Development of Microscale Vehicle Emission Model in Hong Kong

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Vehicle Emission Model

- A tool to estimate vehicle emission / emission factor

- Applications:
  - Environmental assessment
  - Vehicle emission inventory
  - Evaluation of vehicle emission control policies
History

• Before 2005, spread-sheet
  • Vehicle class, age

• Since 2005, EMFAC-HK
  • EMFAC is developed by California Air Resources Board (CARB)
  • Vehicle class, age, speed, temperature, A/C

• Since 2008, PEMS data are used for updating parameters in EMFAC-HK

• ~2015, explore the possible upgrade of the model
  • Microscale model: junction, sec-by-sec prediction
  • Mesoscale model: road level, hourly prediction

Microscale model candidates

• PHEM (Physical model)
• $\Delta P$ (Statistical model)
• MAPM (Modal and Peak Model)

PEMS data used in microscale model development:

• Sec-by-sec real-world vehicle emission data using PEMS from 18 vehicles of
  • Euro V diesel double deck buses (FBDD),
  • Euro V diesel coaches >15 t, and
  • Euro 5 LPG taxis
PEMS data Tested – Buses

- Tested 18 double deck buses (FBDD)
- 4 Euro II, 2 Euro III were tested before and after the SCR retrofit
- 6 Euro V and 6 Euro VI hybrid buses were compared on the same routes
PEMS data Tested

• Tested 42 Euro 2-5 taxis
• Tested before and after CAT replacement
• 1 Euro 2 and 3 Euro 5 were tested on dyno with FTIR
Comparison of real-time NOx emissions from a super emitting and a normal emitting light duty trucks

Green – NOx emission from normal emitter

Red – NOx emission from supper emitter
PHEM/PHEM LIGHT

Prof. Stefan Hausberger
Institute of Internal Combustion Engines and Thermodynamics,
Graz University of Technology,
Graz, Austria
History and Application of PHEM

- Passenger car and Heavy duty Emission Model (PHEM) is the official EU microscale vehicle emission factor model
- PHEM generates emission factors for models
  - HBEFA (German handbook)
  - COPERT
PHEM Modelling Methodology
The PHEM Light model is a simplification of the model PHEM.

- Independent of the engine speed,
- Thermal status of after treatment systems and gear shifts not simulated explicitly

Restrictions of PHEM Light:
Simulation of extreme driver and traffic situations become inaccurate
PHEM Modelling Methodology

Simulation of engine power:

\[ P_e = P_{\text{Roll}} + P_{\text{Air}} + P_a + P_{\text{Grad}} + P_{\text{transm}} + P_{\text{Aux}} \]

**Vehicle specific**
- \( C_d \cdot A \)
- \( m \cdot g \cdot \sin \alpha \)

**Vehicle + tire specific**
- \( m_{\text{vehicle}}, m_{\text{load}} \)
- RRC from diff. sources

**Vehicle specific**
- equivalent rotational masses considered

**Calc. from drive train efficiency**
- maps in PHEM; const efficiency in PHEM Light

\[ P_{\text{roll}} = (m_{\text{vehicle}} + m_{\text{Load}}) \times g \times (F_{r_b} + F_{r_i} \times v + F_{r_4} \times v^4) \times v \]
\[ P_{\text{air}} = C_w \times A_{\text{cross}} \times \frac{P}{2} \times v^3 \]
\[ P_a = (m_{\text{vehicle}} \times A \times v + m_{\text{rot.wheels}} + m_{\text{Load}}) \times a \times v \]
\[ P_{\text{grad}} = (m_{\text{vehicle}} + m_{\text{Load}}) \times g \times \sin \alpha \times v \]
\[ P_{\text{aux}} = P_{\text{aux.norm}} \times P_{\text{rated}} \quad \text{(constant power consumption)} \]

Additional functions for increased accuracy are described in report from research project „COLOMBO“
PHEM Result – Taxi

10 second mean results

Single emission peaks are not simulated exactly.
Our View

- Demand high quality data and vehicle information

- May need more corrections, especially for the prediction of emission peaks
MODAL AND PEAK MODEL (MAPM)

Prof. Christopher Frey
Glenn E. Futrell Distinguished University Professor
Civil, Construction, and Environmental Engineering Department,
North Carolina State University,
North Carolina, U.S.
MOVES Methodology
Results using MOVES Methodology - FBDD

Missing values
New Approach

- The range of VSP/STP, speed should be tailor-made for Hong Kong

- Additional modes for fuel cut-off and peaks

- Further subdivision of Euro V vehicles according to emission levels.
New approach (methodology to define fuel cut-off and peak)

Example: Categorical and Regression Tree (CART) Analysis of five **LPG taxis** to identify fuel cut-off

- **n**: no. of observations
- **x%**: percentage of observations

CO2 emission factor (g/s)

Fuel cut-off
OpModes for FBDD
Example: FBDD in Kowloon

Prediction is based on average of all FBDD within a group, so it will not be able to predict any specific FBDD in that group.
Our View

• The model is a nice modification of the existing MOVES in US

• The locations of the emission peaks can be predicted correctly

• The predicted emissions may not match with measured values
PΔP

Dr. Robin Smit
Hon. Senior Research Fellow, University of Queensland, Queensland, Australia
History

• PΔP is a ‘power-based’ statistical model and it simulates fuel consumption rates and emissions

• Vehicle emission rate (g/s) is fitted to multivariate linear regression algorithm using Power (P) and Change in power (ΔP) as model variables

• The model was developed using empirical data from an Australian real-world cycle emission database
PΔP Modelling Methodology

multiple variable linear regression

\[ e_t = \beta_0 + \beta_1 \ln(1 + P_t^+) + \beta_2 P_t^2 + \beta_3 T(\tau)_t + \beta_4 P_t \Delta P(\tau)_t + \beta_5 P_t T_t + \ldots \]

- All possible ways for emission rate, \( Y_t \): original, log, …
- All possible ways for power, \( X \): original, log, sqrt, …
- Definition of \( \Delta P \) – difference, oscillation (\( \Delta t = 3, 6, 9, 12, 15, 30 \) and 60 seconds, …)

1) power difference: \( \Delta P(\tau)_t = P_t - P_{t-\tau} \)

2) power oscillation: \( \Delta P(\tau)_t = |P_t - P_{t-1}| + \ldots + |P_{t-\tau+1} - P_{t-\tau}| \)

3) normalised power oscillation: \( \Delta P(\tau)^*_t = \Delta P(\tau)_t / \Delta x(\tau)_t \)

- Transformed exhaust temperature, \( F_t \)
PΔP Modelling Methodology

• 86,240 possible “model situations” and many more possible structures for each ‘model situation’

• Best combination of variables and variable definitions by statistical means ⇒ efficient + automated variable selection procedure
PΔP Modelling Methodology: NOx

III – Model performance (NO$_x$)

Best performing model, Taxi_22

Worst performing model, FBDD_11
Our View

• **Advantage**
  • Exhaust Temperature effect is taken into account
  • Explanatory variables are different for different pollutants

• **Disadvantage**
  • Emission peaks cannot be predicted
  • Unrealistic input variables (exhaust temperature)
## Model validation

<table>
<thead>
<tr>
<th>Dataset A</th>
<th>Dataset B (New dataset)</th>
</tr>
</thead>
</table>
| PEMS data for 3 road networks for all the vehicles in the Modelling Dataset, each lasting for 10 minutes | PEMS data for 3 road networks for all the following vehicles which are not in the Modelling Dataset, each lasting for 10 minutes:  
- 1 Euro 5 LPG taxi  
- 1 Euro V diesel coach of 15-24 tonnes  
- 1 Euro V diesel FBDD of about 24 tonnes |

Example: 3 road networks are selected for coach (Dataset A).
Primitive validation results
Primitive validation results
Conclusion

• In high temporal resolution (10 sec):
  • Good accuracy for CO2 only (mean absolute error (MAE) ~20%)
  • For NOx, (MAE: 59% - 223%)

• In low temporal resolution (30 min):
  • Accuracies are reasonable
  • For CO2, (TEE ~2%-13%)

<table>
<thead>
<tr>
<th>TEE for NOx dataset (B)</th>
<th>FBDD</th>
<th>Coach</th>
<th>Taxi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best performing model</td>
<td>27%</td>
<td>15%</td>
<td>20%</td>
</tr>
<tr>
<td>Worst performing model</td>
<td>55%</td>
<td>51%</td>
<td>44%</td>
</tr>
</tbody>
</table>

30 minute average

TEE: Total Emission error in 30 minutes
Way Forward

1. Model framework

Model framework to combine the fleet model, emission factor model, is developing
Way Forward

2. Mesoscale Modelling
   The best microscale model will be used to generate the emission factors for the mesoscale vehicle emission factor model. The model will be validated by the measurement of road side air monitoring station in Mong Kok.
Thank you!
MAPM

- Prof. Chris Frey was the developer of “Modal Binning” approach in US shootout
- The modelling principle is vehicle specific power (VSP)
- VSP is the core of MOVES, USEPA official model

\[ VSP = \nu\{a(1 + \varepsilon) + gr + gC_R\} + \frac{1}{2} \rho \nu^3 \left( \frac{C_D A}{m} \right) \]

Where

- \( a \) = vehicle acceleration (m/s²)
- \( A \) = vehicle frontal area (m²)
- \( C_D \) = aerodynamic drag coefficient (dimensionless)
- \( C_R \) = rolling resistance coefficient (dimensionless, \( \sim 0.0135 \))
- \( g \) = acceleration of gravity (9.8 m/s²)
- \( m \) = vehicle mass (in metric tons)
- \( r \) = road grade
- \( \nu \) = vehicle speed (m/s)
- \( VSP \) = Vehicle Specific Power (kw/ton)
- \( \varepsilon \) = factor accounting for rotational masses (\( \sim 0.1 \))
- \( \rho \) = ambient air density (1.207 kg/m³ at 20 °C)
MOVES Methodology

• **VSP for light duty vehicle**

\[ VSP = v \left[ (1.1) a + g \left( \frac{r}{100} \right) + 0.132 \right] + 3.02 \times 10^{-4} \ v^3 \]

• **Scaled Tractive Power (STP) for heavy duty vehicles**, 

\[ STP = \frac{(A_v \times v_t) + (B_v \times v_t^2) + (C_v \times v_t^3) + \left\{ M_v \times v_t \times (a_t + g r_t) \right\}}{f_{\text{scale}}} \]

<table>
<thead>
<tr>
<th>Source type</th>
<th>Rolling coefficient, $A_v$</th>
<th>Rotating coefficient, $B_v$</th>
<th>Drag coefficient, $C_v$</th>
<th>Source mass factor, $M_v$ (metric ton)</th>
<th>Fixed mass factor, $f_{\text{scale}}$ (metric ton)</th>
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<td>FBDD</td>
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<td>0.003587</td>
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<td>17.1</td>
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<td>0.003715</td>
<td>19.5937</td>
<td>17.1</td>
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</table>
MOVES Methodology
Definitions for “Peak” and “Fuel Cut-Off” Modes

Define multiple emission groups for coaches

<table>
<thead>
<tr>
<th>Mode</th>
<th>Coach Group</th>
<th>STP</th>
<th>STP at Lag 1 (skW/ton)</th>
<th>STP at Lag 2 (skW/ton)</th>
<th>STP at Lag 3 (skW/ton)</th>
<th>STP at Lag 4 (skW/ton)</th>
<th>STP at Lag 5 (skW/ton)</th>
<th>Speed (km/h)</th>
<th>Acceleration (km/h-s)</th>
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</thead>
<tbody>
<tr>
<td>Fuel Cut-off</td>
<td>EGR+ DOC</td>
<td>&lt; 0</td>
<td>&lt; -2.2</td>
<td>&lt; 1.1</td>
<td>&lt; -0.61</td>
<td>&lt; -0.6</td>
<td>&lt; 7.1</td>
<td>≥ 11</td>
<td>-</td>
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<tr>
<td></td>
<td>EGR+ DPF</td>
<td>&lt; -1.4</td>
<td>&lt; -0.76</td>
<td>&lt; -1.1</td>
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<td>-</td>
<td>-</td>
<td>≥ 21</td>
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<tr>
<td></td>
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<td>&lt; 9.9</td>
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<td>-</td>
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<td>SCR-2</td>
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<td>&lt; 0.093</td>
<td>&lt; -0.78</td>
<td>&lt; 0.073</td>
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<td>≥ 9.9</td>
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<tr>
<td></td>
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<td>≥ 9.5</td>
<td>≥ 11 &amp; &lt; 21</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt; 30</td>
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<td>≥ 12</td>
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</table>
Hong Kong Operational Modes (OpModes) for LPG Taxis
Example: Taxi in Kwun Tong

Prediction is based on average of all taxis within a group, so it will not be able to predict any specific taxi in that group.
Example Coach in Kowloon

Prediction is based on average of all coaches within a group, so it will not be able to predict any specific coach in that group.
Overall results for Taxi (Hong Kong Island)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Vehicle ID</th>
<th>10-Second Averages, $R^2$</th>
<th>One Minute Averages, $R^2$</th>
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<td>CO₂</td>
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<td>CO</td>
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<td>0.66</td>
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<td>0.33</td>
<td>0.59</td>
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### Overall results for FBDD (Hong Kong Island)

<table>
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<tr>
<th>Pollutant</th>
<th>Vehicle ID</th>
<th>10-Second Averages, R²</th>
<th>One Minute Averages, R²</th>
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<td>02956142-01</td>
<td>0.71</td>
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</tbody>
</table>
PΔP Modelling Methodology

multiple variable linear regression

Temperature variable:
• Emission relation to the exhaust temperature is modelled by the function $F_t$

\[
F_t = \begin{cases} 
    b_0 + \frac{b_1}{1 + e^{T(\tau_1 - T_0)}} / (b_0 + b_1) & \text{if } b_1 > 0 \\
    b_0 + \frac{b_1}{1 + e^{T(\tau_1 - T_0)}} / b_0 & \text{if } b_1 \leq 0
\end{cases}
\]

$F_t$ is in turn related to the cumulative power for the previous $\Delta t$ and from the start of the vehicle \(\downarrow\)

\[
T_t = \beta_0 + \beta_1 \ln(1 + W(\Delta t)^{\Delta t}) + \beta_2 \ln(1 + W(\tau)^{\Delta t}) + \varepsilon
\]

$\Delta t = 1, 30, 60, 90, 120$ and $150$ s

$\tau$ = the total time accumulated from the start of the vehicle

$W =$ cumulative power
PΔP Modelling Methodology

III – Model performance (CO$_2$)

Best performing model, Taxi TL7376

Worst performing model, SJ3539
**PΔP Modelling Methodology: HC**

**III – Model performance (HC)**

Best performing model, Taxi ST8234

Reasonable performing model, FBDD SU7740
PΔP Modelling Methodology: CO

III – Model performance (CO)

Best performing model, Taxi ST8234

Worst performing model, Taxi NV7285