Trends in Transportation Energy Use and Emissions

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Number of Registered Onroad Vehicles in the U.S.
1970

- U.S. on-road vehicle contributions to national emissions
  - 35% of Nitrogen Oxides ($\text{NO}_x$)
  - 68% of Carbon Monoxide (CO)
  - 42% of Volatile Organic Compound (VOC)
- U.S. Environmental Protection Agency was formed
- Clean Air Act mandated vehicle emission standards
- California allowed to request a waiver under the Clean Air Act
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 ($\text{PM}_{2.5}$)
- By country:
  - India (39,000)
  - China (27,000)
  - U.S. (15,000)
Global In-Use Onroad Vehicle Stock

44% Increase Over 10 Years

Source: OICA, 2018
Global Onroad Vehicle Energy Consumption: Actual to 2014, Projected Thereafter

Source: EIA, 2017d

33% Projected Increase From 2015 to 2050

Source: EIA, 2017d
Best Selling Vehicles in 2018

3. Chevrolet Silverado: 531,158 units
2. Ram trucks: 536,980 units
1. Ford F-Series: 909,330 units

(42 Years in a row at #1)

https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/
Trends from 2010 with Projections to 2040 in the Global Fuel Mix for Electric Power Generation

Source: EIA, 2017
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
- Over 50 heavy duty vehicles (observed routes)
  - 12 dump trucks
  - 8 concrete mixers
  - 6 combination trucks
  - 24 refuse trucks
  - 2 school buses
- Over 40 construction vehicles
- 8 diesel-electric railroad locomotives

Also One Snowmobile and Five Snow Coaches
...and a lawnmower
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: CO₂, CO, HC
FID: THC
NDUV: NO, NO₂
Heated Sample Line
Heavy (~50 lbs)
High Power Demand

Axion
NDIR: CO₂, CO, HC
Electrochemical: NO, O₂
Light-scattering: PM
Water separation bowl
Portable (~30 lbs)
Low Power Demand

ParSYNC
“micro-PEMS”
Electrochemical:
CO₂, NO, NO₂
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)
Factors in Designing a PEMS-based Study

• 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
Portable Emission Measurement System
Global Positioning System (GPS) Receivers with Barometric Altimeters: ROAD GRADE

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 vs. Model Year
  - n = 214

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

- Curb Weight (lb)
  - Cumulative Frequency vs. Curb Weight
  - n = 209

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

Vehicle Specific Power (VSP)

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

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>

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

- CO2 (g/s) vs. Vehicle Specific Power (VSP) Modes
  - n = 214

- CO (mg/s) vs. Vehicle Specific Power (VSP) Modes
  - n = 214

- HC (mg/s) vs. Vehicle Specific Power (VSP) Modes
  - n = 214

- NOx (mg/s) vs. Vehicle Specific Power (VSP) Modes
  - n = 214
Distribution of Driving Time by VSP Modes for Routes A, C, 1, and 3

Time in Each Mode (seconds)

Vehicle Specific Power (VSP) Modes

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

Freeway Route
Arterial Route
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)

Example of a CO Emissions Trace

- **CO (g/sec)**
- **Elapsed Time (minutes)**

- **Acceleration**
- **Stop and Go**
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>Chevrolet Venture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North</td>
<td>South</td>
</tr>
<tr>
<td><strong>Trip Duration (%)</strong></td>
<td>-56</td>
<td>-60</td>
</tr>
<tr>
<td><strong>Ave. Speed (%)</strong></td>
<td>+118</td>
<td>+61</td>
</tr>
<tr>
<td><strong>Control Delay (%)</strong></td>
<td>-77</td>
<td>-78</td>
</tr>
<tr>
<td><strong>Total Stops (%)</strong></td>
<td>-83</td>
<td>-75</td>
</tr>
<tr>
<td><strong>HC Emissions (%)</strong></td>
<td>-54</td>
<td>-38</td>
</tr>
<tr>
<td><strong>NO Emissions (%)</strong></td>
<td>-52</td>
<td>-35</td>
</tr>
<tr>
<td><strong>CO Emissions (%)</strong></td>
<td>-52</td>
<td>-60</td>
</tr>
</tbody>
</table>

Quantifying Real-World Effectiveness of Emission Standards: Tier 1, Tier 2, and Tier 3 Passenger Cars (PC) and Passenger Trucks (PT)

HC (mg/s)

Vehicle Specific Power (VSP) Modes

- Non-hybrid T1 PT (n=4)
- Non-hybrid T1 PC (n=14)
- Non-hybrid T2 PT (n=55)
- Non-hybrid T2 PC (n=77)
- Non-hybrid T3 PT (n=10)
- Non-hybrid T3 PC (n=14)

Source: EPA, 2018
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
Trends in U.S. Light Duty Vehicle Technology: Fuel Delivery

- Carbureted
- Port Fuel Injection (PFI)
- Gas Direct Injection (GDI)

Source: US EPA, 2018
Observed Trend in Real-World Data: Increasing Compression Ratio for More Recent Model Years

Cumulative Frequency

Compression Ratio

Tier 1 (n=18)
Tier 2 (n=132)
Tier 3 (n=24)
Inter-Cycle (n=842) Variability in Cycle Average CO\textsubscript{2} Emission Rates for Average Passenger Cars (PCs)

Inter-cycle variability at a given average speed
Cycle Average Rates vs. Cycle Average Speed for 1,642 Real-World Cycles for An Average Tier 3 Passenger Car

**NO\textsubscript{x}**

- Predicted (mg/mile)
- Average Speed (mph)

**CO**

- Predicted (mg/mile)
- Average Speed (mph)

**HC**

- Predicted (mg/mile)
- Average Speed (mph)

**CO\textsubscript{2}**

- Predicted (g/mile)
- Measured (g/mile)
Cycle Average Rates vs. Cycle Average Speed for 1,642 Real-World Cycles for Average Tier 3 Passenger Cars and Trucks

- **NO\textsubscript{x}**
  - Predicted (mg/mile)
  - Average Speed (mph)
  - Tier 3 PC (n=14)
  - Tier 3 PT (n=10)

- **HC**
  - Predicted (mg/mile)
  - Average Speed (mph)
  - Tier 3 PC (n=14)
  - Tier 3 PT (n=10)

- **CO**
  - Predicted (mg/mile)
  - Average Speed (mph)
  - Tier 3 PC (n=14)
  - Tier 3 PT (n=10)

- **CO\textsubscript{2}**
  - Predicted (g/mile)
  - Measured (g/mile)
  - Tier 3 PC (n=14)
  - Tier 3 PT (n=10)
Cycle Average Rates vs. Cycle Average Speed for 1,642 Real-World Cycles for Average Tier 2 and 3 PCs and PTs
Cycle Average Rates vs. Cycle Average Speed for 1,642 Real-World Cycles for Average Tier 1, 2, and 3 Vehicles

**NO**

- Predicted (mg/mile)
- Average Speed (mph)
- Tier 1 PC (n=14)
- Tier 2 PC (n=77)
- Tier 2 PT (n=55)
- Tier 3 PC (n=14)
- Tier 3 PT (n=10)

**HC**

- Predicted (mg/mile)
- Average Speed (mph)
- Tier 1 PC (n=14)
- Tier 2 PC (n=77)
- Tier 2 PT (n=55)
- Tier 3 PC (n=14)
- Tier 3 PT (n=10)

**CO**

- Predicted (mg/mile)
- Average Speed (mph)
- Tier 1 PC (n=14)
- Tier 2 PC (n=77)
- Tier 2 PT (n=55)
- Tier 3 PC (n=14)
- Tier 3 PT (n=10)

**CO₂**

- Predicted (g/mile)
- Measured (g/mile)
- Tier 1 PC (n=14)
- Tier 2 PC (n=77)
- Tier 2 PT (n=55)
- Tier 3 PC (n=14)
- Tier 3 PT (n=10)
Trends in NO$_x$ Emission Factors: 1990 to 2050

Based on MOVES2014a
Trends in NO\textsubscript{x} Emissions Source Distribution: 1990 to 2050

Based on MOVES2014a
Identifying and Managing Emissions Hotspots

*Highest 80% emission in 12% of trip time*
NO\textsubscript{x} Emission Rates (g/mile): Outbound Trip
NO\textsubscript{x} Emission Rates (g/mile): Inbound Trip
Comparison of Outbound vs. Inbound Segment Average NO_x Emissions and Activity for Route 3
$NO_x$ Emission Rates (g/mile): Outbound Trip
HC Emission Rates (g/mile): Outbound Trip
CO Emission Rates (g/mile): Outbound Trip
CO₂ Emission Rates (g/mile): Outbound Trip
Inter-Segment Variability in Segment Average Emission Rates

- NO\textsubscript{x} Emission Rate (g/mile)
  - Cumulative Frequency vs. NO\textsubscript{x} Emission Rate

- HC Emission Rate (g/mile)
  - Cumulative Frequency vs. HC Emission Rate

- CO Emission Rate (g/mile)
  - Cumulative Frequency vs. CO Emission Rate

- CO\textsubscript{2} Emission Rate (g/mile)
  - Cumulative Frequency vs. CO\textsubscript{2} Emission Rate
Rated Fuel Economy

• Accurate in the U.S.
• Tends to be inaccurate in the EU and countries that use EU regulatory approach
• Why?
  – US rating is based on multiple cycles
  – Wider range of power demand and operating conditions than the EU official cycles

Cold Start vs. Hot Stabilized NO Exhaust Concentration

Cold Start Increment During Real-World Driving

Cumulative Distance (mi)
Assessing Effect of Fuels and Technologies on Real-World Emissions: Selected Examples

E85 vs. Gasoline

<table>
<thead>
<tr>
<th>Vehicle Specific Power Mode</th>
<th>NO as NO₂ (mg/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14</td>
<td></td>
</tr>
</tbody>
</table>

- Gasoline: n=5
- E85: n=5

Hybrid Electric vs. Conventional

Plug-in Hybrid Electric Vehicles

<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>
</tr>
</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>
</tr>
<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>6</td>
<td></td>
</tr>
<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

Gas Direct Injection

<table>
<thead>
<tr>
<th>Route</th>
<th>Fuel Economy</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></td>
<td>24.6</td>
<td>22.2</td>
<td>10.7%</td>
<td>0.01</td>
</tr>
<tr>
<td>1 (Freeway)</td>
<td></td>
<td>29.1</td>
<td>27.5</td>
<td>5.6%</td>
<td>0.04</td>
</tr>
<tr>
<td>All-Routes</td>
<td></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 \( \frac{GDI - PFI}{PFI} \) %
Gas Direct Injection vs. Port Fuel Injection

Vehicle Specific Power (VSP) Mode

PM (g/s)

GDI  PFI
Micro-Scale Framework

Transit Bus Emissions Model

(b) THC vs PM

- THC (mg/mile)
  - 10,000
  - 1,000
  - 100
  - 10
  - 1

- PM (mg/mile)
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50

- 30 ft CNG
- 40 ft CNG
- 60 ft CNG
- 30 ft diesel
- 40 ft diesel
- 60 ft diesel
- 40 ft hybrid
- 60 ft hybrid
Transit Bus Emissions Model

Rankings

Bus Types

- 30 ft CNG
- 40 ft CNG
- 60 ft CNG
- 30 ft diesel
- 40 ft diesel
- 60 ft diesel
- 40 ft hybrid
- 60 ft hybrid
Example: Installation of the PEMS on Construction Vehicles
Real-World Duty Cycles for Nonroad Equipment

Backhoe

Rubber Tire Loader

Normalized MAP
Cumulative Frequency

Load Truck
Mass Excavation
Handling

Soil Handling
Rock Handling
Load Truck
Inter-Cycle and Inter-Vehicle Variability in Mass Per Time Rates for Fuel Use Rates and NO\textsubscript{x} Emission Factors for Motor Graders

![Fuel Use (g/sec) and NO as NO\textsubscript{2} (mg/sec) graphs for different vehicle IDs and activities]
Measurements of Vocational Trucks
Measurements of Concrete Mixer Trucks

• Four cement mixers measured in Atlanta, GA
• Four measured in Vancouver, British Columbia, Canada
Types of Measured Refuse Trucks

- **Front-Loader**: Diesel (6)
- **Roll-Off**: Diesel (6)
- **Side-Loader**: Diesel (6)
- **Side-Loader**: CNG (3)
- **Front-Loader**: CNG (3)
Plug-in Hybrid Diesel-Electric School Bus

Wake County Public School Bus #1 – Plug-In Electric Diesel Hybrid School Bus with International Corporation VT365 Diesel Engine paired with Enova Hybrid Drive; tested on 12/20/2007

VT365 Engine Specifications

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>4-Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder Configuration</td>
<td>V8</td>
</tr>
<tr>
<td>Displacement</td>
<td>6.0 liters</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>18:1</td>
</tr>
<tr>
<td>Aspiration</td>
<td>Turbocharged</td>
</tr>
<tr>
<td>Total Engine Weight</td>
<td>1,062 lb (482 kg)</td>
</tr>
</tbody>
</table>

Long-Haul Sleeper Cab Truck Auxiliary Power Units

• Auxiliary power units (APUs):
  – Small diesel engine-generator
  – Power for electrical air conditioning, heating, and auxiliary loads
Fleet Activity Data: APU Utilization

10 Fleet-A Trucks
- With APU-A
- With APU-B

Average In-service time: 11,300 hours
(as of 2/29/07)

10 Fleet-B Trucks
- With APU-A
- With APU-B

Average In-service time: 8,500 hours
(as of 2/29/07)

Data Acquisition System

Average In-service time: 11,300 hours
(as of 2/29/07)
Measurements of Diesel Passenger Rail Real-World Emissions: Amtrak Piedmont Route

- GPS Receivers
- Prime Mover Engine Exhaust Duct
- Revolutions per Minute Sensor
- Locomotive Activity Recorder
- Portable Emission Measurement System
- Inlet Air Temperature Sensor
- Manifold Absolute Pressure Sensor
Measurements of Diesel Passenger Rail Real-World Emissions: Amtrak Piedmont Route

Charlotte  Salisbury  Greensboro  Durham  Raleigh
Kannapolis  High Point  Burlington  Cary

NO\textsubscript{x} Rate (g/mile)
PM Rate (g/mile)

Segment ID

Eastbound
Westbound
Measurements of Diesel Passenger Rail Real-World Emissions: Amtrak Piedmont Route
Results: Retrofitted Locomotive Selective Catalytic Reduction for NO\textsubscript{x} Control

Over 75% reduction in NO\textsubscript{x} emissions for notches 2 through 8

Cycle average NO\textsubscript{x} emission rates reduced by 70% to 0.8 g/bhp-hr (Lower than EPA Tier 4 level)

Fuel use rate increased slightly due to additional load on the HEP engine to power BATS

Cycle average fuel use rate increased by 0.4 percent
Ongoing Work: Quantify Energy Use and Emissions of DC/Baltimore Area Rail Systems
Example: Washington Metro
Moving Toward a New Paradigm

- **Source control**: ineffective at improving air quality (e.g., ozone, particulate matter)
- **Air quality management**: ineffective at preventing high end exposures to sensitive populations
- **Exposure management**: there are more ways to manage exposure beyond managing air quality
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)
# Average in- to near-vehicle concentration (I/O) ratio by route and ventilation condition

<table>
<thead>
<tr>
<th>Case</th>
<th>Air Source</th>
<th>Window</th>
<th>Fan</th>
<th>AC</th>
<th>Route</th>
<th>Road Type</th>
<th>I/O Ratio (C_{IV}/C_{NV})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>F</td>
<td>3&quot;</td>
<td>0</td>
<td>off</td>
<td>A-out</td>
<td>NF</td>
<td>0.98 ± 0.010</td>
</tr>
<tr>
<td>1-2</td>
<td>F</td>
<td>closed</td>
<td>0</td>
<td>off</td>
<td>A-in</td>
<td>NF</td>
<td>0.94 ± 0.001</td>
</tr>
<tr>
<td>1-3</td>
<td>F</td>
<td>closed</td>
<td>1</td>
<td>off</td>
<td>1-out</td>
<td>10%NF / 90%F</td>
<td>0.95 ± 0.007</td>
</tr>
<tr>
<td>1-4</td>
<td>F</td>
<td>closed</td>
<td>1</td>
<td>on</td>
<td>1-in</td>
<td>90%F / 10%NF</td>
<td>0.89 ± 0.044</td>
</tr>
<tr>
<td>1-5</td>
<td>F</td>
<td>closed</td>
<td>3</td>
<td>off</td>
<td>C-out</td>
<td>half NF / half F</td>
<td>0.91 ± 0.002</td>
</tr>
<tr>
<td>1-6</td>
<td>F</td>
<td>closed</td>
<td>3</td>
<td>on</td>
<td>C-in</td>
<td>half F / half NF</td>
<td>0.87 ± 0.037</td>
</tr>
<tr>
<td>1-7</td>
<td>F</td>
<td>closed</td>
<td>4</td>
<td>off</td>
<td>3-out</td>
<td>NF</td>
<td>0.90 ± 0.020</td>
</tr>
<tr>
<td>1-8</td>
<td>F</td>
<td>closed</td>
<td>4</td>
<td>on</td>
<td>3-in</td>
<td>NF</td>
<td>0.87 ± 0.002</td>
</tr>
<tr>
<td>2-1</td>
<td>R</td>
<td>fully</td>
<td>0</td>
<td>off</td>
<td>A-out</td>
<td>NF</td>
<td>0.97 ± 0.028</td>
</tr>
<tr>
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<td>R</td>
<td>closed</td>
<td>0</td>
<td>off</td>
<td>A-in</td>
<td>NF</td>
<td>0.66 ± 0.003</td>
</tr>
<tr>
<td>2-3</td>
<td>R</td>
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<td>1</td>
<td>off</td>
<td>1-out</td>
<td>10%NF / 90%F</td>
<td>0.81 ± 0.033</td>
</tr>
<tr>
<td>2-4</td>
<td>R</td>
<td>closed</td>
<td>1</td>
<td>on</td>
<td>1-in</td>
<td>90%F / 10%NF</td>
<td>0.69 ± 0.035</td>
</tr>
<tr>
<td>2-5</td>
<td>R</td>
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<td>3</td>
<td>off</td>
<td>C-out</td>
<td>half NF / half F</td>
<td>0.64 ± 0.012</td>
</tr>
<tr>
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<td>3</td>
<td>on</td>
<td>C-in</td>
<td>half F / half NF</td>
<td>0.36 ± 0.082</td>
</tr>
<tr>
<td>2-7</td>
<td>R</td>
<td>closed</td>
<td>4</td>
<td>off</td>
<td>3-out</td>
<td>NF</td>
<td>0.47 ± 0.031</td>
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<tr>
<td>2-8</td>
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<td>closed</td>
<td>4</td>
<td>on</td>
<td>3-in</td>
<td>NF</td>
<td>0.30 ± 0.024</td>
</tr>
</tbody>
</table>
Instrumented Backpack for Measuring PM$_{2.5}$, Ozone, Carbon Monoxide, and Location
Typical Study Routes
Spatial Distribution of Exposure
“Hotspots” (Car, 4/24, PM)
Measured Mean Modal Ratio of PM$_{2.5}$ With Respect to Pedestrian Mode by Time of Day for Summer (II)
## ANOVA: Significant Sources of Variability in PM$_{2.5}$ Exposure Concentrations

<table>
<thead>
<tr>
<th>Source</th>
<th>Ratio</th>
<th>P-Value</th>
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<tbody>
<tr>
<td>Season</td>
<td>13.3</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Location</td>
<td>3.6</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Time</td>
<td>14.4</td>
<td>&lt;0.01</td>
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<tr>
<td>Mode</td>
<td>159.1</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Season*Time</td>
<td>5.8</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Season*Mode</td>
<td>5.2</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Time*Mode</td>
<td>4.5</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>
Exposure and Health

• More work is needed to characterize spatial and temporal variability in emissions, exposure, and adverse effects related to transportation
Personalised Real-Time Air Quality Informatics System for Exposure – Hong Kong (PRAISE-HK)
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Personalised Real-Time Air Quality Informatics System for Exposure – Hong Kong (PRAISE-HK)
2018 Air & Waste Management Association Critical Review

Summary Article in June 2018 EM

Plus… Supplemental Materials

50-page Paper in June 2018 Journal of A&WMA
Conclusions

• Although vehicle emissions are generally decreasing:
  – Vehicles can produce high emissions under real-world operating conditions
  – Vehicle operation, coupled with traffic control and characteristics of the road network and traffic, can lead to localized hotspots
  – Microscale events can dominate trip total emissions
  – The localized hotspots have implications for human exposure
• There is need for ongoing surveillance of real world emissions to validate estimated emission trends and to improve the accuracy of emission estimates.
• Similar methods can be applied to nonroad and rail
• Health impact depends on exposure; therefore, should target efforts to mitigate transport-related exposures.
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Questions?
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