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# Evaluation of the contribution of light-duty vehicles to the underground atmosphere diesel emissions burden

B. Rubeli, M. Gangal & K. Butler
*Natural Resources Canada, CANMET Mining and Mineral Sciences Laboratories, Ottawa, Ontario, Canada*

W. Aldred
*Falconbridge Limited, Kidd Creek Mining Division, Timmins, Ontario, Canada*

ABSTRACT: A series of in-mine field studies were performed to determine the relative contributions of light and heavy-duty vehicles to the underground diesel emissions burden in a metal mine. Based on these tests, a model of the Kidd Creek mine diesel fleet was developed. Light-duty vehicles were responsible for 47% of the underground diesel particulate matter (DPM) burden of the model fleet, while heavy-duty (HD) vehicles were responsible for 53%.

## 1 INTRODUCTION

The aim of this work is to characterize diesel particulate matter (DPM) exhaust emissions from light-duty (LD) and heavy-duty (HD) vehicles in a metal mine and to estimate the relative contributions of both types of vehicles to the overall underground DPM burden.

The field study was divided into two parts. Part one focused on measurement of DPM from seven heavy-duty vehicles including five production load haul dump (LHD) vehicles and two haulage trucks. Part two focused on measurement of DPM emissions from eight light-duty vehicles including three pickup trucks, two tractors and three utility vehicles.

## 2 BACKGROUND

The multi-stakeholder, Diesel Emissions Evaluation Program (DEEP), is presently involved in two major field studies aimed at evaluating high-efficiency diesel filtration technology from the standpoint of their impact on the underground environment and their implementation in underground mines. These studies are primarily focusing on heavy-duty vehicles, although two light duty vehicles were tested as part of the study at INCO Stobie mine. The constantly increasing number of light duty vehicles in underground mines and limited knowledge on their contribution to overall diesel emissions motivated this study.

Data showing the relative contribution of light-duty vehicles to DPM concentrations in a test mine can be used to determine whether further research and work aimed at light-duty engine emissions are needed. The hypothesis is that enhanced efforts in emission control and maintenance aimed at the light-duty fleet may benefit the underground environment.

Traditionally, the size of the engine has been used to differentiate between light, and heavy-duty vehicles. In this study, vehicles that are not used in regular production cycles will be categorized as light-duty units regardless of horsepower. Higher horsepower units involved in ore, waste or fill handling will be considered heavy-duty vehicles. Because of the large size of the engines involved and the intensive nature of the work performed, underground diesel emissions are thought to originate mostly from heavy-duty production equipment. While heavy-duty vehicles are no doubt major contributors, new data suggests that light-duty vehicles could be responsible for a significant and possibly increasing portion of the airborne diesel emissions burden in the mining environment.

## 3 KIDD CREEK MINE DIESEL FLEET

The Kidd Creek Mine is a copper/zinc operation located in Timmins, Ontario. The ore body has been mined through three separate shafts known as the No. 1, No. 2 and No. 3 mines. There is ramp access from the surface to all areas of the mine. Kidd Creek mined 2.2 million tones of ore in 2002.

The Kidd Creek diesel equipment fleet comprises approximately 156 vehicles used underground (Table 1).

Table 1. Breakdown of Kidd Creek U/G diesel fleet.

| Vehicle type | Number |
|---|---|
| Load haul dump (LHD) | 20 |
| Haulage trucks | 2 |
| Pickup trucks U/G | 42 |
| Tractors | 18 |
| Utility vehicles | 74 |
| Total U/G | 156 |

Table 2. Vehicles selected for the U/G field study.

| Vehicle type | Number |
|---|---|
| Load haul dump (LHD) | 5 |
| Haulage trucks | 2 |
| Pickup trucks U/G | 3 |
| Tractors | 2 |
| Utility vehicles | 3 |
| Total U/G | 15 |

The fleet was classified into two main groups; light-duty (LD) and heavy-duty (HD) vehicles. The HD group was further classified into two types: load haul dump (LHD) vehicles and haulage trucks. The LD group was further classified into three types: pickup trucks, tractors and utility vehicles.

It was technically feasible to test ten percent of the Kidd Creek Mine fleet, or 15–16 vehicles. The final selections were based on observation of the fleet, communications with mine staff and technical requirements. The following vehicles were selected (Table 2).

Part One: Heavy Duty: The HD vehicle selections were made in the Phase I report (Grenier 2000). The vehicles tested were different from the original group selected because of availability problems, however the test vehicles are believed to be more representative of fleet operations.

Table 3 shows the HD vehicle duty vehicle testing matrix.

Part Two: Light Duty: The LD vehicle selections were made after observation of the fleet and discussion with operators, supervisors and management. Table 4 shows the light-duty vehicle test matrix.

Table 3. Heavy duty vehicles tested during the field study (part 1).

| Number | Vehicle ID | Task | Engine | Power (HP) |
|---|---|---|---|---|
| 33635 | SCOOPTRAM, TORO 501D | Stope Mucking LHD | Detroit Diesel Series 60, 11.1 L | 285 |
| 33638 | SCOOPTRAM, TORO 501D | Stope Mucking LHD | Detroit Diesel Series 60, 11.1 L | 285 |
| 33638 | SCOOPTRAM, TORO 501D (repeat) | Stope Mucking LHD | Detroit Diesel Series 60, 11.1 L | 285 |
| 33616 | SCOOPTRAM, TORO 400D | Stope Mucking LHD | Detroit Diesel Series 50, 8.5 L | 250 |
| 33626 | SCOOPTRAM, WAGNER ST3.5 | Backfill Mobile Filling No. 1 Mine | Detroit Diesel 4-71, 4.65 L | 180 |
| 33661 | TRUCK, EJC430 | Haulage Truck | Detroit Diesel Series 60, 11.1 L | 300 |
| 33661 | TRUCK, EJC430 (repeat) | Haulage Truck | Detroit Diesel Series 60, 11.1 L | 300 |

Table 4. Light duty vehicles tested during the field trials (part 2).

| Number | Vehicle ID | Task | Engine | Power (HP) |
|---|---|---|---|---|
| 33348 | TRUCK, CHEV 2500 [2000] | 4600 Level Mobile Shop | General Motors L65 6.5L TD | 195 |
| 33325 | TRUCK, FORD SUPER DUTY [2002] | 4600 Level Mobile Shop | Navistar 99F 7.3L TD | 150 |
| 33336 | TRUCK, DODGE RAM 2500 [2001] | Mine "D" Construction | Cummins ISB 5.9L TD | 230 |
| 33966 | TRACTOR, KUBOTA 5030 | Ore & Waste Mobile Equipment No. 3 Mine | Kubota S20802-DI-A 2.8L | 54 |
| 33952 | TRACTOR, KUBOTA 5030 | Construction Upper Mine No. 1 | Kubota S20802-DI-A 2.8L | 54 |
| 33973 | SHOTCRETE, SPRAYER DRIFTEC | Lateral Development | Cummins QSB5.9-240 5.9L | 240 |
| 33872 | SCISSORLIFT, GETMAN A64 | Supply & Sanitation | Deutz F5L413FRW 8.0L | 110 |
| 33899 | BOOM TRUCK, GETMAN A64 | Construction Upper Mine No. 1 | Deutz F6L912W 5.6L | 82 |

These vehicles were selected to be representative of the Kidd Mine fleet. The only key vehicle missing from the trial was a jumbo drill rig. It was not possible to schedule a test for that type of vehicle because of production commitments. It may be possible to simulate drill rig operation from available test data as its duty cycle is similar to the Driftec shotcrete sprayer and it uses the same engine as the Getman boom truck.

## 4 TEST METHODOLOGY

This study focused on diesel particulate matter (DPM) emissions. No attempt was made to look at other gaseous emissions. In order to compare DPM emissions from LD and HD vehicles, it was necessary to monitor three major parameters; engine exhaust flow, DPM mass and duty cycle.

### 4.1 *DPM production measurement*

The ultimate goal of this study is to determine the amount of DPM produced by selected diesel powered vehicles over a specified sampling period and ultimately over a full-shift period. The following general formula can be used to illustrate:

$$M_{DPM} = C_{DPM} \times V_{EXH} \tag{1}$$

where $M_{DPM}$ = Mass of DPM (in milligrams) produced by the vehicle during the sampling period; $C_{DPM}$ = Concentration of DPM in exhaust as measured by the DPM sampling apparatus (milligrams per cubic meter at standard conditions) during the sampling period; $V_{EXH}$ = Total dry exhaust volume produced during the sampling period (cubic meters).

A vehicle that is performing significant work for the mine will be emitting a large volume of exhaust gas. In addition, because of the higher volumes produced, such vehicles have the potential to contaminate the mine workings more quickly.

### 4.2 *Vehicle duty cycle evaluation*

Evaluation of each vehicle's duty cycle will ensure that it is classified correctly as light or heavy-duty. It will also provide insight into the utilization for each vehicle and vehicle type.

All the HD, electronically controlled Detroit Diesel engines provide a percent engine load parameter on the ECU data stream. This data was recorded during each test. In addition, the shotcreter and pick-up truck were also equipped with electronically controlled engines.

Duty cycle data for mechanically controlled engines was determined based on engine rpm, exhaust flow and temperature. Charts were prepared for each vehicle showing the duty cycle distribution.

### 4.3 *Testing sequence*

Each day the vehicle to be tested was brought to either the 4600 or 2800 level service shop. CANMET-MMSL personnel installed the DPM sampling system, data loggers and ambient DPM and dust monitors. Each operator wore a personal sampling pump and train to measure personal exposure.

The vehicle would then proceed to its normal working area. CANMET-MMSL personnel would ride along with the operator to periodically change sample filters and make notes pertaining to the duty cycle.

The test vehicle would perform its normal duties during the shift. The cycle would be interrupted briefly (1–2 minutes) to change the DPM sample filter as required. After a sufficient number of duty cycles were recorded, the vehicle would return to the shop area where the sampling system was removed in preparation for the next shift.

## 5 SAMPLING SYSTEM CONSTRUCTION

Preliminary DPM sampling system construction is explained in the Phase I report (Grenier 2000). After the release of that report, it was decided to modify the system for proportional flow. A control loop was integrated into the DPM sampling system to provide isokinetic sampling flow.

This is achieved by measuring the exhaust flow and temperature. As exhaust mass flow increases, the DPM sampling pump flow is increased proportionally. DPM mass collected on the sample filter is therefore weighted proportionally to the engine operating modes. The system has a fast response and calibrates well against laboratory instruments (Figure 1 and Figure 2).

The sampling system uses a series of interchangeable, averaging pitot tubes that allow exhaust flow feedback control for a the complete range of vehicles tested at the Kidd Creek Mine. Each pitot tube was

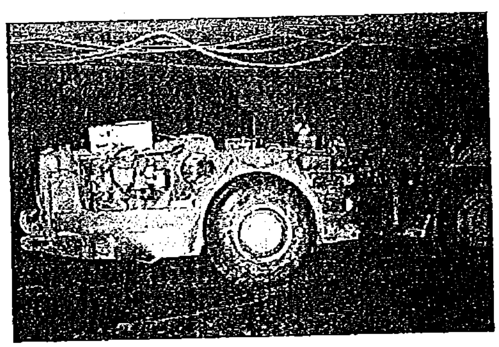

Figure 1. DPM sampling system installed on Wagner ST-3.5 LHD.

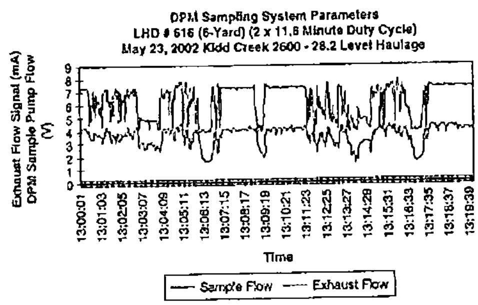


Figure 2. DPM sampling system response.

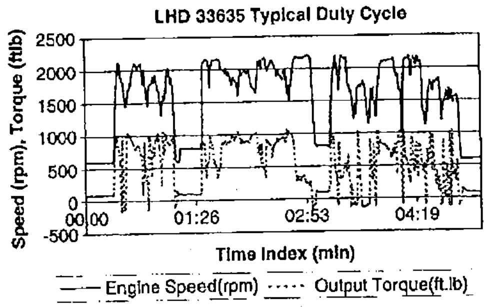


Figure 3. LHD 33635 typical duty cycle.

Table 5. LHD 33635 DPM emissions summary.

| Vehicle | Duty cycle description | DPM (mg/m$^3$) | DPM mass (g) | Run time (min) | DPM mass rate (g/hr) |
|---|---|---|---|---|---|
| LHD 33635 | 4600 fuel bay to 4800 | 12.22 | 1.86 | 10 | 11.13 |
| | Mucking on 4800 | 17.26 | 6.69 | 23 | 17.45 |
| | Mucking on 4800 | 16.34 | 9.75 | 24 | 24.37 |
| | Mucking on 4800 | 25.15 | 7.72 | 16 | 28.96 |
| | Mucking on 4800 | 15.19 | 6.16 | 17 | 21.73 |
| | Mucking on 4800 | 24.21 | 7.90 | 15 | 31.59 |
| | Mucking on 4800 | 15.33 | 5.74 | 20 | 17.23 |
| | Up ramp 4800 to 4600S | N/A | N/A | N/A | N/A |

individually calibrated against laboratory instruments at the CANMET-MMSL Diesel Emissions test facility before use underground.

## 6 HEAVY-DUTY VEHICLE TESTING

Several different types of heavy-duty vehicles were tested for the study, however, only two will be discussed here. Data from the others is included in the summary table (Table 5).

### 6.1 *Load haul dump (LHD) vehicles*

#### 6.1.1 *LHD # 33635 Toro 501D*

This LHD is used for normal production on 4800 Level. The duty cycle is high torque and approximately five minutes in duration (Figure 3).

The field exhaust DPM concentrations are consistent with laboratory data obtained from a similar engine. The DPM mass emission rate while mucking can be three times higher than when traveling to the work area because of transients (Table 5).

### 6.2 *Haulage trucks*

#### 6.2.1 *Truck # 33661*

When descending the ramp empty, the haulage truck engine speed is high, while the developed torque is low (Figure 4). Since the ramp is not wide enough for two-way traffic, the truck must stop repeatedly to allow smaller vehicles time to reverse and clear the way. This is reflected by short idle periods in the chart. Occasionally, if convenient, the truck will reverse and yield.

The engine operating near the peak torque point characterizes the up ramp cycle (Figure 5). The idle sections are where personnel were exchanging DPM filters.

The truck operation modes are best defined as descending the ramp empty, idling, and hauling up the ramp loaded. The lowest DPM production rate occurs at the idle mode (Table 6).

It was initially thought that the descending ramp mode would also have a low DPM emission rate due to the fuel being shut off under compression braking. The field trials have shown that, contrary to this theory, the engine is still developing power as the operator attempts to maintain a vehicle speed consistent with production goals.

This places the engine in a high speed/low torque mode where combustion temperatures are low leading to poor in-cylinder DPM control and higher emissions. In addition, the turbocharger boost pressures at that operating mode are not elevated enough for efficient combustion.

Once the truck has been loaded and is ascending the ramp, the engine can achieve steady state operating conditions, and relative low DPM emissions.

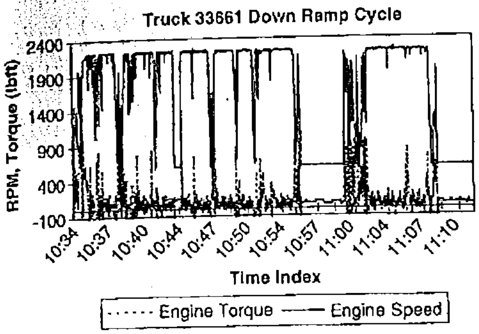


Figure 4. Haulage truck 33661 down ramp cycle.

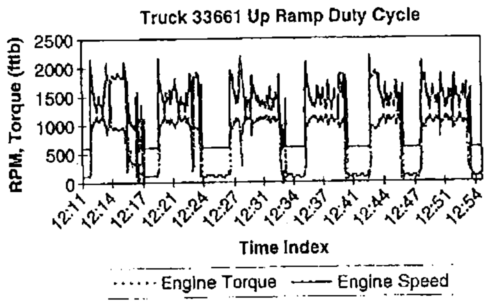


Figure 5. Truck 33661 up ramp cycle.

Table 6. Truck 33661 DPM emissions summary.

| Vehicle | Duty cycle description | DPM (mg/m$^3$) | DPM mass (g) | Run time (min) | DPM mass rate (g/hr) |
|---|---|---|---|---|---|
| Truck 33661 | 4600S to 6400 | 28.13 | 14.68 | 24 | 36.71 |
| | 6400 to 6900 | 25.10 | 5.74 | 12 | 28.70 |
| | Idle on 6900 | 12.77 | 0.36 | 5 | 4.33 |
| | 6900 to 7400 | 25.11 | 9.38 | 19 | 29.63 |
| | 7400 to 7200 | 18.51 | 3.79 | 8 | 28.43 |
| | 7200 to 7000 | 10.34 | 1.43 | 6 | 14.26 |
| | 7000 to 6900 | 11.30 | 2.46 | 8 | 18.46 |
| | 6900 to 6600 | 11.18 | 1.77 | 6 | 17.70 |
| | 6600 to 6400 | 3.68 | 0.66 | 7 | 5.62 |
| | 6400 to 6200 | 2.59 | 0.47 | 8 | 3.49 |
| | 6200 to 5800 | 7.89 | 1.68 | 8 | 12.60 |
| | 5800 to 5600 | 5.91 | 1.08 | 8 | 8.08 |
| | 5600 to 5400 | 5.57 | 0.73 | 5 | 8.70 |
| | 5400 to 5200 | 4.61 | 0.89 | 7 | 7.64 |
| | 5200 to 5100 | 10.09 | 1.93 | 9 | 12.85 |
| | 5100 to 4600S | 9.37 | 3.40 | 12 | 17.01 |

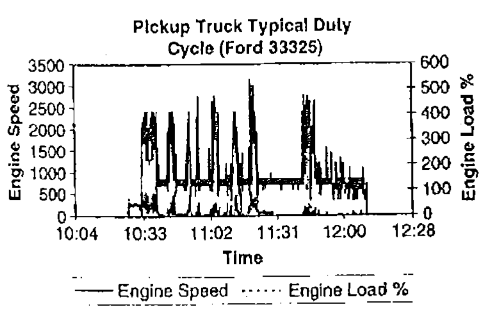


Figure 6. Pick-up truck typical duty cycle (Ford 33325).

## 7 LIGHT-DUTY VEHICLE TESTING

Several different types of light-duty vehicles were tested for the study, however, only two will be discussed here. Data from the others is included in the summary table (Table 6).

### 7.1 *Pick-up trucks*

All three pick-up trucks had a similar duty cycle, serving mainly as personnel and light material transport through the mine. Kidd Mine currently uses pick-up trucks supplied by three major manufacturers; Chevrolet, Ford and Dodge.

All the pick-ups have a large percentage of idle time due to the nature of their work. In addition, the average engine load is 10 to 15% (Figure 6). There are no areas where sustained high power is required. Even when ascending the ramp, the pick-ups have so much extra power that it is possible to quickly exceed recommended maximum ramp travel speeds.

The pick-up trucks are inefficient because the mine must still provide ventilation for the engine rated power according to regulations even though it is almost impossible to apply that power towards useful work.

Table 7. Ford pick-up 33325 DPM emissions summary.

| Vehicle | Duty cycle description | DPM (mg/m$^3$) | DPM mass (g) | Run time (min) | DPM mass rate (g/hr) |
|---|---|---|---|---|---|
| Ford pickup | 4600S to 36-3 | 9.19 | 0.76 | 13 | 3.50 |
| 33325 | 36-3 to 2800S | 3.67 | 0.16 | 8 | 1.22 |
| | 2800S to 28-7 to 2800S | 6.54 | 0.19 | 9 | 1.26 |
| | 2800S to 36-3 | 3.62 | 0.12 | 8 | 0.91 |
| | 36-3 to 2800S | 8.49 | 0.43 | 11 | 2.33 |
| | 2800S to 36-3 | 8.31 | 0.29 | 6 | 2.90 |
| | Idle on 36-3 | 4.20 | 0.10 | 16 | 0.37 |
| | 36-3 to 4600 | 3.30 | 0.17 | 11 | 0.93 |
| | 4600 Level run | 9.38 | 0.36 | 17 | 1.26 |

The trucks do have the advantage of high speed transport through the mine and relatively low DPM emission rate due to their lightly loaded duty cycles (Table 7).

The pick-up trucks have four common duty cycle modes. These modes are: ascending the ramp, descending the ramp, idling, and running on a level.

The idle mode has the lowest DPM mass emissions, ascending the ramp has the highest followed by descending and running on a level. While descending the ramp, the pickup trucks exhibited similar behavior as the HD haulage trucks. It was anticipated that ramp descent would yield the lowest DPM emission rate because of fuel shut off during compression braking. Instead, because of the limited number of transmission ratios available, compression braking in first gear results in too slow a descent.

Shifting to a higher gear increases the vehicle speed to a dangerous level. The operator is then forced to alternately brake and accelerate down the ramp to achieve an acceptable rate of descent, consistent with local ramp conditions. Use of the accelerator pedal injects fuel into the engine, which cannot be burned effectively due to the low in-cylinder temperatures and lack of turbo boost.

The Ford pick-up has a similar modal DPM emissions breakdown as the Chevrolet. The Ford truck was de-rated to approximately 150 HP with an aftermarket device that modifies the demand signal sent to the electronic fuel injection system. The device is effective in reducing the DPM mass emission rates. The Ford had the lowest DPM emission rates (per mode) of any vehicle tested.

Based on the available data, it is possible to rank the pick-up trucks in order of best DPM emissions as Ford first, Dodge second and Chevrolet third. However, it should be noted that only one vehicle of each type was tested. Further testing of more pickups should be done over a longer period of time to develop a more sound opinion. In addition, the effect of the de-ration device on the Ford pick-up should be further examined, perhaps looking at gaseous emissions also.

Finally, the Kidd Mine has begun purchasing new Chevrolet pickups equipped with the 6.6L Duramax 6600 engine. This engine is rated at 300 HP, over 35% more power than the L65 engine it replaces. This vehicle should be tested also.

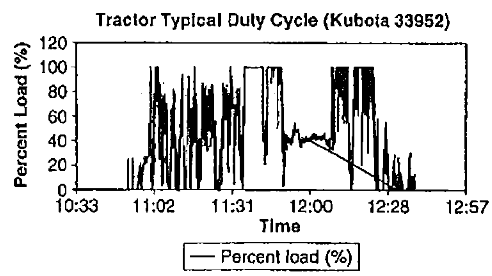


Figure 7. Tractor typical duty cycle (Kubota 33952).

## 7.2 *Tractors*

The Kidd Creek Mine uses tractors for personnel and light material transport also. Due to their slower speed, they are not often used as transport to and from the surface. They are used primarily to access areas where drift conditions preclude the use of pick-up trucks.

From 11:10 to 11:33, the tractor is descending the ramp (Figure 7). This is a highly transient mode of operation. The tractor has no suspension system and must be slowed when ramp conditions deteriorate and then accelerated back up to speed. Due to the effective gearing, the tractor can be operated at steady state conditions during the ramp ascent. The Kubota tractors typically have a higher power utilization averaging 45–50%.

The Kubota tractor is powered by an older, mechanically controlled engine. It is not turbocharged and uses old style pencil-type injectors. As a result the DPM mass emission rates at high engine loads are greater than for either the 8-yard LHD or the 30 ton haulage truck.

Table 8. Kubota tractor # 33952 DPM emissions summary.

| Vehicle | Duty cycle description | DPM (mg/m$^3$) | DPM mass (g) | Run time (min) | DPM mass rate (g/hr) |
|---|---|---|---|---|---|
| Kubota tractor 33952 | 5100 to 5400 | 34.59 | 0.89 | 8 | 6.68 |
| | 5400 to 5800 | 31.73 | 0.85 | 7 | 7.26 |
| | 5800 to 6400 | 30.64 | 0.93 | 8 | 6.97 |
| | 6400 to 5800 | 105.56 | 5.40 | 8 | 40.53 |
| | 5800 to 5400 | 64.90 | 2.90 | 7 | 24.82 |
| | Idle on 5400 | 9.74 | 0.29 | 15 | 1.14 |
| | 5400 to 5100 | 68.48 | 2.73 | 7 | 23.38 |
| | 4600 level run | 36.39 | 2.21 | 13 | 10.21 |

Table 9. Sample fleet DPM emissions.

| Vehicle | Total mass (g) | DPM rate (g/hr) |
|---|---|---|
| LHD 33635 8-yd | 45.8 | 22.0 |
| LHD 33616 6-yd | 43.2 | 15.6 |
| LHD 33626 3.5-yd | 37.8 | 23.6 |
| LHD 33638 8-yd | 43.1 | 22.1 |
| Haulage Truck 33661 | 50.4 | 19.9 |
| Truck 33661 repeat | 43.5 | 12.0 |
| Chevrolet truck 33348 | 4.0 | 3.3 |
| Ford truck 33325 | 2.6 | 1.6 |
| Dodge truck 33336 | 4.3 | 3.1 |
| Kubota Tractor 33966 | 24.5 | 22.7 |
| Kubota Tractor 33952 | 16.2 | 13.3 |
| Shotcreter 33973 | 12.4 | 6.3 |
| Scissorlift 33872 | 10.8 | 6.0 |
| Boom Truck 33899 | 19.5 | 12.9 |

## 8 SAMPLE FLEET DPM EMISSIONS

Table 9 summarizes the DPM emissions for all the vehicles tested at the Kidd Creek Mine. Total DPM mass emissions represent the total mass of DPM in grams emitted by the vehicle into the mine environment during the testing period. The next column is the average DPM emission rate (in grams per hour) for each vehicle, weighted against the time spent at each distinct operating mode.

### 8.1 *General discussion*

Several key points are identified on Table 9. Generally, the HD LHD production vehicles have the highest DPM mass emission rates, followed by the production haul trucks, tractors, utility vehicles, with pick-up trucks having the lowest.

The older technology two-stroke engine on the Wagner ST3.5 (33626) is the likely reason that it has the highest emission rate of the LHD's. The two 8-yard LHD's have similar average DPM emission rates for similar duty cycles, which supports the repeatability of the test method.

Haulage truck 33661 (repeat) spent almost 40% of the test time idling. This is reflected in the lower DPM emission rate from Truck 33661. Interestingly, during those 84 minutes of idling, 3.25 grams of DPM (or 7.5% of the total) were released into the mine environment. Simply shutting the engine down could have stopped this pollution. Although 3.25 grams may seem small, it is more than the total amount released by the Ford pick-up during the entire trial period.

The Kubota tractors demonstrate the wide emissions variability seen with in-use mechanically controlled engines. Fuel system problems are suspected with tractor 33966 and it should be pulled from service for repair. The DPM emission rate from tractor 33966 exceeds all of the HD production vehicles except the two-stroke Wagner ST3.5. This is important because at approximately 50% power utilization, the mine is only getting 27 HP of work from the Kubota tractor but is absorbing the same DPM "burden" as an 8 yard LHD.

The utility vehicles have reasonable DPM emission rates compared to the HD production vehicles. They are usually purpose built for mining and as such the engine and transmission ratios are selected for optimum engine operation. The DPM emission rates of the Deutz 912W engine in the boom truck 33899 and the Deutz 413W engine in the scissorlift 33872 highlight the difference between these series of engines. The Ford pick-up had the lowest DPM emission rate of all the vehicles tested. This is likely due to the deration of the engine from factory specifications. The Dodge pick-up was next, due to the use of a base industrial diesel design with a modern electronically controlled radial fuel injection pump. While in last place among the pick-ups, the Chevrolet truck emissions were still significantly better than the next worst vehicle, the Getman scissorlift.

### 8.2 *Ambient operator exposures*

During the field study, ambient air samplers were mounted in each vehicle cab and worn by the vehicle operator. The following table highlights results of measurements of personal exposure of operators to DPM (Table 10).

Table 10. Operator exposures.

| Operator's Vehicle | EC (mg/m³) | OC (mg/m³) | TC (mg/m³) | EC/OC |
|---|---|---|---|---|
| LHD 33635 8-yd | 0.094 | 0.098 | 0.191 | 0.96 |
| LHD 33616 6-yd | 0.137 | 0.282 | 0.419 | 0.49 |
| LHD 33626 3.5-yd | 0.229 | 0.173 | 0.401 | 1.32 |
| LHD 33638 8-yd | 0.088 | 0.122 | 0.210 | 0.72 |
| Truck 33661 | 0.184 | 0.161 | 0.345 | 1.14 |
| Truck 33661 repeat | 0.180 | 0.159 | 0.339 | 1.13 |
| Chev. truck 33348 | 0.206 | 0.170 | 0.376 | 1.21 |
| Ford truck 33325 | 0.089 | 0.061 | 0.150 | 1.47 |
| Dodge truck 33336 | 0.129 | 0.064 | 0.193 | 2.01 |
| Kubota Tractor 33966 | 0.287 | 0.262 | 0.549 | 1.09 |
| Kubota Tractor 33952 | 0.247 | 0.144 | 0.391 | 1.72 |
| Shotcreter 33973 | 0.087 | 0.053 | 0.140 | 1.63 |
| Scissorlift 33872 | 0.100 | 0.057 | 0.157 | 1.75 |
| Boom Truck 33899 | 0.112 | 0.074 | 0.186 | 1.52 |

Table 11. Tailpipe EC/OC split for sample fleet.

| Vehicle | Tailpipe EC/OC |
|---|---|
| LHD 33635 8-yd | 4.47 |
| LHD 33616 6-yd | 6.04 |
| LHD 33626 3.5-yd | 0.74 |
| LHD 33638 8-yd | 3.09 |
| Truck 33661 | 1.74 |
| Truck 33661 repeat | 2.56 |
| Chevrolet truck 33348 | 2.63 |
| Ford truck 33325 | 1.40 |
| Dodge truck 33336 | N/A |
| Kubota Tractor 33966 | 0.35 |
| Kubota Tractor 33952 | N/A |
| Driftec Shotcreter 33973 | 1.26 |
| Getman Scissorlift 33872 | 0.50 |
| Getman Boom Truck 33899 | 1.68 |

Due to the importance of obtaining real duty cycles, no attempt was made to isolate the test vehicles from other sources of DPM. In particular, DPM exposures of operators during cycles with large portions of ramp travel time should be very carefully considered.

In general, the ambient exposures are a good indicator of tailpipe emissions. The table correctly predicts the Kubota tractor operator is being exposed to high DPM concentrations and the Ford truck operator is exposed to lower levels.

### 8.3 *Tailpipe elemental carbon/organic carbon*

The following table (Table 11) shows the tailpipe EC/OC split for each of the vehicles in the test fleet. EC/OC split can provide information about the composition of DPM emitted by the engine. Electronically controlled engines operating at high load usually have a higher EC/OC split. Mechanical engines at low loads generally have lower EC/OC.

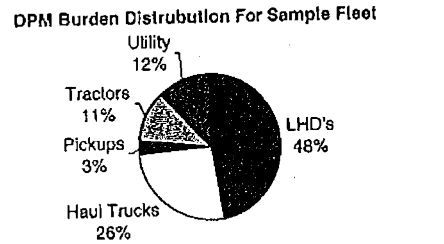


Figure 8. DPM burden distribution for 14-vehicle sample fleet.

HD LHD's have the highest EC/OC split, which is a well-known characteristic of modern electronically controlled diesel engines. Mechanical engines have a more even split, in some cases dropping below unity. LHD 33626 has an EC/OC split also lower than one, which is in accordance with observations previously made on the characteristic of two-stroke engines.

### 8.4 *Sample fleet DPM burden*

Figure 8 shows the division of total DPM burden among the sample test fleet. The breakdown is based on the weighted average DPM emission rate for each vehicle during the sampling period only.

HD vehicles including LHD's and haulage trucks were responsible for 74% of the total DPM burden emitted by the sample fleet. LD vehicles were responsible for 26%.

In order to adequately determine the relative contributions of LD and HD vehicles to the underground DPM burden, the sample fleet data must be extrapolated to the entire Kidd Creek Mine fleet.

## 9 KIDD CREEK MINE FLEET DPM EMISSIONS

To estimate the underground DPM burden at Kidd Creek Mine, the sample fleet test data was extrapolated to represent the entire Kidd Creek Mine diesel fleet. Not every type of vehicle underground could be tested so the following assumptions were made to simplify the comparison.

1) Total U/G fleet of 156 vehicles (from Kidd records, see Table 1).
2) The total fleet is composed only of vehicles from the 14-unit sample fleet.
3) The total fleet operates over the same duty cycles as the sample fleet.
4) The total fleet operates the number of hours outlined in Table 12 (hourly data provided by Kidd Maintenance).

Table 12. Model fleet comparison and DPM burden.

| Vehicle Type | Number | DPM rate (g/hr) | Utilization (hr/yr) | DPM Burden (kg/yr) |
|---|---|---|---|---|
| 8 yd LHD | 10 | 22.05 | 2583 | 569.55 |
| 6 yd LHD | 3 | 15.62 | 1880 | 88.07 |
| 3.5 yd LHD | 7 | 23.63 | 1583 | 261.85 |
| 30t Trucks | 2 | 15.95 | 1600 | 51.04 |
| Chevrolet pickups | 33 | 3.32 | 698 | 76.53 |
| Ford pickups | 1 | 1.56 | 698 | 1.09 |
| Dodge pickups | 8 | 3.07 | 698 | 17.13 |
| Tractors | 18 | 18.00 | 942 | 305.21 |
| Shotcreters | 25 | 6.35 | 651 | 103.33 |
| Scissorlifts | 24 | 6.03 | 686 | 99.34 |
| Boom trucks | 25 | 12.88 | 779 | 250.82 |

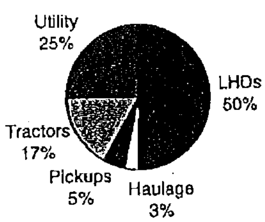


Figure 9. Total Kidd Creek Mine model fleet DPM emissions burden.

Thus, our model fleet is composed of 20 LHDs, ten 8-yard, three 6-yard, and seven 3.5-yard. Both haulage trucks are 30t EJC430s. The 42 vehicle pick-up truck fleet is 79% Chevrolet, 19% Dodge and 2% Ford. All 18 tractors are Kubotas (average of the two tested). The utility vehicle fleet is composed of 25 shotcrete sprayers, 24 scissor lifts and 25 boom trucks.

The fourth assumption about the utility vehicle breakdown is probably the least valid. The wide diversity of utility vehicles underground made selection difficult, because each vehicle is almost unique.

For the model fleet, HD vehicles (LHDs, haulage trucks) are believed to be responsible for approximately 53% of the total underground DPM burden. LD vehicle (tractors, pick-ups utility) are responsible for about 47% of the burden (Figure 9).

## 10 CONCLUSIONS

### 10.1 *General conclusions*

The Kidd Creek Mine model fleet is composed of 14% HD and 86% LD vehicles. Despite this fact, Table 12 shows the underground DPM burden is fairly evenly split between the HD and LD vehicles. HD vehicles and LHD's in particular remain the major contributors to DPM underground. However, LD vehicles are still producing 47% of the underground DPM burden and must be a part of any DPM control strategy.

The DPM mass emission data contained in this report could form the basis for a more comprehensive model of the Kidd Creek diesel fleet. A more refined model could allow strategic planning for DPM emissions and prevent local areas of high concentration by monitoring vehicle distribution in the mine. Emissions data should be used to develop a DPM reduction program including implementation of control technologies.

### 10.2 *Engine operating modes*

Steady state engine operation promotes low DPM emission rates. Emission control systems on HD vehicles such as turbo charging and charge air-cooling perform best over steady state duty cycles. Traffic management and roadway maintenance can help vehicles to achieve this on ramp sections. Somewhat surprisingly, ramp descent in particular can be a high emissions transient cycle, depending on local ramp conditions.

Unnecessary engine idling can be a significant source of DPM emissions, so vehicle engines should be shut off wherever possible.

### 10.3 *Engine type, technology and maintenance*

Even when electronically controlled, older technology two-stroke engines are not able to achieve the same DPM emissions performance as four-stroke engines.

Different engine models from the same manufacturer can have different DPM emission rates. Detroit Diesel Series 50 engines were found to be cleaner than Series 60, while Deutz 413W series were cleaner than 912W.

Engine maintenance has a large effect on DPM emissions. Of two identical tractors, the unit with an obvious fuel system defect had a 41% higher DPM emission rate than the unit in good condition. The operator of this particular vehicle was exposed to the highest ambient DPM concentrations observed during the test.

Engine de-rating, as demonstrated on the Ford pick-up, can have a beneficial effect on DPM mass emissions.

## 11 RECOMMENDATIONS

The Kidd Creek Mine should implement a DPM mitigation strategy, which includes the following components:

Start by applying DPM control technologies to as many 8-yard LHD's as possible. These vehicles are responsible for the largest single portion of the mine DPM burden. Retrofitting all the Toro 501D 8-yard LHD's would allow the maintenance department to maintain one common system and stock of spare parts for one type of vehicle.

Next, DPM control devices should be retrofitted to the Kubota tractor fleet, as they represent the second largest contributor to concentrations of DPM from a single type of vehicle.

After successful implementation of the above two systems, DPM controls should be considered for the utility vehicle fleet, starting with the Deutz 912W series engines. Integration of DPM controls for the utility fleet will be a challenge due to its diversity, but still important as they are a major contributor.

Pick-up trucks and haulage trucks are lesser contributors and can be scheduled for retrofit at a later date.

This paper will not provide any recommendations for DPM emission control devices. The reader is referred to the Diesel Emissions Evaluation Program's (DEEP) two major studies on these devices at www. deep.org.

The Kidd Creek Mine fleet DPM model should be further refined to more closely match the vehicles actually used underground. In addition, the DPM model could be combined with a mine ventilation model to provide the ventilation department with predictions of local ambient DPM concentrations throughout the mine.

The pick-up truck fleet has the highest turnaround of vehicles in the mine. Further emissions testing should be performed on the pick-up truck fleet including non-derated Ford trucks and newer GM Duramax 6600 engines to provide information for a vehicle purchasing strategy.

The Kubota tractor 33966 should be pulled from service and have the fuel system defect corrected, as it is exposing the operator to high DPM concentrations.

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