The Effects of Payload Variance on Mine Haul Truck Energy Consumption, Greenhouse Gas Emission and Cost

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Abstract

The data collected from haul truck payload management systems at various surface mines show that the payload variance is significant and must be considered in analysing the mine productivity, diesel energy consumption, greenhouse gas emission and associated costs. This paper investigates the effects of haul truck payload variance on diesel energy consumption, greenhouse gas emission and their associated cost in surface mining operations. The significance of this investigation is to determine the energy and cost saving opportunities in haul truck operations. This study examines CAT 793D that is one of the mostly used haul trucks in surface mining operations. The rate of greenhouse gas emission corresponding to diesel consumption by haul trucks is calculated according to the Global Warming Potential guidelines. The associated cost of greenhouse gas emission and cost of diesel consumption are determined based on models presented by U.S. Energy Information Administration. The results show that the fuel consumption, rate of greenhouse gas emission and their costs linearly increase as the payload variance rises for all haul road friction and slope conditions. The correlation between the payload variance and cost saving is developed. This correlation is independent of haul road condition and presents the amount of saving for different values of payload variance reduction. The cost saving is calculated for an Australian surface mine as a case study. The analysis showed that up to 45% of cost associated with fuel and $CO_2 - e$ emission is salvable by reducing payload standard deviation from 30 to zero. This amount of saving is equal to 277.71 M$.

Keywords: Fuel consumption; Haul truck; Surface mine; Greenhouse gas emission; Cost

Nomenclature

CCS	Carbon dioxide Capture and Storage
CC_S	Core Case Scenario
$CO_2 - e$	CO_2 Equivalent
$CO_2 - e_{Index}$	CO_2 Equivalent Index
$CO_{2\ Index}$	CO_2 Index
EF	Emission Factor
EIA	Energy Information Administration
FC	Fuel Consumption
FC_{Index}	Fuel Consumption Index
GHGs	Greenhouse Gases
GR	Grade Resistance
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HC_S	High Cost Scenario
LA_S	Limited Alternatives Scenario
LF	Load Factor
NGHGs	Non-Greenhouse Gases
NIO_S	No International Offsets Scenario
P	Power
R	Rimpull
RC	Rimpull Coefficient
RR	Rolling Resistance
SD	Standard Deviation (σ)
TR	Total Resistance
V_{max}	Maximum Haul Truck Speed

1. Introduction

Mining industry consumes a huge amount of energy in various operations such as exploration, extraction, transportation and processing [1, 2]. The main part of this consumed energy can be saved by improving mining technologies [3-6]. The mining method and equipment used mainly determine the type of energy source in any mining operation [7, 8]. In surface mining operations, haul trucks use diesel as the source of energy [9, 10].

Haul trucks are generally used in combination with other equipment such as excavators, diggers and loaders, according to the production capacity and site layout [1]. Haul trucks use a great amount of fuel in surface mining operation; hence mining industry is encouraged to conduct a number of research projects on the energy efficiency of haul trucks [11, 12].

There are different kinds of parameters that affect the amount of fuel consumption by haul trucks such as payload, speed of truck, haul road condition, traffic layout, fuel quality, weather condition, driver behaviour [13-16]. A review of literature indicates that the understanding of energy efficiency of a haul truck is not limited to the analysis of vehicle-specific parameters; and mining companies can often find greater energy saving opportunities by expanding the analysis to include other effective factors such as payload distribution and payload variance [16-18].

Loading process in truck and shovel mining method is a stochastic process [18, 19]. Analysis of haul truck payload data from a number of mine sites around the world shows that the payload distribution can be estimated by a normal distribution function with a satisfactory error; and the variance associated with haul truck payloads is typically large [17, 18, 20, 21]. The payload variance depends on a number of parameters such as particle size distribution, swell factors, material density and fill factor [17-19, 22]. Many attempts have been developed to reduce the payload variance by using the latest developed technologies such as truck on-board payload measurement system, direct connection between this system and the shovel control system and on-line fleet monitoring system [17, 18, 23].

The payload variance not only effects the production and fuel consumption, but it is also an important parameter in the analysis of gas emission and cost. Many research studies have already been conducted to measure the gas emission by haul trucks in mining industry [24-28]. In addition, several numbers of economic models have been presented to predict the cost of diesel and gas emission for industries [29-34].

In this paper, the effects of payload variance on fuel consumption for a popular haul truck in surface mines (CAT 793D) are investigated. A model is presented to estimate the effect of payload variance on the gas emission and the total cost associated with fuel consumption and gas emission. The corresponding energy saving opportunities to the reduction of payload variance are also investigated.

2. Theoretical Analysis

2.1 Haul Truck Payload Variance

Loading performance depends on different factors such as operators' efficiency, weather conditions, utilisation for trucks and shovels, mine planning and mine equipment selection [17, 18]. In addition, to loading a truck in an effective manner, the shovel operator must also strive to load the truck with an optimal payload. An optimal load can be defined in different ways, but it is always designed so that the haul truck will carry the greatest amount of material with lowest payload variance [14]. The payload variance can be illustrated by carrying different amount of overburden or ore by same trucks in each cycle. Based on the capacity and power of truck the range of payload variance can be defined. Payload variance in a surface mine fleet can be effective parameter on productivity by truck bunching phenomena in large surface mines [17]. The increasing of payload variance decreases the accuracy of maintenance program that is because the rate of equipment wear and tear is not predictable when the mine fleet faces with a large payload variance [28, 35]. Minimising the variation of particle size distribution, swell factors, material density and fill factor can be caused to decreasing the payload variance but some of mentioned parameters are not controllable. Hence, the pertinent methods to minimise the payload variance are using truck on-board payload measurement system and on-line fleet monitoring.

2.2 Haul Truck Fuel Consumption

The fuel consumption for haul trucks is determined based on the following parameters: The Gross Vehicle Weight (GVW), which is the sum of the weight of an empty truck and the payload. The maximum haul truck speed (V_{max}), at which the haul truck operates at its best performance [36]. The Total Resistance (TR), which is equal to the sum of Rolling Resistance (RR) and Grade Resistance (GR) when the truck is moving against the grade of the haul road [1]. The Rimpull (R), which is the force available between the tyre and the ground to propel the truck [37]. These parameters are illustrated in Figure 1.

Caterpillar trucks are the most popular vehicles amongst all different brands of trucks used in the mining industry [38]. Based on the power and capacity of haul truck and mine productivity, CAT 793D (Table 1) is selected for the analysis presented in this study. Figure 2 presents the Rimpull-Speed-Grade ability curve extracted from the manufacturer's catalogue for CAT 793D [39].

The rate of haul truck fuel consumption can be calculated from the following equation (Runge [35]).

$$FC = P \times 0.3 \times LF \tag{1}$$

where LF is the ratio of average payload to the maximum load in an operating cycle (Table 2) [25, 37] and P is the truck power determine by [40]:

$$P = R \times V_{max} \tag{2}$$

2.3 Greenhouse Gas Emission

Diesel engines release both greenhouse gases $(GHGs)$ and non-greenhouse gases $(NGHGs)$ emissions into the environment [33]. Total greenhouse gas emissions are calculated according the Global Warming Potential (GWP) and expressed in CO_2 equivalent or $CO_2 - e$ [27].

The following equation can be used to determine the $GHGs$ emissions by haul truck diesel engines [25, 41].

$$GHG_{\ Emissions} = (CO_2 - e) = FC \times EF \tag{3}$$

Where FC is the quantity of fuel consumed (kL) and EF is an emission factor. The emission factor for haul truck diesel engines is 2.7 tonnes $CO_2 - e/kL$ [30, 31, 42].

2.4 Cost of Greenhouse Gas Estimation and Fuel Consumption

2.4.1 Cost of Greenhouse Gas Emission

There are many empirical models with a range of values for the cost of greenhouse gas emission and they are based on U.S potential CO_2 legislation [28].In this project, the U.S. Energy Information Administration (EIA) model as a conservative model is selected. This model assumes different allowance prices per year or in other words a CO_2 penalty under various scenarios: Core Case Scenario (CC_S), High Cost Scenario (HC_S), No International Offsets Scenario (NIO_S), Limited Alternatives Scenario (LA_S) and Limited Alternatives / No International Offsets Scenario [24].

Table 5 presents a prediction of cost $GHGs$ emissions for difference years (from 2015 to 2050) based on the mentioned scenarios [28].

In this project, the latest scenario has been used to calculate the greenhouse gas emission cost. This scenario is a combination of (LA_S) and (NIO_S) scenarios. This scenario presents that, the key low emission technologies, nuclear, Carbon dioxide Capture and Storage (CCS) and renewables will be developed in a timeframe consistent with emission reduction requirements without encountering major obstacles where the use of international offsets is severely limited by cost or regulation.

2.4.2 Cost of Fuel Consumption

The cost of fuel depends on many economic and international policy parameters [43]. There is several numbers of models to estimate the diesel price in the future [44]. The US Energy Information Administration (EIA) model is a famous economic model that can be used in this area [28]. The result of mentioned model is illustrated in figure 3. According to the graph (Figure 3), it can be seen a dramatic rising trend in the price of diesel from 2010 to 2011, after that period the cost of fuel has been fluctuated until 2014. This model estimates the price of diesel would be about one American dollar in 2015.

3. Results and Discussions

3.1 Haul Truck Payload Variance

The variance of payload can be shown by variance of Standard Deviation (SD). Figure 5 shows the different kinds of normal payload distribution (the best estimation function for payload distribution) based on the difference SD for CAT 793D. This illustration shows that by reduction of standard deviation, the range of payload variation is reduced as well. Based on the CAT 793D technical specifications the range of GVW variation is from 165 tonnes (empty truck) to 385 tonnes (maximum payload). Hence, the maximum SD for this truck can be defined 30; that is because, for higher Standard Deviations, the minimum GVW is less than the weight of empty truck and the maximum GVW is more than the maximum capacity of truck.

3.2 Haul Truck Fuel Consumption

3.2.1 Rimpull analysis

The Rimpull-Speed-Grade ability curve for CAT 793D truck (Figure 2) is used to determine the Rimpull (R) and the Maximum Speed (V_{max}) of the truck based on the values of GVW (in the range of 165 to 385 tonnes) and TR (in the range of 1 to 30%). The data for each TR-line (presented in Figure 2) are collected by DATATHIEF® software and the slope of each TR-line (Rimpull Coefficient, RC) is calculated and presented in Table 3. The Rimpull for different values of RC and GVW can be determined by:

$$R = (RC \times GVW \times 110)/600 \tag{4}$$

3.2.2 *Maximum Speed*

The data for maximum speed curve (presented in Figure 2) are collected by DATATHIEF® software and the best correlation between R and V_{max} has been defined by applying a non-linear regression method (Cure Expert Professional Software V.2.1). The following equation presents this correlation.

$$V_{max} = 53.87 - 54.91 \exp(-37.98 R^{-1.31}) \tag{5}$$

3.2.3 *Fuel Consumption*

Figure 4 illustrates the variation of V_{max} and FC with GVW for six values of TR. The results generally show that for all values of total resistance, the V_{max} decreases and the FC increases as the GVW increases. It must be noted that the rate of fuel consumption is calculated based on the best performance of the truck recommended by the manufacturer, which are for the maximum truck speed and the corresponding Rimpull.

Based on the mentioned equations, the fuel consumption by CAT 793D can be calculated by following equation.

$$FC = (16.16 - 16.47 \exp(-37.98 R^{-1.31}) \times R \times LF \tag{6}$$

Equation 5 presents a correlation between rimpull, load factor and fuel consumption by mentioned haul truck in surface mine.

3.3 Effects of Payload Variance on Fuel Consumption

The effect of payload variance on fuel consumption by haul track in different haul road conditions is illustrated in Figure 6. In this figure, total resistance has been changed from 5% to 30% and standard deviation is variable between 0 and 30. It is noted that, to have a better understanding, a fuel consumption index (FC_{Index}) has been defined. This index presents the quantity of fuel used by haul truck to move one tonne mine material (Ore or Overburden) in one hour. Figure 6 demonstrates that, there is a linear relationship between the variation of standard deviation and fuel consumption for a certain haul condition. The FC_{Index} is growing up with increasing total resistance but this upward trend is not equal for different variation of TR.

Finding the best correlation between standard deviation (Payload Index), fuel consumption index (Truck Index) and total resistance (Haul Road Index) can be very important to calculate the effect of payload variance on fuel consumption by haul trucks. Hence, following equation is developed to estimate the fuel used by trucks in different road condition and payload variance.

$$FC_{Index} = \frac{0.259 + 0.019(\sigma) + 0.016(TR)}{1 - 0.001(\sigma) + 0.004(TR)} \quad (7)$$

Equation 7 presents the correlation between standard deviation, total resistance and fuel consumption index.

3.4 Effects of Payload Variance on Greenhouse Gas Emission

The variation of $CO_2 - e$ with standard deviation for CAT 793D is presented by $CO_2 - e_{\ Index}$ in Table 4. The $CO_2 - e_{\ Index}$ presents the amount of greenhouse gas emission generated by truck to haul one tonne ore or overburden in one hour. Based on the tabulated results, it is obvious that the $CO_2 - e_{\ Index}$ increases by growing the standard deviation for each haul road total resistance. This developing trend has been realized with increasing total resistance. Minimum greenhouse gas is emitted in minimum total resistance $(TR = 5\%)$ when the standard deviation has been zero $(\sigma = 0)$ and maximum pollution is generated in maximum total resistance and standard deviation $(TR = 30\% \text{ and } \sigma = 30)$.

3.5 Effects of Payload Variance on Cost

3.5.1 Cost of Greenhouse gas Emission

All scenarios that can be used to predict the cost of greenhouse gas emission estimate that this cost is in the range of \$20.91 to \$53.53 in 2015 (Table 5). In this project, the maximum cost of $CO_2 - e$ emission (\$53.53 per tonne) was considered.

3.5.2 Cost of Fuel Consumption

Figure 3 illustrates that, there is a vast variation in the price of diesel between 2010 and 2015 but it is estimated that the price of this type of fuel would be about one American dollar in 2015 for industrial use. Hence, in this project the price of fuel for haul trucks in surface mines is assumed 0.98 \$ in 2015.

3.5.3 Total Cost

The calculated $FC_{\ Index}$, Cost $_{Index}$ for fuel consumption, $CO_2 - e_{\ Index}$, Cost $_{Index}$ for greenhouse gas emission and Total Cost $_{Index}$ of for CAT 793D with $TR = 5\%$ in 2015 are tabulated in Table 6. In this haul road condition, there is a direct relationship between increasing the payload variance and Total Cost $_{Index}$. Total Cost $_{Index}$ presents the total cost of fuel consumed and $CO_2 - e$ emitted to haul one tonne mine material by truck in one hour. In this case the Total Cost $_{Index}$ can be variable between 0.55 and 1.22 \$/ (hr.tonne) for different value of standard deviation $(\sigma = 0 \text{ to } \sigma = 30)$. Table 6, presents a sample of calculations for one type of total resistance and other calculations have same trend.

3.5.4 Saving Opportunities

The variation of total cost of fuel consumption and greenhouse gas emission can be caused to generate saving opportunities. Using truck on-board payload measurement system and developing a direct connection between truck payload measuring system and shovel or developing an on-line fleet monitoring can be used to reduce the payload variance. Figure 7 illustrates the correlation between standard deviation reduction $(\Delta\sigma)$ and saving $_{\text{Index}}$. Saving $_{\text{Index}}$ presents the amount of saving cost with reducing diesel consumption and greenhouse gas emission for hauling one tonne mine material (Ore or Overburden) in one hour. This graph is independent of haul road condition (Rolling Resistance and Grade Resistance) and presents the quantity of saving for different kinds of standard deviation reduction.

4. Case Study

The effect of GVW variance on haul truck fuel consumption and $GHGs$ emission is an important matters in real mine sits. In this project, a big coal open-pit mine in Australia has been investigated to determine the effect of GVW variance on energy used, $GHGs$ emitted by haul trucks and the cost of them to find saving opportunities.

Figure 8 shows a schematic of the open pit parameters used to model haul truck fleet requirements. The mine parameters are presented in Table 7.

Fleet requirements were calculated using Talpac™ software (Talpac 2013 Release 10). The number of trucks (CAT 793D) in fleet to complete the mine project in 4 years is 135. The total resistance in this case was 15% therefore the FC_{Index} and $CO_2 - e_{\text{ Index}}$ can be measured by using Figure 6 and Table 4 respectively. Based on the cost of fuel consumption and $CO_2 - e$ emission in 2015 that is illustrated in Figure 6 and Table 5 respectively, the total cost is calculated. The price of fuel and $CO_2 - e$ is assumed constant during the operation years. The results of calculation are presented in Table 8. The results show that in this case by reducing one unit of GVW variance, 0.0197 \$/ (hr.tonne) is salvable. The investigated mine is under operation 8 hours in each shift and there are two shifts in each day. This mine has 360 working days at year. The calculation shows that, maximum 45.37% of total fuel and $CO_2 - e$ cost is salvable by reducing σ from 30 to zero. This amount of saving is equal to 277.71 M\$.

5. Conclusions

This paper aimed to develop a model to find saving opportunities based on the reduction of payload variance in surface mines. There is a significant payload variance in loading process in surface mines. This variance needs to be considered in analysing the mine productivity, diesel energy consumption, greenhouse gas emission and associated costs. This paper investigated the effects of payload variance on diesel energy consumption, greenhouse gas emission and their associated cost in surface mining operations. This study examines CAT 793D that is one of the mostly used haul trucks in surface mining operations. Based on the technical specifications of this truck the variation range of payload was assumed between 0 and 30. All data in Rimpull-speed-Grade ability curve for examined truck were digitalised by DATATHIF ® software. The correlations and equations to calculate the maximum speed and fuel consumption were defined. To investigate the effects of payload variance on fuel consumption, greenhouse gas emission and associated costs, main indexes were presented. The associated cost of greenhouse gas emission and cost of diesel consumption are determined based on models presented by U.S. Energy Information Administration. The results show that the fuel consumption, rate of greenhouse gas emission and their costs linearly increase as the payload variance rises for all haul road conditions. The correlation between the payload variance and cost saving is developed. This correlation is independent of haul road condition and presents the cost saving for different kinds of payload variance reduction. Presented model was utilised in a real mine site in Australia as a case study. The results of this project indicated that there is a great saving opportunity by decreasing the payload variance in surface mines that used truck and shovel method for mining operation. This opportunity consists of reducing diesel consumption by haul trucks and reduction of greenhouse gas emission.

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Table Caption

Table 1: Cat 793D mining truck specifications

Table 2: Load Factors (LF) for different conditions

Table 3: Rimpull Coefficient (RC)

Table 4: The variance of CO_2-e $_{Index}$ (kg/hr. tonne) with Standard Deviation (CAT 793D)

Table 5: Different kinds of scenarios to estimate the cost of greenhouse gas [28]

Table 6: Calculated indexes for Cat793D with TR=15% in 2015

Figure Caption

Figure 1: Haul road and truck key parameters

Figure 2: Rimpull-Speed-Grade ability Curve for Truck CAT 793D [39]

Figure 3: Forecast of diesel price [44]

Figure 4: Variation of FC and $V_{\max}$ with GVW for different TR

Figure 5: Normal payload distribution for difference Standard Deviations (CAT 793D)

Figure 6: The variation of FC $_{\text{Index}}$ with Standard Deviation (CAT 793D)

Figure 7: Correlation between standard deviation reduction ($\Delta\sigma$) and saving $_{\text{Index}}$

Figure 8: Schematic of open pit used to model fleet requirements

Table 1: Cat 793D mining truck specifications

Engine	
Engine Model	Cat 3516B HD
Gross Power	1801 kW
Net Power	1743 kW
Weights -Approximate	
Gross Weight	384 tons
Nominal Payload	240 tons
Body Capacity	
Struck	96 m^3
Heaped	129 m^3

Table 2: Load Factors (LF) for different conditions

Operating Conditions	**LF (%)**	**Condition**
Low	20 - 30	Continuous operation at an average GVW less than recommended, No overloading
Medium	30 - 40	Continuous operation at an average GVW recommended, Minimal overloading
High	40 - 50	Continuous operation at or above the maximum recommended GVW

Table 3: Rimpull Coefficient (RC)

Total Resistance (%)	Rimpull Coefficient (RC)	Total Resistance (%)	Rimpull Coefficient (RC)	Total Resistance (%)	Rimpull Coefficient (RC)
1	0.049	11	0.590	21	1.124
2	0.104	12	0.644	22	1.181
3	0.159	13	0.699	23	1.235
4	0.215	14	0.755	24	1.283
5	0.270	15	0.810	25	1.336
6	0.319	16	0.860	26	1.381
7	0.374	17	0.914	27	1.429
8	0.429	18	0.969	28	1.482
9	0.485	19	1.025	29	1.523
10	0.540	20	1.072	30	1.582

Table 4: The variance of CO_2-e $_{Index}$ (kg/hr. tonne) with Standard Deviation (CAT 793D)

σ	TR=5%	TR=10%	TR=15%	TR=20%	TR=25%	TR=30%
0	0.91	1.08	1.32	1.40	1.65	1.73
2	1.02	1.18	1.43	1.51	1.76	1.84
4	1.12	1.29	1.53	1.61	1.86	1.94
6	1.24	1.40	1.64	1.73	1.97	2.05
8	1.34	1.50	1.74	1.83	2.07	2.15
10	1.45	1.61	1.86	1.94	2.19	2.27
12	1.55	1.71	1.96	2.04	2.29	2.37
14	1.67	1.83	2.07	2.16	2.40	2.48
16	1.77	1.93	2.17	2.26	2.50	2.58
18	1.88	2.04	2.29	2.37	2.61	2.70
20	1.98	2.15	2.39	2.47	2.72	2.80
22	2.09	2.26	2.50	2.58	2.83	2.91
24	2.20	2.36	2.61	2.69	2.93	3.01
26	2.31	2.47	2.72	2.80	3.04	3.12
28	2.41	2.58	2.82	2.90	3.15	3.23
30	2.52	2.69	2.93	3.01	3.26	3.34

Table 5: Different kinds of scenarios to estimate the cost of greenhouse gas []

Scenarios	**2015**	**2020**	**2030**	**2040**	**2050**
Core Scenario	$ 20.91	$ 29.88	$ 61.01	$ 124.57	$ 254.37
High Cost	$ 26.60	$ 38.01	$ 77.61	$ 158.48	$ 323.60
No International Offsets	$ 48.83	$ 41.53	$ 84.81	$ 173.17	$ 353.60
Limited Alternatives	$ 31.03	$ 44.34	$ 90.54	$ 184.87	$ 377.50
Lim. Alt / No Intl. Offsets	$ 53.53	$ 76.50	$ 156.20	$ 318.95	$ 651.28

Table 6: Calculated indexes for Cat793D with TR=15% in 2015

σ	FC_{Index} L/(hr. tonne)	$Cost_{Index}$ (Fuel Consumption) $/(hr. tonne)	CO_2-e_{Index} kg/(hr. tonne)	$Cost_{Index}$ (CO_2-e) $/(hr. tonne)	Total $Cost_{Index}$ $/(hr. tonne)
0	0.49	0.48	1.32	0.07	0.55
2	0.53	0.52	1.43	0.08	0.60
4	0.57	0.56	1.53	0.08	0.64
6	0.61	0.60	1.64	0.09	0.69
8	0.65	0.63	1.75	0.09	0.73
10	0.69	0.68	1.86	0.10	0.78
12	0.73	0.71	1.96	0.11	0.82
14	0.77	0.75	2.07	0.11	0.86
16	0.81	0.79	2.18	0.12	0.91
18	0.85	0.83	2.29	0.12	0.95
20	0.89	0.87	2.39	0.13	1.00
22	0.93	0.91	2.50	0.13	1.04
24	0.97	0.95	2.61	0.14	1.09
26	1.01	0.99	2.72	0.15	1.13
28	1.05	1.02	2.82	0.15	1.18
30	1.09	1.06	2.93	0.16	1.22

Table 7: The mine parameters of Case Study

Parameter	**Value**	**Unit**	**Description**
Operation time	16	hr/day	
	360	Day/year	
Pit depth	300	m	
Total ore and wast	2500	Mt	Haulage Requirement
Haulage routs	4		150, 200,250 and 300m
Ramps	2		
Length of the longest	3	Km	
Horizontal haulage distance	60	m	In-Pit
	120	m	Ex-Pit
Width of haul rout	35	m	
Truck down ramp speed	30	km	Limited due to safety
Grade Resistance (GR)	10	%	
Rolling Resistance (RR)	5	%	
Shovels	3		On level 1 (150 m)
	4		On level 2 (200 m)
	2		On level 3 (250 m)
	2		On level 4 (300 m)

Table 8: Case Study Results

Parameter	**Value**		**Unit**	**Description**
	Max (σ=30)	Min (σ=0)		
FC $_{Index}$	1.08	0.49	L/(hr.tonne)	Figure 5
CO_2-e $_{Index}$	2.93	1.32	kg/(hr.tonne)	Table 4
Cost $_{Index}$	1.22	0.55	$/(hr.tonne)	Figure 6 & Table 5
Fuel Consumption	175		L/hr	Average the rate of fuel consumption for truck CAT 793D []
Total operation time	23040		hr	
Total fuel consumption	544.32		M Litre	
Total greenhouse gas emission	1.47		M tonne	
Total cost of fuel consumption and gas emission	612.11		M $	
Saving cost percentage	45.37		%	The percentage of FC_{Index} reduction
Total Salvable Cost	277.71		M $	Total cost × Saving percentage

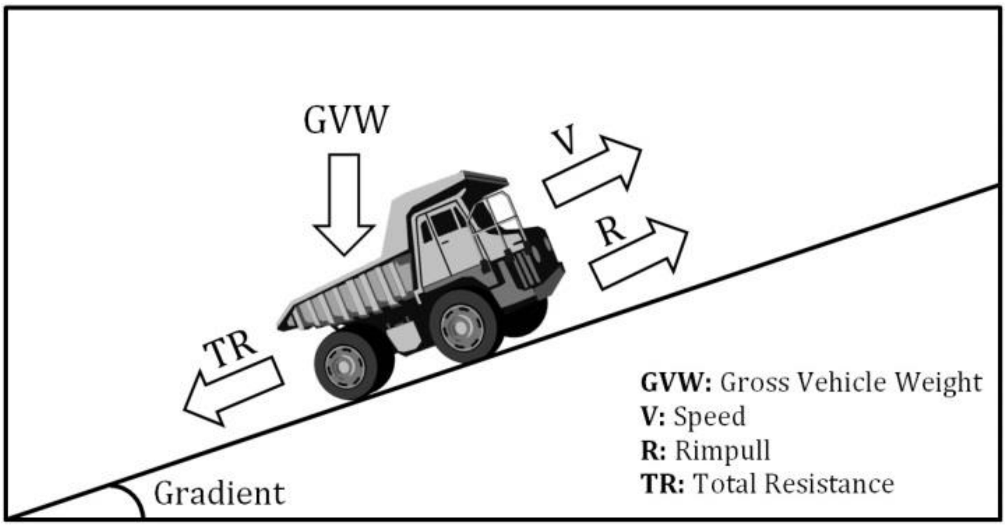

Figure 1: Haul road and truck key parameters

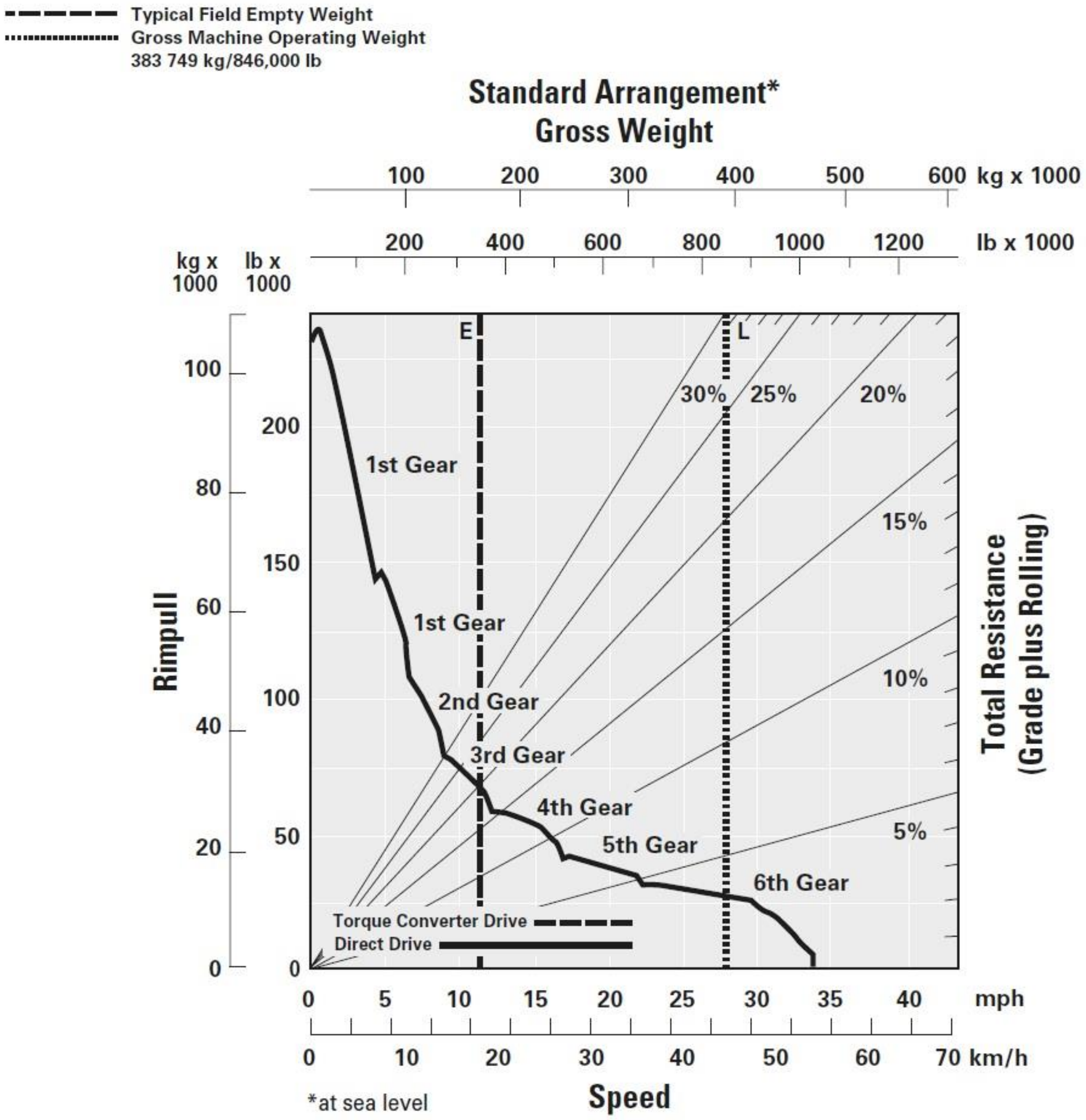

Figure 2: Rimpull-Speed-Grade ability Curve for Truck CAT 793D []

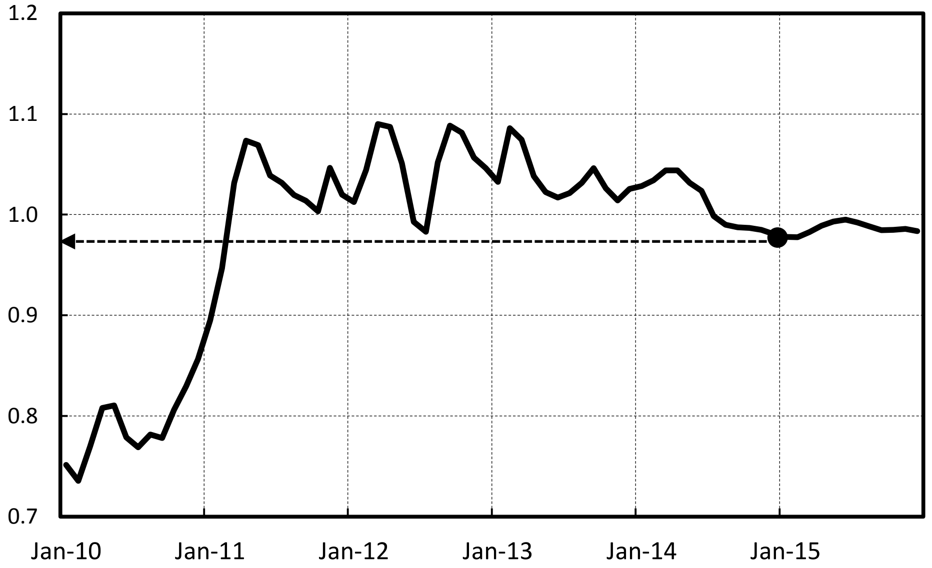

Figure 3: Forecast of diesel price [ ]

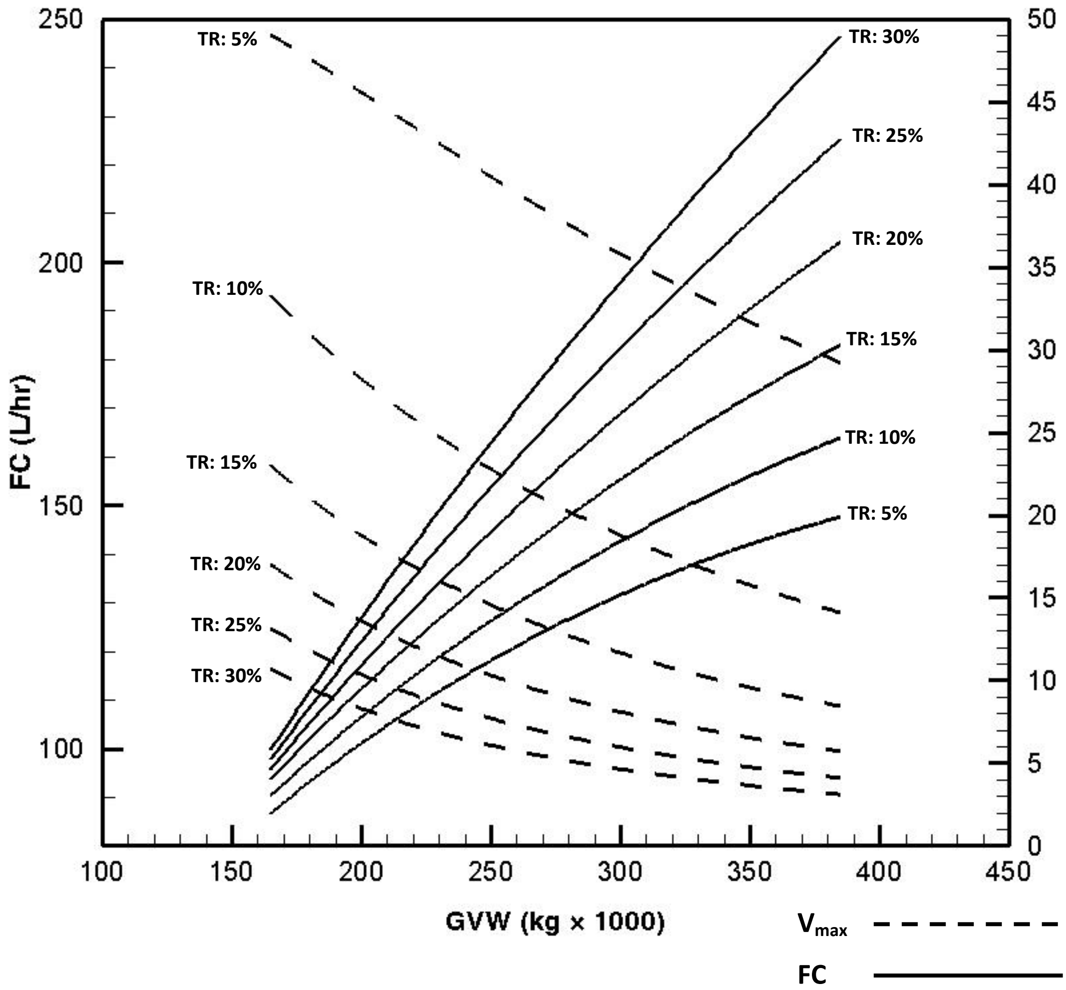

Figure 4: Variation of FC and $V_{\max}$ with GVW for different TR

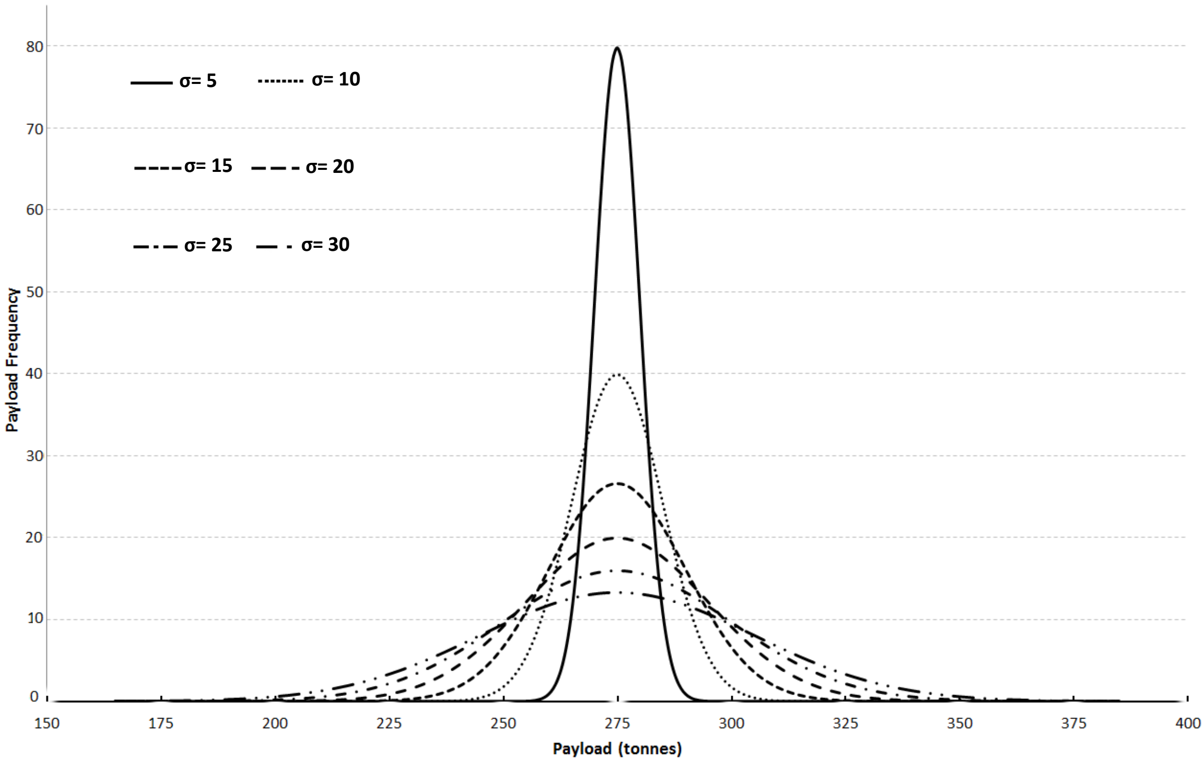

Figure 5: Normal payload distribution for difference Standard Deviations (CAT 793D)

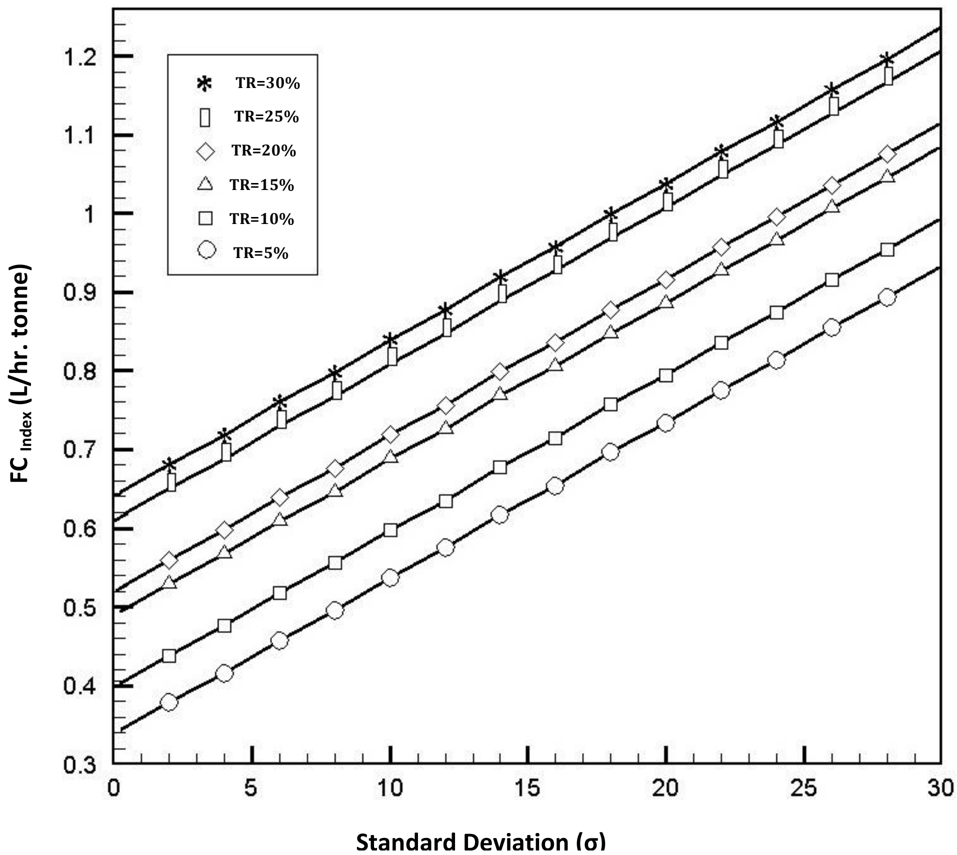

Figure 6: The variation of FC $_{Index}$ with Standard Deviation (CAT 793D)

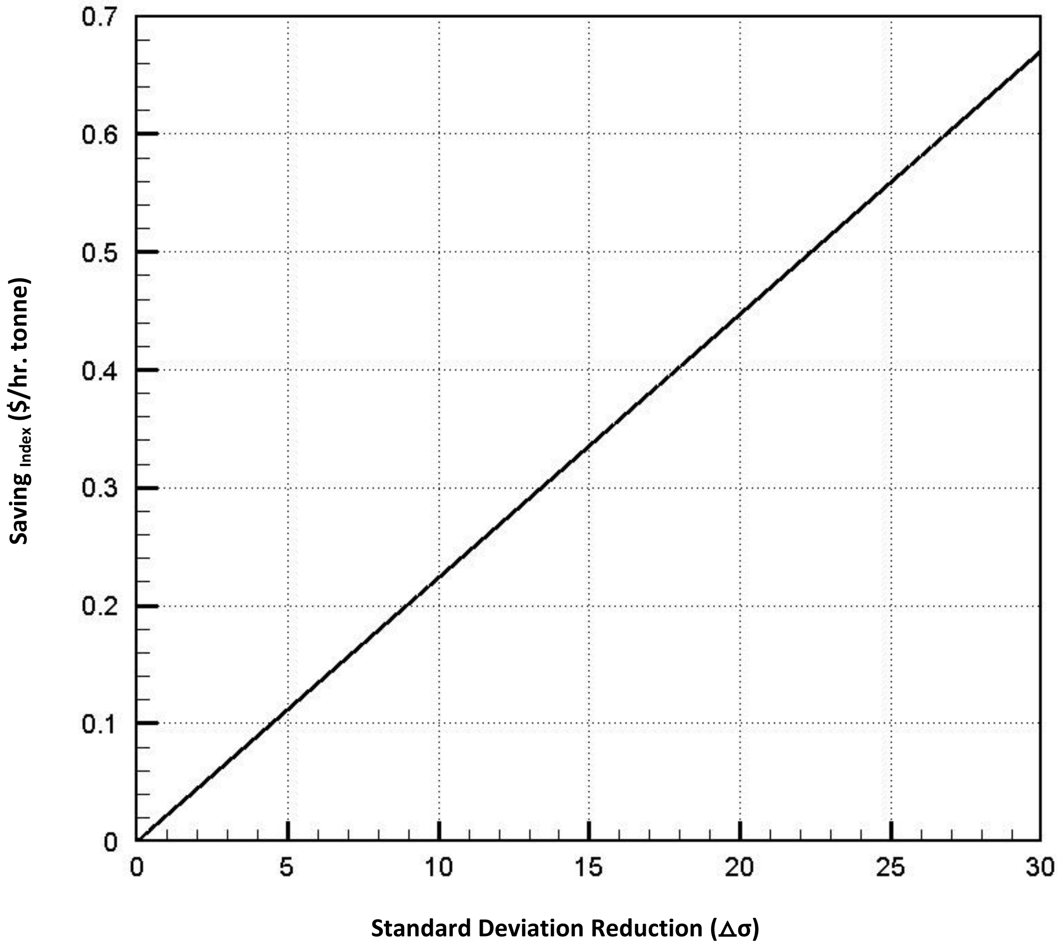

Figure 7: Correlation between standard deviation reduction (∆σ) and saving $_{\text{Index}}$

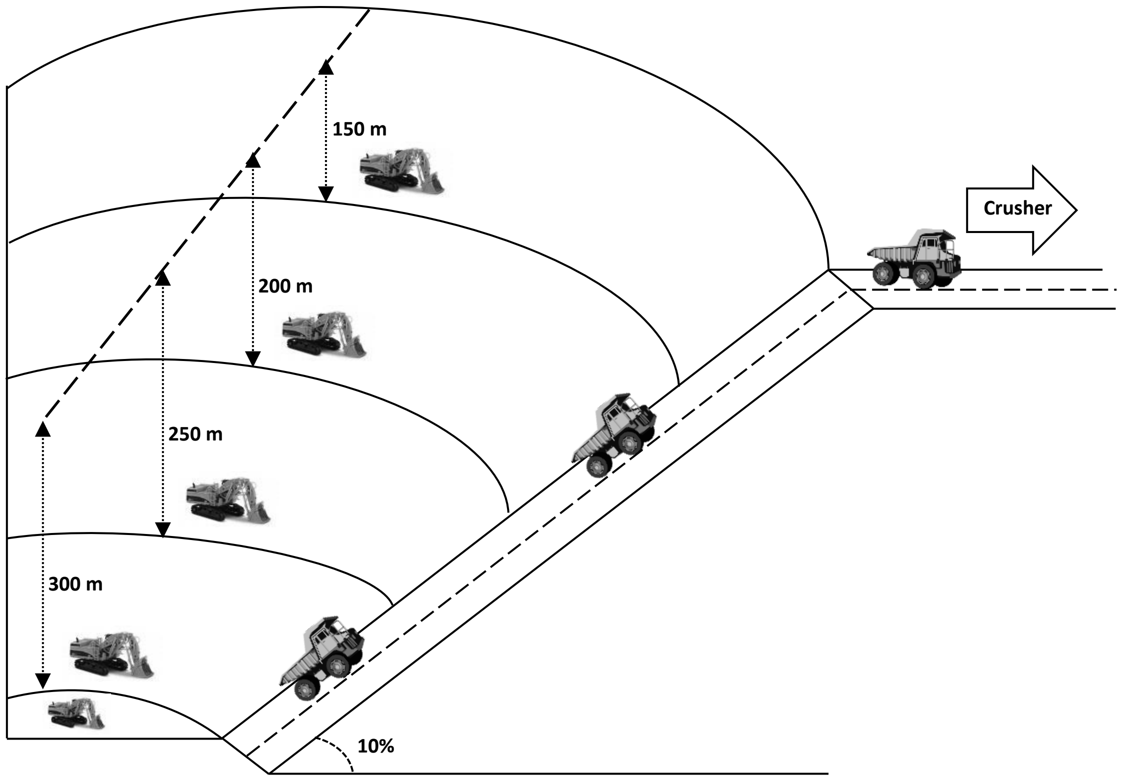

Figure 8: Schematic of open pit used to model fleet requirements