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

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OBJECTIVE

The extent of the contribution of light-duty vehicles to underground air pollution is not well known. Whereas these vehicles may appear to have had an insignificant impact in the past, trends in the Canadian mining industry indicate that some attention should be focused on this part of the underground fleet. This information suggests that the relative portions of the underground power associated with light-duty vehicles could be increasing. This work will characterize the exhaust emissions from light-duty (LD) and heavy-duty (HD) vehicles in a metal mine and estimate the relative contributions of both types of vehicle to the overall underground contaminant burden.

COLLABORATORS

CANMET will be the main delivery group for this study, which will be conducted, in close co-operation with the management, labour and safety and health representatives at Falconbridge's Kidd Creek Mining Division. CANMET will co-ordinate and perform the work associated with characterisation of the underground fleet, exhaust sampling of dpm and evaluation of the relative contribution of both types of vehicles.

IMPACT

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

BACKGROUND INFORMATION

Please see Phase 1 proposal and Phase 1 final report available at www.deep.org.

MONITORED PARAMETERS

Phase 2 launch requires the development of an on-board vehicle instrumentation package capable of determining the following three main parameters.

1) Engine exhaust flowrate (**Vexh**).
2) Mass concentration of diesel particulate matter (**Cdpm**)
3) Vehicle duty cycle as % of rated power (**Dcyc**)

The above parameters have been described in detail in the Phase 1 report. This report will select the best option for determining each parameter.

OPTIONS MATRIX

The following matrix list the available options for each parameter listed in order of increasing cost and complexity. This report will attempt to justify the application of each option based on the relative complexity and scientific accuracy.

Table 1: LDV Project
Instrumentation package options

Test Criteria	Dcyc (Duty Cycle % Rated Power)	Vexh (Exhaust Gas Flow m^3/hr)	Cdpm (DPM Concentration mg/m^3)
1 Simplified	Exhaust temp.	Calculation based on VE	Non-isokinetic sampling and averaging
2 Complex	LSU oxygen / NOx Sensor	Averaging pitot tube	Bosch exhaust smokemeter (EC only)
3 More Complex	Fuel meter (supply – return) / ECU Data	Orifice/Venturi meter	Variable flow pump/ venturi aspirator w/feedback from exhaust flow transmitter
4 Very Complex	Exhaust CO_2 measurement	Hot wire / Vortex / ultrasonic	NanoMet particulate sampling system

ENGINE EXHAUST FLOWRATE (Vexh)

Vexh(1) – Calculation based on volumetric efficiency (VE)

A simple calculation can be performed to approximate exhaust flow based on engine speed and volumetric efficiency. For a four-stroke diesel engine:

$$Vexh = \frac{rpm \times displacement}{2} \times Ve \times \frac{exhausttemp + 273}{ambient + 273}$$

The volumetric efficiency (*VE*) in the above equation can only be estimated for an engine in the field. Several "rules of thumb" are available for use with the above equation. A figure of 0.9 is commonly used for naturally aspirated (NA) engines. However, the efficiency of a NA engine can vary with intake manifold pressure distributions and ram air effects.Figures of 1.35 to 1.5 have been proposed for turbocharged engines. Actual efficiencies of 2.35 have been seen in the laboratory on charge air-cooled engines. *VE* for a turbo engine depends on many factors including turbine speed and pressure ratio. These do not necessarily scale with engine speed. Errors can be large, however this method can be used if required by careful determination of correction factors.

Vexh(2) – Averaging pitot tube

The pitot tube is an accurate, durable tool widely recognised as a standard method of flow measurement. The Underground Mine Environment program has significant experience using this device for measuring ventilation airflow. The system could be adapted for measuring diesel exhaust flow.

The inability to perform a traditional traverse will require the use of an averaging type pitot tube. An electronic pressure transducer that would send a proportional output to a data recorder could measure the pressure differential. The averaging tube needs only a small hole to be drilled in the vehicle exhaust pipe for installation.

Any method to directly measure the exhaust flow rate would be checked against the calibrated venturis at the CANMET Diesel Emissions Testing Facility in Bells Corners, Ontario.

Vexh(3) – Orifice / venturi meter

A primary standard orifice or venturi could be inserted in the vehicle exhaust system. The system would be instrumented and qualified as above. This would require more extensive modifications to the vehicle exhaust system, however, there is an increase in accuracy over the pitot tube system.

Vexh(4) – Hot wire anemometer / Vortex shedding meter / Ultrasonic flowmeter

The above technologies are laboratory devices. They are highly accurate, but have very complex electronics for evaluation. It is unlikely that such systems would survive on-board a vehicle.

MASS CONCENTRATION OF DIESEL PARTICULATE MATTER (Cdpm)

Cdpm(1) – Non-isokinetic sampling and averaging

Diesel particulate would be drawn through a 37mm glass fibre or other suitable filter at approximately 2 litres per minute. The mass of particulate is determined gravimetrically. While this system is acceptable for the evaluation of technologies under the same duty cycle, but is not suitable for quantifying dpm for a particular vehicle duty cycle as the sampling rate is not proportional to the engine exhaust flow rate. Isokinetic sampling equalises the velocity in the sample probe with the velocity in the exhaust pipe. This ensures that a representative sample is drawn through the filter regardless of particle inertia.

As the particulate size diminishes, it more closely behaves like a gas. Thus, non-isokinetic sampling may be defensible for modern engines with high pressure electronic injection and resultant finer particle size distributions.

Cdpm(2) – Bosch Smokemeter

The Bosch smoke meter draws a sample of exhaust gas into a measuring chamber. A light beam is transmitted across the chamber to a photocell. The percent opacity can be determined from the amount of light absorbed by the diesel particulate. This opacity value can be reported as mg/m^3 of elemental carbon fraction based on tables developed by the Motor Industry Research Association (MIRA 1965). The meter is designed to be operated continuously on-board the vehicle.

This meter does not account for the organic carbon fraction of diesel particulate. This assumption could be argued by noting that the ACGIH has changed its identification of diesel particulate to the elemental carbon fraction only in the Notice of Intended Changes for 2001 (ACGIH 2001). Further, many European countries require measurement of EC only rather than dpm. Other agencies, such as the TUV are also considering the EC portion only.

Kittelson (1981), Greeves (1981) and others have found that light absorption coefficient and thus smoke number correlate well with the EC fraction of diesel particulate.

Since direct mass measurements are not needed, anisokinetic, partial flow sampling can be used.

Cdpm(3) - Variable flow pump with feedback from exhaust flow transmitter.

If engine exhaust flow is being measured directly, an output signal will be available to drive a variable flow pump. Such a pump could change the sampling flow rate proportional to the exhaust flow rate, ideally achieving near-isokinetic sampling throughout the vehicle duty cycle.

Some models of high-flow personal sampling pumps can be externally controlled by superimposing a voltage signal onto the flow adjustment potentiometer. By maintaining near-isokinetic sampling, a meaningful determination of total particulate mass can be made based on the total measured exhaust flow. Higher sampling flow rates can be achieved with venturi aspirator pumps.

Cdpm(4) – NanoMet Instrument

The NanoMet instrument is a recently developed tool for characterization of diesel particulate. It is composed of three main parts; a diffusion charging sensor (DC), a photoelectric aerosol sensor (PAS) and a tunable dilution unit. A detailed description of the NanoMet can be found in Kasper (1999).

The Nanomet instrument is a highly sensitive system that is not designed for on-board monitoring of diesel exhaust.

VEHICLE DUTY CYCLE AS A PERCENT OF RATED POWER (Dcyc)

Dcyc(1) – Exhaust temperature

Diesel engine exhaust temperatures can be used to estimate the percent of full load on an engine. A temperature scale would have to be determined for each vehicle. Exhaust temperatures logged during vehicle operation could then be translated into percent full load. A load-time distribution could then be developed for each vehicle. (Stewart 1977) This load-time distribution can be used to characterise the duty cycle of the vehicle.

Dcyc(2) – LSU oxygen

Bosch has developed an oxygen sensor that can operate in the lean exhaust gas environment of a diesel engine. The percent oxygen in the exhaust can be correlated back to fuel/air ratio (Dainty 1990). Thus, if air intake flow (or the exhaust gas flow) is known, the engine fuel rate can be determined. The instantaneous fuel rate can be compared to the maximum fuelling rate for the engine and a load-time distribution could be calculated as above.

Dcyc(3) – Fuel meter (supply – return) / ECU Fuel Rate

Alternatively, the instantaneous fuel rate could be measured directly. Two diesel fuel flow meters are required, one for the supply line and one for the return line. Subtracting the return from the supply gives the engine fuel rate. Most HD diesel engines have the instantaneous fuel rate available on the ECU datastream.

Dcyc(4) – Exhaust CO2 measurement

Direct measurement of exhaust CO2 concentration could be performed with an on-board gas analyser. The exhaust CO2 can be correlated to fuel/air ratio as above.

Note: All the above methods will require an engine speed signal for reference. For light duty vehicles, this can be obtained with an optical reflective pickup or a fuel injection line pickup. For heavy duty vehicles, this can be obtained directly from the engine electronic control system.

PROPOSED LIGHT-DUTY VEHICLE SYSTEM

The proposed light-duty vehicle system will be composed of an averaging pitot tube for exhaust gas flow (**Vexh**), the DPM sampling system will be a variable flow pump with feedback from exhaust flow transmitter (**Cdpm**) as described above, and the duty cycle will be determined from a fuel meter or ECU (**Dcyc**). A diagram of the proposed system is shown below.

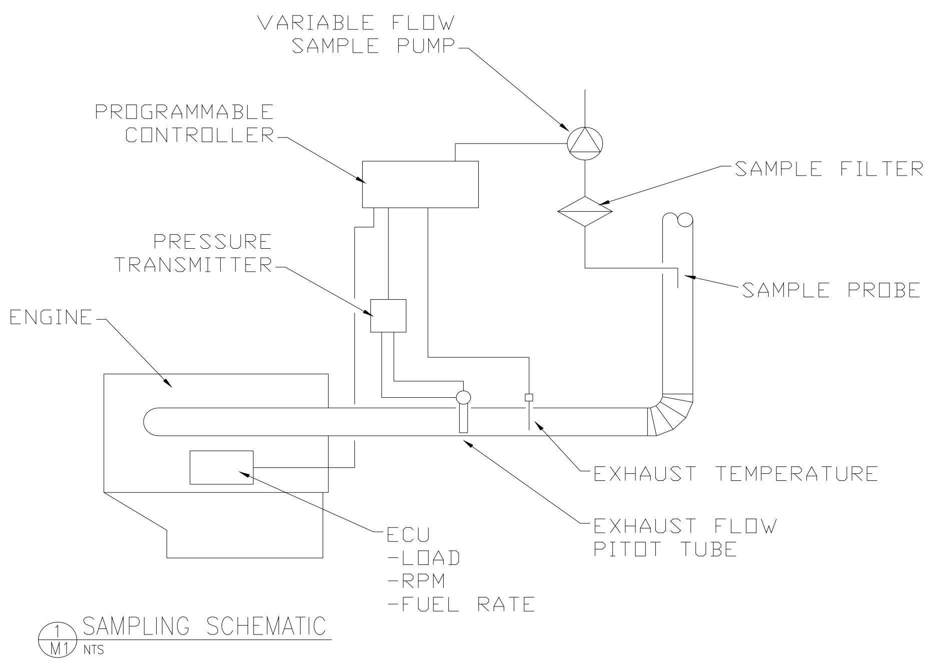

Figure 1: DPM Sampling System Schematic

The system will be calibrated against reference standards at the CANMET diesel test facility. The pitot tubes will be calibrated against standard venturis and the DPM sampling system will be calibrated against a partial flow, micro dilution system.

To obtain proportional DPM sampling, an electrical signal proportional to the engine exhaust flow will be sent to the programmable logic controller (PLC). The PLC will scale the output and send a command signal to a variable flow pump. The pump is backpressure compensated to maintain the set flowrate. As the engine exhaust flowrate changes during the duty cycle, the pump flowrate will automatically be adjusted to maintain proportional sampling.

Proportional sampling parameters have been determined and an example is shown below:

Diesel Engine Data										
Engine	**DDECS60**									
Power	325	HP		**Ideal Airflow**			**Actual Airflow**			
Bore	5.12	in		Max. Flow	1818.85	lb/hr	Max. Flow	4547.13	lb/hr	
Stroke	5.47	in								
Cyl.	6			**Volumetric Efficiency (est.)**			**Fuel Flow**			
Displ.	675.72	cu.in		Rated	250	%	Rated	117.65	lb/hr	
Rated	2100	rpm		Max Torque		%				
Fuel Flow	9.9	gal/hr		Idle		%	**Exhaust Flow**			
BSFC	0.362	lb/HPhr					Max. Flow	4664.78	lb/hr	
Sampling Spool										
Spool Dia.	5	in		**Required Flow For Isokinetic Sampling**						
Probe Dia.	0.152	in		Flow Rate	4.31	lb/hr				
Area Ratio	0.000924				0.97	CFM				
					30.79	**L/min**				
Environmental Conditions										
Temp.	25	C		**DPM In Exhaust Gas:**				**Filter Dimensions**		
Humidity	50	%		Estimated:	25	mg/m3		Diameter	47	mm
Bar Press.	760	mmHg						Area	17.34945	cm2
Air Dens.	0.07383	lb/ft3		**Soot Deposition Rate**				**Filter Face Velocity**		
Correct.	1.11745			Loading	**0.77**	**mg/min**		Velocity	**29.58**	**cm/sec**

Figure 2: Example Proportional Sampling Calculations

HEAVY-DUTY ENGINE TESTS

Although this study targets light-duty vehicles, exhaust sampling will be performed on some heavy-duty vehicles to obtain comparative data. The following vehicles have been tentatively selected as representative of the Kidd Creek heavy-duty fleet.

Haulage trucks

> 33649 DDECS60 285 HP
> 33636 DDEC6V92 275 HP
> 33650 DDECS60 285 HP

LHD production vehicles

33617 DDEC6V92 250 HP
33693 DDEC6V92 300 HP
33654 DDECS60 285 HP
33624 DDEC471 180 HP

LIGHT-DUTY FLEET CHARACTERIZATION AND TESTING

The light-duty fleet at Kidd Creek is quite complex and made up of multiple types of different vehicles.

Diesel pick-ups (may have ECU)
Drills/Bolters/Scalers
Utility trucks (construction/maintenance)
Tractors
Miscellaneous (pumps/generators/lift trucks)

Before and exhaust sampling can be done, six to eight representative vehicles must be selected from the fleet.

These vehicles will then be tested using the above sampling system.

PROJECT SCHEDULING

The first field study at Kidd Creek is tentatively scheduled for December 2001. This will involve testing the selected heavy-duty vehicles and characterising the light-duty fleet.

Represenatative light-duty vehicle will be then selected. The second field study at Kidd Creek is tentatively scheduled for February 2002. This will involve testing the remaining light-duty vehicles. A draft report is expected in March 2002.

REFERENCES:

1) Dodd, A.E., Holubecki, Z., *The Measurement of Diesel Exhaust Smoke*, Motor Industry Research Association (MIRA), 1965/10.

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5) Kasper, M., NanoMet: On-line Characterisation of Nanoparticle Size and Composition, 3rd International ETH Workshop on Nanoparticle Measurement, ETH 1999.

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