Toward Widespread e-Mobility and the Ultimate Solution for Combustion-Generated Nano-Particles

19th ETH-Conference on Combustion-Generated Nano-Particles

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California Air Resources Board

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Zurich, Switzerland
Air Quality Challenges
Span Multiple Scales

Near-Source & Local Hotspots:
PM & air toxics

Regional: Ozone/NOx

Global: Climate Change
We have been going at this for a while

Already In 1972: CARB Aerosol Characterization Experiment (ACHEX)
- Roadway PM measurements
- Rush hour traffic impacts
- Air Resources Board Mobile Air Pollution Laboratory
- Ken Whitby, Virgil Marple, and others from Particle Technology Lab at Univ. of Minnesota

40 years later:
- Now monitoring UFPs near roadway
- Exposure Mitigation still important
- New Roadside Monitoring Network will help

Lee et al., 2013. Atmos.Environ. – UCLA, SCAQMD, and CARB California Environmental Protection Agency

Fig. 4. Comparisons among particle size distributions measured and averaged under different wind directions (i.e., upwind, downwind, and others as depicted in Fig. 1) during the sampling period of one month.
Progress Despite Growth Pressures

- Population ↑2X
- Fleet ↑4X
- Vehicle miles travelled ↑5X
- Economic activity ↑5X

Ground level Ozone ↓80%

Climate Change
“Early actions”
On target to meet 2020 goal for GHG reduction

PM2.5 and PM10
Attainment expected by 2032 for Federal Ambient Air Quality Standards:
Remarkable Progress: The ambient PM2.5 example

- Progress thru current SIPs
  - 15 µg/m³ annual PM2.5 standard
    - South Coast attained in 2013
    - San Joaquin Valley levels decreased 30% over last decade
  - 35 µg/m³ 24-hour PM2.5 standard
    - South Coast expected to attain in 2015
    - San Joaquin Valley remains a challenge

- Challenges in upcoming SIP
  - 12 µg/m³ annual PM2.5 standard
    - SIPs due in 2016
    - 4 nonattainment areas with unique challenges (Calexico, Portola, South Coast, and San Joaquin Valley)
Let’s talk about mobile sources – and specifically gasoline LDV tailpipe emissions

• But first....
• Diesel DPF is a proven solution
• We understand nuances (fill state, green vs aged, etc) that can lead or suppress ultrafine particle formation

![Graph showing particle diameter (nm) vs particle #/mile for different DPF types and No DPF.](image)
# Policies considered for LEVIII PM Standards

Draft Solid Particle Number Limits not Adopted*

<table>
<thead>
<tr>
<th>Vehicle Category (lbs)</th>
<th>LEV II Standards</th>
<th>Proposed Standards</th>
<th>Final (MY 2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM g/mi</td>
<td>SPN #/mi</td>
<td>Interim (MY 2014)</td>
</tr>
<tr>
<td>LDV (0 - 8,500)</td>
<td>0.010</td>
<td>-</td>
<td>0.006</td>
</tr>
<tr>
<td>MDPV (8,501 - 10,000)</td>
<td>0.010</td>
<td>-</td>
<td>0.006</td>
</tr>
<tr>
<td>MDV (8,501 - 14,000)</td>
<td>0.060 - .0120</td>
<td>-</td>
<td>0.008 - 0.012</td>
</tr>
</tbody>
</table>

*CARB Public Workshop, El Monte, CA, May 18, 2010 and White Paper on PM, particle number and black carbon

*Manufacturer must choose to comply with either the PM standard or the SPN standard
What do we mean by UFPs?

Investigation of Ultrafine Particle Number Measurements from a Clean Diesel Truck using the European PMP Protocol

Jorn Dinh Herner, William H. Robertson, and Alberto Ayala
California Air Resources Board

Evaluation of the European PMP Methodologies during On-Road and Chassis Dynamometer Testing for DPF Equipped Heavy-Duty Diesel Vehicles

Kent C. Johnson, Thomas D. Durbin, Heejung Jung, Ajay Chaudhary, David R. Cocker III, Jorn D. Herner, William H. Robertson, Tao Huai, Alberto Ayala, and David Kittelson

Nature of Sub-23-nm Particles Downstream of the European Particle Measurement Programme (PMP)-Compliant System: A Real-Time Data Perspective


Comparison of Particle Mass and Solid Particle Number (SPN) Emissions from a Heavy-Duty Diesel Vehicle under On-Road Driving Conditions and a Standard Testing Cycle

Zhongqing Zheng, Thomas D. Durbin, Jian Xue, Kent C. Johnson, Yang Li, Shaohua Hu, Tao Huai, Alberto Ayala, David B. Kittelson, and Heejung S. Jung
Total and Solid PN versus PM and BC Mass

Solid PN vs. BC Mass
(Ref: Chan et al., 2014 ES&T)

Total PN vs. Gravimetric PM
(Ref, Quiros, et al. ES&T 2015, in review)
Technology for GHG has PM implications

Gasoline Direct Injection:
- Climate and Fuel Efficiency Gains, but:
  - Possible higher PM than pre-mixed Sequential Port Fuel Injected (SPFI) gasoline engines.
  - Engineering specifics determine PM emissions.
  - Commercialized examples exist meeting ARB’s LEV-III standards

<table>
<thead>
<tr>
<th>Conventional Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEV-II GDI</td>
</tr>
<tr>
<td>LEV-II SPFI</td>
</tr>
<tr>
<td>DPF Diesel</td>
</tr>
</tbody>
</table>
PM, PN and the importance of GDI

- GDI mass > PFI mass, especially cold start
- Correlation between mass and total number (and BC not shown)
- Correlation weakens for sub-1mg/mi emission levels
- GDI – 1 mg ~ 2.8 X 10^{12} particles
- PFI – 1mg ~ 1.6 X 10^{12} particles

**Figure S6.** Particle mass (a,d), active surface area (b,e), and total number (c,f) emissions for vehicles meeting the 3 mg/mi standard (n=152, top row), and for vehicles meeting the 1 mg/mi standard (n=115, bottom row).

Is the control technology outcome different for an emission standard based on particle number rather than particle mass?

Figure 5. Scatter plots for (a) total particle number, and (b) surface area versus gravimetric PM mass for each vehicle technology.

California Light Duty Vehicle Tailpipe PM Standards
(passenger cars, light trucks < 8,500 lbs. GVW)

Gasoline vehicles subject to PM standard beginning in 2004

LEV III PM standard
1mg/mi
And Now on the Heavy Duty side:

40+ Years of Progress on Diesel Soot and Associated Climate Benefits from BC Reductions

- Emission standards, fuel standards, and fleet rules
- Statewide BC concentrations in California have decreased from 0.46 µg/m³ in 1989 to 0.24 µg/m³ in 2008 (about 50% reduction)
- Diesel emissions show a corresponding 50% reduction
- This trend extends further back – a decrease of 72% from 1960s to 2000
- Downward BC trend is still continuing

Kirchstetter et al. (2011) Black Carbon and the Regional Climate of California, CARB Contract No. 08-323.
Fleet Average HD Truck Emission Rates Dropping

An Example of PM Retrofit & Accelerated Fleet Turnover

- **Drayage Truck Rule rapid DPF phase-in** driving drop in Black Carbon (BC) HD truck emission factors

- **3X reduction in 2 year period** for BC emission rates observed in-use on 110 Harbor Freeway for On-Road truck fleet

DPF Robustness Affirmed by Large Scale Assessment In-Use

CARB Staff’s overall findings are:

- **PM filters do not increase the likelihood of truck fires** and are manufactured in accordance with federal and state safety requirements;
- **PM filters are effective** in removing more than 98 percent of toxic diesel PM emissions;
- **PM filters are operating properly**, and most trucking fleets are not having problems with their engines or PM filters; and
- **Some fleets are experiencing problems with their PM filters**, but **engine durability issues and inadequate maintenance practices are the primary reasons** for these problems.

Evaluation of Particulate Matter Filters in On-Road Heavy-Duty Diesel Vehicle Applications


May 8, 2015
PM Aftertreatment Reducing Exposure

- Mass emission rates heavily attenuated by DPF aftertreatment technology
- Remaining PM still carries signatures of primary Diesel Particulate Material
- California On-Road fleet rapidly adopting DPF technology
- DPF technology proving robust in the field


Off-Road Diesel Engines without DPFs

• Tier 4 Off-Road Engine PM Mass Standard being met with SCR/non-DPF configurations
  – Simplified aftertreatment system reduces upfront cost
  – Potentially less operational impacts in absence of filter and regeneration

• Areas of Interest
  – PM emission rates In-Use compared to DPF based systems?
  – Breakdown-to-repair duration for PM increasing emissions failures compared to DPF based systems?
  – PM speciation & toxicity assays relative to post-DPF PM. Possibility for different exposure risk per unit PM?
  – Unregulated emission control benefits maintained relative to oxidation catalysts in a DPF system?
  – Outcome of further investigations may indicate need to revisit Tier 4 PM standards
Continued Interest in Combustion Generated Nanoparticles

Toxicity designations historically based on conventional diesel engine exhaust

• Longitudinal epidemiologic studies of aftertreated exhaust needed
  – Recent technology introduction: Evolving legacy fleet turnover
  – Inconsistent Ultrafine Particle definitions impeding monitoring network deployment
  – Lack of monitoring network impedes coordinated UFP exposure assessments
  – Population mobility high relative to PM spatial/temporal variation

• PM chronic exposure studies needed at NO$_2$ levels representative of current production engines

• Going beyond regional PM attainment: High risk exposure assessments: Near Roadway, Vulnerable Populations
Combustion Generated Nanoparticle Challenges

- Measurement
- Exposure/Toxicity assessments
- Causal links between health effects and UFP
- Controls availability beyond current “Best Available Control Technology”
The light at the end of the tunnel

**Q:** How do you eliminate combustion-generated ultrafine particles?

**A:** You eliminate combustion

Zero emission vehicles for clean air and low-carbon transportation
e-Mobility also required by CARB’s other responsibilities:

- **NOx:** to meet current 75ppb ozone standard
  - ↓80% by 2023 from 2010 levels
  - ↓90% by 2032 from 2010 levels
  (US-EPA considering lowering standard further)

- **Greenhouse Gases**
  - ↓ Return to 1990 levels by 2020
  - ↓80% below 1990 levels by 2050

- **Petroleum Use** in Transport Fuel
  - ↓50% by 2030
  - ↓80% by 2050
91% of California population in Ozone Non-Attainment areas.

**Extreme Non-Attainment Areas:**
- San Joaquin Valley
- South Coast

US-EPA considering further lowering of 8-hr ozone standard
Scale of Actions Needed: South Coast Example

Meeting 2023 Ozone standard means:

- Multiple sectors each eliminating majority of their aggregate NOx emissions
- **Additional 2/3**\(^{rd}\) NOx reduction **needed beyond** presently **adopted programs**
- Further incremental improvement difficult in many sectors: Light duty sector already reduced >90%:
  - San Joaquin Valley Air Basin in similar situation

Tons/day NOx in 2023 with currently adopted programs
e-Mobility Essential

• Emissions goals cannot be achieved by **incrementally** improving combustion-based technologies.

• **Further gains will require greater investment:** Criteria emissions are already greatly reduced in Light Duty vehicles.

• “**High emitters**” in the IC vehicle population increasingly **driving emissions inventory.** Identifying and remediating the last remaining broken high emitters from a population difficult and expensive.

• **Beyond Carnot:** GHG gains in Combustion Engines, while important, are subject to severe thermodynamic efficiency limits.
e-Mobility is an Enabler

- **Zero tailpipe PM/NOx**
- **Emission rates** practically *independent* of vehicle age
- A given vehicle can *easily* to *switch among* diversified *renewable energy sources*
  - Vehicle side technology needs no modification to accept new renewable sources of electricity or H₂
  - On-board energy storage provides natural time-shift capability for intermittently available renewables (charging off peak rate savings, Vehicle-to-grid storage, etc)
- **Off-board power generation**
  - Point-of-Use and Energy Generation separation opportunities
  - Plant-scale operational efficiencies and emissions controls can be applied to transportation
- **GHG** benefits *not limited* by IC thermodynamic *efficiency limits*
Electrification is poised to impact a wide range of mobile source categories:

- Passenger Transport
- Goods Movement
- Vocational trucks
- Non-Road

- Cost coming down: $200/kWhr energy storage in sight
California e-Mobility Goals

- Advanced Clean Cars/LEV-III program requirements project ~250,000 ZEVs in 2025
- CA Gov.’s ZEV mandate targeting 1.5M ZEVs by 2025
- MOU with 7 other states for 3.3M ZEVs on the road by 2025

- Hydrogen Fueling seed money being provided by California for initial 100 station network
- 33% renewable electricity grid mix by 2030
- 50% renewable electricity grid mix by 2050
Not Just Passenger Cars: Heavy Duty Investments

- HVIP Vouchers: Incremental cost of HD Hybrids & EVs
- 2100+ Hybrid and Battery Electric purchase vouchers issued to date
- Contributing ~30% growth to national Heavy Duty electrified vehicle market
- Seeking $12M HVIP allocation for FY15/16 as part of $375M for clean transportation
e-Mobility Market Growth Challenges

• Enabling new ZEV infrastructure
• Building ZEV consumer awareness
• ZEV Up-front costs
• Matching duty cycles to ZEV operational abilities
• Expanding commercially availability across all vehicle categories
e-Mobility Infrastructure Development

- Passenger
- Fueling infrastructure
  - Uniform Standards and zoning & permitting
  - Subsidies to early station installation
- SB-375 Coordinated local transportation and land-use planning processes
- Highspeed Rail
E-Mobility not an overnight project

Internal combustion in transportation will remain important in coming years

• Continuing to implement LEV-III Advanced Clean Cars requirements

• Heavy Duty Warranty/In-use Compliance/HD-OBD efforts for clean, durable IC vehicles

• Non-PM efforts as well: Heavy Duty “Low NOx” optional certification categories
Background Slides
CARB Planning Documents


- Vision for Clean Air: Scenario Planning: [http://www.arb.ca.gov/planning/vision/vision.htm](http://www.arb.ca.gov/planning/vision/vision.htm)

- 2015 draft Sustainable Freight Strategy: [http://www.arb.ca.gov/gmp/sfti/sfti.htm](http://www.arb.ca.gov/gmp/sfti/sfti.htm)

- 2015 Heavy Duty Engine and Fuels Technology Assessment: [http://www.arb.ca.gov/msprog/tech/tech.htm](http://www.arb.ca.gov/msprog/tech/tech.htm)

- 2104 Update to 2008 Climate Scoping Plan: [http://www.arb.ca.gov/cc/scopingplan/scopingplan.htm](http://www.arb.ca.gov/cc/scopingplan/scopingplan.htm)
California e-Mobility User Incentives

• Light Duty Vehicles
  – Clean Vehicle Rebate Project: [https://energycenter.org/clean-vehicle-rebate-project](https://energycenter.org/clean-vehicle-rebate-project)
  – Enhanced Fleet Modernization Program: [http://www.arb.ca.gov/msprog/aqip/efmp/efmp.htm](http://www.arb.ca.gov/msprog/aqip/efmp/efmp.htm)
  – Drive Clean website: [http://driveclean.ca.gov/](http://driveclean.ca.gov/)

• Heavy Duty Vehicles
  – theTRUCKSTOP summary of Heavy Duty funding programs [http://www.arb.ca.gov/msprog/truckstop/azregs/fa_resources.htm](http://www.arb.ca.gov/msprog/truckstop/azregs/fa_resources.htm)