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Report No. PNWD-4448

Evaluation of Black Carbon Emission Reductions from Mining Trucks in Russia: The Case of the Murmansk Region

By
Nazar Kholod[a]
Meredydd Evans[a]
Vladimir Malyshev[b]

[a] Battelle Memorial Institute
[b] Murmansk State Technical University

Prepared under a cooperative agreement
with the U.S. Environmental Protection Agency

July 2015

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PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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(9/2003)

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Executive Summary

This report discusses options for black carbon (BC) emission reductions from mining equipment in open pit mines in the Murmansk Region of Russia. The lessons learned in the Murmansk Region can be useful in Russia and Arctic-wide.

The off-road, heavy-duty mining trucks and equipment in the Murmansk Region are very large and use diesel fuel to operate. Each truck burns more than a ton of diesel per day, reflecting its size, power, and long hours of operation. Diesel engines produce BC emissions, a result of incomplete combustion of fuel. Exposure to BC can harm the cardiovascular system and cause premature death. Black carbon is also considered a major contributor to current global warming, alongside carbon dioxide and methane. BC has an additional warming effect in the Arctic when deposited onto ice and snow, which also increases melting.

This report considers the options for BC emission reductions from mining vehicles through engine repowering, vehicle replacement and engine retrofits. Given the short life of engines, mines can quickly replace old Tier 0 engines with new Tier 2 engines. Newer engines are not only much cleaner, but are also more economical and reliable. Based on the information from equipment manufacturers, it is cost-effective for companies to buy these more expensive vehicles; they are also more reliable, fuel efficient and cleaner trucks.

Our analysis shows that mines can recover the additional cost for replacing Tier 0 engines with Tier 2 ones through fuel savings. The lump-sum cost of the 1,000 kW engine upgrade from Tier 1 to Tier 2 is in the range of $20,000-$30,000. Given that a new engine can work three years before its first overhaul, the average cost per year during this period is $7,000-$10,000. The fuel cost savings would be $20,000-$58,000 per year. Replacing a Tier 0 engine with a Tier 2 engine during planned repowering requires a one-time investment and mines can recover this cost during the first year of operations. Mines also could speed up engine replacement to increase savings. Installing a new and more efficient engine could be more cost-effective than the rebuilding of an old engine.

Replacing Tier 0 engines will reduce emissions. Reduction of BC emissions will benefit employees, local communities, and the environment, and, in some instances, improve mine operations. BC emissions reductions would reduce the risk of cancer as well as lung and cardiovascular diseases among mine workers and other residents of Murmansk Region. Reduction of BC emissions in the Arctic will also benefit the global environment through mitigation of the melting effects of global warming.

Acronyms and Abbreviations

BC	black carbon
EPA	U.S. Environmental Protection Agency
EU	European Union
PM	particulate matter
$PM_{2.5}$	particulate matter with a diameter of 2.5 microns or less
WHO	World Health Organization
DERA	Diesel Emissions Reduction Program
DOC	diesel oxidation catalysts
P-DPF	passive diesel particulate filters
A-DPF	active diesel particulate filters
SCR	selective catalytic reduction
EGR	exhaust gas recirculation
MECA	Manufacturers of Emission Controls Association

1. Background

Off-road vehicles are a significant source of emissions world-wide. For example, in the U.S., BC emissions from off-road diesel vehicles account for 33.6% of emissions from all mobile sources (EPA, 2012).

In the Murmansk Region, mining trucks produce the majority of PM and BC emissions due to their size and the mode of operation (Evans et al., 2015). Ore movement is typically the single largest energy-using activity for open pit mines, and mining trucks consume up to 80% of total diesel consumption at the open pit mines.

The role of mining trucks is growing with the increasing scale of mining operations. According to Parker Bay, a mining market research company, the current fleet of mining trucks in the world increased from around 38,500 at the beginning of 2013 to 42,000 in October 2014 (Parker Bay Company, 2014).

The number of mining trucks in Russia is also increasing. BELAZ, the largest supplier of mining trucks to the country, sells about 800 mining trucks to Russia every year and this number has been growing (Petrovich et al., 2013). About 12,500 BELAZ trucks worked in the mining industry in Russia in 2012.

In 2012, 1,725 new mining trucks were sold in Russia; their total value was $1.05 billion. The share of BELAZ was 59.2% and Komatsu 10.2% (Discovery RG, 2015). According to a forecast by the Russian company Discovery Research Group, the mining truck market segments will grow by 1-7% per year during the next decade.

Expansion of mining operations in Russia brings up several important issues. First of all, mining companies need more energy efficient and reliable trucks. Recent developments in mining truck technologies provide significant improvements in productivity, safety and efficiency. New engines are more economical while providing the same power output, which is important given increasing fuel prices in Russia.

Second, most countries have been introducing more stringent environmental requirements, and, in response, engine producers have improved technologies to significantly reduce emissions. Lowering emissions is important for companies and their surrounding communities because diesel emissions, including BC, have negative impacts on health.

By using new cleaner engines, mining companies can improve the air quality and avoid costs associated with health problems. Exhaust gases from mining trucks and equipment also can create a significant problem for mining operations. According to an Apatite mine representative, exhaust emissions from mining trucks can significantly limit visibility in open pit mines, causing work stoppages due to poor air quality to avoid an increased risk of accidents.

2. Climate and Health Effects of Black Carbon Emissions

Mining equipment, especially mining trucks, is a large source of BC emissions. In the Murmansk Region of Russia, mining companies are responsible for up to 70% of all diesel BC emissions (Evans, 2015).

BC is a product of incomplete combustion of fuel, including diesel, and it is a component of particulate matter ($PM_{2.5}$). Research findings show that fine particles cause serious human health problems. The largest of the fine particles are approximately 30 times smaller than the diameter of an average human hair. Because they are so small ($PM_{2.5}$), BC and other fine particles can get into the lungs. Emissions of fine particles ($PM_{2.5}$), including BC, result in premature deaths and risks to the cardiovascular system. People with pre-existing lung or heart disease, as well as elderly people and children, are particularly vulnerable to the impacts of $PM_{2.5}$. There is no evidence of a safe level of exposure or a threshold below which no adverse health effects occur.

In June 2012, the World Health Organization (WHO) reclassified diesel engine exhaust emissions as carcinogenic to humans. The International Agency for Research on Cancer (IARC), which is part of the WHO, found sufficient evidence that exposure to diesel exhaust causes lung cancer (IARC, 2012). According to a WHO study, exposure to $PM_{2.5}$ reduces the life expectancy of the population in Eastern Europe, Caucasus and Central Asia (including Russia) by about 8.6 months on average (WHO, 2013).

BC is also considered a major contributor to current global warming, following carbon dioxide and methane (Stocker et al., 2013). Additionally, BC enhances warming effects in the Arctic when deposited onto ice and snow. By darkening the surface of snow and ice and reducing its reflectivity (albedo), BC facilitates the absorption of solar radiation, increases air temperatures, and accelerates snow and ice melting (Quinn et al., 2011). These effects make the Arctic region exceptionally vulnerable to the warming effects of BC emissions.

3. Emission Standards in the World and in Russia

Off-road vehicles are significant sources of emissions and many countries have adopted regulations aimed at reducing these emissions. Emission standards mainly focus on oxides of nitrogen (NOx) and particulate matter (PM). The U.S., EU and other places have emission standards for hydrocarbons and carbon monoxide as well. This paper analyzes only PM emissions; BC is typically the largest component of diesel PM emissions.

The first emissions regulation for off-road vehicles in the U.S. was adopted in 1994 (Tier 1 emission standards); Tier 2 standards came in force in 2006. The EU followed with its Stage 1 standard for less powerful equipment. Canada adopted U.S. EPA standards for new off-road diesel engines in 1999. China adopted emissions regulations that corresponding to U.S. Tier 2 in 2009. India introduced the standard (Trem) Stage 3a, that also corresponds to U.S. Tier 2 standards, in 2011, and Australia adopted similar standards in 2011.

Mining trucks are mostly equipped with engines with power output over 560 kW. The U.S. adopted its first emission regulation for off-road vehicles with engine power of over 560 kW in 2000 (Table 1).

Table 1. The U.S. EPA off-road diesel engine PM emission standards for engines over 560 kW

EPA Tier	Model Year	PM, g/kWh (g/bhp-h)
Tier 1	2000	0.54 (0.4)
Tier 2	2006	0.20 (0.15)
Tier 3 (voluntary)	2006	0.12 (0.09)
Tier 4 interim	2011	0.10 (0.075)
Tier 4 final	2015	0.04 (0.03)

Source: https://www.dieselnet.com/standards/us/nonroad.php

Russia introduced European standards for new diesel engines for on-road vehicles in 2006 (Government of Russian Federation, 2005). However, Russia does not have emission regulations for off-road construction and mining vehicles.

Russia mostly uses foreign-made, off-road engines. Most mining truck engines in Russia are marked with EPA Tier standards. Since there are no emission control requirements, mining vehicles can be equipped with engines which do not meet even Tier 1 requirements. Engine producers that supply the Russian market, such as Cummins, can supply engines either with or without emission controls (Mining Magazine, 2008). The extent of controls is one of the important uncertainties regarding emission estimates from the mining industry.

Russia has limited production of mining trucks and Belorussian producer BELAZ is the largest suppliers of large trucks to Russia. Most BELAZ trucks are equipped with Cummins engines. Based on information from Cummins, 88% of the large, Cummins-powered, BELAZ mining trucks have no controls on their engine exhaust and the remaining 12% meet EPA Tier 1 requirements (Mueller, 2014). A smaller population of Caterpillar and Komatsu trucks meets Tier 2 requirements. The Tier distribution of a limited number of the MTU engines in Russia is as follows: Tier 0 – 20%, Tier 1 – 75%, Tier 2 – 5% (Madariaga, 2014). The lack of emissions regulations in Russia is a significant hurdle for emissions reductions from off-road vehicles.

4. Fuel Economy and Costs Associated with Emission Reductions

The primary goal of Tier rules is to reduce emissions. In order to meet the most stringent Tier 4 requirements, PM emissions from diesel engines were reduced by 90% from unregulated levels. Emission reductions also are associated with changes in fuel economy and the cost of equipment. U.S. EPA is responsible for impact analysis of the proposed emission reductions rules. EPA analysis initially suggested that the Tier 1 standard was associated with a fuel penalty (increase in fuel consumption) in the range of 3 to 5 percent (EPA, 1994). However, in recent years, because of technological improvements, higher Tier vehicles can actually have significant fuel economy improvements compared to earlier models of lower tier vehicles (Cummins Inc, 2014).

The costs of meeting Tier 1 emission standards were expected to add well under 1 percent to the purchase price of typical new off-road diesel equipment, although for some equipment the standards may cause price increases on the order of 2 or 3 percent (EPA, 1998b).

While introduction of the Tier 1 standard at the end of the 1990s brought some increase in fuel consumption for certain engines, the subsequent standards have been associated with better fuel economy. Learning from previous experience and applying additional R&D enabled manufacturers to optimize a combination of control strategies and techniques (EPA, 2004). Engine manufacturers reported both their energy efficiency gains and cost changes.

Development of Tier 2 engines brought additional benefits for mining operators, in addition to emission reductions. For example, Cummins announced that their QSK19 Tier 2 engine shows the fuel economy, horsepower, torque rise, transient response and service intervals similar to the levels achieved by Tier 1 models of the QSK19. In addition, new QSK19 engines not only last 30% longer, until the first rebuild, but also get an additional 30% longer life after the first rebuild (Cummins Inc, 2014). Belaz install QSK19 engines on its Belaz 7555E dump trucks.

Tier 4 standard requirements demand PM emissions reductions of 90% from the unregulated level. The newest engines have significantly better fuel economy. For example, Cummins Tier 4 Final Solution reduces diesel fuel consumption by up to 7 percent compared with their own Tier 2 engines, depending on the duty cycle (Cummins Inc, 2012). The Cummins QSK50 engine has 5% lower operating costs. In addition, life-to-overhaul for the Tier 4 QSK50 was extended by additional 1,500 hours or more before rebuild (Cummins Inc, 2014). MTU reported that their Tier 4 engines generate fuel savings of up to 5%, compared with previous models.

Additional emission reductions require higher engine production costs. We obtained real life data about the cost and fuel economy from mining trucks suppliers to Russia. The most detailed information was provided by Komatsu.

Komatsu imports mining trucks with payload capacities of 180 and 220 tons from the United States to Russia. These trucks are equipped with Tier 2 1,500 kW and 1,900 kW engines. Komatsu also imports into Russia from Japan and produces in Yaroslavl 90 ton HD785-7 trucks. These trucks are equipped with Tier 2 900 kW engines. A few years ago, Komatsu supplied similar trucks with Tier 0 engines and thus it is easy to compare the changes in the cost of equipment and energy efficiency.

A new Tier 2 engine is 6 percent more expensive than a Tier 0 engine. This also aligns with Komatsu's information that the higher tiered vehicle costs 1-1.5% more than a regular vehicle (assuming that the engine accounts for 15% of the total vehicle cost). The new Tier 2 engines are more powerful, providing 875 kW as opposed to the 783 kW of old Tier 0 engines. HD785-7 trucks have an option to change the power output depending on work conditions. The engines provide 809-895 kW in full capacity mode and 698-750 kW in the economy mode.

Fuel economy is one of the most important factors in selecting mining trucks given the long hours of operation and fuel consumption. The new engine provides up to 12% increase in fuel economy over that of the Tier 0 engine depending on the operation mode.

Given that the increase in total price is incremental, mines should consider switching to newer engines which have better fuel economy and significantly lower emissions.

We should also mention that higher-Tier engines require low sulfur diesel, in part to ensure that selective catalytic reduction systems and other emission controls are not poisoned by the sulfur. While old diesel equipment can run on fuels with high sulfur content, Tier 2 engines require low or ultra-low sulfur fuel. Switching to ultra-low sulfur fuel enables using retrofit technologies, especially DPF, and helps reduce emissions. Russia has significantly increased diesel quality. Currently three types of diesel are available on the Russian market: Euro 3 with maximum sulfur content of 350 ppm, Euro 4 (50 ppm) and Euro 5 (10 ppm). In 2013, Euro 5, with a maximum sulfur content of 10 ppm, accounted for 52% of Russian diesel production for the domestic market while the share of Euro 4 was 18% and Euro 3 was 26% (Novak, 2014). Russia banned production of Euro 3 fuel starting in January 2015 and will restrict production of Euro 4 for the domestic market in 2016. As a result of a targeted tax policy incentivizing low-sulfur diesel production, Russia has sufficient supply of low or ultra-low sulfur diesel. The mining companies in Russia use expensive machinery and fuel quality is very important for proper functioning of the engines.

Diesel with low and ultra-low sulfur content is available in the Murmansk Region. At a stakeholder meeting in Murmansk in 2012, an Apatite mine representative reported that Apatite uses low sulfur diesel (50 ppm).

5. Mining Industry in the Murmansk Region

The mining industry accounts for about 40% of all industrial output in the Murmansk Region. The region produces 100% of Russian apatite and brazilite, 45% of nickel, 35% of nepheline and 9% of its iron ore (VSEGEI, 2012). There are no fossil fuel deposits in the region.

The mining industry is by far the largest industrial consumer of diesel in the Murmansk Region. According to the Murmansk Statistical Service, diesel consumption in the region was 392,000 tons (MSS, 2013). Mines consumed 139,000 tons of diesel, while on-road transport used 65,100 tons (based on bottom up calculations) and locomotives 21,200 tons (Evans, 2015).

According to official statistical data, mining companies in the region consumed 139,000 tons of diesel in 2012. The largest mines in the Murmansk Region are Joint Stock Company Apatite, Kovdorsky GOK, Olenegorsky GOK and Kolskaya GMK. Table 2 shows these mines' diesel consumption.

Table 2. Diesel fuel consumption by largest mines in the Murmansk Region, tons

Mine	2010	2011	2012
Apatite	65,954	67,509	64,469
Kovdorskiy GOK	35,277	42,262	47,395
Olenegorskiy GOK	16,635	18,661	21,233
Kolskaya GMK	5,766	9,786	5,457

Sources: Apatite - http://www.e-disclosure.ru/portal/company.aspx?id=645,
Kovdorsky GOK - http://www.e-disclosure.ru/portal/company.aspx?id=3406,
Olenegorsky GOK - http://www.e-disclosure.ru/portal/company.aspx?id=5740,
Kolskaya GMK - http://www.e-disclosure.ru/portal/company.aspx?id=7833,

The Belorussian automaker BELAZ supplies the majority of the largest trucks, i.e., those with a payload capacity of 130-136 tons. BELAZ trucks are equipped with Cummins engines (QSK 19-C, QST 30-C, QSK45-C and KTA 38-C, KTA 50C engines with mechanical transmission) and MTU or Detroit Diesel engines. Appendix 1 shows technical characteristics of BELAZ trucks.

BELAZ trucks still constitute 70% of the Russian mining fleet (Petrovich et al., 2013). BELAZ trucks have diesel engines with a 780 to 1,200 kW power output. The most popular model of BELAZ trucks used in the mining industry is the BELAZ-75131, which has a payload of 130-136 tons and is equipped with Cummins KTA 50-C engines.

The biggest advantage of BELAZ trucks is that they are significantly less expensive than their competitors. BELAZ was the only producer of large haul trucks in the Soviet Union and has been supplying trucks for decades to open pit mines in Russia and other post-Soviet countries.

Recently, mining companies in Russia have been purchasing more foreign-made trucks, and mines have been gradually replacing the older BELAZ models with Caterpillar, Unit Rig and Komatsu trucks (Appendix 1). However, the share of BELAZ is still higher than 50%.

The turnover rate of equipment and machinery in the mining industry in the Murmansk Region was 15.9% in 2012 (Statistical Yearbook, 2012).

Mining trucks operate for well over 6,000 hours per year (Mining Magazine, 2007). Trucks typically work in three operating modes: driving with full load, empty and idling. The time distribution between these three modes depends on the characteristics of particular mines (depth, haul-road grade, distance travelled, etc.). For example, the average ratio for the load/empty/idling modes at the Eastern mine of Apatite Company is 32:28:40 (Nikitin, 2012). The time distribution is important for specific diesel consumption, and as a result, for emissions.

There are no official data on the number of mining trucks in the Murmansk Region. Using information from individual mines, we estimated that there are no less than 250 mining trucks. Several mines have been expanding their operations in the region. As a result, the number of mining trucks is projected to increase in the near future.

Mines also operate a large variety of diesel equipment including trucks, excavators, bulldozers, drilling rigs, supplementary machinery and on-road vehicles. The common feature of all of them is that Russia does not have emission regulations for off-road vehicles and manufacturers can supply all range of equipment – from Tier 0 (unregulated) to Tier 2. We did not find any evidence that Tier 4 equipment exists in the Murmansk Region. Moreover, the Tier 4 standard does not cover equipment with engines over 560 kW; the European countries have not regulated emissions from these engines yet. As a result, we analyzed emissions only from unregulated engines, Tier 1 and Tier 2 engines.

6. Black Carbon Emissions from Mines in the Murmansk Region

The mining industry is the largest emitter of BC emissions in the Murmansk Region. We estimated that BC emissions in the mining industry are 280 metric tons per year (Evans et al., 2015). BC emissions from each mining company vary and depend on diesel consumption, composition of diesel fleet, modes of operation, specific characteristics of the open-pit mines, etc.

A mine can calculate $PM_{2.5}$ and BC emissions from its diesel fleet using two methods. The first method is based on diesel consumption. The $PM_{2.5}$ emission factor for mining machinery without emission controls (1991-Stage 0) is 3.6 g/kg of fuel and with some control (Stage 1) is 0.97 g/kg of fuel The BC/ $PM_{2.5}$ ratio is 0.5 (EEA, 2013).

The second method for calculation of BC emissions from mining trucks requires data on engine power, hours of operation, time distribution between different modes of operations and Tier standards (PM emission factors).

The U.S. EPA final NONROAD2008a emission inventory model specifies the PM emission factor of unregulated engines over 560 kW as 0.539 g/kWh (0.402 g/bhp-h) (EPA, 2010). The PM emission standard for Tier1engines is 0.54 g/kWh (0.40 g/bhp-h) and the Tier 2 standard is 0.2 g/kWh (0.15 g/bhp-h). In reality, emissions of most compliant vehicles were lower than the maximum allowable values set by the standards. Tier 1 certified engines showed emissions of 0.2594 g/kWh (0.1934 g/bhp-h) and Tier 2 engines emitted 0.1765 g/kWh (0.1316 g/bhp-h) (EPA, 2010), page A11).

Appendix 3 shows the emission calculations for the two most popular BELAZ trucks in Murmansk mines. We calculated BC emissions from BELAZ-75145 and BELAZ-75131 trucks with unregulated engines and Tier 2 engines (Appendix 2).

The BELAZ-75145 mining truck has a payload capacity of 120 tons and is equipped with the Cummins KTA-38C engine with power output 895 kW/1,200hp. BELAZ-75131 has a capacity of 130 tons and a Cummins KTA-50C engine with 1,193 kW/1,600 hp power output. We assume that trucks operate 6,300 hours per year (lower end of the range).

The time distribution between different operational modes is as follows: idling is 40%, driving empty 28%, and driving loaded 32% (Nikitin, 2012). Engine power output while idling is 25% from rated power, driving empty 40%, and driving loaded 85%.

The results of our calculations show that with Tier 0, BELAZ-75145 emits 1,470 kg of PM or 912 kg of BC per year. The more powerful Tier 0 BELAZ-75131 emits 1,960 kg of PM or 1,220 tons of BC. Replacing Tier 0 engines with Tier 1 engines will reduce emissions by almost three-fold. The BELAZ-75145 with a Tier 2 engine would emit only 340 kg of BC and the BELAZ-75131 only 450 kg of BC.

Reduction of PM (BC) emissions from off-road transport will bring significant benefits. Though direct comparison between the U.S. and Russia should be treated with caution, it is still worth approximating the monetized health benefits of emission reductions.

According to EPA estimates, for directly emitted $PM_{2.5}$ from all sources, the benefits of PM emission reductions range from $230,000 to $880,000 per ton of $PM_{2.5}$ reduced in 2015 (2010$) (EPA, 2012). Thus, replacing a Tier 0 engine with Tier 2 engine in a truck with payload capacity of 130 tons will reduce BC emissions by 770 kg per year and save $180,000 to $680,000 annually.

7. Mining Emission Reduction Options

Due to high annual use (6,000 to 7,000 hours per year), mining truck engines often only operate 3-4 years between engine rebuilds. Cummins KTA-38 engines have to be rebuilt after 18,000-24,000 hours of operation and KTA-50 engines after 20,000-26,000 hours (Mueller, 2014). Caterpillar engines can operate 18,000-22,000 hours before rebuilding. MTU engines have to be rebuilt every 20,000 hours of operation (MTU, 2013).

Given that mining trucks operate between 6,000 and 7,000 hours per year and truck engines undergo major maintenance every three to five years, other maintenance options that result in emission reductions may be explored, including engine upgrades, repowering, vehicle replacement, and retrofits.

7.1. Vehicle repowering through engine upgrade

Repowering involves replacing an existing engine with a new one. Repowering mining tucks with new or rebuilt engines offers mine operators the opportunity to extend the working life of high-cost equipment. Replacing an old engine with a new one that has emission controls can also greatly reduce emissions. At the same time, the cost increase is incremental.

In addition, newer engines have better fuel economy. There are many examples of successful engine replacements in the mining industry. Since there are only a few manufacturers of mining engines in the world, international experience is relevant and applicable to Russia (See Box 1).

Box 1. Examples of engine upgrades

Patriot Coal Corporation, Charleston, WV. Patriot Coal repowered Komatsu 730-E haul trucks with new MTU Series 4000 Tier 2 engines. The original Tier 1 engine in the Komatsu 730 truck was from a different manufacturer, had 16 cylinders and produced 2,000 hp. The MTU Series 4000 engine that was installed is capable of producing 2,250 hp with only 12 cylinders. In addition to its compact size and higher power output, the Tier 2 Series 4000 12-cylinder engine delivers up to 20% better fuel economy (MTU, 2012). The MTU engine saves 16,000 gallons (60,000 liters) of fuel or about $50,000 per year. Finally, the life of the new engine is at least 30,000 hours before an engine overhaul is required.

Hanson Aggregates Southeast, LLC, NC. Hanson is one of the world's largest suppliers of heavy building materials to the construction industry. The company repowered its mining fleet in 2008 and 2009. It replaced engines of two Caterpillar 773B haul trucks: the Caterpillar 769C water truck and Caterpillar 988F wheel loader. New Caterpillar engines have better fuel economy and resulted in 10% to 25% of fuel savings (Lawrence, 2010). The company used a grant from the Diesel Emissions Reduction Program (known as "DERA") to finance this upgrade. [1]

There are two particularly important variables which mining companies should take into account when repowering their fleet: 1) Fuel economy savings and 2) Engine price increase.

On average, replacement of a Tier 0 engine with a Tier 2 engine can improve fuel economy by 5-15% (Environment Canada, 2008). The fuel economy of a Tier 2 Komatsu engine is 4-12% better than a Tier 0 engine. Thus, a truck will consume less diesel fuel after an engine upgrade.

We used real data from one of the mines in the Murmansk Region to study fuel consumption by three different mining trucks. At Olenegorskiy GOK, we found that on average, BELAZ 75131 trucks consume 41,545 kg diesel per month, CAT 785C consume 48,463 kg and BELAZ 75145 trucks use 23,205 kg per month.

Thus, the BELAZ 75131 mining truck, with a payload of 130 tons, can consume about 500 tons of diesel fuel per year. Given that the replacement of a Tier 0 engine with a Tier 2 engine can provide a 5-15% improvement in fuel economy, each Belaz can save from 25 to 75 tons of fuel per year.

The price of an average 1,000 kW Tier 2 engine is about $200,000, and Tier 1 engines are 15-20% cheaper (Madariaga, 2014). Cummins announced an average price increase of 18% on 750 kilowatt to 2,000 kilowatt diesel generator sets transitioning from Tier 1 to Tier 2 levels. The price was expected to increase within the range of $16 to $19 per kilowatt above Tier 1 price levels. Komatsu's Tier 2 engine is 6% more expensive than Tier 0.

According to 1998 EPA impact analysis, the incremental cost of Tier 2 engines rated 250 kW or less was expected to be $70 to $460, while bigger engines may face incremental costs of $700 to $1400 (EPA, 1998a). EPA stated that improved fuel economy by Tier 2 engines results in reduction of operating costs, which for several types of engines completely offsets the incremental cost of incorporating new technologies (Appendix 3).

Given that the mining engine market is not competitive in Russia, we assume in our analysis that the lump-sum cost of the 1,000 kW engine upgrade from Tier 1 to Tier 2 is about $20,000-$30,000. Given that a new engine can work 3 years before its first overhaul, the average cost per year during this period is $7,000-$10,000.

The average price the Murmansk mines paid for diesel in 2014 is 30,000 rubles/ton or $778/ton of diesel (without value-added tax). As noted, a BELAZ 75131 with Tier 2 engine can save from

[1] The Diesel Emissions Reduction Program (known as "DERA") is aimed to promote diesel emission reductions. Congress appropriated funds under this program for the first time in FY2008 in the amount of $49.2 million, $120 million was appropriated for FY2009-2010, and $49.9 million for FY11. In January 2010, President Obama signed legislation, reauthorizing DERA grants to eligible entities for projects that reduce emissions from existing diesel engines. The bill authorizes up to $100 million annually for FY2012 through FY2016

25 to 75 tons of fuel per year comparing to the same truck with Tier 0 engine. Thus the net cost savings would be $20,000-$58,000 per vehicle per year.

The results of this analysis show that a mine would benefit from engine upgrades. Replacing a Tier 0/Tier 1 engine with a Tier 2 engine during planned repowering requires a one-time investment, and mines can recover this cost during the first year of operations.

7.2. Speeding up the engine replacement

All diesel equipment requires periodic maintenance; mining trucks have to be rebuilt every 3-4 years. Rebuilding of an old engine is expensive because the cost of an engine overhaul is about 70% of the price of a new engine. A mining company can thus invest in a new Tier 2 engine instead of a Tier 0 engine overhaul. Installing a new and more efficient engine could be more cost-effective than rebuilding an old engine. New engines have better fuel economy, longer time between overhauls, and lower emissions, which compensate for their higher price. This accelerated engine replacement is cost-effective during the lifetime of an engine.

7.3. Vehicle replacement

Mining trucks have relatively short periods of operation in comparison with construction equipment or marine engines. As mentioned previously, Belaz and Caterpillar dominate the market of mining trucks in Russia.

BELAZ trucks remain more affordable due to their much lower price compared to competitors. In addition, Russia encourages the use of domestic or Belarusian equipment through its taxation policy. The disadvantage of BELAZ trucks is their short lifetime. Average BELAZ trucks operate 5-7 years (Zvonar, 2010) while Caterpillar can operate 9-12 years (Anistratov, 2013).

BELAZ mostly produces Tier 0 trucks for Russia and Tier 2 compliant trucks for the market of OECD countries. In 2013, BELAZ exported vehicles to 31 countries. Russian transactions comprised 57% of sales, with additional mining truck exports to Great Britain, the U.S., Germany, South Africa and Sweden. Recently, BELAZ has started a modernization program aimed at expanding its markets. New BELAZ-75574 trucks with a payload capacity of 90 tons will be equipped with MTU12V2000 engines that meet Tier 4i requirements (Novoselov, 2013). BELAZ exports these Tier 4 trucks mostly to OECD countries.

Caterpillar has its own production of engines and can supply trucks to Russia that are equipped with engines from Tier 0 to Tier 4f. Many foreign manufacturers have begun producing their mining trucks in Russia: CAT 773 in Tosno in 2000, Komatsu HD 785 (Tier 2) in Yaroslavl in 2011 and Terex TR100-RM in Chelyabinsk in 2012.

BELAZ’s main competitors are Caterpillar and Komatsu. The experience of the Apatite mine and other companies in the Murmansk Region shows that mines try to use both BELAZ and Caterpillar trucks. For example, Apatite is trying to keep a parity between BELAZ and Caterpillar in its mining fleet (Zvonar, 2010).

Replacing older trucks prior to the end of their operational lifetimes with trucks that meet emission requirements is a viable and also often cost-effective strategy for emissions reduction. According to Apatite, the costs per ton-kilometer for BELAZ and Caterpillar trucks are similar, although the price of a Caterpillar truck is higher than a BELAZ (Zvonar, 2010). However, given that the operational lifetime of Caterpillar trucks is much longer, it is cost-effective for companies to buy more expensive but also more reliable, fuel efficient, and cleaner trucks.

7.4. Retrofits

Mines can also use several retrofit technologies to reduce emissions. There are several benefits associated with emission reductions: reduction of health risks, improvement of air quality and limit negative impact on environment. The challenge is the high cost, and several countries provide incentives to offset this high cost given the tremendous health, environmental and economic benefits.

There are many retrofit options for on-road vehicles. The available technologies include diesel oxidation catalysts (DOC), passive diesel particulate filters (P-DPF), active diesel particulate filters (A-DPF), selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) (Box 2).

Many emission reduction technologies have previously been applied to diesel engines greater than 2,000 hp. Virtually all of these technologies are considered technically viable for large mining trucks (Environment Canada, 2008).

All of these technologies have already been used in Russia for on-road transport. For example, Cummins Emission Solutions supplies to Russia the systems for diesel oxidation catalyst DOC (for engines Euro IV), DOC+PFF (Euro-IV), CCC+DOC+DPF (Euro V, for export), SCR (Euro-IV, V), DOC+DPF+SCR (Euro VI, Tier 4 final, for export) (Sadykov et al., 2014). The mining trucks, however, have much higher rated power and are used more intensively. While the median life of a 250 hp off-highway truck from the NONROAD model is 4,667 hours at rated power, a typical mining truck has rated power between 900 and 1,400 hp and operates between 6,000 and 7,000 hours per year. Thus, applying an analysis used for off-road trucks to mining trucks is problematic.

The cost of retrofits is an important factor in decision-making. Several sources of information on the cost of retrofit technologies for off-road trucks are available. They include a 2007 EPA report on diesel retrofit technologies (EPA, 2006a), a 2009 report by the Manufacturers of Emission Controls Association (MECA, 2014) and a M.J. Bradley & Associates study on oil sand mining fleets for Environment Canada (Environment Canada, 2008).

Box 2. Retrofit technologies for BC emission reductions

Diesel oxidation catalyst (DOC). A diesel oxidation catalyst promotes the oxidation of unburned PM, VOC and CO, producing carbon dioxide (CO_2) and water. A typical DOC can reduce PM emissions by 25-50%. According to EPA estimates, the cost of additional equipment for DOC installation is $500-$2,000 for those engines with power capacities of 250 hp (EPA, 2006b). The study of emissions reduction options for ultra-large mining trucks shows that a standard DOC for mining trucks with power output of 3,500 hp will cost $20,000-$30,000

(Environment Canada, 2008).

Diesel particulate filters (DPF). Diesel particulate filters trap particulate matter from the exhaust stream, preventing it from being released into the atmosphere. DPF can reduce PM emissions by 85%. The Manufacturers of Emission Controls Association's estimate for a DPF is $5,500 for muffler replacement of 300-500 hp engines. According to the study for Environment Canada, a DPF for a 3,500 hp engine will cost between $100,000 and 150,000 (Environment Canada, 2008). Installation of DPFs is associated with additional costs. Passive DPFs may increase fuel consumption by 1-3% and active DPFs may boost fuel consumption by up to 5% (Environment Canada, 2008). Passive filters must be cleaned every 2,000 hours or three times per year. In addition, passive filters require fuel with low sulfur content.

Selective catalyst reduction (SCR). SCR itself does not reduce PM emissions significantly and should be used in conjunction with DOC or DPF. The Manufacturers of Emission Controls Association estimated the SCR cost for a 300-500 hp engine at $18,500-$50,000 (MECA, 2000). EPA estimates show that the cost of a SCR system is $12,000-$20,000 for 250 hp engines (EPA, 2006b). According to the study for Environment Canada, SCR for a 1200 hp mining truck would cost U.S. $50,000-$85,000 (Environment Canada, 2008). In addition, the cost of urea will increase the operational costs (7.5% of fuel use for Tier 1 engine).

Exhaust gas recirculation (EGR). EGR with DPF can reduce PM emissions by more than 85%. EGR requires fuel with low or ultra-low sulfur content. An EPA estimate shows that the EGR cost is $18,000-$20,000 for 250 hp engines (EPA, 2006b). The cost of the system for a 200 hp truck is about $20,000 plus the cost of a DPF (Environment Canada, 2008). MTU uses EGR as a part of their technology package to achieve Tier 4 standard requirements.

In a study for Environment Canada, M.J. Bradley & Associates could not uncover evidence of prior retrofit activity on large mining trucks (Environment Canada, 2008). A representative of MTU engine producer was also not aware of examples of mining truck retrofits (Madariaga, 2014).[2]

Although it is possible to retrofit a mining truck, and there are many possible technical solutions, it is more effective to use engine/vehicle replacement options, given the short lifetime of engine/truck. Engine producers have already invested in technology development and integrated their advanced solutions in new engine models. New engines are more economical, more reliable and much cleaner.

[2] We should note, however, that there are examples of successful retrofits of underground mining equipment. Please see MECA, 2009. Case Studies of Mining Equipment Diesel Retrofit Projects. Manufacturers of Emission Controls Association, Washington, D.C. Available at http://www.meca.org/galleries/files/Mining_Equipment_Diesel_Retrofit_Case_Studies_1109.pdf.

8. Conclusions

Our analysis of black carbon emissions in the Murmansk Region shows that mines emit about 280 tons of BC annually. Mining trucks are the largest source of PM and BC emissions in the Region due to their size and long hours of operation.

Russia does not have emission standards for off-road vehicles, and mines are reluctant to replace Tier 0 engines with newer ones. Belarusian truck producer BELAZ dominates the market of mining trucks in Russia; most BELAZ trucks are equipped with Tier 0 engines.

Our analysis shows that it is cost-effective to replace Tier 0 engines with Tier 2 engines. Not only are new Tier 2 engines much cleaner, but they are also more economical and reliable. Gains in fuel economy help save fuel while producing the same power output. By replacing Tier 0 with Tier 2 engines, the mines can achieve significant reductions in emissions, including those of BC, in the range of 570-770 kg of BC per truck per year. Such upgrades can also save mines $20,000-$58,000 per year per truck because of reduced fuel use.

Mines should invest in cleaner and more reliable Tier 2 engines. Large, socially responsible mining companies can take the lead in this area, thereby providing safer conditions for their employees. Reduction of BC emissions from mining trucks in Russia, especially in the Arctic, will benefit mine workers and local communities as well as the local and global environments.

Acknowledgments

The authors are grateful for research support provided by the U.S. Environmental Protection Agency, Office of International and Tribal Affairs (grant no. X4-83527901) and the U.S. Department of State. We thank the members of the Technical Steering Group and EPA experts for their helpful comments and suggestions. The views and opinions expressed in this paper are those of the authors alone.

Battelle Memorial Institute operates the Pacific Northwest National Laboratory for the U.S. Department of Energy under contract DE-AC05-76RL01831.

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Appendices

Appendix 1. Technical characteristics of mining trucks in Russia

Table 1. Technical characteristics of BELAZ trucks

Model	Payload, tons	Engine	Rated power capacity, kW
75570	90	Cummins QST 30-C	783
75571	90	Cummins QST 30-C	783
7514	120	Cummins KTA 38-C	895
7513	130-136	Cummins QSK45-C	1193
7513A	130-136	MTU DD 12V4000	1194
75131	130-136	Cummins KTA 50-C	1194
75137	130-136	MTU DD 12V4000	1193
75135	110-130	Cummins KTA 38-C	895
75139	130-136	Cummins KTA 50-C	1194

(BELAZ, 2014)

Table 2. Technical characteristics of foreign-made mining trucks

Model	Payload, tons	Engine	Rated power capacity, kW
CAT 777D	90	Caterpillar 3508B EUI	746
CAT 777F	90	Cat C32 ACERT	758
CAT 785C	136	Caterpillar 3512B-EUI	1,082
Komatsu HD-1200	136	Cummins KTTA 38C-1350/ KTA-38-C1200	1,007/895
Komatsu HD785	91	SAA12V140E-3	895
Terex Mining Unit Rig MT 3300 AC	136	MTU/DDC 12 V 4000 / Cummins QSK45	1,286/ 1,193

Appendix 2. Scenarios of BC emissions from mining trucks of different Tier standards

	BELAZ-75145		BELAZ-75131	
	Tier-0	Tier-2	Tier-0	Tier-2
Rated engine power, kW	895	895	1193	1193
Hours per year	6,300	6,300	6,300	6,300
Time, %, idling	40	40	40	40
Time, %, empty	28	28	28	28
Time, %, loaded	32	32	32	32
Time, hours, idling	2,520	2,520	2,520	2,520
Time, hours, empty	1,764	1,764	1,764	1,764
Time, hours, loaded	2,016	2,016	2,016	2,016
Power, idling, 25%, kW	224	224	298	298
Power, empty 40%, kW	358	358	477	477
Power, loaded, 85%, kW	761	761	1,014	1,014
PM emission factors, g/kWh	0.539	0.2	0.539	0.2
Emissions, idling, kg/year	304	113	405	150
Emissions, empty, kg/year	340	126	454	168
Emissions, loaded, kg/year	827	307	1,102	409
Total PM emissions per year, kg	1,471	546	1,961	728
BC/PM ratio for non-road	0.62	0.62	0.62	0.62
BC emissions per year per vehicle, kg	**912**	**338**	**1,216**	**451**

Source: Authors' calculations

Appendix 3. Incremental engine cost of complying with Tier 2 emission standards

Engine Technology	Percent Attributed to Emission Standards	Weighted Unit Cost					
		20 kW	50 kW	100 kW	250 kW	500 kW	750 kW
Engine modifications operating cost (NPV)	50%	$15 $44	$4 $9	$3 $0	$6 $0	$301 $0	$373 $0
Electronic controls	50%	—	—	$267	$300	$165	—
Improved injection	50%	$39	—	$50	$60	$146	$255
EGR operating cost (NPV)	100%	—	$39 $50	—	—	—	—
Turbocharger	50%	—	$76	$69	—	—	—
AA Aftercooler upgrade operating cost (NPV)	100%	—	—	$31 ($147)	$86 ($262)	$594 ($1347)	—
Closed crankcase	100%	$10	—	—	—	—	—
Certification	100%	$8	$6	$6	$12	$148	$55
Total first-year costs operating cost (NPV)	—	$72 $44	$124 $59	$425 ($147)	$463 ($262)	$1355 ($1347)	$683 $0

Source: EPA, 1998. Final Regulatory Impact Analysis: Control of Emissions from Nonroad Diesel Engines. EPA 420-R-98-016. The U.S. Environmental Protection Agency, Washington D.C. Available at http://www.epa.gov/otaq/documents/nonroad-diesel/nr-ria.pdf. Page 57.