Haul truck fuel consumption and CO2 emission under various engine load conditions

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by V. Kecojevic and D. Komljenovic

Abstract ■ Environmental and economic costs related to equipment fuel consumption and carbon dioxide (CO_2) emission present a substantial challenge to the mining industry. Haul trucks are an integral part of the overall surface mining system and they consume a significant quantity of fuel. Consequently, they produce a significant amount of CO_2. The objective of this research is to (i) establish a mathematical relationship among a truck's fuel consumption, power and engine load factors and (ii) determine the amount of a truck's CO_2 emission and the associated cost that may arise from potential CO_2 legislation. In order to achieve these objectives, the authors have considered original equipment manufacturer (OEM) haul trucks, which are commonly used in surface mining operations. The research presented here may be used by mining professionals to help determine the cost and environmental burden of the trucks' application and efficiently manage energy consumption.

Introduction

Haul trucks account for the major share of overall surface mining equipment costs. Fuel consumption is always the primary operating cost associated with trucks. Fundamental changes in fuel conservation, efficiency and reducing negative environmental impact related to CO_2 emission are of crucial importance.

A number of factors contribute to fuel consumption. These factors include truck load, speed, power, weight (empty and gross), accelerations, idle time, fuel quality, aerodynamics, road surface and tire quality, wheel alignment and tires' inflation pressure, road grade, the operator's driving style, outside temperature, weather and adequacy of a truck's maintenance program. The majority of these factors can be controlled to a certain extent by mine operators. Adequate management of these factors may significantly reduce truck fuel consumption while providing required truck performance, without important investments or operational changes. It translates into decreased engine load, which allows for the same performance with lower fuel consumption and, consequently, a lower CO_2 footprint. Thus, this study will analyze the impact of truck power and engine load factors on fuel consumption and on the subsequent CO_2 emissions and cost.

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Fuel consumption

The most accurate method to determine the fuel consumption of trucks is to obtain data from actual mine operations. However, if no such opportunity exists, various equations and data published by the truck original equipment manufacturer (OEM) can be used for estimation purposes.

According to Runge (1998) and Filas (2002), an hourly fuel consumption (FC) (L/hr) can be determined from the following equation:

$$FC = P \times 0.3 \times LF \qquad (1)$$

where P is engine power (kW), 0.3 is unit conversion factor (L/kW/hr) and LF is an engine load factor (the portion of full power required by the truck). Values for the truck engine load factors range from 0.18 to 0.50 (Runge, 1998), while Filas (2002) states that engine load factors typically range between 0.25 and 0.75, depending on the equipment type and use level.

A similar equation for fuel consumption was suggested by Hays (1990):

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

where CSF is the engine-specific fuel consumption at full power (0.213 – 0.268 kg/kW/hr) (0.35-0.44 lb/hp per hr), P is power (kW), LF is engine load factor and FD is the fuel density (0.85 kg/l [7 lb/gal] for diesel). Hays recommends the following values for engine load factors: 25% (light: considerable idle, loaded hauls on favorable grades and good haulage roads), 35% (average: normal idle, loaded hauls on adverse grades and good haulage roads) and 50% (heavy: minimum idle, loaded hauls on steep adverse grades).

Liebherr has developed a method to determine the truck fuel consumption per hour. According to this OEM, the fuel consumption rate is directly proportional to delivered power

Figure 1

Relationship between fuel consumption of Liebherr trucks and their engine power at a load factor of 100%.

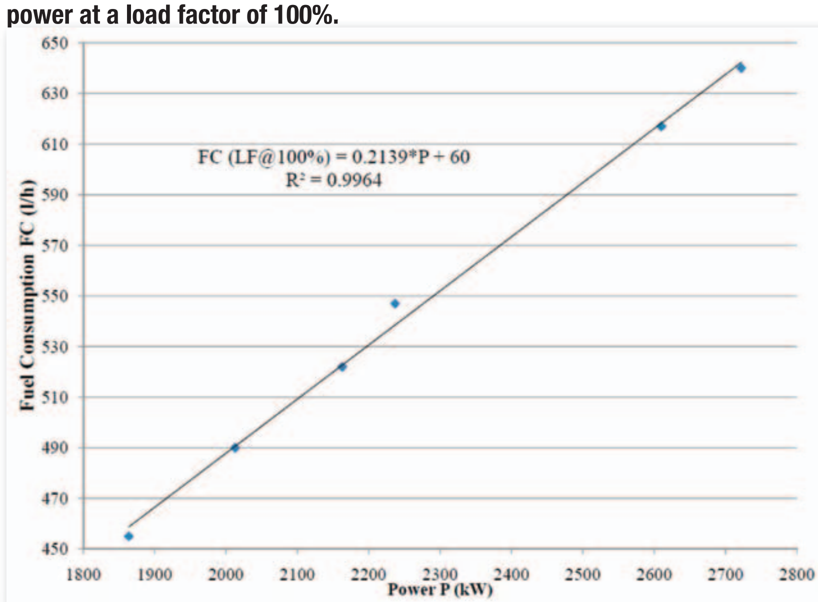
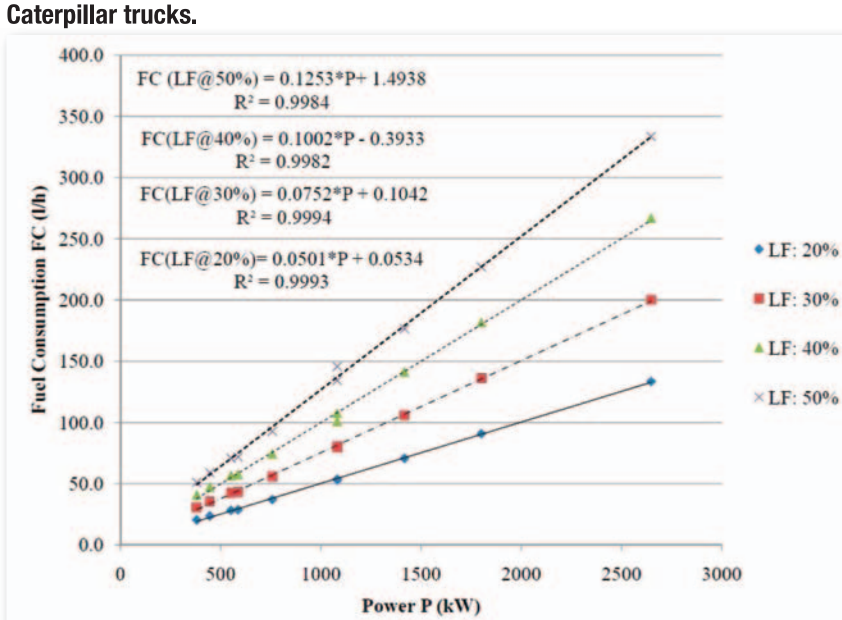


Figure 2

The relationship between fuel consumption (L/hr) and gross power (kW) for Caterpillar trucks.



(Baucom, 2008). An 100% load factor is assumed and the following fuel consumptions were obtained: 455 L/hr (120 gal/hr) for 1,864 kW (2,500 hp) truck power, 490 L/hr (129 gal/hr) for 2,013 kW (2,700 hp), 522 L/hr (138 gal/hr) for 2,163 kW (2,900 hp), 547 L/hr (146 gal/hr) for 2,237 kW (3,000 hp), 617 L/hr (163 gal/hr) for 2,610 kW (3,500 hp) and 640 L/hr (169 gal/hr) for 2,722 kW (3,650 hp). Figure 1 shows a relationship between engine power *P* (kW) and fuel consumption *FC* (L/hr) for Liebherr trucks at 100% engine load factor. Analyzing Fig. 1, it can be concluded that an increase in truck power at a load factor of 100% will lead to an average increase in fuel consumption at the rate of 0.2139 L/hr (0.056 gal/hr) per kW. It should be noted that as engine ratings approach and exceed 2,237 kW (3,000 hp), fuel efficiency (L/hr per kW) continues to improve (Baucom, 2008). A high value of $R^2 = 0.9964$ indicates a strong positive linear correlation between engine power and fuel consumption for Liebherr trucks.

Analyzing Eqs. (1), (2) and the results depicted in Fig. 1, the following can be observed: the gradient of an increase in fuel consumption is 0.300 L/hr (0.079 gal/hr) per kW, from 0.250 L/hr (0.066 gal/hr) per kW to 0.315 L/hr (0.083 gal/hr) per kW, and 0.214 L/hr (0.056 gal/hr) per kW, respectively. Equations 1 and 2 can be used for approximate calculation of fuel consumption, while the result obtained using OEM data reflects modern and more efficient truck engine designs, and is a more relevant and accurate for calculation of fuel consumption at 100% load factor.

Caterpillar (2009) provides data on fuel consumption for its trucks and various engine load factors. According to Caterpillar (2009), an engine continuously producing full-rated horsepower is operating at a load factor of 100%. Trucks may reach 100% load factor intermittently, but seldom operate at this level for extended periods of time (Caterpillar, 2009). During acceleration, the engine usually operates at full power with a load factor of 100%. While idling, a truck engine operates at about 10% of full power (Hays, 1990).

Values of engine load factor are given by Caterpillar (2009) as follows:

- Low: 20%-30% (Continuous operation at an average gross weight less than the recommended. Excellent haul roads. No overloading, low load factor.)
- Medium: 30%-40% (Continuous operation at an average gross weight approaching the recommended. Minimal overloading. Good haul roads, moderate load factor.)
- High: 40%-50% (Continuous operation at or above maximum recommended gross weight. Overloading. Poor haul roads, high load factor.)

Data on engine load factors given by Caterpillar are similar to those provided by Hays (1990) and Runge (1998).

A sample of 10 mining truck models from Caterpillar were selected for this study. All data of Caterpillar trucks related to design characteristics (gross and net power, gross and empty truck weight, payload, body volume) and hourly fuel consumption are available from the manufacturer's handbook (Caterpillar, 2009). Based on these data, the relationship among fuel consumption, power and load factor was established (Fig. 2). The obtained results show that fuel consumption increases in average from 0.050 L/hr (0.013 gal/hr)

Figure 3

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

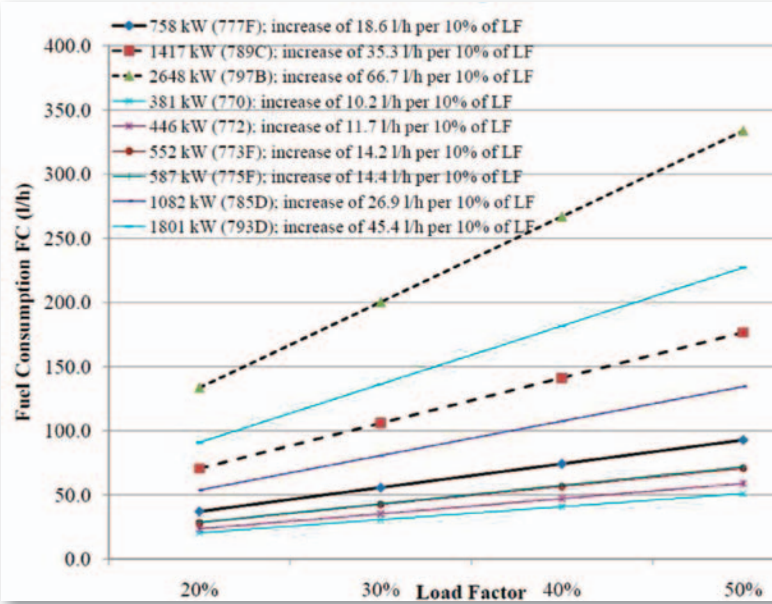


Figure 4

Potential annual savings ($/year) for 10% reduction in load factor.

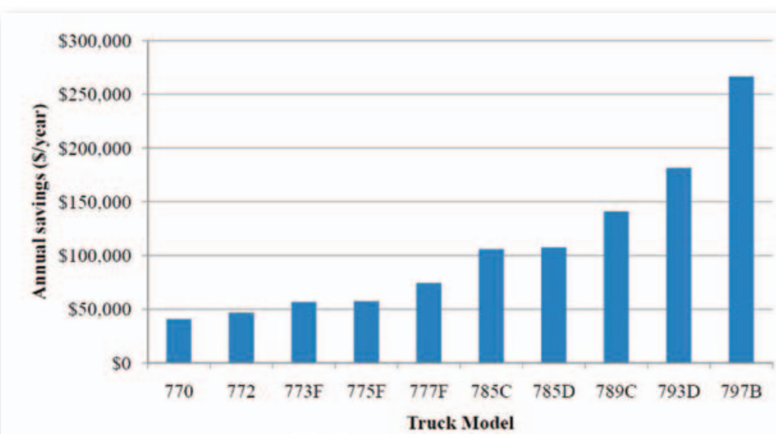
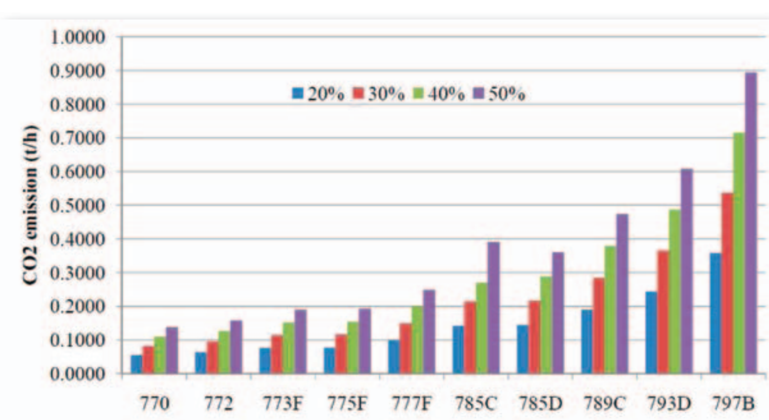


Figure 5

The CO_2 emission (t/hr) of Caterpillar trucks for various engine load factors.



per kW at a load factor of 20% to 0.075 L/hr (0.02 gal/hr) per kW at a load factor of 30%. It can also be seen that the fuel consumption increases from 0.100 L/hr (0.026 gal/hr) per kW at a load factor of 40% to 0.125 L/hr (0.033 gal/hr) per kW at a load factor of 50%. High values of R^2 indicate a strong positive linear correlation between power and fuel consumption for Caterpillar trucks.

Figure 3 shows the change in fuel consumption as a function of load factor for all Caterpillar trucks. It is to be noted that fuel consumption is a linear function of the load factor. However, the former increases faster in absolute values for larger trucks. Also, it can be observed, for example, that the increase in fuel consumption for the smallest truck (Cat 770) is 10.2 L/hr (2.69 gal/hr) for each 10% increase in the load factor. The largest model (Cat 797B) has an increase in fuel consumption of 66.7 L/hr (17.6 gal/hr) for each 10% increase in the load factor. This is an important finding, because mine operators can control factors that influence the load factor (road quality, operator's driving style, load, maintenance, etc.).

Figure 4 shows an example of total annual savings if the load factor is reduced by only 10%. It is assumed that the cost of fuel is $0.8/L ($3/gal). The total number of truck operating hours per year is considered to be 5,000, which is consistent with average data obtained from an operating coal mine in the southern U.S. The number of hours can also be considered as a means of approximately estimating the cost. Therefore, reducing the load factor by 10% can result in $40,800 savings per year for the smallest truck (Cat 770) and almost $267,000 per year for the largest truck (Cat 797B).

Determination of CO_2 emission

The CO_2 emission from combusted fuel can be determined by on site metering. However, on site metering units that continuously monitor equipment emission can be expensive and require permanent maintenance (Mining Environmental Management, 2008). The other alternative is to determine CO_2 emission by using mathematical equations.

The CO_2 emission from diesel fuels in t/hr can be written as:

$$CO_2 = FC \times CF \tag{3}$$

where *FC* is diesel fuel consumption (L/hr), and *CF* is the conversion factor. The conversion factors of CO_2 emission for diesel fuel can be calculated as:

$$CF = CC \times 10^{-6} \times 0.99 \times (44/12) \tag{4}$$

where *CC* is carbon content for the diesel fuel (g/L), and 0.99 is the oxidation factor.

Figure 6

The CO_2 cost ($/hr) for various engine load factors (%).

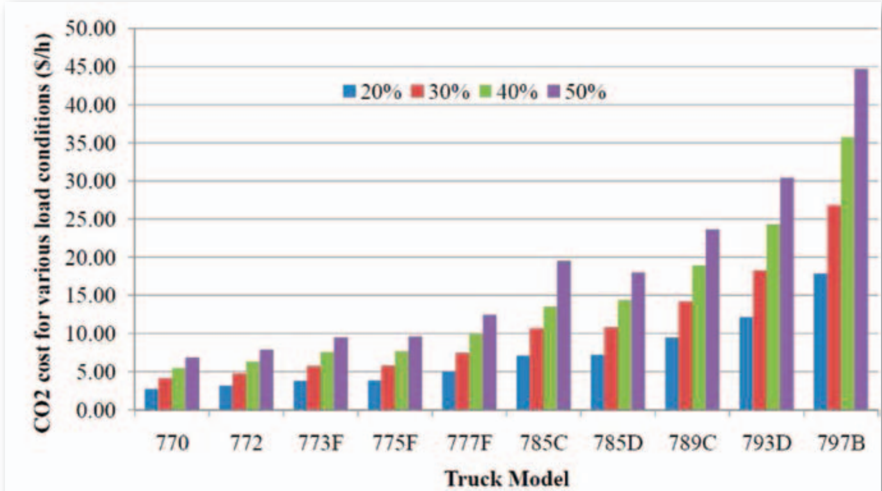
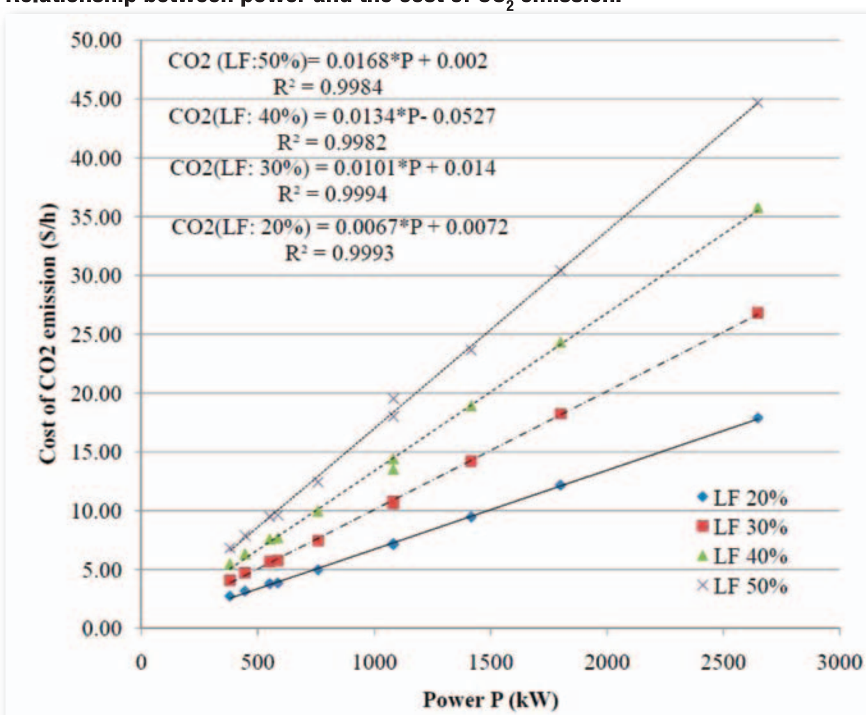


Figure 7

Relationship between power and the cost of CO_2 emission.



According to the Environmental Protection Agency (EPA, 2005), the conversion factor for diesel fuel *CF* 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* = 733 g/L (EPA, 2005). The oxidation factor for all oil and its products is 0.99. Practically, this means that 99% of the fuel burns out, while 1% remains unoxidized.

Figure 5 shows CO_2 emission (t/hr) of Caterpillar trucks for various engine load factors. These values are calculated using an hourly fuel consumption and conversion factor of *CF* = 0.00268 for diesel. The value of CO_2 emission ranges from 0.0547 t/hr (0.0601 st/hr) to 0.1367 t/hr (0.1507 st/hr) for load factors of 20% and 50%, respectively, for the smallest truck (Cat 770), and from 0.3578 t/hr (0.3944 st/hr) to 0.8940 t/hr (0.9835 st/hr) for load factors of 20% and 50%, respectively, for the largest truck (Cat 797B).

There are many empirical models with a range of values for the cost of CO_2 emission, and they are based on potential CO_2 legislation. Two of the most recognized models include the U.S. Energy Information Agency's (EIA) National Energy Modeling System (NEMS) model and the Massachusetts Institute of Technology's (MIT) Emissions Prediction and Policy Analysis (EPPA) model. These models consider a cost of CO_2 that ranges from $17 to $50 per ton of CO_2 emitted (Aziz and Kecojevic, 2008). For the purpose of this study, the value of $50 per ton was considered.

Figure 6 shows the cost of CO_2 emission per hour for various engine load factors. The cost of CO_2 emission ranges from $2.73 to $6.83 per hour for load factors of 20% and 50%, respectively, for the smallest truck (Cat 770) and from $17.89 to $44.70 per hour for load factors of 20% and 50%, respectively, for the largest truck (Cat 797B). Figure 7 depicts the mathematical relationship between the cost of CO_2 emission ($/hr) and truck power (kW).

Figure 8 shows the cost of CO_2 emission on an annual basis, assuming 5,000 operating hours per year. The costs range from $13,668 to $34,170 per year for load factors of 20% and 50%, respectively, for the smallest truck (Cat 770), and from $89,445 to $223,512 per year for load factors of 20% and 50%, respectively, for the largest truck (Cat 797B). Assuming that large-scale surface mining operations may have a fleet of 10 Cat 797B trucks, the cost for CO_2 emission may run from $900,000 to almost $2.3 million.

Figure 9 shows a potential cost savings related to CO_2 emission for the analyzed Caterpillar trucks. These savings are obtained by averaging the values given in Fig. 8 for reducing the load factor by 10%. The results show that savings per 10% load factor may range from approximately $7,000 per year per truck for the smallest model (Cat 770), to approximately $45,000 per year per truck for the largest model (797B).

A study by Leslie (2000) indicates that there is a decrease in fuel consumption when we move to larger and more productive trucks that have more efficient engines. The author also states that, since the production of CO_2 is directly proportional to fuel consumption, the amount of CO_2 released into the atmosphere decreases by 21.4% when moving from a 154-t (170-st) capacity truck to a 218-t (240-st), and another 16.3% from a 218-t (240-st) to a 290-t (320-st) truck capacity. It should be noted that Leslie's study (2000) relates to specific values of fuel consumption (lb/hr per ton of truck

Figure 8

The CO_2 cost ($/year) for various engine load factors (%).

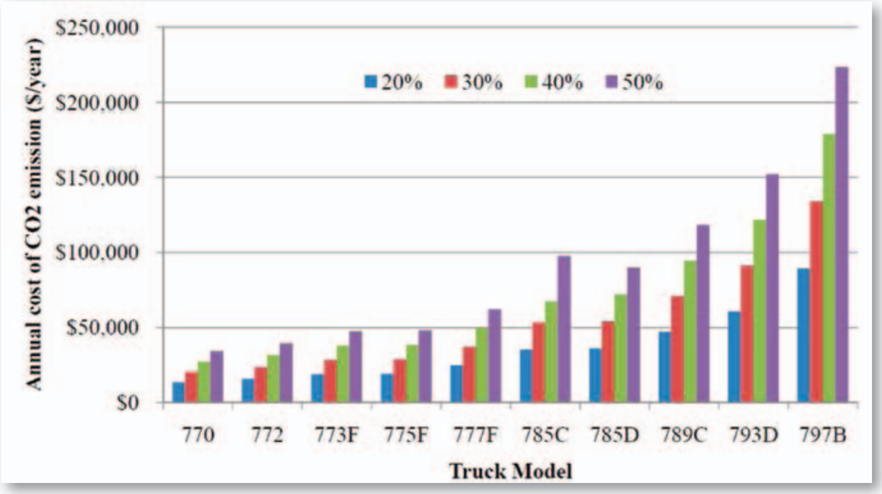
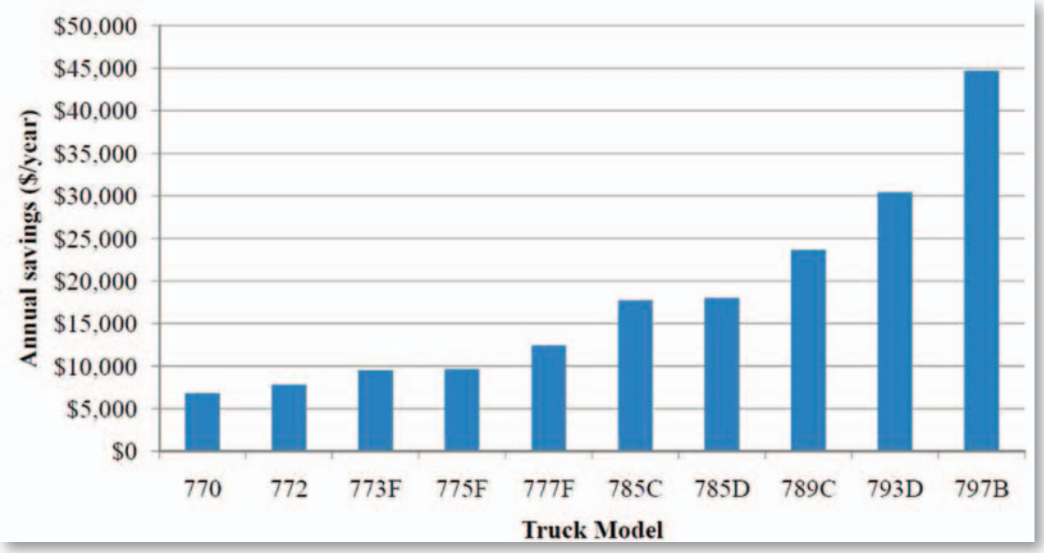


Figure 9

Potential annual savings ($/year) for a 10% reduction in load factor.



capacity), while this study has focused on absolute values of fuel consumption (L/hr) and CO_2 emission (t/hr) for various engine load factors.

Conclusions

This research was carried out to study the fuel consumption and CO_2 emission of haul trucks under various load conditions and to determine the associated costs of such consumption and emission. OEM trucks were considered for this study and it was determined that fuel consumption bears a strong correlation with power and engine load factor. It was determined that a reduction in load factor of 10% can significantly decrease fuel consumption and CO_2 emission and, consequently, reduce operating costs. Future studies may focus on specific factors (acceleration, idle time, road grade, maintenance and quality of road surface, the operator's driving style) to determine the potential savings in fuel consumption and CO_2 emission. ■

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