In-Vehicle Air Exchange Rates, Inside-to-Outside Ratios, and Exposures to Traffic-Related Particulate Air Pollutants

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Talk Overview

Part I: In-Vehicle Testing:
  Ia. Importance of air exchange rate (AER)
  Ib. Tests of ultrafine PM inside-to-outside ratios (I/O)
      Methods, results, models
  Ic. Fleet simulations and in-vehicle exposures

On-Road Tests:
Part II: On-road concentration prediction models

Part III: Emission factors from on-road measurements
Goal of Part I:

To fully characterize what determines in-vehicle particle concentrations and develop predictive models
Motivation

In-vehicle exposures to traffic-related pollution contribute large fraction of overall exposure

Determining health effects of ultrafine PM (UFP) will need to take in-vehicle exposures into account

Epidemiologically-sized studies need epi-friendly models (inputs based on easy-to-obtain information)
Specific Aims

Test a large, representative sample of vehicles (never previously done) for AER (n=59), I/O ratios

Establish relationship between AER and I/O ratios for UFP, develop models

  Extend to other traffic-related particulate pollutants (black carbon, particle-bound PAH, PM2.5, etc.)

Assumption:

  in-vehicle concs = on-road concs x I/O
In-Vehicle AER Background

• The rate of air turnover inside a vehicle. Often measured in air changes per hour
  – Rates near zero if vehicle stationary, windows closed.
  – Goes up dramatically outside air ventilation setting used, or if windows open
  – If windows closed and ventilation on recirculate, goes up with speed and vehicle age or mileage
    • Eg., 15 hr⁻¹ +/- 10 hr⁻¹ at 55 mph
    • Closed window hHomes usually in range of 1 hr⁻¹

• I/O ratios for traffic-related particulates < 1.0, due to losses, but can range from nearly 0 to nearly 1.0
  – I/O = f (air exchange rate [AER])
  – Ideal would be a model of the form:
    I/O = f (vent setting, vehicle characteristics, speed)
Better Determination of AER

Found CO2 to be an excellent tracer gas, as produced by vehicle occupants

   Easy to measure; easy to produce (respiration), steady while resting

Measurements:

   • Build-up rate while parked with windows closed (AER ~ 0) gives source strength
   • Steady-state concentration at steady speed reflects AER

Tested representative sample (age, manufacturer) of 59 cars at 3 - 4 speeds each, multiple ventilation and fan settings.
CO$_2$ Concentrations during AER Measurement

\[ C_{t + \Delta t} = \text{Source}_{\Delta t} + C_{\text{amb}}(1 - e^{-AER \Delta t}) + C_t e^{-AER \Delta t} \]

**In-Vehicle CO$_2$ at Different Driving Speeds/AER**

- **AER = 14.4 h$^{-1}$**
- **AER = 8.4 h$^{-1}$**
- **AER = 5.8 h$^{-1}$**

**Build-up rate (stationary)**

**steady state @ 55 mph**

**40 mph**

**20 mph**
Results: 59 Vehicles

Recirculation (RC)
- Low AERs
- Strong function of speed
- Large car-to-car variability (increases with age, mileage)

Outside air (OA)
- Order of magnitude higher AER
- Fan speed important
AER Models

Separate models for OA and RC ventilation settings; log transformed AER

Generalized estimation models (GEE) to take into account the correlation of multiple measures on each vehicle (not independent samples).

Variables tested:
- Speed; veh age, mileage, manufacturer, interior volume, frontal area; fan setting;
  - Squared terms;
  - Interactions (e.g., speed x age)
GEE Model Results for AER

RC: speed, age
OC: fan strength*, speed
(*“notch number” fraction of max)

Top and bottom surfaces are compact (top) and large cars
AER Model Performance \[ R^2 = 0.7 \]

AERs range from \(~2\) to \(>50\) (\(\ln(2)=0.7\) to \(\ln(54)=4.0\))
Comparison to Other Studies

Decent agreement considering different method (SF6), different country (Australia), and higher speeds.

Model Predictions vs Knibbs et al. (2008) measured at 37 and 68 mph

\[ y = 0.57x + 0.76 \]

\[ R^2 = 0.83 \]
UFP measured using condensation particle counter (CPC) TSI 3007. Evaluated effect of particle size from SMPS.

260 I/O measurements (diff speed, vent/fan settings).

From Knibbs et al. (ES&T, 2010), I/O measurements (Sydney) added to expand the database.
UFP I/O Results vs Predicted AER

- About 66% variability in I/O can be explained by AER model predictions.
Predictive I/O Models \( R^2 > 0.80 \)

I/O mostly driven by, RC or OA

For RC: speed and age, then fan strength
For OA: fan strength, then speed and age
Excellent Agreement for Non-Steady State Condition Tests

- Freeway:
  - Average Speed (mi h⁻¹): 55
  - Average Outside Conc. (cm⁻³): 21000
  - Average In-vehicle Conc. (cm⁻³): 16000
  - Measured AF: 0.24 ± 0.12
  - Model Predicted AF: 0.22

- Arterial Road:
  - Average Speed (mi h⁻¹): 27
  - Average Outside Conc. (cm⁻³): 16000
  - Average In-vehicle Conc. (cm⁻³): 11000
  - Measured AF: 0.30 ± 0.11
  - Model Predicted AF: 0.32
What about Particle Size?

Some increase in RC I/O as size > 0.2 um, but concs little affected. AER far more important than size.
In-Cabin Filters

Fortunately, did not see significant difference between new, loaded or even no filter

Low efficiencies; most losses apparently due to surfaces
Adequate Questionnaire Info for Epi Studies

• Year, mileage, manufacturer of car
• Ventilation selection
  – Open or closed windows?
    • If closed, RC or OA?
      – If OA, what is your fan setting out of how many choices, low to high?
• Time and destination of morning commute & time of return home? (for on-road predictive models, Part II)
Fleet-wide Simulations:
What matters most when you put it all together?

- On-road concentrations measured on LA freeways and arterial roads
- Speed from EPA MOVES 2010 data for rush and non-rush times
- Vehicle characteristics (age, mileage, manuf) for U.S. fleet

- Available as general distribution
  - EPA MOVES, MOBILE6
- Route specific distribution
  - CALTRANS Performance Measuring System
AER and I/O for U.S. Fleet Dist under LA Driving

Vent setting (RC or OA) critical, then road type (speed)
In-vehicle UFP Exposure Distribution
Summary of Differences

Similar 2 to 3x range for in-veh exposures for:

- Ventilation setting choice (RC or OA)
- Freeways versus arterial roads (conc, speed)
- 25th vs 75th % rank vehicle (age and size, manuf)
  - 25th age = 4 years 75th = 11 years

~10x exposure difference (25th to 75th)

- RC on arterial roads: 4,000 to 10,000 #/cm³
- OA on freeways: 35,000 to 90,000 #/cm³

75th % freeway OA commuter probably getting more than half of daily exposure from commute
### Other Pollutant I/O Ratios

<table>
<thead>
<tr>
<th>Color</th>
<th>Pollutant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>PB-PAH or BC</td>
</tr>
<tr>
<td>Yellow</td>
<td>PM2.5</td>
</tr>
<tr>
<td>Green</td>
<td>PM10</td>
</tr>
<tr>
<td>Blue</td>
<td>UFP</td>
</tr>
</tbody>
</table>

![Boxplot of I/O Ratios](image)

- **Ventilation Condition**
  - RC - Mod
  - RC - Full
  - OA - Mod
  - OA - Full
PART II: Modeling the Concentrations of On-Road Air Pollutants in Southern California

Part II slides courtesy of Jun Wu (modified)
STUDY AIMS

• Part II aimed to develop predictive models to estimate on-road concentrations of traffic-related air pollutants using temporal, traffic and meteorological variables.

• These predictions, multiplied by I/O ratios, give exposure
Methods

• The roadways covered the metropolitan Los Angeles area including both Los Angeles and Orange counties.
  
  Over 210 miles of roads (approximately 75% on freeways and 25% on surface streets) during 20 days ranging from March 25 to June 16, 2011

• On-road concentrations were measured at 10 second intervals, average to 60 seconds:
  
  PB-PAH, particle number, nitrogen oxides (NOx), and PM2.5
Study region and routes of on-road pollutant measurements
Method – cont.

• Three types of models were developed
  – Linear regression model
  – Non-linear generalized additive models, with and without accounting for autocorrelation
    (can incorporate both continuous and categorical variables, as well as linear and non-linear relationships)

• Covariates
  – time of day
  – roadway type
  – vehicle speed
  – traffic counts
  – meteorological parameters
## Summary Statistics for the One-Minute Average On-Road Air Pollutants

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Samples</th>
<th>Interquartile range (IQR)</th>
<th>Mean</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB-PAH (ng/m³)</td>
<td>4632</td>
<td>62.6</td>
<td>55.5</td>
<td>31.9</td>
</tr>
<tr>
<td>PNC (particles /cm³)</td>
<td>2154</td>
<td>34500</td>
<td>36830</td>
<td>28570</td>
</tr>
<tr>
<td>NOₓ (ppb)</td>
<td>5337</td>
<td>124</td>
<td>119</td>
<td>99.1</td>
</tr>
<tr>
<td>PM₂.₅ (g/m³)</td>
<td>3992</td>
<td>10.3</td>
<td>25.0</td>
<td>19.8</td>
</tr>
</tbody>
</table>
PAHs (top), PN (bottom) by Road Type (left), Time of Day (right)
NOx (top), PM$_{2.5}$ (bottom) by Road Type (left), Time of Day (right)
### Variance Explained in Linear Regression (LR) or GAM for Selected Variables

<table>
<thead>
<tr>
<th></th>
<th>Vehicle speed (miles/hour)</th>
<th>Weighted AADT</th>
<th>N lanes</th>
<th>Ambient temperature (°C)</th>
<th>On-road wet bulb temperature (°C)</th>
<th>Wind speed (m/s)</th>
<th>Time of day</th>
<th>Roadway type</th>
<th>Total variance explained</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PB-PAH</strong> (ng/m³)</td>
<td>LR</td>
<td>15.6%</td>
<td>8.8%</td>
<td>2.23%</td>
<td>0.1%</td>
<td>-</td>
<td>7.3%</td>
<td>9.1%</td>
<td>43.1%</td>
</tr>
<tr>
<td></td>
<td>GAM</td>
<td>1.9%</td>
<td>2.4%</td>
<td>1.4%</td>
<td>5.7%</td>
<td>-</td>
<td>23.0%</td>
<td>17.2%</td>
<td>51.7%</td>
</tr>
<tr>
<td><strong>PNC</strong> (#particles/cm³)</td>
<td>LR</td>
<td>16.3%</td>
<td>10.4%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>17.8%</td>
<td>3.9%</td>
<td>48.3%</td>
</tr>
<tr>
<td></td>
<td>GAM</td>
<td>2.7%</td>
<td>4.3%</td>
<td>-</td>
<td>13.6%</td>
<td>-</td>
<td>26.8%</td>
<td>16.1%</td>
<td>63.6%</td>
</tr>
<tr>
<td><strong>NOx</strong> (ppb)</td>
<td>LR</td>
<td>16.2%</td>
<td>8.3%</td>
<td>-</td>
<td>0.008%</td>
<td>-</td>
<td>0.2%</td>
<td>5.2%</td>
<td>10.3%</td>
</tr>
<tr>
<td></td>
<td>GAM</td>
<td>2.3%</td>
<td>4.6%</td>
<td>-</td>
<td>6.5%</td>
<td>-</td>
<td>6.7%</td>
<td>17.3%</td>
<td>11.5%</td>
</tr>
<tr>
<td><strong>PM₂.₅ (µg/m³)</strong></td>
<td>LR</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>34.3%</td>
<td>11.84%</td>
<td>0.9%</td>
<td>20.6%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>GAM</td>
<td>-</td>
<td>1.0%</td>
<td>-</td>
<td>7.8%</td>
<td>31.1%</td>
<td>2.6%</td>
<td>30.3%</td>
<td>-</td>
</tr>
</tbody>
</table>
Examples of Decent Predictors

a. Vehicle speed

b. Time of day

c. Weighted AADT

d. Wet bulb temperature
1/4 Holdout and 4 fold Cross Validation for Linear Regression and GAM

<table>
<thead>
<tr>
<th></th>
<th>Linear regression</th>
<th>General additive model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>General</td>
<td>4 fold CV</td>
</tr>
<tr>
<td><strong>PB-PAH</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Samples</td>
<td>3874</td>
<td>3874</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td><strong>PNC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Samples</td>
<td>1784</td>
<td>1784</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.48</td>
<td>0.47</td>
</tr>
<tr>
<td><strong>NO$_x$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Samples</td>
<td>4446</td>
<td>4446</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.41</td>
<td>0.40</td>
</tr>
<tr>
<td><strong>PM$_{2.5}$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Samples</td>
<td>2062</td>
<td>2062</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.68</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Note: General: no cross validation; 4 times CV: 4 times 4-fold cross validation; 1/4 test: three fourths used for training and one fourth used for test.
Model “Weaknesses”

• Data quantity not adequate for grouping data by hour (used 2-3 hour bins); wind direction used only four bins

• Truck activity not included.
  – Much of truck fraction effect “soaked up” by road type variable

• Lots of PN data missing
Part II Conclusions

• **Time of day** accounted for 17-30% of variance, reflecting diurnal variations in emissions or meteorological factors.

• **Traffic predictors** (speed, traffic volume, road type) were statistically significant for PB-PAH, PNC, and NOx, but not for PM2.5, and explained 19-34% of variability.
  – **Temperature** a critical predictor for PM2.5.

• The non-linear GAM explained 5-10% more variance than the linear regression models.

• Autocorrelation regression models performed best, explaining 60, 72, 75 and 89% of the variance in PB-PAH, PNC, NOx, and PM2.5 concentrations, respectively.
Part III: Mobile Monitoring: a Better Tool to Measure Vehicle Emission Factors?
Value of Measuring EF

• Fleet-wide emission factor (EF) trends important in evaluating efficacy of regulations
  – Big drop in HDD emission standards for 2007 and newer vehicles, though HDD fleet turnover slow
  – Additional CA and LA freight movement regulations and voluntary commitments
    • Programs of accelerated truck turnover
    • Bans of older trucks, esp. short haul; retrofits of pre-97
    • Other voluntary programs
Recent CA Fleet Trends

- Light duty (gasoline) vehicle emissions have come down 2 orders of magnitude since 1960s, but downward trends continue...
  - From 2000 to 2010, CO dropped 60% in CA (ARB, 2009) (LEV II standards)
- During same time period, growing HDD vehicle miles and relatively unimproved emissions rates came to dominate freeway emissions
- After 2010 or 2011, HDDs emissions appear to be dropping rapidly.
# EF Measurement Method Options

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamometers</td>
<td>Accurate</td>
<td>• High cost per test&lt;br&gt;• Procurement difficult for HDD; representativeness a challenge</td>
</tr>
<tr>
<td></td>
<td>Can modify driving cycle</td>
<td></td>
</tr>
<tr>
<td>Tunnel Studies</td>
<td>Good sample numbers</td>
<td>• Fleet averages only&lt;br&gt;• Fixed or limited driving conditions (e.g., grade)&lt;br&gt;• Expensive to set up</td>
</tr>
<tr>
<td></td>
<td>Representative of fleet</td>
<td></td>
</tr>
<tr>
<td>Remote Sensing</td>
<td>Good sample numbers</td>
<td>• Snapshot in time and space, so need large numbers of locations, driving conditions</td>
</tr>
</tbody>
</table>
Motivation/Goal

• Is there a lower-cost alternative that efficiently allows capturing:
  • Both fleet-wide and individual vehicle EFs, (mean and variability)?
    – A large representative vehicle sample?
    – A representative mix of different driving speeds, acceleration and grade?
    – Multiple pollutants including PM species like black carbon (BC)(diesel PM)
Our Approach: On-Road Mobile Platform

Hybrid between individual plume EF determination (very labor intensive) and tunnel-style averages:

– Large analysis savings if freeway segment averages used, but distributional spread of EFs appears to be maintained
– Allows larger data set
Methods

1. Need baseline distribution of light-duty (LD), gasoline-only EFs from a truck-restricted freeway
2. Calculate HDD EFs from pollutant concentration change per unit CO\textsubscript{2} above the LD baseline and background concentrations (1\textsuperscript{st} percentile values) for each mile
3. Use freeway segment-specific truck count, traffic volume and speed (CalTrans PeMS sensors)
Sampling

• Routes selected to cover:
  – Freeway segments of differing HDD and LDV mix (3-12%) and LDV only (110) *(EFs should agree)*
  – Range of roadway grades *(EFs should vary)*
• Times of day selected to cover different driving conditions (can further sort by speed, acceleration, etc. to verify representativeness)
Rough Cost Comparison, Mobile vs Tunnel Sampling

- Initially investment of equipment and vehicle ~ ~ 100k
- On-road sampling per day: <$1000
- Analysis: 5-10 hrs per data hour
- Tunnel equivalent data collection ~ ~ 10k
- Tunnel equivalent analysis ~ ~ 25k
HDD EF Distributions by Pollutant (excludes largest freight route, I-710)

HDV Fleet emission factors (per kg of fuel burnt)
Comparison between Different Methods: Means

- NOX (g/kg fuel)
- NO (g/kg fuel)
- PNC (particles m$^3$/kg fuel)
- BC (g/kg fuel)

HDV Fleet emission factors (per kg of fuel burnt)
I-710 in Los Angeles

- Historically most polluted LA freeway

- Recent regulations
  - State-wide regulations
    - Drayage (short trip) truck regulations – retrofitting with DPF; pre-1994 engines banned
    - Expected to reduce 1994-2006 truck emissions by 85% by 2013
  - (San Pedro Bay) Ports Clean Air Action Plan
    - Progressively only allows HDDs meeting 2007 federal emission standards after Jan 1, 2012
    - Expected to eliminate 72% of diesel particulate matter and 22% of NOx
Evaluating the efficacy of recent regulations
Total Freeway Emissions

- PN emission rate
- NOx emission rate

- VMT of HDV
  - 8 - 12%

- NO emission rate vs. VMT
  - Linear Fit I-710 (ER = 7.3 \times 10^{-3} \text{VMT} - 0.066)
  - Linear Fit I-405 (ER = 4.2 \times 10^{-3} \text{VMT} + 0.39)
Part III Conclusions

1. Light duty vehicle air pollution fraction contributions are increasing as HDD EFs rapidly come down
Part III Conclusions

2. Mobile platform measured fleet EFs
   • Means agree well with tunnel studies
   • Distributional spreads appear to have also been captured compared to individual plume studies
   • Potentially far lower cost per campaign
Part III Conclusions

3. I-710, a major freight cargo route, with high HDD fraction—formerly far higher concentrations of BC, ultrafine PM, and NO—now seems comparable to other LA freeways.
   – Especially large drop in 710 HDD EFs in last 1-2 years
   – Accelerated turnover programs at ports appear to be working as planned
     • Going after high emitters appears to have been very effective for BC
Overall Conclusions

• Vehicle AER drives I/O ratios for traffic-related pollutants in predictable ways
  – Model R2s 0.7 to 0.8

• On-road predictive models reasonably good, but need further improvements
  – Recent downward trends in HDD emissions will require period re-calibration of models

• Mobile measurements can serve “double duty” by providing data to serve both on-road models and EF trends
What Next?

- Better arterial on-road models (Part II)
- Characterizing RC vs OA (or open window) choice (weather?)
- Characterizing relationship between AER and I/O for other particulate pollutants (PM2.5, coarse PM, particle-bound PAHs, black carbon...)
- Commuter health study (n of several hundred)
Acknowledgements

• Neelakshi Hudda—measurements, data processing, analysis
• Sandy Eckel—statistical analysis
• Luke Knibbs—Australian study results
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  – NIEHS grant 1K25ES019224-01
Thank you for your attention

Questions?