Air Pollution and Activity During Transportation by Car, Subway, and Walking

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Background: Little evidence exists about the health risks and benefits associated with using public buses and subways rather than cars. The objective of the current study was to assess the magnitude and variance of personal exposure to particulate matter 2.5 microns or smaller (PM$_{2.5}$) and concomitant physical activity energy expenditure (PAEE) for transportation by car, subway, or walking.

Methods: Twenty nonsmoking volunteers from New York City traveled on predetermined routes by car, subway, and walking, for up to 8 hours on 3 different days, between October 2007 and February 2008. Outfitted with a personal monitor with PM$_{2.5}$ aerosol inlet, and a GPS receiver, they completed a detailed physical activity diary for each route. Both metabolic equivalent (MET) and PAEE rates (Kcal/min) were computed from GPS-derived activity durations and speeds, activity-specific METs, and measured body weight.

Results: Total PM$_{2.5}$ exposures did not differ among car, subway, and walking arms (respectively, 21.4, 30.6, and 26.5 g/m$^2$·min, $p=0.19$); but average MET values (respectively, 1.51, 2.03, and 2.60 Kcal/kg·hr, $p<0.0001$) and PAEE rates (1.74, 2.35, and 3.04 Kcal/min, $p<0.0001$) did. After correction for the humidity factor, exposure to PM$_{2.5}$ appeared to be lower for the car arm (13.1 g/m$^2$·min) than for the subway (19.6 g/m$^2$·min) or walking (23.9 g/m$^2$·min, $p=0.004$) arms.

Conclusions: Driving cars was associated with less physical activity but not necessarily less exposure to PM$_{2.5}$ than riding subways or walking in an urban environment. These effect sizes and variances can be used to design larger experiments assessing the health effects of urban transportation.

Introduction

Little evidence exists about health risks and benefits associated with using public buses and subways rather than cars. Health benefits may result from walking to and from stations, standing, and climbing stairs.1–3 There can, however, be harmful effects if commuters using public transportation are more exposed to air pollution than those driving cars.4,5

Given that the short-term health effects of a transportation mode could be incrementally small, large groups must be studied in order to detect changes in both physical activity and exposure to air pollutants. Preliminary research is therefore needed to test methods to assess both physical activity and air pollution exposure at the individual level and to identify simple ways to measure these factors using instruments that do not disproportionately interfere with the daily commute. Such research can also provide estimates of effect size and variance, which enter into power and sample-size calculations for intervention studies.

The current study was conducted in New York City (NYC) to simultaneously compare (1) personal exposure to particulate matter 2.5 microns or smaller (PM$_{2.5}$); and (2) level of physical activity based on time-stamped, objective data (i.e., GPS location and route) and self-reported (e.g., diary describing each minute of the commute) data among 20 volunteers who each completed three (up to) 8-hour arms during which they alternated using a car, the subway, and walking while traveling the same arm-specific route. For this purpose, optimally portable instruments for data collection were selected.
Materials and Methods

Through the use of posters on the campus of Queens College, City University of New York, 20 volunteers were recruited. They were financially remunerated for their time and transportation costs. Being a nonsmoker and either a student or an employee of Queens College were the only enrollment criteria. No volunteer was refused. Signed informed consent was obtained with a protocol approved by the Institutional Review Board (IRB) of Queens College.

Study Arms

The study required each participant to complete a car, subway, and walking arm, each planned to last 8 hours, starting from and returning to the Queens College campus. The car arm consisted of several loops across the borough of Manhattan. The subway arm took the participants to the south end of the Borough of Brooklyn and through Manhattan up to the northern end of the Borough of the Bronx. The walking arm ranged from Midtown Manhattan to the southern tip of Manhattan and back. Recent models of midsized rental cars were provided for the car arm, and travel passes for NYC public transportation were provided for the walking and subway arms. For the subway arm, formal authorization was obtained from the Metropolitan Transportation Authority, which in turn informed the NYC Police Department.

Because the objective was to measure air pollution in cars under realistic conditions, participants were free to use the windows and air circulation features of the car as they wished for their own comfort. However, in order to allow for subsequent analyses of the effect of these ventilation factors on exposure to PM$_{2.5}$, participants were instructed to report in their minute-by-minute diary (discussed below) whether the windows were closed or open and whether the internal circulation was on or off.

Equipment

Air quality monitor. Participants were equipped with an AM510 SidePak™, real-time personal aerosol monitor. The instrument is a laser photometer, which uses light-scattering technology to determine mass concentration of particulate matter. Reliability and validity data related to the measurement of individual exposure to small particulates have been reported.6

The personal aerosol monitors were equipped with a PM$_{2.5}$ size-selective inlet. The sample intake was located in the participants’ breathing zone using conductive tubing attached to the device. Measurements were recorded in 1-minute intervals, and after each completed run, the data were downloaded for analysis.

The GPS receiver. The Garmin Forerunner® 305 GPS receiver recorded participants’ positions several times per minute. This receiver is a wide-angle augmentation system (WAAS)—enabled GPS receiver that uses a SiRFstar III GPS microcontroller chip. Although it is the size of a large watch, this receiver is less dependent than older GPS receivers on a clear view of the sky in order to reach satellites to accurately record latitude and longitude. This receiver can be expected to have greater validity and reliability7 than that reported for older GPS receiver models,8,9 but formal reproducibility in studies such as this is not yet available for this device.

At the beginning of each field day, the receivers were programmed with the participant’s gender, date of birth, and weight, which had been previously measured using a Detecto® medical stadiometer. The data were collected and stored in the device and later downloaded into Garmin’s proprietary Training Center software.

Data were processed using ArcGIS version 9.2 and projected into an ArcMap file containing base maps of the five boroughs of NYC, including a digital elevation model, street layer, subway line layer, and satellite imagery at 1-meter resolution. The GIS analyst removed erroneous GPS waypoints that were >15 meters away from previous or consecutive waypoints. GPS signal errors in cities often are due to the “urban canyon” effect of tall buildings near the GPS receiver.

ET GeoWizards version 9.2.7, an extension of ArcGIS 9.2, was used to compute length and duration of each activity segment occurring above ground. The type of activity for each segment of the GIS model was extracted from the participants’ diary information.

In the absence of a GPS signal along the underground subway sections, GPS data did not discriminate among the various activities inside the station and in subway cars. Underground subway segments were therefore assessed by the interruption of the GPS signal.

Average MET and Physical Activity Energy Expenditure (PAEE) Values

First, MET values were assigned to each transportation mode. A MET of 1 corresponds to the energy expended by the body while lying with no activity (e.g., sleeping). From the Compendium of Physical Activities,10 MET values were extracted for various speeds of walking. Because the GPS-based assessment of physical activity provides exact speeds per segment, a linear regression was used to interpolate the speed/MET data given by the Compendium to estimate speed/MET values not provided by the Compendium. The speed/MET values of the Compendium were perfectly aligned on a straight line, allowing for a safe interpolation. Regressing MET values on speed data yielded the following calibration equation, which was used to estimate the segment and individual, specific MET values:

$$MET = -3.9 + 2.3 \times \text{Speed}, \text{ for speeds between 2.5 and 8 mph.}$$

Walking speeds <2.5 mph were assigned a MET value of 1.5. According to an analysis performed in ArcMap 9.2 using the U.S. Geographic Survey’s digital elevation model at 10-meter resolution, slopes did not exceed a 4% grade along any of the participants’ walking paths. Therefore, the MET values were not adjusted for terrain slope effects. Driving a car and riding on a bus (not including walking to the bus station) were each assigned an average MET value of 1.5. Using the subway, an activity not included in the Compendium, was assigned a MET value of 2.0, equivalent to the value assigned to activities in the “standing miscellaneous” category in the Compendium.

To compute the average MET and PAEE values per arm, each commute was broken down into activity segments, defined by GPS recording (i.e., distance and time) of mode of transportation (e.g., car driving, bus riding, subway riding, ...
walking). Each activity segment was associated with its specific MET coefficient. The average MET value for each study arm was computed as the average of all segment-specific MET values weighted by the segment duration. The product of the MET value (Kcal/kg of body weight/hour) and the duration (in hours) of each activity segment provided the segment-specific Kcal/kg, which, multiplied by the participant weight (kg), provided the PAEE (Kcal) for the segment. The sum of all segment-specific PAEE values provided the total PAEE value for a study arm. The total PAEE was divided by the total arm duration to get the PAEE rate by minute (Kcal/minute) for each study arm.

Physical Activity Diary
In order to match the location information with PM$_{2.5}$ and GPS data, each volunteer was required to maintain a time–activity diary. The diaries had preprinted, minute-by-minute, time and activity columns. The activity column catalogued the most important circumstances that required recording, such as whether the participant was sitting, walking, or standing; whether the car was moving or stopped; and the position of the windows and vents. For the car arm, three participants rode together: one volunteer drove, a second participant recorded the route, and the third completed the physical activity diary. For the walking arm, participants were provided with a digital recorder, allowing them to dictate diary information as they walked. For the subway arm, all participants were responsible for completing the diary on their own. Completing the diary represented a modest burden for the participants because they had to record only the exact time at which a change occurred. With the exception of entering and exiting a subway station, there was a minimum of 5 minutes between changes in activities and usually much longer. Segments of dense changes, such as entering a subway station, did not last long compared to segments of homogenous activity.

At the end of each arm, participants were given a printed copy of their diary, or their digital voice recording, and asked to transcribe the information into a preformatted Excel spreadsheet. It was assumed that they would be more accurate than the research staff in deciphering and coding their notes. The transcription was reviewed by study staff. In some cases, data were entered directly by research staff when participants delayed in completion of this task.

Quality Assessment and Control
The SidePak AM510 personal aerosol monitors were factory calibrated to the respirable fraction of standard ISO 12103, A1 Test Dust (Arizona road dust). Prior to each field use, the instruments were zeroed, the PM$_{2.5}$ inlets cleaned, the flow rates adjusted to 1.7 liters per minute using a Gillian bubble flow meter, and the battery packs recharged. An intercomparison of six SidePak AM510 monitors in indoor and outdoor settings for 7 days each at Queens College showed highly reliable recording (data available upon request).

The relative humidity levels of the sampling environment may affect the accuracy of real-time mass concentration measured by the aerosol photometer. Fine particles, typically those $<2.5\,\mu m$, grow by liquid water accretion on their surfaces whenever the ambient relative humidity increases to levels $>50\%$. Under such conditions, the SidePak AM510 overestimates the mass concentration of the fine fraction that is caused by moisture-induced particle growth. Coarse particles ($>2.5\,\mu m$), in contrast, exhibit negligible humidity-induced growth in proportion to their original size. A correction was made for this possible overestimation of PM$_{2.5}$ under usual levels of daytime winter humidity in NYC using the relationship $^{11}$

$$PM_{2.5}(\text{corrected}) = PM_{2.5}(\text{measured}) / (1 + 0.25(\text{Relative Humidity}^2/[1 - \text{Relative Humidity}]))$$

Relative humidity was computed as an average (over the study hours for a specific day) of hourly ambient relative humidity downloaded from the New York State Department of Environmental Conservation website, in Flushing, Queens (www.dec.ny.gov/airmon/stationStatus.php?stationNo=59).

Equipment Troubleshooting
Each participant’s equipment was set up separately to prevent interference of the instruments with one another. Participant awareness of instruments and their feedback in the field ensured that any problems in data collection (i.e., instrument not working, batteries low) were reported and, if possible, directly corrected by the participants. On-call support was provided throughout each study session.

Data Analysis
Each participant’s data for PM$_{2.5}$ exposure were recorded in units per minute for each arm. The PM$_{2.5}$ value was log-transformed for analysis because its distribution was observed to be lognormal. Geometric means for PM$_{2.5}$ and their 95% confidence intervals (CIs) were computed from the per-minute records, and their variance was corrected for the clustering of observations within subjects (SAS PROC Surveymeans with cluster option). The PM$_{2.5}$ data were analyzed with and without correction for relative humidity levels. Differences across arms were tested using SAS PROC Surveyreg including the cluster option.

The GPS distances were used as recorded. Differences of average MET and PAEE values for the same individuals across transportation modes were compared using ANOVA (SAS PROC GLM) and Dunnett’s post hoc test. SAS version 9.1 was used for all statistical models and parametric tests.

Results
Participant Characteristics
The 20 participants (11 men and nine women) all completed the three routes. Because of recording failures of one monitor and two GPS units, full information was missing for one subway route and two walking routes. The median age was 23 years; the median weight was 74.6 kg.

Particulate Matter$_{2.5}$
In the analysis without correction for the humidity factor (Table 1), differences between geometric means (21.4, 30.6, and 26.7 $\mu g/m^3/min$, for the car, subway, and walking arms, respectively) were not significant, overall ($p=0.19$) or as pair-contrasts. After correcting for humid-
ity, however, the differences were significant ($p < 0.0043$), the difference being the result of the car–subway ($p < 0.02$) and car–walking ($p < 0.08$) contrasts but not the subway–walking contrast ($p < 0.45$).

**Duration, Distance, MET and PAEE Values**

Complete GPS data within each study arm and for the three study arms necessary to compute and compare the physical activity measures were available for 15 participants. The total times and distances measured by the GPS device are given in Table 2. The eight men expended more energy than the seven women for the same runs, but the transportation arm effects were identical in the two genders (data not shown). Given the small sample size, gender-specific results are not reported. For the car, subway, and walking arms, respectively, average MET values were 1.51, 2.03, and 2.60 Kcal/kg·hr ($p < 0.0001$), and median PAEE rates were 1.85, 2.49, and 2.84 Kcal·min ($p < 0.0001$).

**Habitat Conditions of the Car Routes**

An analysis of the car diary data reveals that the highest mean concentrations of PM$_{2.5}$ were observed when both windows were closed and the internal circulation was off (44 g/m$^3$·min); the lowest were observed when the windows were closed and the internal circulation was on (18 g/m$^3$·min). The main effects of windows and circulation, as well as interactions, were highly significant, with $p$ values < 0.001.

**Discussion**

This study has identified relatively simple ways to simultaneously assess transportation-related physical activity on the basis of GPS measures and exposure to PM$_{2.5}$ using a SidePak aerosol monitor. These measurements were compatible with several hours of travel within NYC, and the monitors proved to be dependable, with only three unexplained technical failures among 60 routes of more than 7-hours' duration each.

**Particulate Matter$_{2.5}$**

Exposure levels to PM$_{2.5}$ for the car arm were lower than those for the subway and walking arms, but this difference was significant only after adjusting for ambient humidity levels. An analysis of the diary data indicated that PM$_{2.5}$ levels were lower when windows were closed and the internal circulation was on.

The National Ambient Air Quality Standards promulgated by the Environmental Protection Agency for 2006 are 15 g/m$^3$ annual average, and 35 g/m$^3$ 24-hour average to be exceeded only seven times per year. The average exposures observed for all modes of transportation, with the exception of the car commute after correction for humidity, exceeded the permitted annual average level.

The current humidity-corrected results are consistent with previous results showing that Londoners who walk along the same short route (average 12.8 minutes) as a diesel car (average 3.7 minutes, but repeated to

### Table 1. Exposure to PM$_{2.5}$ ($\mu$g/m$^3$·min) by study arms; New York, Winter 2007–2008

<table>
<thead>
<tr>
<th>Variable</th>
<th>Statistics</th>
<th>Car ($n=7941$ in 20 subjects)</th>
<th>Subway ($n=6299$ in 19 subjects)</th>
<th>Walking ($n=5929$ in 18 subjects)</th>
<th>ANOVA $p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$ ($\mu$g/m$^3$·min)</td>
<td>Geometric M</td>
<td>21.4 (15.7, 29.2)</td>
<td>30.6 (22.9, 40.9)</td>
<td>26.7 (17.2, 41.6)</td>
<td>0.1914*</td>
</tr>
<tr>
<td></td>
<td>(95% CI)$^a$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM$_{2.5}$, corrected$^a$</td>
<td>Geometric M</td>
<td>12.5, 25, 42</td>
<td>21, 26, 65</td>
<td>10, 29, 60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(95% CI)$^a$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$Based on 20,169 assessments of exposure, each 1 minute in duration; variance corrected for individual clusters of 1-minute assessments of exposure to PM$_{2.5}$

$^b$Corrected for relative humidity

*Post hoc $t$-test: $p < 0.05$ for all pair-wise comparisons

P25, 25th percentile; P75, 75th percentile; PM$_{2.5}$, particulate matter ≤ 2.5 micrometers in diameter

### Table 2. Measured variables for 15 subjects with complete GPS data; New York, Winter 2007–2008

<table>
<thead>
<tr>
<th>Variables</th>
<th>Statistics</th>
<th>Car</th>
<th>Subway</th>
<th>Walking</th>
<th>ANOVA $p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average MET (Kcal/kg·hr)</td>
<td>M</td>
<td>1.51</td>
<td>2.03</td>
<td>2.60</td>
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<tr>
<td></td>
<td>SE</td>
<td>0.01</td>
<td>0.04</td>
<td>0.14</td>
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<tr>
<td></td>
<td>Median</td>
<td>1.50</td>
<td>2.01</td>
<td>2.65</td>
<td></td>
</tr>
<tr>
<td>PAEE rate (Kcal/min)</td>
<td>M</td>
<td>1.74</td>
<td>2.35</td>
<td>3.04</td>
<td>&lt;0.000*</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>0.09</td>
<td>0.14</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>1.85</td>
<td>2.49</td>
<td>2.84</td>
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</tr>
<tr>
<td>Total duration (min)</td>
<td>M</td>
<td>441</td>
<td>464</td>
<td>437</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>13</td>
<td>10</td>
<td>9.7</td>
<td></td>
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<tr>
<td></td>
<td>Median</td>
<td>460</td>
<td>478</td>
<td>447</td>
<td></td>
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<tr>
<td>Total distance walked (km)</td>
<td>M</td>
<td>0.75</td>
<td>2.26</td>
<td>23.05</td>
<td>&lt;0.0001*</td>
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<tr>
<td></td>
<td>SE</td>
<td>0.23</td>
<td>0.25</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>0.59</td>
<td>1.98</td>
<td>22.53</td>
<td></td>
</tr>
</tbody>
</table>

*Post hoc $t$-test: $p < 0.05$ for all pair-wise comparisons

PAEE, physical activity energy expenditure

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match the walking time) were more exposed to fine, very fine, and ultrafine particles than those that drove cars. Nonetheless, interpreting the humidity-corrected means is not straightforward. Particulate measurements made inside cars and in subways were at higher ambient air temperatures and thus lower relative humidity than those made in the street, resulting in a lower particulate reading by the photometer. In studies conducted as follow-up studies to this one, a desiccant jacket has been added to expose the sample air flow to a lower humidity environment before it meets the optical sensor of the instrument. This more cumbersome equipment needs to be carried in a piece of luggage.

**Average MET and PAEE Values**

The average MET value per arm was lower for car travel (1.51 Kcal/kg·hr) than for subway travel (2.03 Kcal/kg·hr) or walking (2.6 Kcal/kg·hr). Computing the PAEE rate provided a convenient and flexible tool to compare the energy expended during car rides, subway rides, or walking. Consider a typical commute between Manhattan and Queens College: walking for 10 minutes to the subway station, spending 30 minutes in the subway stations and trains, then walking for another 15 minutes. A commuter weighing 73 kg (161 pounds) with a height of 169 cm (5’6”) would expend (2.35×30 + 3.04×25 =) 146.5 Kcal. If the same commute takes 30 minutes by car, the corresponding PAEE would be (1.74×30 =) 52.2 Kcal, assuming parking was available close to home and to work. Because it is likely that the 30 minutes of transportation saved by the car commute will be used for sedentary activities, the difference represents the extra 100 Kcal/day needed, approximately, per person, to stop the progression of the ongoing obesity epidemic in the U.S.12

**Limitations**

The exposure of subway commuters to coarse and ultra-coarse particles such as metal particles released by the tracks and the train brakes was not assessed.4 Their health effect, however, is unclear. In Sweden, standardized mortality ratios for lung cancer are increased for professional drivers in urban areas13 but not for subway drivers.14 On the other hand, car drivers may be more exposed to volatile organic compounds, which were not assessed in this study. Two Danish car drivers with the air recirculation vent closed had greater exposure to benzene, toluene, ethylbenzene, and xylene than two bikers traveling over the same route for 4 hours on 2 different days.15 In other reports, volatile organic compounds were also more concentrated inside cars versus outside of cars16–18 or inside subway cars.19 Therefore, the present findings cannot be extrapolated beyond exposure to PM$_{2.5}$.

Several assumptions had to be made to assess physical activity. First, a MET value of 1.5 was assigned for both car driving and bus riding (not including walking to the bus station), because neither car nor bus modes have zero activity. Car travel may involve movement of hands and arms, and bus travel requires energy to enter, exit, and move in the bus. It was also assumed that the average MET value for using the subway was higher than that for car driving, and it was assigned a MET value of 2.0, which should allow for walking and stair climbing required to enter and exit the subway stations, and standing or sitting during the segment. The fact that participants self-entered the data from their physical activity diary can also be viewed as a limitation. The validity and reliability of this method still need to be evaluated.

**Conclusion**

These first simultaneous estimates of physical activity and air pollution for various transportation modes indicate that driving cars is associated with less physical activity but not necessarily with less exposure to PM$_{2.5}$ than riding subways or walking in an urban environment. These results provide effect sizes and variances needed to design larger experiments assessing the health impacts of various modes of urban transportation.

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