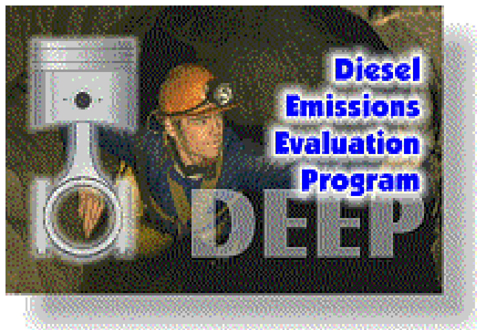
Report of Investigation Submitted to the
Diesel Emissions Evaluation Program (DEEP)



EVALUATION OF THE CONTRIBUTION OF LIGHT-DUTY VEHICLES TO THE UNDERGROUND ATMOSPHERE DIESEL EMISSIONS BURDEN

PHASE I

by

Michel Grenier, Mahe Gangal, Dave Young,

Kevin Butler, Eric Edwardson and Vince Feres

With the kind collaboration of

Falconbridge Limited – Kidd Creek Mining Division

CANMET - Mining and Mineral Sciences Laboratories Report 2000-030(CR)

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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 contaminant burden. The work is divided into two distinct phases. This reports deals with results of the initial phase.

Some of the issues that were examined as part of the first phase include: mine selection and selection criteria, characterization of the mine's diesel fleet, duty cycle assessment method, raw exhaust DPM sampling issues and determination of the cross-section of the fleet to be tested during Phase II. Results dealing with each of the above aspects are presented here. The scope of the work presented here is much wider than what had been originally proposed as part of Phase I.

This report is being submitted to DEEP's Technical Committee, as agreed, before going ahead with the second and final phase of the light-duty vehicle study.

Background

DEEP is presently involved in two major field studies aimed at evaluating high-efficiency diesel filtration technology from the standpoint of impact on the underground environment and issues related to implementation. These studies are concerned for the most part with heavy-duty vehicles.

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

Light-Duty vs Heavy-Duty vehicles - definitions

Traditionally, the size of the engine has been used to differentiate between light, and heavy-duty vehicles. In this study, vehicles regardless of horsepower that are not used in regular production cycles will be categorized as light-duty units. Higher horsepower units involved in ore, waste or fill handling will be considered heavy-duty vehicles.

Available data

Because of the 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.

Data from the Ontario Ministry of Labour's 1996 province-wide survey gives a snap shot profile of the diesel fleet used in underground mines (1). While these data originate from Ontario, one can assume they are representative of the Canadian mining industry at large. Reported data indicate that on a number basis, the light-duty vehicles (80% of which are equipped with engines of 100hp or less) have gone from 30% of the fleet in 1977 to 63% in 1996. Opposite trends are observed for both Load, Haul and Dump vehicles (LHDs also referred to as scooptrams) and haulage trucks which go from 41% to 26% and 20% to 11%, respectively, in the same time interval.

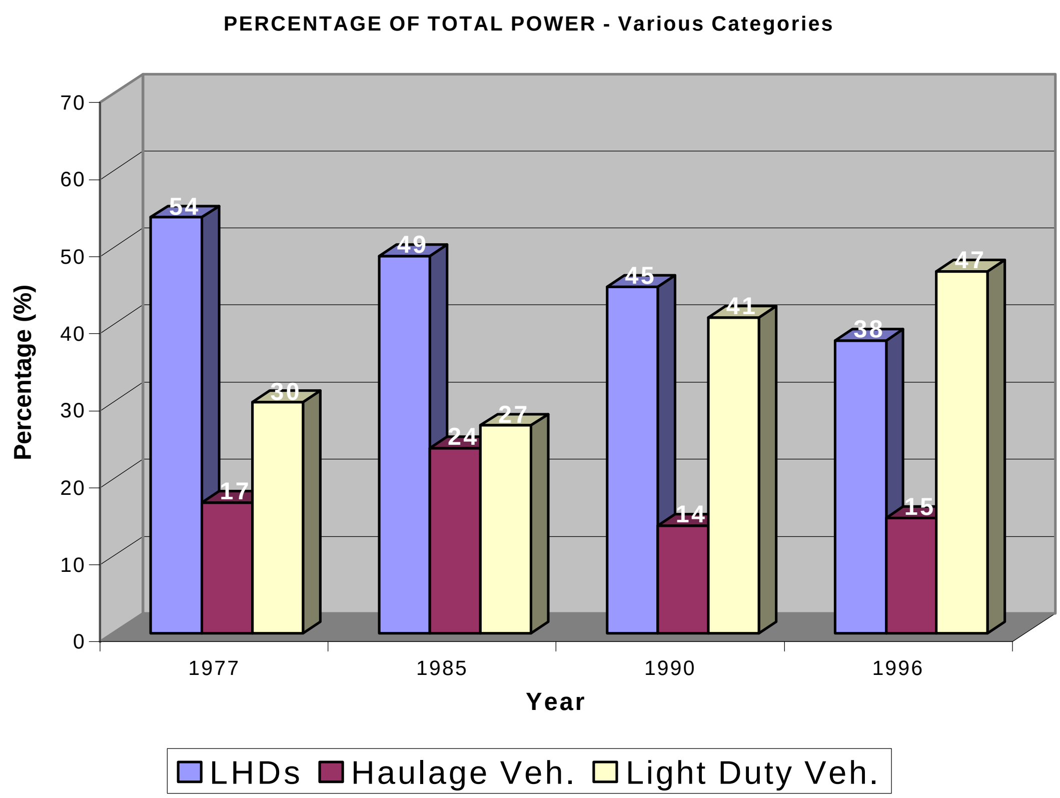

Figure 1. Total underground power for various types of vehicles in Ontario.

While on a number basis, light-duty vehicles may be gaining on the production fleet, the total power underground is still perceived as being made up mostly of heavy duty vehicles. Information shown in Figure 1 indicates that this may no longer be the case. When data related to engine power is used in conjunction with the number of vehicles, it is possible to get an idea of the relative percentage of total underground power. Figure 1 shows the relative percentage of power that can be assigned to traditional heavy-duty machines (LHDs and haulage vehicles) and compares it to that of light-duty vehicles. These data were also derived from the 1996 Ontario Ministry of Labour survey.

These numbers tell us that the total power associated with haulage vehicles has remained essentially stable in the 20 years spanned by the survey. LHDs meanwhile have gradually gone from 54% to 38% of the underground power while light-duty vehicles now make up close to half of the underground diesel power.

As ore is mined at greater depths, efficient coordination of underground staff will probably cause the dependence on utility vehicles to increase. There is every reason to believe that the present trends will be maintained in the short to medium term.

Factors affecting diesel emissions

Engine size, displacement and hence the volume of exhaust gas produced is a primary factor affecting the amount of particulate produced by diesel engines. The amount of work performed by each engine, or the duty-cycle during a representative shift is also important. While it is usually assumed that heavy-duty vehicles work at least 6 hours of an 8 hour shift, there is a scarcity of published data concerning the duty-cycle of light-duty machines. Indeed the opinion of mining people that have been approached varies when asked about the level of use of light-duty vehicles. Some say that the vehicles only work a few hours a day (at the beginning and end of the shift, lunch, etc.) while others say that in their experience, most utility vehicles probably operate at least as much as, if not more than heavy-duty machines.

A true picture of the impact of light-duty vehicles in mines requires a better knowledge of duty-cycles. This will be achieved in this study by discussions and interviews with users and/or by testing target vehicles in real-time by monitoring data such as exhaust temperature, rpm, etc. over several shifts. In some cases, direct observation by technical staff may be used to closely define the duty cycles of some equipment.

Another factor is linked to engineering breakthrough in diesel engine technology. The advent of more efficient mechanical engines and electronically controlled engines for large production vehicles means that light-duty vehicles may be slowly losing ground from the point of view of exhaust quality. This is reflected in the ventilation volumes required on a per brake horsepower basis according to certification documentation. Over the past ten years, ventilation values for light-duty vehicles have remained relatively constant while in some instances large engines require in the order of 30% less air volumes to dilute diesel exhaust contaminants (2). This could significantly affect the exposure of light-duty vehicle operators and the general mine population at peak times such as the beginning and the end of the shift.

Finally, emissions may be affected by differences in the way light-duty and heavy-duty vehicles are used and how often they are maintained. Many mines have enhanced maintenance schedules for heavy-duty vehicles because of the importance of this portion of the fleet with respect to production.

Test Mine Selection

The objective of the proposed work deals with raw exhaust measurement of DPM and the relative contribution of LD vs HD vehicles in a particular operation. While efforts have been made to select a representative operation, variations such as the characteristics of the ventilation system, the depth of the mine and indeed the type of mining can differ significantly from operation to operation. These factors can have a significant effect on the airborne concentration of DPM and it is not within the scope of this work to extrapolate airborne concentration values to make inferences about other mines.

The aim is to choose a mine whose fleet is large enough to gain some level of comfort from a statistical standpoint. In other words, the fleet profile will allow the research to target several types of light-duty and heavy-duty vehicles. The mine will also need to be representative of an average Canadian metal mine. The typical mine profile could be selected by comparing to Ontario mine fleet data as reported by the Ontario Ministry of Labour (1). Finally the host mine has to be willing to extend a significant amount of in-kind efforts in the form of field technical support.

Table 1 lists the fleet profiles of mines that were tentatively targeted for the study. The mine that most closely reflects the Ontario data is the Falconbridge Onaping operation. The fleet at Onaping is also large enough to provide a good number of every type of vehicle that needs to be investigated. The Falconbridge Ltd. Kidd Creek Mining Division also has a large enough fleet. While the percentage of power associated with light-duty vehicles in this mine is higher than the Ontario average, their willingness to actively participate and provide the substantial support needed, made it the mine of choice for this study.

Vehicle Type	*Kidd Creek*		*Lockerby*		*Lindsley*		*Onaping/Craig*	
LHDs	6395	29%	2547	44%	1554	53%	5655	34%
Haulage Truck	1590	7%	1220	21%	435	15%	3020	18%
Service/Utility/Drills	14153	64%	1996	35%	958	32%	8110	48%
Total	22138	100%	5763	100%	2938	100%	16785	100%

Table 1. Installed horsepower in some Ontario metal mines.

There are at least two reasons for the higher than average light-duty vehicle percentage at Kidd Creek Mining Division. First, due to the depth and complexity of the mine, Kidd Creek uses a large fleet of 31, 175 hp pick-up trucks for a total of 5400 hp. Also, upon closer scrutiny, large horsepower vehicles (LHDs) which were originally categorized as heavy-duty, have been placed in the miscellaneous light-duty vehicle table. The same effect would likely be seen in the data for other mines if a more exhaustive study had been conducted.

It should be stated again that measurement of raw exhaust DPM concentrations is the aim of this study. The comparison between the contribution of light-duty and heavy-duty vehicles is the ultimate goal. While the results of this work will apply to the Kidd Creek Mining Division, individual and pooled vehicle information should provide a good idea of the impact of each type of vehicle and allow for some degree of extrapolation to other mining operations.

Kidd Creek Mining Division Underground Diesel Fleet

The Kidd Creek mine diesel fleet profile is summarized in Table 2. Comprehensive fleet data is tabulated in Appendix A. The total installed horsepower is 22,138 hp. This is made up of 14,153 hp associated with so-called light-duty vehicles and 7,985 hp associated with heavy-duty vehicles. These data were arrived at as a result of thorough consultation with mine site production and maintenance staff. The heavy-duty equipment list contains only large engine vehicles directly involved in ore/rock transportation. LHDs used in clean-up activities or on construction duty are not maintained as frequently. Therefore they are listed as light-duty vehicles.

Vehicle Description	*Number of Vehicles*	*Total Engine Horsepower*
LHDs (HD)	25 units	6395 hp
Haulage Trucks (HD)	6 units	1590 hp
Pick-up Trucks (LD)	31 units	5425 hp
Drills/Bolters/Scalers (LD)	24 units	2760 hp
Utility Trucks/Tractors (LD)	56 units	4036 hp
Misc (LD)	31 units	1932 hp
Total light-duty: 14153 hp (64%)	**Total heavy-duty: 7985 hp (36%)**	

Table 2. Fleet description (installed power, bhp) at Kidd Creek Mining Division.

<u>Vehicles targeted for exhaust sampling and selection criteria</u>

The quantity of diesel exhaust emissions can be affected by several factors. First, it is likely that differences in DPM production exist as a result of the type and general use of vehicle (light- vs heavy-duty). It is the objective of this study to assess the impact that each of these categories have on the underground environment.

Next, within each one of these categories, several other factors can come into play. First, the type, make and model of the engine used is a major variable. As mentioned earlier, whereas several models of engines can be used to power a scooptram, certification data shows that all engines differ in DPM production rates. In this study, vehicles will be selected in order to target all or the greatest majority of engine types. As an example, for scooptrams (LHDs), two DDEC 6V92, one DDEC S-60 and one DDEC 4-71 will be tested on two separate days. This selection is representative of 92% of the installed power on LHDs at Kidd Creek.

The question of duty cycle then comes into play. For heavy-duty vehicles this can be characterized in a fairly straight forward manner. The repetitive nature of the work and the ease with which these vehicles can be located at any given time makes duty cycle assessment a relatively simple task. For this type of vehicle, production data including work area and number of trips logged will be recorded.

Variations within the same engine type and vehicle could be influenced by factors such as age and maintenance. From discussions with maintenance engineers, the fleet at Kidd Creek is powered almost exclusively by electronically controlled engines, these are maintained every 150 hours (weekly) and are less than two or three years old. Because of this, it is not believed that age or state of maintenance will be a significant factor of influence. In any case these factors will be monitored by using CO sampling on as large as possible a cross-section of the heavy-duty fleet.

Efforts will also be made to select vehicles for sampling in the two main mining blocks (mines 1 and 3). Discussions with mine personnel suggest that vehicles working in mine 3 could be subjected to more rugged duty cycle conditions.

Similar criteria will be applied to light-duty vehicle selection, although factors such as duty-cycle, age and maintenance will become more of an issue. More information will be gathered that will help in the selection of targeted light-duty vehicles during the first portion of field testing dedicated to heavy-duty vehicles sampling.

Heavy-duty equipment – LHDs

Kidd Creek mine uses 25 LHDs. All but one of these units are Detroit Diesel powered vehicles. The most popular engine at this point is the 6V92 series with 15 units, followed by 4 each of the 4-71 and S-60 series and one S-50 series engine. One 185 hp unit is powered by a Deutz F8L413FW engine. Twenty-two of the 25 units are used exclusively in areas designated as Mine 1 and Mine 3 blocks. For this reason, targeted vehicles for the second phase testing will be selected from these areas. Four vehicles have been identified at this point and are listed in Table 3. These directly represent 23 of the 25 LHDs used at Kidd Creek.

Vehicle Number	Mine Area	Engine Type	Horse Power	Test Days
33617	1	DDEC-6V92	250	2
33693	3	DDEC-6V92	300	2
33654	3	DDEC-S-60	285	2
33624	1	DDEC-4-71	180	2

Table 3. LHDs selected for testing at Kidd Creek Mining Division

Heavy-duty equipment – Haulage trucks

The haulage trucks at Kidd Creek are used exclusively in Mine blocks 1 and 3. There is a total of 6 units ranging in horsepower from 185 to 285 hp. Again, all but one of the trucks are powered with Detroit Diesel engines. Three trucks have been selected for DPM testing for the second phase and they are listed below. These represent 5 of the 6 haulage trucks presently in use at Kidd Creek.

Vehicle Number	Mine Area	Engine Type	Horse Power	Test Days
33649	3	DDEC-S-60	285	2
33636	1	DDEC-6V92	275	2
33650	3	DDEC-S-60	285	2

Table 4. Haulage trucks selected for testing at Kidd Creek Mining Division

Light-duty equipment – Pick-up trucks

Kidd Creek Division is fairly unique in comparison to other metal mines in its use of pick-up trucks. Taking contractor pick-ups into account, it makes use of 31 high horsepower units for supervisors and maintenance crews. This allows key people and staff to be very mobile in a deep and complex mine. All but two of the 31 units are powered by 175 hp Cummins diesel engines. As mentioned above, these trucks are used all over the mine during normal mining activities.

For these, as for other light-duty vehicles, the final selection of vehicles to be tested will not be made at this point. Instead, more information will be gathered on the first field trip to Kidd Creek. While one group of the research team characterizes raw exhaust emissions from heavy-duty vehicles, another group will be involved in gathering information on light-duty vehicle deployment and used in order to select light-duty test vehicles for the second field trip. Then a cross-section of pick-up trucks and other light-duty vehicles will be selected for intensive DPM testing, based on criteria similar to those above for heavy-duty vehicles.

Light-duty equipment – Drills, bolters and scalers

The list of equipment associated with drilling and bolting contains 24 units. This is a varied group in that it ranges widely in make, model and size of engine. Horsepower varies between 62 and 225 hp and manufacturers include Ford, Deutz and Detroit. The duty cycle assessment here will be critical since most of the units require diesel power for locomotion but revert to air or electrical power for the drilling, bolting or scaling cycle.

Again, in this instance, the final selection of vehicles to be tested for raw exhaust particulate emissions will be performed after completion of the first set of field tests.

Light-duty equipment – Utility trucks

The utility truck fleet is made up of 21 units used by warehouse, maintenance and construction crews as well as the mine department. Eighteen of the 21 units are powered by Deutz engines ranging in power between 78 and 144 hp. The remaining three units are higher power units with engines manufactured by Detroit Diesel. Here again the final test vehicle selection will be made after the first field trip.

Light-duty equipment – Tractors

There are 35 tractors used at Kidd Creek Mining Division. These are all relatively low power units ranging between 25 and 62 hp. These are also used widely by mining and maintenance departments. Several engine manufacturers are represented here, including Kubota, Perkins, and Ford. Final selection of test vehicles will be performed after completion of the first field trip.

Light-duty equipment – Miscellaneous units

The miscellaneous vehicle group contains 31 units that are also listed in Appendix A. This table contains one additional column with the heading Duty Cycle. This column was added to identify the vehicle and task at Kidd Creek Mining Division. The vehicles were classified as miscellaneous if they did not belong in the other lists or if they were heavy-duty vehicles used in a light-duty process (which would impact the maintenance schedule frequency).

These units include cement pumpers and trucks, bull dozers, LHDs used in clean-up activities, generators, graders and forklifts. As expected, these vehicles have the widest ranging specifications of engine manufacturer and horsepower. Here also, the final selection of vehicles to be tested will take place after the first field trip is complete.

DPM Production Measurement

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

$$M_{DPM} = C_{DPM} \times V_{EXH} \qquad Eq.1$$

Where: M_{DPM} = Mass of DPM produced by the vehicle (milligrams)

C_{DPM} = Concentration of DPM in exhaust as measured by the DPM sampling apparatus (milligrams per cubic meter at standard conditions)

V_{EXH} = Total dry exhaust volume produced during the sampling period (cubic meters at standard conditions)

From Equation 1, the process can be summarized in the need to accurately assess the exhaust DPM concentration and the exhaust flow.

<u>Assessment of the DPM concentration in exhaust</u> - C_{DPM}

Ideally, raw exhaust DPM sampling should be performed using a dilution process in order to closely simulate situations where hot exhaust is rapidly emitted into mine air (3). While experimental equipment exists to perform diluted exhaust sampling (4,5), it is bulky, complex and does not lend itself to machine mounted, full-shift sampling procedures.

In this first phase, results from a non-diluted heat-traced probe were compared to those obtained using a diluted laboratory based system. The heat-traced sampling apparatus is shown in Figure 2. It consists of a heat-traced line which prevents the sampled exhaust gases from condensing within the line. The sampled air is then passed through a 37-mm quartz membrane filter which collects the sampled DPM. A 15-watt bulb is located close to the filter holder within a metal enclosure to prevent condensation while keeping the filter assembly at a temperature of less than 50°C. The temperature within the enclosure is sensed and logged throughout the sampling process. Gases are pumped using Gilian self-regulated samplers. These were calibrated and set at a fixed flow rate of between three and five litres per minute (L/min).

Figure 2. Heat-traced DPM sampling apparatus showing: 1- the data logger (sample temperature), 2- the filter holder, 3- the heat-traced sampling line, 4- the sampling pump and 5- the stainless steel filter assembly enclosure.

The collected DPM is then quantified using a thermal-optical analytical method according to the NIOSH 5040 protocol. The method measures both the organic and elemental carbon components of the exhaust particulate; these are then added to calculate the total carbon mass (TC). The method is described in detail elsewhere (6). Using the TC measurement as the DPM mass, the pump flow rate and the sampling time, the DPM concentration, C_{DPM} can be derived in milligrams per cubic meters (mg/m^3).

Comparison of non-diluted, heat-traced sampling to standard dilution sampling

In order to validate the non-diluted sampling procedure used in this study, it was compared to standard diluted sampling equipment at CANMET's diesel research facility in Bells Corners. The laboratory at Bells Corners routinely performs diesel engine certification testing to CSA (7) and MSHA Standards for diesel engines destined for use underground.

The dilution apparatus used at the laboratory is a Sierra, BG-2 (8) full flow fractional sampler which dilutes exhaust gases to ISO specifications. The system satisfies all ISO 8170-1 requirements for equivalency compared with the U.S. EPA full dilution test systems, operated on a steady-state engine regime basis. The dilution approach uses filtration and weighing of the filters to assess total DPM concentration in the exhaust stack.

The test engine used for this comparison was a Detroit Diesel D706LTE rated at 123 hp @ 2600 RPM. The engine was operated at steady-state conditions between 870 and 2300 RPM at 50% load. Table 5 shows the results of DPM sampling as measured by the dilution apparatus and the heat-traced line. The tests were performed at six different engine regimes and the concentration values shown are calculated as the average of two distinct tests at each regime.

Engine RPM	*BG-2 Micro-dilution apparatus (mg/m^3)*	*Heat-traced probe (mg/m^3)*	*% Difference*
2300	36.8	31.2	15
2050	37.2	30.1	19
1800	41.4	38.2	8
1560	48.7	37.0	24
1400	57.1	41.4	28
870	2.8	2.4	14
		Average	18%

Table 5. Results of comparison tests for the heat-traced probe DPM sampler.

Results in Table 5 indicate that the heat-traced probe method underestimates by 18% on average. Part of the reason for this difference is due to the fact that the heat-traced probe, contrary to the dilution method did not use an overall gravimetric assessment of the sample. Rather, only the Total Carbon components are measured using the NIOSH 5040 method. Other non-carbon based components, including inorganic sulfates, cannot be accounted for using the NIOSH analytical method.

MSHA's document for the proposed rule respecting Diesel Particulate Matter Exposure in U/G Metal and Non-Metal Mines (9) states that : " total carbon comprises 80-85% of the DPM emitted by diesel engines…". This agrees closely with the data in Table 5, which on average show that the heat-traced method yields results that are 82% of the gravimetrically based dilution approach.

Assessment of the exhaust rate of flow – V_{EXH}

The second parameter which needs to be measured accurately is the engine's exhaust volume as a function of time. This was done indirectly in the first phase by calculating the integrated air flow using the method demonstrated in the sample calculation in Appendix B. Here, the engine displacement, the assumed engine volumetric efficiency, the fuel/air ratio and atmospheric variables (temperature, relative humidity and atmospheric pressure) are used to deduce the total exhaust volume during the actual sampling session.

Figures 3 and 4 show the vehicle fitted with the sampling apparatus during phase one tests. Figure 3 shows a rear view of the vehicle while sampling data was being downloaded. The heat-traced line, the ECOM exhaust gas monitor, the DPM sampling box and a 24 volt power-pack can also be seen on this picture. Figure 4 shows a general side view of the warehouse truck and identifies the RPM, temperature, relative humidity and atmospheric pressure sampling points.

The estimation of the exhaust flow worked well during Phase I tests as this was applied to a naturally aspirated Deutz engine. During the next phase, turbo-charged engines will be sampled and a more direct method of exhaust flow measurement will be used. This method is used in Australia and requires a pitot tube inserted directly into the exhaust stream as well as a differential pressure monitor.

An eight-inch “Airfoil” pitot tube manufactured by Shortridge Instruments Ltd. and a Rosemount Model 1151 Alphaline pressure transmitter will be tested in Bells Corners prior to use in the second phase. This will make the overall instrument package more compact/rugged and therefore more reliable.

Vehicle Duty-cycle Determination and On-site Emissions Characterization

Due to the nature of the DPM sampling protocol used, full-shift sampling for DPM is not feasible, at least not for the number of vehicles targeted. To monitor an entire shift would not only be extremely work intensive, but it could also interfere with the actual regular duties of the targeted mine vehicle, to the extent that data might not be representative.

Alternatives to full-shift sampling will be used in Phase II depending on the vehicles sampled and the nature of the work performed on a daily basis.

Heavy-duty vehicles

The heavy-duty vehicles as selected in this study are all linked to direct production duty. These duties consist mainly of ore handling and transportation. Hence, these vehicles tend to be used in very repetitive duty cycles. LHDs and haulage trucks typically run between a loading and dumping point and carry out as many as 30 to 50 trips per shift.

The sampling procedure for HD vehicles will focus on the accurate monitoring of emissions on a per trip basis in order to then extrapolate results to a full shift contribution. The period at the beginning and the end of the shift will also be observed, monitored and characterized, if it is felt that the contribution to the overall total could be significant.

Figure 3. Warehouse truck flat-bed with: 1- heat-traced DPM sampling line, 2- ECOM gas analyzer, 3- DPM sampling box and 4- 24 volt power pack.

Figure 4. Warehouse truck showing: 1- RPM sampling on fuel injector lines, 2- relative humidity and temperature probe and 3- atmospheric pressure monitor.

Although this is not within the scope of the study, if time and resources are available, as large a cross-section of all of the LHDs and trucks will be tested for exhaust CO concentration while the vehicles are at full torque converter stall condition. This test is used routinely in the U.S. to evaluate the state of maintenance of engines (10), and is recognized to be a good surrogate measurement with respect to DPM emissions (11). This may give an insight as to the overall health of the U/G production fleet and more importantly a good indication of whether or not the selected test vehicles are representative of the fleet at large.

Production data for the entire HD fleet will also be obtained from the mining department for the test days. Again, this will help validate the test vehicle selection and confirm the relevance of the DPM tests performed on them.

Light-duty vehicles

Light-duty vehicle cycles will be harder to characterize because of the nature of the work performed with them. These have more erratic duty cycles. The work and hence the emissions are likely to vary significantly as a function of time through the shift and perhaps even on a day to day basis. Because of this, ideally, entire shifts would have to be logged for the characterization of DPM emissions. Alternatively, the duty cycles can be observed, and broken down into distinct duty patterns that can then be specifically tested for DPM emissions. This information can then be used to deduce the full shift emissions. Several points needed to be clarified and indeed tested before this approach could be applied.

Duty-cycle monitoring

The assessment of the work duty for light-duty vehicles will be done by performing interviews with operators, by direct observation, by logging engine parameters (exhaust temperature, RPM, exhaust back pressure) or a combination of these. Which approach is used will depend on the type of vehicle and the anticipated duty-cycle.

Afterwards, the LD vehicle's duty will be broken down into specific modes and the percentage of time the vehicle spends in each mode will be determined for the full shift. An example of this approach is given in the next section.

Duty-cycle and emission assessment of a warehouse truck

This test was performed on a Wagner model UT45A utility truck powered by a Deutz F6L912W engine rated at 78 hp @ 2300 RPM. The test was designed mainly to evaluate the sampling and data acquisition instrumentation. It was also used to test the approach described in the previous section. In other words using set operating modes for DPM emission testing to extrapolate to full-shift.

Filter #	*Vehicle Duty*	*Total Carbon, TC (mg/hr)*	*Sample Time (min)*	*TC Produced During Sampling (mg)*
Filter K-46	Garage to ramp	2258.68	26	979
Filter K-45	Down to 2100	3406.48	22	1249
Filter K-44	2100 to 2400	3450.75	10	575
Filter K-42	2400 to 44-1	2188.51	33	1204
Filter K-41	44-1 to 5800	2736.25	19	866
Filter K-40	5800 to 6500	3693.87	9	554
Filter K-38	6500 to 5800	6869.90	13	1488
Filter K-37	5800 to 4900	5252.97	15	1313
Filter K-36	4900 to 44-1	5137.06	17	1455
Filter K-35	44-1 to 32-2	3522.27	23	1350
Filter K-34	32-2 to 2000	3542.07	19	1122
Filter K-33	2000 to 16-2	3868.69	9	580
Filter K-32	16-2 to 800	3008.41	11	552
Filter K-30	800 to 300	3371.56	10	562
Filter K-29	300 to Garage	2294.23	15	574
			TOTAL	**14424**

Table 6. Full-shift assessment of warehouse truck DPM production – July 28th.

On the first day of tests, a full shift assessment of DPM emissions was performed. In other words, the filter collection process described earlier was used to collect DPM in the warehouse truck exhaust during the entire shift. Table 6 shows the results of the full shift sampling day. Fifteen samples were collected which cover DPM sampling while the vehicle left the surface warehouse with supplies in the morning, delivered all the way down to 6500 Level and then returned to the warehouse in the afternoon. Sample times varied between 9 and 33 minutes for a total of 251 minutes of actual sampled vehicle operation. For the above tests, it was assumed that each sample was collected during periods of steady-state engine operating conditions.

Total carbon production during these tests varied between 6870 mg/hr when the vehicle was traveling up-ramp from the bottom of the mine and 2190 mg/hr when the vehicle was traveling down ramp between 2400 and 44-1 levels.

By adding the contribution from the 15 filters, it can be seen that the warehouse truck emitted a total of 14424 mg of total carbon during the shift.

The time line data from that sampling exercise was examined and used to breakdown the vehicle's duty into three modes: traveling up ramp, traveling down ramp and traveling on a level surface. It was determined that the vehicle operated 122 minutes, 93 minutes and 36 minutes, respectively, going up ramp, down ramp and on level ground (see Table 7).

Duty	*Total Carbon Production Rate (mg/hr)*	*Time for each Mode (min)*	*TC Produced for each Mode (mg)*
Up ramp	4726,76	122	9611
Down ramp	3469,58	93	5378
Level	2745,97	36	1648
		ESTIMATED SHIFT TOTAL	**16637**

Table 7. Estimation of DPM production, July 28th shift, using 10-minute sample modes.

The next day, 10 minute intervals of each of these three modes were characterized for DPM emissions and the emission numbers were used in conjunction with the amount of time that this particular mode was performed during the previous day of sampling. Results of this test are shown in Table 7. It can be seen that the total estimated DPM production for the entire shift is 16637 mg. This estimate is 15.3% greater than the actual full-shift sampling exercise. This approach therefore seems to be a good alternative to full-shift sampling and it is also less work intensive and easier to coordinate in an underground setting.

Concerns related to transient operation during normal duty-cycles

One problem with the above estimation of a full-shift evaluation of DPM production is the fact that it does not include transient portion of the duty-cycles. These are portions of time during which the engine is not operating at steady-state, but rather is accelerating or decelerating. This could cause serious discrepancies if the transient modes make up a large percentage of the overall duty-cycle.

Figure 5 shows, amongst other data, the RPM measured on the warehouse truck while it was traveling up-ramp, back to the surface warehouse. It can be seen that this particular vehicle spends very little time in transient modes. This is because in underground operations, vehicles' transmissions are locked to prevent operation beyond 2nd gear. This provides maximum torque and prevents the vehicle from attaining unsafe speeds. The result is that vehicles usually achieve cruising speed in a matter of seconds and remain at maximum rpm. This seems to be reflected in the good agreement observed in the alternative sampling procedures reported in the previous section.

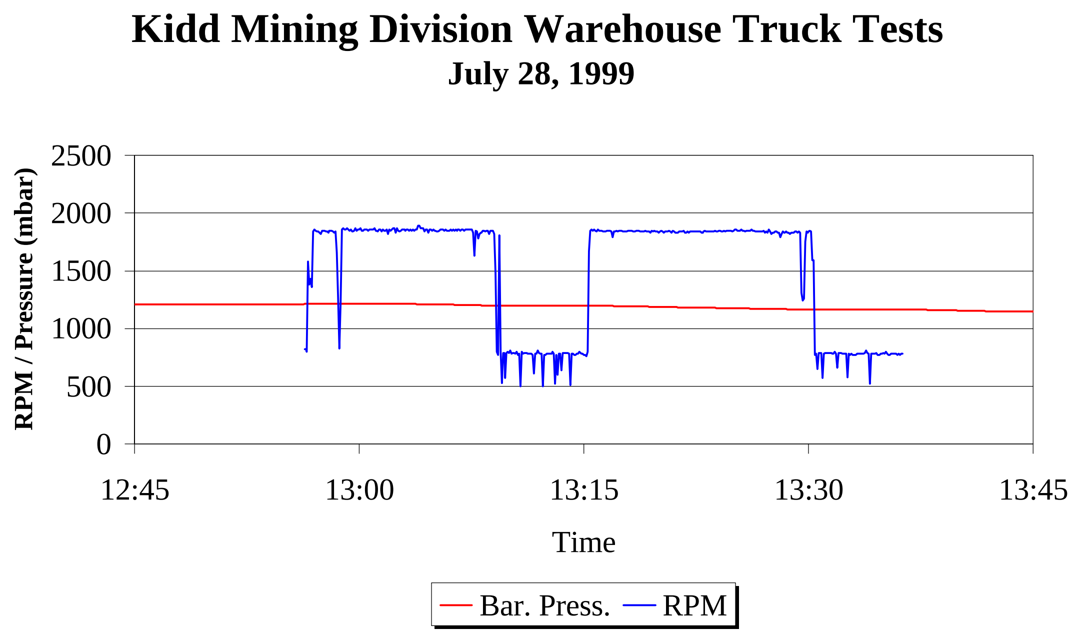

Figure 5. Portion of datalogger traces for RPM and barometric pressure – July 28th, 1999.

Phase II Scheduling

Phase II will take place in the first half of 2000. The anticipated schedule is as follows:

Task	*Scheduled Date*
Testing of exhaust flow monitoring equipment – CANMET Lab	Jan. 31st, 2000
Presentation to Kidd Creek Mining Division	Mid-Feb., 2000
First series of field tests (DPM testing of heavy-duty vehicles and characterization of light-duty vehicles duty cycles)	March 2000*
Second series of field tests (DPM testing of light-duty vehicles)	April-May 2000*
Draft report	June 2000

* Close coordination with Inco and Noranda filter test projects is necessary.

Conclusion

While a lot was learned during the first phase of this work, what is retained for the most part is the fact that this will be a difficult study to coordinate underground. A substantial amount of mine cooperation will be required. Large deviations from the original project proposal are not forecasted, however, and it is anticipated that costs will remain within the original budget of $177,600. The DEEP Technical Committee will be advised well ahead of time of options and modifications that may affect the final outcome or overall budget.

Acknowledgement

The authors would like to express their gratitude to Heather Langfeld former Chair and the Falconbridge Ltd. representative on the DEEP Technical Committee for identifying, helping to develop and supporting this project.

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APPENDIX A

Falconbridge Ltd., Kidd Creek Mining Division – Diesel fleet

Kidd Creek Fleet Breakdown
Category: LHDs; 25 units

Veh. No.	Engine	Hp	Location	Strokes	Type
33601	F8L413FW	185	1	4	HD
33617	6V92DDEC	250	1	2	HD
33618	"	250	1	2	HD
33619	"	250	SALVAGE	2	HD
33620	"	250	1	2	HD
33621	"	250	1	2	HD
33623	4-71DDEC	180	3	2	HD
33624	"	180	3	2	HD
33625	"	180	2	2	HD
33626	4-71DDEC	180	1	2	HD
33630	6V92DDEC	250	3	2	HD
33631	S 50DDEC	250	3	4	HD
33632	6V92DDEC	300	3	2	HD
33638	"	300	1	2	HD
33639	"	300	3	2	HD
33640	"	300	1	2	HD
33641	"	300	1	2	HD
33642	"	300	3	2	HD
33647	"	300	2	2	HD
33652	"	250	3	2	HD
33653	"	250	1	2	HD
33654	S-60DDEC	285	3	4	HD
33656	"	285	1	4	HD
33657	"	285	3	4	HD
33658	"	285	3	4	HD
TOTAL		**6395**			

Kidd Creek Fleet Breakdown
Category: Haulage trucks; 6 units

Veh. No.	Engine	Hp	Location	Strokes	Type
33632	F8L413FW	185	3	4	HD
33649	S-60DDEC	285	3	4	HD
33650	"	285	3	4	HD
33655	"	285	3	4	HD
33636	6V92DDEC	275	1	2	HD
33637	"	275	3	2	HD
TOTAL		**1590**			

Kidd Creek Fleet Breakdown
Category: Dodge Pick-ups; 31 units

Veh. No.	Engine	Hp	Location	Strokes	Type
33351	Cummins	175	3 mine	4	LD
33352	¨	¨	3 mine	¨	LD
33353	¨	¨	VENT	¨	LD
33354	¨	¨	GEOL	¨	LD
33355	¨	¨	MTCE	¨	LD
33356	¨	¨	OHES	¨	LD
33357	¨	¨	1 mine	¨	LD
33358	¨	¨	2 mine	¨	LD
33362	¨	¨	ELEC	¨	LD
33363	¨	¨	ELEC	¨	LD
33375	¨	¨	WHSE	¨	LD
33376	¨	¨	1 mine	¨	LD
33377	¨	¨	CONS	¨	LD
33378	¨	¨	MTCE	¨	LD
33379	¨	¨	ELEC	¨	LD
33380	¨	¨	1 mine	¨	LD
33381	¨	¨	3 mine	¨	LD
33382	¨	¨	1 mine	¨	LD
33383	¨	¨	GEO	¨	LD
33974	¨	¨	CONS	¨	LD
33978	¨	¨	ENG	¨	LD
33979	¨	¨	ENG	¨	LD
33982	¨	¨	ENG	¨	LD
33350	¨	¨	ELEC	¨	LD
00003	DODGE	¨	---	¨	LD
00004	DODGE	¨	---	¨	LD
00009	GM	¨	---	---	LD
00010	CHEV	¨	---	---	LD
00011	DODGE	¨	---	¨	LD
00012	¨	¨	---	¨	LD
00013	¨	¨	---	¨	LD
TOTAL		**5425**			

Kidd Creek Fleet Breakdown
Category: Drills, bolters, scaler; 24 units

Veh. No.	Engine	Hp	Location	Strokes	Type
00347	F6L912W	78	1	4	LD
33403	¨	¨	1	4	LD
33420	¨	¨	1	4	LD
33438	4-71 DDEC	225	3	2	LD
33450	F6L912W	78	3	4	LD
33453	¨	¨	2	4	LD
33454	¨	¨	3	4	LD
33458	¨	¨	3	4	LD
33460	¨	¨	1	4	LD
33463	¨	¨	3	4	LD
33466	¨	¨	3	4	LD
33497	3 CYL. FORD	62	3	4	LD
33938	F6L912W	82	3	4	LD
33962	Deutz - 1013 C	152	1	4	LD
33926	F6L912W	78	1	4	LD
33934	¨	89	2	4	LD
33939	¨	82	3	4	LD
33961	F5L 413 FRW	116	2	4	LD
33985	4-71 DDEC	225	1	2	LD
33986	¨	¨	3	2	LD
33990	¨	¨	3	2	LD
33991	¨	¨	1	2	LD
33884	F6L912W	78	CONS	4	LD
33949	F5L 413 FRW	116	1	4	LD
TOTAL		**2760**			

Kidd Creek Fleet Breakdown
Category: Utility trucks; 21 units

Veh. No.	Engine	Hp	Location	Strokes	Type
33422	F6L912W	78	3	4	LD
33428	¨	¨	1	4	LD
33844	¨	¨	WHSE	4	LD
33855	¨	¨	CONS	4	LD
33865	¨	¨	1	4	LD
33867	¨	78	3	4	LD
33872	F5L413FRW	116	3	4	LD
33874	¨	116	CONS	4	LD
33885	F6L912W	78	WHSE	4	LD
33899	¨	78	CONS	4	LD
33906	¨	¨	MTCE	4	LD
33909	¨	¨	2	4	LD
33857	¨	¨	WHSE	4	LD
33930	¨	82	3	4	LD
33931	¨	82	3	4	LD
33941	¨	82	CONS	4	LD
33942	F5L413FRW	116	3	4	LD
33946	4-71 DDEC	139	WHSE	2	LD
33987	F6L413FRW	144	3	4	LD
33988	S-60 DDEC	225	WHSE	4	LD
33989	4-71 DDEC	150	CONS	2	LD
TOTAL		**2110**			

Kidd Creek Fleet Breakdown
Category: Tractors; 35 units

Veh. No.	Engine	Hp	Location	Strokes	Type
33801	M5030KUB	54	CONS	4	LD
33812	PERKINS	56	3	4	LD
33813	M5030DT	85	3	4	LD
33814	3 CYL. FORD	34	O/F	4	LD
33817	PERKINS	56	1	4	LD
33818	3 CYL. FORD	62	ELEC	4	LD
33820	3 CYL. FORD	62	3	4	LD
33844	M5030DT	54	3	4	LD
33825	BOBCAT	---	O/F	4	LD
33826	M5030DT	54	MTCE	4	LD
33829	3 CYL. FORD	62	WHSE	4	LD
33831	M5030DT	54	MTCE	4	LD
33833	3 CYL. FORD	52	ELEC	4	LD
33836	3 CYL. FORD	62	1	4	LD
33851	M5030DT	54	1	4	LD
33853	"	54	GEOL	4	LD
33854	"	54	2	4	LD
33859	"	54	1	4	LD
33860	"	54	MTCE	4	LD
33861	"	54	3	4	LD
33862	"	56	O/F	4	LD
33871	"	54	3	4	LD
33883	3 CYL. FORD	25	1	4	LD
33927	M5030	54	ENG	4	LD
33933	M5030DT	56	MTCE	4	LD
33944	"	54	O/F	4"	LD
33945	M5030DT	54	TRAIN	4	LD
33948	"	56	3	4	LD
33952	"	56	CONS	4	LD
99353	"	56	MTCE	4	LD
33954	"	56	CONS	4	LD
33956	"	56	1	4	LD
33957	"	56	1	4	LD
33958	"	56	CONS	4	LD
33966	"	56	O/F	4	LD
TOTAL		**1926**			

Kidd Creek Fleet Breakdown
Category: Misc; 31 units *

Veh. No.	Engine	Hp	Location	Type	Duty Cycle
00344	F4L912W	45	3	LD	CEMENT PUMPER
20020	¨	45	---	LD	GENERATOR
33429	3CYL KUBOTA	32	O/F	LD	EXCAVATOR
33554	¨	62	O/F	LD	CEMENT TRUCK
33558	¨	62	O/F	LD	CEMENT TRUCK
33800	¨	21	O/F	LD	EXCAVATOR
33916	F6L912W	78	1	LD	DOZER
33917	¨	78	3	LD	DOZER
33932	3 CYL.	54	O/F	LD	THOMAS LOADER
33935	F6L912W	86	CONS	LD	SHOTCRETE
33963	4 CYL.	80	CONS	LD	CAT LOADER
33965	JOHN DEERE	90	2	LD	GRADER
45277	F4L912W	45	CONS	LD	CEMENT PUMPER
45322	¨	¨	O/F	LD	CEMENT PUMPER
45323	¨	¨	O/F	LD	CEMENT PUMPER
45331	F3L912W	30	CONS	LD	SHOTCRETE
45397	F3L912W	30	M/S	LD	WATER PUMP
45398	F3L912W	30	CONS	LD	SHOTCRETE
45399	F3L912W	30	CONS	LD	SHOTCRETE
45448	F3L912W	30	CONS	LD	SHOTCRETE
33503	F6L912W	78	1	LD	CLEAN-UP
33543	F RW-6	139	O/F	LD	CLEAN-UP
33549	F6L413FW	139	O/F	LD	CLEAN-UP
33600	F8L413FW	185	CONS	LD	CEMENT DUTY
33607	F4L912W	55	1	LD	CLEAN-UP
33847	F3L912	45	O/F	LD	FORKLIFT
33850	F3L912	¨	MTCE	LD	FORKLIFT
33840	F3L912	¨	SALV.	LD	FORKLIFT
33852	KUBOTA	26	O/F	LD	FORKLIFT
33873	4 CYL	116	O/F	LD	FORKLIFT
33810	F3L912	41	MTCE	LD	FORKLIFT
TOTAL		**1932**			

* All four stroke

APPENDIX B

Sample calculation – DPM in raw exhaust

CALCULATION OF DPM PRODUCTION IN RAW EXHAUST

DPM data collected using non-diluted heat-traced line

(Formulæ listed in project proposal)

Filter No.	K-46
Duty cycle portion	Garage to U/G ramp
Date	28/07/99
Sample flow rate (L/min)	2.00
Sample time (min)	26.00
OC sample mass (mg)	0.1196
EC sample mass (mg)	0.4369
O_2 (%)	16.4
Exhaust temperature (°F)	342.1
Ambient temperature (°F)	75.5
Ambient pressure (mbar)	974.5
RPM (r/min)	1348
Relative humidity (%)	54.5
Engine displacement (cu. inches)	345.1
Volumetric efficiency (%)	90
Huel H_2 content (%wt)	13.5
Gas temperature (DPM sample, °F)	109.4
Calculations:	
Pressure (psfa)	2035.24
Actual air density (lb/ft^3)	0.072
Air flow uncorrected (lb/hr)	523.34
PT correction	0.981
Air flow corrected (lb/hr)	513.34
H_2O in dry air (lb H_2O /lbda)	0.011
H_2O correction in air (lb H_2O /lbda)	0.011
H_2O in air (lb/hr)	5.586
Dry Air Flow (lb/hr)	507.75
Fuel/air ratio (f/a)	0.0287
Fuel rate (lb/hr)	14.584
Wet exhaust gas flow (lb/hr)	527.92
H_2O of combustion (lb/hr)	17.72
H_2O in wet gas (lb/hr)	23.31
Dry exhaust gas flow (lb/hr)	504.62
Mol. weight dry gas at f/a (lb/mol)	29.538
Wet sample density (lb/ft^3)	0.068
Wet sample flow at pump (lb/hr)	0.287
Std dry sample density (lb/ft^3)	0.077
Dry sample flow (m^3/min)	0.0018
Organic carbon in dry sample at std. (mg/m^3)	2.604
Elemental carbon in dry sample at std. (mg/m^3)	9.509
Total carbon in dry sample at std. (mg/m^3)	12.113
Dry exhaust gas flow at std. (lb/hr)	186.47
Organic carbon during vehicle cycle (mg/hr)	485.55
Elemental carbon during vehicle cycle (mg/hr)	1773.13
Total carbon during vehicle cycle (mg/hr)	2258.68