Trends in Vehicle Emissions Based on Real-World Measurements

H. Christopher Frey
frey@ncsu.edu

Department of Civil, Construction & Environmental Engineering
North Carolina State University
Raleigh, NC 27695

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Health Burden

- Air pollution from motorized road transport
- Premature death
- Global estimates range between 184,000 and 242,000 (Bhalla et al., 2014; Chambliss et al., 2014)
- Based on fine particulate matter (PM$_{2.5}$)
- By country:
  - India (39,000)
  - China (27,000)
  - U.S. (15,000)
Key Questions

• How can we measure the *real-world* energy use and emissions of the transportation system?
• What are the key sources of variability in the emission inventory?
• What are the trends in vehicle fuels, vehicle technology, fuel efficiency, and emissions?
• How effective are fuel economy and emissions standards?
### Measurement Methods

- Chassis dynamometer
- Engine dynamometer
- Tunnel studies
- Remote sensing
- Chase vehicles
- **Portable emission measurement systems**
- Mobile emissions laboratories
- Automotive sensors
- Twin site ambient measurements
- Inverse modeling
- Evaporative emissions
- Low cost sensors
Using Portable Emission Measurement System (PEMS) to Measure Real-World Vehicle Activity, Fuel Use and Emissions

- **Infrastructure Data**: Vehicle location (GPS), road grade (via altimeter and GPS, if applicable)
- **Vehicle Technology and Fuels**: Engine size, fuel properties
- **Behavior** (Vehicle Dynamics): Speed, Acceleration, Engine RPM
- **Ambient conditions**: temperature, humidity, pressure
- **Vehicle Fuel Use and Emissions**: Gas analyzers for NO, HC, CO, CO₂ and surrogates for PM (e.g., opacity, black carbon)


Overview of Measurements at NC State

- Over 200 light duty vehicles (on RTP routes)
  - 2/3 passenger car
  - 1/3 passenger truck
- 50 heavy duty vehicles (observed routes)
  - 12 dump trucks
  - 8 concrete mixers
  - 6 combination trucks
  - 24 refuse trucks
- Over 40 construction vehicles
- 7 diesel-electric railroad locomotives
PEMS Technology and Trends

• First on-board emission measurement dates to at least 1954
• In 1980s and 1990s, some research groups assembled their own instruments
• First commercially available PEMS was the Clean Air Technologies International (CATI) “Montana System”. First one was purchased by NC State in 1999
• PEMS commercially available from Sensors, Inc., AVL, Horiba, GlobalMRV, 3DATX, MAHA, and others
PEMS Variations: Examples

SEMTECH-DS
CFR 1065 Compliant
NDIR: CO\textsubscript{2}, CO, HC
FID: THC
NDUV: NO, NO\textsubscript{2}
Heated Sample Line
Heavy (~50 lbs)
High Power Demand

Axion
NDIR: CO\textsubscript{2}, CO, HC
Electrochemical: NO, O\textsubscript{2}
Light-scattering: PM
Water separation bowl
Portable (~30 lbs)
Low Power Demand

ParSYNC
“micro-PEMS”
Electrochemical: CO\textsubscript{2}, NO, NO\textsubscript{2}
PM: light-scattering, opacity, ionization
Water separation
Portable (~10 lbs)
Low Power Demand
PEMS Technology and Trends

- PEMS have been validated/benchmarked to reference methods in numerous studies.
- Generally perform well for gaseous pollutants
- There is not as yet a “standard” method for measuring particles
  - Surrogates for particle mass typically based on laser light-scattering or photoacoustic methods
  - In Europe, focus is on solid particle number (SPN) rather than particle mass
  - Ongoing development efforts
- Additional pollutants: HCHO, HONO, others…
- PEMS tailored to purpose (e.g., not all measurements need to be CFR 1065 compliant)
Key Elements of Using PEMS

• Purpose?
  – How will the data be used?
  – What data are needed?

• Study design
  – Observable but not controllable: e.g., traffic, ambient conditions
  – Controllable: choices of vehicles, fuels, drivers, routes, timing of data collection

• Instruments
• Calibration
• Maintenance
• Repair
• Installation on vehicle
• Data collection
• QA/QC
• Data analysis
• People
• Training
Portable Emission Measurement System
On-Board Diagnostic Data Logging

Alternatively, can use an exhaust flow meter
Instrumented Vehicle
# Measured Variables

<table>
<thead>
<tr>
<th>Gas and PM Sensors</th>
<th>Engine Sensors or ECU</th>
<th>GPS</th>
<th>Weather Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>• NO, NO₂, NOₓ</td>
<td>• Engine RPM</td>
<td>• Latitude</td>
<td>• Temperature</td>
</tr>
<tr>
<td>• CO</td>
<td>• Manifold Pres.</td>
<td>• Longitude</td>
<td>• Humidity</td>
</tr>
<tr>
<td>• CO₂</td>
<td>• Fuel Flow</td>
<td>• Elevation → Road Grade</td>
<td>• Pressure</td>
</tr>
<tr>
<td>• HCs</td>
<td>• Intake Air Flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• O₂</td>
<td>• Exhaust Flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• PM</td>
<td>• Ground Speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Torque</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

20 or more variables recorded at 1 Hz for 3 to 10 hours

HCs = Hydrocarbons; PM = Particulate Matter
Data Quality Assurance

1. imputing missing seconds of data
2. synchronizing concentration and engine data
3. checking for errors in IAT, RPM, and MAP values
4. correcting for ambient air infiltration before/after zeroing
5. correcting for non-updating concentration data
6. correcting for negative concentrations
7. correcting for significant inter-gas analyzer discrepancy
8. comparing estimated and gas pump fuel use
Characteristics of Measured Light Duty Gasoline Vehicles

- Model Year: Cumulative Frequency
  - n = 214

- Rated Engine Horsepower (hp): Cumulative Frequency
  - n = 214

- Curb Weight (lb): Cumulative Frequency
  - n = 209

- Accumulated Mileage (miles): Cumulative Frequency
  - n = 214
Selected Routes in Raleigh and Research Triangle Park

Vehicle Specific Power (VSP)

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

Where

- \( a \) = vehicle acceleration (m/s\(^2\))
- \( A \) = vehicle frontal area (m\(^2\))
- \( C_D \) = aerodynamic drag coefficient (dimensionless)
- \( C_R \) = rolling resistance coefficient (dimensionless, \( \sim 0.0135 \))
- \( g \) = acceleration of gravity (9.8 m/s\(^2\))
- \( m \) = vehicle mass (in metric tons)
- \( r \) = road grade
- \( v \) = 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/m\(^3\) at 20 °C)

### VSP Modes

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Definition (kW/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VSP &lt; -2</td>
</tr>
<tr>
<td>2</td>
<td>-2 ≤ VSP &lt; 0</td>
</tr>
<tr>
<td>3</td>
<td>0 ≤ VSP &lt; 1</td>
</tr>
<tr>
<td>4</td>
<td>1 ≤ VSP &lt; 4</td>
</tr>
<tr>
<td>5</td>
<td>4 ≤ VSP &lt; 7</td>
</tr>
<tr>
<td>6</td>
<td>7 ≤ VSP &lt; 10</td>
</tr>
<tr>
<td>7</td>
<td>10 ≤ VSP &lt; 13</td>
</tr>
<tr>
<td>8</td>
<td>13 ≤ VSP &lt; 16</td>
</tr>
<tr>
<td>9</td>
<td>16 ≤ VSP &lt; 19</td>
</tr>
<tr>
<td>10</td>
<td>19 ≤ VSP &lt; 23</td>
</tr>
<tr>
<td>11</td>
<td>23 ≤ VSP &lt; 28</td>
</tr>
<tr>
<td>12</td>
<td>28 ≤ VSP &lt; 33</td>
</tr>
<tr>
<td>13</td>
<td>33 ≤ VSP &lt; 39</td>
</tr>
<tr>
<td>14</td>
<td>39 ≤ VSP</td>
</tr>
</tbody>
</table>

Deceleration, or Downhill  

Idle  

Cruising, Acceleration, or Uphill

Average Vehicle Specific Power (VSP) Modal Rates for 214 Light Duty Gasoline Vehicles

- CO2 (g/s)
- CO (mg/s)
- HC (mg/s)
- NOx (mg/s)

Vehicle Specific Power (VSP) Modes

n = 214
Distribution of Driving Time by VSP Modes for Routes A, C, 1, and 3

- Route A (n=211)
- Route C (n=211)
- Route 1 (n=211)
- Route 3 (n=209)

Vehicle Specific Power (VSP) Modes

- Freeway Route
- Arterial Route
Operating Modes (OpModes) for the U.S. Environmental Protection Agency MOVES Model

Vehicle Specific Power (kW/ton)

MOVES Operating Mode

0 1 11 12 13 14 15 16 21 22 23 24 25 26 27 28 29 30 33 35 37 38 39 40

Speed: [1–25] mph
Speed: [25–50] mph
Speed ≥ 50 mph

Decelerating
Idling
Coasting, VSP < 0
Coasting, VSP < 0

Average MOVES OpMode Rates for 214 Light Duty Gasoline Vehicles

- **CO₂**
- **HC**
- **CO**
- **NOₓ**

**Brake Deceleration**
- 1-25 mph
- 26-50 mph
- >50 mph

**Brake Deceleration**
- 1-25 mph
- 26-50 mph
- >50 mph
Distribution of Driving Time by OpModes for Routes A, C, 1, and 3

- Freeway Route
- Arterial Route

MOVES Operating Modes (OpModes)

- 0-11
- 12-25
- 26-50
- >50 mph

Route A (n=211)
Route C (n=211)
Route 1 (n=211)
Route 3 (n=209)
Comparison of Cycle Averages Based on 14 VSP Modes and 23 MOVES OpModes: \( \text{CO}_2 \) and \( \text{NO}_x \)

**Carbon Dioxide**
- 214 vehicles
- 839 driving cycles
- \( y = 1.010x \)
- \( R^2 = 0.960 \)

**Nitrogen Dioxide**
- 214 vehicles
- 848 driving cycles
- \( y = 0.994x \)
- \( R^2 = 0.990 \)
Examples of Completed Studies

- Real-world effectiveness of
  - Emission standards
  - Emissions controls (e.g., TWC, SCR, DPF)
- Trends over time (e.g., model years, standards)
- Vehicle classes
- Vehicle technology (e.g., HEV, PHEV, FFV, GDI)
- Diesel vs. gasoline fuels
- Alternative vs. conventional fuels
- Cold starts
- Road functional class
- Level of service, congestion
- Effect of road grade

- Identification of emissions hotspots
- Roundabout vs. signalized intersections
- Signal timing and coordination
- Idle reduction
- Driver behavior and driving cycles
- Alternative routes for an Origin/Destination pair
- Siting of remote sensing locations
- Comparison of transport modes (e.g., rail vs. passenger car)
Example Speed Trace: Chapel Hill Road (NC 54)

- crosses intersection

Example of a CO Emissions Trace

- **Acceleration**
- **Stop and Go**

Graph showing CO emissions over time, with peaks indicating acceleration and extended flat lines indicating stop and go periods.
Real World Data: Distribution of Travel Time, Distance, and Emissions by Mode

Distribution of Time, Distance Driven, Fuel Use, and Air Pollutant Emissions by Driving Mode for an Example Commuting Trip

Source: North Carolina State University
Measured Comparison of Uncongested and Congested Traffic Flow on Chapel Hill Rd.

<table>
<thead>
<tr>
<th></th>
<th>Ford Taurus</th>
<th></th>
<th>Chevrolet Venture</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direction</strong></td>
<td>North</td>
<td>South</td>
<td>North</td>
<td>South</td>
</tr>
<tr>
<td><strong>Trip Duration (%)</strong></td>
<td>-56</td>
<td>-60</td>
<td>-43</td>
<td>-44</td>
</tr>
<tr>
<td><strong>Ave. Speed (%)</strong></td>
<td>+118</td>
<td>+61</td>
<td>+137</td>
<td>+64</td>
</tr>
<tr>
<td><strong>Control Delay (%)</strong></td>
<td>-77</td>
<td>-78</td>
<td>-80</td>
<td>-80</td>
</tr>
<tr>
<td><strong>Total Stops (%)</strong></td>
<td>-83</td>
<td>-75</td>
<td>-84</td>
<td>-80</td>
</tr>
<tr>
<td><strong>HC Emissions (%)</strong></td>
<td>-54</td>
<td>-38</td>
<td>-59</td>
<td>-45</td>
</tr>
<tr>
<td><strong>NO Emissions (%)</strong></td>
<td>-52</td>
<td>-35</td>
<td>-57</td>
<td>-41</td>
</tr>
<tr>
<td><strong>CO Emissions (%)</strong></td>
<td>-52</td>
<td>-60</td>
<td>-60</td>
<td>-52</td>
</tr>
</tbody>
</table>

Quantifying Real-World Effectiveness of Emission Standards: Tier 1, Tier 2, and Tier 3 Standards for Passenger Cars (PC) and Passenger Trucks (PT)
Real-world rates typically higher than the certification level…

… but less than or equal to the level of the standard

Empirical Trends in Vehicle Emissions (Example)

- From 1990 to 2010, onroad CO emission rates decreased by 80% to 90% in Los Angeles, Houston, and New York.
- From 1990 to 2012, ambient concentrations of diesel particulate matter decreased by 68% in California.
- VOC emissions have decreased.

Warneke et al., 2012
Inter-Cycle (n=842) Variability in Cycle Average CO$_2$ Emission Rates for Average Passenger Cars (PCs)

Inter-cycle variability at a given average speed
Inter-Cycle (n=842) Variability in Cycle Average NO$_x$ Emission Rates for an Average Vehicle
Inter-Cycle (n=842) Variability in Cycle Average CO Emission Rates for an Average Vehicle
Cold Start Increment During Real-World Driving
Assessing Effect of Fuels and Technologies on Real-World Emissions: Selected Examples

E85 vs. Gasoline

Hybrid Electric vs. Conventional

Plug-in Hybrid Electric Vehicles

Gas Direct Injection

<table>
<thead>
<tr>
<th>Mode State</th>
<th>Main Energy Resource</th>
<th>Energy Use g/mile</th>
<th>CO₂</th>
<th>CO</th>
<th>HC</th>
<th>NOₓ</th>
<th>SOₓ</th>
<th>PM₂.₅</th>
<th>PM₁₀</th>
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</thead>
<tbody>
<tr>
<td>HI</td>
<td>Oil</td>
<td>90</td>
<td>290</td>
<td>55</td>
<td>730</td>
<td>582</td>
<td>54</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>WV</td>
<td>Coal</td>
<td>84</td>
<td>112</td>
<td>51</td>
<td>241</td>
<td>332</td>
<td>35</td>
<td>62</td>
<td></td>
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<tr>
<td>CD</td>
<td>Gas</td>
<td>73</td>
<td>153</td>
<td>47</td>
<td>112</td>
<td>51</td>
<td>5</td>
<td>4</td>
<td></td>
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<tr>
<td>VT</td>
<td>Nuclear</td>
<td>87</td>
<td>115</td>
<td>28</td>
<td>45</td>
<td>22</td>
<td>3</td>
<td>4</td>
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<tr>
<td>ID</td>
<td>Hydro</td>
<td>81</td>
<td>77</td>
<td>28</td>
<td>36</td>
<td>23</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>--</td>
<td>--</td>
<td>69</td>
<td>78</td>
<td>71</td>
<td>118</td>
<td>92</td>
<td>8</td>
<td>11</td>
</tr>
</tbody>
</table>

CD = Charge Depleting. CS = Charge Sustaining

<table>
<thead>
<tr>
<th>Route</th>
<th>GDI (mpg)</th>
<th>PFI (mpg)</th>
<th>% Diff</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (City)</td>
<td>24.6</td>
<td>22.2</td>
<td>10.7%</td>
<td>0.01</td>
</tr>
<tr>
<td>1 (Freeway)</td>
<td>29.1</td>
<td>27.5</td>
<td>5.6%</td>
<td>0.04</td>
</tr>
<tr>
<td>All-Routes</td>
<td>26.1</td>
<td>24.1</td>
<td>8.2%</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Note: n= 25 “Composite GDI” vehicles and n = 25 “Composite PFI” Vehicles. Percentage difference is value of \( \frac{\text{GDI} - \text{PFI}}{\text{PFI}} \) × 100%
Gas Direct Injection vs. Port Fuel Injection

![Graph showing PM (g/s) vs. Vehicle Specific Power (VSP) Mode for GDI and PFI.]
Spatial Distribution: Measured Segment Average NO$_x$ Emission Rates (g/mile)
International Comparison: Example: Raleigh, USA and Lisbon, Portugal

- Portable Emissions Measurement System (PEMS)
  - Carbon Dioxide (CO₂)
  - Nitric Oxide (NO)
  - Carbon Monoxide (CO)
  - Hydrocarbon (HC)

- On-Board Diagnostic Data Logger (OBD)
  - Vehicle Speed
  - Mass of Fuel Flow
  - Mass of Air Flow
  - Engine Revolutions per Minute

- Global Positioning System (GPS)
  - Vehicle Position
    - Latitude
    - Longitude
    - Elevation
Comparison of Lisbon, Portugal and Raleigh, USA Driving Cycles for Gasoline Vehicles

Lisbon Cycles Typically Have Higher Average Emission Rates Than Raleigh Cycles
Micro-Scale Framework

Transportation, Exposure, and Health

- Evidence for and estimates of the health effects of traffic-related air pollution
- Empirical evidence regarding near-road exposure concentrations
- Empirical evidence regarding in-vehicle exposures
- Methods for modeling human exposure

Source: Grieshop, Saha (NCSU), Khlystov (DRI)
Exposure and Health

• More work is needed to characterize spatial and temporal variability in emissions, exposure, and adverse effects related to transportation.
Conclusions

- Vehicle emissions contribute substantially to exposure and health burden
- There is not a standard PEMS: a PEMS can be selected related to study objective
- PEMS are continuing to develop
- PEMS can be deployed to address a wide range of study objectives: e.g., emission inventory, compliance, model validation, technology assessment, traffic control, roadway design,...
- Key advantage: representative, real-world vehicle operation
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frey@ncsu.edu