Brake-wear PM Research for California Emission Inventory

CARB: Sonya Collier, Seungju Yoon, Jeff Long, Sam Pournazeri, Jorn Herner
ERG: Alan Stanard, John Koupal, Sandeep Kishan and the rest of the ERG team
LINK: Carlos Agudelo, Ravi Vedula and the rest of the LINK team
CalTrans: Simon Bisrat, Yoojoong Choi, Mauricio Serrano
U.S. EPA
CARB Goals

- Protect the public from the harmful effects of air pollution
  - Regulatory measures
  - Enforcement
  - Setting standards
  - Monitoring
  - State Implementation Plan (SIP)
CARB Goals

- Reduce exposure in communities most impacted by air pollution
- Reduce air quality disparity between communities

* EJ monitors are located in areas disproportionately impacted by environmental factors and have lower socioeconomic status
Sources of PM2.5 in South Coast Air Basin (2012)

- Waste Disposal
- Cleaning and surface coatings
- Petroleum production and marketing
- Fuel Combustion
- Industrial processes
- Off-road vehicles
- On-road motor vehicles

EMFAC 2017
Mobile Source Inventory

Tire Wear
Brake Wear
Tailpipe Exhaust

PM2.5 (Tons per Day)

Total Vehicle Population (millions)
Inventory Basics: Brake Wear

PM emitted per braking event from laboratory measurements

# of braking events per mile

# of brakes per vehicle

Miles driven per day

Vehicle Population

Cycle Averaged PM EF

X Airborne Factor

Heavy Duty Urban Dynamometer Driving Cycle

Unified Cycle

Emissions in Tons/Day

VMT

CARB
Source Data

- EMFAC 2007 and earlier: 1983 data
- EMFAC 2011 and later: 2000/2003 data
- NOTE! data source studies not designed specifically to meet EMFAC needs (cycle based)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of individual</td>
<td>7 (Top GM models, &gt;80% of marketshare)</td>
<td>3 (LM-mid size, SM-truck, NOA-full size)</td>
</tr>
<tr>
<td>brake pads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of individual</td>
<td>21 (varied brake id’s and temperatures)</td>
<td>11 (3-4 UDP tests for 3 types of pads: LM, SM, NAO)</td>
</tr>
<tr>
<td>tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycles/Total Brake Events</td>
<td>BSL-035 (100, 200, 300, 400 °C) 50→0 km/hr, 0.3 g</td>
<td>UDP (24 brake events, 0.6-1.6 m/s²)</td>
</tr>
<tr>
<td>Method</td>
<td>Enclosed brake dyno</td>
<td>Enclosed brake dyno</td>
</tr>
</tbody>
</table>
**Source Data Adaptation**

- Data was extrapolated to cover all technology groups and standard drive cycles

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Braking Cycle</th>
<th>Braking Frequency (Apps/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Cars and SUVs</td>
<td>UC</td>
<td>4</td>
</tr>
<tr>
<td>Medium-HD Trucks</td>
<td>ARB-MHD</td>
<td>5</td>
</tr>
<tr>
<td>Heavy-HD Trucks</td>
<td>ARB-HD</td>
<td>1.2</td>
</tr>
<tr>
<td>Urban Transit Buses</td>
<td>OCTA</td>
<td>8.2</td>
</tr>
<tr>
<td>School Buses</td>
<td>MHD-LS Transient</td>
<td>14</td>
</tr>
</tbody>
</table>

- Wheel load dependence extrapolated from available data (linear fits)
Brake Wear PM Emission Factor Summary

- HDVs have high EFs
  - More brakes, different cycle
- Buses have high EFs
  - Many stops in typical cycle
- Not speed dependent
Priorities for new emission factor development

• Use CA relevant vehicles and brake components
• LDVs, MDVs, HDVs
• Identify speed dependent braking cycle reflecting CA behavior
• Identify cycles for LDVs, MDVs and HDVs
• Use methods being adopted by JRC (Enclosed brake dynamometer)
• Maintain realistic temperatures
• Develop method to simulate regenerative braking
Proposed Work

**LDVs**
- Market Share Analysis
- 6-7 vehicle choices
- On-road testing
- Real world CA activity data
- Final drive cycles, real temperatures
- ~90 tests

**HDVs**
- Market Share Analysis
- 4-5 vehicle choices
- On-road testing
- Validation enclosed dyno and PM sampling systems
- Final drive cycles, real temperatures
- ~40 tests

Vehicle N:
- Front brake pads
- Rear brake pads/drums
- Popular aftermarket pads
- Loaded/unloaded Replicates

CARB
New project will capture larger market, materials and conditions

<table>
<thead>
<tr>
<th></th>
<th>Previous Source Data</th>
<th>Current Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicles represented</td>
<td>6 (LDA)</td>
<td>3 (LDA)</td>
</tr>
<tr>
<td></td>
<td>4 (LDT)</td>
<td>2 (LDT)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-3 (LDA-regen capable)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 (HDV)</td>
</tr>
<tr>
<td>Number of individual brake pads</td>
<td>10 (LDV)</td>
<td>24 (LDV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 (HDV, tractor and trailer)</td>
</tr>
<tr>
<td>Number of tests</td>
<td>32</td>
<td>130</td>
</tr>
<tr>
<td>Cycles/Total Brake Events</td>
<td>UDP, BSL-035/~285</td>
<td>TBD/1000's to 10,000's</td>
</tr>
<tr>
<td>Test Conditions</td>
<td>Discretized temperatures, brake force</td>
<td>Continuous distribution, focused on realistic conditions</td>
</tr>
<tr>
<td>Method</td>
<td>Enclosed brake dyno</td>
<td>Commonly accepted enclosed brake dyno (TF2)</td>
</tr>
</tbody>
</table>
Results will include...

- Updated emission factors
  - Cycle based - Speed dependent
  - Regenerative braking effects
  - Effects of load, vehicle type, pad type
- On different time scales, explore various effects on mass, PN, PM size:

<table>
<thead>
<tr>
<th>Cycle Averaged</th>
<th>Micro-trip Averaged</th>
<th>Individual Brake Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle configuration</td>
<td>Speed</td>
<td>Braking power</td>
</tr>
<tr>
<td>Pad material</td>
<td>Driving behavior</td>
<td>Temperature</td>
</tr>
<tr>
<td>Repeatability</td>
<td>Repeatability</td>
<td>Repeatability</td>
</tr>
</tbody>
</table>

- Chemical composition
Comprehensive Research Approaches for Brake PM in California

- **Bottom up approach**
  - External contract with ERG/LINK
  - Many advantages
  - Some disadvantages
- **Second bottom up approach**
  - In-house project
  - Full chassis dyno tests
- **Top down approach**
  - External contract with UC Riverside
  - Roadside measurements
- **Health effects**
  - External contract with UCLA
  - Epidemiology study (LA)

**Integrated:** PM2.5, PM10 (Mass, Composition)
**Real time:** PN, PM size, PM2.5, PM10, composition
Traffic counts, met data

**Calculate fraction of non-exhaust**

**Desired Results:**
- EFs vs speed, fleet mix
- Fraction of non-exhaust/exhaust PM
- Impact on downwind communities
Closing remarks

- Inform programs and policies for AQ improvement
- Transportation planning, conformity
- Provide much needed information for health related projects
- Assess scope of BWPM issues

Updated Inventory

Top down approach

Bottom up approach

Health effects
REFERENCES

• https://ww2.arb.ca.gov/
• EMFAC Documentation: https://www.arb.ca.gov/msei/categories.htm
Appendix: Research Approaches
Bottom Up Approach: External Research Contracts with ERG/LINK

- Driving behavior
  - Representative CA
  - EU: Novel World Harmonized Light Vehicle Test Program (WLTP) Brake Cycle
  - Temperature range
- Modern materials and vehicles
  - Market-share Research
  - Brake pads and rotors
    - Aftermarket parts
  - CA fleet relevant vehicles
    - Range of vehicle weights
- Regenerative braking
- Collect brake wear PM in brake dyno
  - Simulate all of the above parameters

Desired Results:
- Updated EFs: PM mass per cycle, effects of vehicle weight, cycle speed
- PM mass, PM size, PN per braking event, material, weight, etc.
- Chemical composition
Bottom Up Approach: In-House

- Use sealed running loss-SHED
- Recruit representative vehicles
- Determine appropriate dilution factors and particle loss rates
- Derive EFs per cycle

**Desired Results:**
- Cross-check with enclosed dyno results
- PM mass, PM size, PN per braking event, material, weight, etc.
- Chemical composition

See also Schauer et al.
Top Down Approach: Roadside Measurement + Dispersion Model

- Use laboratory derived source profiles
- Location with varying speeds and fleet mixes
- Derive EFs
- Input into dispersion model

Integrated:
PM2.5, PM10 (Mass, Composition)

Real time:
PN, PM size, PM2.5, PM10, composition
Traffic counts, met data

Calculate fraction of non-exhaust

Desired Results:
- EFs vs speed, fleet mix
- Fraction of non-exhaust/exhaust PM
- Impact on downwind communities