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Scripted drives: A robust protocol for generating exposures to traffic-related air pollution

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Abstract

Commuting in automobiles can contribute substantially to total traffic-related air pollution (TRAP) exposure, yet measuring commuting exposures for studies of health outcomes remains challenging. To estimate real-world TRAP exposures, we developed and evaluated the robustness of a scripted drive protocol on the NJ Turnpike and local roads between April 2007 and October 2014. Study participants were driven in a car with closed windows and open vents during morning rush hours on 190 days. Real-time measurements of PM_{2.5}, PNC, CO, and BC, and integrated samples of NO₂, were made in the car cabin. Exposure measures included in-vehicle concentrations on the NJ Turnpike and local roads and the differences and ratios of these concentrations. Median in-cabin concentrations were 11 µg/m³ PM_{2.5}, 40 000 particles/cm³, 0.3 ppm CO, 4 µg/m³ BC, and 20.6 ppb NO₂. In-cabin concentrations on the NJ Turnpike were higher than in-cabin concentrations on local roads by a factor of 1.4 for PM_{2.5}, 3.5 for PNC, 1.0 for CO, and 4 for BC. Median concentrations of NO₂ for full rides were 2.4 times higher than ambient concentrations. Results were generally robust relative to season, traffic congestion, ventilation setting, and study year, except for PNC and PM_{2.5}, which had secular and seasonal trends. Ratios of concentrations were more stable than differences or absolute concentrations. Scripted drives can be used for generating reasonably consistent in-cabin increments of exposure to traffic-related air pollution.

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Keywords

car commute; in-cabin; traffic-related air pollution; in-vehicle exposures; particulate matter; nitrogen oxides

1. Introduction

Being on or near heavily-trafficked roadways has been associated with acute adverse cardiovascular and respiratory outcomes (Laumbach et al., 2014; Laumbach et al., 2010; McCreanor et al., 2007; Peters et al., 2000; Peters et al., 2004; Peters et al., 2013; Sarnat et al., 2014). Air pollution exposure may affect health through oxidative stress pathways. Increased concentrations of biomarkers for oxidative stress pathways have been observed in study participants in studies for both general air pollutants (Huang et al., 2012; Rich et al., 2012) and pollutants related to highway traffic in a relatively unpolluted region (Laumbach et al., 2014; Laumbach et al., 2010; Patel et al., 2013; Pettit et al., 2015). Exposure to traffic-related air pollution (TRAP) is one possible cause of these adverse outcomes (Fruin et al., 2008; Lane et al., 2016; Laumbach et al., 2014).

For many individuals in the industrialized world, a substantial fraction of exposure to traffic-related air pollutants (e.g., ultrafine particles) may be experienced while commuting (Knibbs et al., 2011). For example, it has been estimated that Los Angeles residents experience 33% to 45% of their total exposure to ultrafine particles during the ~6% of their time that is spent on daily driving commutes (Fruin et al., 2008). Not only are Americans exposed to peak concentrations of traffic-related air pollution during their commutes, but many commute long distances. In 2011, 8.1 % of American workers who did not work at home, and 14.6 % of workers living and working in New Jersey, had one-way driving commutes of 60 minutes or greater (McKenzie, 2013).

To study the health effects of short-term exposures to traffic under real-world conditions, robust exposures with well-characterized variability and sufficient duration are needed. Scripted drive studies have demonstrated increased in-cabin concentrations of many traffic-related air pollutants while travelling on busy roadways (Greenwald et al., 2014; Hudda et al., 2011; Jiao and Frey, 2014; Laumbach et al., 2014; Laumbach et al., 2010; Lawryk et al., 1995; Lawryk and Weisel, 1996; Mapou et al., 2013; Pettit et al., 2015; Sarnat et al., 2014; Zhu et al., 2008). Many of those studies have used scripted commutes, in which study participants drive or ride in private cars (their own or provided) through routes selected for high traffic volume and/or diesel vehicle intensity (Greenwald et al., 2014; Jiao and Frey, 2014; Laumbach et al., 2014; Laumbach et al., 2010; Lawryk et al., 1995; Lawryk and Weisel, 1996; Sarnat et al., 2014). Factors affecting in-cabin concentrations in these studies have included vehicle age and model, seasonality, traffic congestion, and road type (Greenwald et al., 2014; Hudda et al., 2011; Weichenthal et al., 2015; Zhu et al., 2007). In addition, closing windows or vents in the cars has been shown to reduce pollutant infiltration and decrease concentrations in the vehicle cabin (Greenwald et al., 2014; Hudda et al., 2011; Zhu et al., 2007). In-cabin concentrations typically follow the same trends as on-road concentrations, which are strongly associated with land use and the density of gasoline and

diesel-powered vehicles (Weichenthal et al., 2015; Zhu et al., 2008). However, it is unclear to what extent the relationships between in-cabin concentrations on commuting highways and on local roads are affected by seasonality, traffic congestion, ventilation setting, or secular trends. Rigorous evaluations of real world exposure protocols, including defining the appropriate metrics, will support the use of these protocols in panel studies to evaluate the acute and subacute effects of TRAP exposure during commuting.

We have conducted five scripted drive studies (three previously published) on the relationship between commuting exposures to traffic-related air pollution and varying biomarkers of early biological effects (Laumbach et al., 2014; Laumbach et al., 2010; Pettit et al., 2015). In this work, we explore the in-cabin measurements made during those studies to explain some key factors affecting the relationship between in-cabin exposures to air pollution on a 12-lane highway (NJ Turnpike) and exposures in other locations. Our specific aims were to (1) examine in-vehicle concentrations of PM_{2.5}, PNC, CO, BC, and NO₂, and correlations of these pollutants, during scripted car rides on the NJ Turnpike and local roads between April 2007 and October 2014; (2) compare in-cabin concentrations of air pollutants on the NJ Turnpike to in-cabin concentrations on local roads and ambient concentrations at regulatory monitoring stations; and (3) test whether season, traffic congestion (measured as travel time on the NJ Turnpike), ventilation setting, or study year modifies the relationship between in-cabin concentrations on the NJ Turnpike and on local roads.

2. Methods

2.1 Scripted Drives

We evaluated a standard protocol for quasi-controlled in-cabin exposures from five successive studies. The studies featured scripted passenger vehicle drives on the New Jersey Turnpike (NJT) between April 2007 and October 2014 (Table 1). Individual studies (NJT 1-5) lasted from 9 to 24 months, with 21-84 drives per study (190 total). Drives were made from 08:30 to 10:45 on weekday mornings throughout the year. For uniformity of the exposure protocol, drives were only conducted when the forecast probability of precipitation during the ride was <50%; there was intermittent or light rain on ~5% of drives and no drives were conducted in steady rain. Each drive included 26 miles on local streets and 60 miles on the NJ Turnpike (Figure 1). All rides started at the Environmental and Occupational Health Sciences Institute clinic parking lot (EOHSI) at Rutgers University, and a short break was taken at the halfway point at the Vince Lombardi service area before returning to EOHSI. For most of the New Jersey Turnpike part of the drive, there were two sets of 3 lanes (the inner set for cars only and the outer set for cars and trucks) in each direction (12 lanes total). The scripted drives took place entirely in the right-most (i.e., outermost) car and truck lane to maximize exposure to air pollutants emitted by diesel-powered vehicles. Windows were kept closed and the car vent was open (i.e., recirculation or max air setting off) with a medium fan setting to mix the air within the car cabin. The temperature settings (heat and air conditioning) were adjusted as needed for passenger comfort. Air sampling inlets constructed of Tygon tubing were positioned near the center of the vehicle passenger compartment. On average, there were ~130 000 vehicles per day on the New Jersey Turnpike during each of the study periods and 13% of the traffic volume consisted of diesel

trucks (data from New Jersey Turnpike Authority). Except for the beginning of the first study (NJT 1), all drives occurred after the transition to ultra-low sulfur diesel in pumps in the United States.

Measurement methods used during each study are summarized in Table S1. The pollutants measured in real-time (1-second intervals) were fine particulate matter (PM_{2.5}; AM510 Sidepak, TSI, Shoreview, MN), particle number concentration (PNC; CPC 3007, TSI), carbon monoxide (CO; T15v or T15n, Langan Products, San Francisco, CA), and black carbon (BC; AE51 microaethalometer, AethLabs, San Francisco, CA). To minimize noise due to mechanical vibrations, the microaethalometer was placed in a pouch suspended between the front passenger seats. The CPC was placed on a horizontal surface and tied down (e.g., on seat and held by seatbelt).

In addition, integrated samples of nitrogen dioxide (NO₂) were collected on C₁₈ Sep-Pak cartridges (Waters Corp., Milford, MA, USA) coated with a solution of potassium hydroxide (KOH) and triethanolamine (TEA). Samples were collected onto cartridges at a nominal flow rate of 1 L/min (Legand Legacy pump, SKC Inc., Eighty Four, PA, USA). NO₂ samples were stored at 4 °C in a chemical analysis laboratory at EOHSI until analysis. Nitrite and nitrate were extracted with 2 ml of a 6:1 v/v HPLC-grade water and methanol solution. Extracts were analyzed by ion chromatography (Waters Ion PAK HR column and UV detector) with a pH 9.1 buffered mobile phase of 10 mM borate and 10 mM boric acid (Wang et al., 1999). Concentrations were determined by use of sodium nitrite (Sigma-Aldrich US) and potassium nitrate (Sigma-Aldrich US) calibration curves produced on the day of analysis ($R^2 > 0.999$).

Data from the different monitors were merged by time-stamp and assigned to drive segments based on written daily logs. The drive consisted of two segments: 1) local roads between EOHSI and the New Jersey Turnpike, and 2) the New Jersey Turnpike. The “full ride” included the outgoing (northbound and eastbound) and incoming (southbound and westbound) portions of both segments.

All pollutant data were quality-controlled by standard methods. Measurements were checked for unreasonable values with boxplots and summary statistics. Outliers were maintained because there was no methodological reason to exclude them, they did not affect the overall results, and the instruments reported typical measurements at the start and end of drives with upper extremes. Where available (i.e., Sidepak, aethalometer, CPC), two monitors of the same type were run simultaneously, and agreement of the monitors was evaluated to confirm measurement accuracy. In addition, all Sidepak calibration factors were post-processed to 0.41 because different calibration factor settings were used in the different NJT studies. This calibration factor was based on experiments done with diesel exhaust in the controlled exposure facility at Rutgers University. Raw aethalometer data were processed by the ONA algorithm to remove mechanical vibrations (Hagler et al., 2011) and adjusted for filter loading using the recommended correction factor of $k=0.004$ (Cheng and Lin, 2013). Since CO was calibrated 1 ppm high to increase amplifier stability, 1 ppm was subtracted from all CO measurements for better comparison with ambient monitors (Langan, 2006). All CO values < 0 (i.e., below the monitor detection limit) were assigned a value of 0.001 ppm.

2.2 Baseline Measurements

The baseline measurements for each day were the median concentrations measured on local (i.e., non-turnpike) roads between the NJ Turnpike and EOHSI (Figure 1). The local roads include one interstate highway, Route 287, which had substantial diesel traffic on half as many lanes (3 in each direction versus 6 on the turnpike) as the NJ Turnpike.

In addition, we obtained ambient concentration data from the NJ DEP sites nearest to EOHSI via the US Environmental Protection Agency Air Quality System Data Mart (AQSDM) internet database (New Jersey Department of Environmental Protection, 2014; US Environmental Protection Agency, 2015). Hourly $PM_{2.5}$ was measured in New Brunswick (AQS Code 34-023-0006) by Tapered Element Oscillating Microbalance (TEOM) analyzers before June 30, 2013 and beta particle attenuation (BAM; Thermo 5014i, Franklin, MA, data obtained directly from NJ DEP) after October 16, 2013. Hourly NO_2 was measured at the NJ DEP Rutgers University site (AQS Code 34-023-0011) via chemiluminescence (Thermo 42). Hourly measurements of CO and BC were obtained from the Elizabeth lab site (AQS Code 34-039-0004), located at Interchange 13 near the New Jersey Turnpike. CO was measured by the nondispersive infrared method (Thermo 48) with a detection limit of 0.5 ppm. BC was measured via optical absorption using an aethalometer (Teledyne API Model 633, San Diego, CA; obtained directly from NJ DEP) at Elizabeth Lab between 2013 and 2015. All baseline measurements were averaged over the same time period as in-cabin measurements for direct comparison within each day. No ambient measurements were available for PNC. The NJ DEP sites were 200 m (Elizabeth Lab), 1000 m (New Brunswick), and 1100 m (Rutgers University) from the center of the nearest lane of the New Jersey Turnpike.

2.3 Analysis

In-cabin air pollutant concentrations measured on the full ride, on local roads, and on the NJ Turnpike were compared to ambient air pollutant concentrations. In-cabin measurements on the NJ Turnpike were also compared to measurements on local roads. Inter-pollutant correlations were measured as the Pearson correlations among daily mean ($PM_{2.5}$, PNC, CO, BC, and NO_2) and real-time (1-second) measurements ($PM_{2.5}$, PNC, CO, and BC). For the comparisons of in-cabin concentrations on the NJ Turnpike to in-cabin concentrations on local roads and to ambient concentrations, two alternative measures of exposure were also considered: the absolute difference in concentration (ΔC), and the relative difference (ratio). The three measures of exposure (concentration, ΔC , and ratio) were evaluated by study as well as by day of year (a proxy for seasonality). Comparisons among studies were made using Tukey boxplots and Kruskal-Wallis multiple comparison tests. We also evaluated whether season, traffic congestion, ventilation setting, and study year modified the difference between NJ Turnpike and local road exposure by examination of scatter plots and ANOVA Type III F-tests. All analyses were done in R version 3.1.0 (R Core Team, 2014) and tests were considered statistically significant at the $p < 0.05$ level.

2.4 Human Subjects Statement

The individual NJ Turnpike studies were approved by the Rutgers University Institutional Review Board (IRB), and all subjects gave written informed consent.

3. Results

3.1 In-Cabin Concentrations

The median in-cabin concentrations for the entire ride from leaving the EOHSI parking lot to returning to the parking lot were 11 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$, 40 000 particles/ cm^3 PNC, 0.3 ppm CO, 4 $\mu\text{g}/\text{m}^3$ BC, and 20.6 ppb NO_2 (Table 2). Median concentrations were lower on local roads (e.g., 8 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ and 15 000 particles/ cm^3) than on the NJ Turnpike (e.g., 13 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ and 52 000 particles/ cm^3). The measured concentrations varied by study (Figure 2). $\text{PM}_{2.5}$ decreased over time with a particularly large decrease between NJT 2 and NJT 3, consistent with secular trends reported at state monitoring sites (data not shown). PNC was highest in NJT 1 and NJT 5, and lower in NJT 2, NJT 3, and NJT 4. Median CO was near or below the detection limit for all studies. BC did not statistically differ between NJT 3 and NJT 5, the only studies for which it was measured. NO_2 concentrations varied from 13 ppb to 37 ppb, with only one study (NJT 4) statistically different from the others.

Among daily mean concentrations, the highest Pearson correlations were found for $\text{PM}_{2.5}$ with NO_2 ($r=0.60$ in NJT 1 and 0.63 in NJT 5) and $\text{PM}_{2.5}$ with BC ($r=0.67$ in NJT 5) (Table 3). Daily mean $\text{PM}_{2.5}$ was also highly correlated with BC overall ($r=0.58$) and in NJT 3 ($r=0.55$). Both the magnitude and statistical significance of many of the daily mean correlations varied across studies. Real-time (1-second) Pearson correlations were generally positive ($p<0.05$) with smaller confidence intervals than the daily mean correlations (Table S2).

3.2 Comparison of NJ Turnpike and Non-Turnpike In-Cabin Concentrations

3.2.1 Local Roads—Real-time measurements of $\text{PM}_{2.5}$, PNC, and BC were higher on the NJ Turnpike than on local roads (Table 4). These differences were statistically significant and large for PNC (38 000 particles/ cm^3) and BC (5 $\mu\text{g}/\text{m}^3$). $\text{PM}_{2.5}$ was 3.0 $\mu\text{g}/\text{m}^3$ higher on the NJ Turnpike than local roads, while CO was essentially the same on the NJ Turnpike and local roads. The differences between NJ Turnpike and local road concentrations of PNC and $\text{PM}_{2.5}$ increased over time, especially between NJT 1 and NJT 2 (Figure 3). However, the differences between NJ Turnpike and local road concentrations of CO and BC were similar across studies, suggesting that the sources and emissions of these pollutants were similar for the time period being considered. These results were also consistent across drives; median concentrations were higher on the NJ Turnpike than on local roads for 89% of $\text{PM}_{2.5}$ comparisons, 99% of PNC comparisons, 100% of BC comparisons, and 42% of CO comparisons.

The ratio of real-time in-cabin concentrations on the NJ Turnpike relative to local roads was generally greater than or equal to 1, except for CO (Table 5). In-cabin concentrations on the NJ Turnpike were 1.4 ($\text{PM}_{2.5}$), 3.5 (PNC), 1.0 (CO), and 4 (BC) times higher than in-cabin concentrations on local roads. The ratios for $\text{PM}_{2.5}$ increased between NJT 1 and NJT 3, and the ratios for PNC increased between NJT 1 and NJT 2. The NJ Turnpike to local road ratios of BC were lower in NJT 5 than in NJT 3. Ratios of $\text{PM}_{2.5}$ varied somewhat across studies, while ratios of PNC (NJT 2 – NJT 5) and CO (all five studies) were each the same in the different studies ($p<0.05$; Figure 4).

The sensitivity of the observed differences to the definition of local road was tested using NJT 5, which was the only study to have different logged entries for state highway 287 N and non-highway local roads. During NJT 5, in-cabin concentrations measured on 287 N were consistently higher than in-cabin concentrations on local roads (Figure S1). Concentrations on 287 N were $2 \mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$, 35 000 particles/ cm^3 , 0.2 ppm CO, and $3 \mu\text{g}/\text{m}^3$ BC higher than concentrations on non-highway local roads (Table S3). Ratios of concentrations on 287 N to concentrations on non-highway local roads were 1.4 ($\text{PM}_{2.5}$), 3.6 (PNC), 1.2 (CO), and 4 (BC).

3.2.2 Ambient Monitors—In-cabin concentrations measured during drives were higher than those measured at ambient monitors (Table 4). The median integrated in-cabin NO_2 concentration was 10 ppb higher than ambient concentrations. In-cabin concentrations of $\text{PM}_{2.5}$ on local roads were $2.0 \mu\text{g}/\text{m}^3$ higher than ambient concentrations. Similarly, in-cabin concentrations of black carbon on local roads were $5 \mu\text{g}/\text{m}^3$ higher than concentrations at ambient monitors. There was essentially no difference in median CO on local roads relative to the ambient monitor (median difference: 0.0 ppm, IQR: $-0.2 - 0.3$ ppm). In-cabin concentrations over the full ride were 1.3 ($\text{PM}_{2.5}$), 0.8 (CO), 2 (BC), and 2.4 (NO_2) times higher than ambient concentrations (Table 5). Time spent on the NJ Turnpike was the main contributor to the elevation of $\text{PM}_{2.5}$ and BC above ambient levels. The ratio of in-cabin CO to ambient concentrations was not significantly different from 1.

3.3 Assessment of Modifying Effects

3.3.1 Season—The relationship between in-cabin concentrations on the NJ Turnpike and those on local roads was generally not affected by season (Figure 5). There were two notable exceptions. First, in-cabin PNC on the NJ Turnpike was lower in summer than what would have been otherwise expected based on concentrations on local roads. Second, BC concentrations on the NJ Turnpike were lowest in winter and highest in summer. However, even with these seasonal effects, no significant interactions with season affected the slope of the relationships between in-cabin concentrations on the two types of roads (Table 6).

3.3.2 Traffic Congestion—Traffic congestion as measured by travel time on the NJ Turnpike (sum of northbound and southbound time) was similar across studies (individual study means = 51–63 min, individual study standard deviations = 6–10 min) and had limited correlations with measured in-cabin concentrations. Spearman correlations of measured in-cabin concentrations with travel time were small and non-significant for PNC ($\rho = 0.12$, $p = 0.09$), CO ($\rho = 0.13$, $p = 0.08$), $\text{PM}_{2.5}$ ($\rho = 0.03$, $p = 0.70$), and BC ($\rho = 0.10$, $p = 0.41$). There was a significant interaction of $\text{PM}_{2.5}$ with quartiles of travel time (Table 6); however, this interaction did not change consistently in the same direction for increasing travel time and is therefore unlikely to be a meaningful difference (Figure 6). Although daily traffic volumes were not available for most of the drives, northbound and southbound traffic volumes were similar on different days in October 2014 so we did not separate the northbound and southbound parts of the drive on the NJ Turnpike (data from NJ Turnpike Authority not shown).

3.3.3 Ventilation Setting—Additional drives with closed vents (not included in main analyses) during NJT 2 allowed for sensitivity analysis of ventilation setting effects. Higher in-cabin concentrations were measured when the vents were open relative to when they were closed for PM_{2.5} (median 22 µg/m³ vs 15 µg/m³), PNC (median 42 000 particles/cm³ vs 21 000 particles/cm³), and NO₂ (median 45.2 ppb vs 28.5 ppb; Table 7, Figure S2), consistent with previous literature (Greenwald et al., 2014; Hudda et al., 2011). The median CO concentration was 0.4 ppb for both vent settings. Relative to in-cabin concentrations on local roads, in-cabin PNC was significantly higher (p=0.004) and in-cabin PM_{2.5} concentrations were borderline significantly higher (p=0.15) on the NJ Turnpike when the vents were open than when the vents were closed (Table 6). There were no interactions affecting the slope of the NJ Turnpike and local road relationships for PM_{2.5}, PNC, or CO (Figure 7).

3.3.4 Study Year—There were few changes in the relationship between in-cabin concentrations on the NJ Turnpike and on local roads over time (Figure 8). Local roads, but not the NJ Turnpike, had higher PNC in NJT 1 than in other studies, leading to significant PNC main effects (p<0.0001) and interactions (p=0.03) with study (Table 6). CO was lower in NJT 4 than in other studies. No other significant main effects or interactions were observed. The general lack of substantial differences in different studies suggests that changes in the car type and year of the study did not affect the exposures associated with the scripted drive methods.

4. Discussion

We have evaluated the ability of a quasi-experimental protocol to consistently generate increased air pollution exposures for mechanistic studies of the effects of exposure to traffic on 190 drives over a period of 8 years. For >90% of drives we measured higher in-cabin concentrations of PM_{2.5}, PNC, and BC on a commuting highway with heavy diesel traffic (the NJ Turnpike) relative to local roads. We did not observe elevated concentrations of CO, most likely because CO concentrations were typically close to the detection limit of the monitor. The elevated in-cabin concentrations on the NJ Turnpike relative to other roads were consistent with previous studies in other parts of North America (Greenwald et al., 2014; Weichenthal et al., 2015; Zhu et al., 2008). Our comparisons may be sensitive to the definition of local roads; we showed that including 287 N in our definition of local roads produced conservative estimates of the relative increase of traffic-related air pollutant concentrations on the NJ Turnpike relative to local roads. However, since 287 N is typical of roads driven by participants in daily life and on their way to study visits at EOHHSI, combining 287 N and local roads likely is an acceptable measure of non-turnpike driving exposures for these populations.

We showed that relative exposures (especially ratios) were more stable metrics than in-cabin concentrations; although differences between concentrations are often used in scripted studies, it is probably more statistically sound to use ratios or log-transformed concentrations. Variability in all exposure metrics between individual drives was expected and accepted due to the real-world nature of the scripted drives. In the future, scripted drives like these can also be used to determine the most appropriate exposure metrics (e.g., peak,

mean, or median concentrations) for health studies by exploring the nature of the dose-response relationship between exposure to specific pollutants and health outcomes.

In our assessment of modifying effects, we showed that relationships between in-cabin concentrations on the NJ Turnpike and on local roads were robust to season, traffic congestion, ventilation setting, and (for the most part) study year. While some unavoidable differences in conditions (e.g., multiple vehicles, seasonal and secular trends) introduced uncertainty in the measurements, these variations also improved the overall generalizability and applicability of our results. However, some of the remaining differences among the NJ Turnpike studies may have been related to changes in air exchange rates due to vehicle characteristics like age, interior volume (e.g., NJT 1 was conducted in a SUV), and cabin air filter efficiency (Hudda and Fruin, 2013; Zhu et al., 2007), and future studies could achieve even higher consistency among measurements by obtaining a single vehicle for all measurements.

Differences could have also been related to changes in vehicular emissions and ambient concentrations over the course of the studies. NJT 1 occurred during a recession during which diesel truck traffic volume was reduced, and at the tail end of the ultra-low sulfur diesel fuel (ULSD) phase-in (U.S. Environmental Protection Agency, 2011). In addition, there was a secular trend in ambient $PM_{2.5}$ over the years of the studies, with a particularly large decrease of $\sim 3 \mu g/m^3$ from NJT 1 through NJT 3 and the highest in-cabin $PM_{2.5}$ concentrations were mainly observed on several days with much higher ambient $PM_{2.5}$ than other days (US Environmental Protection Agency, 2015). Federal diesel vehicle emission regulations for particulate matter (0.01 g/bhp-hr) were implemented in model year 2007 and regulations for NO_X (0.20 g/bhp-hr) were phased in between model years 2007 and 2010 (DieselNet, 2015). In addition, municipal diesel vehicle particle and NO_X control technologies have slowly been upgraded since 2008 through the NJ Mandatory Diesel Retrofit program, although it is unknown to what extent this would have affected diesel-powered vehicle emissions on the NJ Turnpike.

Although we compared real-time measurements to ambient measurements at the NJ DEP regulatory sites, differences in measurement techniques contributed to uncertainty in the comparisons between in-cabin and ambient concentrations. Due to differences in particle composition, photometers, including the Sidepak used to measure $PM_{2.5}$ in this study, are known to report higher concentrations than the federal reference methods used at regulatory sites (Jiang et al., 2011; Wallace et al., 2006). While we used an experimental calibration factor to adjust Sidepak measurements for better comparison with NJ DEP monitors, residual differences that may have varied by season likely remained (Wallace et al., 2006). Similarly, there may be residual differences between the microAethalometer and the NJ DEP rack-mounted aethalometer due to site and season-specific factors in loading and aerosol properties (Cheng and Lin, 2013). Although no correction was made for differences between integrated samples and chemiluminescence measurements of NO_2 , we expect that differences between the two measurement methods were $\sim 10\%$ based on measurements reported by Wang et al. (1999). In addition, ambient PNC measurements were not available and we did not adjust for multiple particle incidence in the CPC because we used non-parametric methods for comparisons and only the top 8% of PNC measurements were likely

to be affected (Collins et al., 2013). However, all of the comparisons with ambient concentrations suggest that the monitor calibrations were in reasonable agreement because similar results were obtained when measurements on local roads were used as the baseline for comparison.

From the outcomes of this work, we have the following recommendations for researchers planning scripted drive studies. First, identify appropriate ambient or typical exposures for comparison prior to the study, and conduct baseline measurements prior to and during the scripted drives. Second, if multiple measurement methods are being used, establish comparability of the reported concentrations, preferably with local calibrations to avoid uncertainties due to comparability of portable monitors with ambient air quality monitors. Third, this and previous analyses show that in-cabin concentrations, like on- and near-road concentrations, vary over multiple years and seasons (Greenwald et al., 2014; Patton et al., 2014; Weichenthal et al., 2015). Since scripted drives with study participants must be scheduled well in advance, it may be difficult to select for specific weather conditions and therefore researchers should conduct their studies at times of the year with the highest probability of desired conditions. Assessing exposure as ratios of on-road concentrations relative to ambient concentrations may help to control for seasonality. Alternatively, all drives of a study requiring consistent in-cabin concentrations could be conducted in the same season. Standardizing drive times, locations, and ventilation settings could also improve levels of comparability across studies. Additional research would be needed to determine whether these results are generalizable to other locations.

5. Conclusions

We assessed the robustness of a scripted drive field protocol used over a period of 8 years to generate exposure contrasts for mechanistic studies of the effects of traffic-related air pollution on health outcomes. We found higher in-cabin concentrations of traffic-related air pollution in passenger vehicles during scripted drives on a 12-lane commuting highway with heavy diesel traffic than on local roads. Scripted drives with controlled vehicle settings generated reasonably robust increases in exposure with respect to season, traffic congestion, ventilation setting, and study year. Location and season affected in-cabin concentrations of some pollutants as well as the differences in air pollutant concentrations between the highway and local roads, and should be considered during study design to obtain the desired exposure contrasts for the pollutants of interest. Our scripted drive protocol is applicable to studies of human responses to real-world traffic exposures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

1. Scripted drives on the NJ Turnpike and local roads on 190 days over 8 years.
2. Measured PM_{2.5}, PNC, CO, BC, and NO₂ in the car cabin.
3. Higher concentrations on NJ Turnpike (NJT) compared to local roads.
4. NJT exposure increase robust to season, traffic congestion, and ventilation.

Figure 1. Scripted round-trip drives between EOHSI (Rutgers) and the Vince Lombardi Service Area (Rest Stop) on the New Jersey Turnpike. Ambient air pollutant measurements were obtained from the NJ DEP sites at Elizabeth Lab, New Brunswick, and Rutgers University.

Figure 2. Tukey boxplots of measured real-time concentrations of (a) PM_{2.5}, (b) PNC, (c) CO, (d) BC, and (e) NO₂ for full drives in NJT 1-5. Letters within each box represent statistically different groups according to the Kruskal-Wallis test ($p < 0.05$).

Figure 3.

Tukey boxplots of the arithmetic difference between median NJ Turnpike concentrations and local road concentrations of (a) $PM_{2.5}$, (b) PNC, (c) CO, and (d) BC for NJT 1-5. Letters within each box represent statistically different groups according to the Kruskal-Wallis test ($p < 0.05$).

Figure 4.

Tukey boxplots of the ratio of median NJ Turnpike concentrations to median local road concentrations of (a) PM_{2.5}, (b) PNC, (c) CO (outliers not shown: 47, 102 (5 instances), 157 (2 instances), 185, 212, and 322 (2 instances)), and (d) BC for NJT 1-5. Letters within each box represent statistically different groups according to the Kruskal-Wallis test ($p < 0.05$).

Figure 5.

Relationship between in-cabin concentrations of PM_{2.5}, PNC, CO, and BC on the NJ Turnpike and in-cabin concentrations on local roads for winter (DJF = December, January, February), spring (MAM = March, April, May), summer (JJA = June, July, August), and fall (SON = September, October, November). Note: The axes are drawn on a log-scale because the concentrations are not normally distributed.

Figure 6.

Relationship between in-cabin concentrations of PM_{2.5}, PNC, CO, and BC on the NJ Turnpike and in-cabin concentrations on local roads by quartile of travel time on the NJ Turnpike (a proxy for traffic congestion). Note: The axes are drawn on a log-scale because the concentrations are not normally distributed.

Figure 7.

Relationship between in-cabin concentrations of $PM_{2.5}$, PNC, and CO on the NJ Turnpike and in-cabin concentrations on local roads for in study NJT 2 under conditions of open and closed vents. Note: The axes are drawn on a log-scale because the concentrations are not normally distributed.

Figure 8. Relationship between in-cabin concentrations of PM_{2.5}, PNC, and CO on the NJ Turnpike and in-cabin concentrations on local roads as a function of study number. Note: The axes are drawn on a log-scale because the concentrations are not normally distributed.

Table 1

Study overview.

Study name	NJT 1 (Laumbach et al., 2010)	NJT 2	NJT 3 (Laumbach et al., 2014)	NJT 4 (Pettit et al., 2015)	NJT 5	Overall
Health outcomes^a	BP, P-nitrite	BP, HR, HRV, P- nitrite, EBC- nitrite	BP, HR, HRV, EBC-nitrite	BP, HR, HRV, P- nitrite	BP, HR, P-nitrite	
Participant disease status	All Diabetic	All COPD	All Healthy	Diabetic & Healthy	All Healthy	
# drives	21	15 ^b	42	84	28 ^c	190
Start date	04/23/2007	10/13/2008	1/12/2010	9/20/2010	12/13/2013	04/23/2007
End date	01/23/2008	10/8/2009	4/26/2011	8/29/2012	10/21/2014	10/21/2014
Earliest start time	8:17	8:00	8:00	8:16	8:04	8:00
Latest end time	13:55	13:55	11:38	11:45	11:30	13:55
Turnpike ADT^d	N/A	136 000	132 000	131 000	132 000	131 000
Turnpike % Diesel	N/A	12	13	13	13	13
ULSD use^e	92% - 95%	98%		>99%		92% - 100%
Vent Filter		Unmodified			Removed	
Vehicle	Ford Explorer SUV & Chevy SUV		1998 or 2002 Ford Taurus		2005 Ford Taurus	

^aThe health outcomes were blood pressure (BP), heart rate (HR), heart rate variability (HRV), plasma nitrite (P-nitrite), and exhaled breath condensate nitrite (EBC-nitrite).

^bIn NJT 2, 15 drives were conducted in following the standard protocol and included in inter-comparison of studies. 15 additional drives with vents closed were used for sensitivity analysis.

^cNJT 5 had a small number of runs because many of the drives had two participants in the same car.

^dADT is the average daily traffic in vehicles per day.

^eNJT 1 took place towards the end of the phase in of ultra-low sulfur diesel fuel (ULSD) from low sulfur diesel fuel (U.S. Environmental Protection Agency, 2011).

Table 2

Median (25th percentile, 75th percentile) of concentrations of PM_{2.5}, PNC, CO, BC, and NO₂ at NJ Department of Environmental Protection sites, for full rides, and on local roads or the NJ Turnpike only. All values are presented as the median (25th percentile, 75th percentile) of all measurements.

Pollutant	Ambient ^a	Full Ride	Local roads only	NJ Turnpike only
PM _{2.5} (µg/m ³)	8.8 (4.2, 15.3)	11 (6, 17)	8 (5, 13)	13 (8, 19)
PNC (10 ³ #/cm ³)	--- ^b	40 (20, 69)	15 (7, 34)	52 (32, 82)
CO (ppm)	0.25 (0.25, 0.50) ^b	0.3 (0.0, 1.0)	0.2 (0.0, 0.9)	0.4 (0.0, 1.0)
BC (µg/m ³)	2.46 (1.67, 3.81) ^b	4 (2, 9)	2 (1, 4)	6 (3, 11)
NO ₂ (ppb)	8 (4, 16)	20.6 (12.7, 28.6)	--- ^b	--- ^b

^a Ambient measurements were collected from the nearest NJ DEP site monitoring each pollutant. The site for PM_{2.5} was in New Brunswick, the sites for CO and BC were at Elizabeth lab, and the site for NO₂ was at Rutgers University (New Brunswick).

^b Because NO₂ was measured as a single integrated sample for each drive, and there was no ambient PNC monitor, these data were not available.

Table 3

Pearson correlations with 95% confidence intervals of daily mean concentrations.

Study	Pollutant	PNC	CO	BC	NO ₂
Overall	PM_{2.5}	0.19 (0.04, 0.33)	0.16 (0.01, 0.30)	0.58 (0.39, 0.72)	0.42 (0.29, 0.54)
	PNC		0.21 (0.07, 0.35)	−0.18 (−0.41, 0.07)	0.22 (0.07, 0.36)
	CO			0.15 (−0.10, 0.39)	0.22 (0.07, 0.36)
	BC				0.37 (0.13, 0.57)
NJT 1	PM_{2.5}	0.06 (−0.39, 0.49)	−0.26 (−0.62, 0.19)	--- ^a	0.60 (0.23, 0.82)
	PNC		−0.07 (−0.50, 0.38)	---	0.13 (−0.33, 0.54)
	CO			---	0.12 (−0.33, 0.53)
	BC				--- ^a
NJT 2	PM_{2.5}	0.45 (−0.08, 0.78)	0.35 (−0.19, 0.73)	--- ^a	0.59 (0.06, 0.86)
	PNC		0.51 (−0.01, 0.81)	---	−0.34 (−0.75, 0.26)
	CO			---	−0.15 (−0.65, 0.44)
	BC				--- ^a
NJT 3	PM_{2.5}	−0.15 (−0.43, 0.17)	0.16 (−0.15, 0.44)	0.55 (0.29, 0.73)	−0.01 (−0.32, 0.29)
	PNC		0.17 (−0.14, 0.45)	−0.17 (−0.45, 0.15)	0.36 (0.06, 0.60)
	CO			0.37 (0.07, 0.61)	0.36 (0.07, 0.60)
	BC				0.23 (−0.08, 0.50)
NJT 4	PM_{2.5}	0.24 (0.01, 0.44)	0.34 (0.13, 0.52)	--- ^a	0.04 (−0.19, 0.26)
	PNC		0.54 (0.36, 0.68)	---	0.38 (0.17, 0.56)
	CO			---	−0.00 (−0.23, 0.22)
	BC				--- ^a
NJT 5	PM_{2.5}	−0.09 (−0.51, 0.35)	0.59 (0.21, 0.81)	0.67 (0.35, 0.85)	0.63 (0.28, 0.83)
	PNC		−0.19 (−0.58, 0.28)	−0.26 (−0.62, 0.19)	0.17 (−0.28, 0.56)
	CO			0.25 (−0.21, 0.61)	0.16 (−0.29, 0.55)
	BC				0.72 (0.43, 0.88)

^aBC was not measured in NJT 1, NJT 2, and NJT 4.

Table 4

Daily median increase in concentration (C) on the NJ Turnpike relative to local roads, and on local roads and the NJ Turnpike relative to ambient measurements at the Department of Environmental Protection sites.^a All values are presented as the median (25th percentile, 75th percentile) of all measurements.

Pollutant	Difference in Concentrations in Data Subsets			
	Full ride – Ambient	Local roads only – Ambient	NJ Turnpike only – Ambient	NJ Turnpike only – Local roads
PM _{2.5} (µg/m ³)	2.0 (−0.9, 5.6)	1.9 (−2.0, 6.0)	2.3 (−0.6, 5.8)	3 (1, 5)
PNC (10 ⁴ #/cm ³)	--- ^b	--- ^b	--- ^b	3.8 (2.6, 5.8)
CO (ppm)	−0.0 (−0.2, 0.3)	−0.0 (−0.2, 0.4)	−0.0 (−0.2, 0.3)	0.0 (0.0, 0.2)
BC (µg/m ³) ^c	5 (3, 6)	5 (2, 6)	5 (3, 6)	5 (3, 7)
NO ₂ (ppb)	10 (2, 20)	--- ^b	--- ^b	--- ^b

^a Ambient measurements were collected from the nearest NJ DEP site monitoring each pollutant. The site for PM_{2.5} was in New Brunswick, the sites for CO and BC were at Elizabeth lab, and the site for NO₂ was at Rutgers University (New Brunswick).

^b Because NO₂ was measured as a single integrated sample for each drive, and there was no ambient PNC monitor, these comparisons could not be made.

^c Black carbon was only measured during NJT 3 and 5.

Table 5

Daily median ratio of concentrations on the NJ Turnpike relative to local roads, and on local roads and the NJ Turnpike relative to ambient measurements^a at the Department of Environmental Protection sites. All values are presented as the median (25th percentile, 75th percentile) of daily medians.

Pollutant	Ratio of Concentrations in Data Subsets			
	Full ride/Ambient	Local roads only / Ambient	NJ Turnpike only / Ambient	NJ Turnpike only / Local roads only
PM _{2.5} (µg/m ³)	1.3 (0.9, 1.8)	1.2 (0.8, 1.9)	1.3 (0.9, 1.8)	1.4 (1.2, 1.8)
PNC (10 ⁴ #/cm ³)	--- ^b	--- ^b	--- ^b	3.5 (2.6, 5.4)
CO (ppm)	0.8 (0.0, 2.2)	0.9 (0.0, 2.2)	0.8 (0.0, 2.2)	1.0 (1.0, 1.5)
BC (µg/m ³) ^c	2 (1, 2)	2 (1, 3)	2 (1, 3)	4 (3, 6)
NO ₂ (ppb)	2.4 (1.3, 4.6)	--- ^b	--- ^b	--- ^b

^a Ambient measurements were collected from the nearest NJ DEP site monitoring each pollutant. The site for PM_{2.5} was in New Brunswick, the sites for CO and BC were at Elizabeth lab, and the site for NO₂ was at Rutgers University (New Brunswick).

^b Because NO₂ was measured as a single integrated sample for each drive, and there was no ambient PNC monitor, these comparisons could not be made.

^c Black carbon was only measured during NJT 3 and 5.

Table 6

ANOVA Type III p-values for modifying effects on the relationship between in-cabin concentrations on the NJ Turnpike and in-cabin concentrations on local roads (all log-transformed).

Modifying Effect	Pollutant	p (main effect)	p (interaction)
Season^a	PM _{2.5}	0.12	0.53
	PNC	<0.0001	0.23
	CO	0.09	0.70
	BC	0.0001	0.34
Traffic Congestion^b	PM _{2.5}	0.26	0.02
	PNC	0.34	0.99
	CO	0.16	0.82
	BC	0.40	0.77
Ventilation Setting^c	PM _{2.5}	0.15	0.12
	PNC	0.004	0.82
	CO	0.68	0.15
	BC	0.41	0.86
Study Number	PM _{2.5}	0.13	0.30
	PNC	<0.0001	0.03
	CO	0.04	0.23
	BC	0.41	0.86

(d) The comparison by study number included NJT 1, NJT 2, NJT 3, NJT 4, and NJT 5.

^aSeasons are defined as **DJF** = Dec, Jan, Feb; **MAM** = Mar, Apr, May; **JJA** = Jun, Jul, Aug; **SON** = Sep, Oct, Nov.

^bTraffic congestion (measured as travel time) was split by quartile **Q1** = 30.1 - 56 min; **Q2** = 56 - 59 min; **Q3** = 59 - 62 min; **Q4** = 62 - 93 min.

^cFor NJT 2 only, additional drives were made with the vents closed. The comparison is between open and closed vents.

Table 7

Median (IQR) of concentration, daily median increase in concentration (C) on the NJ Turnpike relative to local roads, and daily median ratio of concentrations on the NJ Turnpike relative to local roads of PM_{2.5}, PNC, CO, and NO₂ by ventilation setting for NJT 2.^a

Pollutant	Ventilation Setting Concentration		Difference in Concentration NJ Turnpike only – Local roads only		Ratio of Concentrations (unitless) NJ Turnpike only / Local roads only	
	Closed	Open	Closed	Open	Closed	Open
PM _{2.5} (µg/m ³)	15 (12, 22)	22 (15, 30)	1 (0, 4)	5 (1, 7)	1.1 (1.0, 1.2)	1.2 (1.1, 1.5)
PNC (10 ⁴ #/cm ³)	21 (13, 28)	42 (21, 70)	1.3 (0.9, 1.9)	4.6 (3.1, 4.8)	2.6 (1.7, 3.2)	3.8 (2.5, 5.6)
CO (ppm)	0.4 (0.1, 0.8)	0.4 (0.1, 0.7)	0.1 (–0.0, 0.2)	0.0 (0.0, 0.2)	1.1 (1.0, 1.4)	1.2 (1.0, 1.6)
NO ₂ (ppb)	28.5 (19.1, 37.3)	45.2 (21.5, 66.7)	--- ^b	--- ^b	--- ^b	--- ^b

^aThe ventilation settings were Closed vents (n=15) and Open vents (n=15). Statistically significantly different pairs according to the Kruskal-Wallis test are bold.

^bBecause NO₂ was measured as a single integrated sample for each drive, these comparisons could not be made.