THE EFFECT OF ROAD GRADE ON DUMP TRUCK DIESEL FUEL CONSUMPTION

by Harjuni Harjuni

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THE EFFECT OF ROAD GRADE ON DUMP TRUCK DIESEL FUEL CONSUMPTION

Harjuni [1)*)] & Realingga Octariando [2)]
Faculty of Engineering, University of Mulawarman, Gunung Kelua Campus,
St. Sambaliung No. 9 Samarinda 75119
[*)]harjunihasan@yahoo.co.id

ABSTRACT

Road grade and mining activities are inseparable. Since the mining pit elevation is lower, the road should be constructed following the topographic contour. Road grade may affect the speed, travel time, and fuel consumption. Road grade is known to be directly proportional to the energy required by dump trucks to overcome resistance. Higher road grade leads to more fuel consumption, and lower road grade leads to less fuel consumption. Under laden conditions, every 1% increase in road grade leads to a 21.615% increase in CAT 773D dump truck fuel consumption, 26.274% increase in HD-465-7 dump truck fuel consumption, and 19.014% increase in Volvo A40E. Meanwhile, under unladen conditions, every 1% increase in road grade led to 21.002% more fuel consumption in CAT 773D, 21.022% in HD 465-7, and 18.925% in Volvo A40E. A maximum road grade of 8% was recommended to save fuel consumption 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, despite its advantages, dump trucks consume about 0.04 gal per fwhp-hour during the operation*(Wang, Q. et al., 2021; Douglas D. Gransberg, 2015)*.

Hauling costs may account for 50% of the total operating cost in mining activities. Thus, minimizing fuel consumption may significantly lower the operating cost (*W. Hustrulid et al., 2013)*. Dump truck fuel consumption covers around 30% of the total energy used in surface mining activities (*Elnaz Siami-Irdemoosa et al., 2015)*.

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 *(Boriboonsomsin, K., & Barth, M., 2009 ; Natural Resources, 2019)*.

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 known to be 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.

2.2 Road Construction

The primary characteristic of the mining road that affects fuel consumption is the percentage gradient *(Elnaz Siami-Irdemoosa et al., 2015)*. Surface conditions on mining roads are rougher than on highways, where the grade can be up to 15% and loads of up to 350 tonnes *(Dindarloo, S. R. et al., 2016)*. The total distance was 689.12m, divided into four segments with road grades of +8%, +9%, +5%, and 0% (Figure 1).

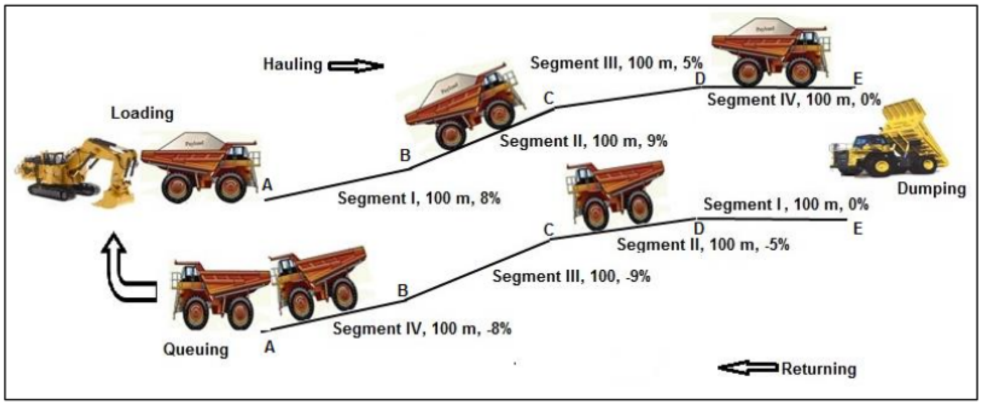

Figure 1. Road Construction

2.3 Dump Truck Specifications

Objects of this study were dump trucks used in the mining site, including Caterpillar, Komatsu, and Volvo, with the following specifications (Table 1)

Table 1. Dump Truck Specification

Drivetrain	Dump Truck Spesification (***Travel Empty***)		
	CAT 773D	**HD 465-7**	**Volvo A40D**
Gross Power (HP)	682	739	426
Net Power (HP)	650	715	420
Engine Displacement (ltr)	27	23,15	12
Nominal Payload Capacity (ton)	54.1	55	37
Vehicle Weight (ton)	39.50	43.10	30.02
Actual Payload Average (ton)*)	54.978	53.732	39,214
Rated Engine Speed (rpm)	2000	2000	1800

Source : (David Varea, 2017, Volvo Articulated Hauler A35D/A40D, and Komatsu HD465-7/HD605-7, *)*Payload metre)*

2.4 Factors Affecting Fuel Consumption

Four factors are known to affect a vehicle fuel consumption, namely the vehicle performance, traffic, environmental condition, and driving behavior *(Lin et al.,2011)*. More specifically, factors influencing dump truck fuel consumption includes the vehicle condition, travel distance, road grade, speed, rolling resistance, grade resistance, and horsepower *(Brown Andrew, JR., at al., (2011)*

a) The Speed and Travel Time

Speed refers to the time required to pass through a certain distance Haworth, N. and Symmons, M., (2001). Slower dump truck speed leads to longer travel distances, likely to result in increased fuel consumption. However, higher speed may lead to faster engine rotation and eventually increased fuel consumption. A speed of 60 km/hour is known to exhibit the lowest fuel consumption, meaning that the speed higher or lower than 60km/hour may lead to higher fuel consumption. This condition indicates that speed and fuel consumption is associated in a certain point.

Speed refers to the time it takes to travel a distance that, which may affect travel time duration and affecting fuel consumption, so a longer travel time may cause more fuel consumption *(Samaras, Christos E., 2012,* Figure 3).

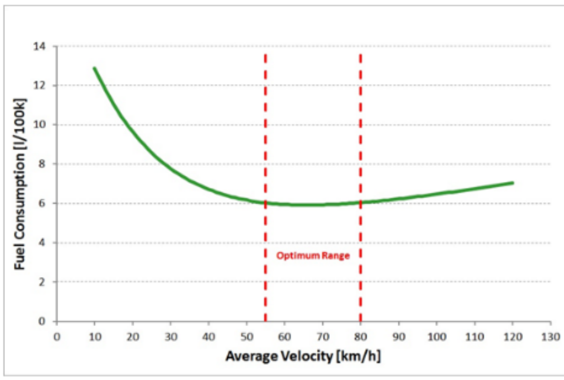

Figure 3. Relationship Average Speed - the Average Fuel Consumption
(Samaras, Christos E., 2012)

The figure shows that speed and fuel consumption have a relationship. In general, the speed of conveyance can be determined by the equation, namely :

$$V = \frac{s}{t} \; or \; V = \frac{375 \; x \; HP \; x \; MA}{Rimpull} \qquad \text{(eq. 1)}$$

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

c). Loaded Factor

Herbert L. Nichols (2005) argues that reducing load may result in lower fuel consumption since the load factor is related to the percentage of engine power (*Klanfar, M. et al., 2016*). In the same vein, a 10% decrease in vehicle's load may result in a 6% to 8% increase in fuel economy (US Department of Energy 2021)

c) Grade Resistance

According to *Johanson & Associates, LLC, (2021)* , grade resistance refers to the gravitational force on a vehicle. Road grade is an important factor in mining operations because it relates directly to transportation, both braking and overcoming inclines. A vehicle's force to travel up a frictionless slope is known as 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. *(Gransberg, Dougles D, et al., 2006).* Dwayne D. Tannant et al., (2001) 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:

$$\text{Total Resistance/Effective Grade (\%)} = \text{RR (\%)} + \text{GR (\%)} \quad \text{(eq.2)}$$

d) 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 forces acting on the vehicle *(Karlsson R. et al., 2011)*. The rolling resistance is defined as the energy loss per distance travelled by a car due to non-elastic deformations of the tires and failures in the wheel suspension system. Energy dissipation in road pavement structures also contributes to the rolling resistance *(Lasse G. et al., 2015)*. Rolling resistance coefficient increase is likely to lead to the fuel consumption increase. In other words, the road surface may account for the nearly double rolling resistance, affecting changes in fuel consumption by around 10 %. Therefore, the road surface and the maintenance standard of the surface are pivotal factors affecting the rolling resistance and fuel consumption *(Bendtsen H, 2004)*. 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 3% increase in rolling resistance; during the wet periods when road condition is poorer, the rolling resistance may rise up to to 4%; finally, under extremely poor conditions, the rolling resistance may rise to 10–16%, but only over small sections of the haul road and for short periods of truck travel *(Soofastaei, A., et al., 2016)*. The access road in this study is assumed to have the same conditions as a hard, dry, and well-maintained road. Hence an rolling resistance of 2% is employed in the analysis (Table 2).

Table 2 : Typical value for rolling resistance *(Soofastaei, A., et al., 2016)*

No	Road Condition	Rolling Resistance (%)
1	Bitumen, concrete	1.5
2	Dirt-smooth, hard, dry and well maintained	2.0
3	Gravel-well compacted, dry and free of loos material	2.0
4	Dirt-dry but not firmly packed	3.0
5	Gravel-dry not firmly compacted	3.0
6	Mud-with firm base	4.0
7	Gravel or sand-loose	10.0
8	Mud-with soft spongy base	16,0

e) 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 surface of the road. 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 known as rimpull. Maximum rimpull is a function of 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 *(Gransberg, Dougles D, et al., 2006)* (eq.3):

$$RP = \frac{375(hp)(e)}{V} \quad \text{(eq. 3)}$$

Where RP is the maximum rimpull (lbs), HP is the horsepower of the engine, e 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 :

$$RP_R = W(RR + 20 (\pm S)) \quad \text{(eq. 4)}$$

Where: RP_R is the rimpull required (lbs), W the weight of the vehicle (tons), RR the rolling resistance (lbs/ton), and S the slope of grade (%).

Magnitude rimpull at all three dump trucks are determined based on the data chart as follows (Figure 5, 6, and 7):

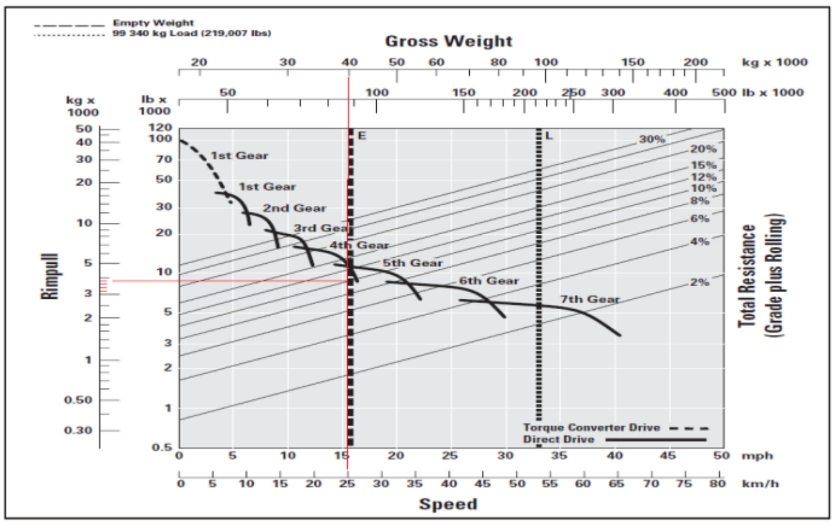

Figure 5. Chart of rimpull determine CAT 773D (Travel Empty), *(Caterpillar Performance Handbook Edition 47)*

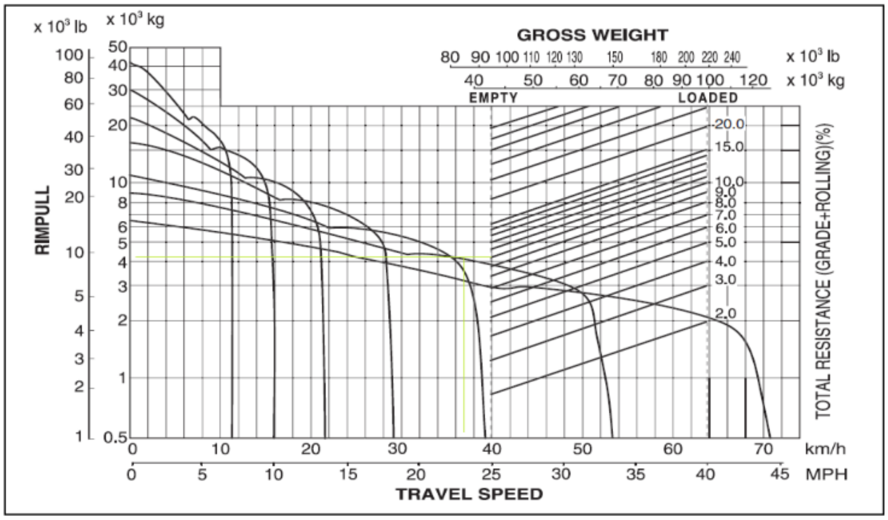

Figure 6. Chart of rimpull determine HD 465-7 (Travel Empty)
(Komatsu HD465-7/HD605-7)

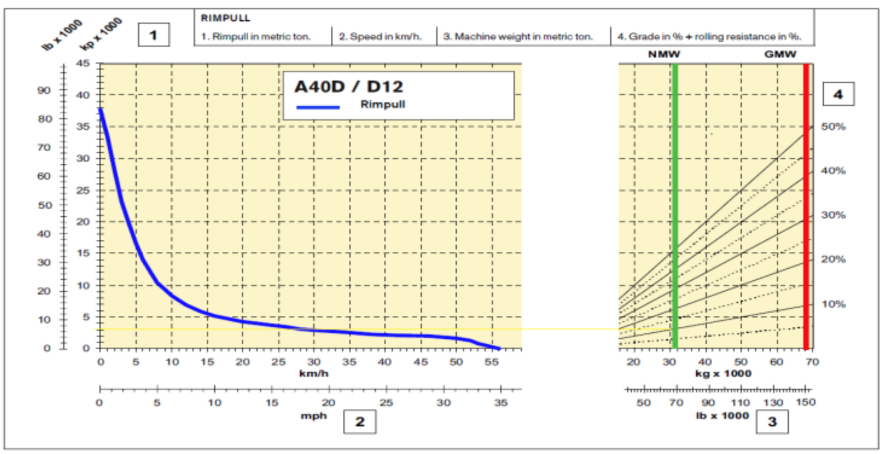

Figure 7. Chart of rimpull determine Volvo A40D (Travel Empty)
(*Volvo Articulated Hauler AD35D/AD40D*)

f) Engine Power

Power refers to the number of works should be done per time unit. In mechanical equipment like truck, excavator, bulldozer, and other mechanics, horsepower is commonly used as the power unit (Hindren A. Saber., et al., 2013).
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 (SI). The metric horsepower equals 4,500 kilogram-metres per minute (32,549 foot-pounds per minute), or 0.9863 horsepower *(horsepower, 2020)*. Horsepower represents an engine working time measurement that equals

to 33.000 ft-lb per minute *Herbert L Nichols Jr. et al., (2010)*. The following equation can be used to calculate the required horsepower at different working conditions, especially in a grade road.

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

Where : HP is Horsepower (hp), GMW is weight of unit (kg), TR is Resistance total (%), V is Velocity (km/jam)

2.4 Fuel Consumption Analysis

Giannelli R.A., et al., (2005) study on seven different engines found that the off-highway efficiency varies, ranging from 39% - 46% or 43% on average, and standard deviation of 2% with engine size ranging from 0.2 to 34.5 liters. The three main components of the engine model include friction and engine efficiency, maximum torque, and load, which can be derived from fuel consumption relationship (FR) :

$$\text{FR} = \frac{1}{LHV}\left(\frac{kNVd}{2000}\right) + \frac{P}{\text{ni}} \qquad \text{(eq. 6)}$$

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 (litre), 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 table 3 below.

Table 3. Efficiency & Friction Engine in Diesel Engines *(Giannelli R.A., et al., 2005)*

Engine displacement (litres)	*k (bar)*	*k standart error (bar)*	*1 / n*	*1 / n standart error*	R^2	*n*
0.20	8.7	0.9	2.43	0.10	0.93	0.421
0.92	5.2	0.4	2.37	0.09	0.83	0.410
2.20	3.4	0.2	2.46	0.05	0.95	0.444
3.90	2.5	0.2	2.25	0.04	0.99	0.462
3.90	3.1	0.5	2.16	0.09	0.95	0.451
4.00	3.3	0.3	2.22	0.04	0.99	0.413
6.00	2.3	1.0	2.42	0.10	0.92	0.392
7.40	2.0	0.4	2.55	0.05	0.98	0.446
7.60	3.6	0.3	2.24	0.05	0.99	0.424
8.30	2.4	0.5	2.36	0.06	0.98	0.437
8.80	2.4	0.6	2.29	0.05	0.98	0.430
10.00	2.3	0.2	2.33	0.02	0.99	0.410
10.10	3.1	0.3	2.44	0.04	0.99	0.458
10.20	2.2	0.4	2.18	0.03	0.998	0.419
10.50	2.5	0.5	2.39	0.06	0.98	0.461
12.70	1.8	0.2	2.17	0.02	0.99	0.441
34.50	2.3	0.2	2.27	0.03	0.99	0.412

III. RESULTS AND DISCUSSION

3.1 Engine Speed and Horsepower

Horsepower values may vary depending on the road grade, total resistance, and speed. (*Herbert L Nichols Jr. et al., 2010*). The estimate and analysis result of (eq.1) (eq.2), (eq.4) (eq.5), and (fig. 5,6,7) obtain the value of total resistance, horsepower, and Rimpull, while the engine speed value was obtained from the observation (Table 4).

Table 4. Engine speed and horsepower

	Loaded			Empty		
	Segment I	Segment II	Segment III	Segment II	Segment III	Segment IV
Grade (%)	+8	+9	+5	-5	-9	-8
Rolling Resistance	2	2	2	2	2	2
Total resistance	10	11	7	7	11	10
HD 465-7						
Engine Speed (rpm)	1752.530	1785.035	1766.283	1813.165	1855.123	1843.169
Horsepower (KW)	431.441	453.372	351.803	76.295	227.702	185.011
Rimpull (lb)	9400	10000	5800	6393.34	10141.16	9259.32
CAT 773 D						
Engine Speed (rpm)	1851.48	1861.92	1815.18	1851.15	1917.63	1879.50
Horsepower (KW)	455.95	469.08	391.92	81.33	226.41	186.54
Rimpull (lb)	9600	10020	4400	5731.96	9259.32	8377.48
VOLVO A4OD						
Engine Speed (rpm)	1578.52	1584.53	1545.48	1556.28	1610.81	1582.28
Horsepower (KW)	276.95	287.60	245.71	57.92	163.33	136.47
Rimpull (lb)	62000	6600	4400	4850.12	7275.18	6834.26

The table shows that the horsepower and the engine rotation increases with increasing grade roads and total resistance.

3.2 Diesel Fuel Consumption

Under the laden condition, the engine consumes 30% more fuel than the unladen condition at the same speed (*Herbert L Nichols Jr. et al., 2010)*. The calculation result of (eq. 6) shows the diesel consumption of Caterpillar CAST 773D, Komatsu HD 465-7, and Volvo 140D dump trucks under laden and unladen condition in a 0%, 5%, 8%, and 9% road grade (Table 5).

Table 5. Diesel Fuel Consumption

Grade (%)	Diesel Fuel Consumption (liter / 100 m)					
	Loaded			Empty		
	CAT 773D	*HD 465-7*	*Volvo A40D*	*CAT 773D*	*HD 465-7*	*Volvo A40D*
0%	0,134	0,121	0,105	0,061	0,053	0,024
+5%	0,450	0,462	0,371	0,204	0,206	0,143
+8%	0,652	0,676	0,516	0,292	0,295	0,201
+9%	0,747	0,752	0,586	0,322	0,324	0,220

As shown in Table 5, higher road grade leads to higher fuel consumption, both under laden and unladen conditions.

3.3 Regression Analysis

Interpolation method was applied to regression trend line using linear approach in order to obtain the fuel consumption for every road grade level, presented in a chart. The following Table 6 and Figure 8 present the regression value.

Table 6. The regression value under laden and unladen condition

Dump Truck	Regression Value	
	Loaded	Empty
CAT 773D	y = 0,066x + 0,134	y = 0,029x + 0,060
HD 465-7	y = 0,072x + 0,100	y = 0,029x + 0,058
VolvoA40E	y = 0,050x + 0,123	y = 0,019x + 0,047

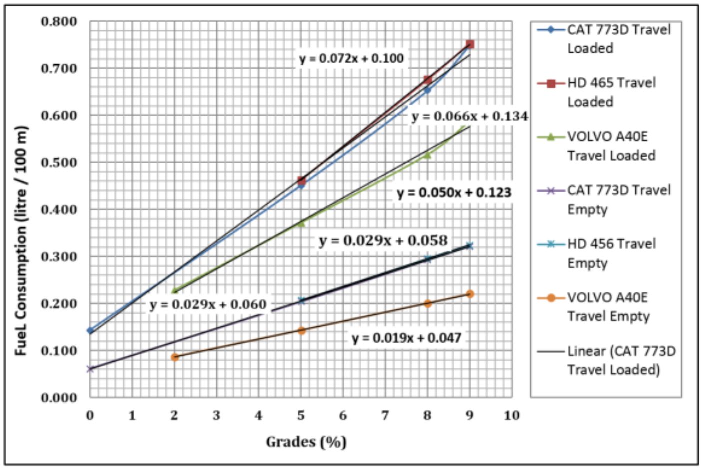

Figure 8. Linear Regression Fuel Consumption chart

The graph illustrates the amount of fuel consumption on a dump truck for every road grade increase and the results are as follows (Table 7).

Table 7. Diesel fuel consumption per road grade increase

Grade (%)	*Dump Truck* CAT 773D				*Dump Truck* HD 465-7				*Dump Truck* Volvo A40E			
	Loaded		Empty		Loaded		Empty		Loaded		Empty	
	Fuel Consumption (ltr)	(%)	Fuel Consumption (ltr)	(%)	Fuel Consumption (ltr)	(%)	Fuel Consumption (ltr)	(%)	Fuel Consumption (ltr)	(%)	Fuel Consumption (ltr)	(%)
0	0.134	0.00	0.060	0.00	0.100	0.00	0.058	0.00	0.123	0.00	0.047	0.00
1	0.202	50.75	0.089	48.33	0.172	72.00	0.087	50.00	0.173	40.65	0.066	40.43
2	0.270	33.66	0.118	32.58	0.244	41.86	0.166	33.33	0.223	28.90	0.085	28.79
3	0.338	25.19	0.147	24.58	0.316	29.51	0.145	25.00	0.273	22.42	0.104	22.35
4	0.406	20.19	0.176	19.73	0.388	22.79	0.174	20.00	0.323	18.32	0.123	18.27
5	0.474	16.75	0.205	16.48	0.460	18.56	0.203	16.67	0.373	15.48	0.142	15.45
6	0.542	14.35	0.234	14.15	0.532	15.65	0.232	14.29	0.423	13.41	0.161	13.38
7	0.610	12.55	0.263	12.39	0.604	13.53	0.261	12.50	0.473	11.82	0.180	11.80
8	0.678	11.15	0.292	11.03	0.676	11.92	0.290	11.11	0.523	10.57	0.199	10.56
9	0.746	10.03	0.321	9.93	0.792	10.65	0.319	10.00	0.573	9.56	0.218	9.55
Average		**21.62**		**21.02**		**26.27**		**21.43**		**19.01**		**18.95**

As presented in table 7, every 1% road grade increase leads to 19.01% - 26.27% increase in fuel consumption under laden condition and 18-95% -21.43% under unladen condition. This result proves that road grade affects fuel consumption, as depicted in figure 9.

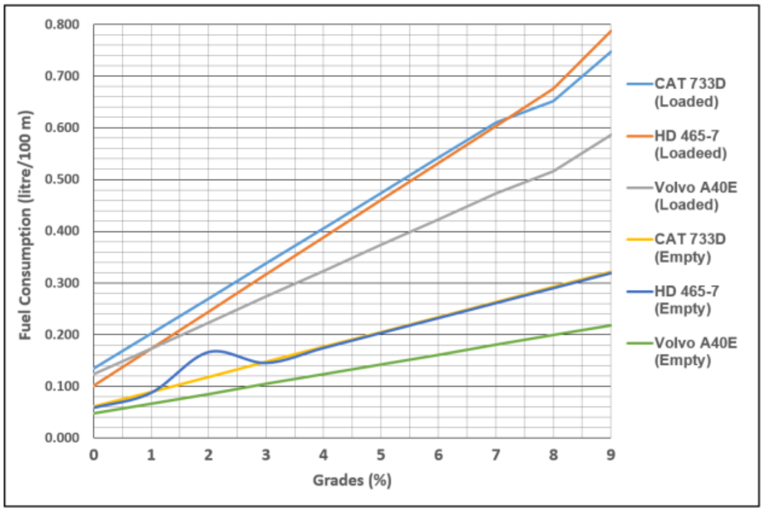

Figure 9. Effect of Road Grade on fuel consumption
in loaded and empty conditions

As shown in Figure 9, 0%-8% road grade exhibits a constant increase in fuel consumption, whereas the road grade increase from 8% to 9% exhibits a significant fuel consumption increase. This indicates that an 8% grade is the recommended maximum road grade for hauling activities in the mining area.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. Every 1% road grade increase leads to a higher engine speed of 0.38% -1.82% and horsepower of 2.79%.
2. Under the laden conditions CAT 773D exhibited 21.615% increase in fuel consumption, while HD 465-7 shows 26.274% ,and Volvo A40E showed 19.014% for every 1% road grade increase.
3. In the laden conditions, the fuel consumption of CAT 773D, HD465-7, and Volvo A40E increases by 21.022%, 21.433%, and 18.952% 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

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