International Journal of Mining Science and Technology 26 (2016) 995–1001

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

A comprehensive investigation of loading variance influence on fuel consumption and gas emissions in mine haulage operation

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ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form 9 October 2015
Accepted 28 February 2016
Available online 19 September 2016

Keywords:
Energy consumption
Haul truck
Surface mine
Greenhouse gas emissions
Cost

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 emissions and associated costs. The aim of this study is to determine the energy and cost saving opportunities for truck haulage operations associated with the payload variance in surface mines. The results indicate that there is a non-linear relationship between the payload variance and the fuel consumption, greenhouse gas emissions and associated costs. A correlation model, which is independent of haul road conditions, has been developed between the payload variance and the cost saving using the data from an Australian surface coal mine. The results of analysis for this particular mine show that a significant saving of fuel and greenhouse gas emissions costs is possible if the standard deviation of payload is reduced from the maximum to minimum value.

1. Introduction

Mining industry consumes a large amount of energy in various operations such as exploration, extraction, transportation and processing [1]. A considerable amount of this energy can be saved by better managing the operations [2–5]. The mining method and equipment used mainly determine the type of energy source in any mining operation [6]. In surface mining operations, haul trucks use diesel as the source of energy [7–10]. Haul trucks are generally used in combination with other equipment such as excavators, diggers and loaders, according to the production capacity and site layout. 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 [11–13].

There are many kinds of factors that affect the rate of fuel consumption for haul trucks such as payload, truck velocity, haul road condition, road design, traffic layout, fuel quality, weather condition and driver skill [14–18]. A review of the 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 [17,19–21].

Loading process in truck and shovel operations is a stochastic process [20]. An analysis of the haul truck payload data obtained 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 [19–21]. The payload variance depends on a number of parameters such as the particle size distribution, the swell factors, the material density, truck-shovel matching, number of shovel passes and the bucket fill factor [19,20,22]. Many attempts have been made 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 [19,20].

The payload variance not only affects the production rate and fuel consumption, but it is also an important parameter in the analysis of gas emissions and cost. Many research studies have already been conducted on the measurement of the haul truck gas emissions in the mining industry [23–27]. In addition, several numbers of economic models have been presented to predict the cost of diesel and gas emissions [28].

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

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http://dx.doi.org/10.1016/j.ijmst.2016.09.006
2095-2686/

2. Theoretical analysis

2.1. Haul truck payload variance

Loading performance depends on different factors such as bench geology, blast design, muckpile fragmentation, operators' efficiency, weather conditions, utilisation for trucks and shovels, mine planning and mine equipment selection [19,20]. In addition, for loading a truck in an effective manner, the shovel operator must also strive to load the truck with an optimal payload. The optimal payload 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 [15]. The payload variance can be illustrated by carrying different amount of ore or overburden by same trucks in each cycle. The range of payload variance can be defined based on the capacity and power of truck. The payload variance in a surface mine fleet can influence productivity greatly due to truck bunching phenomena in large surface mines [19]. The increasing of payload variance decreases the accuracy of maintenance program. This is because the rate of equipment wear and tear is not predictable when the mine fleet faces with a large payload variance. Minimising the variation of particle size distribution, swell factors, material density and fill factor can decrease the payload variance but it must be noted that some of the mentioned parameters are not controllable. Hence, the pertinent methods to minimise the payload variance are real-time truck and shovel payload measurement, better fragmentation through optimised blasting and improvement of truck-shovel matching.

2.2. Haul truck fuel consumption

The fuel consumption for haul trucks is determined based on the following parameters (see Fig. 1):

- The Gross Vehicle Weight (*GVW*), which is the sum of the weight of an empty truck and the payload.
- The Haul Truck Velocity (*V*).
- The Total Resistance (*TR*), which is equal to the sum of Rolling Resistance (*RR*) and the Grade Resistance (*GR*) when the truck is moving against the grade of the haul road.
- The Rimpull Force (*RF*), which is the force available between the tyre and the ground to propel the truck.

Caterpillar trucks are the most popular vehicles amongst all different brands of trucks used in Australian mining industry. Based on the power and capacity of haul truck and mine productivity, CAT 793D was selected for the analysis presented in this study. The specification of selected truck is presented in Table 1.

Fig. 2 presents the Rimpull-Speed-Grade ability curve extracted from the manufacturer's catalogue for CAT 793D.

The rate of haul truck fuel consumption can be calculated by the following equation [24].

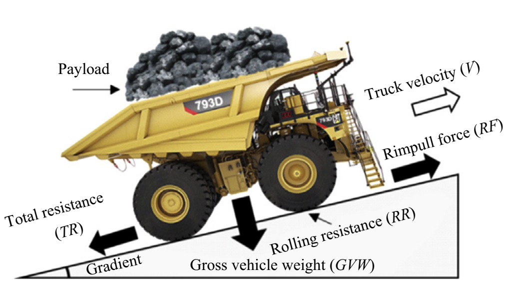

Fig. 1. Haul road and truck key parameters.

Table 1
CAT 793D haul truck specifications [28].

	Specification	Value
Engine	Engine model	CAT 3516B HD
	Gross power (kW)	1801
	Net power (kW)	1743
Weights-approximate	Gross weight (tonnes)	384
	Nominal payload (tonnes)	240
Body capacity	Struck (m^3)	96
	Heaped (m^3)	129

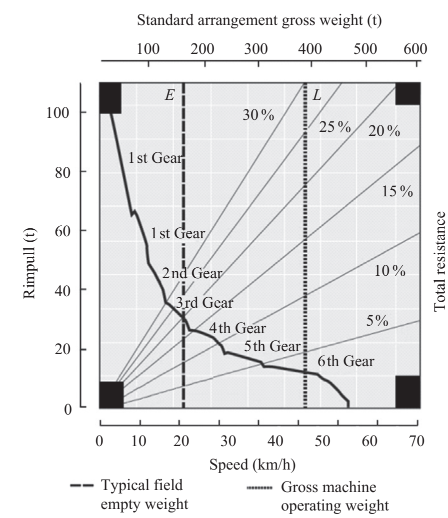

Fig. 2. Rimpull-Speed-Grade ability curve for truck CAT 793D [28].

$$FC = 0.3(LF \cdot P) \quad (1)$$

where *LF* is the ratio of average payload to the maximum load in an operating cycle. The percentage of *LF* in different condition is presented in Table 2 [24] and *P* is the truck power (kW).

For the best performance of the truck operation, *P* is determined by:

$$P = \frac{1}{3.6}(RF \cdot V_{max}) \quad (2)$$

where *RF* is the force available between the tyre and the ground to propel the truck. It is related to the torque (*T*) that the truck is capable of exerting at the point of contact between its tyres and the road and the truck wheel radius (*R*).

$$RF = \frac{T}{R} \quad (3)$$

In this paper, the fuel consumption by haul trucks has been simulated based on the above mentioned formulas.

Table 2
Load Factors (*LF*) for different conditions [22].

Operating conditions	*LF* (%)	Conditions
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*

2.3. Greenhouse gas emissions

Diesel engines emit both Greenhouse Gases (GHG_S) and Non-Greenhouse Gases ($NGHG_S$) into the environment [28]. Total greenhouse gas emissions are calculated according to the Global Warming Potential (*GWP*) and expressed in CO_2 equivalent or CO_2-*e* [23,24]. The following equation can be used to determine the haul truck diesel engine GHG_S emissions [23,29].

$$GHG_{emissions} = (CO_2\text{-}e) = FC \times EF \tag{4}$$

where *FC* is the quantity of fuel consumed (kL) and *EF* is the emission factor. *EF* for haul truck diesel engines is 2.7 t CO_2-*e*/kL [30–32].

2.4. Cost of greenhouse gas estimation and fuel consumption

2.4.1. Cost of greenhouse gas emissions

There are many empirical models for the cost estimation of greenhouse gas emissions, based on the US potential CO_2 legislation [27]. For this research project, the US Energy Information Administration (EIA) model, which is known 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 *NIOs*/*LAs* [23].

Table 3 presents a prediction of cost GHG_S emissions for difference years (from 2015 to 2050) based on the mentioned scenarios [27].

In this study, the latest scenario which is a combination of (NIO_S) and (LA_S) scenarios has been used to calculate the *GHGs* cost. This scenario states that the key low emissions technologies, nuclear, Carbon dioxide Capture and Storage (*CCS*) and renewables will be developed in a timeframe consistent with emissions 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. There are several numbers of models which can be used to estimate the future diesel price [33]. The EIA model can be used in this area as well. A graph showing the forecast of diesel price estimated from this mode is shown in Fig. 3.

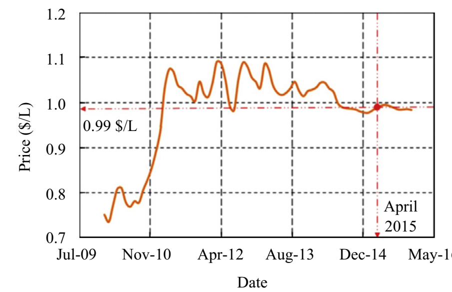

Fig. 3. Forecast of diesel price [30].

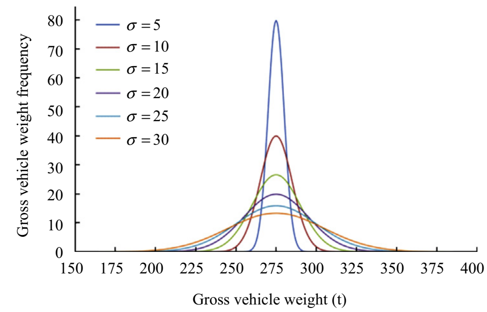

Fig. 4. Normal payload distribution for difference standard deviations (σ) (CAT 793D).

3. Results and discussion

3.1. Haul truck payload variance

The payload variance can be shown by variance of Standard Deviation (σ). The standard deviation measures the amount of variation from the average. A low standard deviation indicates that the data points tend to be very close to the mean; a high standard deviation indicates that the data points are spread out over a large range of values. Fig. 4 illustrates the different kinds of normal payload distribution (the best estimation function for payload distribution [20]) based on the difference σ for CAT 793D.

This illustration shows that by reduction of σ, the range of *GVW* variation is reduced as well. Based on the CAT 793D technical specifications the range of *GVW* variation is between 165 tonnes (empty truck) and 385 tonnes (maximum payload). Hence, the maximum σ for this truck can be defined as 30; that is because, for higher σ, 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 (see Fig. 2) is used to determine the Rimpull (*R*) and the Maximum Truck Velocity (V_{max}) of the truck based on the values of *GVW* (in the range of 165–385 tonnes) and *TR* (in the range of 1–30%). In this study DataThief® 5.6 and Curve Expert Professional V.2.1 were used to find an equation for *R* as a function of *TR* and *GVW*.

$$R = 0.183\,GVW(0.006 + 0.053\,TR) \tag{5}$$

3.2.2. Maximum truck velocity

The data for maximum truck velocity curve are collected by DataThief® software and the best correlation between *R* and V_{max} has been defined by applying a non-linear regression method

Table 3
Different kinds of scenarios to estimate the cost of greenhouse gas ($/tonne CO_2-*e*) [24].

Scenarios	2015	2020	2030	2040	2050
Core Case scenario (*CCs*)	20.91	29.88	61.01	124.57	254.37
High Cost scenario (*HCs*)	26.60	38.01	77.61	158.48	323.60
No International Offsets scenario (*NIOs*)	31.03	41.53	84.81	173.17	353.60
Limited Alternatives scenario (*LAs*)	48.83	44.34	90.54	184.87	377.50
No Intl. Offsets/Lim. Alt scenario (*LAs*/*NIOs*)	53.53	76.50	156.20	318.95	395.28

(Curve Expert Professional Software V.2.1). The following equation presents this correlation.

$$V_{max} = a - b \times \exp(-c \times R^d) \quad (6)$$

where a = 53.867, b = 54.906, c = 37.979 and d = −1.309.

3.2.3. Fuel consumption

Fig. 5 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 velocity and the corresponding Rimpull.

3.3. Effects of payload variance on fuel consumption

The effect of payload variance on haul truck fuel consumption in different haul road conditions is illustrated in Fig. 6.

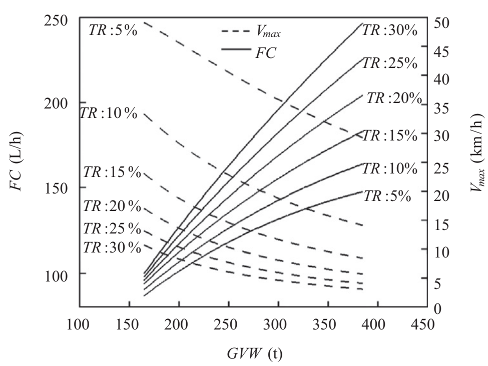

Fig. 5. Variation of V_{max} and *FC* with *GVW* for different *TR*.

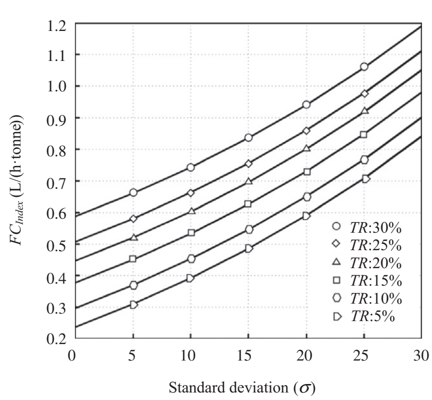

Fig. 6. Variation of FC_{Index} with standard deviation (σ) (CAT 793D).

In this figure, *TR* has been changed from 5% to 30% and σ is varied 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 a haul truck to move one tonne of mine material (Ore or Overburden) in an hour. Fig. 6 demonstrates that, there is a non-linear relationship between σ and FC_{Index} for all haul road total resistance. Moreover, the FC_{Index} rises with increasing *TR*.

3.4. Effects of payload variance on greenhouse gas emissions

The variation of CO_2-*e* with σ for CAT 793D is presented by CO_2-e_{Index} in Table 4. The CO_2-e_{Index} presents the amount of greenhouse gas emissions generated by truck to haul one tonne ore or overburden in an hour.

Based on the tabulated results, it is obvious that there is a non-linear relationship between CO_2-e_{Index} and the standard deviation for each haul road total resistance. The minimum greenhouse gas is emitted for the minimum total resistance (*TR* = 5%) when the standard deviation has been zero (σ = 0) and the maximum pollution is generated for the maximum total resistance and standard deviation (*TR* = 30% and σ = 30).

3.5. Effects of payload variance on cost

3.5.1. Cost of greenhouse gas emissions

All scenarios that can be used to predict the cost of greenhouse gas emissions estimate that this cost is in the range of $20.91–53.53 in 2015 (Table 3). In this project, the maximum cost of CO_2-*e* emissions ($53.53 per tonne) was considered.

3.5.2. Cost of fuel consumption

Fig. 3 illustrates that there is a vast difference in the price of diesel between 2010 and 2015 but it is estimated that the price of this type of fuel will be approximately $1 per litter in 2015 for industrial use. Hence, in this project the price of fuel for haul trucks in surface mines is assumed $0.99 per litter in 2015.

3.5.3. Total cost

The calculated FC_{Index}, the cost of fuel consumed by haul truck for each σ (*Fuel Cost*$_{Index}$), the greenhouse gas emitted by haul truck to move one tonne of mine material in an hour (CO_2-e_{Index}), the cost of greenhouse gas emissions (CO_2-*e Cost*$_{Index}$) and *Total Cost*$_{Index}$ for CAT 793D with *TR* = 5% in 2015 are tabulated in Table 5.

In this haul road condition, there is a direct relationship between increasing the payload variance and *Total Cost*$_{Index}$. The *Total Cost*$_{Index}$ presents the total cost of fuel consumed and CO_2-*e* emitted to haul one tonne mine material by truck in an hour. In this case, the *Total Cost*$_{Index}$ can be vary between $0.42 and $1.10/(h·tonne) for different values of standard deviation (σ = 0–30).

3.5.4. Saving opportunities

The variation of total cost of fuel consumption and greenhouse gas emissions can be used for saving opportunities. Using a truck

Table 4
Variance of CO_2-e_{Index} (kg/h·tonne) with σ (CAT 793D).

σ	*TR* = 5%	*TR* = 10%	*TR* = 15%	*TR* = 20%	*TR* = 25%	*TR* = 30%
0	0.64	0.80	1.02	1.21	1.37	1.58
5	0.84	1.00	1.22	1.40	1.57	1.78
10	1.06	1.22	1.44	1.63	1.79	2.01
15	1.31	1.47	1.69	1.88	2.04	2.26
20	1.59	1.76	1.97	2.16	2.32	2.54
25	1.91	2.07	2.29	2.48	2.64	2.86
30	2.27	2.43	2.65	2.84	3.00	3.22

Table 5
Calculated indexes for CAT793D with *TR* = 15% in 2015 (sample).

σ	FC_{Index} L/(h·tonne)	*Fuel Cost*$_{Index}$ \$/(h·tonne)	CO_2-e_{Index} kg/(h·tonne)	CO_2-*e Cost*$_{Index}$ \$/(h·tonne)	*Total Cost*$_{Index}$ \$/(h·tonne)
0	0.38	0.37	1.02	0.05	0.42
5	0.45	0.44	1.22	0.07	0.51
10	0.53	0.52	1.44	0.08	0.60
15	0.63	0.61	1.69	0.09	0.70
20	0.73	0.72	1.97	0.11	0.83
25	0.85	0.83	2.29	0.12	0.95
30	0.98	0.96	2.65	0.14	1.10

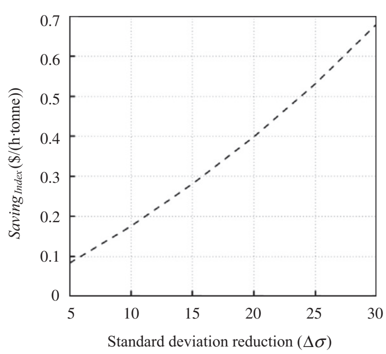

Fig. 7. Correlation between $\Delta\sigma$ and *Saving*$_{Index}$.

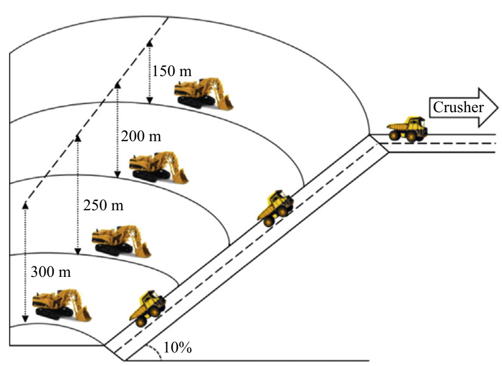

Fig. 8. Schematic of open pit used to model fleet requirements.

Table 6
Mine parameters of case study.

Parameter	Value	Description
Operating hours per year (h/year)	4799	
Pit depth (m)	300	
Total ore and wast (Mt)	2500	Haulage requirement
Haulage routs	4	150, 200, 250 and 300 m
Ramps	2	
Length of the longest ramp (km)	3	
Horizontal haulage distance (m)	60 120	In-pit Ex-pit
Width of haul road (m)	35	
Truck down ramp speed (km)	30	Limited due to safety considerations
Grade Resistance (GR) (%)	10	
Rolling Resistance (RR) (%)	5	
Shovels	3 4 2 2	On level 1 (150 m) On level 2 (200 m) On level 3 (250 m) On level 4 (300 m)

on-board payload measurement system, developing a direct connection between the truck payload measurement system and the shovel, improvement of truck-shovel matching or developing an on-line fleet monitoring can be used to reduce the payload variance. Fig. 7 illustrates the correlation between the Standard Deviation Reduction ($\Delta\sigma$) and the *Saving*$_{Index}$. The *Saving*$_{Index}$ presents the amount of saving cost with reducing diesel consumption and greenhouse gas emissions for hauling one tonne mine material (ore or overburden) in one hour. This graph is independent of haul road condition (*RR* and *GR*) and presents the quantity of saving for different kinds of $\Delta\sigma$.

Finding the best correlation between the $\Delta\sigma$, and the *Saving*$_{Index}$ can be very important in calculation of the effect of payload variance on production cost. Hence, the following equation has been developed to estimate the *Saving*$_{Index}$ for different road conditions and values of the $\Delta\sigma$.

$$Saving_{Index} = 0.01(\Delta\sigma)^{1.25} \quad (7)$$

Eq. (6) presents the correlation between *Saving*$_{Index}$ and $\Delta\sigma$.

4. Case study

The effect of payload variance on haul truck fuel consumption and GHG_S emissions is an important matter in real mine sites. In this project, a large surface mine in Australia has been investigated to determine the effect of payload variance on energy used, GHG_S emitted by haul trucks and the cost of them to find saving opportunities.

Fig. 8 shows a schematic diagram of the surface parameters used to model haul truck fleet requirements. The mine parameters used for this case study are presented in Table 6.

Fleet requirements are calculated using Talpac™ software. The average of *TR* in this case is 15%. Therefore, FC_{Index} and CO_2-e_{Index} can be measured by using Fig. 6 and Table 4, respectively. The total cost is calculated based on the cost of fuel consumption and CO_2-*e* emissions in 2015 that is illustrated in Fig. 3 and Table 5, respectively. The price of fuel and CO_2-*e* is assumed constant during the years of operation. The results of calculation are presented in Table 7.

The results show that in this case by reducing one unit of payload variance, \$0.02/(h·tonne) is salvable. The case study mine is under 8 h of operation in each shift and there is one shift in each day. This mine has 360 working days at year. The calculation shows that, maximum 35% of total fuel and CO_2-*e* cost is salvable by reducing σ from 30 to zero. This amount of saving is equal to million \$7.33 annually.

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 emissions and associated costs. This paper investigated the effects of

Table 7
Case study results.

Parameter	Value		Description
	Max (σ = 30)	Min (σ = 0)	
FC_{Index} (L/(h·tonne))	0.98	0.38	Fig. 5
CO_2-e_{Index} (kg/(h·tonne))	2.65	1.02	Table 4
$Cost_{Index}$ ($/(h·tonne))	1.10	0.42	Fig. 6 and Table 5
Truck fuel consumption (empty) (L/h)	175		Average the rate of fuel consumption for empty truck CAT 793D [32]
Truck greenhouse gas emission (empty) (kg/h)	682		
Truck cost of fuel and greenhouse gas (empty) ($/h)	209		
Average truck payload (t)	142		
Fleet size (Truck)	15		
Total production per year (Mt/year)	19		
Truck availability (%)	80		
Loader availability (%)	85		
Queue time at loader (min/cycle)	3.05		
Spot time at loader (min/cycle)	0.95		
Average loading time (min/cycle)	2.06		
Travel time (hauling) (min/cycle)	16.13		
Travel time (returning) (min/cycle)	6.03		
Spot time at dump (min/cycle)	0.76		
Average dump time (min/cycle)	1.02		
Average cycle time (min)	30.00		
Average No. of bucket passes	3		
Rate of fuel consumption (fleet) (L/h)	3774.9	2429.7	
Rate of greenhouse gas emission (fleet) (kg/h)	11795.4	8124.6	
Rate of cost (fleet) ($/h)	4349.1	2821.5	
Total fuel consumption annually (ML/year)	18.12	11.66	
Total greenhouse gas emission annually (10^6 kg/year)	56.61	38.99	
Total cost of fuel consumption and greenhouse gas emission annually (10^6 $/year)	20.87	13.54	
Saving cost percentage (%)	35		
Total saveable cost (10^6 $/year)	7.33		

payload variance on diesel energy consumption, greenhouse gas emissions and their associated cost in surface mining operations. This study examined CAT 793D model truck, which 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 to be between 0% and 30%. All data in Rimpull-Speed-Grade ability curve for examined truck was digitalised by DataThief® software. The correlations and equations to calculate the maximum truck velocity and fuel consumption were defined. To investigate the effects of payload variance on fuel consumption, greenhouse gas emissions and associated costs, main indexes were presented. The associated cost of greenhouse gas emissions and cost of diesel consumption were determined based on models presented by US EIA. The results showed that the fuel consumption, rate of greenhouse gas emissions and their costs non-linearly increase as the payload variance rises for all haul road conditions. The correlation between the payload variance and cost saving was 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 cost saving opportunity by decreasing the payload variance in surface mines that used truck and shovel method for mining operation. This can be achieved by using a truck on-board payload measurement system and on-line fleet monitoring.

Acknowledgments

The authors would like to acknowledge CRC Mining and the University of Queensland for their financial support for this study.

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