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Particulate Matter and Aldehyde Emissions From Idling Heavy-Duty Diesel Trucks

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ABSTRACT

As part of a multi-agency study concerning emissions and fuel consumption from heavy-duty diesel truck idling, Oak Ridge National Laboratory personnel measured CO, HC, NO_x, CO_2, O_2, particulate matter (PM), aldehyde and ketone emissions from truck idle exhaust. Two methods of quantifying PM were employed: conventional filters and a Tapered Element Oscillating Microbalance (TEOM). A partial flow micro-dilution tunnel was used to dilute the sampled exhaust to make the PM and aldehyde measurements. The work was performed at the U.S. Army's Aberdeen Test Center's (ATC) climate controlled chamber. ATC performed 37 tests on five class-8 trucks (model years ranging from 1992 to 2001). One was equipped with an 11 hp diesel auxiliary power unit (APU), and another with a diesel direct-fired heater (DFH). The APU powers electrical accessories, heating, and air conditioning, whereas a DFH heats the cab in cold weather. Both devices offer an alternative to extended truck-engine idling. Exhaust emission measurements were also made for the APU and DFH. Trucks were idled at a high and low engine speed in the following environments: 32 °C (90 °F) with cabin air conditioning on, –18 °C (0 °F) with the cabin heater on, and 18 °C (65 °F) with no accessories on. ATC test technicians adjusted the air conditioning or heater to maintain a target cabin temperature of 21 °C (70 °F). Each test was run for approximately three hours.

Comparison of the results from the APU to those from the idling trucks implies that use of an APU to replace truck idling gives fuel savings (and CO_2 reduction) on the order of 60-85%, 50-97% reductions in NO_x, CO and HC, and PM reductions of -20% to 95%. PM emissions from the APU were higher than the “best” idling truck engine cases. The diesel-fired heater had significantly lower emissions and fuel consumption than the APU. The potential for fuel savings and environmental benefits are readily apparent.

Results for PM emissions showed a wide range of emissions rates from <1 g/hr to over 20 g/hr, with the newest trucks in the 1-5 g/hr range. PM emissions generally decreased with an increase in ambient temperature and increased disproportionately with an increase in engine speed. Aldehyde mass emissions rate increased with both decreasing temperature and increasing engine speed. The mass emissions rate of regulated gaseous species generally increased with increasing engine speed. A comparison of PM measurements with the TEOM and the filter-based methods is presented.

INTRODUCTION

It is estimated that in the U.S. each day, an average of several hundred thousand class-8 trucks with sleeper cabs idle for long time periods while the driver sleeps or rests.[1] Attention has been given to the large amount of exhaust emissions and fuel consumed by this practice. The fuel consumption due to such idling is thought to be at least 2 million gallons per day;[1] this is a concern of the U.S. DOE and a motivation for involvement of the Oak Ridge National Laboratory (ORNL) in this effort.

The U.S. Environmental Protection Agency (EPA) initiated a study two years ago examining emissions and fuel usage from in-use idling trucks at the Aberdeen Test Center (ATC). Experimental efforts were carried out in June of 2001 and May of 2002. ORNL was only involved in the May, 2002 portion of the effort. The project was co-funded by EPA, the New Jersey Department of Transportation (NJDOT) and the Department of Energy (DOE). Testing was carried out in a large environmental chamber by ATC personnel and personnel from the ORNL. EPA provided their Remote

On-board Vehicle Emissions Recorder (ROVER), an on-board gaseous emissions analyzer; ORNL provided conventional laboratory gaseous emissions analyzers, as well as a dilution system used to allow measurement of PM and aldehydes/ketones.

An effort was included to explore the impact of idle reduction technologies on emissions. A diesel-powered auxiliary power unit (APU) configured to provide cab climate control and battery charging, was tested at the –18 °C and the 32 °C ambient conditions. A diesel direct-fired heater (DFH) capable of providing cab heat in winter conditions was tested at the –18 °C condition. These devices are offered commercially, and are designed to be used in place of extended idling of the truck engine during driver rest periods. The same measurements made for the idling trucks were made for these units.

Two companion SAE reports describe in detail the trucks and gaseous emissions measurements using ROVER.[2,3] This report details the gaseous emissions, PM measurements (by two methods) and formaldehyde and acetaldehyde measurements made by ORNL.

EXPERIMENTAL

TRUCK AND AUXILIARY UNIT DESCRIPTION

Five trucks and two auxiliary devices were tested. Table 1 lists the year, make and engine model of the trucks, and includes the auxiliary devices. The APU and DFH were (permanently) installed on the 2001 Freightliner and the 1997 International trucks respectively. The particular APU in this study serves as a small generator-set, supplying 12 Volt power (charges the batteries). It also includes a power take-off that drives an auxiliary air conditioning compressor (for hot weather), warms the truck-engine cooling loop and allows operation of the cab heater system (for cold weather). The DFH unit is an air heater, providing cabin heat.

ID	Truck year and model	Engine or Device Model
A	1999 Volvo	DDC Series 60
B	1992 Ford	Caterpillar 3406
C	1998 Freightliner	Cummins N14
D	2001 Freightliner	DDC Series 60
E	1997 International	Caterpillar 3406
APU	Pony Pack	Kubota Z-482E
DFH	Espar Products, Inc.	D1LC

Table 1. Truck and engine year, make and model.

Each of the trucks was tested at three environmental chamber temperature settings: –18 °C, 18 °C, and 32 °C. At times, the environmental chamber was unable to maintain –18 °C, but never went above –10 °C. At the 18 °C setting, no accessory loads were used with the exception of those needed for engine system operation (e.g. cooling fan, alternator). At the –18 °C chamber setting, the cabin heater was set to maintain a 21 °C cabin temperature. At the 32 °C condition, the truck air conditioning system was operational and set to keep the cabin at 21 °C.

The test matrix also included a low-speed and high-speed idle condition for each truck; these were set at 600 and 1200 rpm respectively, in most cases. It was found that not all of the trucks could easily be set at these speeds: the low idle speed for truck C was 625 rpm and the low and high speeds for truck E were 700 and 1100 rpm. Truck C was also idled at 800 and 1000 rpm with the chamber set to 18 °C, to gain further insight into idle speed versus emissions (discussed in companion reports [2,3]).

In addition to testing the five trucks, the APU was evaluated at the –18 °C condition while providing cabin heat, and at the 32 °C condition while providing cabin air conditioning. The APU also “feeds” the 12 Volt electrical system. The DFH was tested at the cold condition while providing cabin heat.

GAS MEASUREMENTS

A standard bench of gas analyzers, composed of California Analytical instruments, was used for quantifying concentration of CO, HC, NO_x, CO_2, and O_2 in the raw (undiluted) exhaust. Exhaust flow rate measurements were obtained by EPA-provided flow meter modules, which are calibrated pressure-drop type devices.

DILUTION TUNNEL

Because of logistical considerations and the constant engine conditions, a micro-dilution tunnel was used to dilute the exhaust for the PM and aldehyde measurements. The micro-dilutor is an ORNL design based on the work of Abdul-Khalek *et al.*[4] and is described in detail elsewhere.[5] An ejector pump uses HEPA-filtered air to draw in and dilute the exhaust. The dilutor was placed in a room immediately adjacent to the environmental chamber. A heat-traced 9.5 mm OD X 5000 mm stainless steel line was used to transfer the raw exhaust to the dilutor. While a shorter transfer line would have been more desirable, the truck mufflers could not be removed, so the sample was withdrawn from the top of the muffler, just prior to entrance into the ROVER flow meter. Figures 1 and 2 show a truck with the exhaust sampling equipment installed. To further avoid condensation, the dilutor surface temperature was maintained at 50 °C. Inlet flow measurements were made at the start and finish of the tests using a DryCal primary reference standard, and dilution flow was maintained with a mass flow controller set at 100 lpm and calibrated prior to the study with a dry gas meter.

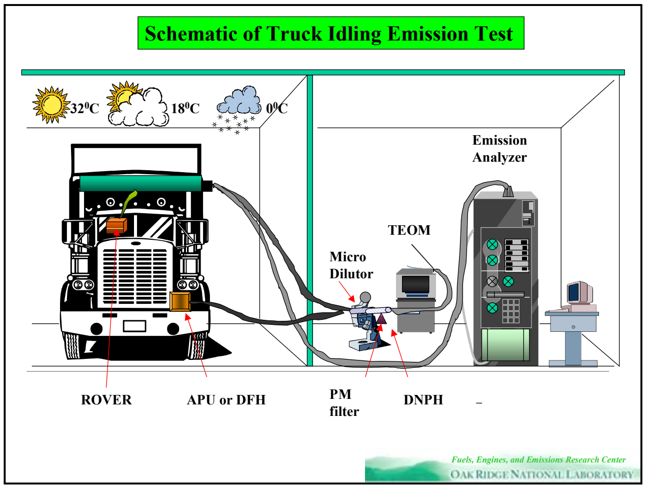

Figure 1. Drawing of basic idle emissions test system.

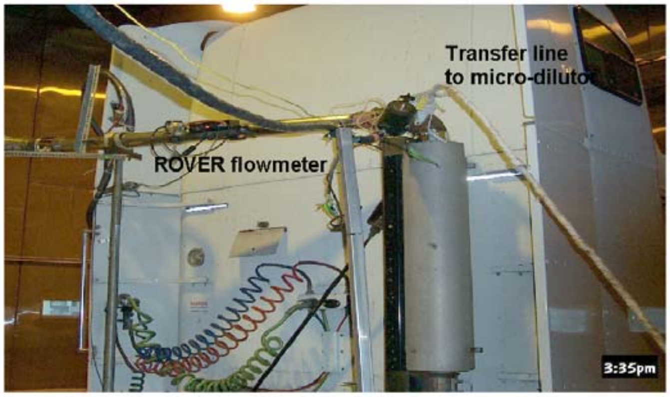

Figure 2. Sampling equipment and ROVER installed on truck exhaust

There were isolated problems during the 37 tests of inlet orifice clogging (twice) and condensation in the transfer line (once). The line and dilutor were run for several minutes after the end of the test to insure no exhaust remained in the lines.

PM MEASUREMENTS

PM mass emissions were measured two ways. A Tapered Element Oscillating Micro-balance (Rupprecht & Patashnick Co., Inc. TEOM model 1105) provided time-resolved measurement, and a 47 mm filter holder was used to measure an integrated sample over the last 90 minutes of the test. The exhaust flow rate, as measured by EPA's ROVER, was used to calculate mass emissions rate.

TEOM Measurements

Leak-sealed TEOM filters containing a 12 mm fluorocarbon-coated quartz fiber filter element (Pallflex TX40) were used throughout. The flow was set at 2.5 lpm. Pressure measurements were recorded throughout the test, and pressure corrections applied as described by others.[6] The transfer line temperature was set at 50 °C, and the instrument at 47 °C. Mass emission rate was calculated based on the slope of the total mass vs. time for the last 30-45 minutes of the test.

Filter measurements

Fluorocarbon coated quartz fiber filters (Pallflex TX40HI20WW) were conditioned in a laboratory and weighed on a microbalance prior to installation into a filter cassette. No secondary filter was used. The cassettes were installed in a stainless steel filter holder. Pump flow was set at ~25 lpm, and total volume was measured downstream of the diaphragm pump with a dry gas meter. Typical total volumes were about 2000 liters. After exposure, the filter cassette was removed and allowed to equilibrate to the laboratory environment prior to weighing. The microbalance had a resolution of 10 µg. Due to the lack of control over laboratory air temperature and humidity, some error is expected in the filter weights.

ALDEHYDE MEASUREMENTS

Dilute exhaust was sampled through two solid-phase extraction cartridges in series containing 2,4-dinitrophenyl hydrazine, or DNPH (Waters 37500). The flow was set at 1 lpm, and a 90 min sample was taken. The primary and secondary cartridges were eluted and analyzed individually according to the previously published methods.[7]

RESULTS AND DISCUSSION

FUEL CONSUMPTION AND REGULATED GAS EMISSIONS

Results for fuel consumption and regulated gaseous emissions varied widely depending on the truck and ambient conditions, as would be expected. Fuel consumption was estimated using the carbon emissions rates and the estimated exhaust flow rate. Approximate ranges (extremes) were found to be 0.5-1.8 gallons/hr fuel, 50-350 g/h NOx, 10-80 g/h HC and 22-295 g/h CO.

A series of bar charts are given in Figs. 3-5 (a, b, and c) which summarizes and compares results for estimated fuel consumption, NOx, and PM emissions. Detailed numerical results of all regulated emissions (NO_x, CO HC, PM), CO_2 emissions and calculated fuel consumption are tabulated in the Appendix. Increasing engine speed virtually always increased fuel use and the mass output of these emissions. This is significant, because truckers often set their idle speeds high enough to maintain a comfortable cabin interior and to maintain accessory loads. This trend plainly seen in Figs. 3-5, and also is true for HC and CO (see Appendix) for all tests, and for most of the aldehyde measurements.

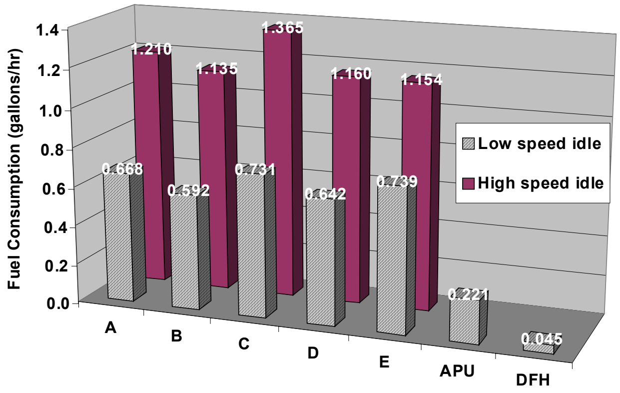

Fig. 3a. Fuel consumption for the –18 °C condition.

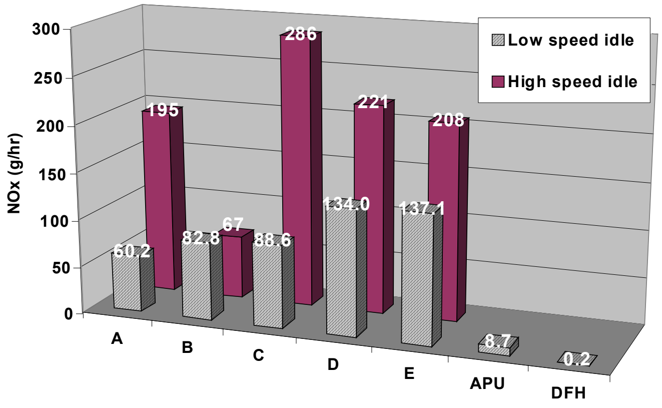

Fig. 4a. NOx emissions for the –18 °C condition.

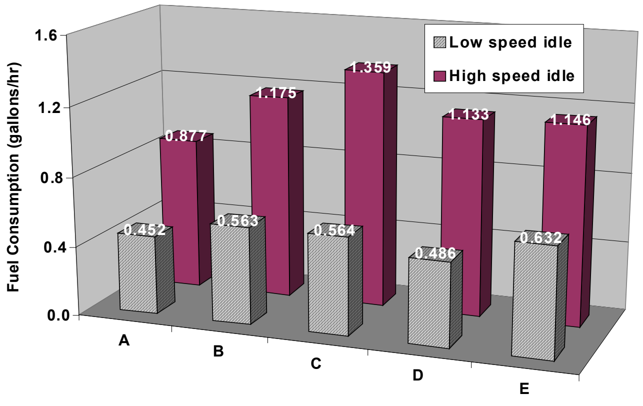

Fig. 3b. Fuel consumption for the 18 °C condition.

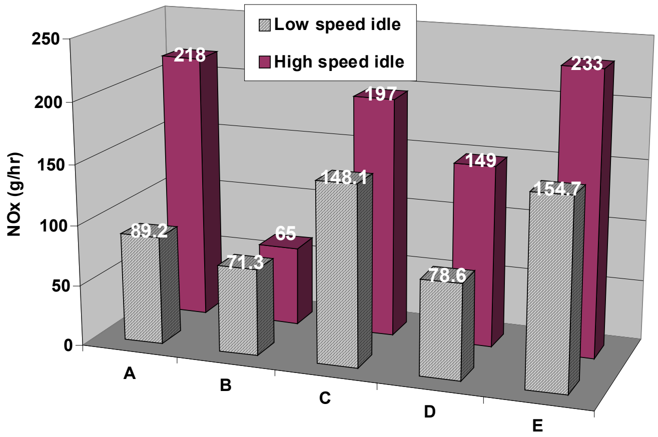

Fig. 4b. NOx emissions for the 18 °C condition.

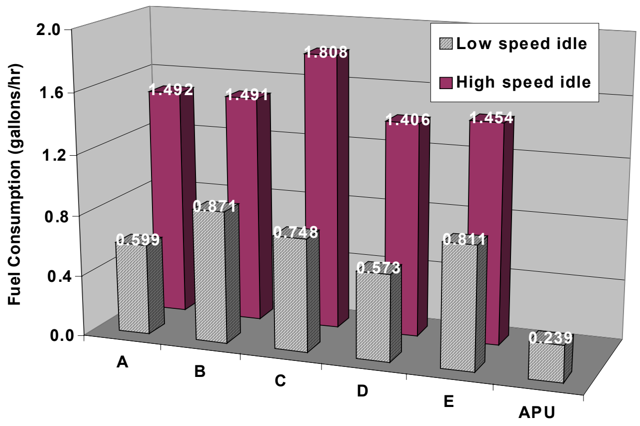

Fig. 3c. Fuel consumption for the 32 °C condition.

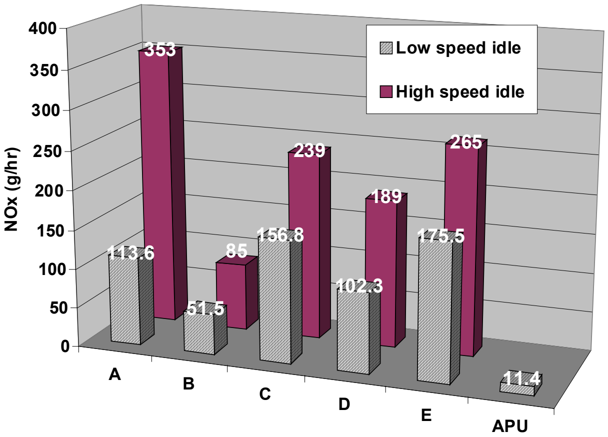

Fig. 4c. NOx emissions for the 32 °C condition.

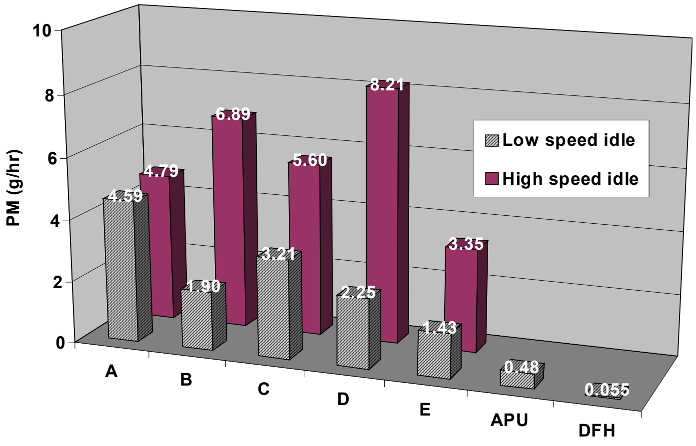

Fig. 5a. PM emissions for the -18 °C condition.

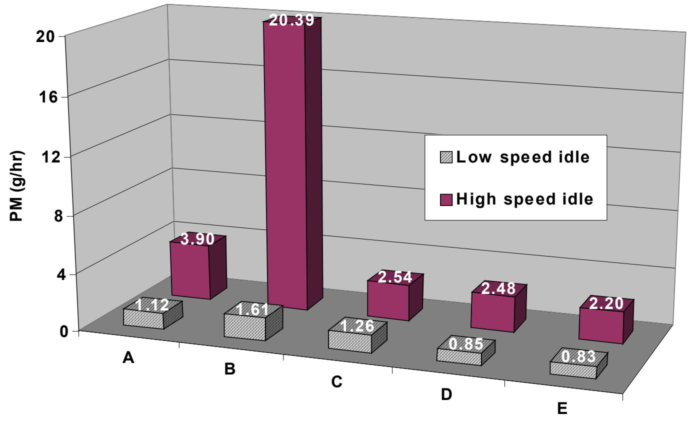

Fig. 5b. PM emissions for the 18 °C condition.

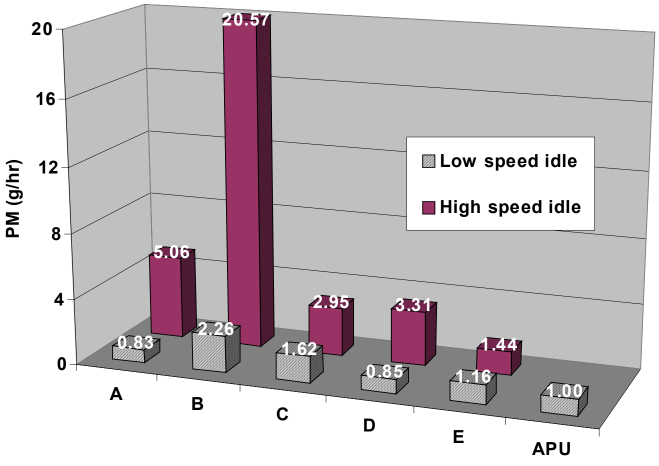

Fig. 5c. PM emissions for the 32 °C condition

The results from testing the APU show fuel consumption is 60-85% less than for idling the trucks and reduction of 50-97% NO_x, CO and HC. The diesel-fired heater had significantly lower emissions and fuel consumption than the APU, to the extent that the NO_x, CO and HC are essentially negligible compared to the "best" truck idling cases and the fuel consumption and PM emissions are only a few percent compared to truck idling.

PM MASS EMISSIONS

The results for the PM mass emissions in g/hr at –18 °C, 18 °C, and 32 °C from the five trucks are shown in Figures 5(a), (b), and (c) respectively. No accessory loads were run at the 18 °C condition, so the APU and DFH were not tested at this temperature. In general, there is a significant difference in the PM emissions for the higher engine speeds, and the oldest truck, a 1992 Ford, had by far the largest increase in emissions when the speed was increased. These data were confirmed by the TEOM as well. Maximum oil consumption typically occurs at high-speed idle conditions, so it is possible that the age of the truck contributed to this result.

Comparing figure 5(a) to 5(b) and 5(c), illustrates the impact of cold operation on PM emissions. With the exception of 1992 Ford truck, the engines produced higher PM emissions under the cold temperatures than under the warmer conditions. This is expected due to the high levels of unburned fuel that are typical at cold idle conditions. A clear trend is not seen between the 18 °C and the 32 °C condition. At 32 °C, the air conditioning loads, as well as the increased engine cooling fan loads increase power requirements significantly over those of the other conditions (cabin heating adds a very small load to the engine). This higher load combined with elevated intake temperature would likely raise the combustion temperature and improve flame quality when compared to the –18 °C and 18 °C condition.

Figure 4 illustrates the increases in NOx for the trucks operating at 32 °C, consistent with the typical NOx/PM tradeoff. In contrast, the oldest truck, truck B, shows an increase in PM emissions for this case, but produces lower NOx. This truck had the earliest form of electronic engine controls, so it is likely that injection timing remained fixed unlike the newer trucks.

The APU PM emission in Figure 5a (cold condition) is significantly lower than any of the trucks, even at the low idle speed. The DFH is seen to have nearly insignificant PM emissions. Higher PM emissions were measured (Figure 5c) for the APU at the 32 °C condition, comparable in quantity to trucks A, D and E. The APU has a small Kubota industrial engine with indirect fuel injection, and simple controls - technologically quite different from the truck engines. This engine is also operating at significant load (rather than an idle condition) in both cases. The emissions trends would not be expected to follow those for the truck engines.

Time-resolved PM measurements

The TEOM was used in this research in an attempt to have time-resolved PM measurements during cold start and idle operation. The companion papers to this one show wide swings in NOx due to the engine cooling fan and a/c compressor turning on and off. We were unable to observe the same kinds of time-resolved changes in PM emissions. Due to the sample location, a very long (5 m) sample transfer line was required, and we think this may have limited our ability to see transient changes in PM. Figure 6(a) shows a typical 3-hour TEOM trace for an experiment. The mass accumulation is very linear, even at the earliest points. Figure 6(b) shows a comparison of the two PM measurement methods used in this research. TEOM values from the last 30 minutes of the run were used to calculate emission rates. Pressure corrections were made to the TEOM result. Note that the TEOM reports lower PM emissions rates than the filter. The main cause of this is likely the high amount of volatile organics in the PM and the higher temperature (50 °C) at which the TEOM operates. In contrast, the filter holder is at room temperature (~25 °C), so is more likely to collect water vapor and more of the HCs.

ALDEHYDE AND KETONE EMISSIONS

Because the levels of aldehyde emissions were unknown going into the study, a 90 min. sampling time was chosen for the aldehyde sampling. Samples from the first set of tests with truck A, at the 18 °C (65 °F) chamber condition, were analyzed and, based on the favorable results, the 90 min. sampling time was kept throughout the program. Unfortunately, truck A at that condition had the lowest aldehyde formation, and subsequent tests with different trucks and environmental temperatures at times resulted in overloading of the DNPH cartridges for formaldehyde and acetaldehyde. Thus, when the value of formaldehyde and/or acetaldehyde in the secondary cartridge exceeded 50% of the amount in the first cartridge, the cartridges were considered to be overloaded. For these tests, values are reported as > 2000 mg/hr, since the true values are unknown. The DNPH cartridges for truck E and the DFH were lost in transit, so are not reported here.

To illustrate the extent of aldehyde emissions, the results for truck C for all of the aldehyde emissions as a function of engine speed are shown in Figure 7. In general, aldehydes increased as a function of engine speed and increased as temperature decreased. The lighter aldehydes are much higher, with levels of formaldehyde approaching the same levels of PM emissions, 1-3 g/hr. In Figures 8 and 9, formaldehyde and acetaldehyde values for four trucks and the APU are reported for the cold and hot chamber conditions. Note that values are much higher for the –18 °C points than the 32 °C points. Also, the APU has significantly lower emissions of these pollutants, most likely due to its higher exhaust temperature.

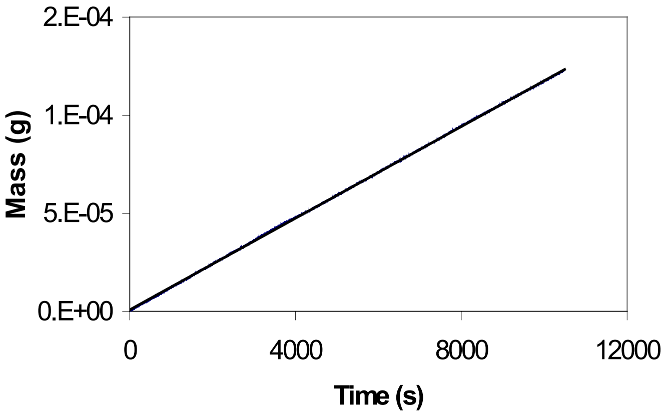

Figure 6(a). Typical TEOM results for 3-hour idling test.

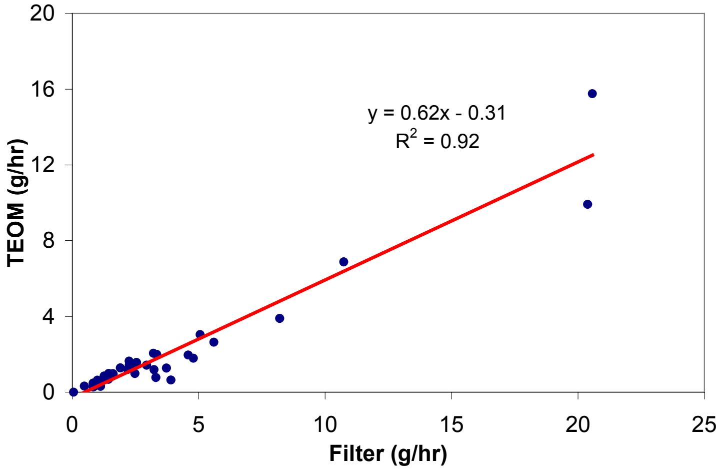

Figure 6(b). Correlation between PM filter results and TEOM results for all of the tests

As speed increases, there is less time for the partially oxidized exhaust products to completely oxidize in the exhaust pipe and on the metal surfaces of the exhaust system. Similarly, the cold surfaces of the exhaust systems at –18 °C quench oxidation reactions before they reach completion to CO_2. The condensation and re-entrainment of unburned HCs in the exhaust likely provides a continuous source of C for the formation of these undesirable emissions. Since formaldehyde and acetaldehyde are identified as air toxics, and are likely to be regulated specifically from mobile sources, there is clearly a need to address this problem with exhaust temperature management and engine controls.

Advanced diesel emissions control technology, such as diesel particulate filters, may or may not address this problem. Further investigation into the air toxics emissions from idling trucks is warranted.

CONCLUSIONS

As part of a broad effort to examine the consequences of extended idling of sleeper-cabin trucks, this paper addresses fuel use, and NO_x, CO, HC PM and aldehyde emissions. Results from testing an APU powering a truck cabin compared to the idling trucks implies that an APU can achieve fuel savings on the order of 60-85% and 50-97% reductions in NO_x, CO and HC. PM is seen to be generally reduced by using the APU, but the results ranged from an increase of 20% to a 95% mass reduction. The diesel-fired heater had significantly lower emissions and fuel consumption than the APU, to the extent that the NO_x, CO and HC are essentially negligible compared to the "best" truck idling cases and the fuel consumption and PM emissions are only a few percent compared to truck idling. The potential fuel savings and overall environmental benefits are readily apparent.

With the exception of the oldest truck, PM decreased with increasing ambient temperature, and increased with increased idle engine speed. Similarly, aldehydes decreased at higher temperatures and increased with increasing engine speed. Both trends can be explained by the presence of unburned HCs in the exhaust. Unburned HCs contribute to the soluble organic fraction (SOF) fraction of PM, increasing PM mass. Unburned HCs also lead to partial oxidation products, as represented by the aldehydes. Because of the high emission levels of two air toxics, formaldehyde and acetaldehyde, there is a need for further study to understand the overall contribution of idling trucks to the source profile. In addition, the positive results of the APU may imply that idle reduction technologies can have a major impact on the emissions of these pollutants as well as the regulated pollutants.

ACKNOWLEDGEMENTS

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DISCLAIMER

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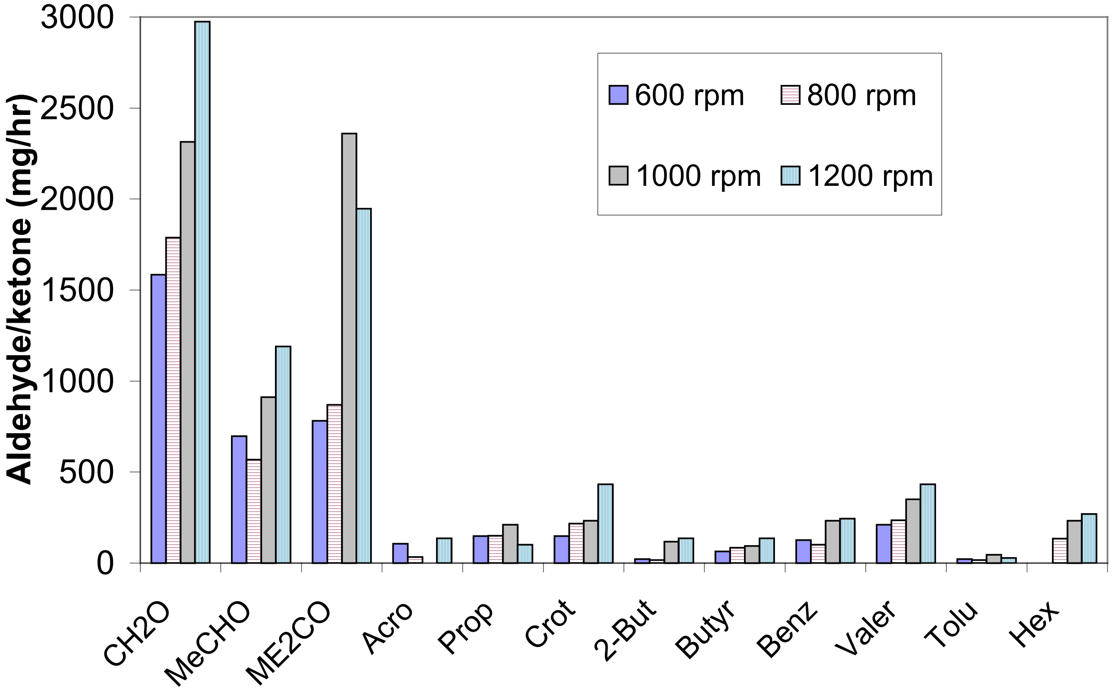

Figure 7. A comparison of all aldehyde emissions for Truck C as a function of engine speed. Ambient temperature was 18 °C. CH2O = formaldehyde; MeCHO = acetaldehyde; ME2CO = acetone; Acro = acrolein; Prop = propionaldehyde; Crot = crotonaldehyde; 2-But = 2 butanone/methacrolein; Butyr = butyraldehyde; Benz= benzaldehyde; Valer = valeraldehyde; Tolu = tolualdehdye; Hex = hexaldehyde.

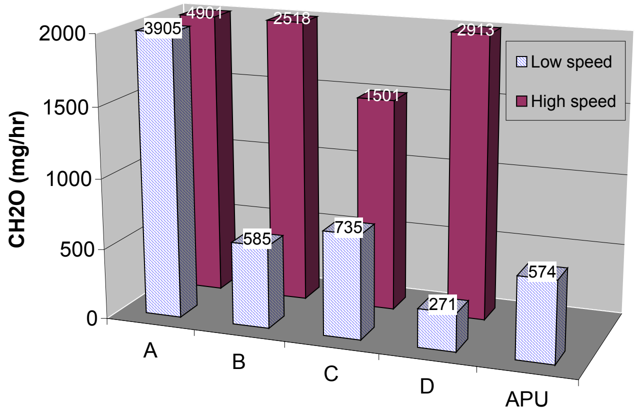

Figure 8(a). Formaldehyde emissions from four trucks at -18 °C.

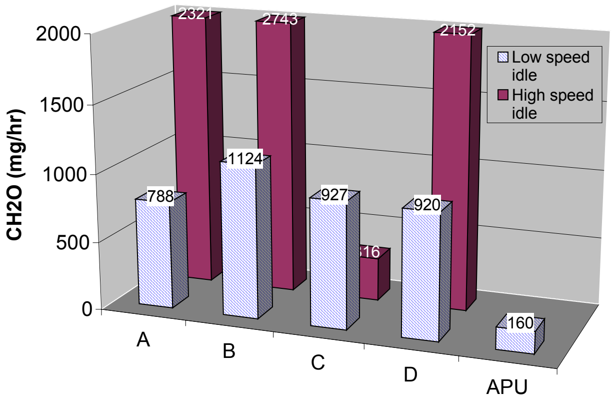

Figure 8(b). Formaldehyde emissions from four trucks at 32 °C.

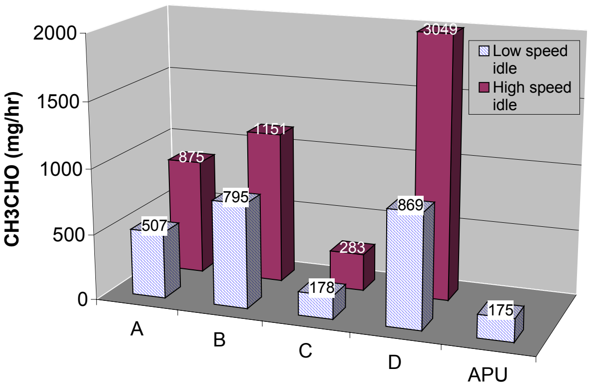

Figure 9(a). Acetaldehyde emissions from four trucks at -18 °C.

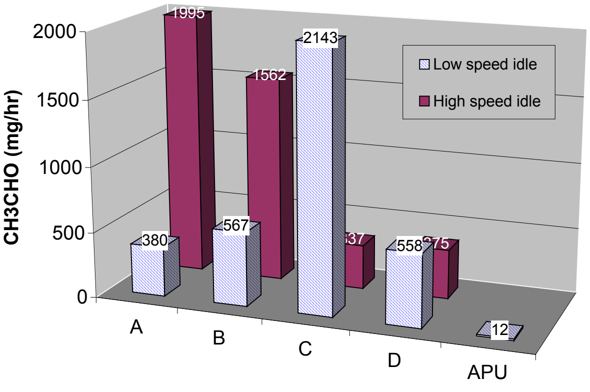

Figure 9(b). Acetaldehyde emissions from four trucks at 32 °C.

APPENDIX

DATA SUMMARY

		Chamber									Calculated
		Set point	Engine	Load	Exhaust					Filter	Fuel
Truck or device	Test	Temperature	Speed	Type	Flow	HC	NOx	CO2	CO	PM	Consumption
	No.	(°C)	(rpm)		(g/h)	(g/h)	(g/h)	(g/h)	(g/h)	(g/h)	(g/h)
2001 Freightliner	30	-18	600	heat	306120	20.0	134	6205	85.9	2.25	2016
2001 Freightliner	29	-18	1200	heat	546947	51.4	221	11077	214	8.21	3644
1999 Volvo truck	6	-18	600	heat	285672	50.3	60.2	6207	194	4.59	2100
1999 Volvo truck	7	-18	1200	heat	573377	70.5	195	11387	295	4.79	3801
1998 Freightliner	19	-18	625	heat	322979	28.7	88.6	7106	62.4	3.21	2296
1998 Freightliner	20	-18	1200	heat	576406	79.6	286	13206	102	5.60	4287
1997 International	34	-18	700	heat	374228	20.8	137	7163	95.5	1.43	2323
1997 International	33	-18	1100	heat	578304	41.9	208	11179	133	3.35	3627
1992 Ford	21	-18	600	heat	350383	42.8	82.8	5688	52.8	1.91	1859
1992 Ford	22	-18	1200	heat	608055	89.4	66.6	10886	102	6.89	3567
"Pony Pack" APU	28a	-18	3000*	heat	36707	7.8	8.7	2146	25.0	0.478	696
Diesel-fired heater	38	-18	N/A	heat	2981	0.040	0.2	445	0.1	0.055	140
2001 Freightliner	25	32	600	a/c	240154	19.4	102	5613	27.8	0.854	1800
2001 Freightliner	26	32	1200	a/c	488302	53.2	189	13709	97.0	3.31	4416
1999 Volvo truck	5	32	600	a/c	244318	50.3	114	5784	24.7	0.827	1883
1999 Volvo truck	8	32	1200	a/c	532045	36.8	353	14611	104.6	5.06	4687
1998 Freightliner	17	32	625	a/c	285618	33.1	157	7324	22.6	1.62	2350
1998 Freightliner	18	32	1200	a/c	563363	79.6	239	17693	62.6	2.95	5680
1997 International	36	32	700	a/c	321462	9.8	176	8024	22.2	1.16	2546
1997 International	37	32	1100	a/c	519544	20.9	265	14357	53.3	1.44	4567
1992 Ford	11	32	600	a/c	302128	40.1	51.5	8454	68.9	2.26	2735
1992 Ford	12	32	1200	a/c	590811	79.9	85.2	14445	119	20.6	4686
"Pony Pack" APU	27a	32	3000	a/c	34172	4.2	11.4	2351	10.8	0.995	750
2001 Freightliner	23	18	600	none	233799	25.2	78.6	4720	29.8	0.849	1526
2001 Freightliner	24	18	1200	none	472263	56.0	149	10999	82.9	2.48	3559
1999 Volvo truck	4	18	600	none	248222	36.6	89.2	4356	25.3	1.12	1420
1999 Volvo truck	3	18	1200	none	485927	59.2	219	8457	66.5	3.90	2754
1998 Freightliner	13	18	625	none	282991	20.0	148	5539	17.1	1.26	1772
1998 Freightliner	14	18	800	none	371529	42.8	158	11838	32.3	2.31	3785
1998 Freightliner	15	18	1000	none	447882	63.6	155	9515	44.4	3.73	3081
1998 Freightliner	16	18	1200	none	534960	74.3	197	13230	62.0	2.54	4269
1997 International	31	18	700	none	328784	13.7	155	6228	22.3	0.827	1985
1997 International	32	18	1100	none	532369	27.0	233	11266	52.3	2.20	3599
1992 Ford	9	18	600	none	308183	19.1	71.3	5530	20.6	1.61	1770
1992 Ford	10	18	1200	none	574963	51.6	64.8	11428	87.2	20.39	3692

* Approximate speed (not measured) of the Pony Pack APU engine [8]