(REVISION)

Assessment of Possible Worst-case NO_2 Exposure Scenarios Related to Catalyst-based Diesel Trap Aftertreatment

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BACKGROUND

Problem Statement

Measurements of emissions from heavy-duty diesel vehicles (HDDVs) equipped with catalyst-based diesel particle filters (CB-DPFs) show an increase in nitrogen dioxide (NO_2) emissions while total emission of oxides of nitrogen (NO_X) remain approximately constant. In the atmosphere, NO_X emissions emitted primarily as nitric oxide (NO) are oxidized to NO_2 by sunlight-induced reactions of volatile organic compounds (VOC) and then lead to formation of ozone, nitric acid, and ammonium nitrate ("secondary" PM, a major component of PM2.5 in California). For CB-DPF-equipped vehicles, the fraction of NO_X that is emitted as NO_2 is higher, accelerating this process. However, this photochemical "acceleration" can be offset by the 90% VOC reductions measured for CB-DPF-equipped vehicles. Photochemical modeling conducted for southern California (Dabdub et al., 2004; McNerny, 2001; DaMassa, 2002) and central California (McNerny, 2001; DaMassa, 2002) indicate the VOC reductions balance the NO_2 increases for NO_2 fractions of 20% (that is, 20% of the NO_X emitted by a trap-equipped vehicle is emitted in the form of NO_2). This limit is independent of vehicle/engine type, but it is based on an assumption of 90% penetration of DPFs. NO_2 fractions greater than 20% will increase ozone and secondary PM2.5 in the populated areas of California that already exceed state and national ambient air quality standards. These results led the Air Resources Board to adopt an NO_2 fraction up to 20% as an absolute emission limit in 2002. Last year, a three-year delay was given to the retrofit manufacturers in recognition of their difficulties in meeting the goal (requirement), technical issues with the limit, and the high need for the significant reductions offered by the DPFs of emissions of diesel particulate matter (DPM), a known toxic air contaminant and a major contributor to California's PM-related health and visibility problems (Lloyd and Cackette, 2001).

This 20% limit is now being re-considered due to the continuing technological limits encountered by trap manufacturers, and a 30% incremental limit has been proposed. For the purposed evaluation, this will be assumed to equal a 40% absolute limit (30% incremental limit plus approximately 10% engine-out NO_2, emissions).

While the prior analyses (Dabdub et al., 2004; McNerny, 2001; DaMassa, 2002) concluded that even future, large-scale (90%) penetration of compliant CB-DPFs would not cause violations of state and national ambient air quality standards for NO_2 – primarily due to large NO_X emission reductions expected over the next decade – these investigations only looked at the regional scale and not microenvironments that potentially cause the highest NO_2 exposures. The measurement-based exposure investigation of worst-case microenvironments presented here is conducted to complement a microscale modeling exercise (Servin, 2004) and investigates the impacts of both current technology and assumed compliant HDDVs on NO_2 levels. The previous assumption of 90% penetration has also been revised in favor of a more realistically scenario that involves use of a mix of technology and an estimated DPF penetration of 50%.

NO_2 and PM Health Effects

Epidemiological studies of the health effects of ambient air pollution report statistically significant associations between NO_2 exposure and adverse health effects including, respiratory symptoms, cardiorespiratory hospital admissions, reduced lung function, and mortality. A discussion is offered by our group in Dabdub et al. (2004). Evidence from controlled human exposure studies of healthy subjects generally suggests little effect on pulmonary function and respiratory symptoms at NO_2 concentrations up to several times typical ambient levels. However, several recent papers on responses of asthmatics to NO_2 exposure suggest that NO_2 might enhance responsiveness to allergen challenge at concentrations near the current California ambient air quality standard.

In contrast, epidemiological studies consistently report statistically significant associations between both short and long-term PM exposure and increased mortality; increased hospital admissions, particularly for heart and/or lung related causes; increased respiratory infections, such as influenza and bronchitis; exacerbation of asthma; reduced lung function; and increased respiratory symptoms. Although PM is quite diverse in terms of particle size, chemical composition, and mix of chemical species among different areas based on the mix of local sources, similar associations are found across the U.S., Canada, Europe, and Asia (Dabdub et al., 2004).

While it is not possible to conduct a quantitative risk assessment evaluating NO_2 increases against DPM reductions, DPM-related health effects are generally considered more severe, leading to nearly 2000 deaths in California at population-weighted exposure of 1.8 $\mu g/m^3$ estimated for the year 2000, as well as significant morbidity effects (Lloyd and Cackette, 2001).

Exposure Scenarios Evaluated

In this evaluation of potentially high NO_2 exposures related to the use of CB-DPFs, three scenarios with potential for high exposure were considered, including the possibility of the simultaneous occurrence of the three, although under less extreme conditions, as will be described. These three scenarios were:

(1) Driving on the 710S Freeway (segment from Long Beach to the 5 Freeway, the busiest truck corridor in California) assuming high numbers of trap-equipped HDDVs (based on ARB on-road NO/NO_2 measurements made on the 710 Freeway [Westerdahl et al., 2004]);

(2) Riding in a trap-equipped diesel school bus, with re-entrainment of a fraction of the bus's own exhaust into the cabin ("self pollution") (based on measurements from the ARB School Bus Study [Fitz et al., 2003; Behrentz et al., 2004a,b; Sabin et al., 2005]).

(3) Closely following a trap-equipped diesel school bus in stop-and-go traffic (based on tracer gas measurements from the recent ARB-funded study, "Evaluation of Mechanisms of Exhaust Intrusion into School Buses and Feasible Mitigation Measures"). These measurements were conducted during real-world driving of buses closely following one another. Comparisons were also made with the studies of Brown et al. (2000) and Kittelson et al. (1988), investigating real-world dilution rates of tractor trailers.

Scenarios (2) and (3) can occur at the present time, while Scenario (1) will depend on the future fleet penetration of the trap technology. Figure 1 illustrates the basic principle of the simple exposure model used in this analysis. Current ambient (background) NO_2 concentrations are reflected in the measurements used in the Scenario 1 calculations, but would have an additive effect on the concentrations calculated in Scenarios 2 and 3.

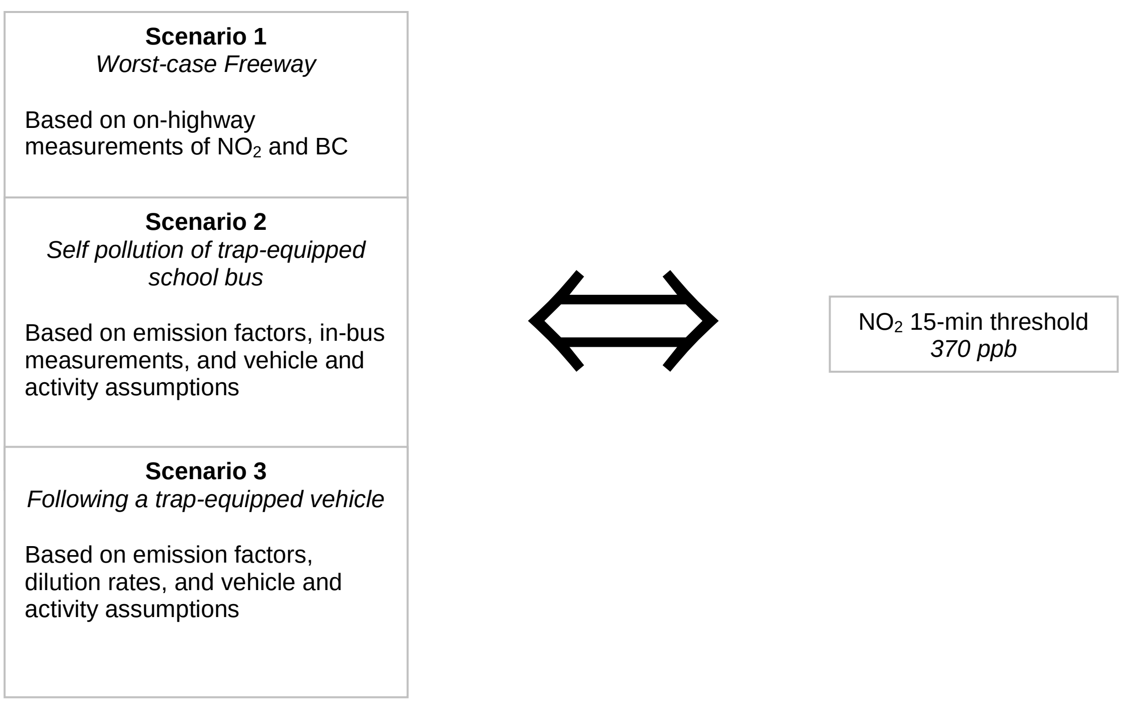

Figure 1. Exposure Scenario Evaluation

For each of these individual exposure scenarios, “extreme” (~90th percentile) concentrations, emission rates, or conditions were used. In addition, the post-trap NO_2 fractions were assumed in the extreme case to be 70% of the total NO_X when operated with ultra-low sulfur diesel fuel (10 to 50 ppm) and catalyst inlet temperatures between 275 and 325 degrees Celsius (Warren et al., 1998). The high case is assumed to be 50% of the total NO_X. This case is reflective of in-use levels measured over rigorous driving cycles (Ayala et al., 2002). The other NO_2 fractions were based on the proposed 40% and 30% NO_2 fraction limits for 2007 and 2009, respectively, and the current 20% limit.

A worst-case, combined scenario was created by the concurrence of these three events. However, the likelihood of these three scenarios occurring at 90th percentile is extremely small. Therefore, 50th percentile concentrations (labeled “high” due to the high exposure conditions) were chosen to be a more realistic value for the worst-case, combined scenario.

The higher NO_2 levels evaluated in this exercise are a result of CB-DPF use. Thus, simultaneous reductions in total DPM emissions on the order of 85% and concurrent reduction in DPM exposures were also incorporated.

The three scenarios above are considered the worst-case exposures to the public as emissions from workplace HDDVs such as refuse trucks or construction equipment undergo more dilution before exposing the public compared to emissions from closely-followed HDDVs which undergo less dilution before reaching vehicle occupants, especially at low speeds and short following distances. HDDV idling scenarios were not considered as California has regulations in place to limit idling from school buses and other HDDV. Occupational exposures were not considered as these are situations are governed by other agencies, regulatory programs, and health-based standards in California.

The 250 ppb hourly NO_2 California standard was assumed to be the threshold target for health effects. However, a time period of 15 minutes was assumed to be a more reasonable duration of exposure under the three scenarios described above. This is because vehicles usually do not exclusively follow each other for long periods of time, and the 710S freeway segment is itself only 16 miles long. Outside of this freeway segment, HDDV traffic is much reduced and, consequently, NO_X concentrations are lower. The hourly 250 ppb standard was extrapolated to a higher concentration (370 ppb) corresponding to the shorter averaging time as described in a later next section.

The analyses discussed in this paper yield the results illustrated in Figures 2 and 3. The deployment of CB-DPFs into the fleet results in increased emissions of NO_2 and a corresponding increase in personal exposure (Figure 2). However, there are simultaneous benefits of significant reductions in emitted DPM and resulting lower exposures (Figure 3). Throughout this document, these exposure reductions are presented in both DPM and black carbon (BC) concentrations because in several studies, DPM concentrations were derived from BC measurements. A detailed discussion regarding this conversion is given in Fruin et al., (2003).

SUMMARY OF RESULTS

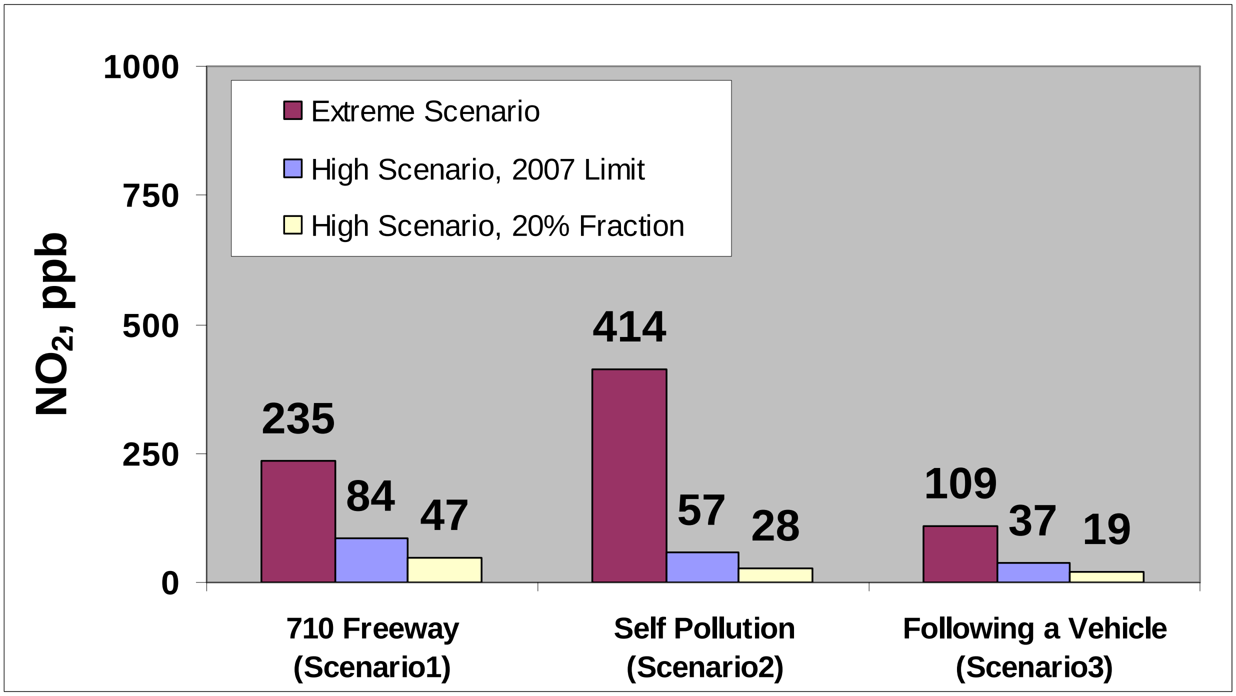

Figure 2. NO_2 concentrations in worst-case scenarios.

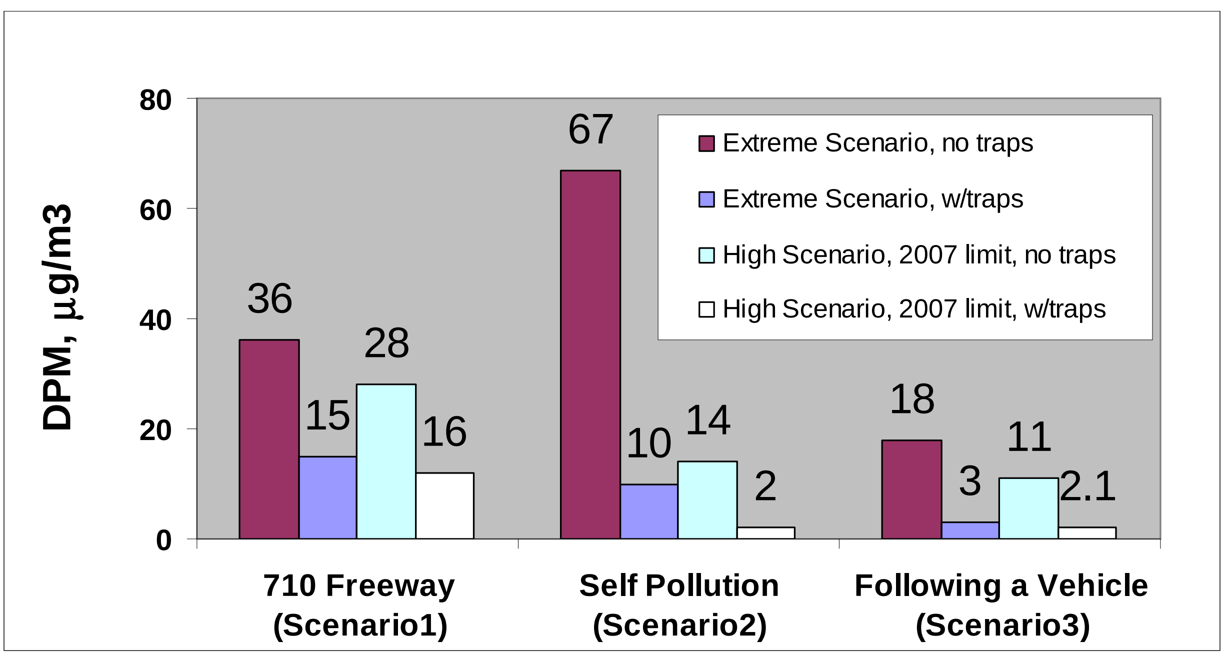

Figure 3. DPM concentrations in worst-case scenarios, with and without CB-DPFs.

CALCULATIONS

NO_2 Concentration Threshold

To estimate equivalent concentrations to the 250 ppb hourly standard for different averaging times, a power law relationship was used. This relationship was based on a modification of Haber's Law (where the product of constant concentration and time is assumed to elicit the same health effect). This assumption was used by the California Office of Environmental Health Hazard Assessment (OEHHA) to calculate toxic air pollutant standards as described in their document "The Determination of Acute Reference Exposure Levels for Airborne Toxicants" (OEHHA, 1999). OEHHA used the equation:

$$(\text{Conc})^n \text{ X Averaging Time = Constant} \qquad \text{(ten Berge et al., 1986)}$$

where the exponent *n* ranged from 0.8 to 3.5, depending on the compound and the averaging time (ten Berge et al., 1986). Based on the animal NO_2 exposure studies of Hine et al. (1970), ten Berge et al. assigned a value of 3.5 to the exponent *n* for NO_2. Based on the above equation, the 15-minute threshold NO_2 concentration corresponding to 250 ppb for one hour is **370** ppb. (This value is more conservative [lower] than if the default OEHHA value for *n* of 2 is used, which would give 500 ppb.)

Scenario 1 - Worst-Case Freeway NO_2 Scenarios

The highest possible roadway NO_2 concentrations in California were assumed to occur on the 710S Freeway, with the highest diesel truck traffic volumes in Los Angeles. NO_2 concentrations were assumed to increase if significant fractions of the diesel trucks were equipped with CB-DPFs, while overall NO_X emissions from these trucks were assumed to remain unchanged.

Baseline NO and NO_X concentrations were determined from recent on-road measurements. In Spring 2003, NO_X, NO, and NO_2 concentrations were measured on four different days (Westerdahl et al., 2004). NO concentrations were 410 ± 130 ppb, NO_X concentrations were 470 ± 150, and NO_2 averaged 15% of total NO_X. The highest segment-average NO concentration was 570 ppb, and NO_X concentrations for this day were 670 ppb. The conditions are illustrated in Table 1.

Table 1. Elements of Scenario 1 - Worst-Case Freeway NO_2 Levels

SCENARIO	NO_X Concentrations	Trap Penetration Rates	Trap-Equipped Fleet Average NO_2 Fraction	Freeway Concentrations
Extreme conditions	670 ppb (highest daily 710S average)	50%	70%	670 ppb NO_X x 70% NO_2 fraction x 50% penetration =**235** ppb NO_2
High conditions, new 2007 limit	470 ppb (average of 710S for four days)	50%	40%	470 ppb NO_X x 40% NO_2 fraction x 50% penetration = **94** ppb NO_2
High conditions, new 2009 limit	470 ppb (average of 710S for four days)	50%	30%	470 ppb NO_X x 30% NO_2 fraction x 50% penetration = **71** ppb NO_2
High conditions, current limit	470 ppb (average of 710S for four days)	50%	20%	470 ppb NO_X x 20% NO_2 fraction x 50% penetration = **47** ppb NO_2

Table 2. Estimated DPM Reductions due to Traps, Scenario 1

Scenario 1 - DPM Exposure Reduction due to Traps on Worst-Case Freeway

SCENARIO	BC Concentrations	DPM Concentrations	Trap Penetration Rates	Trap Efficiency	Freeway DPM Reductions
Extreme conditions	17.5 µg/m³ BC (highest daily average for 710S)	**35.7** µg/m³ DPM (highest daily average for 710S)	50%	85%	35.7 µg/m³ x 50% penetration x 85% removal = **15** µg/m³ DPM
High conditions, new 2007 limit	13.8 µg/m³ BC (average of four days for 710S)	**28.2** µg/m³ DPM (average of four days for 710S)	50%	85%	28.2 µg/m³ times 50% penetration x 85% removal = **12** µg/m³ DPM
High conditions, new 2009 limit	13.8 µg/m³ BC (average of four days for 710S)	**28.2** µg/m³ DPM (average of four days for 710S)	50%	85%	**12** µg/m³ DPM
High conditions, current limit	13.8 µg/m³ BC (average of four days for 710S)	**28.2** µg/m³ DPM (average of four days for 710S)	50%	85%	**12** µg/m³ DPM

The deployment of CB-DPFs, which result in increased tailpipe NO_2 emissions, concurrently result in reduced emission of and exposures to DPM. The magnitude of the reductions, illustrated in Table 2, was based on Aethalometer measurements of black carbon (BC) made during the study by Westerdahl et al. (2004). To convert these BC concentrations, a factor of 2.04 was used, the same value as used in the ARB Toxic Air Contaminant Identification Document (ARB, 1998). This is a reasonable value, based on evaluating elemental carbon (EC) fractions in diesel engines as a function of load, and the Aethalometer response to EC (Fruin et al., 2004). However, it is acknowledged that EC emissions from HD engines display a strong dependence on duty cycle (ARB, 2004), but such consideration is beyond the scope of the present exercise.

Scenario 2 - Worst-Case School Bus NO_2 Self Pollution Scenarios

Self pollution has been shown to be an important contributor to pollutant concentrations on board school buses in a study conducted for ARB (Fitz et al., 1998; Behrentz et al., 2004a,b; Sabin et al., 2004). Self pollution appears to be worse when windows are closed and generally increases with the age of the bus. Unfortunately, in general older diesel engines (~1993 and older) are not good candidates for the CB-DPFs because of their relatively high PM emissions, which tend to overwhelm the filters.

Intrusion Rates

ARB's school bus study found the following fractions of exhaust making it back into the bus cabin based on measurements of an inert tracer gas added to the bus exhaust (Behrentz et al., 2004; Fitz et al., 2003) during closed window conditions:

Table 3. Intrusion Rates from ARB's School Bus Study

Model Year	Rate of Intrusion
1975	0.29%
1985	0.13%
1993	0.02%
1998	0.04% (trap-equipped bus)
2002	0.04% (CNG bus)

Based on these figures, we assumed "high" and "extreme" intrusion rates of 0.04% and 0.10%, respectively.

NO_2 Emission Rates and Concentrations in Exhaust and Cabin

NO_X emission rates are taken from the available literature and are assumed, for the extreme case, to be levels as measured over a rigorous driving cycles such as the New York Bus Cycle (NYBC). In the case of "high" emission rates, those are assumed to be levels representative of heavy-duty engine emissions over the certification cycle (UDDS) (Ayala et al., 2002).

Assuming a nominal 9000 liters per minute of exhaust produced by a heavy-duty engine (8.3 L, 4-stroke, turbocharged operating at 1500 rpm) as done in the school bus study (Fitz et al., 2003) over a duty cycle like the Central Business District (which is 2 miles long and lasts 10 minutes):

Table 4. Scenario 2 – Self Pollution

SCENARIO	NO_2 Emission Rates	NO_2 Concentrations in Exhaust	In-cabin Concentration
Extreme conditions	50 g NO_X/mile x 70% = 35 g NO_2/mile	(35 g NO_2/mile x 2 miles) / (10 minutes x 9000 lpm) = 0.0008 g NO_2/liter = 777,000 µg/m^3 = 414,000 ppb NO_2	0.10% x 414,000 = **414** ppb
High conditions, new 2007 limit	30 g NO_X/mile x 40% = 12 g NO_2/mile	(12 x 2)/(10 x 9000) = 267,000 µg/m3 = 142,000 ppb NO_2	0.04% x 142,000 = **57** ppb
High conditions, new 2009 limit	30 g NO_X/mile x 30% = 9 g NO_2/mile	(9 x 2)/(10 x 9000) = 200,000 µg/m3 = 107,000 ppb NO_2	0.04% x 107,000 = **43** ppb
High conditions, current limit	30 g NO_X/mile x 20% = 6 g NO_2/mile	(6 x 2)/(10 x 9000) = 133,000 µg/m3 = 70,600 ppb NO_2	0.04% x 70,600 = **28** ppb

Scenario 2 - DPM Exposure Reductions due to Traps on School Buses

The use of CB-DPFs in the scenario described above would result in reductions of PM emissions and a corresponding reduction in the DPM exposures due to self pollution.

PM emission rates were taken from the latest heavy-duty truck emissions research (CRC Project E-55). Admittedly, bus engines are designed to meet more stringent emission standards than truck engines and the available research literature supports this assertion for in-use bus emissions. However, because the California school bus fleet still includes a significant number of older mid-1980 engines and because the E-55 dataset is the most comprehensive to date, it is reasonable to consider those emission factors in the context of this exercise. PM show strong reductions as model year advances (Clark et al., 2003). Over transient operation, the extreme case corresponding to the 90^{th} percentile results in emissions of 3 g of PM/mile. In the case of high emissions, the E-55 study suggests emissions of 1.8 g of PM/mile. Assuming the same engine parameters and operating conditions as those used above to calculate in-cabin concentrations for NO_X yields the following results:

Table 5. Estimated Self-Pollution DPM Reductions in Scenario 2

	Intrusion Rates	DPM Emission Rates	DPM Concentration in Exhaust	In-Cabin Concentration due to Self-Pollution	Reductions in On-Board Concentrations due to Traps
Extreme Conditions	0.10 %	3 g PM/mile	(3 g PM/mile x 2 miles) / (10 minutes x 9000 lpm) =0.0000667g PM/liter = 66,700 µg/m³ DPM	0.10% x 66,700 µg/m3 = **67** µg/m³ DPM	67 x 85% = 57 µg/m³ DPM= **28** µg/m³ BC
Current 2007 Limit	0.035%	1.8 g PM/mile	(1.8 x 2) / (10 x 9000) = 40,000 µg/m³ DPM	0.04% x 40,000 µg/m3 = **14** µg/m³ DPM	14 x 85% = 12 µg/m³ DPM= **6** µg/m³ BC
Current 2009 Limit	0.035%	1.8 g PM/mile	40,000 µg/m³ DPM	**14** µg/m³ DPM	**6** µg/m³ BC
Current Limit	0.035%	1.8 g PM/mile	40,000 µg/m³ DPM	**14** µg/m³ DPM	**6** µg/m³ BC

For comparison, the ARB School Bus Study average in-cabin concentration for the uncontrolled diesel buses with windows closed was 12.5 µg/m³ BC, which reflects both self-pollution and roadway concentrations.

Scenario 3 - Worst-Case Followed Vehicle NO_2 Exposure Scenarios

Driving at low speeds with accelerations (stop-and-go traffic) during times of little or no wind is a worst-case scenario for high exposures to emissions from surrounding vehicles and, particularly, from the vehicle being followed. Reduced dilution occurs due to reduced air speeds around the vehicle and reduced turbulent mixing; higher emissions occur due to accelerations from stops or low speeds.

The worst type of diesel vehicle to follow is a low-exhaust diesel vehicle, i.e., either a delivery truck or school bus (Fruin et al., 2004). Significantly greater BC concentrations were measured inside vehicles following diesel vehicles with low exhaust pipe locations, which are typically located at the rear or the center of the vehicle, compared to vehicles with high exhaust locations like tractor-trailer combinations, which have exhaust pipes near the front of the vehicle (Fruin et al., 2004).

Since the last analysis of 9/28/05, real-world measurements have become available for estimating school bus exhaust emission dilution using tracer gas measurements. These data were available as part of the ARB-funded, follow-up school bus study (final report due out August 2006). In this case, SF_6 (sulfur hexafluoride) tracer gas was released from the tail pipe of a school bus, in proportion to engine intake air volumes, in order to achieve relatively constant tracer gas concentrations in the exhaust. (Constant tracer gas concentration in the exhaust was necessary to accurately determine the percent of the bus's exhaust penetrating into the follower bus cabin.) Another school bus followed

behind, measuring tracer gas concentrations inside the cabin. Thus, dilution ratios calculated from these tests are a good estimation of exhaust dilution experienced during real-world driving (for school buses). Tests were conducted over a 10-mile, square loop, in Riverside, CA, on the afternoon of April 19, 2005.
The lowest dilution of exhaust appeared to occur in two situations: first, when buses were accelerating from a stop while initiating a right turn, with winds shifting from cross winds to tail winds; and second, when the buses were going uphill. The highest five tracer gas concentrations for two run conditions (open windows or closed windows) were determined, and the average dilution rates for time intervals containing these conditions (1, 5 and 15 minutes) were calculated. These are shown in Figure 3.

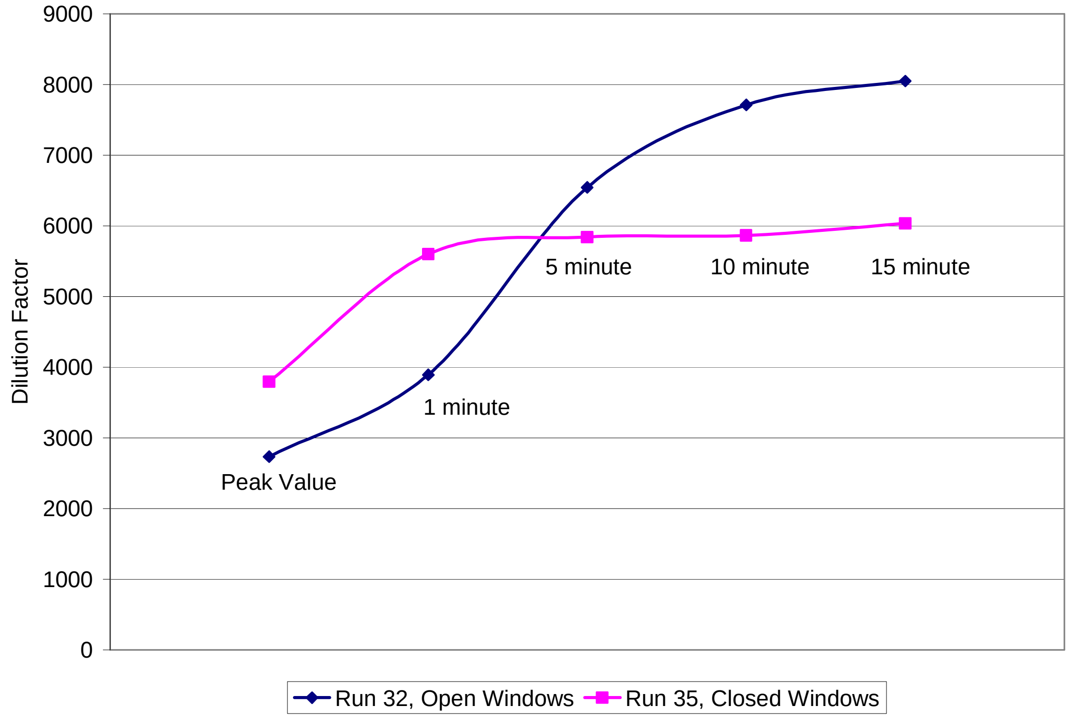

Figure 3. Dilution factors from SF_6 Tracer Gas Measurements from a Leader-Follower School Bus Tests

The longer the averaging time, the greater the average dilution, as the worst case mixing appeared to involve short-lived conditions such as hard accelerations and/or close spacing. The single-worst (lowest) 1, 5, and 15 minute dilution from these experiments (for both open and closed windows) were 3800, 5600, and 5800, respectively. To account for the presence of winds during these tests (3 to 4 meter per second), which would enhance dilution, we chose to use the lowest one-minute average dilution of 3800, as this is a reasonably conservative, lower-limit dilution of conditions that could probably not be maintained for 15 consecutive minutes in real driving.

The reason for the large increase in dilution over the previously-used, numerical modeling estimates of dilution from Chan et al. (2001) (before actual measurements were available) comes from the effect of the following bus not receiving exhaust at only centerline concentrations, but rather from a range of distances from the exhaust centerline; this drastically increases dilution.

Comparing to the only previous studies found to have measured actual dilution of exhaust plumes in real driving, Kittelson et al. (1988) as cited in Brown et al. (2000) measured dilution rates of 1000 about 30 meters from the stack of a tractor-trailing at 50 to 55 mph, up to a dilution factor of about 2500 at 100 meters from the truck stack. Dilution rate was found to increase linearly with distance until the turbulent wake of the vehicle, where an extra three-fold dilution occurred. Again, the effect of measuring along a plume centerline significantly lowered the measured dilution of the tractor-trailer plume compared to the average dilution that would occur over a larger cross-sectional area, so these measured dilutions are in general agreement with our measurements.

Table 6 presents the estimated NO_2 concentrations from closely following a trap-equipped school bus.

Table 6. Scenario 3 – Following Trap-Equipped Vehicle

	NO_2 Concentrations in Exhaust (Same as Scenario 2)	**In-cabin Concentration**
Extreme Conditions	425,000 ppb NO_2	414,000 ppb/ 3800 = **109** ppb NO_2
Current 2007 Limit	142,000 ppb NO_2	142,000 / 3800 = **37** ppb NO_2
Current 2009 Limit	107,000 ppb NO_2	107,000 / 3800 = **28** ppb NO_2
Current Limit	70,600 ppb NO_2	70,600 / 3800 = **19** ppb NO_2

For comparison, the only direct measurements of NO_2 concentrations of a CB-DPF-equipped vehicle (at close range) available were the measurements of Allansson et al. (1999). In this work, Allansson et al. measured NO_2 near an idling truck with a low exhaust pipe. Fourteen 1-, 10-, and 30-second NO_2 measurements 1 meter downwind of the exhaust were made. The maximum 30-second concentration was 1250 ppb. Maximum concentrations decreased with increasing averaging time. Other direct measurements were collected in the most recently funded ARB school bus study as discussed above.

To estimate a maximum 15-minute concentration, the maximum concentrations for 1, 10, and 30 seconds were plotted and extrapolated to 15 minutes, as shown in Figure 4.

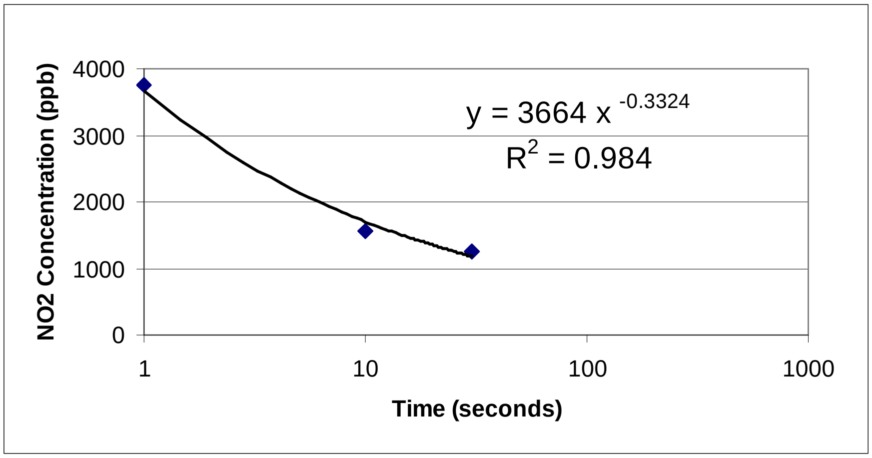

Figure 4. Maximum NO_2 Concentration versus Time for Near-Field Idling Tests

The 15-minute concentration extrapolated from the equation above is 380 ppb, near the 370 ppb standard derived for 15 minutes. However, this 380 ppb figure is quite uncertain, not only from the extrapolation made above, but also because this study did not include accelerations or calm wind conditions. Finally, the NO_2 emission rates for this vehicle were not given, so it is also unknown how the vehicle studied compares to typical school bus emissions.

Scenario 3 - DPM Exposure Reductions due to Traps on Followed Vehicle

Like the followed-vehicle NO_2 exposure scenario, the DPM concentrations and exposure reductions due to traps are inversely proportional to dilution rates. These are presented in Table 7.

Table 7. Estimated Followed-Vehicle DPM Reductions for Scenario 3

	DPM Emission Rates (same as scenario 2)	DPM Concentration in Exhaust	Following Vehicle In-cabin Concentration	Reductions in On-Board Concentrations due to Traps
Extreme Conditions	3 g PM/mile	(3 g PM/mile x 2 miles)/(10 minutes x 9000 lpm) = 0.0000667g PM/liter = 66,700 µg/m³ DPM	66,700 / 3800 = **18** µg/m³ DPM	18 x 85% = 15 µg/m³ DPM= **7.5** µg/m³ BC
Current 2007 Limit	1.8 g PM/mile	(1.8 x 2)/(10 x 9000) = 40,000 µg/m³ DPM	40,000 / 3800 = **11** µg/m³ DPM	11 x 85% = 8.9 µg/m³ DPM= **4.4** µg/m³ BC
Current 2009 Limit	1.8 g PM/mile	40,000 µg/m³ DPM	**11** µg/m³ DPM	**4.4** µg/m³ BC
Current Limit	1.8 g PM/mile	40,000 µg/m³ DPM	**11** µg/m³ DPM	**4.4** µg/m³ BC

CONCLUSIONS

The one-hour NO_2 California standard of 250 ppb was converted to a 15-minute threshold of 370 ppb to facilitate the evaluation of shorter and more likely high exposure traffic conditions that could occur on a California freeway.

Table 7 below presents estimated NO_2 concentrations for the worse-case, combined scenario (simultaneous occurrence of the three "high" exposure scenario conditions). For the case of traps meeting the soon-to-be-proposed limit of a 40% NO_2 fraction (30% incremental fraction assumed over a 10% engine-out baseline), the 370 ppb limit does not appear to be exceeded.

	In-Cabin NO_2 Concentration for Worse-Case Combined Scenario (Combination of Scenarios 1-3)
Current 2007 Limit	188 ppb
Current 2009 Limit	142 ppb
Current Limit	94 ppb

In the cases of individual "high" exposure conditions for non-compliant CB-DPFs, where the NO_2 to NO_X fractions were assumed to be a more realistic 30% or 40%, as proposed for 2009 and 2007, respectively, and the fleet penetration of the CB-DPF technology was a less ambitious 50%, the 370 ppb standard does not appear to be exceeded by any of the NO_2 limits. However, results from this analysis suggest that the NO_2 threshold may be violated for the "extreme" bus self-pollution scenario at a high NO_x-per-mile emission rate and a 70% NO_2 fraction.

The same situations that resulted in increased NO_2 exposures concurrently yielded significant reductions in exposures to DPM. Neither of these issues should be considered in isolation. DPM is a toxic air contaminant in California and the importance of reductions in DPM exposures are clearly a high agency priority, as delineated in California's Diesel Risk Reduction Plan. While a quantitative assessment of the relative importance of increased NO_2 exposure in the context of simultaneous reduced DPM exposure is not possible, it is understood that most of the air pollution-related health effects in California are due to high levels of PM2.5 and PM10, including DPM.

This analysis concludes that compliance with the anticipated NO_2 fraction emission limit of 40% for 2007, based on preventing increases in ozone and secondary PM2.5, would also *prevent exceedances of the current California 1-hour NO_2 ambient air quality standard, even under worst-case exposure scenarios.* When compliant HDDVs become available, we suggest additional and targeted on-road studies to continue to monitor the performance of the technology and to measure NO_2 exposures for real-world driving in congested traffic.

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