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Impact of Bulldozer's Engine Load Factor on Fuel Consumption, CO_2 Emission and Cost

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Abstract: Problem statement: Bulldozers consume a large amount of diesel fuel and consequently produce a significant quantity of CO_2. Environmental and economic cost issues related to fuel consumption and CO_2 emission represent a substantial challenge to the mining industry. **Approach:** Impact of engine load conditions on fuel consumption and the subsequent CO_2 emission and cost was analyzed for Caterpillar bulldozers. Results were compared with the data on bulldozers' fuel consumption from an operating coal surface mine in the United States. **Results:** There is a strong linear correlation among power, fuel consumption and engine load factor. Reduction in load factor by 15% may significantly reduce the fuel consumption and the CO_2 emission. **Conclusion/Recommendation:** Application of appropriate bulldozer's load factor may help mine operators manage fuel consumption, cost and environmental burden.

Key words: Engine load factor, fuel consumption, CO_2 emission, mining industry, linear correlation, caterpillar bulldozers, diesel fuel, low idling, bulldozers consume, mining operations

INTRODUCTION

Bulldozers are used extensively in coal, metal and non-metal surface mining operations. They are applied for variety of tasks including construction and maintenance of haulage roads; preparation and clean-up of benches and loading areas; stripping overburden; maintaining waste dump by spreading material, pushing over dump slope and grading dump area and slopes; pushing material to hopper for loading; relocation of electric cables, pumps and pipes; assisting disabled vehicles and ripping unconsolidated rocks. Every surface mining operation has a fleet of various sizes of bulldozers where the largest one can reach an engine power of nearly 860 kW.

Bulldozers consume a large amount of fuel. Consequently, they produce a significant quantity of CO_2. Fundamental changes in fuel conservation; efficiency and reducing negative environmental impact related to CO_2 emission are of crucial importance.

There are a number of factors that contribute to the fuel consumption of bulldozers. Shikata (2009) indicates that fuel consumption is highly dependent on factors such as site geography, including level or sloping ground, as well as soil composition. The author also points that fuel consumption can be reduced by avoiding high idling whenever possible. Test results of Komatsu model D155-6 reveals that switching from high idling to low idling for 30 min a day saves on fuel consumption by 1,710 liters a year. Turning the engine off rather than using low idling for one hour a day saves on fuel consumption by 2,430 liters a year (Shikata, 2009). Author also lists several recommendations that enhance fuel efficiency: (i) dozing from the front of the dozing zone instead of back-to-front method, improve fuel efficiency by 11%, (ii) dozing material with a downward gradient and (iii) avoiding shoe slippage and stalling. Other factors that influence the consumption include bulldozer power, weight, fuel quality, the operator's skill, outside temperature, weather and adequacy of bulldozer's maintenance program. Detailed study on impact of outside temperature on fuel consumption was conducted by Al-Hasan (2007).

An adequate management of above factors may reduce fuel consumption while providing required performance without significant investments or operational changes. It translates into decreased engine load which allow the same performance with lower fuel

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consumption and consequently lower CO_2 footprint and costs.

The objective of this research was to (i) establish mathematical relationship among bulldozer's fuel consumption, power and engine load factors, (ii) determine the amount of CO_2 emission and (iii) determine the cost associated with fuel consumption and CO_2 emission. These objectives were considered for Caterpillar bulldozers. Obtained results were compared to the data on bulldozers' fuel consumption from an operating coal surface mine in the United States.

MATERIALS AND METHODS

Fuel consumption: According to Runge (1998), an hourly fuel consumption FC ($l\ h^{-1}$) can be determined from the following equation (1)**:**

$$FC = RP \times 0.3 \times LF \quad (1)$$

where, RP is a equipment rated power (kW), 0.3 is unit conversion factor ($l\ kWh^{-1}$) and LF is an engine load factor (the portion of full power required by the equipment). Values for the bulldozers' power and engine load factors are given in Table 1.

The similar equation for fuel consumption was suggested by Filas (2002), i.e. Eq. 2:

$$FC = (CSF \times P \times LF)/FD \quad (2)$$

Where:

CSF = The engine specific fuel consumption at full power (0.213-0.268 kg kWh^{-1})
P = Rated brake power (kW)
LF = Engine load factor
FD = The fuel density (0.85 kg l^{-1} for diesel)

Values for engine load factors suggested by Filas (2002) range between 25 and 75%, while recommends the following values**:** 45% (light**:** Considerable idle or travel with no load); 60% (average**:** Normal idle, normal production dozing, back track push loading scrapers, steady shovel cleanup); and 75% (heavy**:** Minimum idle and reverse travel, heavy production dozing, chain and shuttle push loading scrapers, steady ripping).

Table 1**:** Bulldozer power and associated engine load factors

	Load factor	
Power (kW)	low range	High range
160	0.4-0.52	0.67-0.83
276	0.36-0.51	0.63-0,83
575	0.36-0.41	0.63-0.67

Caterpillar Tractor Company (1984) provides data on fuel consumption for its bulldozers. According to this manufacturer, an engine continuously producing full rated power is operating at a load factor of 100%. It may reach a 100% load factor intermittently, but seldom operate at this level for extended periods of time. Periods spent at idle, travel in reverse, traveling empty, close maneuvering at part throttle and operating downhill are examples of conditions which reduce load factor. Values of engine load factor are given by Caterpillar Tractor Company (1984) as follows:

- Low: 35-50% (Pulling scrapers, most agricultural drawbar, stockpile, coal pile applications. No impact Intermittent full throttle operation)
- Medium: 50-65% (Production dozing in clays, sands, gravels. Push loading scrapers, borrow pit ripping, most land clearing applications. Medium impact conditions. Production landfill work); and
- High: 65-80% (Heavy rock ripping. Push loading and dozing in hard rock. Working on rock surfaces Continuous high impact conditions.)

For the purpose of this study, a sample of six bulldozer models from the Caterpillar was selected. Data for Caterpillar bulldozers related to power P (kW), hourly fuel consumption FC ($l\ h^{-1}$) and load factors LF (%) are available from the manufacturer's handbook (Caterpillar Tractor Company, 1984). Based on these data, the relationship between fuel consumption and power was established. Change in fuel consumption as a function of engine load factor was also determined. Hourly and annual costs for various load factors were calculated assuming the unit cost of fuel at \$0.8 per liter and 5,200 operating hours per year.

Data on fuel consumption per month and number of operating hours per month for three Caterpillar bulldozers were observed and collected from an operating surface coal mine in the U.S. Dividing the monthly fuel consumption by the number of operating hours per month, average hourly fuel consumption was obtained.

CO_2 Emission: The CO_2 emission from the diesel fuels can be written as Eq. 3:

$$CO_2 = FC \times CF \quad (3)$$

where:

FC = Diesel fuel consumption ($l\ h^{-1}$)
CF = Conversion factor

The conversion factors of CO_2 emission for the diesel fuel can be calculated as Eq. 4:

$$CF = CC\times10^{-6} \times 0.99\times(44/12) \quad (4)$$

where, CC is carbon content for the diesel fuel (g l^{-1}) and 0.99 is oxidation factor.

According to Environmental Protection Agency (2005), the conversion factor for diesel fuel is 0.00268. This factor is calculated based on the carbon residue in one liter of diesel. The carbon content for the diesel is CC = 738.2 grams per liter (Environmental Protection Agency, 2005). The oxidation factor for all oil and its products is 0.99. Practically, this means that 99% of fuel burns out, while 1 % remains un-oxidized. Detailed discussion on emission factors is also given by Zabihian and Fung (2010)

CO_2 emission (t h^{-1}) of Caterpillar bulldozers at various engine load factors was determined using an hourly fuel consumption and conversion factor of CF = 0.00268 for diesel.

There are number of empirical models with a range values for the cost of CO_2 emission and they are based on potential CO_2 legislation. Two most recognized models include U.S. Energy Information Agency's (EIA) the National Energy Modeling System (NEMS) model and Massachusetts Institute of Technology's (MIT) Emissions Prediction and Policy Analysis (EPPA) model. These models consider the cost of CO_2 in that ranges from \$17-\$50 per tonne of CO_2 emitted. For the purpose of this study, the value of \$50 per tonne was considered.

RESULTS

Relationship between fuel consumption and power is shown in Fig. 1. Mathematical relationship between fuel consumption and power at various load factors (Fig. 1) can be expressed as follows Eq. 5-8:

$$FC(LF = 80\%) = 0.2178\times P + 2.148, \quad R^2 = 0.9995 \quad (5)$$

$$FC(LF = 65\%) = 0.1761\times P + 2.0695, \quad R^2 = 0.9994 \quad (6)$$

$$FC(LF = 50\%) = 0.1348\times P + 1.6289, \quad R^2 = 0.9997 \quad (7)$$

$$FC(LF = 35\%) = 0.0949\times P + 1.1526, \quad R^2 = 0.9992 \quad (8)$$

Figure 2 shows the change in the fuel consumption as a function of load factor for Caterpillar bulldozers including D6R, D7G, D8R, D9T, D10T and D11R.

Mathematical relationship between bulldozer fuel consumption and load factor (Fig. 2) can be expressed as follows Eq. 9-14:

$$FC(D11R; P = 634\ kW) = 1.7433\times LF - 0.1167, \quad R^2 = 1 \quad (9)$$

$$FC(D10T; P = 433\ kW) = 1.2273\times LF - 0.5467, \quad R^2 = 0.9996 \quad (10)$$

$$FC(D9T; P = 306\ kW) = 0.8687\times LF - 0.1733, \quad R^2 = 0.9999 \quad (11)$$

$$FC(D8R; P = 228\ kW) = 0.6333 \times LF + 0.3333, \quad R^2 = 1 \quad (12)$$

$$FC(D7G; P = 150\ kW) = 0.4333\times LF + 0.8333, \quad R^2 = 1 \quad (13)$$

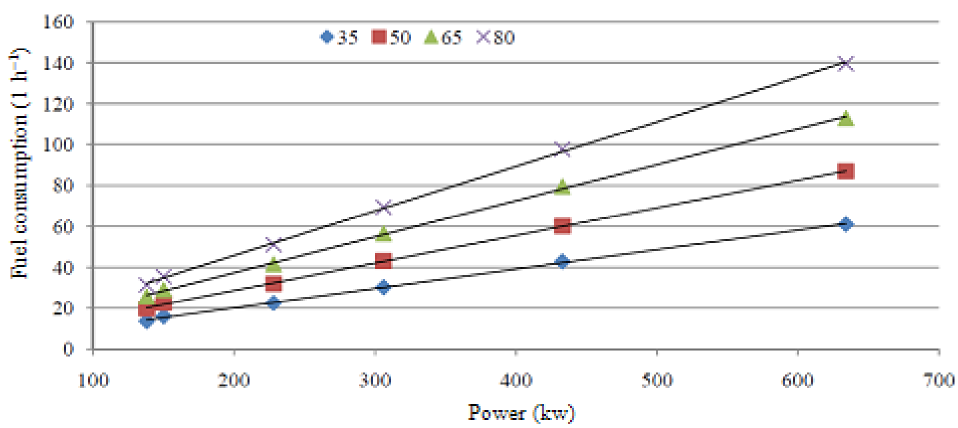

Fig. 1: The relationship between fuel consumption and power at various load factors

$$FC(D6R;P = 138\ kW) = 0.396\times LF - 0.17$$
$$R^2 = 0.9998 \quad (14)$$

Figure 3-4 show hourly and annual costs, respectively, for various load factors.

Figure 5 shows the hourly fuel consumption for ureD11R bulldozers (1, 2, 3) from the operating surface coal mine.

Figure 6 shows CO_2 emission (t h^{-1}) for Caterpillar bulldozers at various engine load factors. Fig. 7 shows the cost of CO_2 emission per hour at various engine load factors while Fig. 8 presents the cost of CO_2 emission on annual basis.

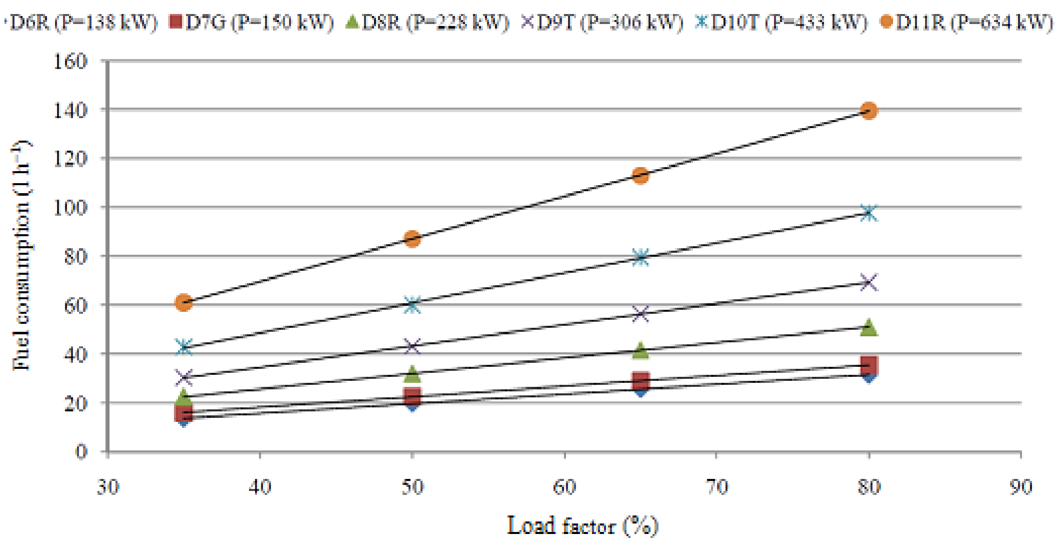

Fig. 2: Change in fuel consumption as a function of engine load factor

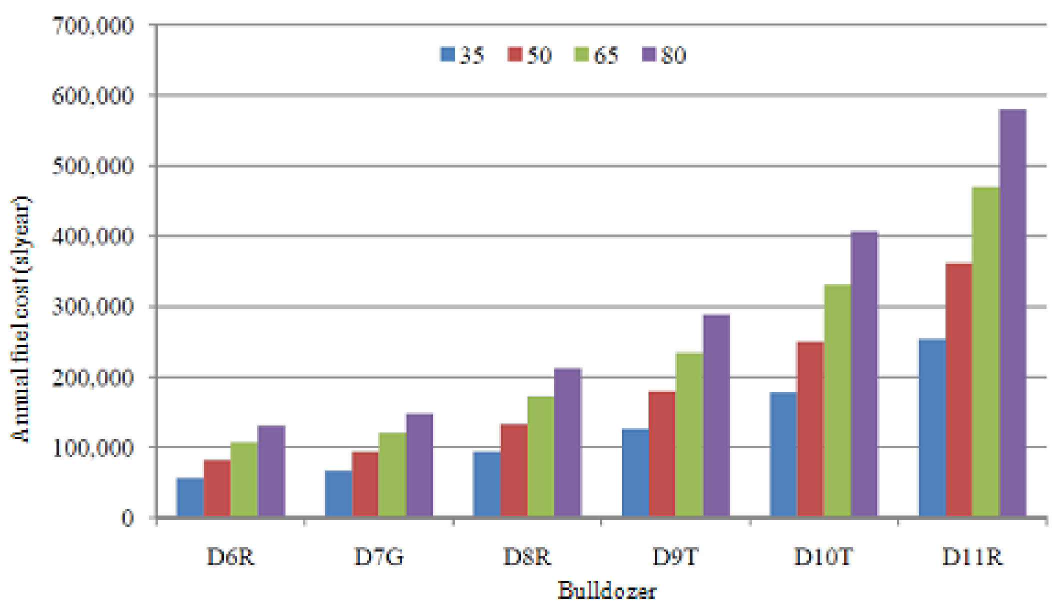

Fig. 3: Hourly fuel cost at various load factors

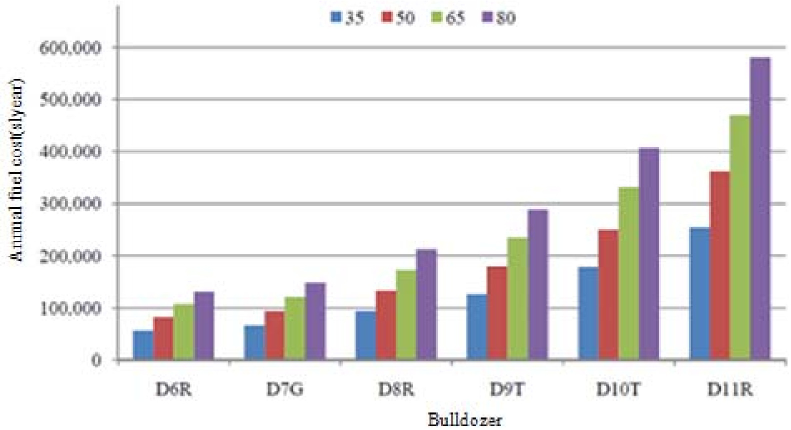

Fig. 4: Annual fuel cost at various load factors

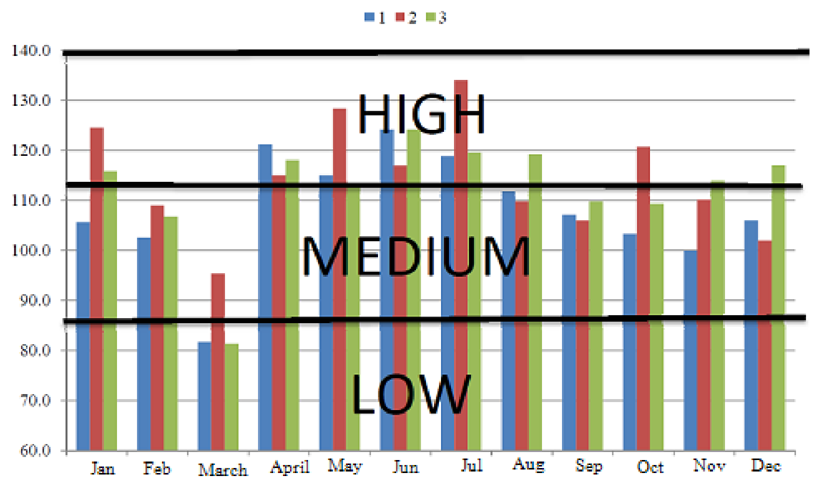

Fig. 5: Average hourly fuel consumption for three D11R bulldozers in a coal surface mine

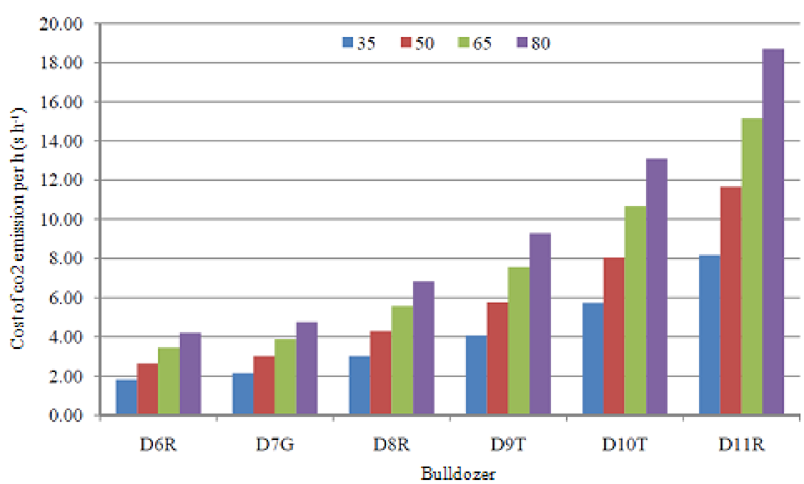

Fig. 6: The CO_2 emission (t h^{-1}) of Caterpillar bulldozers at various engine load factors (%)

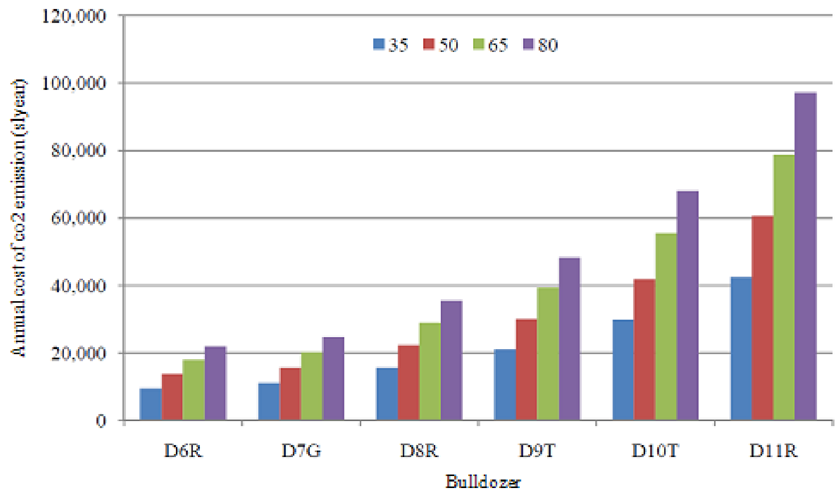

Fig. 7: The CO_2 cost ($ h^{-1}) at various engine load factors (%)

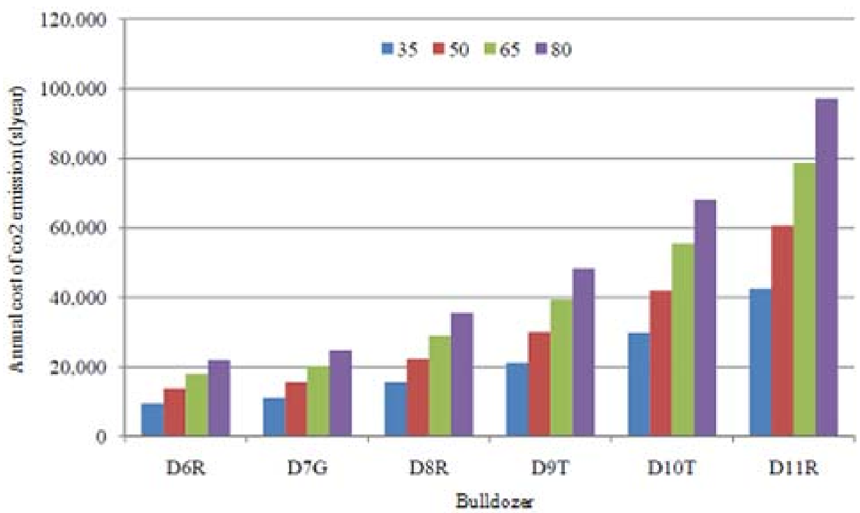

Fig. 8: The CO_2 cost ($/ year) at various engine load factors (%)

DISCUSSION

Results in Fig. 1 show that the fuel consumption increases from 0.0949 l h^{-1} per kW at a load factor of 35% to 0.1348 l h^{-1} per kW at a load factor of 50%. It also can be noted that the fuel consumption increases from 0.1761 l h^{-1} per kW at a load factor of 65% to 0.2178 l h^{-1} per kW at a load factor of 80%. High values of R^2 indicate a strong positive linear correlation between power and fuel consumption for Caterpillar bulldozers.

Results in Fig. 2 indicate that fuel consumption is a linear function of the load factor. However, the former increases faster in absolute values for larger bulldozers. It can also be observed, for example, that the increase in fuel consumption for the smallest bulldozer (D6R) is 6.1 l h^{-1} for each 15% increase in the load factor. The largest model (D11R) has an increase in fuel consumption of 26 l h^{-1} for each 15% increase in the load factor. High values of R^2 indicate a strong positive linear correlation between load factor and fuel consumption for Caterpillar bulldozers.

According to the results shown in Fig 3, hourly cost for the largest bulldozer (D11R) ranges from $48.8 at load factor of 35% to $111.6 at load factor of 80%. The annual costs (Fig. 4) for the same bulldozer span from $253,760 (LF = 35%) to $580,320 (LF = 80%). Reducing the load factor by 15%, a total of $21.2 per hour and \$110,240 per year per single bulldozer can be achieved.

According to data presented previously in Fig. 2, the fuel consumption of D11R ranges from 61 L h^{-1} to 87 l h^{-1} at low engine load conditions (LF = 35-50%), from 87-113 L h^{-1} at medium engine load conditions (LF = 50-65%) and from 113-139.5 L h^{-1} at a high engine load conditions (LF = 65-80%). Therefore, it can be noted that all three D11R bulldozers in a studied operating coal mine were working at a high engine load conditions during the April, June and July and consequently reached high fuel consumption (Fig. 5).

Two bulldozers (2-3) also reached high fuel consumption in January. It is also important to note that none of the three bulldozers had exceeded the upper level of fuel consumption recommended by the manufacturer. Authors were not able to obtain any information related to specific operating conditions in the mine to draw any meaningful conclusion on high fuel consumptions during these four months. However, the mine operator may use these findings to further analyze operating conditions that result in increased fuel consumption.

Results given Fig. 6 indicate that the value of CO_2 emission ranges from 0.0364-0.0842 t h^{-1} at load factors of 35 and 80%, respectively, for the smallest bulldozer (D6R) and from 0.1635-0.3739 t h^{-1} at load factors of 35 and 80%, respectively, for the largest bulldozer (D11R).

The cost of CO_2 emission (Fig. 7) ranges from \$1.82 to \$4.21 per hour at load factors of for the smallest bulldozer (D6R) and from \$8.17 to \$18.69 per hour at load factors 35 and 80%, respectively, for the largest bulldozer (D11R).

The annual costs (Fig. 8) range from \$9,476 to \$21,880 per year at load factors of 35 and 80%, respectively, for the smallest bulldozer (D6R) and from \$42,505 to \$97,204 per year for load factors of 35 and 80%, respectively, for the largest bulldozer (D11R). Assuming that a large scale surface mining operations may have, for instance, a fleet of 10 Caterpillar D11R bulldozers then the cost for CO_2 emission may run from \$425,050 to almost \$1-milion per year. Reducing load factor for 15% can decrease CO_2 emission by \$18,466 per year per one bulldozer.

CONCLUSION

This research was carried out to study impact of bulldozer's engine load factors on fuel consumption, CO_2 emission and to determine associated costs. The Caterpillar bulldozers were considered for this study and it was determined that fuel consumption is in strong correlation with power and engine load factor.

It was determined that reduction in load factor of 15% can significantly decrease fuel consumption and CO_2 emission and consequently reduce operating costs. Future studies may focus on specific factors such as slope grade, idle time and rock properties to determine the potential savings in fuel consumption and CO_2 emission.

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