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

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

William H. Robertson & Alberto Ayala
California Air Resources Board

June 28, 2015
Zurich, Switzerland

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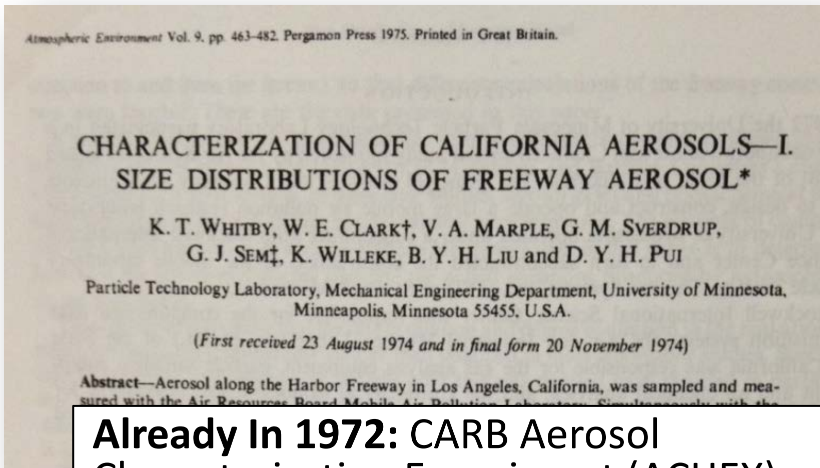
Air Quality Challenges Span Multiple Scales

We have been going at this for a while



Atmospheric Environment Vol. 9, pp. 463–482. Pergamon Press 1975. Printed in Great Britain.

CHARACTERIZATION OF CALIFORNIA AEROSOLS—I. SIZE DISTRIBUTIONS OF FREEWAY AEROSOL*

K. T. Whitby, W. E. Clark†, V. A. Marple, G. M. Sverdrup, G. J. Sem‡, K. Willeke, B. Y. H. Liu and D. Y. H. Pui

Particle Technology Laboratory, Mechanical Engineering Department, University of Minnesota, Minneapolis, Minnesota 55455, U.S.A.

(*First received 23 August 1974 and in final form 20 November 1974*)

Abstract—Aerosol along the Harbor Freeway in Los Angeles, California, was sampled and mea-

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

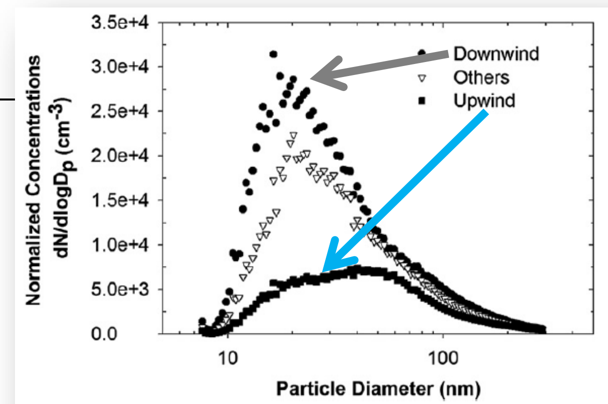


Fig. 4. Comparisons among particle size distributions measured and averaged under different wind directions (i.e., upwind, downwind, and others as depicted in Fig. 1) during the sampling period of one month.

Lee et al., 2013. Atmos.Environ. – UCLA, SCAQMD, and CARB

Progress Despite Growth Pressures

PM2.5 and PM10
Attainment expected by 2032
for Federal Ambient Air Quality Standards:

Ground level
Ozone ↓**80%**

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

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

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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)

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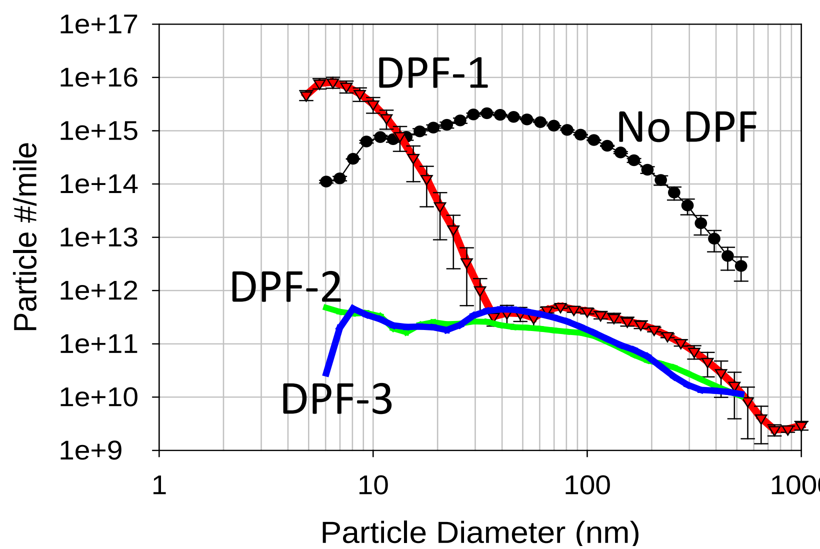
Let's talk about mobile sources –
and specifically gasoline LDV tailpipe emissions

- 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



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Policies considered for LEVIII PM Standards

Draft Solid Particle Number Limits not Adopted*

Vehicle Category (lbs)	LEV II Standards		Proposed Standards* (full useful life)			
			Interim (MY 2014)		Final (MY 2017)	
	PM g/mi	SPN #/mi	PM g/mi	SPN #/mi	PM g/mi	SPN #/mi
LDV (0 - 8,500)	0.010	-	0.006	6×10^{12}	0.003	3×10^{12}
MDPV (8,501 - 10,000)	0.010	-	0.006	6×10^{12}	0.003	3×10^{12}
MDV (8,501 - 14,000)	0.060 - .0120	-	Final (MY 2016)			
			PM g/mi	SPN #/mi		
			0.008 - 0.012	TBD		

*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?

2007-01-1114

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

Aerosol Science and Technology, 43:962–969, 2009

ISSN: 0278-6826 print / 1521-7388 online
DOI: 10.1080/02786820903074810

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

Kent C. Johnson,[1] Thomas D. Durbin,[1] Heejung Jung,[1] Ajay Chaudhary,[1] David R. Cocker III,[1] Jorn D. Herner,[2] William H. Robertson,[2] Tao Huai,[2] Alberto Ayala,[2] and David Kittelson[3]

Aerosol Science and Technology, 46:886–896, 2012

ISSN: 0278-6826 print / 1521-7388 online
DOI: 10.1080/02786826.2012.679167

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

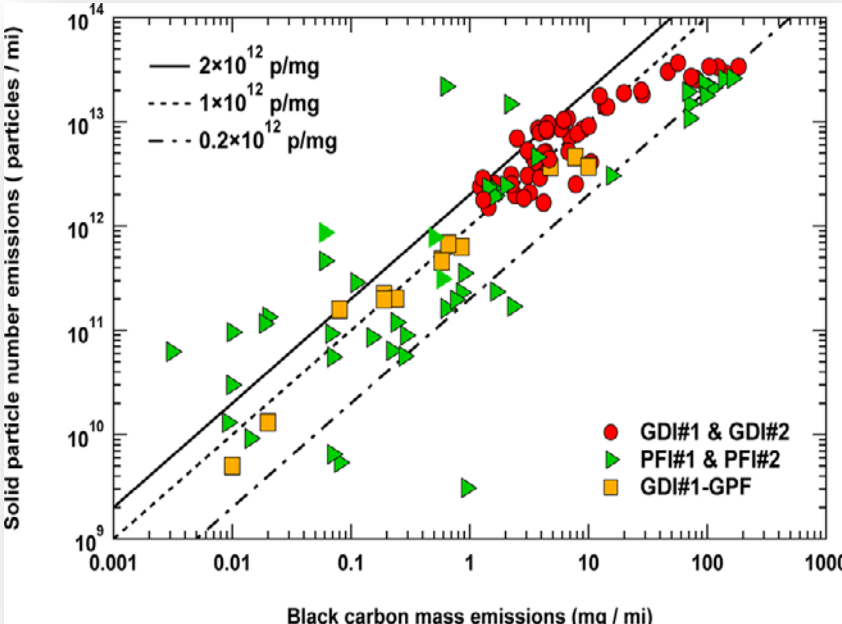
Zhongqing Zheng,[1,2] Thomas D. Durbin,[1] Georgios Karavalakis,[1] Kent C. Johnson,[1] Ajay Chaudhary,[1] David R. Cocker III,[1] Jorn D. Herner,[3] William H. Robertson,[4] Tao Huai,[5] Alberto Ayala,[5] David B. Kittelson,[6] and Heejung S. Jung[1,2]

Environmental Science & Technology

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

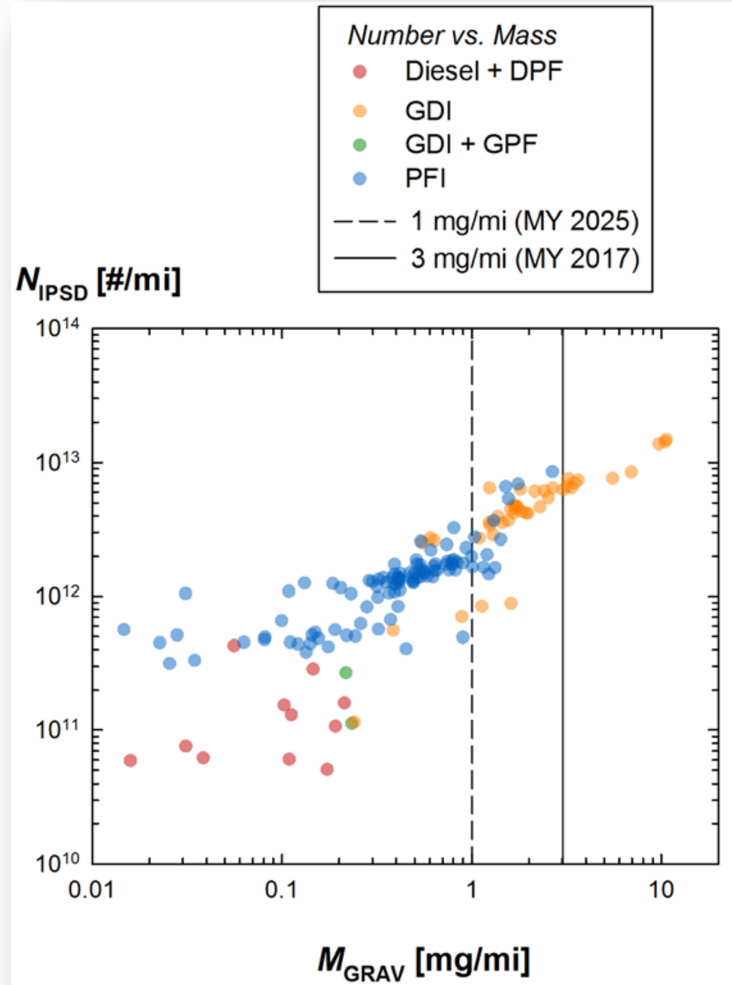
Zhongqing Zheng,[†,‡] Thomas D. Durbin,[‡] Jian Xue,[†,‡] Kent C. Johnson,[‡] Yang Li,[†,‡] Shaohua Hu,[§] Tao Huai,[§] Alberto Ayala,[§] David B. Kittelson,[‖] and Heejung S. Jung*[,†,‡]

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)

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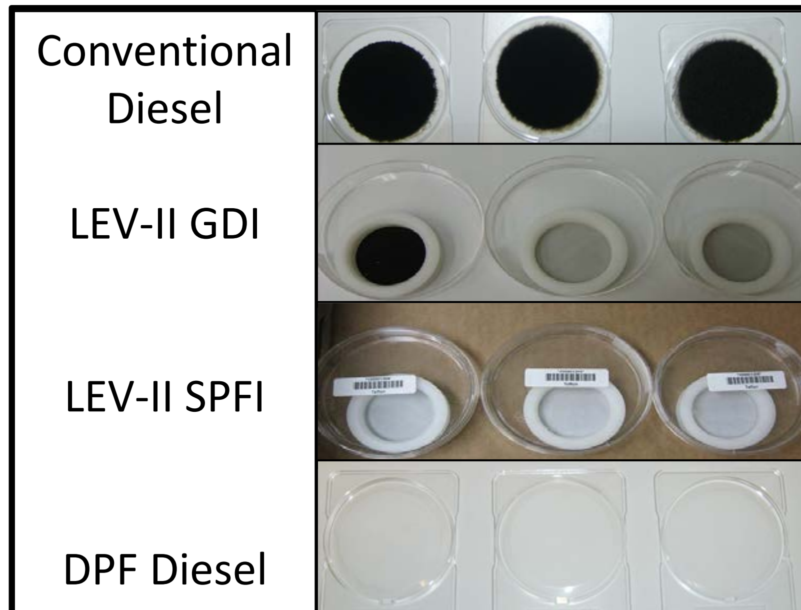
Technology for GHG has PM implications

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



PM, PN and the importance of GDI

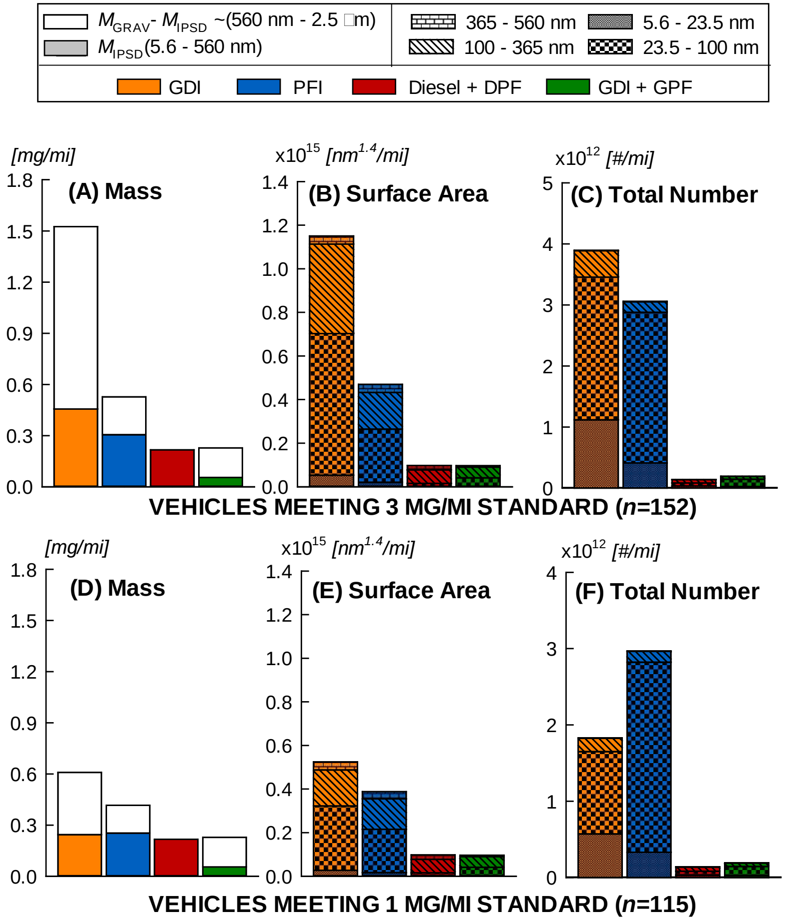


Figure S6. Particle mass (a,d), active surface area (b,e), and total number (c,f) emissions for vehicles meeting the 3 mg/mi standard (n=152, top row), and for vehicles meeting the 1 mg/mi standard (n=115, bottom row).

- 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 10^2 particles

Quiros et al., Measuring Particulate Emissions of Light Duty Passenger Vehicles Using Integrated Particle Size Distribution (IPSD). *Enviro. Sci. Technol.* Feb 2015. In review.

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

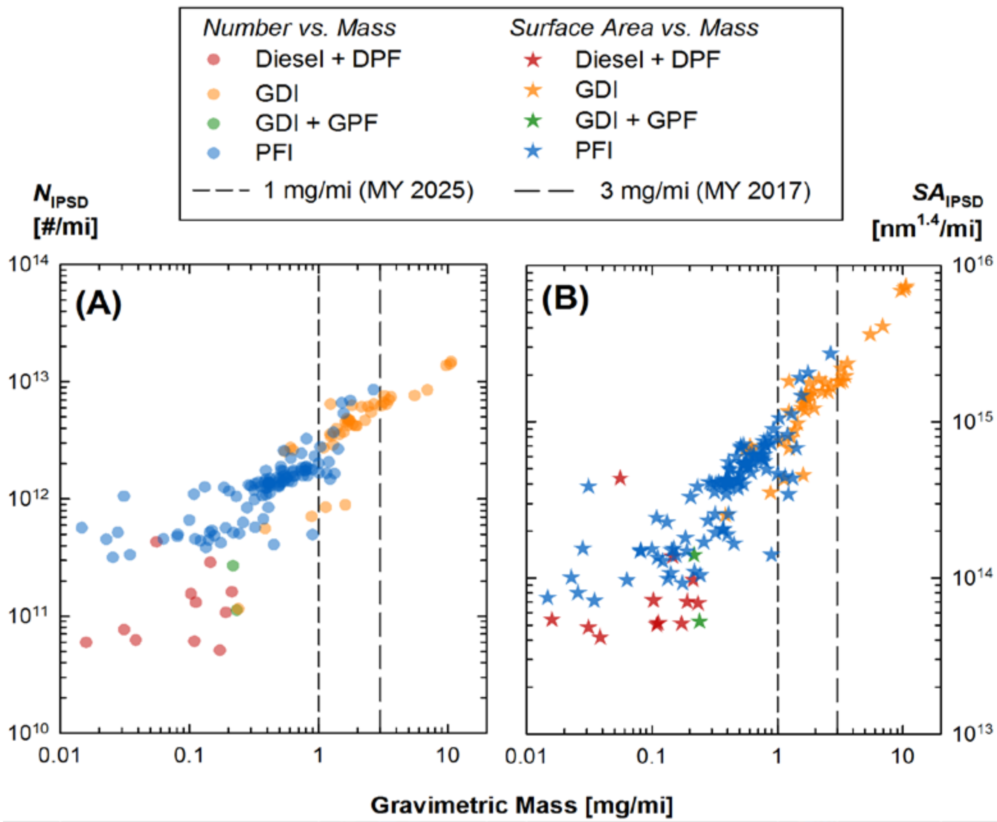
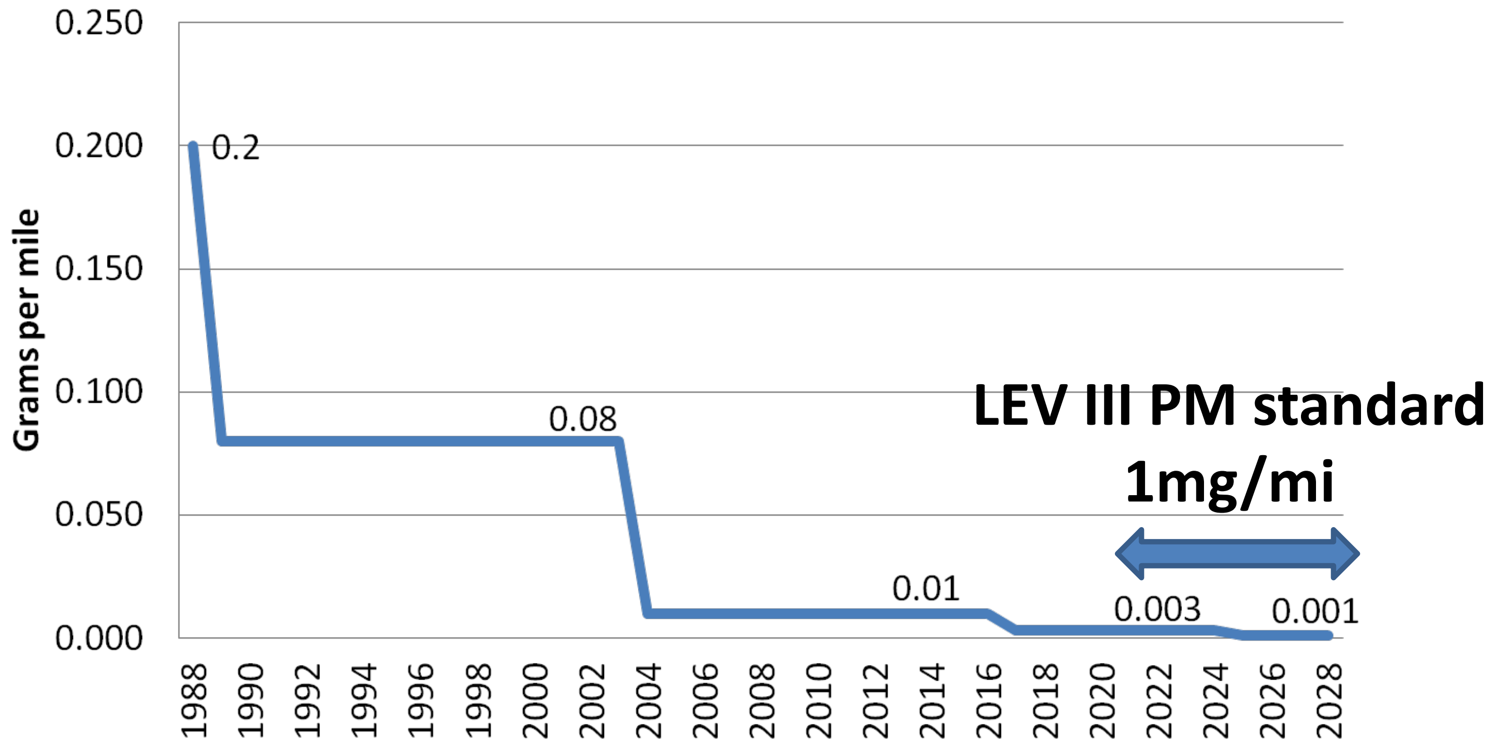


Figure 5. Scatter plots for (a) total particle number, and (b) surface area versus gravimetric PM mass for each vehicle technology.

Quiros et al., Measuring Particulate Emissions of Light Duty Passenger Vehicles Using Integrated Particle Size Distribution (IPSD). *Enviro. Sci. Technol.* Feb 2015. In review.

California Light Duty Vehicle Tailpipe PM Standards

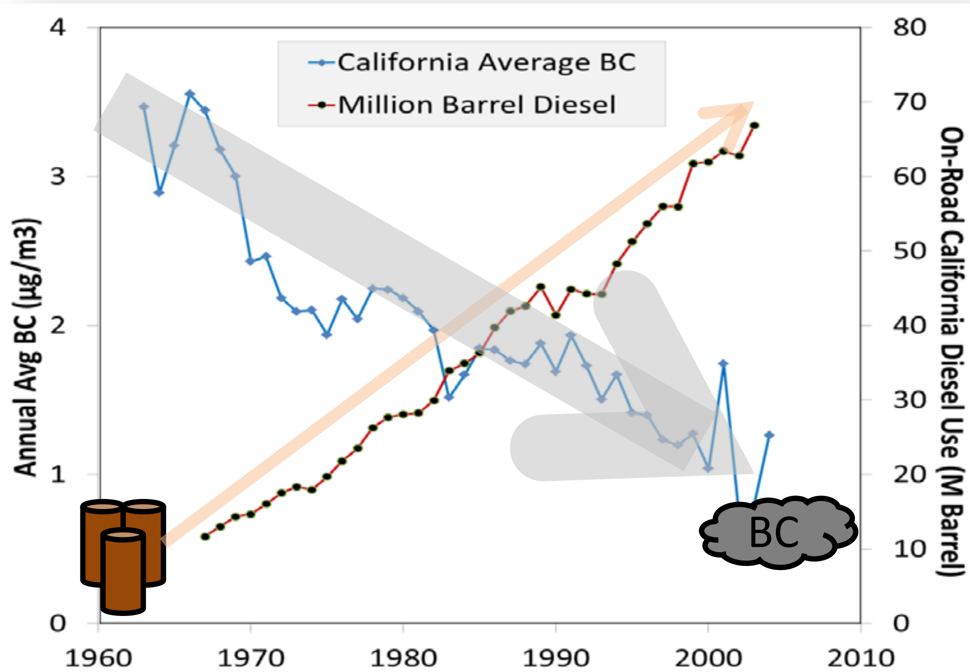
(passenger cars, light trucks < 8,500 lbs. GVW)



Gasoline vehicles subject to PM standard beginning in 2004

And Now on the Heavy Duty side:

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



Kirchstetter et al. (2011) Black Carbon and the Regional Climate of California, CARB Contract No. 08-323.

- Emission standards, fuel standards, and fleet rules
- Statewide BC concentrations in California have decreased from 0.46 µg/m^3 in 1989 to 0.24 µg/m^3 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

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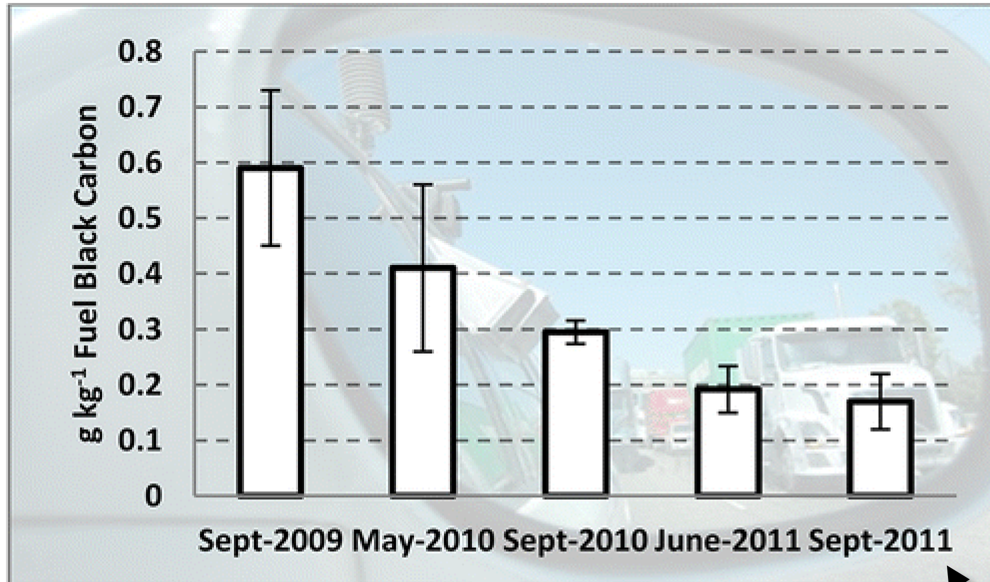
Fleet Average HD Truck Emission Rates Dropping

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



Kozawa, et. al. *Verifying Emission Reductions from Heavy-Duty Diesel Trucks Operating on Southern California Freeways,* Environ. Sci. Technol., 2014, *48* (3), pp 1475–1483

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DPF Robustness Affirmed by Large Scale Assessment In-Use

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

http://www.arb.ca.gov/msprog/onrdiesel/documents/DPFEval.pdf

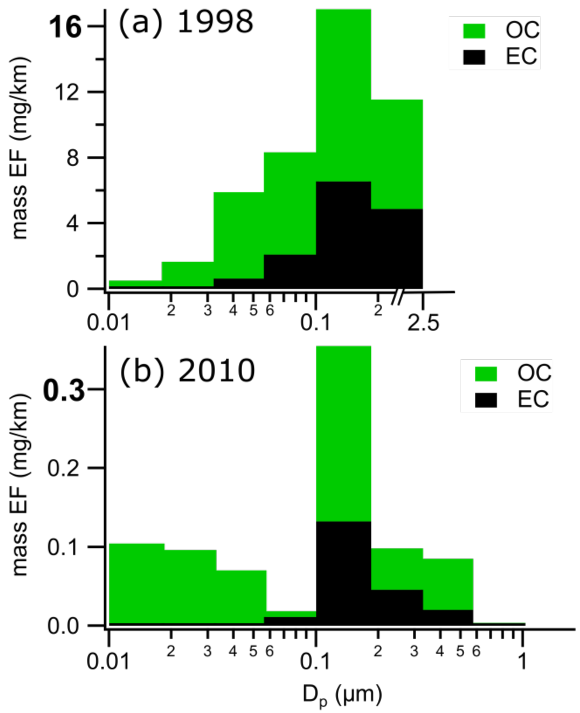
May 8, 2015

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.

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[1]



Ruehl, et. al. *Similarities and Differences Between "Traditional" and "Clean" Diesel PM,* Emission Control Sci. and Technol., January 2015, 1(1), pp 17-23

[1]*Evaluation of Particulate Matter Filters in On-Road Heavy-Duty Diesel Vehicle Applications*, http://www.arb.ca.gov/msprog/onrdiesel/documents/DPFEval.pdf

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

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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

California's significant remaining Ozone

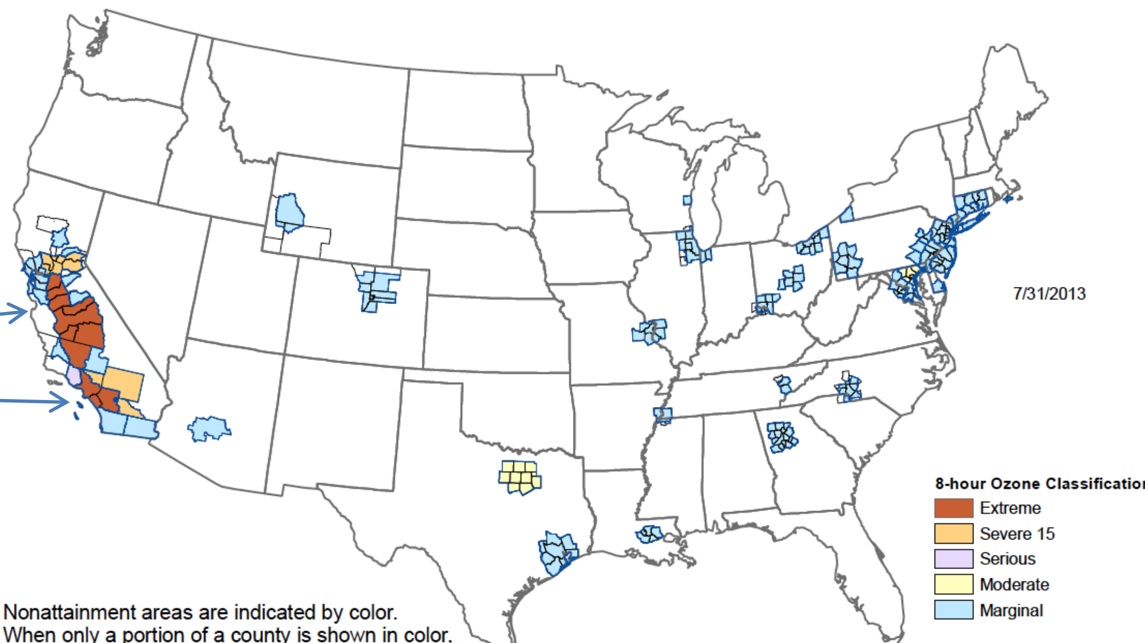
91% of California population in Ozone Non-Attainment areas.

Extreme Non-Attainment Areas:

- San Joaquin Valley
- South Coast

US-EPA considering further lowering of 8-hr ozone standard

8-Hour Ozone Nonattainment Areas (2008 Standard)



Nonattainment areas are indicated by color. When only a portion of a county is shown in color, it indicates that only that part of the county is within a nonattainment area boundary.

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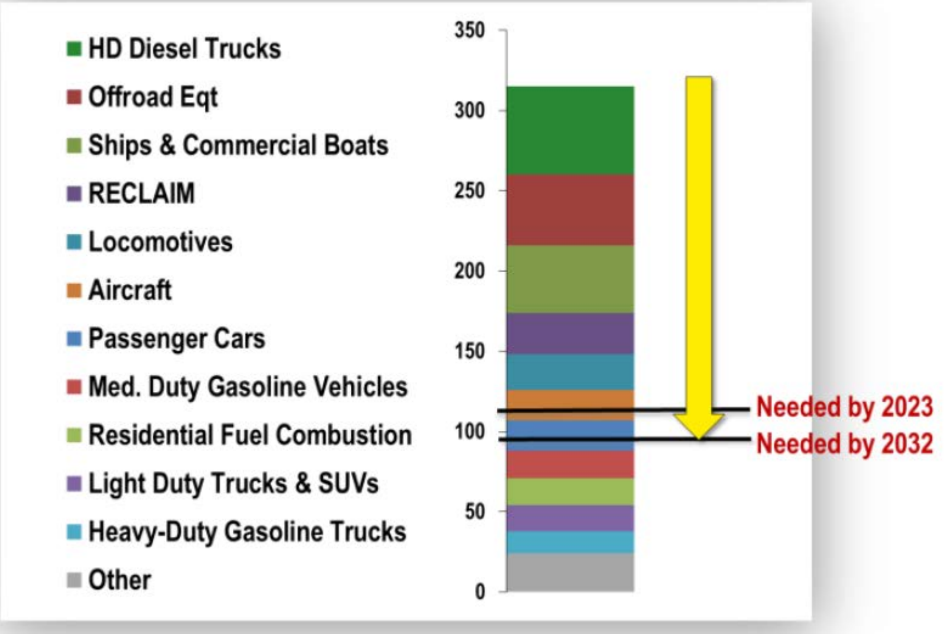
Scale of Actions Needed: South Coast Example

Meeting 2023 Ozone standard means:

- Multiple sectors each eliminating majority of their aggregate NOx emissions
- **Additional 2/3rd** 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

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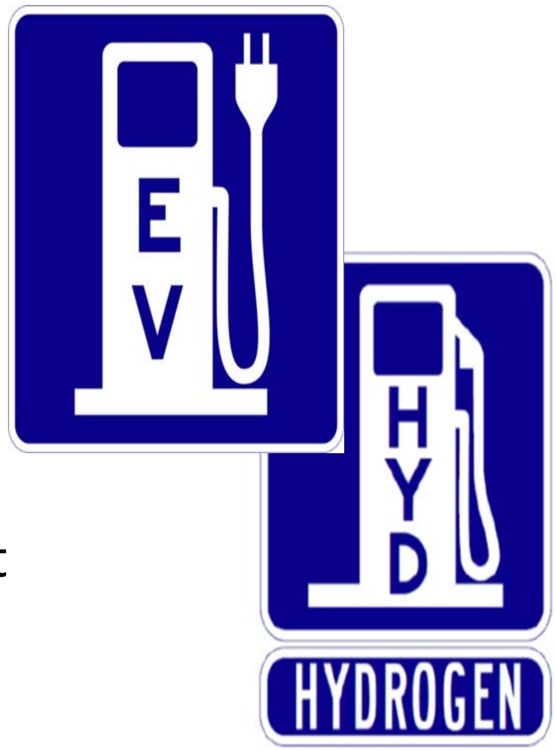
e-Mobility Essential

- **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

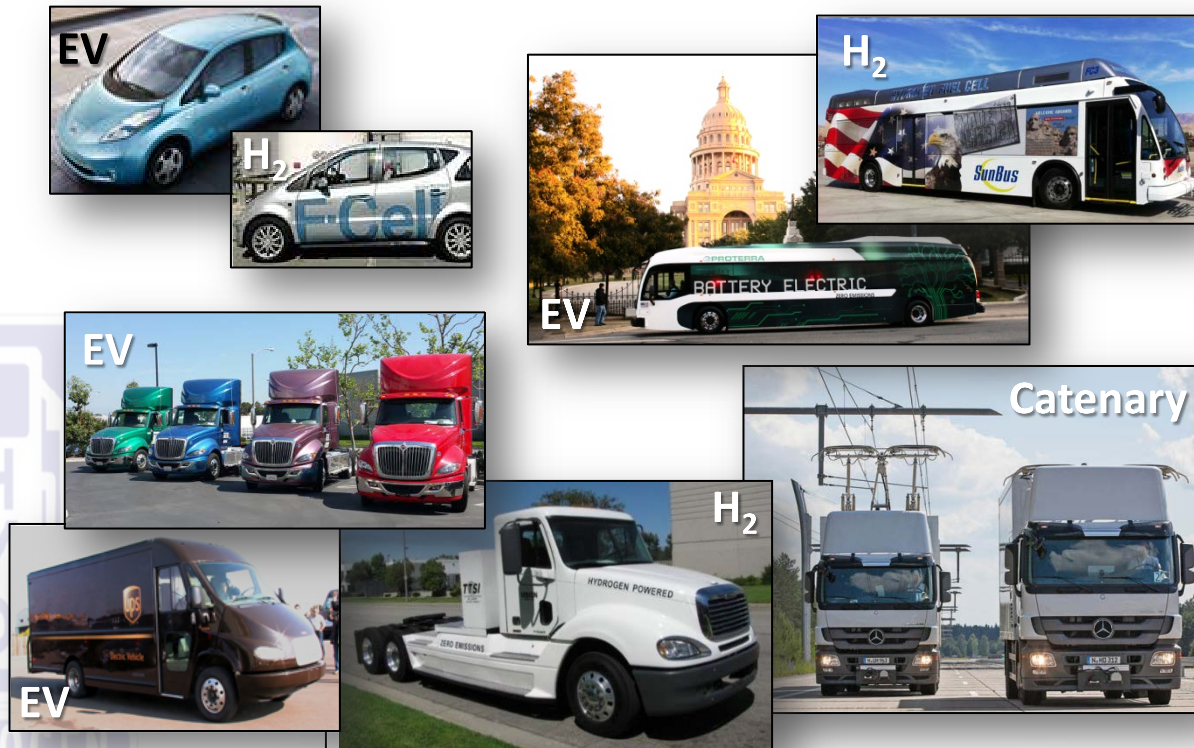
- **Zero tailpipe** PM/NOx
- **Emission rates** practically **independent of** vehicle **age**
- A given vehicle can **easily** to **switch among** diversified **renewable energy sources**
  - Vehicle side technology needs no modification to accept new renewable sources of electricity or H_2
  - On-board 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 Widely Applicable

Electrification is poised to impact wide range of mobile source categories:

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

- Cost coming down: $200/kWhr energy storage in sight



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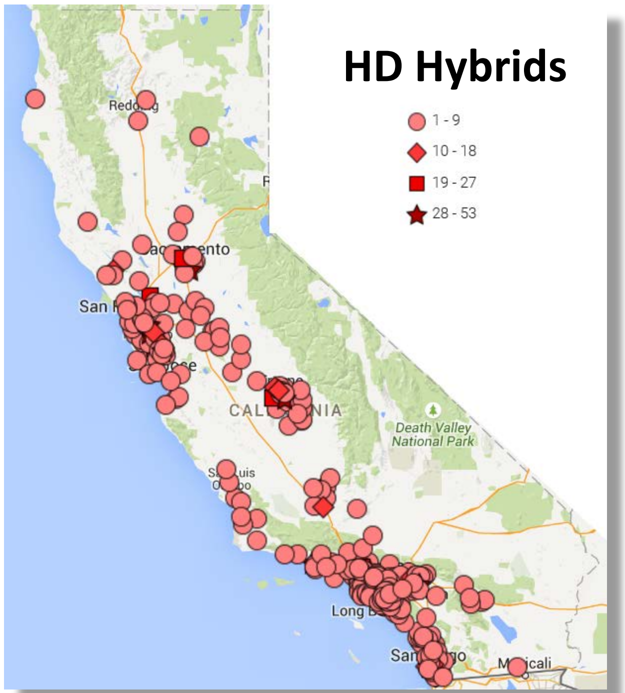
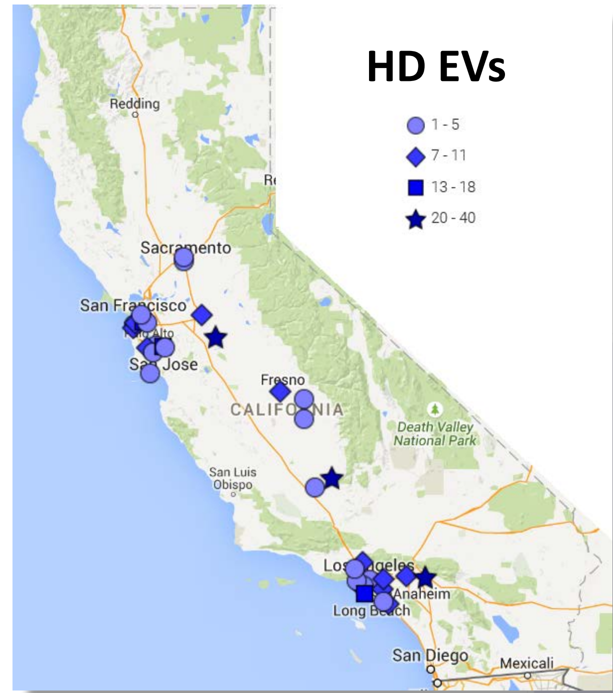
California e-Mobility Goals

- 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

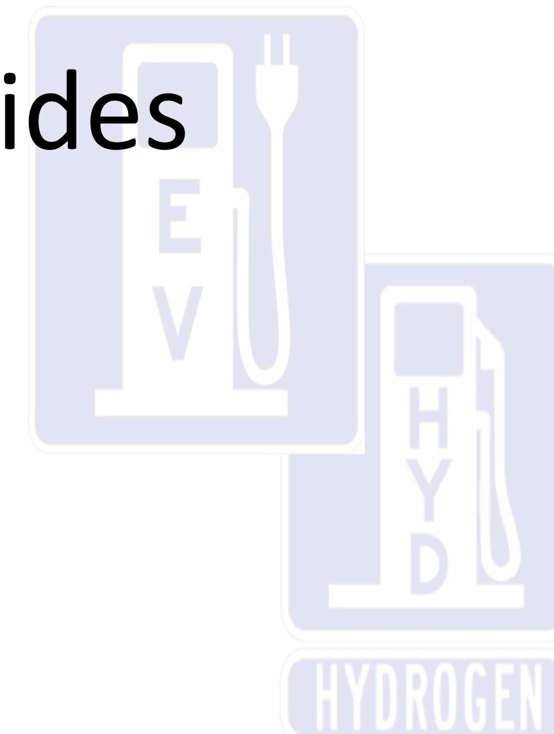
- Passenger
- Fueling infrastructure
  - Uniform Standards and zoning & permitting
  - Subsidies to early station installation
- SB-375 Coordinated local transportation and land-use planning processes
- Highspeed Rail

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

- Governor’s Zero Emission Vehicles Action Plan: http://opr.ca.gov/docs/Governor's_Office_ZEV_Action_Plan_(02-13).pdf
- Vision for Clean Air: Scenario Planning: http://www.arb.ca.gov/planning/vision/vision.htm
- 2015 draft Sustainable Freight Strategy: 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
- 2104 Update to 2008 Climate Scoping Plan: 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*
  - Enhanced Fleet Modernization Program: *http://www.arb.ca.gov/msprog/aqip/efmp/efmp.htm*
  - Drive Clean website: *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*
  - California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP): *http://www.californiahvip.org/*
  - DRIVE: Alternative and Renewable Fuel and Vehicle Technology Program: *http://www.energy.ca.gov/drive/*