EXPOSURE TO ENVIRONMENTAL TOBACCO SMOKE IN AN AUTOMOBILE

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ABSTRACT

We measured exposures to ETS in a moving minivan under three different ventilation scenarios: drivers window open/ventilation off, windows closed/ventilation on, and windows closed/ventilation off. The driver smoked a single cigarette while we measured the concentration of ETS using laser aerosol monitors and the outside air exchange rate using a tracer gas decay technique. The indoor concentrations of respirable particulate matter increased during smoking by factors of 13 to 300 depending upon the ventilation configuration. The calculated exposure for a five hour automobile trip with the windows closed/ventilation off and with a smoking rate of 2 cigarettes per hour is 25 times higher than the same exposure scenario in a residence. Smoking low tar cigarettes or operation of air cleaners or ventilation equipment cannot reduce concentrations in automobiles to acceptable levels. The most effective solution to protecting passengers from ETS exposure is not to smoke in the automobile.

INDEX TERMS

Automobile, Environmental Tobacco Smoke, Sulfur Hexafluoride, Tracer Gas, Ventilation

INTRODUCTION

Environmental tobacco smoke (ETS) contains thousands of compounds many of which are toxic and irritating and some of which are known carcinogens. These compounds include gas phase compounds such as carbon monoxide, formaldehyde and hydrogen cyanide. In addition, ETS contains airborne particulate matter (i.e. tar) that consists of fine liquid droplets of condensed organic matter that contain many toxic compounds including benzo(a)pyrene and other carcinogenic polycyclic aromatic compounds. The particulate phase compounds are in the respirable range (i.e. less than 3 μm mass medium diameter). Automobiles typically have some type of mechanical ventilation system. These ventilation systems provide an adjustable supply of air that can provide heating, or if air conditioning is installed, cooling. These ventilation systems can be set to provide outside air or recirculated air (i.e. called "economy mode" in some automobiles with air conditioning). Automotive ventilation systems typically do not have filters which can significantly reduce air contaminant concentrations from ETS. In automobiles exposures can be significant because of the very small indoor air mixing volume (i.e. less than a couple m^3). In this study we measured the exposure to ETS in a moving automobile under three different operation scenarios: drivers window open and ventilation off, windows closed and ventilation on, and windows closed and ventilation off.

METHODS

For each test the driver smoked a single low tar cigarette while driving a 1996 minivan on city streets. We measured the real time concentration of ETS in the rear seat at breathing height and in the outside air using laser aerosol monitors that were calibrated for the same brand tobacco smoke in an environmental chamber. We also simultaneously measured the outside air exchange rate in the automobile using a tracer gas decay technique.

Three tests of the exposure to ETS in automobiles were conducted. In each test a 1996 minivan was used for the tests and the driver (left seated) smoked a single low tar cigarette (FTC tar 11 mg) while driving city streets over a 5.6 km route. Speeds ranged from 0 to 40 kph, and averaged approximately 30 kph. The cigarette was smoked in the right hand of the driver. A researcher sat in the back seat during the tests. The first test was conducted with the drivers window open and the automobile ventilation system off. The second test was conducted with the all windows closed and the ventilation system on medium speed with the airflow set for delivery to the lower and upper portions of the front seat area. The third test was conducted with all windows closed and the ventilation system off.

Calibration of Laser Aerosol Monitor for ETS. The concentration of tobacco smoke was measured using a laser aerosol monitors (TSI, DustTrak) calibrated for cigarette smoke. The laser aerosol monitors used in this study are 90 degree light scattering laser photometers. Calibrations of the laser aerosol monitors were conducted in 12.4 m^3 test chamber. The chamber was supplied with 190 Lpm of HEPA filtered air (i.e. 0.9 ach) so as to maintain a positive pressure in the test chamber and eliminate infiltration of surrounding lab air. A mixing fan was continuously operated throughout the test at a rate of 143 ach. This high rate of mixing was selected to insure that the ETS concentrations collected by the gravimetric samplers and the laser aerosol monitors were similar. Previous chamber studies of ETS (Offermann, 1985), have shown that high mixings rates of 174 ach cause little increase in the surface deposition rate (i.e. less than 0.1 ach) or change in the particle size distribution. The chamber was purged prior to the test with HEPA filtered air. A single low tar cigarette from the same package of those used for the automobile tests was smoked by the same person smoking in the automobile tests. The indoor concentrations were simultaneously monitored in the test chamber using two laser aerosol monitors and a pair of gravimetric sampler each of which were co-located. The laser aerosol monitors measure the concentrations once per second and were programmed to log one minute average concentrations and 30 second average concentrations for Monitors 1 and 2 respectively. The laser aerosol monitors measured the concentrations commencing 35 minutes before the cigarette was lit and continuing for 30 minutes after the cigarette was put out. The gravimetric samplers consisted of two pre-weighed 37 mm 5.0 µm PVC membrane filters which air was drawn through at a rate of 20.3 Lpm and 22.6 Lpm during a 33 minute period commencing one minute after the cigarette was lit. Immediately following this tests the gravimetric samples were weighed using a microbalance and the concentration determined from the net weight gain of the filter and the volume of air sampled. The average gravimetric concentration was calculated as the average concentration determined from the two gravimetric samples. The average concentration as determined by the laser aerosol monitor for the same period of time the gravimetric air samplers were operating was calculated. The calibration coefficient for the laser aerosol monitor for ETS was calculated as the ratio of the average gravimetric concentration to the laser aerosol average concentration.

ETS Measurements. The concentration of tobacco smoke was measured using two laser aerosol monitors calibrated for ETS as described above. Monitor 1 was configured to sample the air of the automobile at breathing height in the center rear passenger seat every second. Monitor 2 was configured to sample the outside air through a sampling line that was sealed through an opening in the front passenger seat window every 30 seconds.

Air Exchange Rate Measurements. For the three automobile tests the air exchange rate was measured using a tracer gas decay technique. A quantity of 240 cc of 0.106% sulfur hexafluoride (SF_6) gas in air was injected into the automobile with all windows closed and the ventilation off and mixed for 15 seconds by manually fanning the indoor air. The first tracer gas sample was then collected and the mode of ventilation was initiated (i.e. windows open/closed, ventilation on/off). Samples were collected by drawing air into 20 cc polypropylene syringes. A total of 9 samples were collected in 30 second intervals following the initial sample. The syringe samples were analyzed within 24 hours using a gas chromatograph equipped with an electron capture detector. The air exchange rate was calculated directly from the decay rate of the concentration of SF_6.

RESULTS AND DISCUSSION

The results of the calibration of the laser aerosol monitors are summarized in Table 1. The low calibration factor of 0.23 is not unanticipated. Combustion aerosols such as ETS are predominantly submicron particles and scatter much more light on a unit mass basis than the larger particle size aerosol used by the manufacturer to calibrate the monitors (i.e. Arizona Road Dust). Measurements conducted by the manufacturer of the laser aerosol monitor used in this study confirm similar calibration coefficients for other combustion aerosols such as incense (Sreenath, 1999)

Table 1. Calibration results for two laser aerosol monitors using ETS from a single low tar cigarette smoked in a 12.4 m^3 test chamber.

Average Gravimetric Analyses ($\mu g/m^3$)	**Average Laser Aerosol Monitors ($\mu g/m^3$)**	**Calibration Factor (ETS/Laser Aerosol Monitor)**
635	Monitor 1: 2,714	0.23
	Monitor 2: 2,789	0.23

The results of the measurements of air exchange rates and respirable particulate matter in the three tests conducted in a moving automobile are summarized in Table 2.

Table 2. Results of the measurements air exchange rates and respirable particulate conducted in a moving automobile under three different ventilation scenarios.

Test	**Ventilation Mode**	**Air Exchange Rate (air changes per hour)**	**Average ETS Concentration During Smoking ($\mu g/m^3$)**	**Total ETS Exposure ($\mu g\text{-}hr/m^3$)**
1	Windows Open Ventilation Off	71	92	9
2	Windows Closed Ventilation On	60	693	68
3	Windows Closed Ventilation Off	4.9	1,195	868

The air exchange rates ranged from 4.9 ach with the windows closed and ventilation off to 60 ach with the windows closed and ventilation on to 71 ach with the drivers window open and the ventilation off. We also calculated the mixed air volume inside of the automobile from the tracer gas decay data. The tracer gas concentration decay data was plotted and the steady exponential decay rate that developed was extended back to the time that tracer gas was injected. This concentration along with amount of tracer gas injected was used to calculate a mixed air volume in the automobile of 2.0 m^3. This compares to the indoor air volume of 6.1 m^3, which was calculated from the interior dimensions of the automobile without accounting for the displacement of air by passengers, seats, and dashboard. This large difference illustrates the importance of accounting for the displacement of indoor air when calculating mixed air volumes in small indoor spaces such as automobiles.

The outdoor concentration of respirable particulate matter measured during the automobile tests with a second laser aerosol monitor averaged less than 10 $\mu g/m^3$ (i.e. 7 $\mu g/m^3$ for Test 1, 6 $\mu g/m^3$ for Test 2, 4 $\mu g/m^3$ for Test 3). The increase in the indoor concentration of respirable particulate matter over the outdoor concentration was a factor of 13 with the drivers window open and the ventilation off, 115 with the windows closed and the ventilation on, and 300 with the windows closed and the ventilation off.

The fact that the average concentration during smoking is so much lower in Test 1 as compared to Test 2 (e.g. 13% of the concentrations in Test 2) while the outside air exchange rate are relatively similar (e.g. just 18% higher) is attributed to a portion of the ETS escaping directly out of the open driver's side window in Test 1. The fact that the concentrations in Test 3 are just 1.7 times higher than those in Test 2 while the outside air exchange rate was more than a factor of 10 lower, is partly attributed to a reduced response rate of the laser aerosol monitor at the higher concentrations of ETS experienced in Test 3. Since ETS particles are condensed liquid droplets, they coalesce quickly at higher concentrations. For instance, if 8 spherical particles of ETS coalesce into a single particle, the diameter of that particle only increases by a factor of two. The reflective surface area of this larger particle is just one half of the combined reflective surface area of the 8 individual smaller particles. This results in a response rate for the larger particles that is one half that for the smaller particles. We believe that the calibration coefficient determined in the test chambers is most accurate for the tests which were conducted at concentrations similar to those concentrations in the test chamber. Thus, since the concentrations in Test 3 were significantly higher than those during calibration, the concentrations measured in Test 3 may be underrepresented. Similarly, since the concentrations in Test 1 were significantly lower than those during calibration, the concentrations measured in Test 3 may be overrepresented.

Figure 1 depicts the real time concentrations of respirable particulate matter for each of the three tests conducted in the moving automobile. One can easily see that for Tests 1 and 2, where there is a very high air exchange rate (e.g. 60-71 ach), that the indoor concentrations are rapidly reduced to background levels after the cigarette is put out (e.g. less than 3 minutes) while the concentrations in Test 3, where the air exchange rate was just 4.9 ach, persist for a much longer period of time (e.g. calculated to be more than 2 hours). A better measure of the occupants exposure for these three scenarios than the average ETS concentration during smoking, is to calculate the total exposure to the ETS generated from a single cigarette under each of the three ventilation scenarios. This calculation was done numerically for Tests 1 and 2 over the entire period that the indoor concentrations were elevated over background. For this analyses the measured outdoor concentrations were subtracted from the measured indoor concentrations. For Test 3 the same numerical calculation of exposure was conducted up until the point that the test was terminated and the windows of the automobile were opened. We calculated the residual exposure for this test by dividing the concentration measured at the end of the test by the negative of the slope of the natural logarithm of the concentration as function of time at for the latter portion of the test. The results of these calculations are presented in Table 2.

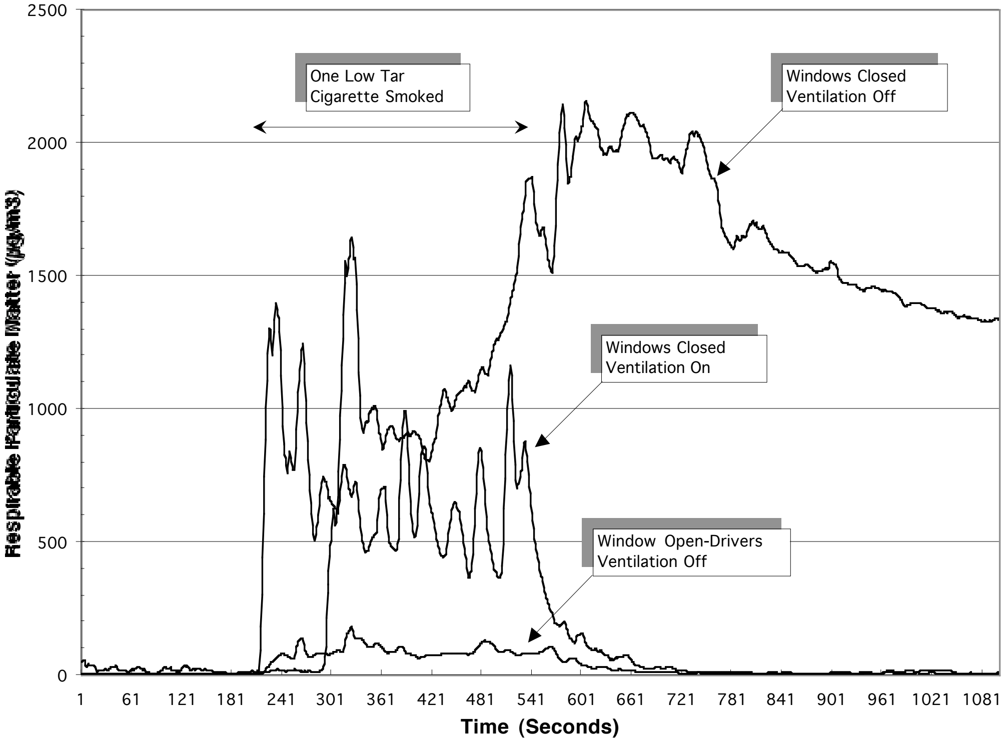

Figure1. The concentration of respirable particulate matter measured in a moving automobile for three different ventilation scenarios.

To further put these concentrations into perspective we have calculated the average ETS concentrations in a residence and compared these to those in an automobile using a simple indoor air quality model (Offermann et. al., 1984). For the residence we assumed an indoor air volume of 340 m^3 and an air exchange rate of 0.50 ach. For the automobile scenarios we used the same air exchange rates as measured in this study along with the measured mixed air volume of 2.0 m^3. For both the residential and automobile scenarios we used an emission rate of 12.5 mg per cigarette and a smoking rate of 2 cigarettes per hour and assumed perfect mixing and no surface deposition of particles. The calculated average concentration for a five hour automobile exposure with the windows closed and the ventilation off or outside air off (e.g. recirculation or “economy” cooling mode) is 25 times higher than the same exposure scenario in a residence. For the other two automobile scenarios, ventilation on with windows closed and ventilation off with drivers window open, the concentrations are both about double the residential scenario.

CONCLUSIONS

Indoor concentrations of ETS can be especially significant in automobiles due to the small indoor air volume, measured to be 2.0 m^3 for a minivan in this study. The calculated average concentration for a five hour automobile exposure with the windows closed and the ventilation off or outside air off (e.g. recirculation or "economy" cooling mode) is 25 times higher than the same exposure scenario in a residence. Smoking low tar cigarettes or operation of air cleaners or ventilation equipment cannot reduce concentrations to acceptable levels. The most effective solution to protecting passengers from ETS exposure is not to smoke in the automobile.

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