The HKD3D Study
A dynamic three-dimensional exposure model for Hong Kong

Ben Barratt, HEI Annual Conference, 1 May 2017
Populations across the world are increasingly exposed like this:
The HKD3D Study

• Request for Applications (RFA) Aim:
  – To develop and demonstrate improved methods for exposure assessment of traffic-related air pollution.

• Objectives:
  – To investigate the behavior and distribution of air quality in a 3D urban landscape using air quality sensor networks and population mobility datasets;
  – to develop, evaluate and demonstrate a dynamic 3D air pollution exposure model for Hong Kong (HK); and
  – to create an incremental methodology that can be applied in megacities across Asia and the developing world.
HKD3D Study Design

WP1: HK LUR Model
- spatial monitoring
- land use layers

WP2: HK 3D LUR Model
- canyon monitoring
- 3D map layer

WP3: HK D3D LUR Model
- travel behaviour survey data
- infiltration & travel microenvironment

WP4: Evaluation and translation
- HK elderly cohort mortality

WP = Work Package
HK = Hong Kong
LUR = Land Use Regression
3D = 3-dimensional
Work Package 1:
2-dimensional Land Use Regression (LUR)
Summer and winter spatial campaigns

- NO₂ and NO at 40 sites by Ogawa badges
- NO₂ at 173 sites by diffusion tube by Hong Kong Environmental Protection Department (HK EPD)
- PM₂.₅ and Black Carbon (BC) at 80 sites for 24 hours
- PM₂.₅ and BC at 4 sites for 2 weeks
- NO₂, NOₓ and PM₂.₅ continuous at 15 reference sites (HK EPD)
### 2D LUR explanatory variables

<table>
<thead>
<tr>
<th>NO₂</th>
<th>NO</th>
<th>PM₂.₅</th>
<th>Black Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>R²</td>
<td>0.46</td>
<td>0.50</td>
<td>0.59</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.43</td>
<td>0.48</td>
<td>0.54</td>
</tr>
<tr>
<td>Root-mean-square error (RMSE)</td>
<td>28 μg/m³</td>
<td>62 μg/m³</td>
<td>4.0 μg/m³</td>
</tr>
<tr>
<td>Variables</td>
<td>Expressway road length (1000m)</td>
<td>Elevated road length (500m)</td>
<td>Expressway road length (25m)</td>
</tr>
<tr>
<td></td>
<td>Main road length (50m)</td>
<td>Build Volume (25m)</td>
<td>Distance from Shenzhen</td>
</tr>
<tr>
<td></td>
<td>Elevated road length (5000m)</td>
<td>Industrial (25m)</td>
<td>Car Park Density (1000m)</td>
</tr>
<tr>
<td></td>
<td>Open Area (300m)</td>
<td>Population density (100m)</td>
<td>Car Park Density (25m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Government (100m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Industrial (25m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- R² similar to comparable models in the region, but lower than most western LURs
Work package 2:
Vertical monitoring campaigns
Canyon monitoring campaigns

• Warm and cool seasons
• 2 open sites, 4 canyon sites (+ 4 street/rooftop canyon sites)
• BC (microaethalometer), PM$_{2.5}$ (TSI Sidepak), CO+NO+NO$_2$ (AQMMesh electrochemical sensors)
## Canyon identification and recruitment

<table>
<thead>
<tr>
<th>District</th>
<th>Height/Width Ratio</th>
<th>Annual Average Daily Traffic (AADT)</th>
<th>Population Density</th>
<th>Description</th>
<th>Floors (A)</th>
<th>Floors (B)</th>
<th>Response Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jordan</td>
<td>7.4</td>
<td>Low</td>
<td>High</td>
<td>Old residential slab</td>
<td>1, 3, 9, 15</td>
<td>3, 13</td>
<td>7% (24/360)</td>
</tr>
<tr>
<td>Mong Kok</td>
<td>3</td>
<td>Med</td>
<td>High</td>
<td>Large residential towers</td>
<td>2, 5, 12, 20</td>
<td>11, 14, 20</td>
<td>5% (17/321)</td>
</tr>
<tr>
<td>Hung Hom</td>
<td>2.1</td>
<td>High</td>
<td>High</td>
<td>Large residential towers</td>
<td>2, 3, 5, 11, 14</td>
<td>2, 6, 13</td>
<td>2% (10/585)</td>
</tr>
<tr>
<td>North Point</td>
<td>3.6</td>
<td>High</td>
<td>High</td>
<td>Mixed age residential tower and slab</td>
<td>3, 5, 9, 10, 16</td>
<td>2, 17</td>
<td>2% (12/532)</td>
</tr>
<tr>
<td>Sai Wan</td>
<td>-</td>
<td>High</td>
<td>High</td>
<td>Residential slab</td>
<td>2, 4, 11, 15</td>
<td>none</td>
<td>3% (7/260)</td>
</tr>
<tr>
<td>Choi Hung</td>
<td>-</td>
<td>High</td>
<td>High</td>
<td>Residential slab</td>
<td>1, 4, 6, 19</td>
<td>none</td>
<td>2% (6/400)</td>
</tr>
</tbody>
</table>

(Plus street level and rooftop level paired monitoring at four AQMS sites)
Vertical dispersion of traffic emissions

No evidence of stagnation within canyons

Vast majority of the population lives within the well mixed zone
Vertical dispersion of traffic emissions

- No evidence of stagnation within canyons
- Vast majority of the population lives within the well mixed zone
- Little protective effect inside homes
## Pollution infiltration into homes

<table>
<thead>
<tr>
<th></th>
<th>( \text{PM}_{2.5} ) warm</th>
<th>( \text{PM}_{2.5} ) cool</th>
<th>( \text{BC} ) warm</th>
<th>( \text{BC} ) cool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural ventilation</td>
<td>81%</td>
<td>91%</td>
<td>88%</td>
<td>91%</td>
</tr>
<tr>
<td>Mechanical ventilation</td>
<td>40%</td>
<td></td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td>US homes (MESA-Air)</td>
<td>47%-62%</td>
<td></td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

- Implications for socioeconomic status (SES), energy use, building design, schools
  - All homes and schools have air conditioning, but it is rarely used to save money.
Implications for urban development

From this...

To this
Work Package 3:
Dynamic 3D model
Model design

• Utilized LUR model exposure estimates, infiltration factors, transport microenvironment factors (from literature) and Travel Characteristic Survey (n=101,385) for population mobility.

• Staged model evaluation to identify exposure measurement error and possible bias in risk estimates

  ➢ Stage 1: Ambient exposure at residential address
  ➢ Stage 2: Indoor exposure at residential address
  ➢ Stage 3: Dynamic with indoor microenvironments
  ➢ Stage 4: Dynamic with indoor + transport microenvironments
Impact of mobility by age group (PM$_{2.5}$)

1 – <18 years
2 – 18-64 years
3 – 65=> years

Exposure estimates for populations aged <18 vs >65 years:

PM$_{2.5}$: +13%
NO$_2$: +14%
BC: +39%
Work Package 4:
Evaluation
HK Elderly Health Service Cohort

- Epidemiologic effect estimates based on an existing cohort of 66,000 Hong Kong residents above the age of 65 (~9% of population of this age) where floor of residence is known.
- Risk estimates and confidence intervals calculated for a range of health outcomes using increasing exposure model complexity: 2-dimensional (2D), 3-dimensional (3D) and dynamic 3-dimensional (D3D).
2D vs D3D hazard ratios

<table>
<thead>
<tr>
<th>Cause of Death</th>
<th>Fine particulates (PM$_{2.5}$)</th>
<th>Nitrogen Dioxide (NO$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2D</td>
<td>D3D</td>
</tr>
<tr>
<td>All natural causes</td>
<td>1.03 (1.01, 1.06)*</td>
<td>1.07 (1.04, 1.09)*</td>
</tr>
<tr>
<td>Cardiovascular</td>
<td>1.06 (1.02, 1.10)*</td>
<td>1.10 (1.05, 1.14)*</td>
</tr>
<tr>
<td>Ischemic Heart Disease (IHD)</td>
<td>1.03 (0.97, 1.10)</td>
<td>1.09 (1.03, 1.17)*</td>
</tr>
<tr>
<td>Cerebrovascular</td>
<td>1.06 (0.99, 1.13)</td>
<td>1.08 (1.01, 1.16)*</td>
</tr>
<tr>
<td>Respiratory</td>
<td>1.02 (0.97, 1.06)</td>
<td>1.06 (1.01, 1.11)*</td>
</tr>
<tr>
<td>Pneumonia</td>
<td>1.00 (0.94, 1.06)</td>
<td>1.05 (0.99, 1.12)</td>
</tr>
<tr>
<td>COPD</td>
<td>1.06 (0.97, 1.15)</td>
<td>1.09 (1.00, 1.19)</td>
</tr>
<tr>
<td>External causes</td>
<td>1.02 (0.90, 1.16)</td>
<td>1.04 (0.90, 1.19)</td>
</tr>
</tbody>
</table>

Hazard ratios (95% Confidence Interval) per interquartile range (IQR) increase of pollutants for baseline exposure. *p<0.05.

Dynamic component had little impact due to cohort’s age-related homogeneity.
Some challenges

1. Field conditions (heat, monsoon, pollution, security, travel)
2. Canyon resident recruitment, especially at ground floor
3. Subtle vertical gradients, requiring high sensor precision
4. Derivation of a region-wide canyon decay rate
The importance of inter-unit precision

The figure and table compare multiple units of the same instrument type.
- Co-location precision and reference testing pre and post campaign (PM$_{2.5}$)
Co-location precision and reference testing pre and post campaign (PM$_{2.5}$)
Electrochemical stability issues

- Inter-unit precision scaling of electrochemical sensors was not maintained during campaigns
- Issues with stabilisation, temperature, humidity, drift
- High humidity caused frequent sensor failures

<table>
<thead>
<tr>
<th>NO</th>
<th>R²</th>
<th>Gradient</th>
<th>Offset (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test period:</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>UNIT01 (ref)</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>UNIT02</td>
<td>0.69</td>
<td>0.11</td>
<td>0.71</td>
</tr>
<tr>
<td>UNIT03</td>
<td>0.98</td>
<td>0.99</td>
<td>0.98</td>
</tr>
<tr>
<td>UNIT04</td>
<td>0.99</td>
<td>0.99</td>
<td>0.87</td>
</tr>
<tr>
<td>UNIT05</td>
<td>0.96</td>
<td>0.97</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Inter-unit precision test results during summer canyon campaign
Assigning a decay typography

• Hypothesis was that different canyon types would produce consistently different decays, necessitating a typography
• More rapid mixing than expected meant that a more general approach was needed, assuming a common decay factor
• Exponential decay shape assumed based on published literature
Continuous decay or well mixed?

KTAQMS
- measured
- modelled

MKAQMS
- measured
- modelled
Study conclusions

• Improved urban building design appears to be stimulating the dispersion of local traffic-related air pollutant emissions in street canyons, with no evidence of widespread stagnation found.

• Rapid vertical dispersion means that high resolution 2D models will overestimate roadside residential exposure above ground floor.

• Typical Hong Kong residences provide very little protection from outdoor air pollution, unless you can afford mechanical ventilation and/or work in a modern office.

• Dynamic models can identify differential exposures between population subtypes; on average, young males are in the highest exposure group in Hong Kong.

• A more personalised exposure methodology led to stronger evidence for the health impact of air pollution on respiratory and cardiovascular health in Hong Kong than previously published.
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Co-Investigators and research staff:

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