance Raw	HaulToPlant/Dump/Stk	h/cycle	0.0000327	0.0000332	0.0000213	0.0000258
Maintenance Factor	HaulToPlant/Dump/Stk	h/cycle	2.3000	2.3000	2.3000	2.3000
Total Excluding Unavailability		h/cycle/mbelow	0.0016375	0.0016303	0.0012322	0.0012271
WAIT-TIME CHARACTERISTICS						
Describes the curved part of the graph, which is where you'd usually operate.						
Truck Wait as Function of Excavator Wait	WaitTruck = k/WaitExc^n					
Parameter k = a.depth + b	depth is in metres					
Constant a			0.0000105	0.0000144	0.0000039	0.0000022
Constant b			0.00095	0.00131	0.00045	0.00025
Constant n			0.77500	0.53375	0.80190	0.76567
Generalisation for Prober						
Seven points on the non-linear curve						
Excavator Wait % above No-Wait Cycle Time						
W1	InPitWaitTime		140.0%	140.0%	140.0%	140.0%
W2	InPitWaitTime		71.2%	65.8%	67.5%	63.9%
W3	InPitWaitTime		33.1%	26.6%	28.7%	24.5%
W4	InPitWaitTime		19.7%	13.3%	15.3%	11.1%
W5	InPitWaitTime		10.1%	3.6%	7.0%	4.0%
W6	InPitWaitTime		3.8%	0.7%	2.4%	1.1%
W7	InPitWaitTime		1.6%	0.2%	1.0%	0.4%

Truck Wait % above No-Wait Cycle Time						
W1	InPitWaitTime		4.3%	3.8%	2.6%	1.6%
W2	InPitWaitTime		7.3%	5.6%	4.6%	2.9%
W3	InPitWaitTime		13.2%	9.1%	9.2%	6.1%
W4	InPitWaitTime		19.7%	13.3%	15.3%	11.1%
W5	InPitWaitTime		33.1%	26.6%	28.7%	24.5%
W6	InPitWaitTime		71.2%	65.8%	67.5%	63.9%
W7	InPitWaitTime		140.0%	140.0%	140.0%	140.0%

5.4 Appendix D – Mining Cost Model

MODEL SETTINGS					
Case Number		5	6	7	8
Fleet Name		**Medium**	Medium	**Small v2**	Small v2
MineTwin Description		Medium Manned @8(	Medium Autonomou:	Small v2 Manned @80%	Small v2 Autonomous
Fleet					
Excavator Model		Generic 31t Excavator	Generic 31t Excavator	Generic 13t Excavator	Generic 13t Excavator
Truck Model		Heavy Rigid 100t	Heavy Rigid 100t	Vocational 40t	Vocational 40t
Truck Control		Manned	Autonomous	Manned	Autonomous
Truck Nominal UofA Time - MineTwin model sets downtime to approx match this.		80%	95%	80%	95%
				z	
Hours Per Year		8760	8760	8760	8760
1 Source					
Maximum Vertical Rate of Advance	benches/ y	6	6	6	6
2 Drill & Blast					
Drill & Blast	US$/t				
OX	US$/t	$0.02	$0.02	$0.02	$0.02
TR	US$/t	$0.18	$0.18	$0.18	$0.18
FR	US$/t	$0.36	$0.36	$0.36	$0.36
Period Costs - Mining Exc Load & Haul	US$M/y	20	20	20	20
Labour + Maintenance + G&A	US$M/y	20	20	20	20
Capital Costs - Mining Exc Load & Haul	US$M	50	50	50	50
3 Load					
Excavator Model		Generic 31t Excavator	Generic 31t Excavator	Generic 13t Excavator	Generic 13t Excavator
Excavator Shovel Capacity	t	31	31	13	13
Loading Capacity					
Availability		80%	80%	80%	80%
Allowance for bench moving etc		10%	10%	10%	10%
Total Excavator Cycle Time - No-Wait	h/cycle	0.0604	0.0587	0.0531	0.0527
Total Excavator Cycle Time - On-bench, No-Wait, No Unavail (MineTwin)	h/cycle	0.04418	0.04281	0.03871	0.03837
[Operating Delay] Idle	h/cycle	0.00060	0.00060	0.00055	0.00054
[Non-Productive Time] Moving	h/cycle	0.00002	0.00003	0.00000	0.00000
[Non-Productive Time] Waiting for excavating	h/cycle	0.00186	0.00049	0.00039	0.00005
[Productive Time] Excavating	h/cycle	0.04170	0.04170	0.03777	0.03777
[Operating Delay] Moving between benches (not in MineTwin)	h/cycle	0.00417	0.00417	0.00378	0.00378
[Downtime] Maintenance (not in MineTwin)	h/cycle	0.01209	0.01175	0.01062	0.01054
Treat the above differently: Calc after wait applied as blanket %		20%	20%	20%	20%
Initial Fleet Number of Excavators		5	5	11	11
Initial Excavator Calendar Time Limit	**h/y**	**43800**	43800	**96360**	96360
Prober guide on max mass loaded per year	t/y	70,935,498	73,749,472	72,061,440	72,947,079
Make this large enough that can handle the minimum wait for Excavators					
Minimum available excavator wait (of MineTwin only)		1.6%	0.2%	1.0%	0.4%
Minimum available excavator cycle time	h/cycle	0.0611	0.0588	0.0535	0.0528
Approximate tonnage rates (Note: Model uses Exc time instead of tonnes)					
Capacity - On-Bench, No-Wait, No Unavail (MineTwin)	t/h	2,241	2,312	1,033	1,043
Capacity - No-Wait	t/h	1,638	1,686	753	759
Maximum tonnage at minimum excavator cycle time	t/h	1,620	1,684	748	757
Variable Costs - Excavators	*US$/t*				
When Loading (inc on-bench move)					
Diesel	L/t	0.061043582	0.059	0.055769336	0.055316839
Burn rate	L/h	100	100	42	42
Electricity	kW	0	0	0	0
Power Consumption	kWh/h				
Other Consumables and Maintenance	$/h	238.8	238.8	130.2	130.2
Source		Trakindo_CAT fleet cost models_MASTER_v14_04J2116 SPR Equipment_costs.xlsx			
GET rate	$/h	38	38	10	10
Buckets, Bodies and Ropes rate	$/h	6	6	4	4
Oil and Grease Rate	$/h	8	8	1	1
Periodic services including parts	$/h	120	120	74	74
Maintenance Labor Cost	$/h	68	68	41	41
Periodic replacement capex as variable cost	$/h	45.0	45.0	30.0	30.0
Operating life	h	60000	60000	30000	30000
Sustaining capex as hourly cost	$/h	45.0	45.0	30.0	30.0
When Idling, Unavailable or Other Movement					
Diesel	L/t	0	0	0	0
Electricity	kW	0	0	0	0
Other Consumables	$/h	0	0	0	0

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	Period Costs - Excavators	US$M	3.7	3.7	5.7	5.7
	Labour	US$M	1.73	1.73	3.74	3.74
	Operator Cost pa	US$k	80	80	80	80
	Allowance for G&A	US$k	20%	20%	20%	20%
	Shift coverage		3.50	3.50	3.50	3.50
	Num excavators		5	5	11	11
	Number Operators		18	18	39	39
	Maintenance Overheads	US$M	2.0	2.0	2.0	2.0
	Value		2	2	2	2
	Capital Costs - Excavators	US$M	13.5	13.5	9.9	9.9
	Cost per Excavator	US$M	2.7	2.7	0.9	0.9
	Capital cost increase per hour additional capacity	$/h	308.2	308.2	102.7	102.7
4	In-Pit Haul					
	Minimum Haul Depth	m	0	0	0	0
	Maximum Haul Depth	m	460	460	460	460
	Variable Costs - Haul					
	Diesel	L/t				
	In-pit Constant	L/t	0.00000	0.00000	0.00000	0.00000
	In-pit Gradient	L/t/mbelow	0.00145	0.00145	0.00145	0.00145
	Tyres and Other Consumables	Assume no consumption when unavailable/idling				
	In-pit Constant	$/t	0.04168	0.04168	0.03783	0.03780
	In-pit Gradient	$/t/mbelow	0.00202	0.00165	0.00151	0.00125
	Total	$/hutilised	95.0	95.0	38.5	38.5
	GETs rate		0.0		0.0	
	Tyres rate	$/h	14.0	14.0	2.0	2.0
	Buckets, Bodies and Ropes rate	$/h	3.0	3.0	3.0	3.0
	Oil and Grease Rate	$/h	4.5	4.5	2.1	2.1
	Periodic services including parts	$/h	37.1	37.1	3.0	3.0
	Maintenance Labor Cost	$/h	36.5	36.5	28.4	28.4
	Periodic replacement capex as variable cost					
	In-pit Constant	$/t	0	0	0	0
	In-pit Gradient	$/t/mbelow	0.00102	0.00090	0.00053	0.00065
	Operating life	h	25000	25000	15000	15000
	Sustaining capex as hourly cost	$/h	48.00	52.00	13.33	20.00
5	Haul to Stockpile					
	General Flat Haul calculation					
	No wait time at tip-points					
	Haul Distance	km	1.2	1.2	1.2	1.2
	Truck Time Usage					
	Constant flat haul 1200m - all-inclusive	h/t	0.00150	0.00116	0.00355	0.00274
	Truck Time Usage - all-inclusive	h/cycle	0.1484	0.1147	0.1421	0.1098
	Variable Costs - Haul	Assume no consumption when unavailable/idling				
	Diesel					
	Constant flat haul 1200m	L/t	0.0769	0.0769	0.0769	0.0769
	Tyres and Other Consumables					
	Constant flat haul 1200m	$/hutilised	95.0400	95.0400	38.4500	38.4500
	Periodic replacement capex as variable cost					
	Constant flat haul 1200m	$/hutilised	48.0	52.0	13.3	20.0
	Constant flat haul 1200m	$/t	0.0720	0.0602	0.0474	0.0549
6	Haul to Crusher					
	No wait time at tip-points					
	Haul Distance	km	1.2	1.2	1.2	1.2
	Truck Time Usage					
	Constant flat haul 1200m - with unavailability	h/t	0.00150	0.00116	0.00355	0.00274
	Variable Costs - Haul	Assume no consumption when unavailable/idling				
	Diesel					
	Constant flat haul 1200m	L/t	0.0769	0.0769	0.0769	0.0769
	Tyres and Other Consumables					
	Constant flat haul 1200m	$/hutilised	95.0400	95.0400	38.4500	38.4500
	Periodic replacement capex as variable cost					
	Constant flat haul 1200m	$/hutilised	48	52	13	20
	Constant flat haul 1200m	$/t	0.0720	0.0602	0.0474	0.0549

7 Haul to Dump					
No wait time at tip-points					
Haul Distance	km	1.2	1.2	1.2	1.2
Truck Time Usage					
Constant flat haul 1200m - with unavailability	h/t	0.00150	0.00116	0.00355	0.00274
Variable Costs - Haul	Assume no consumption when unavailable/idling				
Diesel					
Constant flat haul 1200m	L/t	0.0769	0.0769	0.0769	0.0769
Tyres and Other Consumables					
Constant flat haul 1200m	$/hutilised	95.0400	95.0400	38.4500	38.4500
Periodic replacement capex as variable cost					
Constant flat haul 1200m	$/hutilised	48	52	13	20
Constant flat haul 1200m	$/t	0.0000	0.0000	0.0000	0.0000
8 Rehandle Stockpile To Plant					
Stockpile to Plant distance	km	0.6	0.6	0.6	0.6
Truck Time Usage					
Constant flat haul - with unavailability	h/t	0.001692	0.001422	0.003947	0.003307
Truck Time Usage - with unavailability	h/cycle	0.167529	0.140792	0.157876	0.132270
[Operating Delay] Idle	h/cycle	0.0011	0.0014	0.0010	0.0009
[Productive Time] Move to Loading	h/cycle	0.0229	0.0233	0.0223	0.0224
[Non-Productive Time] Wait For Loading	h/cycle	0.0279	0.0235	0.0263	0.0220
[Productive Time] Loading	h/cycle	0.0417	0.0417	0.0378	0.0378
[Productive Time] Move to unloading	h/cycle	0.0276	0.0280	0.0263	0.0265
[Non-Productive Time] Wait for unloading	h/cycle	0.0000	0.0000	0.0000	0.0000
[Productive Time] Unloading	h/cycle	0.0178	0.0178	0.0177	0.0177
[Operating Standby] Failure	h/cycle	0.0234	0.0004	0.0217	0.0004
[Operating Delay] Refueling	h/cycle	0.0004	0.0001	0.0004	0.0001
[Non-Productive Time] Move to idle	h/cycle	0.0002	0.0001	0.0001	0.0001
[Downtime] Moving to maintenance	h/cycle	0.0000	0.0000	0.0000	0.0000
[Downtime] Maintenance	h/cycle	0.0045	0.0046	0.0043	0.0044
Variable Costs - Haul	Assume no consumption when unavailable/idling				
Diesel					
Constant flat haul	L/t	0.050	0.050	0.050	0.050
Tyres and Other Consumables					
Constant flat haul	$/hutilised	95.0400	95.0400	38.4500	38.4500
Constant flat haul	$/t	0.1608	0.1352	0.1518	0.1271
Periodic replacement capex as variable cost					
Constant flat haul	$/hutilised	48	52	13	20
Constant flat haul	$/t	0.0812	0.0740	0.0526	0.0661
9 Base Haul Fleet					
Calc based on stockpile rehandle. Do not allow fewer than two trucks.					
Truck Model		Heavy Rigid 100t	Heavy Rigid 100t	Vocational 40t Class 8	Vocational 40t Class 8
Truck Capacity	t	99	99	40	40
Number Trucks - Base Fleet		5	4	11	10
Truck Calendar Time Per Year	h	8760	8760	8760	8760
Stockpile to Plant time per cycle - all-inclusive	h	0.1675	0.1408	0.1579	0.1323
Mass movement rate	t/h	591	703	253	302
Num Trucks Required (fractional)	#	4.64	3.90	10.81	9.06
Truck Calendar Time Limit	**h**	**43800**	**35040**	**96360**	**87600**
Nominal Mass Haulage	t/y	7,617,611	7,574,634	8,430,962	9,472,235
Period Costs - Truck Base Fleet - Applied against TruckB hour limit	US$M	4.7	4.8	6.7	5.5
Labour	US$M	1.7	1.5	3.7	1.7
Operator Cost pa	US$k	80	80	80	80
Allowance for G&A	US$k	20%	20%	20%	20%
Shift coverage		3.50	3.50	3.50	3.50
Num truck operators		5.0	0.4	11.0	1.0
Num central operators		0.00	4.0	0.00	4.0
Operators required		18	16	39	18
Maintenance Overheads	US$M	3.0	3.0	3.0	3.0
Const		3.00	3.00	3.00	3.00
Pronto Cost	US$M	0.0	0.3	0.0	0.8
Annual fee per truck	US$M/y/Truck	0.000	0.075	0	0.075
Truck Capital	(dynamic)				
Cost per Truck Total	US$M/truck	1.2	1.3	0.2	0.3
Cost per Truck	US$M/truck	1.2	1.2	0.2	0.2
Automation	US$M/truck	0	0.1	0	0.1
Cost Base Haul Fleet	US$M	6.0	5.2	2.2	3.0

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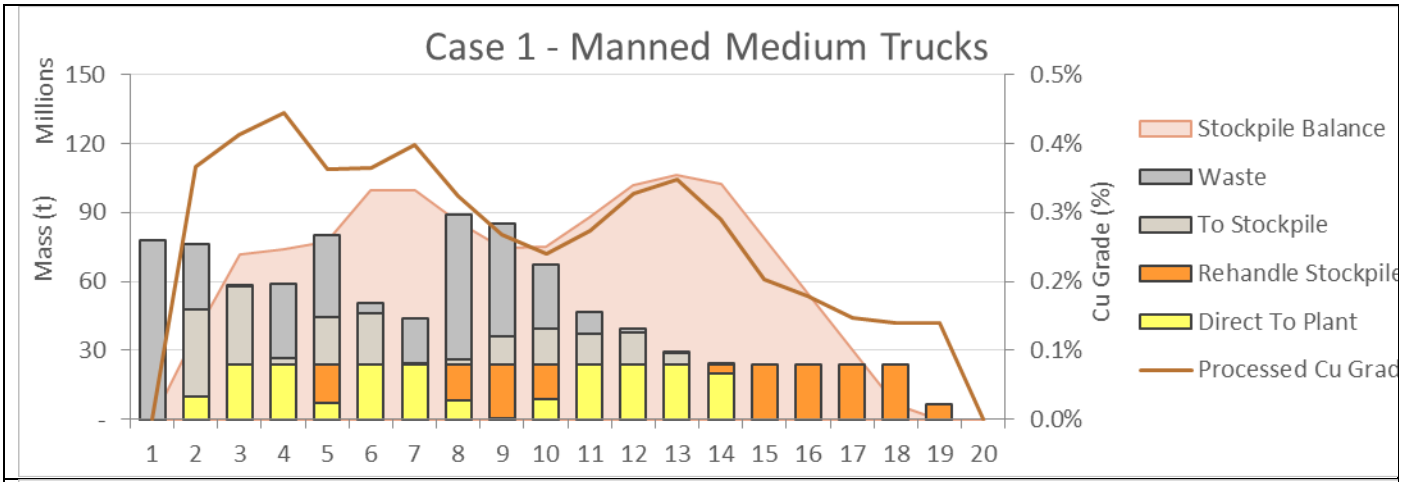
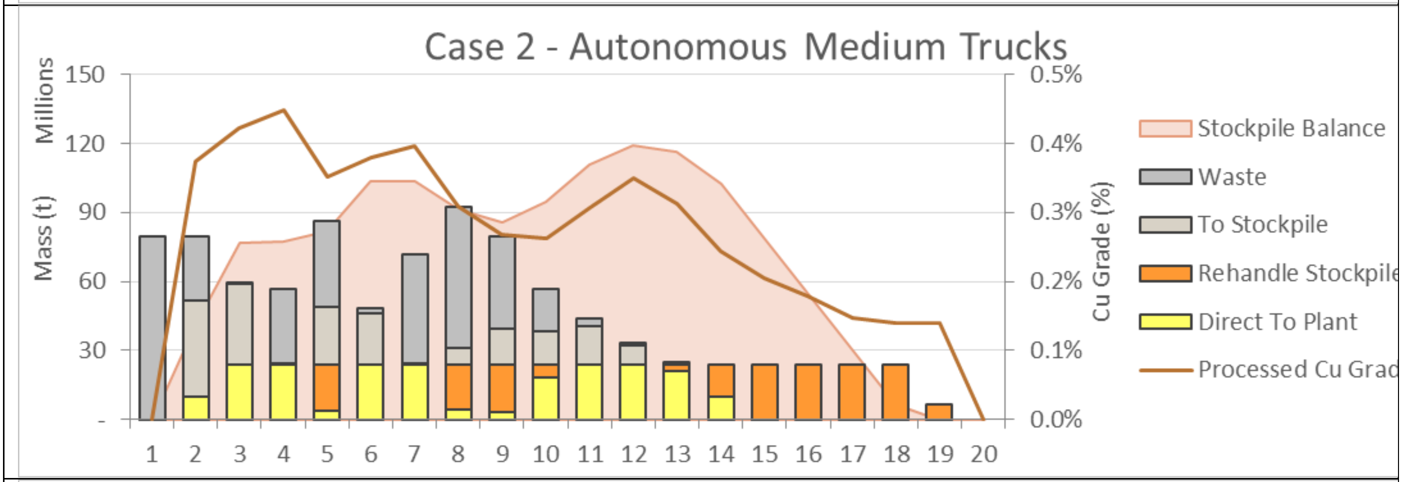
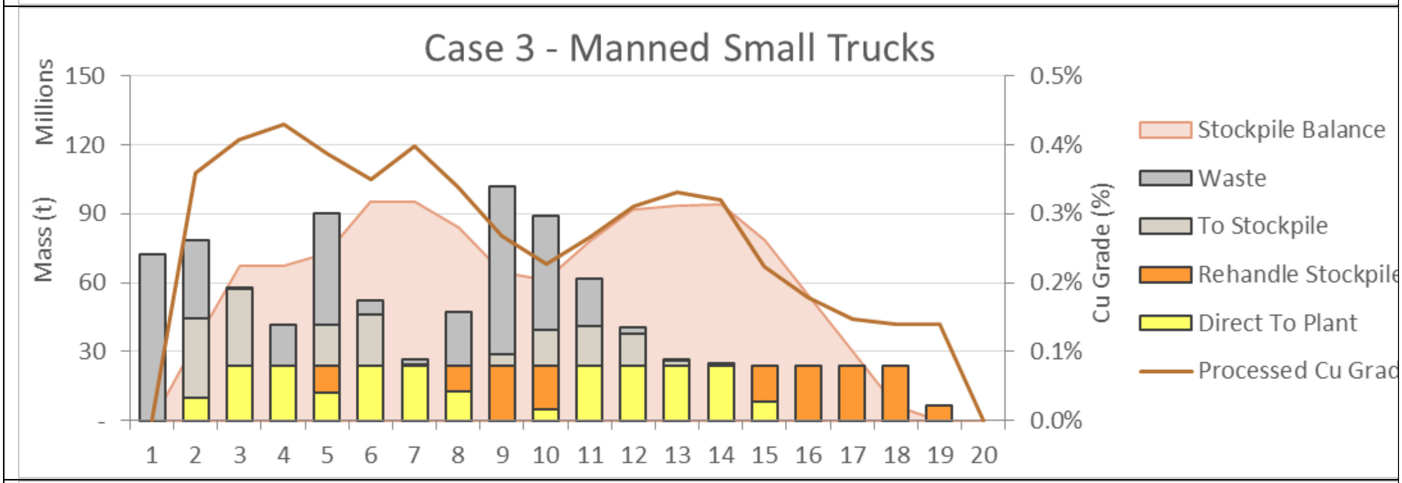
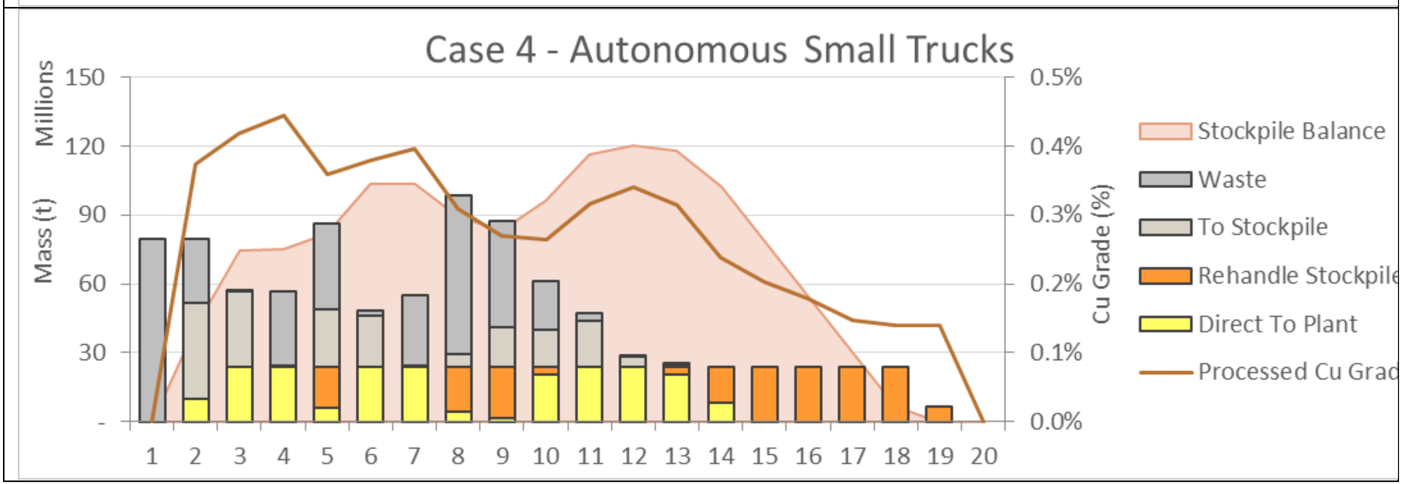
10	Main Haul Fleet					
	Truck Model		Heavy Rigid 100t	Heavy Rigid 100t	Vocational 40t Class 8	Vocational 40t Class 8
	Truck Capacity		99	99	40	40
	Number of Trucks optimised by Prober					
	Minimum Num Trucks		18	16	33	30
	Minimum Truck Calendar Time Limit	**h/y**	**157680**	**140160**	**289080**	**262800**
	Nominal Mass Haulage	t	27,423,398	30,298,535	25,292,885	28,416,706
	Period Costs - Main Haul Fleet					
	Per Truck	US$M/y/Truck	0.34	0.11	0.34	0.11
	Labour	US$M/y/Truck	0.34	0.03	0.34	0.03
	Operator Cost pa	US$k	80	80	80	80
	Allowance for G&A	US$k	20%	20%	20%	20%
	Shift coverage		3.50	3.50	3.50	3.50
	Num truck operators per shift per truck		1.0	0.1	1.0	0.1
	Number Operators	#/y/Truck	3.5	0.35	3.5	0.35
	Maintenance Overheads	US$M/y/Truck	0.00	0.00	0.00	0.00
	Pronto Cost	US$M/y/Truck	0.000	0.075	0.000	0.075
	Minimum Period Cost	US$M	6.0	0.5	11.1	1.0
	Minimum Labour Cost	US$M	6.0	0.5	11.1	1.0
	Minimum Number Operators	#	63	6	116	11
	Minimum Maintenance	US$M	0.0	0.0	0.0	0.0
	Ref Cost one truck		0.0	0.0	0.0	0.0
	Minimum Pronto Cost	US$M	0.0	1.2	0.0	2.3
	Variable-ised Period Costs - for Trucks above minimum					
	Allowance for variability/contract		30%	30%	30%	30%
	Total per hour	US$/h	49.9	16.1	49.9	16.1
	Capital Costs - Main Haul Fleet					
	Use Capital Scaling to size this limit					
	Cost per Truck Total	US$M/truck	1.20	1.30	0.20	0.30
	Minimum cost of main haul fleet	US$M	21.6	20.8	6.6	9.0
	For Extension of fleet					
	Capital cost per calendar hour	US$/h	137.0	148.4	22.8	34.2
11	Diesel Supply					
	Diesel Cost Rate	US$/L	0.5	0.5	0.5	0.5
12	Electricity Supply					
	Electricity Cost Rate	US$/kWh	0.1	0.1	0.1	0.1
13	Plant					
	Mass Limit	**Mt**	24	24	24	24
	Recovery		82%	82%	82%	82%
	Variable Costs	US$/t	6	6	6	6
	Period Costs	US$M/y	40	40	40	40
	Capital Cost	US$M	800	800	800	800
14	Sell Product					
	Net Copper Price	US$/t	7500	7500	7500	7500
		US$/lb	3.35	3.35	3.35	3.35

5.5 Appendix E – Result Charts

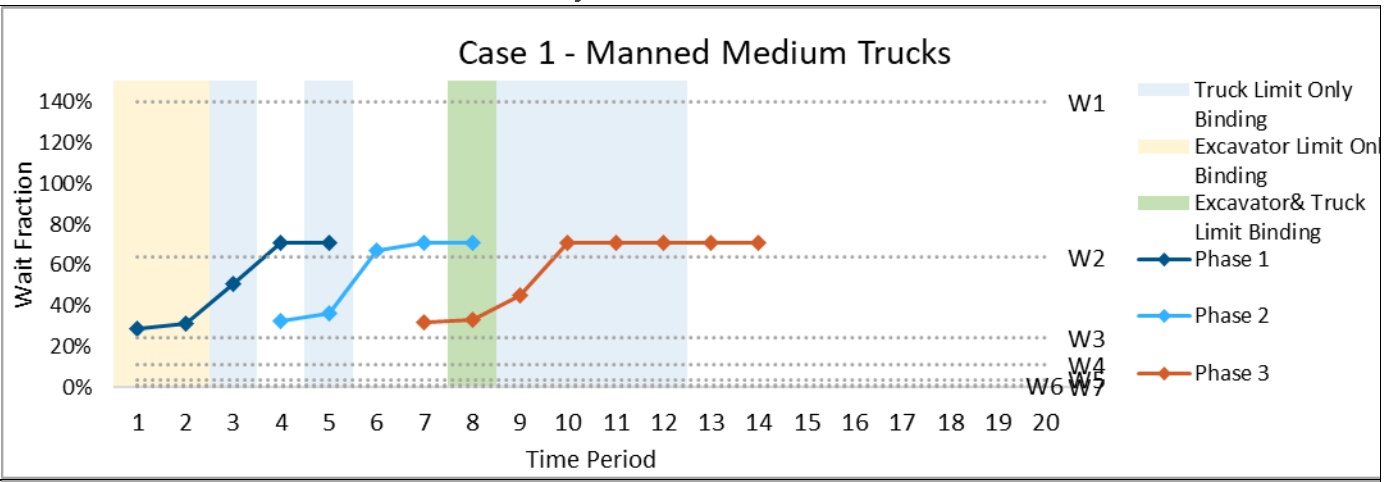


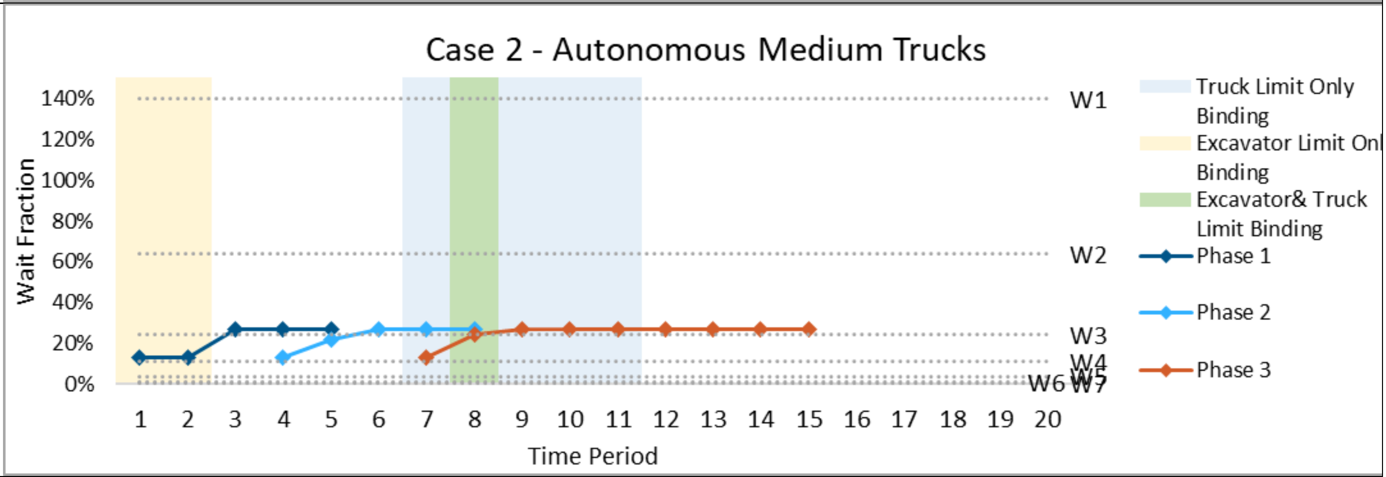


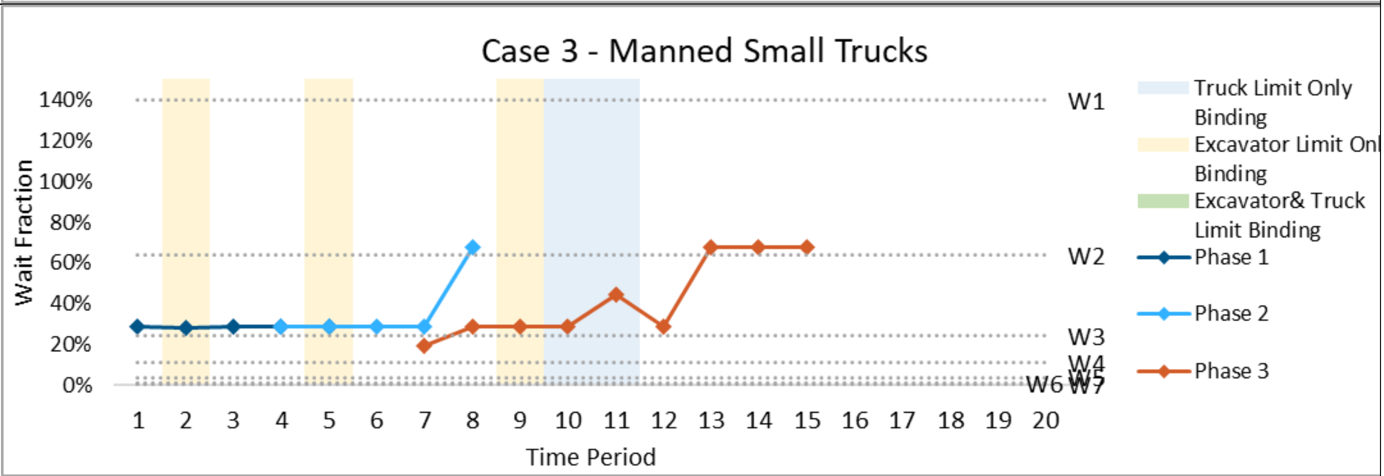


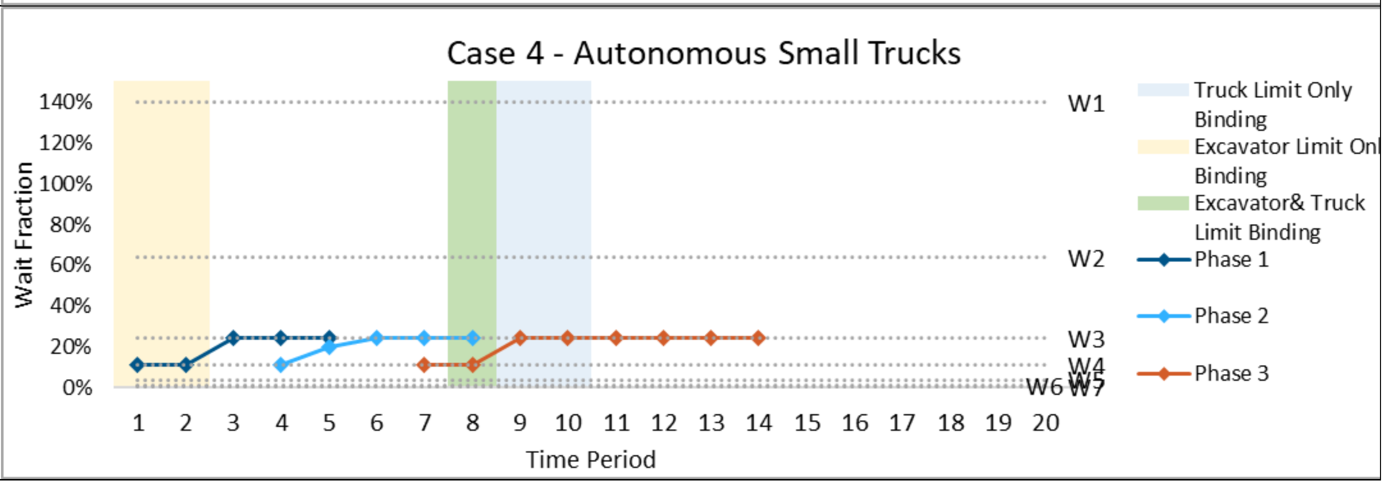


5.5.1 Excavator Wait % above Zero-Wait Cycle Time

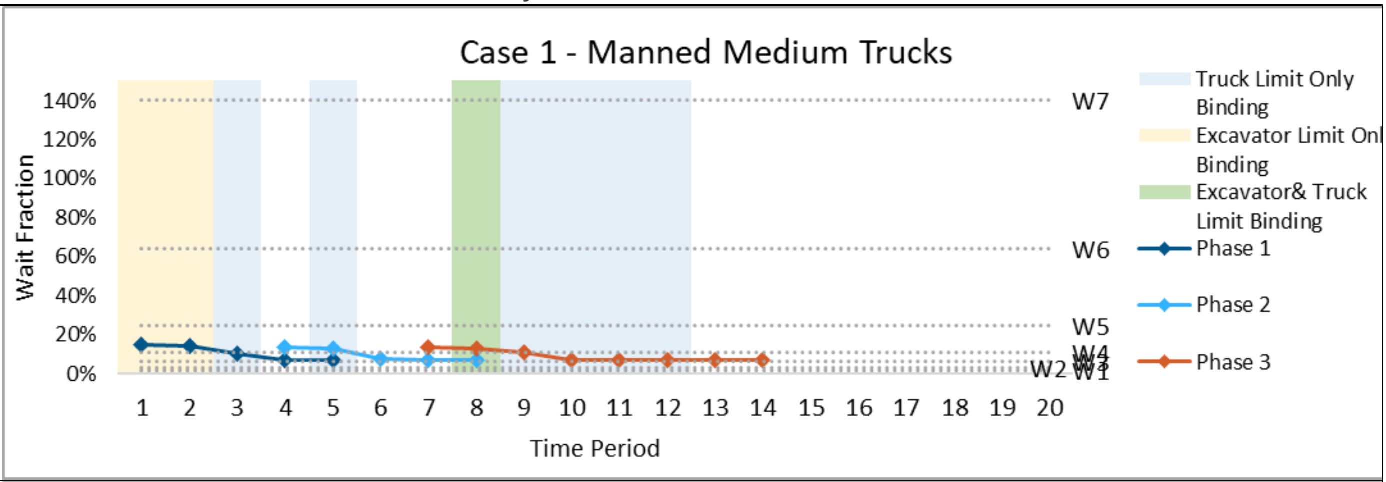


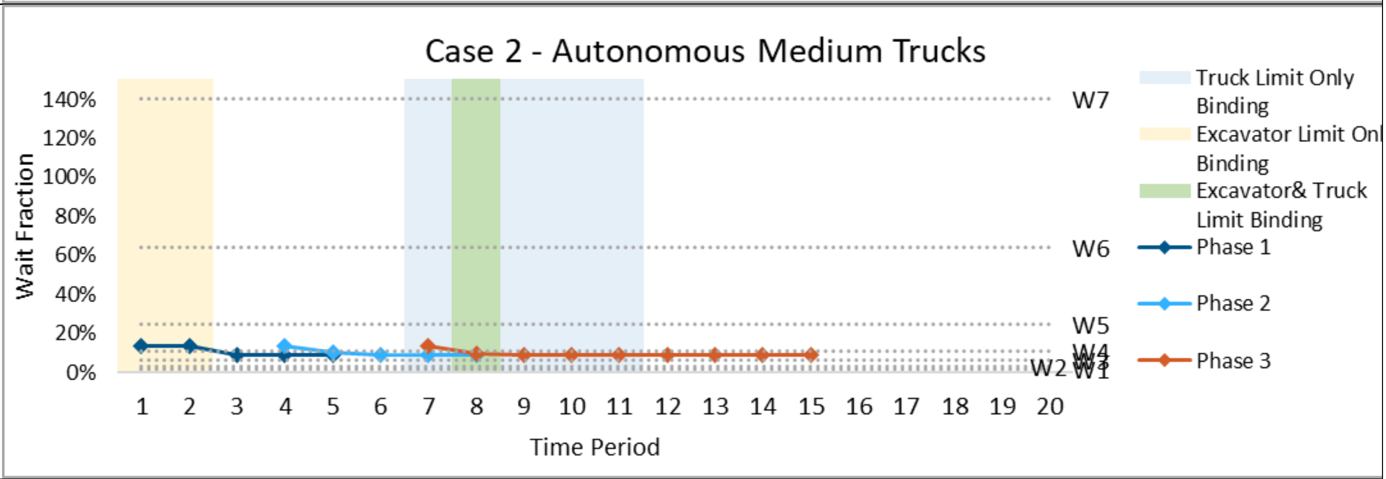


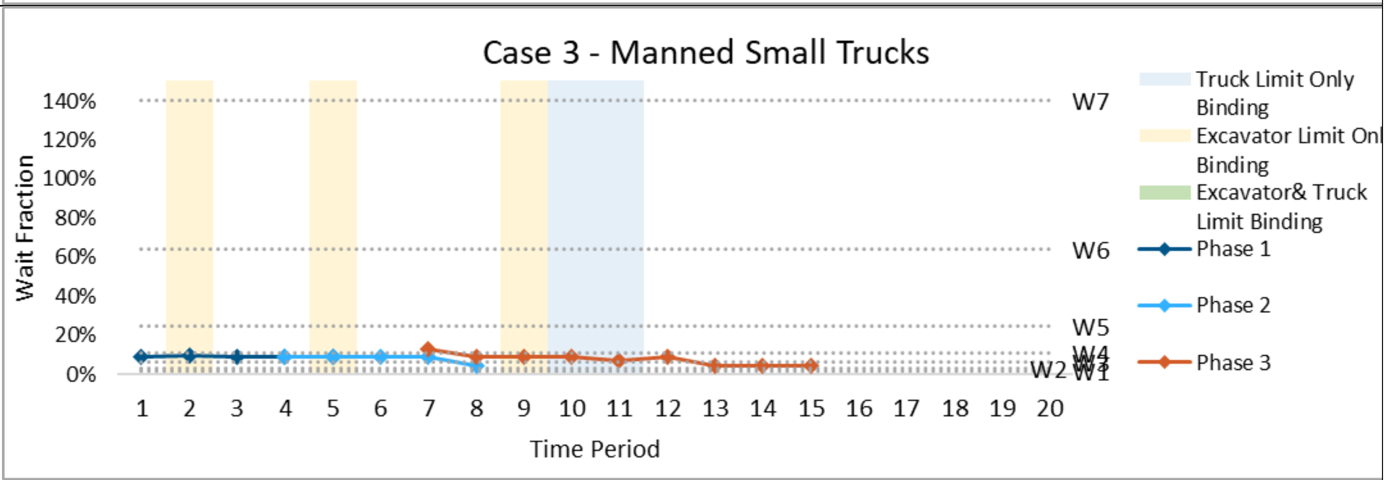


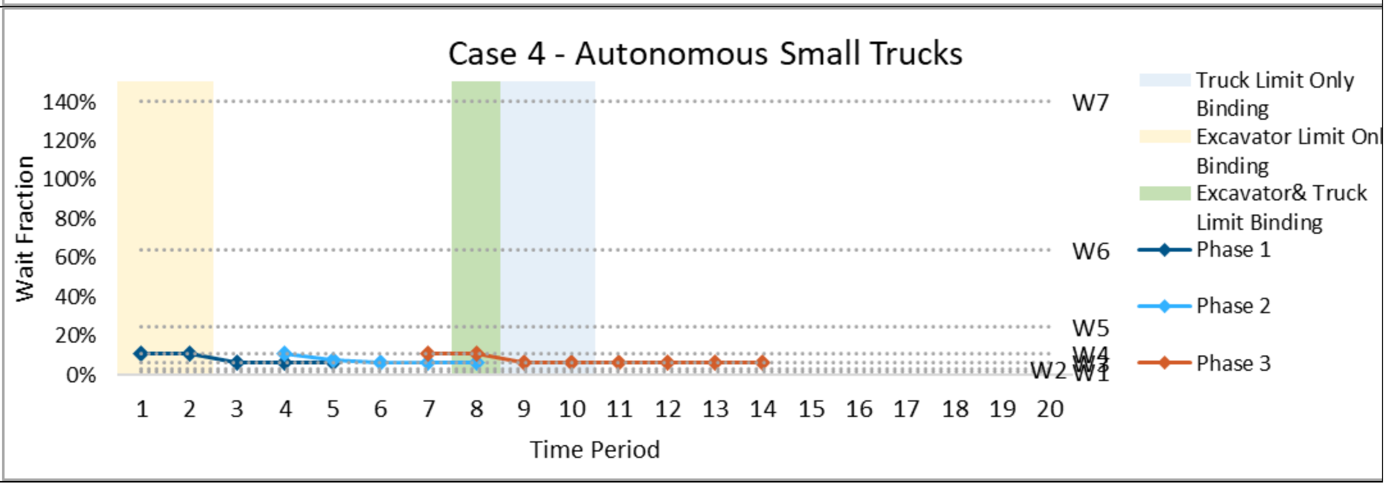


5.5.2 Truck Wait % above Zero-Wait Cycle Time

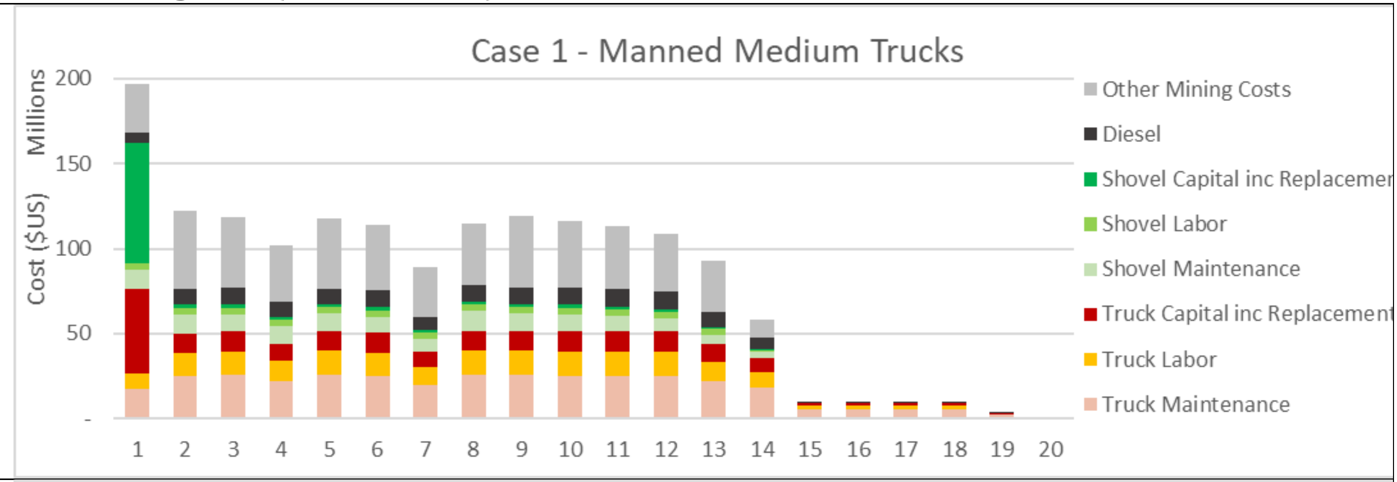


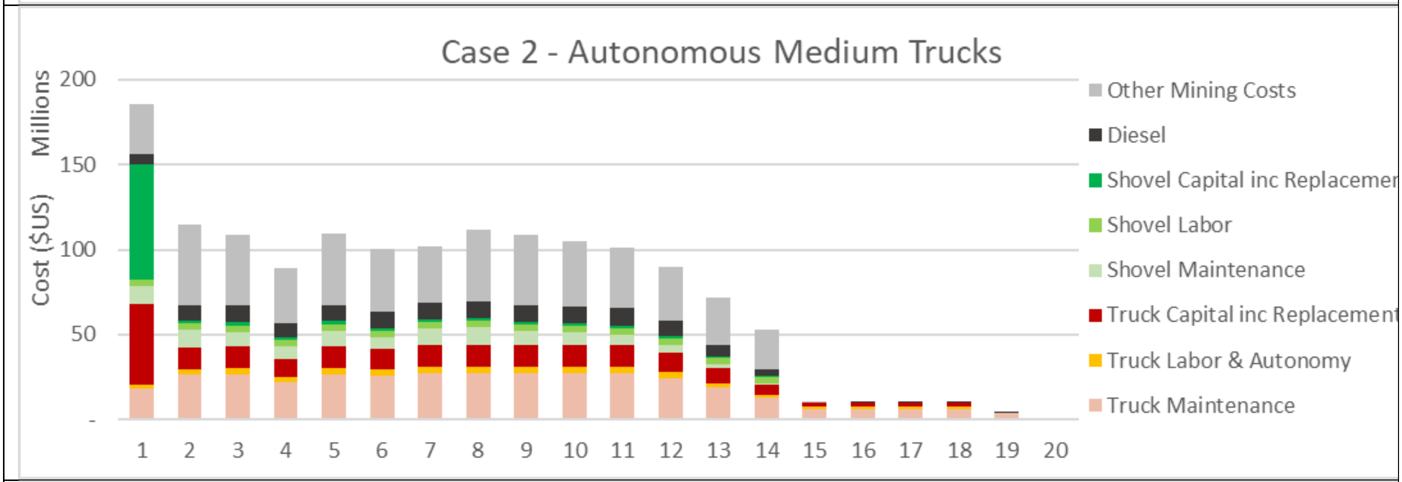


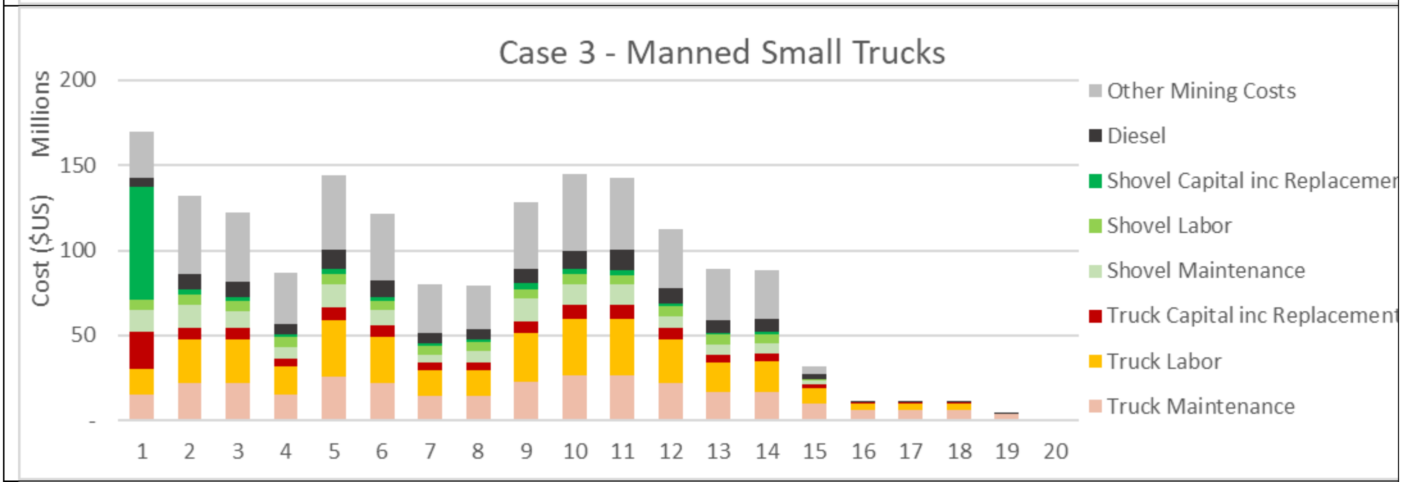


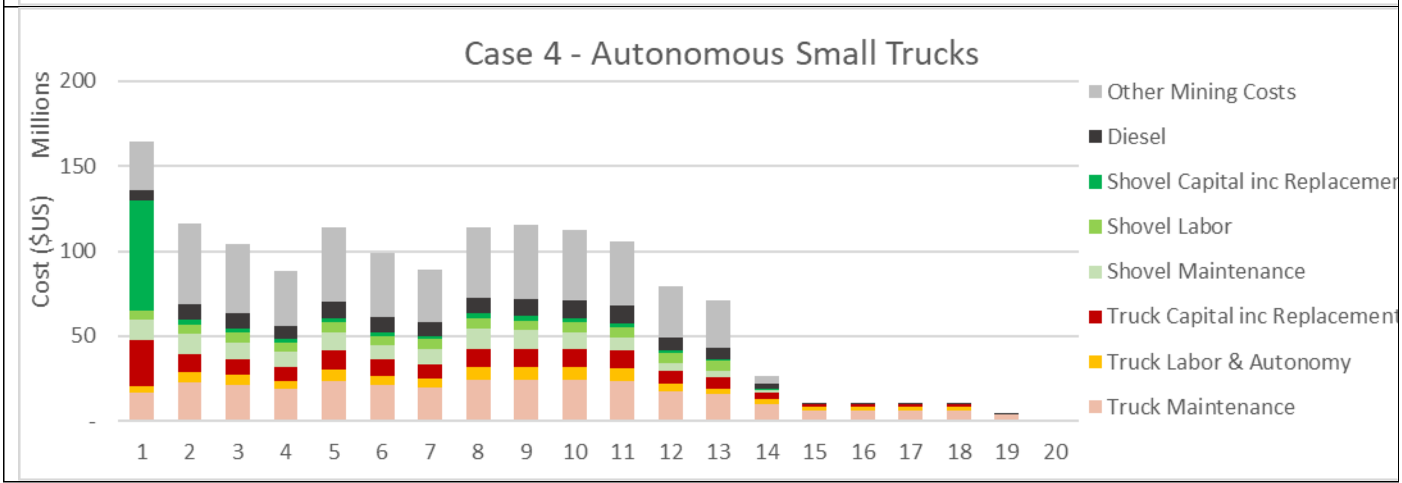


5.5.3 Mining Costs (not discounted) over LOM









5.6 Appendix F – Result Discounted Cash Comparison

Discounted Cash	1	2	3	4				
	Manned Medium Truck	Autonomous Medium Truck	Manned Small Truck	Autonomous Small Truck		Diff 2 - 1	Diff 3 - 1	Diff 4 - 1
NPV	**390**	**479**	**356**	**510**		**89**	**- 34**	**120**
Total Revenue	**3,820**	**3,834**	**3,809**	**3,834**		**14**	**- 11**	**14**
Copper	3,820	3,834	3,809	3,834		14	- 11	14
Total Costs	**3,430**	**3,355**	**3,453**	**3,324**		**- 75**	**23**	**- 106**
Total Mining Costs	**994**	**918**	**1,016**	**887**		**-75**	**23**	**-106**
Total Mining Variable Costs	**575**	**567**	**502**	**530**		**-9**	**-73**	**-46**
Drill & Blast	136	138	133	138		2	-3	2
Shovel - Diesel	17	14	13	12		-3	-3	-4
Shovel - Other Cost	79	65	83	77		-14	4	-2
Shovel - Periodic Replacement Cost	15	12	19	18		-3	4	3
Haul - Diesel	58	59	57	59		1	-1	1
Haul - Time-Based Maintenance	180	180	146	148		0	-34	-31
Haul - Periodic Replacement Cost	91	98	51	77		7	-40	-14
Total Mining Period Costs	**316**	**254**	**439**	**282**		**-62**	**123**	**-34**
Drill + Blast + Other overheads	159	165	165	159		6	6	-1
Shovels	30	31	47	46		1	18	16
Haul Labor	98	18	198	24		-80	99	-74
Haul Maintenance Overheads	28	28	28	28		0	0	0
Autonomy Ongoing Cost	-	12	-	25		12	0	25
Total Mining Capital Costs	**103**	**98**	**75**	**76**		**-5**	**-28**	**-27**
Shovels	63	61	59	57		-2	-5	-6
Haul Trucks	39	36	16	18		-3	-23	-21
Haul Fleet Base	6	5	2	3		-1	-4	-3
Haul Fleet Main	20	19	6	8		-1	-14	-12
Haul Fleet Extension	14	12	8	7		-1	-6	-6
Total Plant Costs	**2,437**	**2,437**	**2,437**	**2,437**		**0**	**0**	**0**
Plant Variable Costs	1,153	1,153	1,153	1,153		0	0	0
Plant and G&A Period Costs	358	358	358	358		0	0	0
Plant and Other Capital Costs	926	926	926	926		0	0	0