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The Effect of Road Grade on Dump Truck Fuel Consumption

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Abstract

Road grade and mining activities are inseparable. Considering that a mining site is located in a lower elevation, the haul road is usually constructed following the topographic contour. A road grade is likely to affect the speed, travel time, and fuel consumption and is directly proportional to the energy required by dump trucks to overcome resistance. A higher road grade leads to more fuel consumption, while a lower road grade is likely to consume less. This study found that every 1% road grade increase results in 0.482%-0.515% increased engine speed and 2.79% horsepower under laden conditions. It was also found that every 1% road grade increase leads to 21.95% more fuel consumption in CAT 773D dump truck, 23.64% in HD-465-7 dump truck, and 13.29% more fuel consumption in Volvo A40E. Meanwhile, under unladen conditions, every 1% increase in road grade resulted in 7.64% more fuel consumption in CAT 773D, 20.60% in HD 465-7, and 23.75% in Volvo A40E. This study recommends an 8% maximum road grade to save fuel for hauling activities in the mining area.

Keywords

Road grade, Dump truck, Fuel consumption

I. Introduction

Dump truck serves as the main conveyance of mining activity, especially open-pit mining, due to their flexibility, climbing ability, adaptability to challenging conditions, and high productivity. However, dump trucks consume about 0.04 gal per hour during the operation [1, 2]. Transportation costs can reach 50% of the total operating costs in mining activities, so minimizing fuel consumption can significantly reduce operating costs [3]. Dump truck fuel consumption covers around 30% of the total energy used in surface mining activities [4]. One of the factors affecting dump truck consumption is road grade. The steeper road may lead to more power required and longer traveling time due to grade resistance, thus consuming more fuel [5, 6].

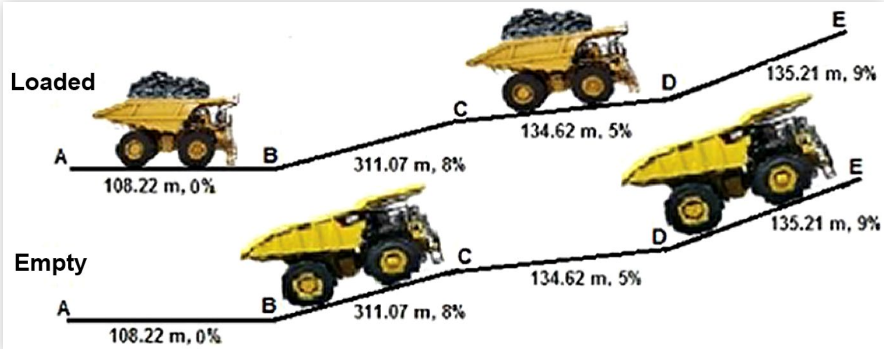
Road grade in mining activities is unavoidable as the mining pit has low elevation, requiring the road to be constructed following the topographic contour. Road grade is directly proportional to dump truck increased fuel consumption. Therefore, it is necessary to conduct a study to find out the effect of road grade on fuel consumption as a part of the effort to minimize fuel consumption in mining activities.

II. Methodology

2.1. Location of Research and Time

The present study was conducted from March to August 2021 on overburden hauling activities from the mine pit to the disposal area in a coal open-pit mine in Kutai Kartanegara, East Kalimantan.

FIGURE 1 Road construction.



2.2. Road Construction

The primary characteristic of the mining road that affects fuel consumption is the percentage gradient [4]. Surface conditions on mining roads are rougher than on highways, where the grade can be up to 15% and loads of up to 350 tons [7]. The total distance was 689.12 m, divided into four segments with road grades of +8%, +9%, +5%, and 0% (Figure 1).

2.3. Dump Truck Specifications

Objects of this study were dump trucks used in the mining site, including Caterpillar, Komatsu, and Volvo, with the specifications based on the following references [8, 9, 10] (Table 1).

2.4. Factors Affecting Fuel Consumption

Four factors affect a vehicle's fuel consumption: vehicle performance, traffic, environmental condition, and driving behavior [11]. More specifically, factors influencing dump truck fuel consumption includes the vehicle condition, travel distance, road grade, speed, rolling resistance, grade resistance, and horsepower [12].

TABLE 1 Dump truck specification.

	Dump truck specification (*travel empty*)		
Drivetrain	**CAT 773D**	**HD 465-7**	**Volvo A40D**
Gross power (HP)	682	739	426
Net power (HP)	650	715	420
Engine displacement (liter)	27	23.15	12
Nominal payload capacity (tons)	54.1	55	37
Vehicle weight (tons)	39.50	43.10	30.02
Actual payload average (tons)*	54.978	53.732	39.214
Rated engine speed (rpm)	2,000	2,000	1,800

* Source: Payload meter.

a. The Speed and Travel Time

Speed refers to the time it takes to travel a distance, which may affect travel time duration and affect fuel consumption, so that a longer travel time may cause more fuel consumption [13]. In general, the speed of conveyance can be determined by the equation, namely:

$$V = \frac{s}{t} \quad \text{or} \quad V = \frac{375 \times \text{HP} \times \text{MA}}{\text{Rimpull}} \qquad \text{Eq. (1)}$$

where V is the velocity (m/s), s is the distance (m), t is travel time (s), HP is horsepower, MA is mechanical availability.

b. Rimpull

Rimpull refers to the maximum tensile force provided by the engine or the magnitude of tensile strength given by a machine tool to the surface of the wheel or tire that touches the road's surface. The size of rimpull depends on the speed or gear used. The tractive force between the driving wheels and the surface on which they drive is called rimpull. Maximum rimpull is engine power and the gear ratio between the engine and the driving wheels if the traction coefficient is high enough that the tires do not slip. Maximum rimpull can be calculated using the equation below [14].

$$\text{RP} = \frac{375(\text{HP})(e)}{V} \qquad \text{Eq. (2)}$$

where RP is the maximum rimpull (lb), HP is the horsepower of the engine, e is the efficiency of the engine (decimals), and V is the velocity (miles per hour, mph).

The following formula calculates the rimpull required to overcome slope and rolling resistances:

$$\text{RP}_\text{R} = W\left(\text{RR} + 20\left(\pm S\right)\right) \qquad \text{Eq. (3)}$$

where RP_R is the rimpull required (lb), W is the weight of the vehicle (tons), RR is the rolling resistance (lb/tons), and S is the slope of grade (%).

c. Rolling Resistance (RR)

Rolling resistance can be defined as the force acting on a vehicle caused by the interaction between the vehicle and the road surface. However, gravitational resistance due to the longitudinal slope is excluded, and the resistance is due to side

TABLE 2 Typical value for rolling resistance.

No.	Road surface condition	Rolling resistance (%)
1	Asphalt, concrete	1.3
2	Rolled gravel	2.0
3	Dirt-smooth, hard, dry, and well maintained	2.0
4	Dirt-dry but not firmly packed	3.0
5	Gravel-dry not firmly compacted	3.0
6	Unpaved road	5.0
7	Gravel or sand-loose	10.0
8	Field	10.0-35.0

forces acting on the vehicle [15]. The rolling resistance is defined as the energy loss per distance traveled by car due to nonelastic deformations of the tires and failures in the wheel suspension system. Energy dissipation in road pavement structures also contributes to the rolling resistance [16]. The rolling resistance for typical haul roads is 2% if the road is hard and well-maintained. Meanwhile, lower quality at bench and area close to the dump end is expected to lead to a 3% increase in rolling resistance and during the wet periods when the road condition is poorer, the rolling resistance may rise to 4%. Under extremely poor conditions, the rolling resistance may rise to 10-16% [17], (Table 2).

The access road in this study is assumed to have the same conditions as a hard, dry, and well-maintained road. Hence a rolling resistance of 2% is employed in the analysis.

d. Grade Resistance

Grade resistance refers to the gravitational force. Road grade is an important factor in mining operations because it relates directly to transportation, both braking and overcoming inclines [18]. A vehicle's force to travel up a frictionless slope is grade resistance (does not include rolling resistance). The amount of work required to propel an automobile up a sloping surface is proportional to the slope of the character. The effort needed to drive a vehicle down a sloping terrain is roughly proportional to the slope [14, 19]. Meanwhile, total resistance represents the combined effect of rolling resistance and grade resistance. It can be calculated by summing the two variables to find the resistance in kilogram forces or effective value in a percentage as follows:

$$\text{Total resistance/Effective grade}(\%) = \text{RR}(\%) + \text{GR}(\%) \qquad \text{Eq. (4)}$$

e. Engine Power

Power refers to the number of works are done per time unit. In mechanical equipment such as a truck, excavator, bulldozer, and other mechanics horsepower is commonly used as the power unit [20]. One horsepower has an electrical equivalent of 746 watts and a heat equivalent of 2,545 BTU per hour in the International System of Units (S.I.). The metric horsepower equals 4,500 kilogram-meters per minute (32,549 foot-pounds per minute), or 0.9863 horsepower [21]. Horsepower represents an engine working time measurement that equals 33,000 ft-lb per minute [22]. The following equation can calculate the required horsepower at different working conditions, especially in a graded road.

$$\text{HP} = \frac{\text{GMW} \times \text{TR} \times V}{273.75} \qquad \text{Eq. (5)}$$

where HP is horsepower (HP), GMW is weight of unit (kg), TR is resistance total (%), and V is velocity (km/jam).

f. Loaded Factor

The reducing load may result in lower fuel consumption since the load factor is related to the percentage of engine power. In the same vein, a 10% decrease in vehicle's load may result in a 6% to 8% increase in fuel economy [22, 23].

2.5. Fuel Consumption Analysis

The study on seven different engines found that the off-highway efficiency varies from 39% to 46% or 43% on average, and standard deviation of 2% with engine size ranging from 0.2 to 34.5 liters [24]. The three main components of the engine model include friction and engine efficiency, maximum torque, and load, which can be derived from the fuel consumption relationship (FR):

$$\text{FR} = \frac{1}{\text{LHV}}\left(\frac{kNVd}{2{,}000}\right) + \frac{P}{\eta i} \qquad \text{Eq. (6)}$$

where FR is fuel consumption (kg/s), LHV is fuel lower heating value (kJ/kg), k is engine friction (kPa), N is engine speed (rpm), Vd is engine displacement (liter), P is dump truck power (kW), and n is an efficiency of wheel drive (%).

To value low heating value (LHV) or assumptions used value of 43,000 kJ/kg because the machine used is a diesel engine. The value of engine displacement (Vd) is used to determine the engine friction value (k) and the efficiency of tandem wheels (n) based on ref [24].

III. Results and Discussion

3.1. Performance of Dump Truck

The horsepower values vary, depending on the road grade, total resistance, and speed [22]. The calculation and analysis results of Equations 1, 2, 4, and 5 show the total resistance, horsepower, and Rimpull values. Meanwhile, the engine speed value was obtained by observing the indicator (Table 3).

Table 3 shows that in a 9% grade, a significant engine speed and engine power increase, longer travel time, and lower vehicle speed were noticed in three dump trucks, both in laden and unladen conditions.

Higher speeds can cause faster engine rotation and eventually more fuel consumption [25]. Meanwhile, lower speed can also result in longer travel time and increased fuel

TABLE 3 Dump truck performance.

	Loaded				Empty			
	A-B (8%)	B-C (9%)	C-D (5%)	D-E (0%)	A-B (8%)	B-C (9%)	C-D (5%)	D-E (0%)
Grade (%)	8	9	5	0	8	9	5	0
Rolling resistance	2	2	2	2	2	2	2	2
Total resistance	10	11	7	2	10	11	7	2
CAT 773 D								
Engine speed (rpm)	1,869.50	1,917.63	1,852.16	1,848.76	1,801.48	1,841.92	1,765.18	1,731.09
Engine power (kW)	455.95	469.08	391.92	171.73	186.54	226.41	81.33	75.66
Travel time (s)	20.14	24.56	16.02	10.30	17.27	19.57	6.59	5.42
Speed (mph)	11.01	10.29	13.52	20.73	17.95	18.68	16.65	21.84
Mechanical availability (%)	77.01	77.01	77.01	77.01	77.01	77.01	77.01	77.01
Engine displacement (liter)	27.00	27.00	27.00	27.00	27.00	27.00	27.00	27.00
Rimpull (lb)	15,992.82	17,592.99	11,195.88	3,198.70	4,012.22	4,680.71	1,885.65	1,337.36
HD 465-7								
Engine speed (rpm)	1,823.17	1,885.12	1,801.17	1,789.25	1,728.53	1,785.12	1,710.28	1,708.78
Engine power (kW)	431.44	453.37	351.80	178.04	185.01	227.70	76.30	75.66
Travel time (s)	22.60	25.69	18.68	8.92	16.47	17.69	13.55	7.98
Speed (mph)	16.14	15.42	18.80	21.49	26.25	27.69	21.65	21.84
Mechanical availability (%)	86.09	86.09	86.09	86.09	86.09	86.09	86.09	86.09
Engine displacement (liter)	23.15	23.15	23.15	23.15	23.15	23.15	23.15	23.15
Rimpull (lb)	11,537.20	12,689.74	8,075.23	3,575.95	3,041.94	3,548.91	1,520.97	1,495.04
VOLVO A4OE								
Engine speed (rpm)	1,682.28	1,750.81	1,650.28	1,626.12	1,632.28	1,674.57	1,595.48	1,578.16
Engine power (kW)	276.95	287.60	245.71	185.10	136.47	163.33	57.92	28.07
Travel time (s)	27.65	35.33	22.27	17.63	17.06	17.93	14.78	10.85
Speed (mph)	14.69	13.87	18.61	24.54	27.64	28.35	23.46	34.10
Mechanical availability (%)	88.78	88.78	88.78	88.78	88.78	88.78	88.78	88.78
Engine displacement (liter)	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00
Rimpull (lb)	8,393.49	9,232.38	5,875.27	3,357.35	2,197.89	2,564.05	1,098.91	366.29

consumption. They also state that the speed higher or lower than 37.28 mph can cause higher fuel consumption, implying that speed and fuel consumption are correlated at a certain point.

The increased total resistance increases fuel consumption. He further states that road surface conditions affect rolling resistance, resulting in a 10% improved fuel consumption. Therefore, road surface maintenance plays a vital role in affecting rolling resistance and fuel consumption [26].

3.2. Fuel Consumption

A simple, efficient, realistic fuel consumption interpretation is pivotal to support hauling activities [27]. Tables 4-6 show the fuel consumption calculation of Caterpillar CAT 773D, Komatsu HD 465-7, and Volvo 140D under laden and unladen conditions using Equation 6.

The calculation shown in the Tables 4-6 applies only to certain road grades (i.e., 0%, 5%, 8%, and 9%). To determine the fuel consumption in each road grade, linear interpolation, the first-degree polynomial, and a line between two input points were used to determine the central value. The calculation results are shown in Table 7 and Figure 2.

As presented in Table 7, every 1% road grade increase leads to 13.29%-23.64% increase in fuel consumption under laden condition and 7.64%-23.75% under unladen condition. Under the laden condition, the engine consumes 30% more fuel than the unladen condition at the same speed [22]. A steeper road and heavier vehicle result in lower speed, thus increasing the fuel consumption [27].

3.3. Recommended Maximum Road Grade

A maximum road grade defines a recommended road grade value to save dump truck fuel consumption in hauling activities. This value is determined based on the reading of significantly increased value at a certain point. As shown in Figure 3, a truck under a laden condition on a 0% to 8% gradient tends to show a linear fuel consumption increase, whereas, on a 9% grade, the fuel consumption drastically increases. Based on this result, a 8% grade is determined as the initial hypothesis as the recommended maximum grade. The last two points (i.e., 8% and 9% gradient to 15% gradient) are extrapolated (Table 8) to prove the proposed hypothesis.

TABLE 4 Fuel consumption CAT 773D.

		Loaded				Empty			
Parameter	**Unit**	**A-B (8%)**	**B-C (9%)**	**C-D (5%)**	**D-E (0%)**	**A-B (8%)**	**B-C (9%)**	**C-D (5%)**	**D-E (0%)**
Engine friction (*k*)	kPa	212.800	212.800	212.800	212.800	212.800	212.800	212.800	212.800
Engine speed (*N*)	rps	31.158	31.961	30.869	30.813	30.025	30.699	29.420	28.852
Engine displacement (*Vd*)	liter	27.00	27.00	27.00	27.00	27.00	27.00	27.00	27.00
Engine efficiency (n_i)	%	0.422	0.422	0.422	0.422	0.422	0.422	0.422	0.422
Fuel lower heating value (LHV)	kJ/kg	43,000	43,000	43,000	43,000	43,000	43,000	43,000	43,000
Specific gravity of fuel	kg/m^3	840	840	840	840	840	840	840	840
Fuel consumption (FR)	kg/s	0.027	0.028	0.024	0.012	0.006	0.007	0.014	0.012
	m^3/s	0.000032	0.000033	0.000028	0.000014	0.000007	0.000008	0.000017	0.000015
	m^3	0.000652	0.000818	0.000451	0.000141	0.000127	0.000152	0.000113	0.000079
	liter	**0.652**	**0.818**	**0.451**	**0.141**	**0.127**	**0.152**	**0.113**	**0.079**

TABLE 5 Fuel consumption HD 465-7.

		Loaded				Empty			
Parameter	**Unit**	**A-B (8%)**	**B-C (9%**	**C-D (5%)**	**D-E (0%)**	**A-B (8%)**	**B-C (9%)**	**C-D (5%)**	**D-E (0%)**
Engine friction (*k*)	kPa	203.968	203.968	203.968	212.800	203.968	203.968	203.968	212.800
Engine speed (*N*)	rps	30.386	31.419	30.020	29.821	28.809	29.752	28.505	28.480
Engine displacement (*Vd*)	liter	23.15	23.15	23.15	27.00	23.15	23.15	23.15	23.15
Engine efficiency (n_i)	%	0.427	0.427	0.427	0.422	0.427	0.427	0.427	0.422
Fuel lower heating value (LHV)	kJ/kg	43,000	43,000	43,000	43,000	43,000	43,000	43,000	43,000
Specific gravity of fuel	kg/m^3	840	840	840	840	840	840	840	840
Fuel consumption (FR)	kg/s	0.025	0.026	0.021	0.012	0.012	0.014	0.006	0.006
	m^3/s	0.000030	0.000031	0.000025	0.000014	0.000014	0.000017	0.000007	0.000007
	m^3	0.000677	0.000808	0.000463	0.000125	0.000229	0.000296	0.000092	0.000058
	liter	**0.677**	**0.808**	**0.463**	**0.125**	**0.229**	**0.296**	**0.092**	**0.058**

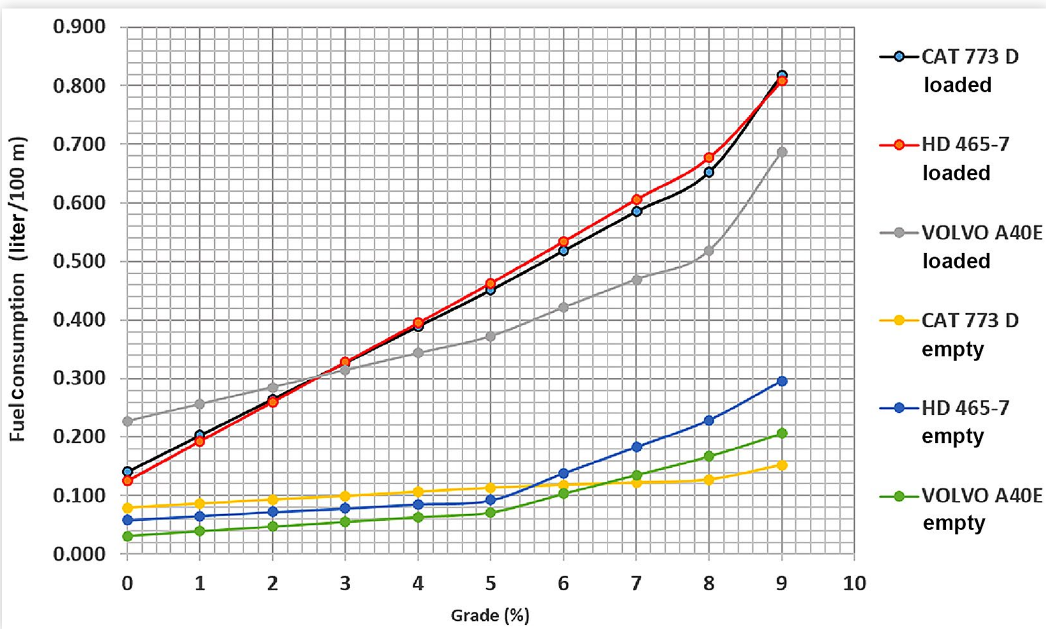
TABLE 6 Fuel consumption VOLVO A40E.

		Loaded				Empty			
Parameter	**Unit**	**A-B (8%)**	**B-C (9%)**	**C-D (5%)**	**D-E (0%)**	**A-B (8%)**	**B-C (9%)**	**C-D (5%)**	**D-E (0%)**
Engine friction (*k*)	kPa	187.569	187.569	187.569	187.569	187.569	187.569	187.569	187.569
Engine speed (*N*)	rps	28.038	29.180	27.505	27.102	27.205	27.910	26.591	26.303
Engine displacement (*Vd*)	liter	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00
Engine efficiency (n_i)	%	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.437
Fuel lower heating value (LHV)	kJ/kg	43,000	43,000	43,000	43,000	43,000	43,000	43,000	43,000
Specific gravity of fuel	kg/m^3	840	840	840	840	840	840	840	840
Fuel consumption (FR)	kg/s	0.016	0.016	0.014	0.011	0.008	0.010	0.004	0.002
	m^3/s	0.000019	0.000019	0.000017	0.000013	0.000009	0.000012	0.000005	0.000003
	m^3	0.000518	0.000687	0.000372	0.000227	0.000167	0.000206	0.000071	0.000031
	liter	**0.518**	**0.687**	**0.372**	**0.227**	**0.167**	**0.206**	**0.071**	**0.031**

TABLE 7 Fuel consumption per road grade increase.

Grade (%)	CAT 773 D fuel consumption				HD 465-7 fuel consumption				VOLVO A40E fuel consumption			
	Loaded		Empty		Loaded		Empty		Loaded		Empty	
	(liter)	(%)	(liter)	(%)	(liter)	(%)	(liter)	(%)	(liter)	(%)	(liter)	(%)
0	0.141	0.00	0.079	0.00	0.125	0.00	0.058	0.00	0.227	0.00	0.031	0.00
1	0.203	43.97	0.086	8.86	0.193	54.40	0.065	12.07	0.256	12.78	0.039	25.81
2	0.265	30.54	0.093	8.14	0.260	34.72	0.072	10.77	0.285	11.33	0.047	20.51
3	0.327	23.40	0.099	6.45	0.328	26.15	0.078	8.33	0.314	10.18	0.055	17.02
4	0.389	18.96	0.106	7.07	0.395	20.43	0.085	8.97	0.343	9.24	0.063	14.55
5	0.451	15.94	0.113	6.60	0.463	17.22	0.092	8.24	0.372	8.45	0.071	12.70
6	0.518	14.86	0.118	4.42	0.534	15.33	0.138	50.00	0.421	13.17	0.103	45.07
7	0.585	12.93	0.122	3.39	0.606	13.48	0.183	32.61	0.469	11.40	0.135	31.07
8	0.652	11.45	0.127	4.10	0.677	11.72	0.229	25.14	0.518	10.45	0.167	23.70
9	0.818	25.46	0.152	19.69	0.808	19.35	0.296	29.26	0.687	32.63	0.206	23.35
Average		**21.95**		**7.64**		**23.64**		**20.60**		**13.29**		**23.75**

FIGURE 2 Graph of linear interpolation fuel consumption.



Thus, the average grade value is used (Figure 3).

Figure 3 shows that 8% grade is recommended as the maximum road grade value to save fuel consumption in mining activities.

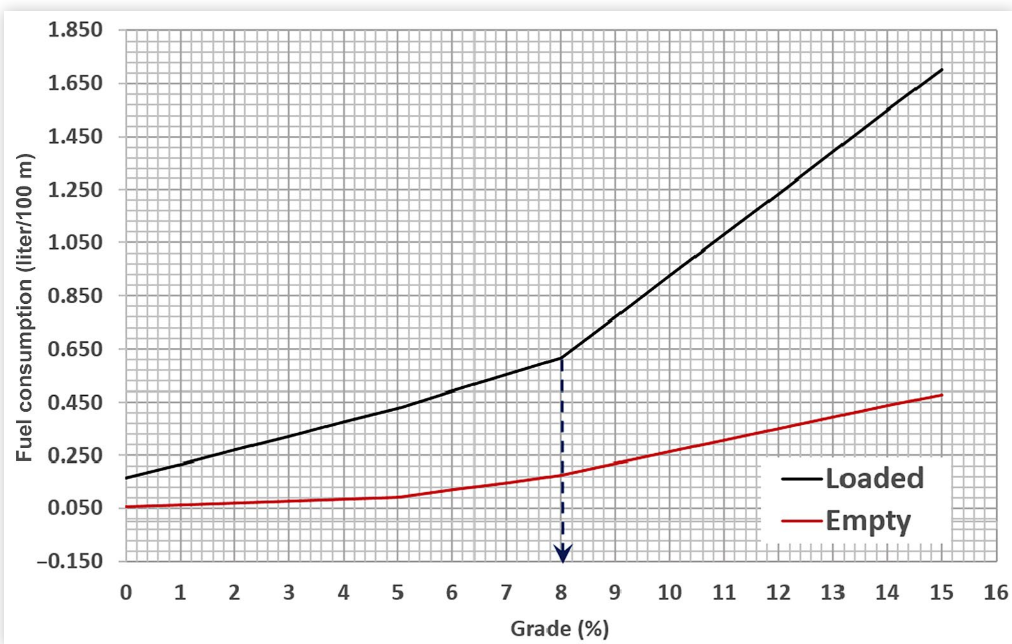
IV. Conclusions and Recommendations

1. Every 1% road grade increase leads to a higher engine speed of 0.482%-0.515% and horsepower of 2.79%.
2. Under the unladen conditions, CAT 773D exhibited a 7.15% increase in fuel consumption, while HD 465-7 showed 20.61%, and Volvo A40E showed 32.12% for every 1% road grade increase.
3. In the laden conditions, the fuel consumption of CAT 773D, HD465-7, and Volvo A40E increases by 22.99%, 24.69%, and 13.46% for every 1% road grade increase, respectively.
4. A maximum road grade of 8% is recommended to save fuel consumption for hauling activities in the mining area.

TABLE 8 Fuel consumption extrapolation.

	Fuel consumption (liter)				Fuel consumption (liter)			
	Loaded				Empty			
Grade (%)	CAT 773D	HD 465-7	VOLVO A40E	Average	CAT 773D	HD 465-7	VOLVO A40E	Average
0	0.141	0.125	0.227	0.164	0.079	0.058	0.031	0.056
1	0.203	0.193	0.256	0.217	0.086	0.065	0.039	0.063
2	0.265	0.260	0.285	0.270	0.093	0.072	0.047	0.071
3	0.327	0.328	0.314	0.323	0.099	0.078	0.055	0.077
4	0.389	0.395	0.343	0.376	0.106	0.085	0.063	0.085
5	0.451	0.463	0.372	0.429	0.113	0.092	0.071	0.092
6	0.518	0.534	0.421	0.491	0.118	0.138	0.103	0.120
7	0.585	0.606	0.469	0.553	0.122	0.183	0.135	0.147
8	0.652	0.677	0.518	0.616	0.127	0.229	0.167	0.174
9	0.818	0.808	0.687	0.771	0.152	0.296	0.206	0.218
10	0.984	0.939	0.856	0.926	0.177	0.363	0.245	0.262
11	1.150	1.070	1.025	1.082	0.202	0.430	0.284	0.305
12	1.316	1.201	1.194	1.237	0.227	0.497	0.323	0.349
13	1.482	1.332	1.363	1.392	0.252	0.564	0.362	0.393
14	1.648	1.463	1.532	1.548	0.277	0.631	0.401	0.436
15	1.814	1.594	1.701	1.703	0.302	0.698	0.440	0.480

FIGURE 3 Recommended maximum road grade.



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