# Motorists' Exposure to Traffic-Related Air Pollution: Modeling the Effects of Traffic Characteristics

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Submitted to the 90th Annual Meeting of the Transportation Research Board, January 2011, Washington, D.C.

July 2010

7,355 words [4,605 + 2 table x250 + 9 figures x250]

**ABSTRACT**
This paper proposes a road-user exposure model that is a function of fundamental traffic characteristics. The model is then applied to a 14-mile congested corridor in Portland, Oregon using real-world traffic data. The modeling results show a wide range of exposures through the corridor over the course of a day and suggest that traffic congestion increases motorists' exposure to traffic-related pollution. Large peak-period trip exposures are primarily the result of increased exposure durations due to longer travel times. Roadway exposure concentrations (and temporal inhalation rates) also increase during peak periods due to heavy traffic flows and increased marginal emissions rates (though the direct effects of traffic speed on exposure concentrations were small for the case studied). Traffic-induced dispersion increases with higher flows – slightly offsetting the increased roadway emissions during heavy traffic flow. It should be noted that while travel time is the dominant factor in high peak-period exposure, long travel times are driven by traffic characteristics. From a roadway perspective, these results suggest that exposure mitigation should focus on reducing the time spent in the roadway and reducing the volume flow of vehicles on the roadway – while recognizing that these are intertwined travel behaviors. In particular, traveler delay time is less deleterious when spent on low-flow sections than high-flow sections. Finally, individual travelers can greatly reduce their roadway exposure by adjusting their departure time to less congested, lower volume periods.

## INTRODUCTION

Roadway congestion is increasing, and various efforts are underway to reduce its negative impacts (*1*, *2*). Urban freeways carry most of the congestion in the U.S., which has increased more than 50% over the past decade (*2*). Heavy congestion can increase motor vehicle emissions of air pollutants (*3*), which progressively degrade urban air quality (*4*). Because of coincident vehicle and human activity, exposure to traffic-related air pollution increases with urbanization (*5*). Air pollution in general has been shown to adversely affect human health (*6*), and exposure to traffic-related pollution in particular is associated with many negative health outcomes (though most causal links are still not conclusive) (*7*). The transportation microenvironment is an important activity zone as residents of many developed countries spend, on average, more than one hour per day in motor vehicles (*8*). While increasing levels of urban congestion have been well documented, the effects of congestion on road users' exposure to pollution have not.

Literature reviews by Kaur, Nieuwenhuijsen, & Colvile (*9*) and Han & Naeher (*10*) show broad variations in measured pollutant concentrations in different transportation microenvironments. Most past research on road-user exposure is empirical and aggregate because isolating the contributions of individual factors (such as congested traffic characteristics) is difficult and requires a diverse array of measuring equipment. Large-scale exposure models treat journeys as single, static microenvironments, though recent efforts have attempted to model exposure during travel in more detail (*8*). More detailed models estimate journey exposure using time-weighted averages of air quality concentrations in various sub-microenvironments (i.e. segments of a trip). Modeling of exposure in transportation microenvironments allows experimental control but requires integration of traffic, emissions, air quality, and activity models with significant input data.

In light of the health risks posed by human exposure to traffic-related air pollution, this research attempts to model the effects of congested freeway traffic on motorists' exposure. The central hypothesis tested in this research is that freeway congestion increases drivers' inhalation of traffic-related pollution. The main contribution of this research is a proposed road-user exposure model that is a function of fundamental traffic state characteristics. The proposed model is estimated and applied for travelers on a freeway in Portland, Oregon. The focus of this research is to enhance our understanding of the impacts of traffic characteristics on travelers' exposure. The precise estimation of exposure concentrations or mass inhalation rates is outside the scope of this research. This modeling is one step in a larger study effort to quantify the impacts of traffic characteristics on emissions, air quality, and exposure.

## MODELING ROADWAY EXPOSURE

The modeling approach agglomerates sub-microenvironments of roadway segments (i.e. "links") for a trip on a freeway corridor (which is itself part of a longer journey). The major components included in the model are traffic state (speed and flow), roadway emissions, travel speed, pollutant dispersion, and breathing rate (see Figure 1). The endogenous elements are only those directly affected by traffic congestion and travel mode. The major assumptions and simplifications of the modeling approach are:

- Homogeneous, steady-state traffic states on roadway segments (neglecting traffic state transitions or unsteady traffic conditions)
- Emissions of counter-flowing vehicle traffic are ignored
- A steady-state Gaussian line-source dispersion approximation is used

Each sub-microenvironment (section of freeway) is modeled by a homogenous set of freeway and environmental characteristics. The traffic state is represented by flow $q$ (in veh/hr) and speed $v$ (in mph). Travel speed is represented as $s$ (in mph). The background concentration $Bg$ is exogenous to the model (though the level of congestion is probably correlated with elevated background concentrations due to peak-period traffic around the city). The pollution emissions rate is $E$ (in grams per vehicle-mile). Although $E$ is determined by many factors, the only endogenous factor is traffic speed; exogenous influences then include vehicle fleet details, fuel formulation, and weather (temperature and humidity). Dispersion of roadway emissions in the plane perpendicular to the roadway is represented by the parameter $D$ in $m^2$/sec, which is controlled by meteorological conditions and traffic-induced turbulence. The penetration of air pollutant concentrations into the vehicle cabin is represented by a unit-less scaling factor $P$, which is the ratio of in-vehicle concentration to the surrounding concentration. The breathing rate is represented by $V_e$ in $m^3$/hr, which is a function of travel speed for active modes but constant for motor vehicles, and will also vary with individual traveler characteristics.

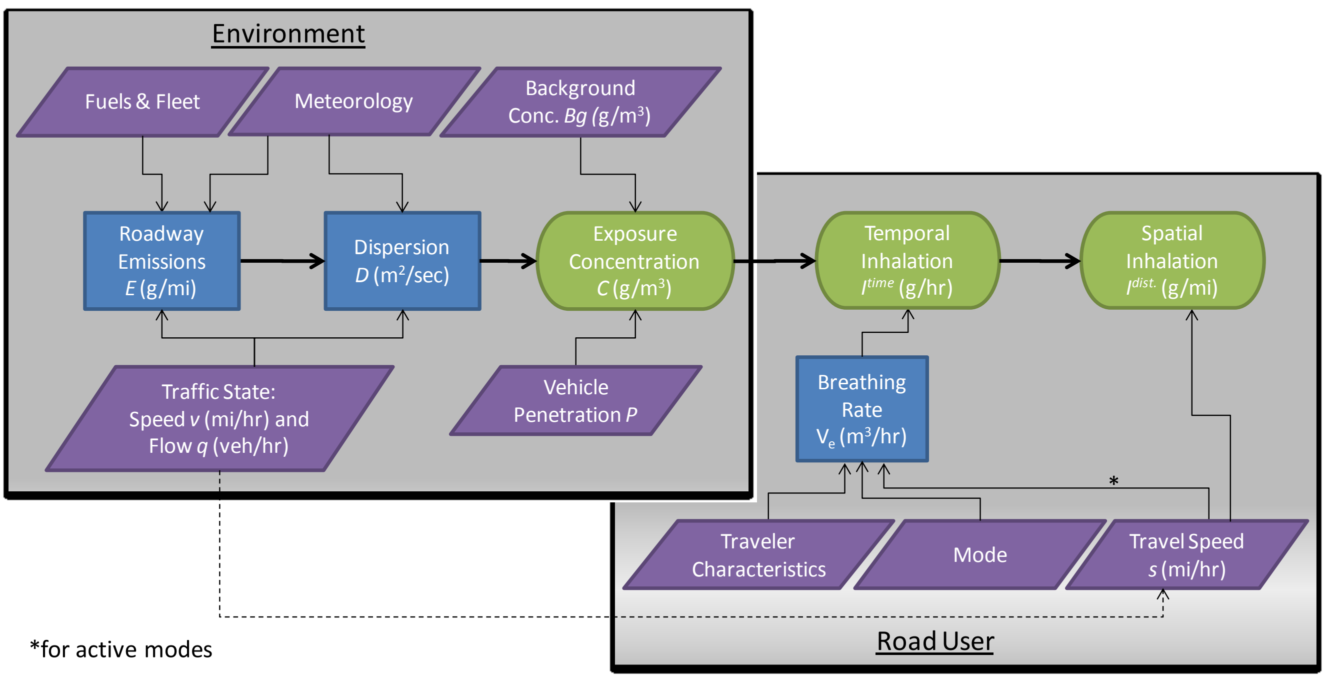



**Figure 1. Components of travel exposure model**

Combining these variables, the exposure concentration $C_i$ for a road user in sub-microenvironment $i$ using mode $k$ (in $g/m^3$) is the combined roadway and ambient pollution

$$C_{i,k} = \left(\frac{E_i \cdot q_i}{D_i} + Bg_i\right) P_{i,k}\ . \tag{1}$$

The temporal inhalation rate is $I_{i,k}^{time} = C_{i,k} \cdot V_e$ and the inhalation rate per unit travel distance (in g/mi) is

$$I_{i,k}^{dist.} = \frac{I_{i,k}^{time}}{s_{i,k}} = \left(\frac{E_i \cdot q_i}{D_i} + Bg_i\right) \frac{P_{i,k} \cdot V_{e_{i,k}}}{s_{i,k}}\ . \tag{2}$$

The total inhalation $U$ (in mass) over a series of roadway segments $i$ is

$$U_k = \sum_i \left[I_{i,k}^{dist.} \cdot L_i\right] = \sum_i \left[\left(\frac{E_i \cdot q_i}{D_i} + Bg_i\right) \frac{P_{i,k} \cdot V_{e_{i,k}} \cdot L_i}{s_{i,k}}\right], \tag{3}$$

where $L_i$ is the length of roadway traveled in segment $i$. The average spatial inhalation rate (in g/mi) is

$$\overline{I_k^{dist.}} = \frac{U_k}{\sum_i L_i} = \sum_i \left[\left(\frac{E_i \cdot q_i}{D_i} + Bg_i\right) \frac{P_i \cdot V_{e_i} \cdot p_i^{dist.}}{s_i}\right], \tag{4}$$

where $p_i^{dist.}$ is the fractional distance of travel occurring in segment or sub-microenvironment $i$, $p_i^{dist.} = \frac{L_i}{\sum_i L_i}$. Finally, the average temporal inhalation rate (in g/hr) is

$$\overline{I_k^{time}} = \frac{U_k}{\sum_i \left( {L_i}/{s_{i,k}} \right)} = \sum_i \left[ \left( \frac{E_i \cdot q_i}{D_i} + Bg_i \right) P_i \cdot V_{e_i} \cdot p_i^{time} \right], \quad (5)$$

where $p_i^{time} = \frac{{L_i}/{s_{i,k}}}{\sum_i \left( {L_i}/{s_{i,k}} \right)}$ is the fractional time of travel occurring in segment $i$. Equations 4 and 5 can be simplified by modal characteristics or some of the further assumptions of this analysis, described below. The following sections present methods for estimating the exposure model parameters, which are summarized in Table 1.

**Table 1: Summary of Model Variables**

| Variable | Symbol | Units | Endogenous Factors |
|---|---|---|---|
| **Emissions Rate** | *E* | [mass/vehicle-distance] (g/veh-mi) | *v* |
| **Traffic Flow** | *q* | [veh/time] (veh/hr) | Traffic state |
| **Traffic Speed** | *v* | [distance/time] (mi/hr) | Traffic state |
| **Dispersion Parameter** | *D* | [distance$^2$/time] (m$^2$/sec) | Traffic, wind |
| **Travel Speed** | *s* | [distance/time] (mi/hr) | Mode, *v* |
| **Breathing Rate** | $V_e$ | [volume/time] (m$^3$/hr) | Mode, *s* |
| **Vehicle Penetration** | *P* | None | Mode |
| **Background Conc.** | *Bg* | [mass/volume] (g/m$^3$) | None |

**Traffic States**

For the corridor study below, traffic states (speed and flow) are based on real-world data. We also employ basic traffic flow theory for some analyses. Assuming homogenous traffic conditions on each freeway segment, we can use the fundamental flow-density-speed relationships and first-order macroscopic traffic dynamics described by May (*11*). Each traffic state is a point on the flow-density (*q-k*) plane, with a speed corresponding to the slope of the line from the origin (i.e., $q=kv$). For these relationships $q$ is traffic flow in veh/hr, $k$ is traffic density in veh/mi, and $v$ is traffic speed in mi/hr. Values for constructing the flow-density relationship can be taken from the well-known Highway Capacity Manual (HCM), using the standard basic freeway sections (*12*). The HCM also describes qualitative level-of-service (LOS) indicators, A-F, based on traffic density thresholds, where LOS F is fully congested (travel demand exceeds roadway capacity). This is a simple but common traffic modeling approach representing homogenous, stationary traffic states on sections of uninterrupted roadway. The macroscopic model represents average conditions – and so is well suited for use with aggregate traffic data and a macroscopic emissions model.

**Emissions Rates**

For application with macroscopic traffic characteristics, emissions rates are based on average travel speeds. This approach can capture the average emissions characteristics of congested driving with appropriate driving patterns (*13*), though the effects of unique microscopic traffic characteristics (such as around toll lanes) are typically not modeled. Emissions-average speed relationships can vary by pollutant (*3*) and vehicle fleet (i.e. class, age, emissions technology) (*14*), but a full investigation of different emissions-speed curves is beyond the scope of this paper.

For model application average speed-based emissions rates for CO (carbon monoxide), $NO_x$ (nitrogen oxides), $PM_{2.5}$ (particulate matter smaller than 2.5 microns), HC (hydrocarbons), and VOC (volatile organic compounds) are estimated for January 2010 in Portland, Oregon using the MOVES 2010 emissions model (*15*). These emissions rates are based on a typical daytime mix of vehicle classes on I-5, obtained from the Oregon Department of Transportation (*16*). Where available, county-specific inputs are used (meteorology, vehicle inspection and maintenance program, fuel formulation), and national averages are used for other model inputs (vehicle age distributions). The estimates are for freeway travel only, and the modeled emissions are running exhaust emissions; evaporative, refueling, brake/tire wear, and start emissions are not included. The impacts of particulate resuspension are similarly excluded.

The modeled vehicular emissions rates can be combined with traffic states to produce roadway emissions rates (in kilograms per hour per lane-mile of roadway), as shown in Figure 2 for $NO_x$. The roadway emissions rates are plotted as contours on the traffic speed-flow plane, with illustrative real-world traffic states added from I-5NB in Portland, Oregon on January 21, 2010. The traffic states are 5-minute aggregations of dual-loop detector data, and so represent average conditions on a road segment. Roadway emissions rates increase with flow rate, and at very high and very low travel speeds.

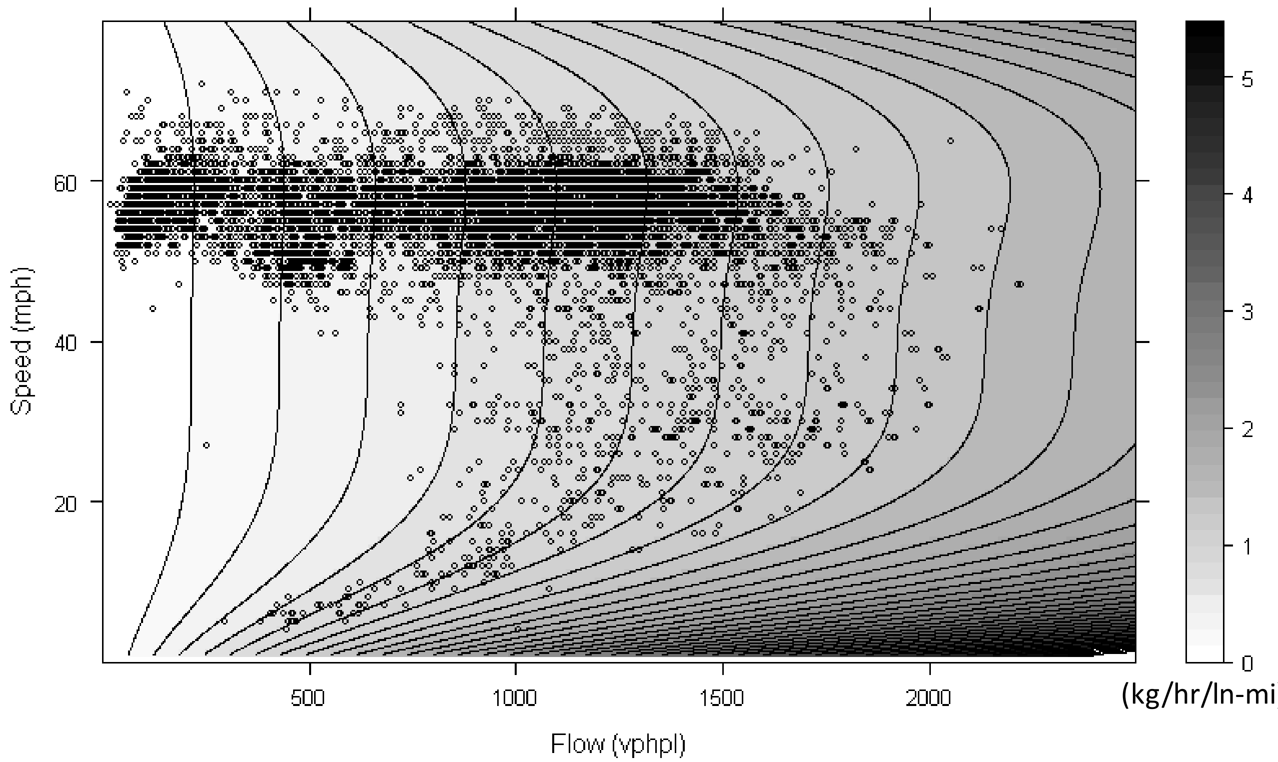



**Figure 2. $NO_x$ emissions mapped to traffic states, with illustrative real-world traffic data from I-5NB in Portland, Oregon on January 21, 2010 (5-minute aggregated traffic data)**

**Breathing Rates**

Most traffic exposure research accounts for uptake with a breathing/ventilation rate (*17-19*), though McNabola et al. (*20*) use a much more complex human respiratory tract model for pollutant absorption. Pollutant uptake can become quite complicated when accounting for factors such personal characteristics, nose vs. mouth breathing, pulse rate, and pollutant compound solubility. Even simple ventilation rate can vary greatly by activity level and personal characteristics (*21*, *22*). A constant, average breathing rate of 0.66 $m^3$/hr is used here for drivers (based on O'Donoghue et al. (*23*), which also agrees well with Wijnen et al. (*24*)). Average bicyclist and pedestrian breathing rates can be modeled as linear functions of travel speed, as in McNabola et al. (*21*).

**Vehicle Penetration**

The penetration of pollutants into the vehicle depends primarily on the cabin air exchange rate and is represented by *P*, a ratio of the in-vehicle concentration to the surrounding concentration. Empirical and modeling studies show that *P* can vary greatly with vehicle ventilation conditions and cabin particle filters (*25-27*). Clifford, Clarke, & Riffat (*28*) emphasize the time-lag effect of the vehicle cabin, aside from its potential effects as a barrier. Because the cabin air exchange rate can be affected by speed (*17*), *P* could also be a function of the traffic state. Others have suggested that for fine particulates and CO the vehicle shell has no effect –

implying a *P* value of 1.0 (*9*). In this research we neglect penetration (*P* = 1), assuming that any traffic-related effects on *P* are minimal, and acknowledging that well-sealed cabins with air filters could reduce concentrations levels.

**Background Concentration**

In the model formulation background concentration, *Bg*, includes ambient concentrations and the emissions of counter-flowing and other nearby traffic. These factors are exogenous to this study and the impacts of a congested freeway traffic stream are isolated by excluding background concentrations (*Bg* = 0). In this way we are modeling only the traffic-related components of total exposure; for pollutants with significant background concentrations, the traffic impacts would be diminished.

**Dispersion**

The dispersion parameter *D* relates pollutant source strength to a concentration at a location of interest, primarily governed by meteorological and traffic conditions. The broad dispersion modeling approach applied here is a semi-infinite continuous line-source Gaussian plume approximation. The technique is essentially the basis of the popular CALINE series of roadway dispersion models (*29*), and comes from a seminal paper by Benson (*30*) which accounted for a highly-turbulent roadway mixing zone. Assuming steady-state conditions dominated by cross-road advection, the concentration *c* at height *z* can be calculated from the ground-level line source strength *Q* in mass/length/time, the crosswind speed *U*, and a statistical approximation of the plume height at some location $\sigma_z$ (the standard deviation of the plume density in the vertical direction)

$$c = \frac{2Q}{\sqrt{2\pi} U \sigma_z} \exp\left(\frac{-z^2}{2\sigma_z^2}\right). \tag{6}$$

The roadway line source *Q* is the combined effect of the average vehicle emissions rate and the traffic flow, $Q = E \cdot q$ (in mass/length/time). Combining the other factors to a single variable *D*, *Q* can be related to the exposure concentration as $c = Q/D$, and from a rearrangement of Equation 6,

$$D = \frac{\sqrt{\pi} U \sigma_z}{\sqrt{2} \exp\left(\frac{-z^2}{2\sigma_z^2}\right)}. \tag{7}$$

Assuming a receptor height *z* of 1m, the remaining step is estimation of the vertical dispersion $\sigma_z$. Research has shown that in addition to local winds, vehicle-induced mechanical turbulence has a significant effect on turbulent dispersion around a roadway (*31*-*33*). The effect of the traffic stream on dispersion varies with the traffic speed, traffic density, and size of vehicles. Unfortunately, most roadway dispersion models are intended for use downwind of a roadway, and do not model vehicle-induced turbulence in detail (or at all). When vehicle-induced turbulence is included, it is usually insensitive to traffic characteristics, e.g. (*29*, *34, 35*) – though efforts are under way to incorporate vehicle-induced turbulence in to air dispersion models with more sophistication (*36*).

Because traffic characteristics are the pith of this study, extra effort was made to account for dispersion sensitivity to traffic. The adopted approach to estimating the plume height $\sigma_z$ is based on the vehicle wake theory developed by Eskridge, Rao, Thompson, Catalano, and others from wind tunnel studies in the late 1970's, which is incorporated in the ROADWAY dispersion models (*31*, *37*). The ROADWAY model itself is impractical for this application because it requires microscopic traffic data (individual vehicle paths and speeds), whereas this is a more macroscopic analysis. Vehicle wake theory was also recently used for dispersion modeling in an integrated traffic and air quality simulation (*38*).

The vehicle wake theory is used to estimate the turbulent kinetic energy (TKE) produced by a moving vehicle in a wind field, as illustrated in Figure 3. The TKE behind a vehicle varies with wind speed and direction, vehicle size and drag coefficient, and vehicle speed. For application with macroscopic traffic characteristics in this study, the cumulative roadway TKE from a traffic stream is calculated by assuming equal spacing and distribution of vehicles in each lane and averaging over the roadway. As with other implementations of vehicle wake theory, this assumes independence of turbulent energy plumes.

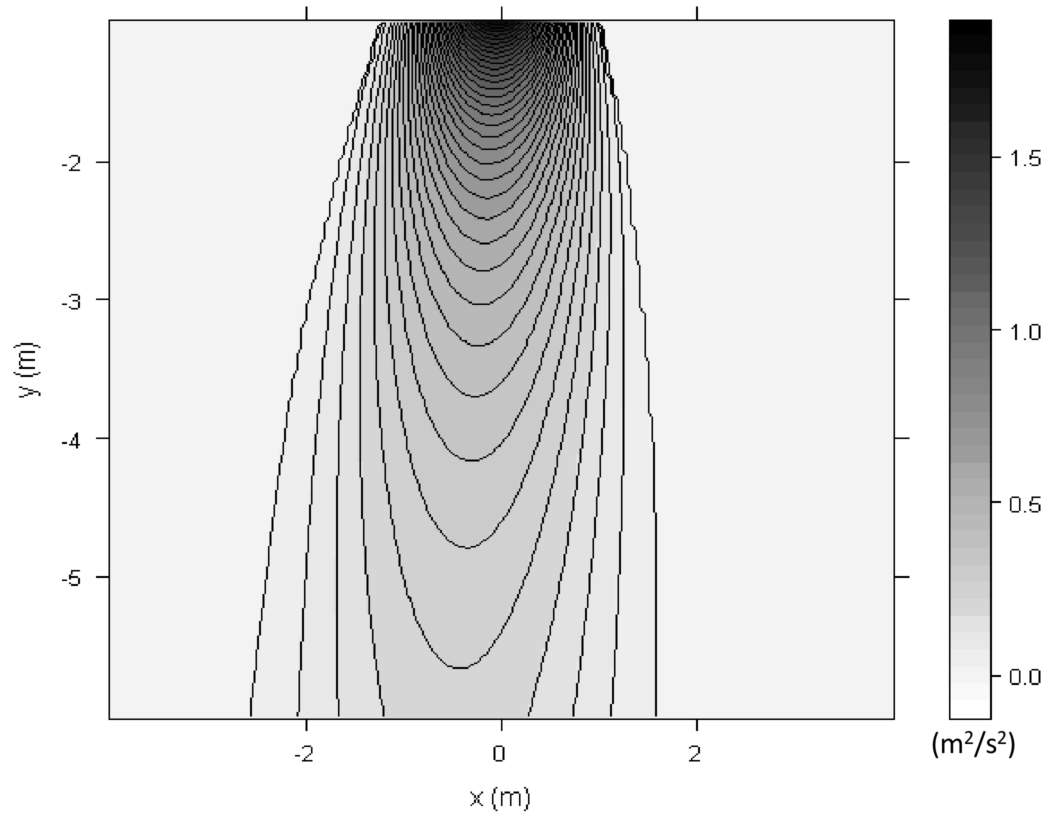



**Figure 3. Example TKE ($m^2/s^2$) plume behind a single vehicle, as predicted by vehicle wake theory Vehicle speed = 45 mph, wind speed = 5 mph, wind angle = 45 degrees**

The TKE contributing to vertical dispersion is the variance in vertical wind speed, $w'^2$. To the vehicle-induced turbulence is added a component of roadway-scale atmospheric turbulence as a function of wind speed $u$, approximated simply as $(0.1 * u)^2$, from Bastner-Klein, Berkowicz, & Plate (*39*). The vertical turbulent diffusion coefficient $E_z$ in the classical advection-diffusion equation can be determined as the product of the characteristic length and velocity scales of the turbulent eddies (*34*, *40*), approximated by the composite vehicle height $H_{veh}$ and the square root of the TKE,

$$E_z = H_{veh}\sqrt{w'^2}. \tag{8}$$

Using the statistical turbulence relationship

$$E_z = \frac{1}{2}\frac{d\sigma_z^2}{dt} \tag{9}$$

from Pasquill (*41*) and assuming constant $E_z$ (because of steady-state traffic and meteorology), the plume height can then be estimated as

$$\sigma_z = \sqrt{2tE_z} \quad (41). \tag{10}$$

We calculate $t$ as the residence time in the roadway,

$$t = t_r = \frac{W_{road}}{U} \tag{11}$$

where $W_{road}$ is the roadway width and $U$ is the crosswind speed perpendicular to the roadway – based on the assumption that advection dominates pollutant transport (part of the Gaussian continuous line-source model (*29*)). To constrain the model to this assumption a minimum crosswind speed of 0.5 m/s is assumed. This modeling uses vehicle size parameters from Baumer et al. (*40*) and Wang et al. (*42*), as shown in Table 2. The composite vehicles are weighted combinations of light duty (LD) and heavy duty (HD) characteristics, based on the fraction of heavy vehicles in the roadway.

**Table 2. Assumed vehicle parameters for dispersion estimates**

| | Light Duty Vehicles | Heavy Duty Vehicles |
|---|---|---|
| ***$C_d$*, drag coefficient** | 0.3 | 0.9 |
| ***H*, vehicle height (m)** | 1.4 | 3.5 |
| ***W*, vehicle width (m)** | 1.8 | 2.4 |
| ***L*, vehicle length (m)** | 5.5 | 22.5 |

The above methodology produces dispersion parameter estimates with changing traffic states as shown in Figure 4, where calculated values of *D* are plotted on the traffic speed-flow plane, along with solid lines representing HCM theoretical traffic states for free-flow speeds of 60, 65, and 70mph, and dashed lines separating HCM level of service regions (both described above). Higher speeds and flows both increase roadway dispersion, as expected. For generally uncongested traffic (LOS A-E), increasing flows increase dispersion, while increasingly severe levels of congestion in LOS F have lower dispersion estimates. Since *D* is inversely proportional to traffic-related pollutant concentrations, lower dispersion in heavy congestion will lead to higher roadway concentrations at a given emissions intensity. The dispersion estimates are also moderately sensitive to wind speed and direction, and the fraction of heavy duty vehicles.

Like most dispersion modeling this approach is only a rough approximation, and is used as a reasonable estimate of traffic effects while recognizing that short-term concentration values vary widely. Of particular note, this assumes a longitudinally well-mixed roadway air mass, and will likely not accurately represent an idling or extremely slow-moving queue, where the proximity of tailpipes and following vehicles' air intakes can become a dominant factor (*43*, *44*).

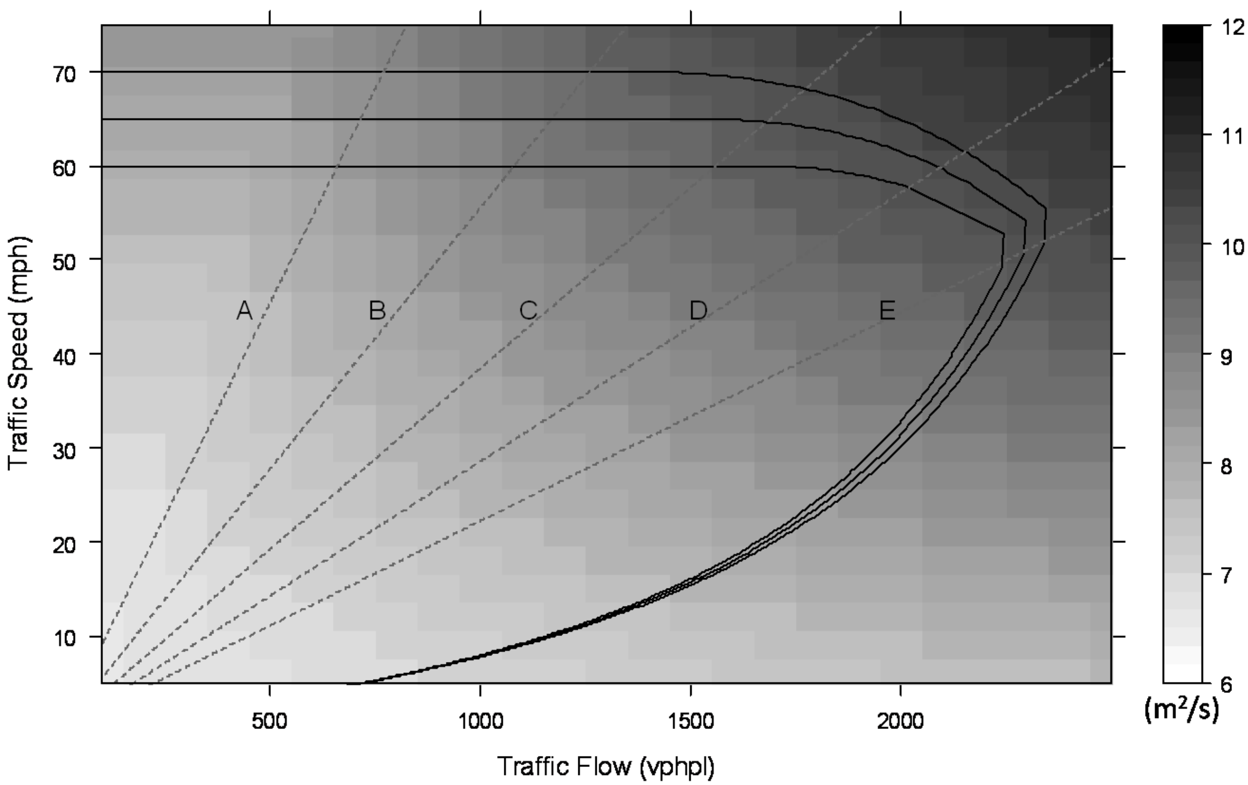



**Figure 4. Roadway dispersion estimates, *D* ($m^2$/s), with HCM traffic state curves and LOS regions Wind speed = 5 mph; wind angle = 45 degrees; 3 lanes of 4 m width each**

## CORRIDOR STUDY

To investigate congestion effects on exposure, the exposure model was applied for travelers over 4 days on a 14-mile stretch of I-5 NB through Portland, Oregon – see Figure 5. Simulated travelers departed from Milepost 290 on the southern end of the corridor every 5 minutes from 6am until 8pm on each day of study (January 19-22, 2010). Their exposure was modeled over 15 freeway segments (of approximately 1 mile each) up to Milepost 305. The freeway segments are delineated by the midpoints between traffic sensors. Traffic conditions (speed and flow) on each link are based on archived inductive dual-loop detector data, as mined from the PORTAL transportation data archive at Portland State University (portal.its.pdx.edu; see (*45*)). The traffic data were used in 5-minute aggregated form, which has been shown elsewhere to best approximate average freeway travel speeds (*46*, *47*). Although an HOV lane exists at the end of the corridor, it was not used by the simulated travelers (though the emissions/dispersion impacts of the HOV lane vehicles are included). The HD vehicle fraction is based on average vehicle classification data on this section of I-5, with 8.7% HD (*16*). As local wind data were not available along the freeway, the model used an assumed 5mph wind at 45 degrees clockwise from the direction of traffic flow. Although the local wind speed can have a large effect on pollutant concentrations through dispersion, it is independent of the traffic state and so held constant in the model to investigate traffic effects alone.

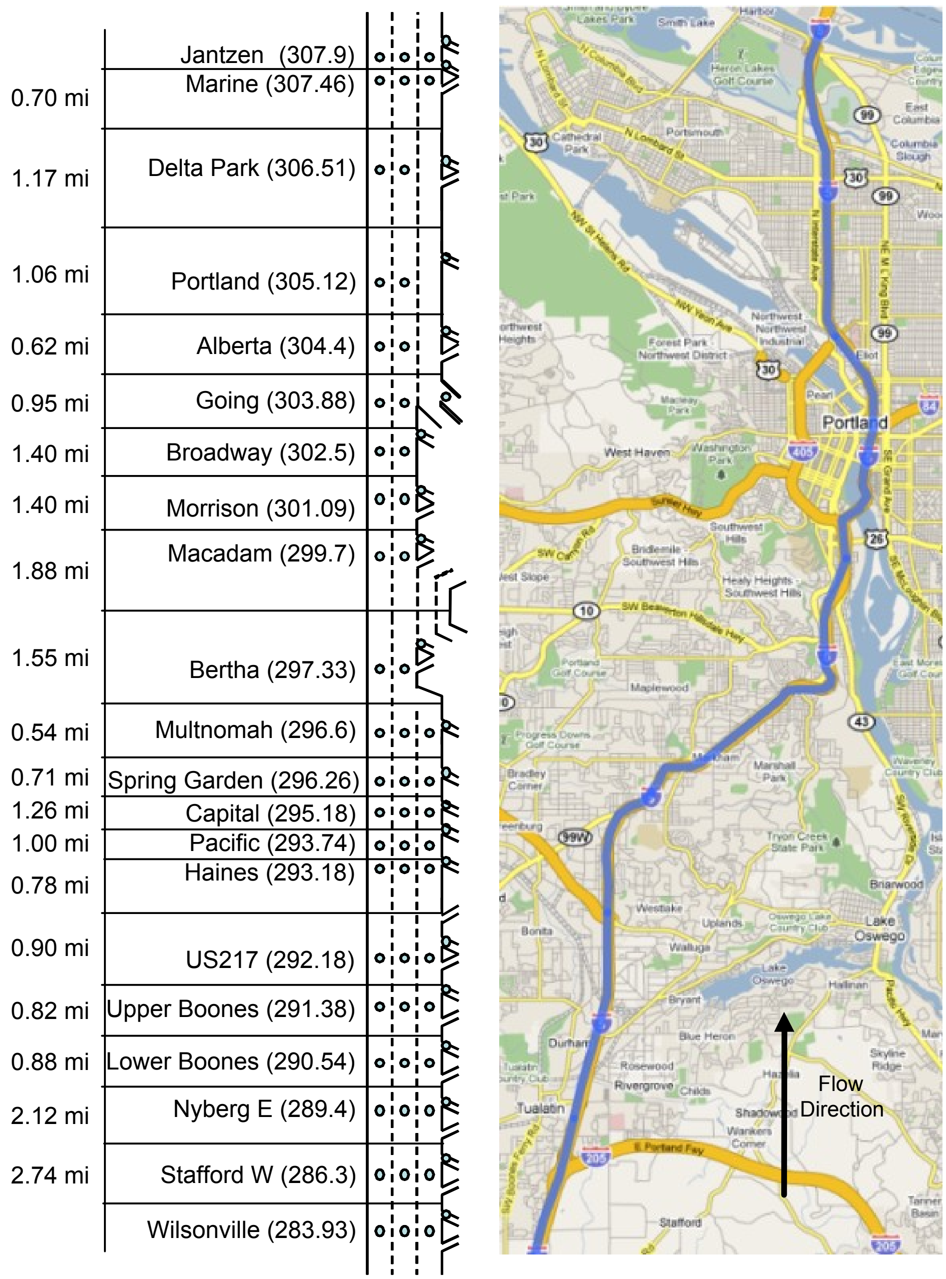
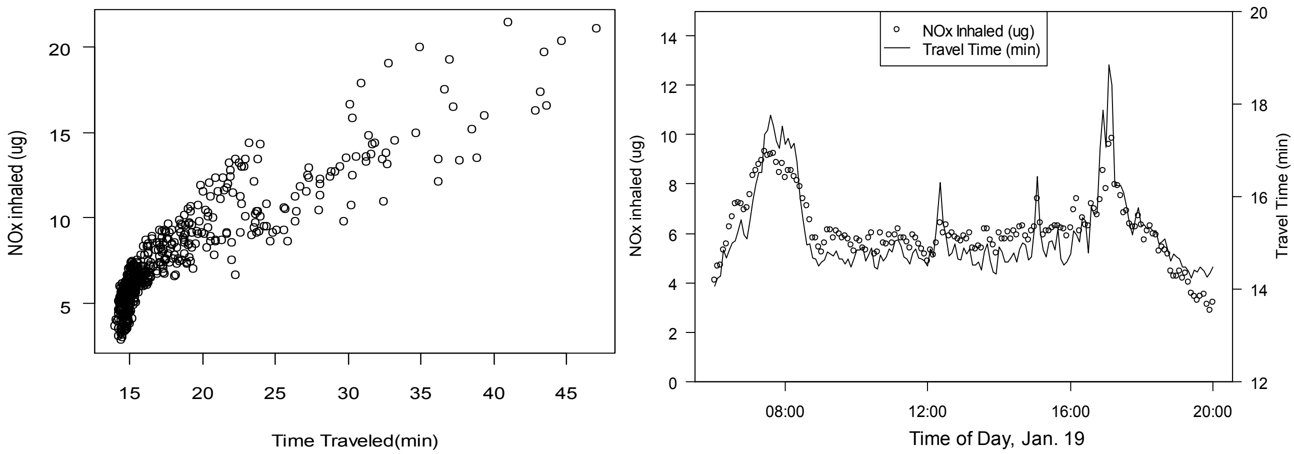



**Figure 5. I-5 NB study corridor, (*source:* (*48*))**

**Model Results**

Model results affirm that congestion (as indicated by traveler delay) increases motorists' exposure to traffic-related air pollution. Figure 6a shows total mass (in micrograms) of $NO_x$ inhaled over the 14-mile trip versus trip travel time. There is a range of exposure at any given travel time, but the trend is clearly increasing exposure with delay. This same relationship held for all pollutants studied (CO, $NO_x$, HC, VOC, and $PM_{2.5}$). In fact, the correlation coefficients of total inhalation between all pairs of pollutants were 0.97 or greater, and most were over 0.99. This correlation reflects the fact that MOVES-modeled emissions rates (in mass per vehicle-mile) had similar relationships with travel speed for various pollutants – though the absolute values vary greatly. In the interests of space economy, the remaining exposure results are presented for $NO_x$ only.




(a) (b)

**Figure 6. Congestion effects: total NOx inhalation and travel time for all days (a), and January 19 (b)**

The variation in $NO_x$ total trip exposure over 4 days was fairly high, with a Variation Coefficient (VC, standard deviation divided by the mean) of 40%. The travel time VC was similarly high, at 31%. As expected from Figure 6a, the total exposure is highly correlated with travel time, and a single factor linear ANOVA reveals that travel time explains 82% of the variance in total $NO_x$ inhalation. Not only is total exposure directly proportional to travel rate (1/*s* in Equation 3), but travel time is positively correlated with traffic flow *q*, marginal emissions rate *E,* and the inverse of dispersion 1/*D*. This relationship is seen over the course of a day in Figure 6b, where higher exposures and travel times are both experienced during the AM and PM peak periods. Controlling for travel time, the temporal-average trip $NO_x$ inhalation rates over the corridor (in mass/time, from Equation 5) have a lower VC of 17% over the 4 days.

Looking at the segment level, travel rate (time per mile) is still the dominant factor in spatial inhalation rates $I_{i,k}^{dist.}$, followed by traffic flow *q* (multifactor linear ANOVA deviance shares of 74% and 14%, respectively; the *v*-*q* interaction variable was the next largest factor). Dispersion *D* only fluctuated slightly due to traffic characteristics over the four days (VC of 6%); it generally acted to offset increased exposure during high-flow periods. The dispersion parameter will vary more when considering changing wind direction and speed, which could dominate the effects of traffic-induced turbulence on dispersion (a topic for further study).

For segment temporal exposure rates, $I_{i,k}^{time}$, *q* is the dominant factor, while *v* has a minor impact. Figure 7 shows the time-based $NO_x$ inhalation rates over each segment versus traffic speed and flow. At both congested and free-flow speeds, travelers experienced a wide range of time-based exposure rates. Other than its effect on travel rate (which is absent from $I_{i,k}^{time}$), traffic speed slightly affected emissions and dispersion rates, but neither one as much as traffic flow affected them. Similarly, marginal vehicular emissions rates *E* (per vehicle-mile, a function of *v*) were not highly variable (VC of 9%), though roadway emissions *Q* (per hour per mile of roadway; essentially *E*q*) were, with a VC of 36%. The high correlations in total exposure between pollutants are the combined effect of similar emissions-speed relationships and the dominance of other, shared factors in the total exposure estimate (such as *q*, *s*, and *D*).

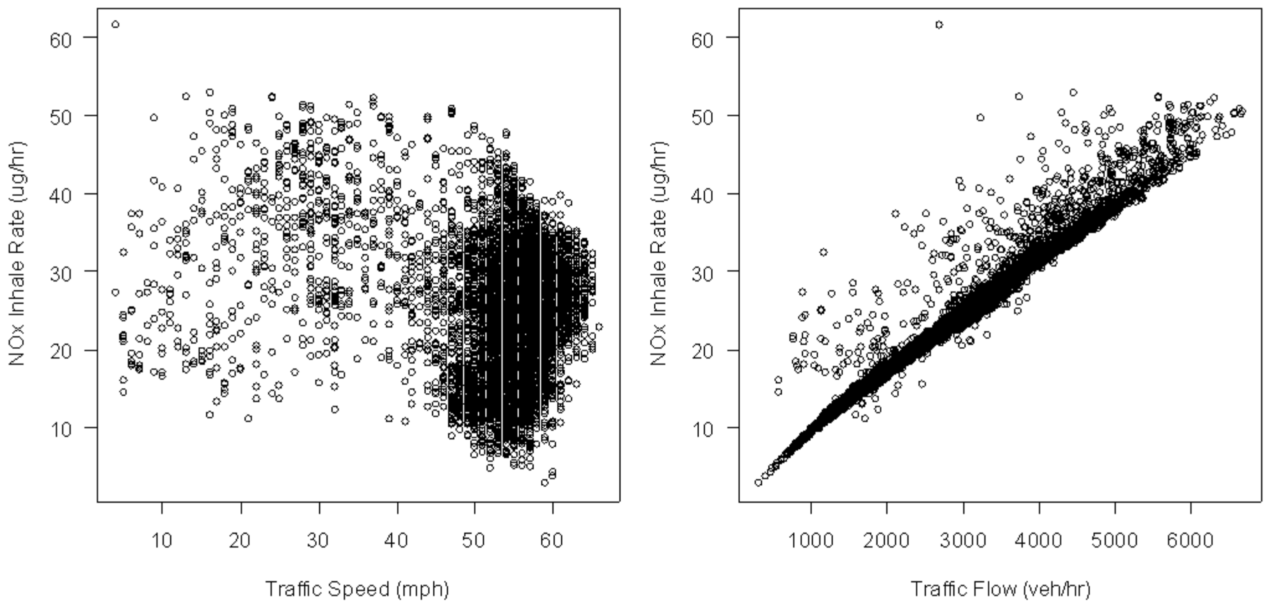



**Figure 7. Time-based segment $NO_x$ inhalation rates with traffic characteristics**

As a further illustration of the impacts of travel time, consider an alternative hypothetical traveler who traverses the same road segments at the same times as the travelers in the congested traffic stream, but at a constant free-flow speed unhindered by other vehicles (a free-flowing HOV lane, for example, where $s$ is independent of $v$). These travelers have the same exposure concentrations $C$ as the motorists in congestion, but shorter (or equal) exposure durations. Figure 8 compares the total trip inhalations over the course of a day for a traveler in the congested stream and a constant-speed traveler (at 60mph, for 14 minutes total travel time). Although there is a moderate increase in exposure during the day, the extreme exposures during the AM and PM peaks are avoided. The large exposure peaks during peak-period congestion are primarily the result of increased time in the traffic stream (exposure duration), while the influence of traffic on exposure concentrations is secondary.

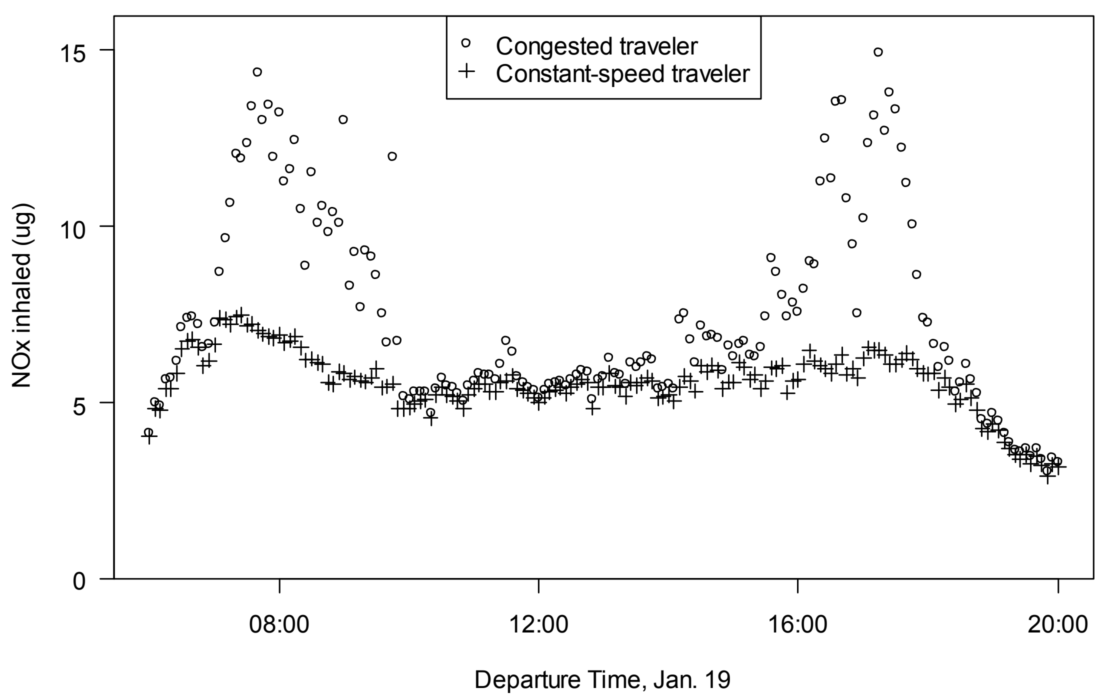



**Figure 8. Comparison of total trip inhalation for congested and constant-speed (60mph) travelers**

The variability in trip exposures is illustrated in Figure 9, where individual trip trajectories are plotted as cumulative mass inhaled versus traveled distance and time. The slopes of these trajectories are the inhalation rates, and we can clearly see the effects of bottlenecks spatially in the first panel, where congestion around miles 4 and 8 rapidly increase total exposure for some motorists (both are bottlenecks upstream of major interchanges). High-exposure motorists experience much of their inhalation at isolated locations, while the rest of their trip has a similar slope to that of the motorists not experiencing congestion. From an exposure point of view, there are clearly “hot spots” on the corridor with long travel durations and high traffic flows.

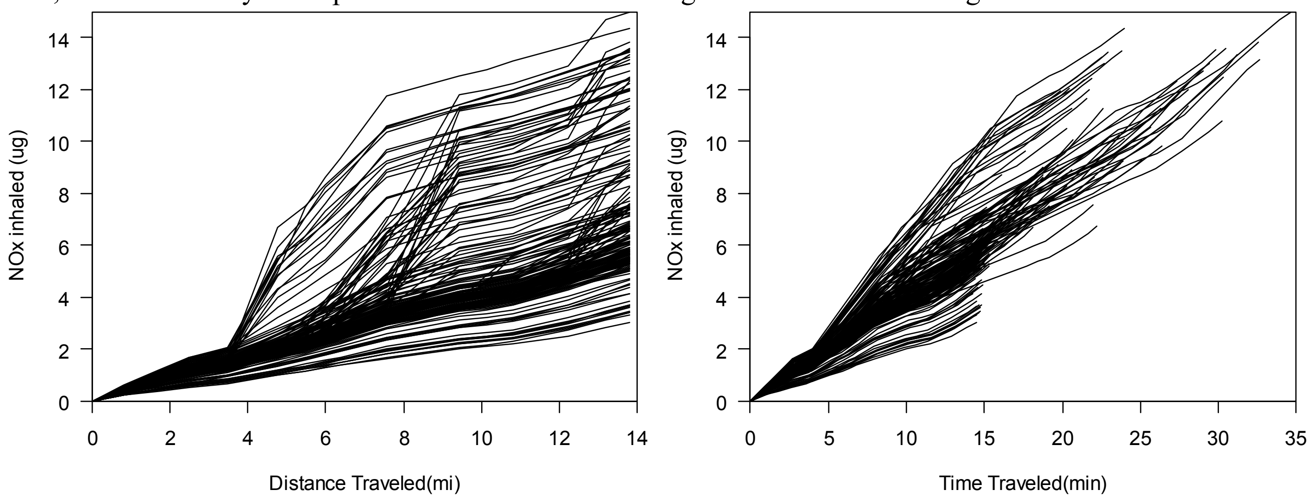



**Figure 9. Trip trajectories in mass inhaled versus distance and time traveled**

The second panel in Figure 9 shows the temporal intensity of exposure, and we see that free-flowing trips (around 15 minutes) terminate with much lower total inhalation than longer trips. That said, there was still a wide range of exposures for moderate-delay trips (20-25 minute travel times). Based on the above analysis, the varying slopes in this plot are primarily determined by surrounding traffic flows; a fixed amount of delay is less harmfully experienced on a lower-flow section than a higher-flow section.

## CONCLUSIONS

This paper proposes and applies a road-user exposure model that is a function of fundamental traffic state characteristics. The modeling results of the case study show a wide range of exposures through a freeway corridor over the course of a day and suggest that traffic congestion does increase motorists’ exposure to traffic-related pollution. Traffic characteristics affect motorists’ exposure in multiple ways. Large peak-period trip exposures are primarily the result of increased exposure durations due to longer travel times. This is reflected by more moderate traffic impacts on exposure for road users with travel speeds unaffected by the traffic state. Roadway exposure concentrations (and temporal inhalation rates) also increase during peak periods due to heavy traffic flows and increased marginal emissions rates (though the direct effects of traffic speed on exposure concentrations were small for the case studied). Traffic-induced dispersion increases with higher flows – slightly offsetting the increased roadway emissions during heavy traffic flow.

It should also be noted that while travel time is the dominant factor in high peak-period exposure, long travel times are driven by traffic characteristics. Excess travel demand volumes increase exposure by causing traveler delay, in addition to increasing roadway emissions through high flows and increased marginal emissions rates. Motorists’ exposure to traffic-related pollution can be mitigated by diverse strategies, including cleaner vehicles and fuels, more efficient roadways, and changing travel behaviors (trips, routes, and modes). From a roadway perspective, these results suggest that the focus should be on reducing the time spent in the roadway and reducing the volume flow of vehicles on the roadway – while recognizing that these are intertwined travel behaviors. In particular, traveler delay time is less deleterious when spent on low-flow sections than high-flow sections. Individual travelers can greatly reduce their roadway exposure by adjusting their departure time to less congested, lower volume periods.

These results have been presented with respect to departure time, not total trips taken. As such, they represent varying marginal exposure for a motorist, depending on when they enter the corridor. For a population perspective, these would be weighted by travel flows, which would reflect the increased numbers of motorists during peak periods (when most congestion occurs). For a broader picture of the role of congestion in overall exposure we would also need to consider background concentrations and alternative exposure environments, indirect congestion effects on mode choice, routing, and land use, and travel delay effects on time allocation, (such as in Zhang & Batterman (*49*)).

These conclusions are based on the results of a modeling exercise with many assumptions and approximations. Salient weaknesses include the imprecise representation of "stop-and-go" conditions, the use of homogenous, steady traffic states, and the simplified modeling of roadway dispersion. Next steps include in-vehicle air quality measurements to validate these results and modeling of other road users such as counter-flowing motorists, bicyclists, and pedestrians (on parallel paths). Additionally, continued modeling efforts will investigate exposure effects of seasonal flows, HOV lanes, and local wind conditions. Continued development of mesoscopic roadway dispersion models is another important research path. Finally, we hope to use exposure modeling to estimate the health impacts of congestion – marginally for travelers and cumulatively for the Portland metropolitan region.

## ACKNOWLEDGMENTS

The authors would like to thank for their support of this project: the Oregon Transportation Research and Education Consortium (OTREC) and the U.S. Department of Transportation (through the Eisenhower Graduate Fellowship program).

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