Investigation into Pedestrian Exposure to Near-Vehicle Exhaust Emissions

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Abstract

Background

Inhalation of diesel particulate matter (DPM) is known to have a negative impact on human health. Consequently, there are regulations and standards that limit the maximum concentrations to which persons may be exposed and the maximum concentrations allowed in the ambient air. However, these standards consider steady exposure over large spatial and time scales. Due to the nature of many vehicle exhaust systems, pedestrians in close proximity to a vehicle's tailpipe may experience events where diesel particulate matter concentrations are significantly higher than regulations allow for brief periods of time.

Methods

In order to quantify these exposure events, instruments which measure specific exhaust constituent concentrations were placed near a roadway and connected to the mouth of a pedestrian surrogate, a mannequin named "Roland." By measuring concentrations at Roland's mouth during drive-by events with a late model diesel truck, a representative estimate of the exhaust constituent concentrations to which a pedestrian may be exposed was obtained. Typical breathing rates were then multiplied by the measured concentrations to determine the mass of pollutant inhaled.

Results

The average concentration of diesel particulate matter measured over the duration of a single drive-by test often exceeded the National Ambient Air Quality Standard (NAAQS) of 35 $\mu g/m^3$ and the Mine Safety and Health Administration (MSHA) exposure limit of 160 $\mu g/m^3$. It was also observed that higher concentrations of diesel particulate matter were measured at the height of a stroller than were measured at the mouth of a mannequin.

Conclusions

Although diesel particulate matter concentrations during drive-by incidents were significantly higher than regulations and standards allow, the durations were short (less than 15 seconds). Consequently, for the case of a particular well-tuned late-model year vehicle, it was determined that the observed amount of particulate matter inhaled was insignificant compared to the amount inhaled daily at ambient conditions. Indeed, exposure to thousands of drive-by incidents with this vehicle within 8 hours would approach the mass inhaled for 8 hours at the Mine Safety and Health Administration exposure limit. However, existing data published elsewhere show that in-use vehicle emissions may exceed the roadside levels measured here by greater than an order of magnitude. Finally, it was determined that children, infants, or people breathing at heights similar to that of a passing vehicle's tailpipe may be exposed to higher concentrations of particulate matter than those breathing at higher locations, such as adults standing up.

Background

There is extensive literature that supports the relationship between atmospheric diesel particulate matter (DPM) and adverse human health effects [1-3]. Consequently, standards have been set to regulate the allowable level of ambient particulate matter and limit the maximum concentration to which persons can be exposed. In the U.S., airborne particulate matter less than 2.5 microns in size ($PM_{2.5}$) is required to be at or below 35 $\mu g/m^3$ over a 24 hour period and an annual arithmetic mean of 15 $\mu g/m^3$ [4]. However, those air quality standards address exposures averaged over large spatial (greater than 100 meters) and time (24 hours) scales. In addition, the Mine Safety and Health Administration (MSHA) set an occupational exposure limit on diesel particulate matter of 160 $\mu g/m^3$ averaged over an 8 hour period, effective May 2008 [5]. Because it is estimated that 35% of ambient $PM_{2.5}$ typically is contributed by mobile sources [6], there has been interest in the possibility of health effects due to elevated exposures near roadways [7]. In literature, the term "near roadway" refers to the distance from a roadway at which pollutants are measured, typically less than 300 meters. This paper is concerned with exposures that are even closer to the vehicle exhaust than the distances termed "near roadway" in the literature. In fact, this paper uses the term "near vehicle" to show the closeness of the exposure to the passing vehicle.

While most automobile exhausts are directed to the rear of the vehicle, many vehicles around the world, specifically pickup trucks, employ tailpipes that direct exhaust towards the passenger side of the vehicle. Since right side tailpipes direct emissions towards U.S. sidewalks and roadsides, there is reason to be concerned that people on sidewalks and near roadways are exposed to hazardous exhaust constituents at levels greater than typical "near roadway" levels. Because their faces are closer to the level of tailpipes, children and babies in strollers could be even more heavily exposed.

When exhaust is emitted from a diesel vehicle, it can be characterized as a plume of particles and gaseous materials. It is plausible that within such plumes particle concentrations may substantially exceed regulations, especially for brief periods. Wind tunnel studies [8,9] show that there may not be any appreciable evolution of particle sizes within a plume and that dilution ratios can range from 75 to 125 at a distance of 8.5 meters downstream of the tailpipe. In contrast to these findings, a vehicle chase study [10] observed actual dilution ratios as large as 1,000:1 in two seconds. However, the chase study was conducted at freeway speeds of 40 to 55 mph, which is more than double the local street speeds (20 to 25 mph) tested in this study and did not consider the stop and go traffic often encountered on busy streets. Therefore, it is reasonable to believe that dilution rates would be far lower at local street speeds for two reasons: (i) the travel time for the plume to reach a sidewalk is very short, providing little time for appreciable dilution, and (ii) the turbulence imparted to surrounding air by slow-moving vehicles would be relatively low. Hence, it is plausible that pedestrians may be exposed to diesel particulate matter concentrations significantly higher than regulations allow, though perhaps for brief periods as each vehicle passes a pedestrian or idles at the sidewalk. In addition, since pedestrians are generally walking in front of stores, shops, and other buildings, it is quite likely that concentrations would build over time, especially when traffic is heavy or stop and start.

Although there is a limited amount of information regarding acute and short-term (e.g. less than 8 hours) exposures to diesel exhaust, there is strong evidence from human and animal studies that exposures to high concentrations of diesel exhaust (6,000 $\mu g/m^3$) can cause acute irritation, neurophysiological symptoms, and respiratory symptoms [2]. Since data from dilution tunnel measurements [11-13] can not accurately simulate this type of actual human exposure, drive-by experiments are necessary.

The aim of this study was to quantify the short, local exposures that may be experienced by pedestrians in the immediate vicinity of a vehicle's tailpipe during a vehicle drive-by incident. Although the study does not seek to elucidate health effects from short, high exposures, there is no reason to assume that the health effects are linear with respect to ingested mass. For example, health effects due to inhalation of cyanide, a poison to humans, appear to be linear with respect to inhaled dose until a certain dose is inhaled, above which death is certain [14].

The vehicle studied here was a diesel-fueled pickup truck, which has an original tailpipe that discharges directly toward the sidewalk. Multiple scenarios, including exposure to a simulated adult or a child in a stroller beside the road, were examined for different vehicle operating conditions during the "drive-by." The concentrations of diesel particulate matter that reach a pedestrian's mouth were measured and compared to both ambient pollution levels and to regulations and standards governing personal exposure. In addition, both the short-term, time-weighted average exposure and the cumulative mass of particulate matter potentially inhaled per event were quantified.

Methods

Study site

The study was conducted during August 2007 in Morgantown, West Virginia on a two-lane road bisecting the WVU Evansdale campus. The study location was chosen for its minimal traffic congestion and the presence of an adequate power supply within 100 feet. Additionally, the land on one side of the road was relatively flat for about 5 m, providing a simple topography that should be comparable to most urban sites. Unlike many urban sites, there were no buildings nearby that could have contained contaminated air. Preliminary measurements revealed that background concentrations of pollutants of interest were very low.

Apparatus

Particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2), and oxides of nitrogen (NOx) were measured continuously using a Cambustion DMS500 Fast Particle Spectrometer, a Horiba AIA-220 CO/CO_2 analyzer, and an EcoPhysics

CLD-822 NOx analyzer, respectively. The Cambustion DMS500 Fast Particle Spectrometer is a mobility-based particle sizing instrument used to measure or count particles between 5 and 1,000 nanometers in mobility diameter. The DMS500 operates by charging each particle precisely using a corona discharge as it flows into a strong electrical field contained inside a classifier column. This electrical field then deflects the particles towards the electrometer detectors depending upon each particle's aerodynamic drag/charge ratio (mobility). When the particles contact the detectors at different points throughout the column, the increase in current due to each particle's charge is measured. The outputs from the 22 electrometers are then processed in real time to provide spectral equivalent diameter data and other desired particle parameters.

Although the particles in diesel exhaust do not have a constant density and are not always spherical, both spherical shape and constant density are typically assumed when estimating mass using sample data from instruments designed to measure particle number-weighted size distribution via particle mobility [15]. For example, the TSI Engine Exhaust Particle Sizer™, a mobility-based instrument that operates on the same principle as the DMS500, requires the assumption of spherical particles of unity density to calculate mass [16]. Mobility-based instruments are based on Stokes' law which can be used to determine each particle's equivalent spherical diameter. The equivalent spherical diameter defines the equivalent diameter of a spherical particle of unity density with the same settling velocity as the collected particles [15].

Though this approach has been used by some [16], others have instead developed more accurate correlations between particle size and mass. A recent study [17], which compared the DMS500 and a Scanning Mobility Particle Sizer (SMPS), showed the development of the following correlation between particle size and mass for the DMS500:

$$Mass(\mu g) = 1.54 \times 10^{-16} \cdot D_{eme}^{3.19} \qquad \text{Eq. 1}$$

where D_{eme} is the electrical mobility equivalent diameter in nanometers. Both of these approaches for calculating mass from DMS500 particle number data were applied to the data from this study and compared to each other.

The Horiba AIA-220 analyzer, installed in a custom measurement system, measured CO and CO_2 continuously using nondispersive infrared (NDIR) technology. The custom measurement system, housed inside a stainless steel container, consisted of a pump to control and provide adequate sample flow, a particulate filter to remove any particles that may damage the instrument, and a cooler to remove all water vapor from the sample. Including the analyzer, the measurement system used a sample flow rate of about 7 liters per minute. The EcoPhysics CLD-822 analyzer measured NOx continuously using the principle of chemiluminescence. This analyzer was used separately, without a custom measurement system and used a flow rate of approximately 2 liters per minute.

Although the Horiba and EcoPhysics analyzers are often considered to be continuously integrated and nearly instantaneous, they are not. In a typical emissions measurement laboratory setup, these analyzers have been found to have response delays up to 15 seconds [18]. However, the bulk of these delays are not caused by the analyzers alone, rather, they are also due to the flow of exhaust through a vehicle's exhaust system and travel time through the emission sampling system. According to manufacturer user manuals, the Horiba and EcoPhysics analyzers have delays of 0.5 to 10 s and less than 1 s, respectively, from the time a sample enters the analyzer until it is detected by the sensor. The sample tubing used in this study was approximately

15 ft long with an inner diameter of 0.126 in. The transport delays for the analyzer sampling systems were calculated using this information and Equation 2:

$$T_D = \frac{V}{F} \qquad \text{Eq. 2}$$

where T_D is the transport delay, V is the volume of the sample line and sampling system, and F is the sampling system flow rate. The transport delays were calculated to be approximately 3 and 11 seconds for the Horiba and EcoPhysics sampling systems, respectively. The time delays between sample collection at the probe inlet and sensor response are given by the manufacturer specifications stated previously and are in addition to the transport delays presently discussed.

Before testing began, the gaseous analyzers were calibrated using gases of known concentration and linear regression using 11 points over a range from 0 to 2.003 % for the CO_2 analyzer, 0 to 99.8 ppm for the CO analyzer, and 0 to 101 ppm for the NOx analyzer. To do this, both the known concentrations and their corresponding analog voltage outputs were recorded. Quadratic polynomial regression equations were developed from the calibrations and used to predict concentrations from measured voltages.

The vehicle in the test was a 2006 Dodge Ram 2500 with a 5.9 L, 325-hp diesel engine that discharges its combustion products through an exhaust system outfitted with an oxidation catalytic converter. The tailpipe discharges towards the passenger side of the vehicle behind the rear wheel. An AutoTap OBDII Diagnostic Scanner connected to an on-board laptop computer running AutoTap software was used to monitor and record broadcast engine control unit (ECU) data. The software allowed the vehicle operator to monitor in real-time the calculated percentage load which made it possible to maintain the desired engine load when passing the sampling location.

At the sampling location, a life-like mannequin named Roland with a detachable Styrofoam™ head was used as a surrogate for human pedestrians. The mannequin along with the emissions measurement equipment can be seen in Figure 1. Including the head, the mannequin was about 72 inches tall (i.e. approximately 64 inches at the mouth). Sample probes, located in the mouth of the mannequin, extended though the back of the Styrofoam™ head and attached to Teflon transport tubing 15 feet in length connected to the analyzers. To mimic a child in a stroller, the mannequin's head, sample probes and all, were placed inside a stroller and positioned near the roadway. During this setup, the sample probes were approximately 34 inches from the ground.

Scenarios observed

Although the term "pedestrian" typically refers to a person walking or traveling on foot, for the purposes of this study the term was broadened to include persons who are near roadways and either walking or standing. Also, the term does not distinguish between individuals who are nearby for occupational or personal reasons. Analyzers were placed along the test road to measure exhaust constituents at the mouth of a surrogate pedestrian. During periods of sampling, a diesel fueled vehicle was driven past the mannequin and the analyzers under different operating conditions.

Though there have been several studies to analyze near-tailpipe vehicle exhaust or near-roadway exposure [19-22], few have instrumented the vehicle to record ECU data during the drive-by incidents, as was done in this study. The mannequin, which has been fully described above, was placed beside the roadway to simulate an adult male standing on the sidewalk next to a roadway. In addition, the mannequin's head was removed and placed in a stroller to simulate a child in a stroller. For the third test scenario, the mannequin was removed and the sample probes were attached to a 1" square stand to allow for comparison of samples taken at the same height with and without the presence of the simulated human.

The three operating conditions varied when the test vehicle passed the sampling location were (i) acceleration at full load, (ii) acceleration at 50% load, and (iii) cruising at a constant velocity with high engine speed. These operating conditions were chosen because all three commonly occur near pedestrians and could be expected to produce very different levels of diesel particulate matter expulsion. Several studies [23-25] have shown that the formation of particulate matter and other diesel exhaust constituents varies greatly with engine operation. The highest particulate concentrations and emission rates observed in the third study were linked to heavy engine acceleration, high engine speed, and high torque [25].

The acceleration tests were accomplished by accelerating the vehicle from a rolling start (5 mph) past the sampling location while monitoring the engine load to ensure that the proper load was maintained while the vehicle passed the sampling location. The cruising tests were accomplished by accelerating the vehicle to approximately 25 mph and maintaining a constant speed for at least 30 yards before passing the sampling location. During these drive-by tests, the vehicle operator attempted, when near the sample locations, to keep the vehicle at a distance of about 20 inches from the curb and thus 30 inches horizontally from the sample probes. Four to six drive-bys were conducted for each combination of scenarios.

Pollution monitoring

Teflon sample lines from the analyzers were connected directly to the mannequin's mouth and run roughly 15 ft to sampling devices. Air was sampled continuously providing continuous emissions data as the test vehicle passed the mannequin during each test run. Data from all of the analyzers were recorded simultaneously by connecting the analog outputs of the Horiba and EcoPhysics analyzers to the analog inputs on the Cambustion DMS500 via modified coaxial cable. A program, supplied with the Cambustion DMS500, was used both to control the DMS500 instrument and to record the PM, CO, CO_2, and NOx measurements. The resulting measurements were associated with specific test vehicle engine conditions by synchronizing the computer used to record analyzer measurements with the computer recording engine data. The time at which the vehicle passed the sampling point was recorded using a Microsoft Visual Basic™ program custom written for this study. Using these time-stamped data, the engine conditions during each test could be correlated with the emissions measured during each test. To ensure that emissions linked with the test vehicle were not affected by other vehicles, the drive-by runs were conducted when there were no other vehicles nearby.

Because the particle size range of the DMS500 typically accounts for 80 to 95 percent of the total particulate matter mass found in diesel exhaust [26], the resulting measurements can be assumed to approximate $PM_{2.5}$ concentrations. Thus, PM measurements were taken to estimate $PM_{2.5}$ exposure, CO was measured as an attempt to correlate CO concentrations with PM concentrations (see [27]), and CO_2 and NOx were measured to help quantify the dilution ratio of the exhaust exiting the test vehicle's tailpipe.

Data reduction

Once all the data had been acquired from testing, a program custom-written in Microsoft Visual Basic for Applications (VBA) ™ was used to extract the desired data from text files and import it into a Microsoft Excel™ file. During extraction, the gaseous sample concentrations where calculated from the observed voltages using the corresponding calibration equations. In addition, the concentration of particulate matter in micrograms per cubic meter of air (μg/m3) was computed using the previously mention analyses correlating particle diameter and mass.

A vehicle's exhaust system and the emission sampling system both have considerable time delays (up to 12 seconds) [18,28,29], although raw exhaust measurements, such as obtained in this study, typically have shorter time delays than standard dilution tunnel measurements [29]. Consequently, all figures containing this gaseous data had to be corrected based on the manufacturer's specifications as well as the measured sampling delays. By combining the transport delays and manufacturer specified delays mentioned previously, the delay for the CO and CO_2 data was estimated to be approximately 3.5 seconds, and the delay for the NOx data was estimated to be about 12 seconds. Furthermore, the instantaneous pollutant concentration data obtained from analyzers are diffused in time [29] because they do not represent the instantaneous emissions that may arise due to a short lived engine operating condition. No corrective measures were taken to rectify the data because the nature of the diffusion was unknown.

Exposure estimation

Human exposure to diesel exhaust is typically considered as an average particulate matter concentration over a certain amount of time. For example, the MSHA exposure limit is a concentration averaged over an 8 hour period [5]. During drive-by incidents, the measured concentration of particulate matter is initially equivalent to the background concentration but quickly increases to a maximum as the exhaust plume reaches the sample lines. It then decreases back to the background concentration levels as the exhaust is diluted by mixing with ambient air.

In order to estimate the exposure pedestrians may experience, the instantaneous sample concentrations of diesel particulate matter obtained at 5 Hz from the DMS500 were mathematically averaged over the duration of each drive by incident. For this study, the duration of an incident was defined as the time interval beginning when the exhaust plume from the tailpipe produced a noticeable increase in particulate matter concentration at the computer and ending when the exhaust plume had diluted sufficiently that the measured concentration of particulate matter was near background levels again. The noticeable increase in concentration or beginning of an event was determined by first computing the standard deviation of the background concentration for two to four seconds starting at the events time stamp. A three point running average of the concentration was then computed. If this value was greater than the average background concentration plus 10 times the standard deviation of the background concentration, the time associated with the second point in the three point average was considered to be the time the event began. The end of the event was similarly determined to be when the value of the running average was less than the average background concentration plus 10 times the standard deviation of the background concentration.

To compare the estimated mass inhaled during the drive-by incidents with the estimated mass inhaled at ambient conditions, maximum and minimum ambient conditions were specified. The ambient concentrations considered were equivalent to (i) the National Ambient Air Quality Standard and (ii) the ambient concentration in

Darrington, Washington, a city which the EPA considers to have good air quality. These ambient concentrations of 35 and 5 μg/m^3, respectively, represent reasonable maximum and minimum expected ambient concentrations of particulate matter.

Since the number of drive-bys in the study was fewer than the number pedestrians may experience on city sidewalks, the estimated exposures for typical pedestrians were determined by multiplying the average test values by a reasonable estimate of typical frequency of drive-bys. For the latter, it should be noted that the theoretical maximum traffic volume a single lane road can support is given by the ratio of vehicle speed and vehicle spacing [30]. Assuming a speed limit of 25 mph, such as that of the test road, and a vehicle spacing of 40 feet (approximately two car lengths), the maximum traffic volume that can be obtained is 3,300 vehicles per hour. Of course, not all vehicles are diesel-powered and gasoline engines also emit particles at measurable mass and number levels [31,32]; particle mass and number emissions from gasoline vehicles are orders of magnitude smaller than from diesel vehicles. Using the assumptions made in the EPA's MOBILE6 emissions model, it was determined that 1.02% of all light duty vehicles and class 2B and class 3 heavy duty vehicles produced in the U.S. in 2008 were diesel fueled [33]. This percentage implies that on average 33 diesel fueled vehicles pass a single point on a road, such as described above, every hour. Therefore, over an 8 hour period, a typical incident count could be as high as 264. Note that this 8 hour time period comes from an occupational exposure standard.

Another type of short-term exposure considered to be applicable to drive-by incidents, such as explored in this study, is exposure per inhalation. This type of short-term exposure deals with single inhalations of very high concentrations. To determine this exposure as a worst case scenario, an incident from each scenario with the highest instantaneous concentrations was aligned with the inspiration of a breath. Inspiration lengths of 2.5 and 1.5 seconds were used to imitate walking and standing breathing rates, respectively. This maximum amount of particulate matter inhaled in a single breath during a drive-by incident was then compared to the amount of particulate matter inhaled in a single breath at the same ambient conditions stated previously.

Results and Discussion

Drive-by test results

The raw data from typical drive-by tests can be seen in Figure 2. Figure 2A represents the case where the test vehicle accelerated past Roland at full load. Figure 2B corresponds to the case where the test vehicle accelerated past Roland at part load. Figure 2C shows the case in which the test vehicle was driven past Roland at a constant velocity with high engine speed and low load. In these figures, the driving conditions of the test vehicle, namely engine speed and calculated percentage load, as well as the concentrations of the desired exhaust constituents at the mouth of Roland were plotted versus time.

Although Figure 2 only shows one typical plot obtained from each driving condition considered, it can be seen that the curves representing instantaneous particulate matter concentration are quite different in each plot. This is because peak concentrations and durations of exposure incidents varied widely from test to test and because truck operation differed from case to case. Wind speed and direction greatly affected the peak concentrations measured and the durations of the exposure incidents by affecting the exhaust travel time from the tailpipe to the sample lines and varying the exhaust dilution and amount of residual entrainment in eddies. The vehicle operator also affected the repeatability of tests due to varied pedal commands and vehicle positioning with respect to the sampling point.

The average incident particulate matter concentrations observed and the corresponding incident durations can be seen in Table 1. The average particulate concentrations measured throughout the full load acceleration tests were 124.97 and 199.16 $\mu g/m^3$ for the adult pedestrian and child in stroller scenarios, respectively. In addition, the average duration of these incidents was determined to be approximately 5.1 and 12.67 seconds, respectively. This implies that on average a pedestrian would be exposed to diesel particulate matter concentrations that are more than three times the National Ambient Air Quality Standard and approach the exposure limit set by the Mine Safety and Health Administration for more than 5 seconds per drive-by incident. However, it would take more than 5,000 of these specific drive-by incidents to approach the same mass of diesel particulate exposure as the MSHA exposure limit. It must be considered, though, that these results were obtained via a simplistic model that represents an in-use minimum vehicle PM expulsion. In reality, a large number of drive-bys would have a more significant effect on exposure because ambient levels of pollutants would build as not all of the pollutants are carried away or dispersed.

The maximum concentrations averaged over 1.5 seconds observed for the adult pedestrian and child in stroller scenarios were 613 and 1,114 $\mu g/m^3$, respectively. These concentrations are 17 and 32 times greater than the NAAQS and 4 and 7 times the MSHA exposure limit. Additionally, the maximum concentrations averaged over 2.5 seconds observed for the adult pedestrian and child in stroller scenarios were 396 and 860 $\mu g/m^3$, respectively. These concentrations are 11 and 25 times greater than the NAAQS and 2 and 5 times the MSHA exposure limit. However, these maximum concentrations were observed for approximately 1.5 and

2.5 seconds which is minuscule compared to the 8 hour average of the MSHA exposure limit. Although it would be difficult to observe a large number of exposures of this type such that it would lead to exposure similar to the MSHA exposure limit, the dose obtained from a single short event such as these may be considerable. This can not be verified, however, because few particulate dose studies on humans have been conducted.

The fact that the test vehicle is a new model vehicle with a catalytic converter must also be taken into consideration. In-use fleet PM emissions vary from vehicle to vehicle. For example, in the E-55/59 California truck emissions inventory program, medium duty trucks were exercised through a transient test cycle, termed MHDTLO, and it was found that a 1990 model year truck emitted PM at a level that was 10.2 times higher than one model year 2000 truck, and 15.3 times higher than another model year 2000 truck [34]. A 1995 truck yielded PM ratios of 4.5 and 6.3 relative to the two model year 2000 trucks [34]. The 2006 truck used in the present study had low mileage, and it is assumed that the PM emissions represent an in-use minimum for vehicles prior to 2007 models with exhaust filtration. It is reasonable to believe that many in-use trucks would yield PM levels substantially higher than those yielded by the 2006 diesel pickup.

Exposure

Breathing rates for men, women, and children both walking slowly and standing still, (see Table 2), were obtained from a study [35] produced by the California Air Resources Board and multiplied by the average incident concentrations. In this way, the mass of diesel particulate matter inhaled per drive-by incident by men, women, and children could be computed. To see if this inhaled amount was significant relative to the amount normally inhaled over a 24 hour period, the daily mass of particulate matter inhaled by pedestrians at different ambient concentrations was calculated. These values can be seen in Table 3.

The measured concentration of particulate matter and the corresponding mass inhaled by an adult male pedestrian both walking and standing for a typical drive-by incident can be seen in Figure 3. The amount of diesel particulate matter inhaled by adults and children after being subjected to 264 average drive-by incidents was calculated and can be seen in Table 3, which also shows the PM mass inhaled daily at ambient levels. It can be seen that in a relatively dirty city, where the ambient pollution level is equivalent to the National Ambient Air Quality Standard, 264 average drive-by incidents can increase the mass inhaled by an adult and a child by as much as 6% and 17%, respectively. In a clean city, however, the same exposure can increase mass inhaled by as much as 42% and 116%, respectively.

In addition to effects of multiple average drive-by incidents on daily inhalation, the effects of per inhalation exposure were considered. For this analysis, incidents from each scenario with the highest particulate concentrations observed were aligned with the inspiration of a breath. To determine if this inhaled mass was significant, it was compared to the calculated mass of PM inhaled per breath at the same ambient conditions mentioned previously. These values are shown in Table 4.

In a relatively dirty city, where the ambient pollution level is equivalent to the National Ambient air Quality Standard, an adult and a child could inhale as much as 12 and 21 times more diesel particulate matter mass, respectively, in a single inhalation during a drive-by incident than at ambient conditions. However, in a relatively clean city, such as Darrington, Washington, an adult and a child could inhale as much as 82 and 149 times more diesel particulate matter mass, respectively, per breath than at ambient conditions. However, without short-term health effects understanding, it is not possible to project the effect of brief, highly elevated PM levels on a roadside pedestrian.

Conclusions

Pedestrians subjected to drive-by incidents by diesel fueled vehicles can be exposed to concentrations of diesel particulate matter significantly higher than regulations allow for brief periods of time (less than 15 seconds). Because the durations of these exposures are so short, the amount of diesel particulate matter inhaled due to repeated drive-by incidents by a clean late-model year vehicle is insignificant compared to the amount inhaled at ambient conditions. With the test vehicle utilized in this study, it would take 1,000 incidents in a 24 hour period to approach the same daily exposure at ambient particulate concentrations equivalent to the NAAQS. Also, it would take 5,000 incidents in an 8 hour period to approach the MSHA exposure limit. However, these numbers are based on a vehicle representative of in-use minimum particulate expulsion and the exposure model does not consider the build up of pollutants over time. Including both of these considerations, exposure to actual in-use vehicles could be orders of magnitude greater than the results obtained in this study. It is therefore recommended that additional research on this topic be conducted to fully quantify the exposure pedestrians may experience due to in-use fleet vehicles and to consider the effect of pollutant build up.

Additionally, during drive-by incidents diesel particulate matter concentrations are higher at heights similar to that of the tailpipe on the passing vehicle. Consequently, small children walking or in strollers are exposed to higher concentrations of particulate matter than adults walking or standing nearby. However, this likely depends on the horizontal distance between the tailpipe and the pedestrians. Based on these results it appears that exposure is likely related to position relative to a vehicle's tailpipe. Thus, it is recommended that additional research on the subject be conducted to consider many other locations where exposure may be increased due to position relative to a vehicle's tailpipe.

Competing interests

The authors have no competing interests related to this research topic.

Authors' contributions

All three authors were responsible for planning the study and interpreting data. The bulk of the data acquisition and processing was conducted by Neil Buzzard. Nigel Clark provided expertise in the vehicle emissions area, while Steven Guffey provided expertise in understanding human exposure to pollutants.

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Figures

Figure 1 – Mannequin and Test Setup

The top photograph shows the emissions measurement equipment and Roland alongside the test road. The bottom photographs show the mannequin's head with sample tubes in the mouth and their attachment to the transport tubing.

Figure 2 – Raw drive-by test data

The raw data from drive-by tests in which the test vehicle was driven past a mannequin are plotted versus time. Plot A represents the case involving accelerating the test vehicle past the sample location at full load. Plot B corresponds to the case where the test vehicle accelerated past the sample location at part load. Plot C shows the case in which the test vehicle was driven past the sample location at a constant speed with high engine speed and almost zero load.

Figure 3 – PM concentration and mass inhaled by a pedestrian for a typical acceleration test

Once the data was acquired following a typical drive-by acceleration test, particle size-mass correlations and human breathing rates were applied to the data. The red line in the figure represents the PM concentration measured at the mannequin's mouth. The light blue line corresponds to the mass inhaled using the breathing rate of an adult walking. The dark blue line represents the mass inhaled using a breathing rate of an adult standing still.

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Tables

Table 1 - Average incident concentrations and corresponding durations

Scenario	Run	Average Incident Concentration (ug/m^3)	Incident Duration (s)
Mannequin	1	87.5	5.4
	2	84.99	6.6
	3	104.82	4.4
	4	227.92	5.8
Stroller	1	364.27	8.6
	2	233.88	6.4
	3	238.72	9.2
	4	245.7	10.8
	5	200.45	15.4
	6	139.86	6.8

Table legend text.

Table 2 - Breathing rates for adults and children (LPM)

	Adult Male	Adult Female	Children
Walking	24	20	14
Standing	11	8	7

Table legend text.

Table 3 - Mass inhaled from 264 drive-by incidents and daily inhalation at ambient levels (µg).

Scenario	Drive-by		NAAQS		Darrington, WA	
Mannequin	**Adult Male**	**Adult Female**	**Adult Male**	**Adult Female**	**Adult Male**	**Adult Female**
Walking	72.58	60.49	1209.60	1008.00	172.80	144.00
Standing	33.27	24.19	554.40	403.20	79.20	57.60
Stroller	**Child**		**Child**		**Child**	
Walking	116.55		705.60		100.80	
Standing	58.27		352.80		50.40	

Table legend text.

Table 4 - Maximum mass inhaled per breath during worst drive-by and at ambient levels (µg).

Scenario	Drive-by		NAAQS		Darrington, WA	
Mannequin	**Adult Male**	**Adult Female**	**Adult Male**	**Adult Female**	**Adult Male**	**Adult Female**
Walking	0.1583	0.1317	0.0350	0.0291	0.0050	0.0042
Standing	0.1123	0.0818	0.0096	0.0070	0.0014	0.0010
Stroller	**Child**		**Child**		**Child**	
Walking	0.2293		0.0233		0.0033	
Standing	0.1300		0.0061		0.0009	

Table legend text

Figure 1

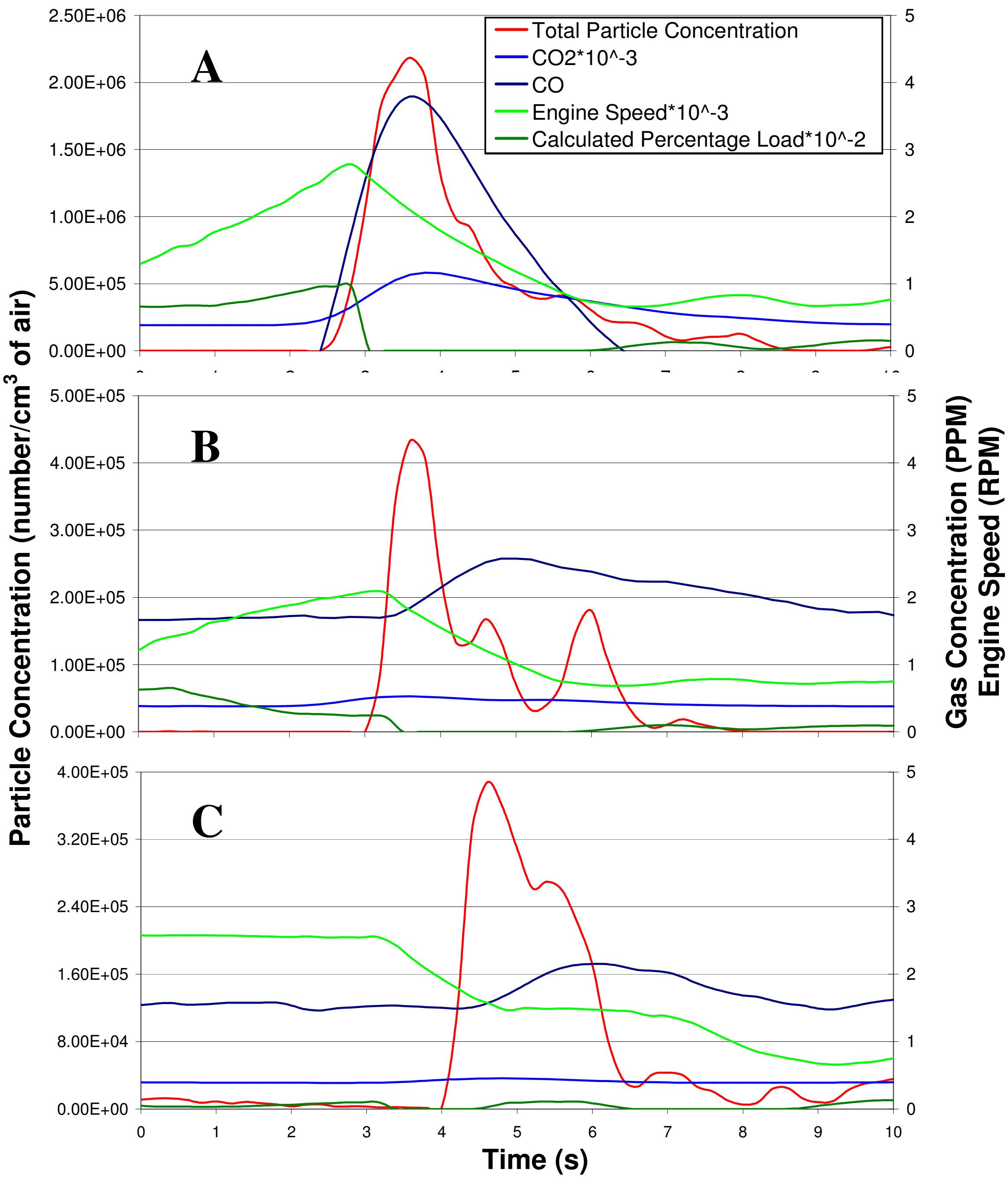
A
B
C
Total Particle Concentration
CO2*10^-3
CO
Engine Speed*10^-3
Calculated Percentage Load*10^-2
2.50E+06
2.00E+06
1.50E+06
1.00E+06
5.00E+05
0.00E+00
5.00E+05
4.00E+05
3.00E+05
2.00E+05
1.00E+05
0.00E+00
4.00E+05
3.20E+05
2.40E+05
1.60E+05
8.00E+04
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Particle Concentration (number/cm3 of air)
Gas Concentration (PPM)
Engine Speed (RPM)
Time (s)

Figure 2

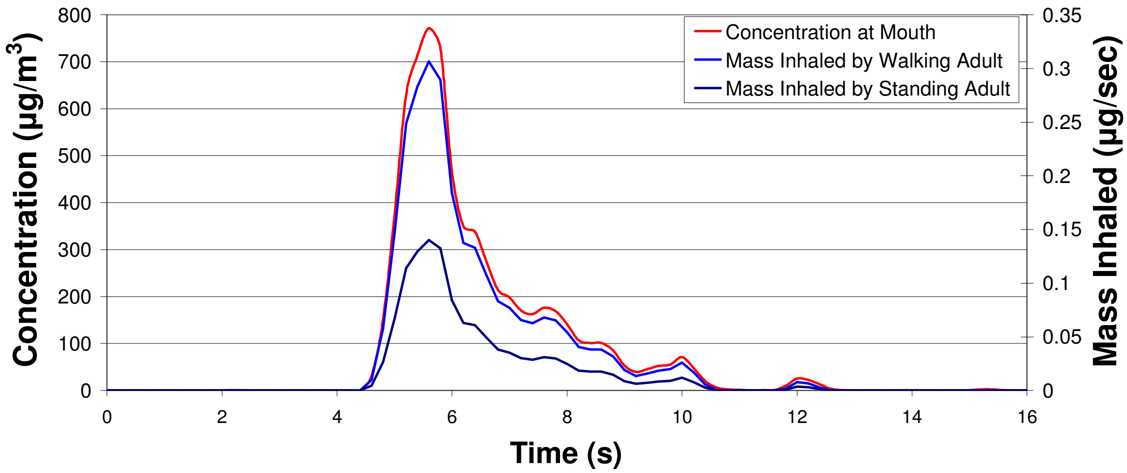
Concentration at Mouth
Mass Inhaled by Walking Adult
Mass Inhaled by Standing Adult
Concentration (µg/m³)
Mass Inhaled (µg/sec)
Time (s)
800
700
600
500
400
300
200
100
0
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
12
14
16

Figure 3