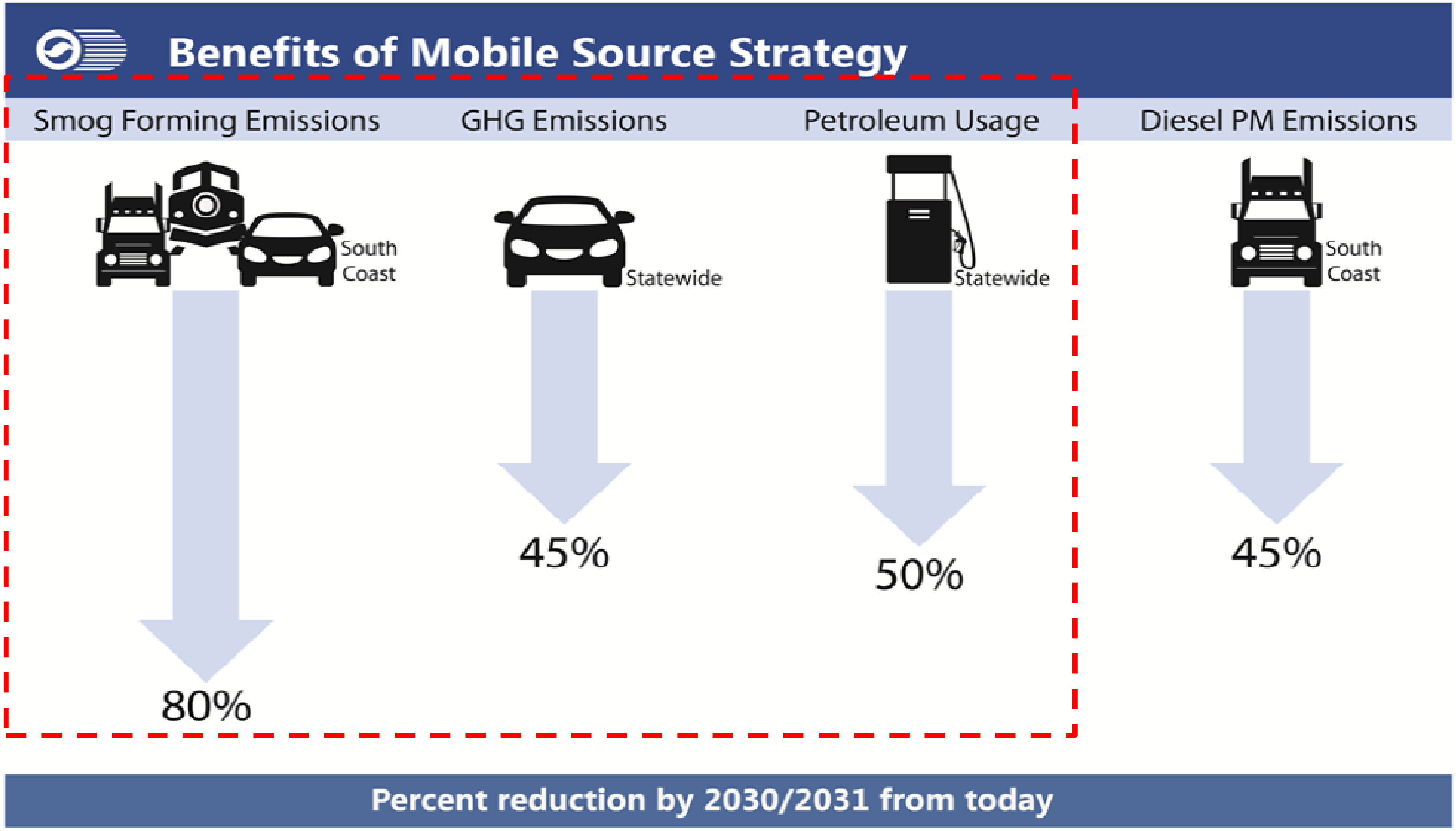
On-road particle and gaseous emissions from a PFI and GDI hybrid electric vehicle (in the winter)

Jacob Swanson[1], Chengguo Li[2], Shaohua Hu[3], Shishan Hu[3], Liem Pham[2], Heejung Jung[2]

[1]Minnesota State University, Mankato
[2]University of California, Riverside
[3]California Air Resources Board

In 2012, the ARB adopted the Advanced Clean Cars program, which included an increased zero-emissions vehicles (electric vehicles and hydrogen fuel cell vehicle), and hybrid electric vehicles for MY 2018 through 2025

Mobile sources strategy from ARB



Most previous HEV studies were conducted at modest temperatures

Hu et al. 2016
- Two PHEVs (PFI) vs 2015 GDI conventional vehicle on chassis dyno (~20°C)
- PFI has lower emissions of CO_2, PM mass and particle compared to GDI engine
- Cold start particle emissions still represent the majority of particle emissions

ARB report. 2017
- On-road test under the ambient temperature (~20°C)
- 2013 Toyota Prius PHEV(PFI) vs 2016 Hyundai Sonata PHEV (GDI
- The GDI engine has higher NOx + HC emissions than that of PFI engine

Holmen et al. 2014
- On-road test under the ambient temperature (summer and winter, 0~35^{o}C)
- 2010 Toyota Camry vs 2010 Camry HEV (GDI)
- Re-ignition HEV of PN >> Stable HEV of PN, Re-ignition high 30-70 nm emissions

Research objectives for tests conducted in cold weather in MN winter (Feb, -3°C ± 3)

- Compare cold weather on-road emissions between PFI engine and GDI engine
- Compare “Cold cold” starts with “re-ignition events” on city and highway drive cycles
- Evaluate the impact of “re-ignition” events on maintaining catalyst temperature

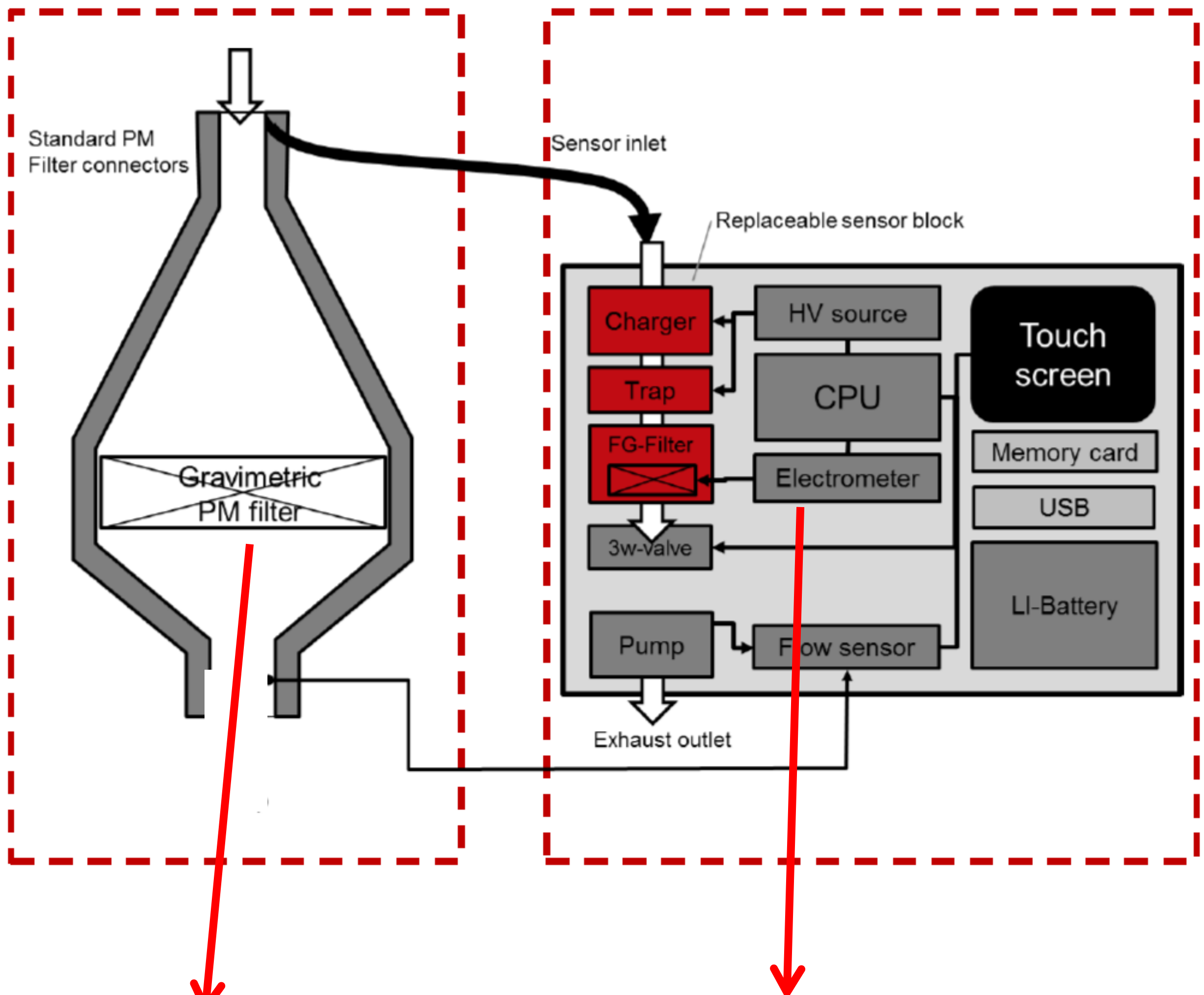
HEVs specifications and instruments

Vehicle specifications (HEVs)		
	Toyota Prius	Hyundai Sonata
Year	2016	2015
Engine Type	1.8L, I4, 121 hp	2.4L, I4 199 hp
MPG	54 city, 50 highway	36 city, 40 highway
Electric motor	60 hp	47 hp
Battery output	45kW	47kW
Fuel injection	PFI	GDI
Gasoline engine	71 hp @4800 rpm	159 hp @ 5,500 rpm

Instruments

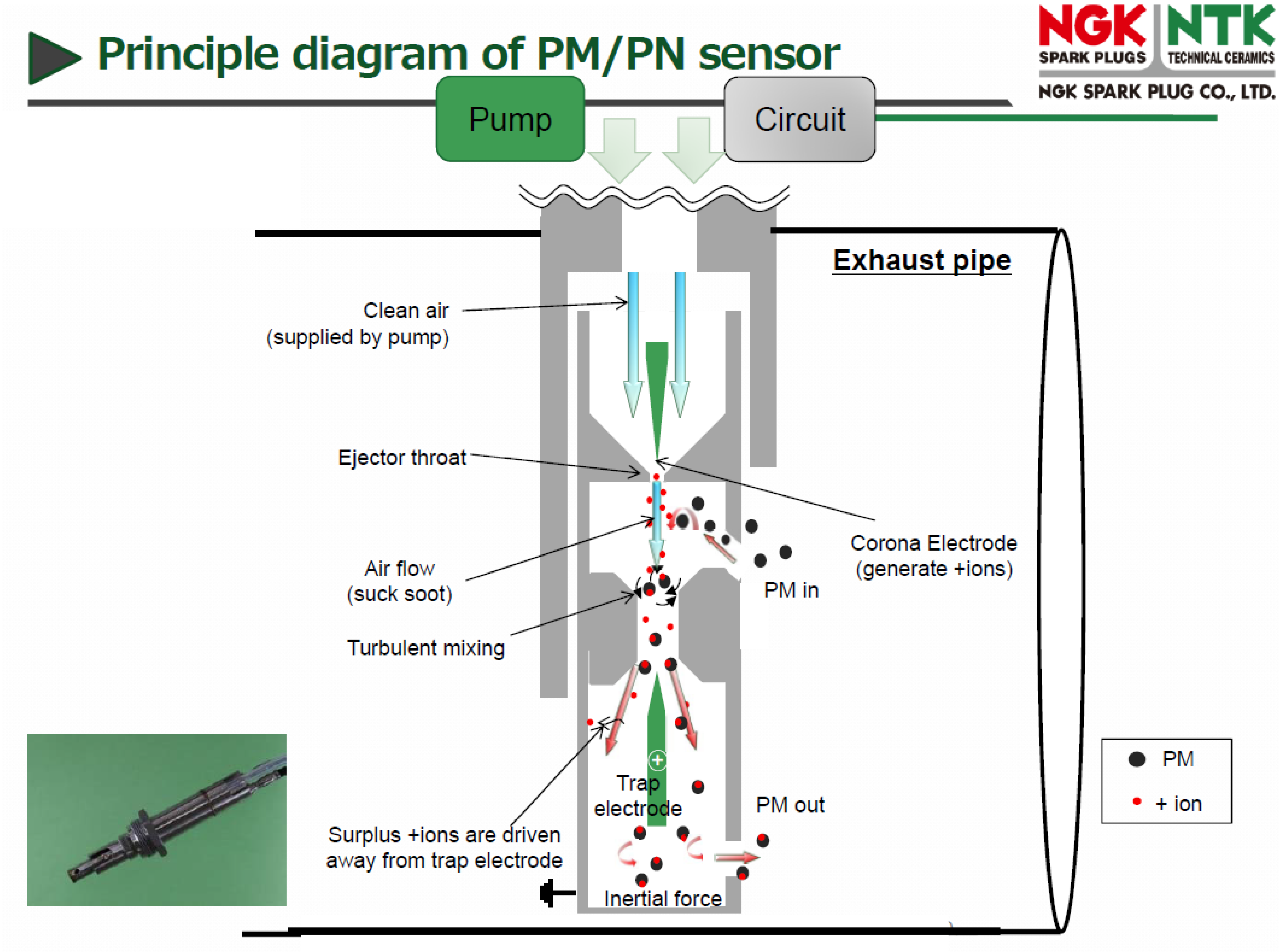
- **EEPS: dilute particle number-total and size**
- **E-filter – charged particles**
- **Thermal dilutor: total and solid particles**
- **NGK/NTK tailpipe sensor**
  - **NO_x emissions, PN concentration, PM concentration**

Dekati e-filter is a diffusion charger combined with a gravimetric filter

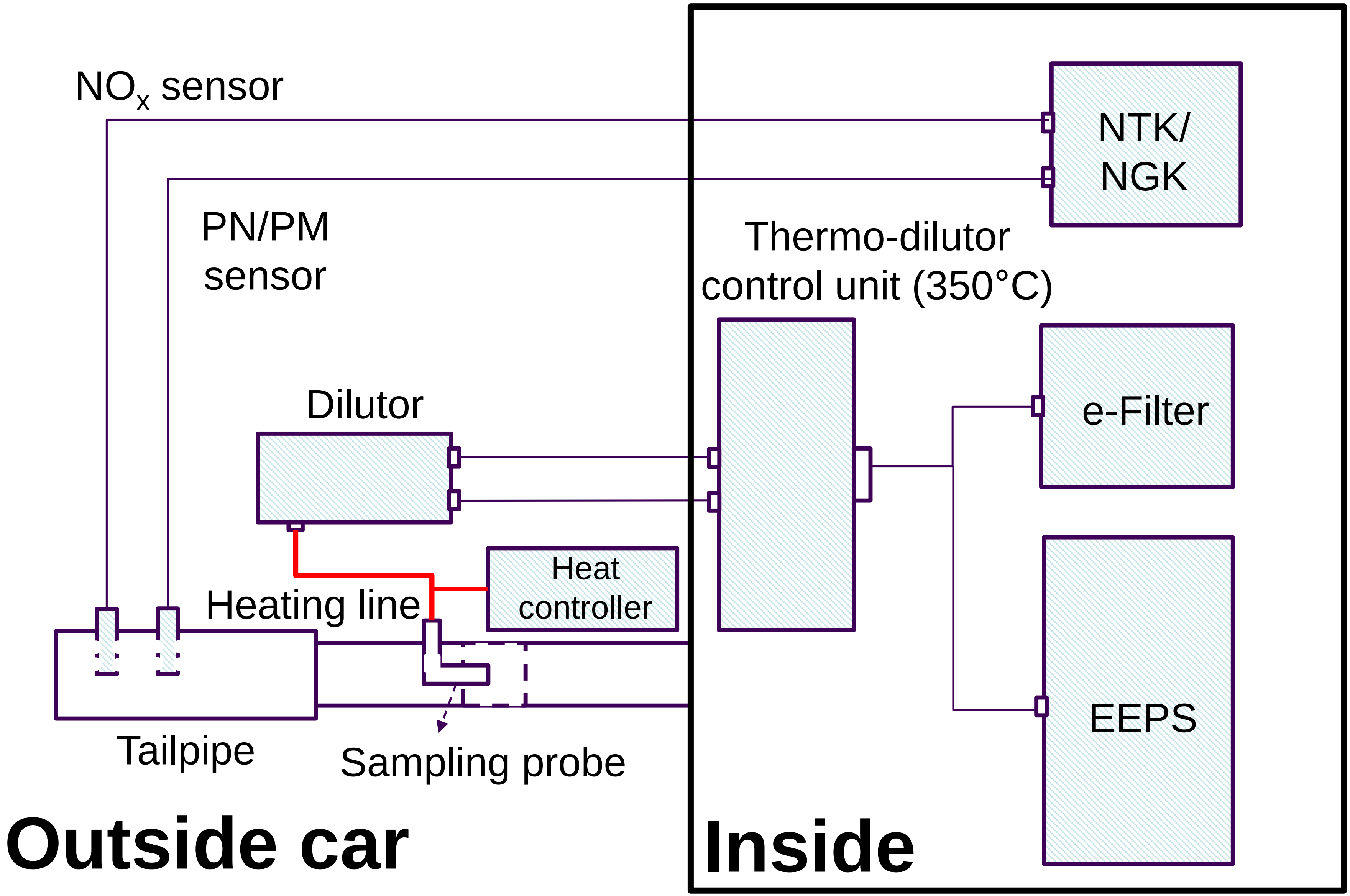


Mass scales with total **current**

NTK/NGK PM/PN raw tailpipe sensor



Particle and gas sampling apparatus



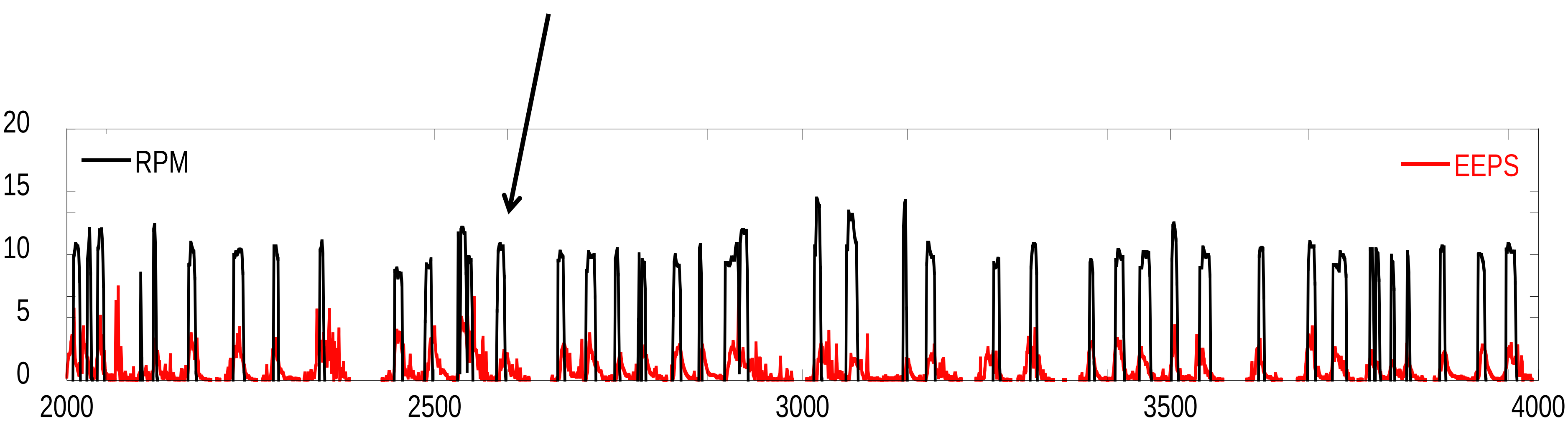

VEHICLE
EMISSIONS
TESTING
IN PROGRESS


VEHICLE
EMISSIONS
TESTING
IN PROGRESS
hybrid

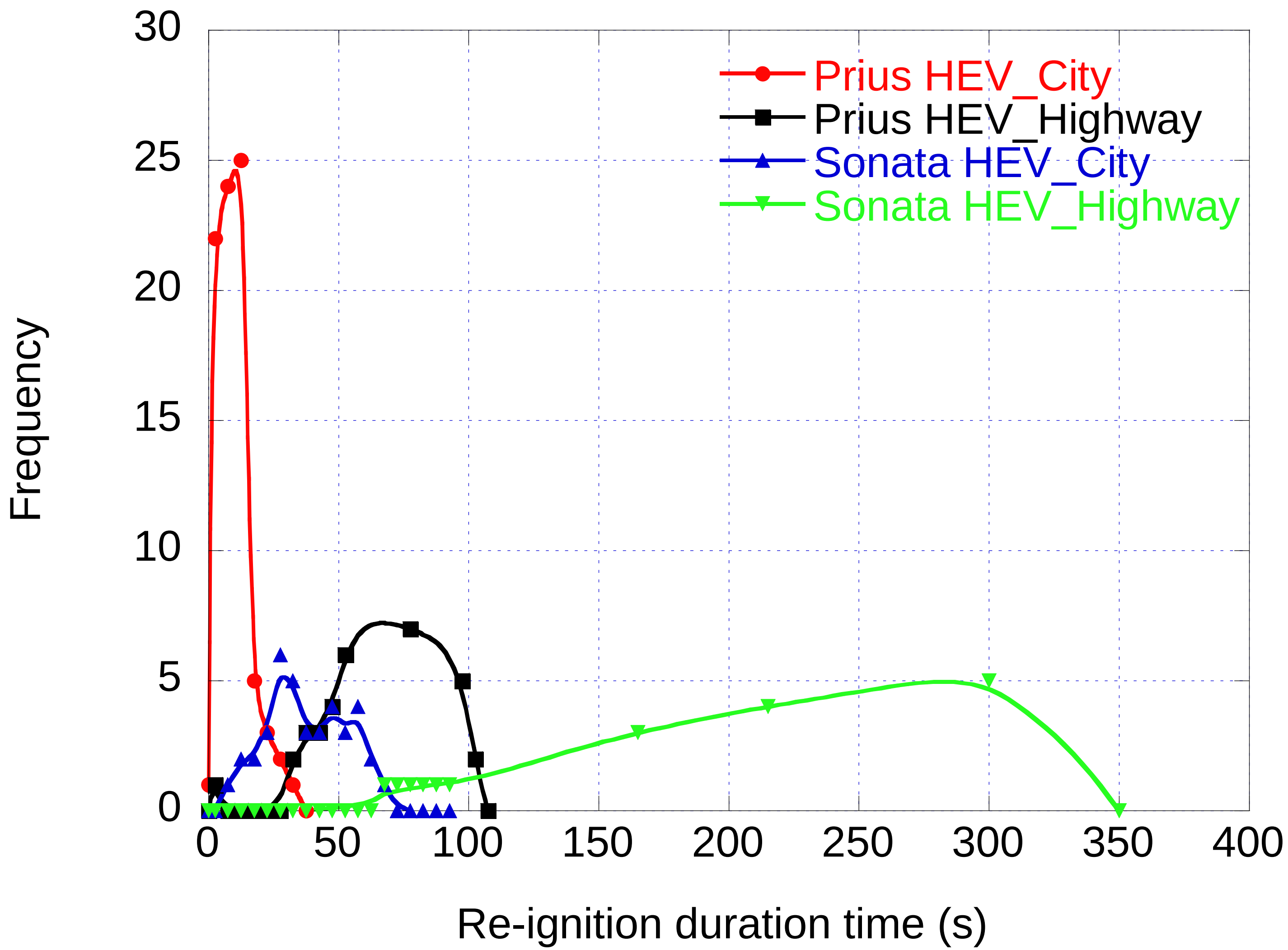
Example time series of driving data

Multiple days of prescribed city and highway drive cycles (2 hr / each)

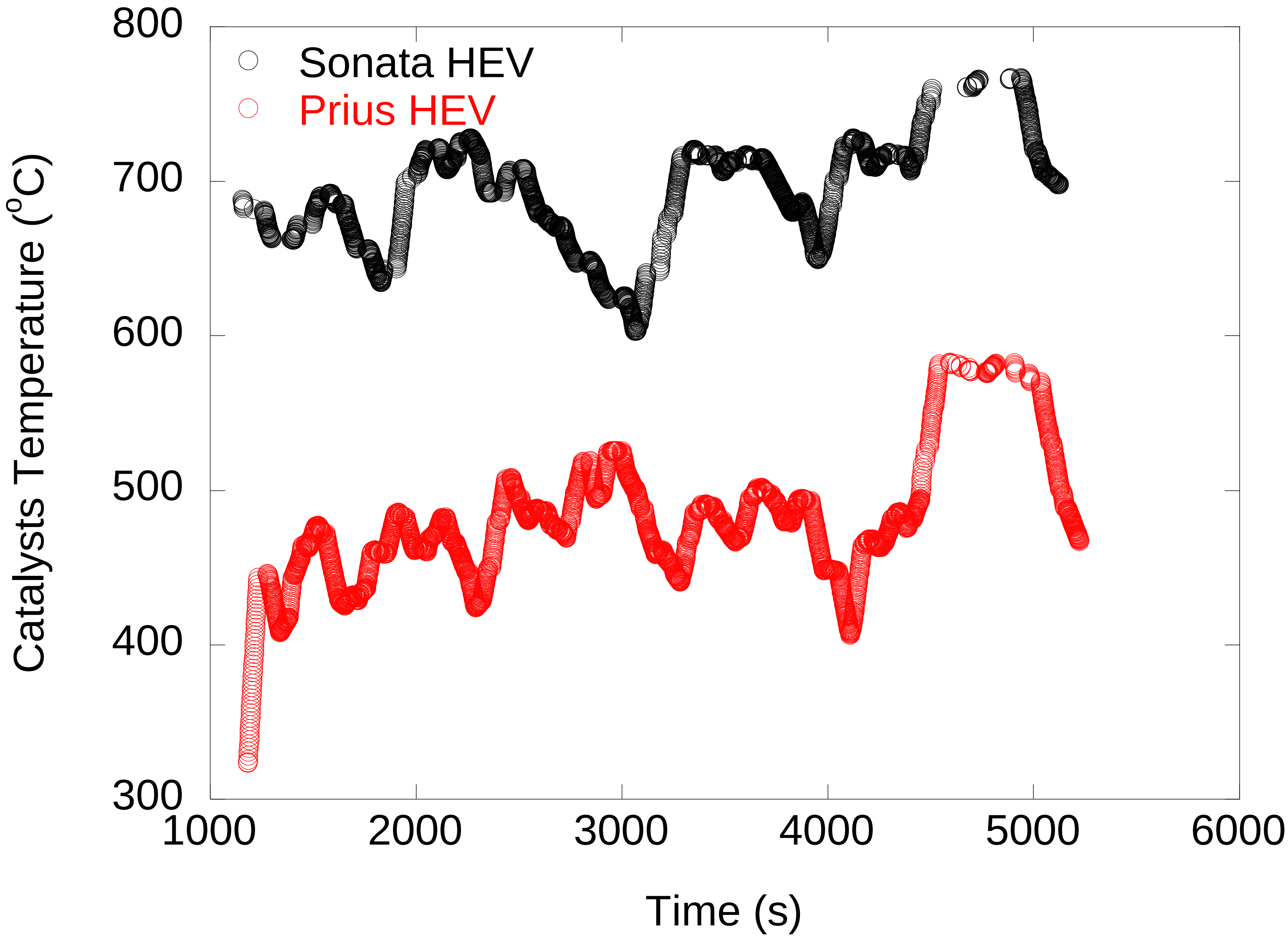
About 1 “re-ignition” event per minute (Prius)



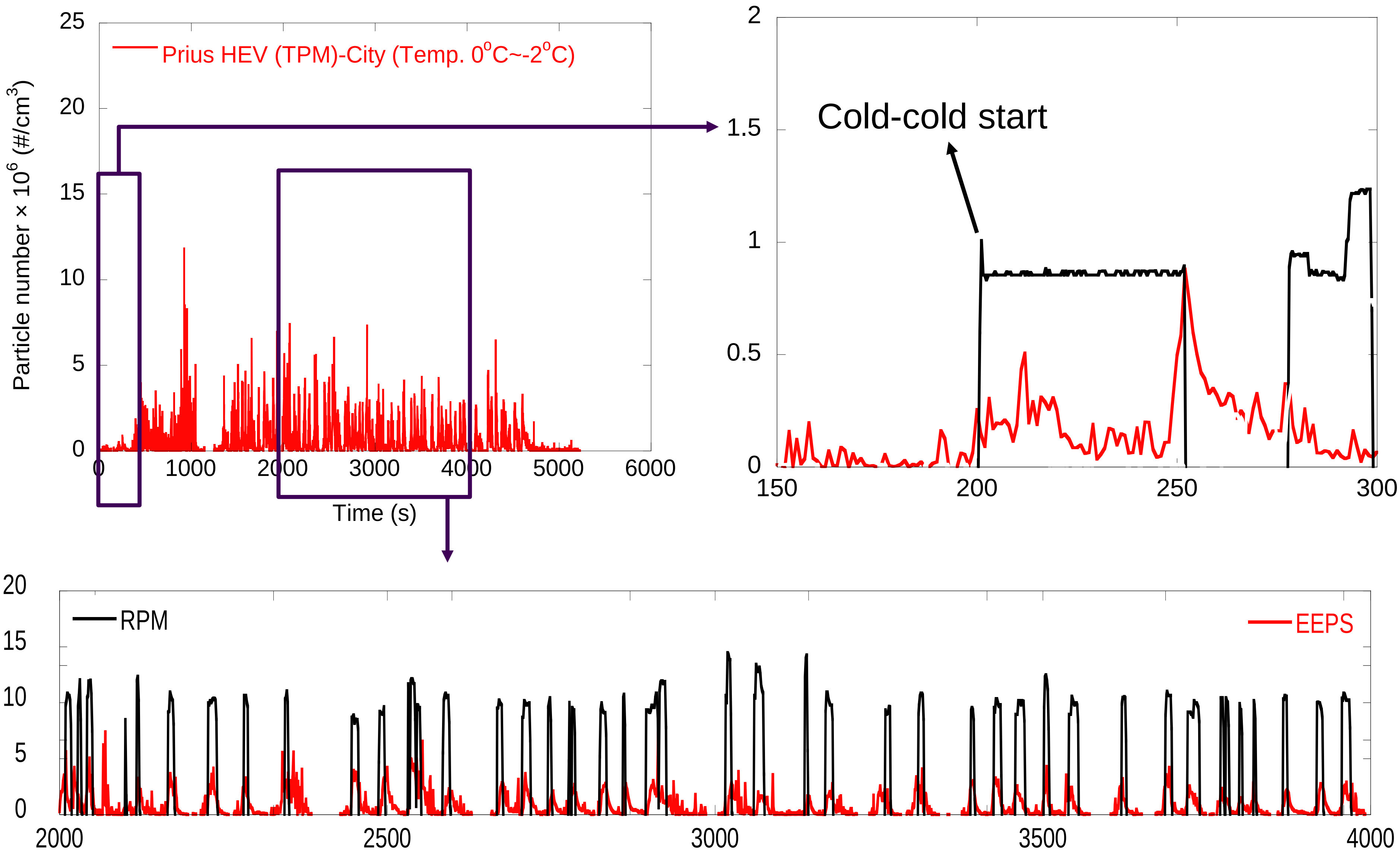
Frequency and duration of re-ignition events for Prius and Sonata were very different



Catalyst temperatures do not drop below the expected light-off temperature

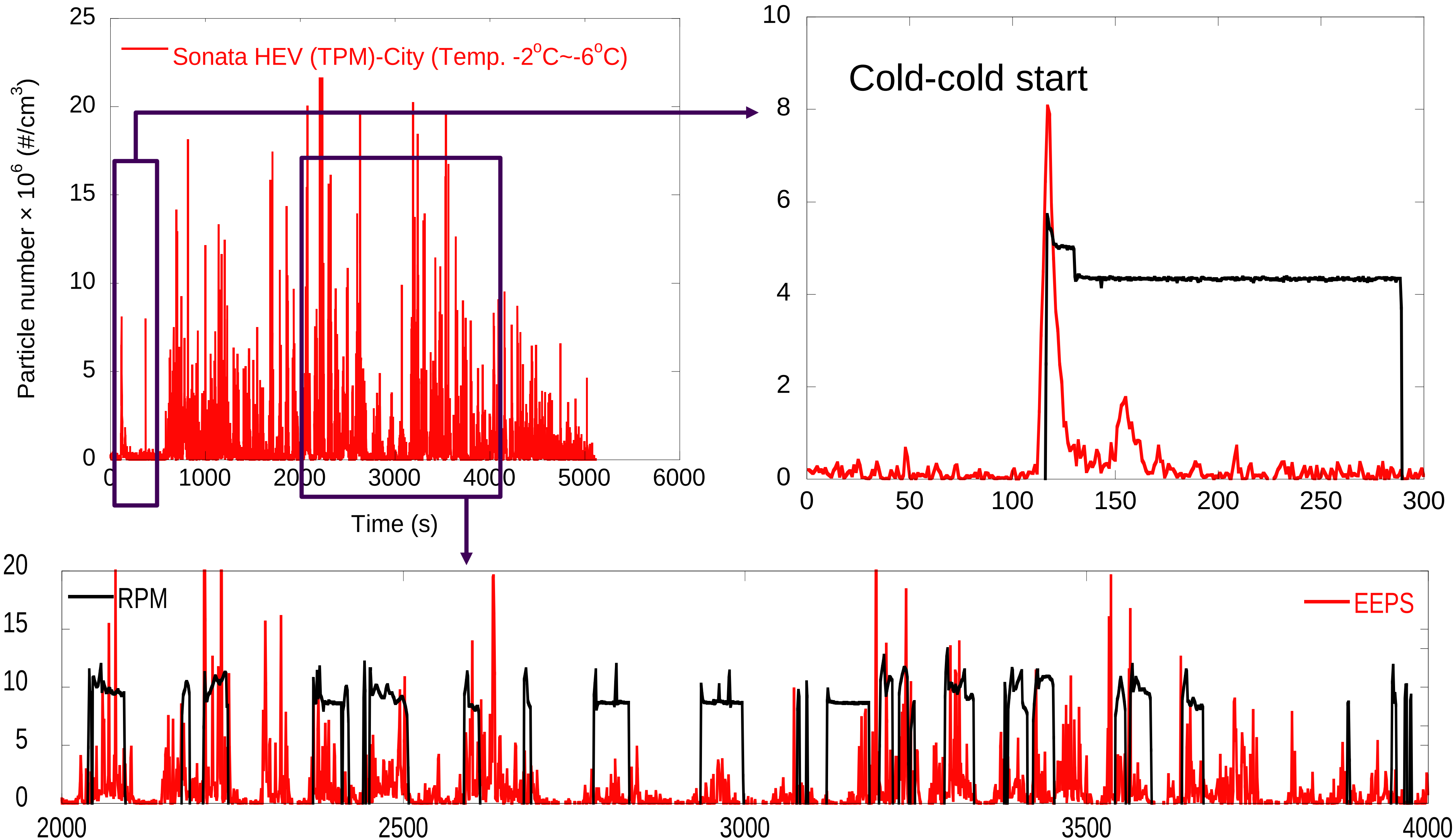


Particle number time series – Prius

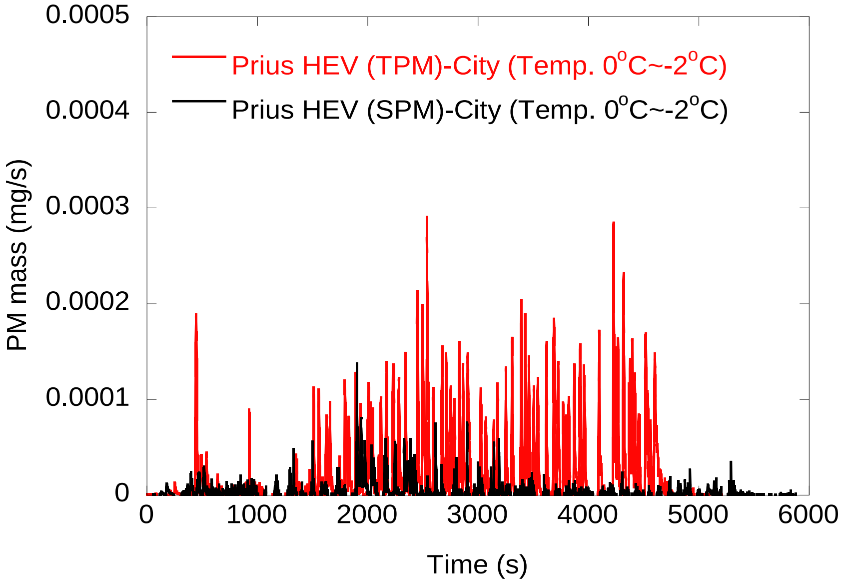


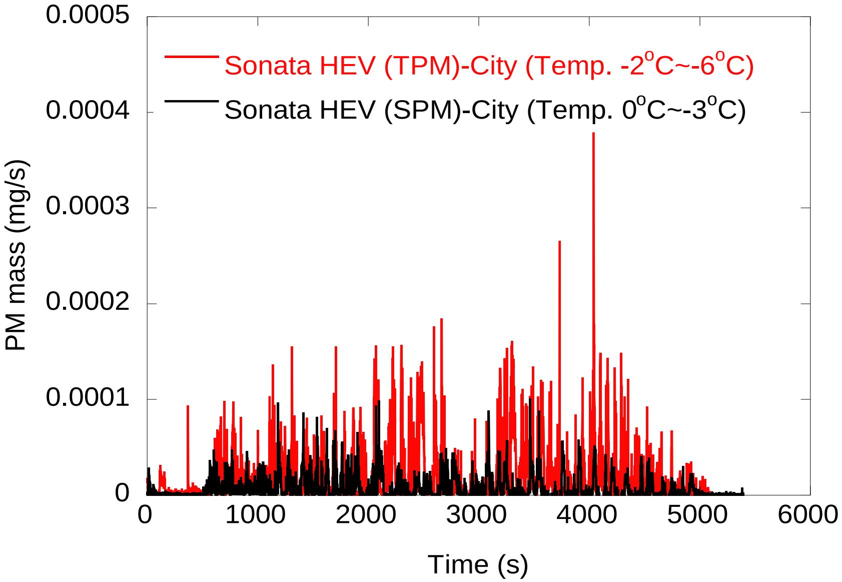
Route-1 city

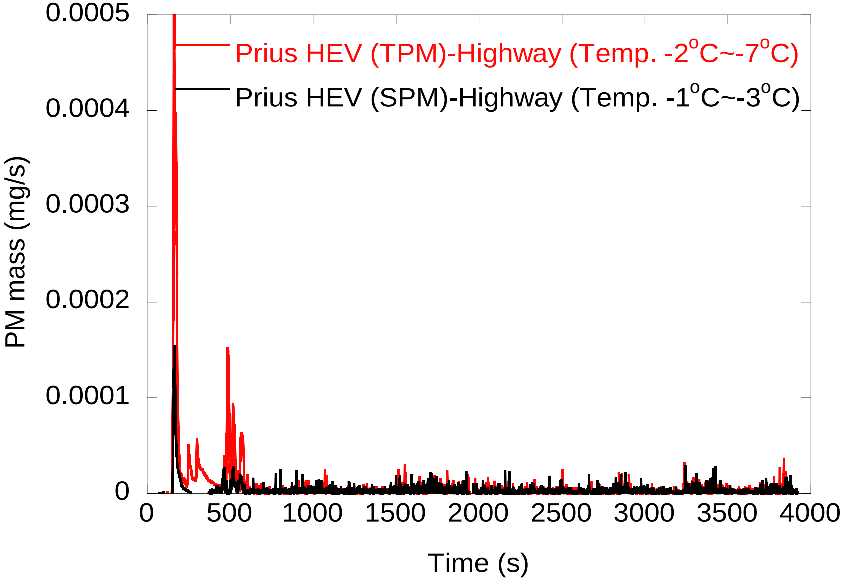
Particle number time series – Sonata

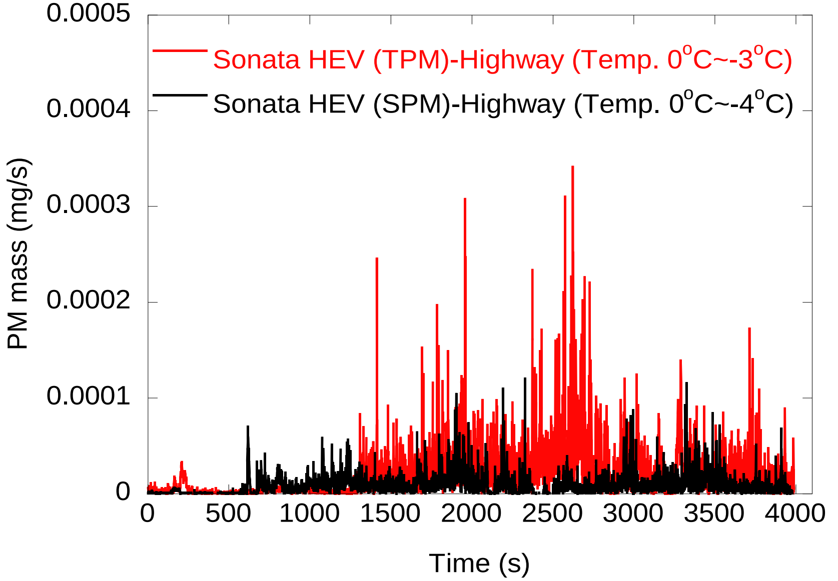


Particle mass time series

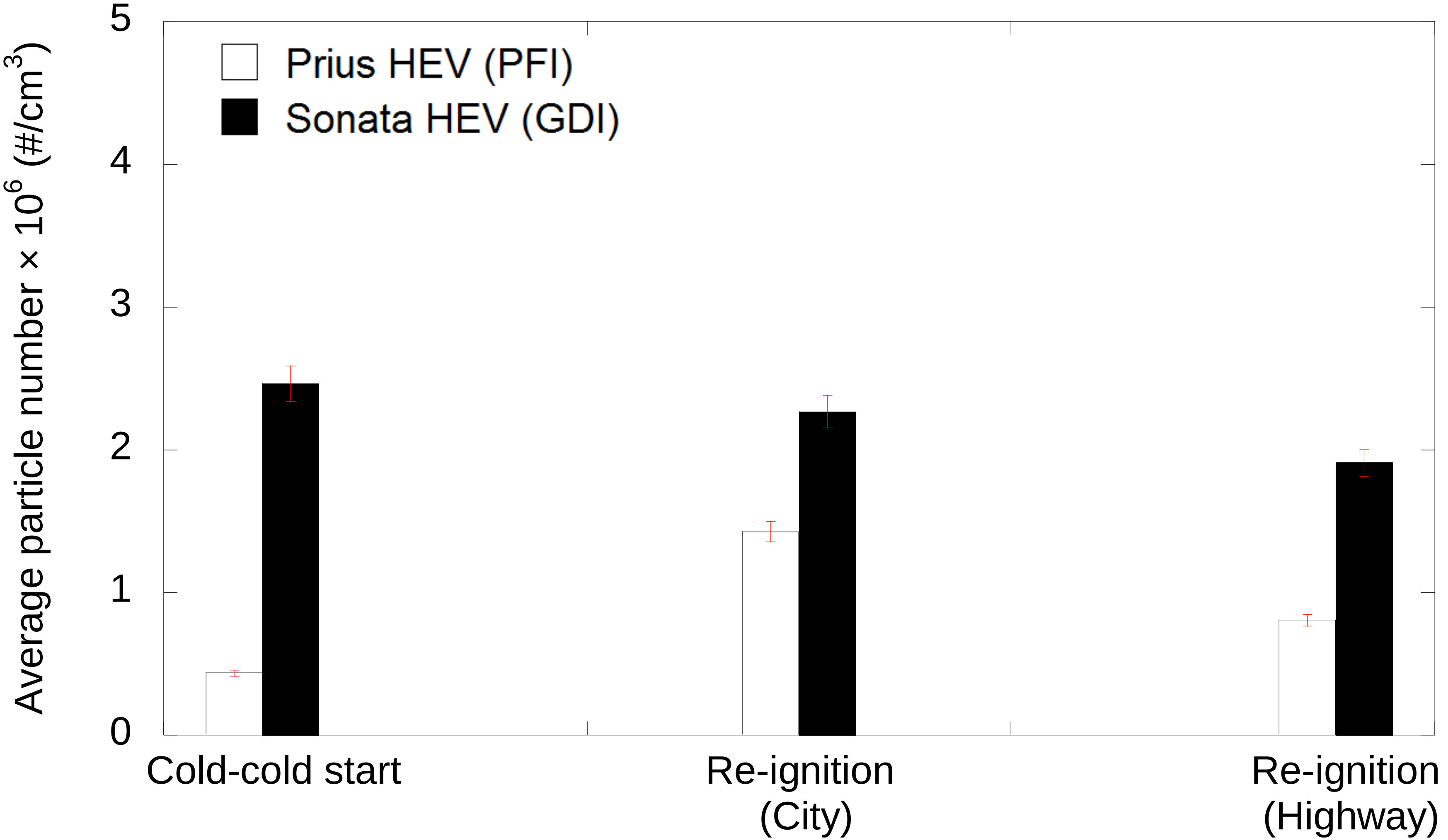




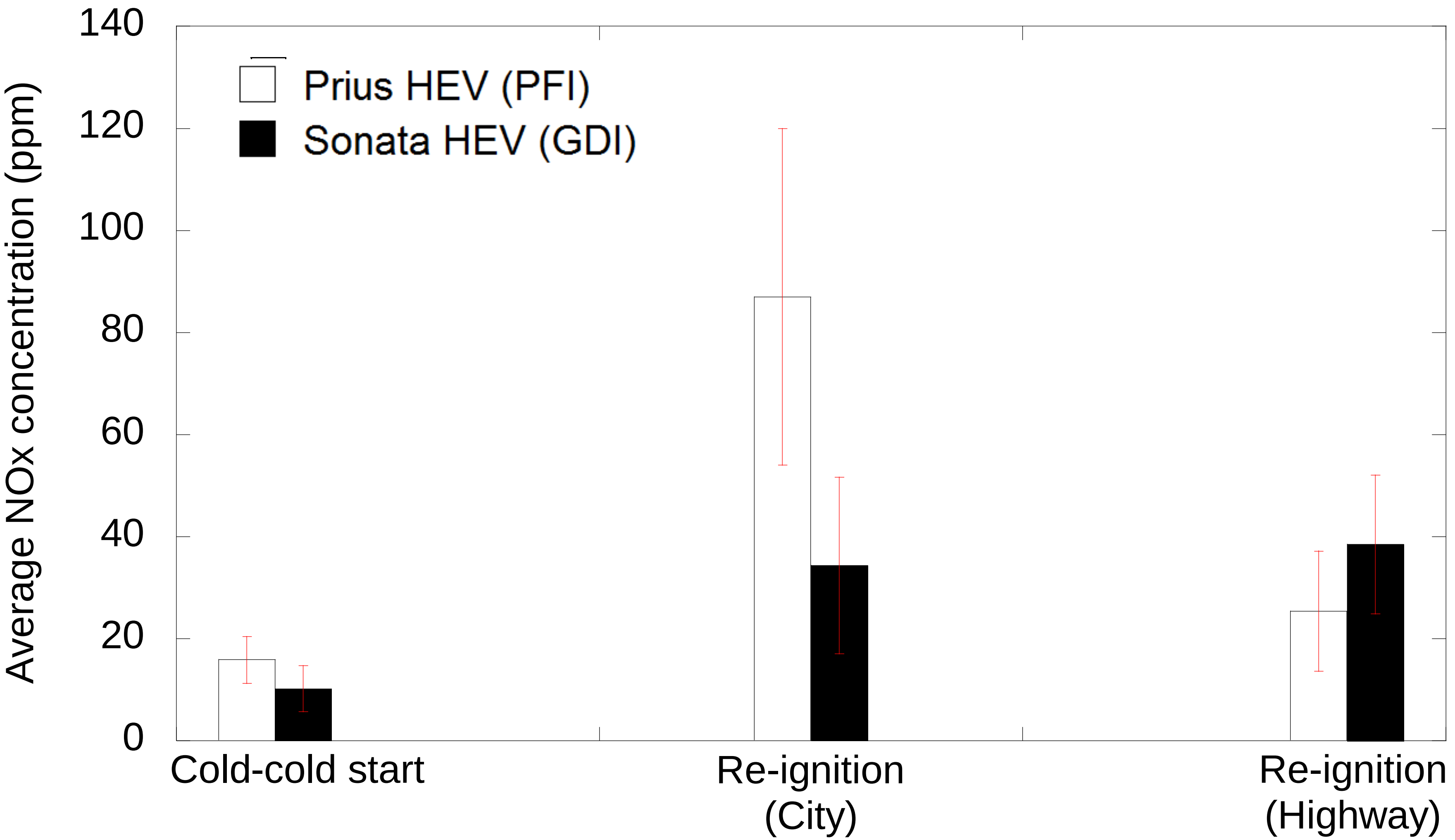




Summary of total particle number emissions



Summary of NO_x emissions



Particle instrument correlations (r^2)

Total particles (solid and semi-volatile)

Condition		PN: EEPS vs NTK	PM: EEPS vs NTK	EEPS (PM) vs E-current
City	Prius	0.80	0.46	0.40
	Sonata	0.22	0.14	0.51
Highway	Prius	0.34	0.26	0.65
	Sonata	0.08	0.01	0.31

Only solid particles

Condition		PN – EEPS vs NTK	PM – EEPS vs NTK	PM_EEPS vs E-current
City	Prius	0.77	0.70	0.96
	Sonata	0.38	0.27	0.85
Highway	Prius	0.22	0.22	0.95
	Sonata	0.01	0.05	0.65

Summary – re-ignition events and catalyst temperature

- **City**
  - Prius re-ignition events very short (10 s) and frequent (every ~ 1 min)
  - Sonata re-ignition events are ~ 75 s and less frequent (every ~ 2 min)
- **Highway**
  - Prius re-ignition events are ~ 45 s in duration
  - Sonata re-ignition events are ~ 5 min in duration

For both vehicles, design and prevailing conditions result in catalyst temperatures remaining well above light-off temperatures always

→ re-ignition particle and NO_x emissions are low

Summary – comparison of emissions and instrument correlations

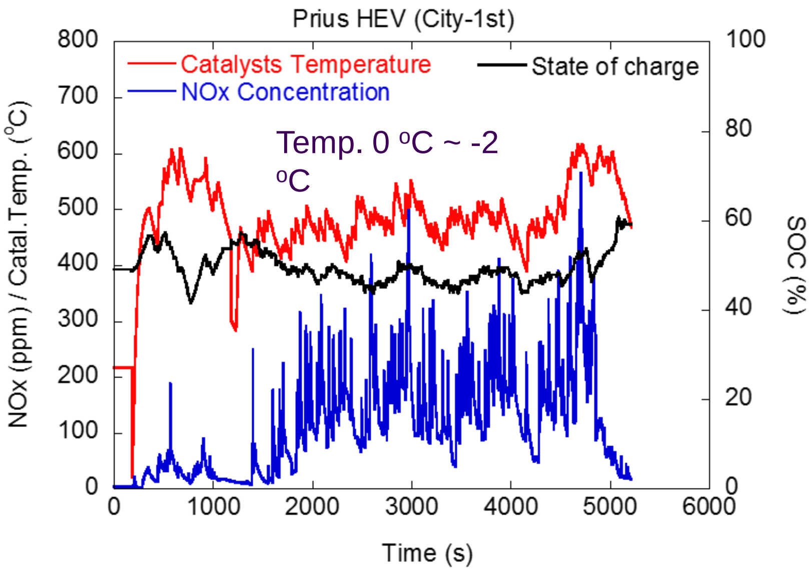
- Cold cold start emissions
  - NO_x: Sonata ~ Prius
  - PM: Sonata ~ 5 x Prius
- City "re-ignition" emissions
  - NO_x: Sonata ~ 0.5 x Prius
  - PM: Sonata ~ Prius
- Highway "re-ignition" emissions
  - NO_x: Sonata ~ Prius
  - PM: Sonata ~ 2 x Prius

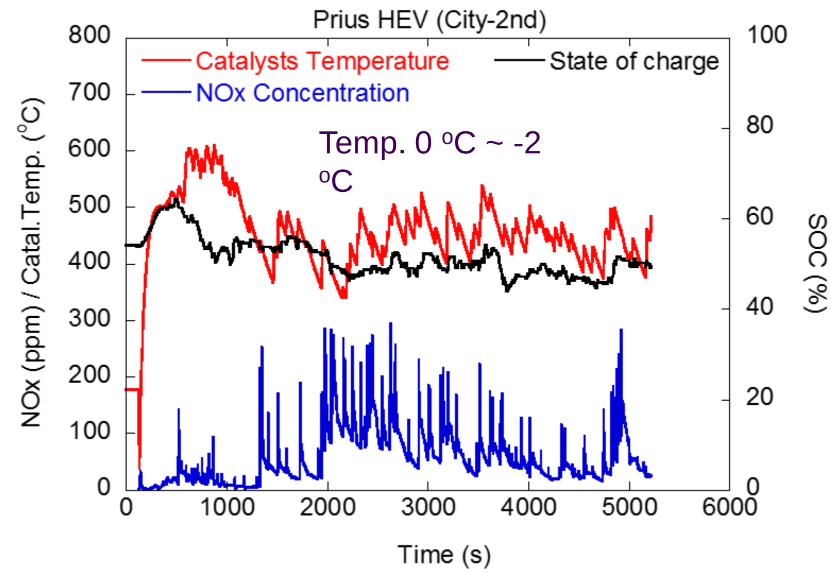
Re-ignition emissions generally higher than cold start

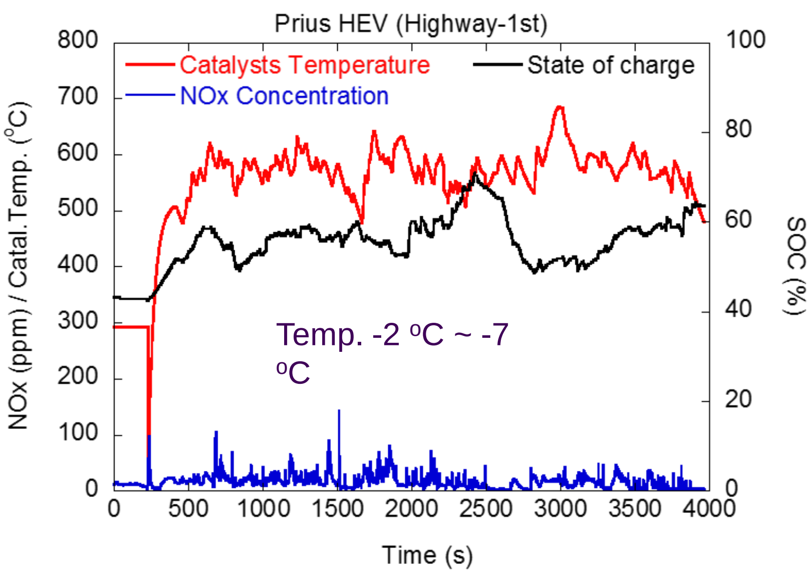
- EEPS number and mass did not correlate with NGK/NTK number and mass, respectively
- EEPS mass correlated very well with E-filter – and I expect even better correlation with $Dp^{1.4}$

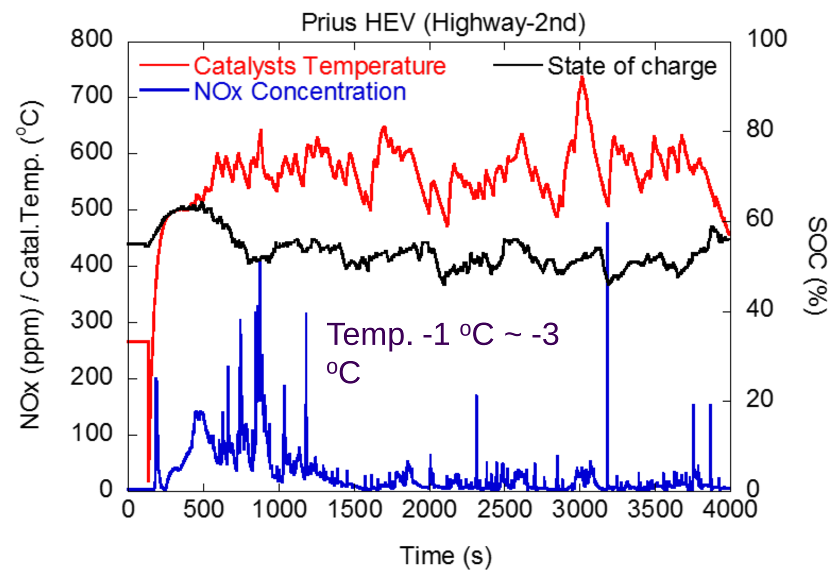
Questions?

NOx emission from Prius HEV

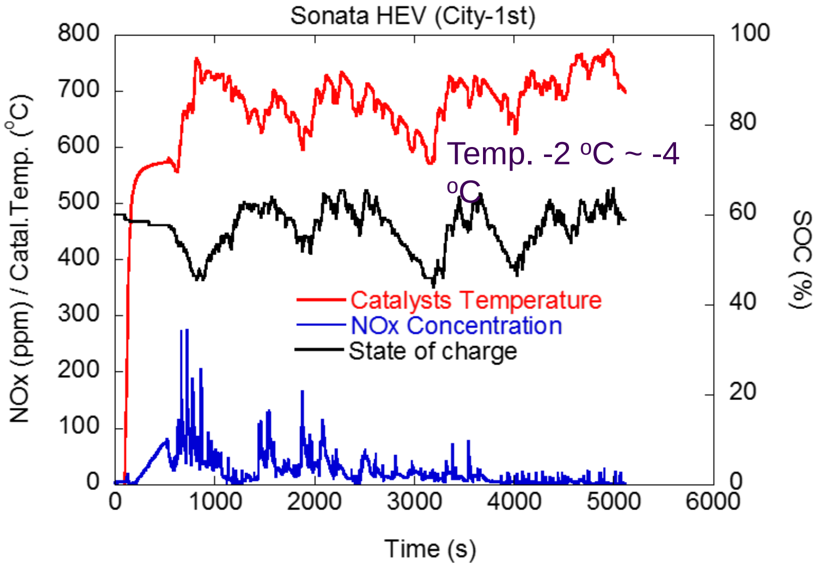


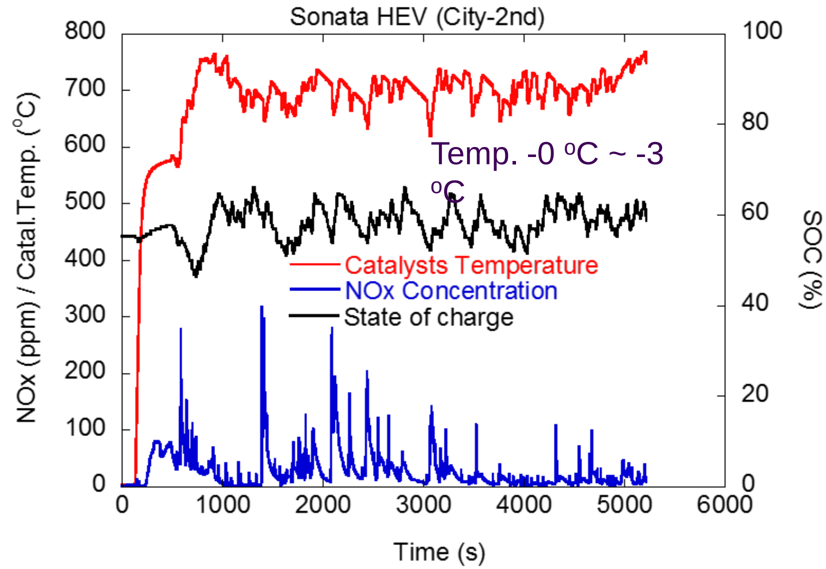


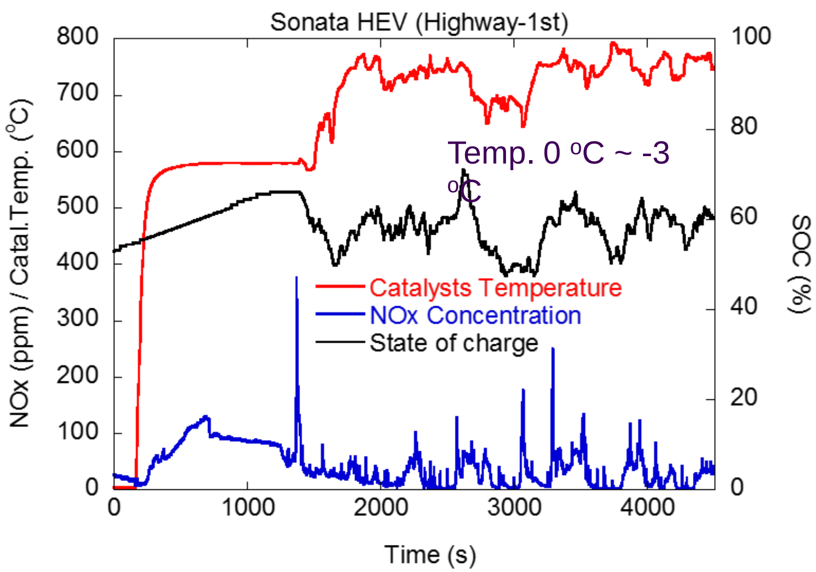


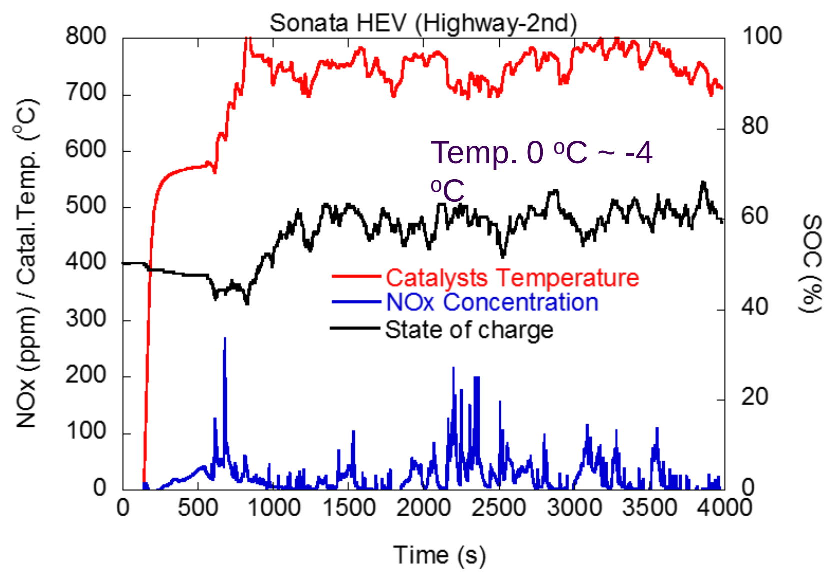


NOx emission from Sonata HEV

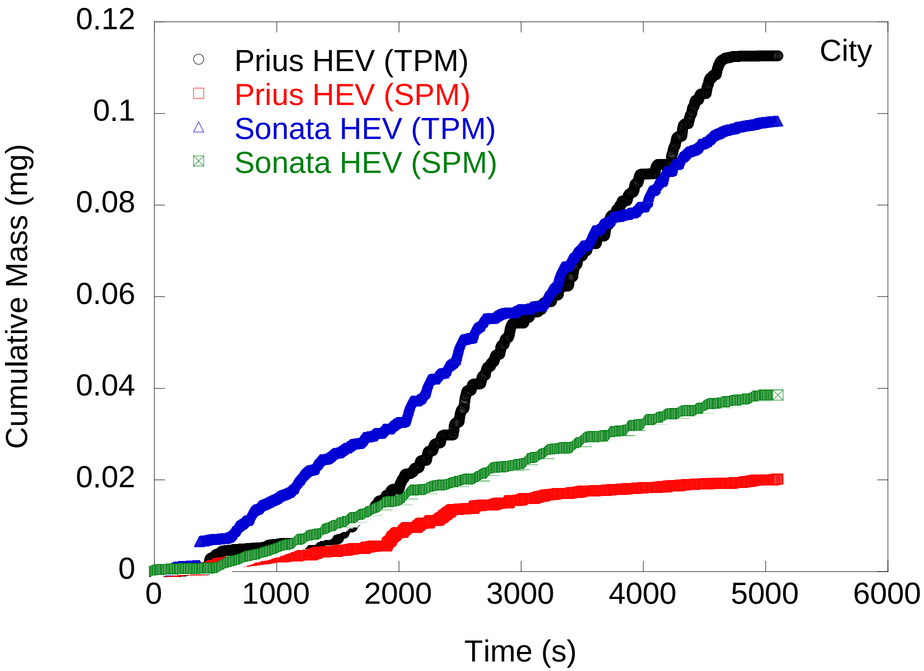


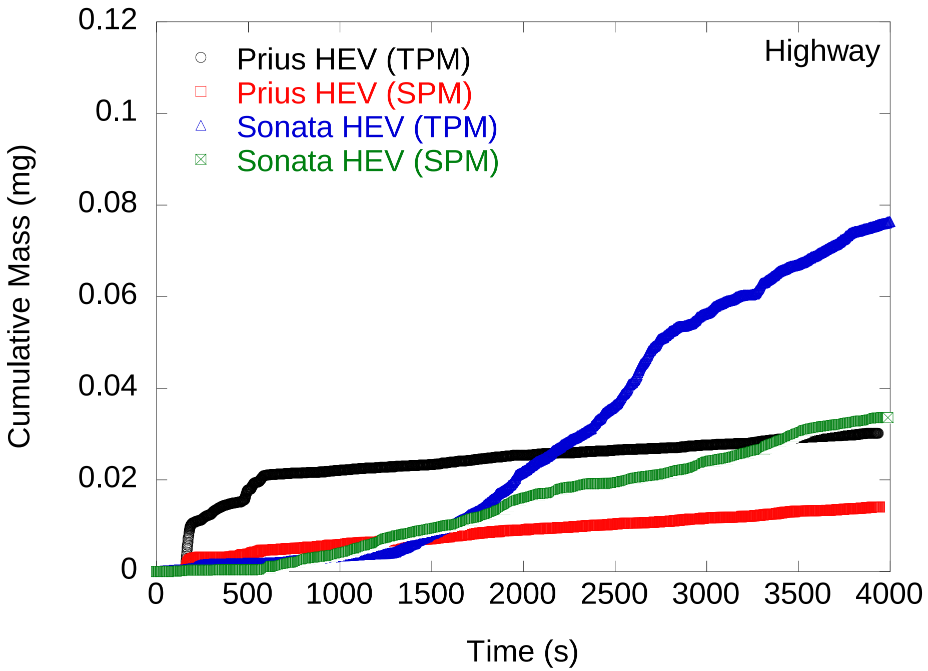






PM cumulative mass





Summary – comparison of emissions

- Prius HEV vs. Sonata HEV NOx emissions
  -63% of NOx for Prius > Sonata when cold-cold start
  -Re-ignition events during city and highway driving
  :230 % of NOx emissions for Prius > Sonata (City)
  :52 % of NOx emissions for Sonata>Prius (Highway)

- Prius HEV vs. Sonata HEV particle number (PN)
  -300 % of PN for Sonata > Prius when cold-cold start
  -Re-ignition events during city and highway driving
  :53 % of PN emissions for Sonata > Prius (City)
  :140 % of PN emissions for Sonata>Prius (Highway)

Specifications of the HEVs

Vehicle specifications (HEVs)		
	Toyota Prius	Hyundai Sonata
Year	2016	2015
Engine Type	1.8L Hybrid I4 121hp	2.4L Hybrid I4 199hp 154ft. lbs.
MPG	54 city, 50 highway	36 city, 40 highway
Electric motor	**60 hp**	**47 hp (35kW) @ 1,6303,000 rpm**
Motor type/voltage	**Nickel-metal hydride /123**	**Interior-Permanent Magnet Synchronous Motor/270 V**
Battery output	**45kW**	**47kW**
Battery type/voltage	**ZVW50 model (Nickel-Metal hybride battery)/240 V**	**Lithium polymer battery/270 V**
Fuel Injection	**PFI**	**GDI**
Gasoline engine	71 Ib-ft @4800 rpm	159 hp @ 5,500 rpm
Torque	120.2 Ib-ft @ 4000 rmp	154 Ib-ft @ 4,500 rpm
Transmission	CVT	6-Speed Shiftable Automatic
Curb Weight	**3075 lbs**	**3,508 lbs**

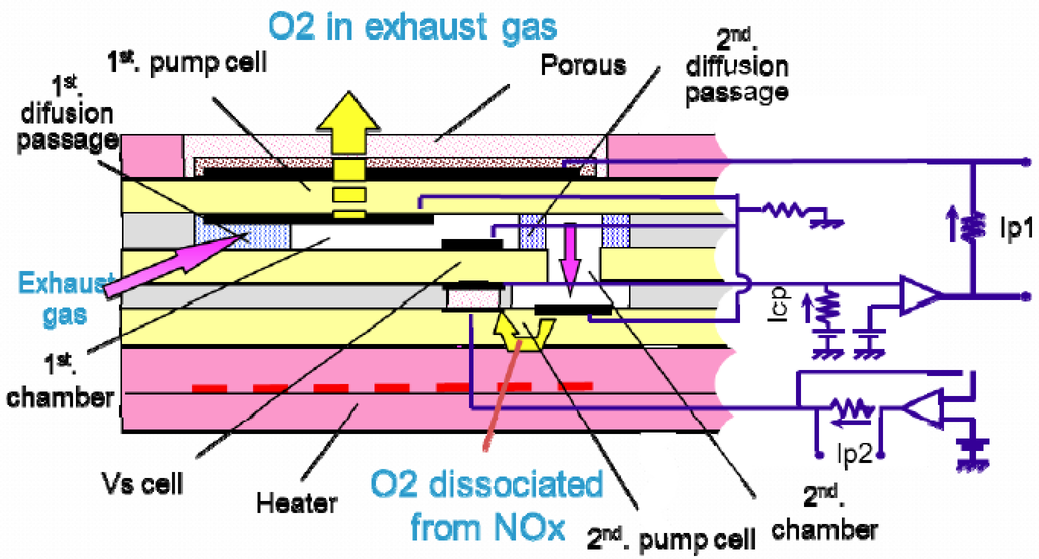
NTK/NGK_NOx sensor

▶ Principle diagram of NOx sensor

NGK SPARK PLUGS | NTK TECHNICAL CERAMICS
NGK SPARK PLUG CO., LTD.

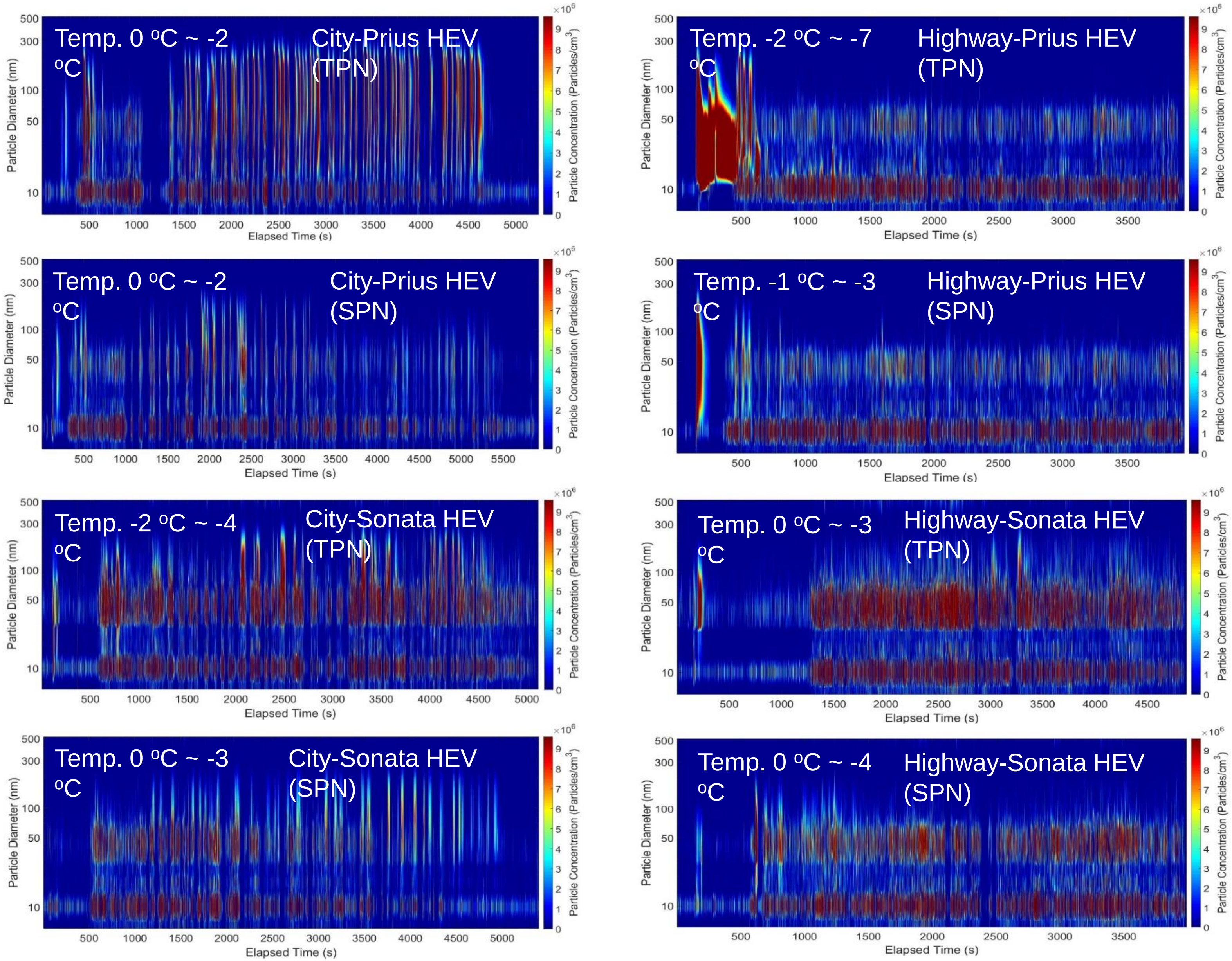
Confidential

Principle of NTK NOx Sensor

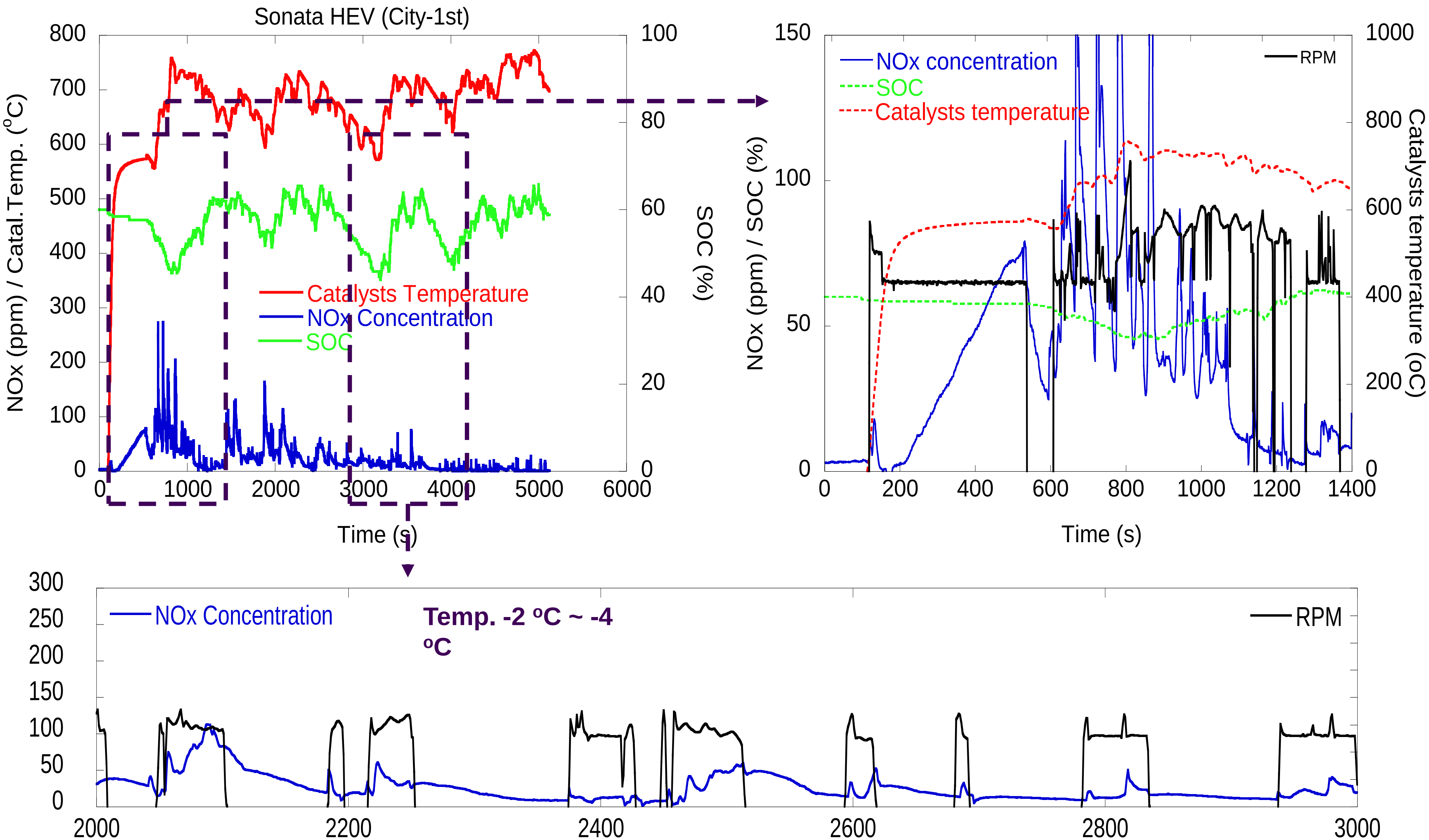


NTK NOx sensor can measure
O2 and NOx at the same moment.

Particle number-Contour



NOx vs RPM_Sonata HEV



On-road particle and gaseous emissions from a PFI and GDI hybrid electric vehicle (in the winter)

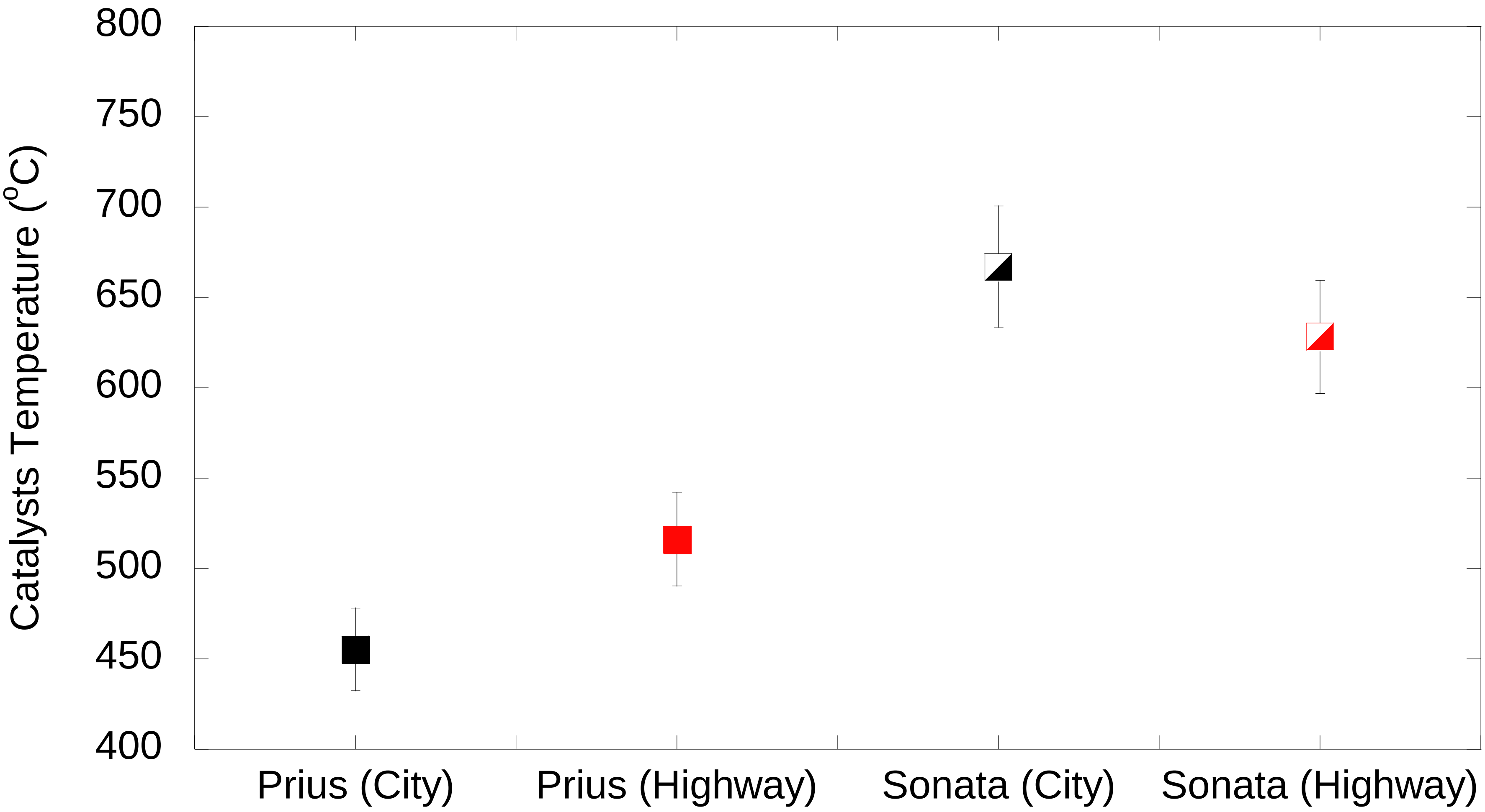
Jacob Swanson[1], Chengguo Li[2], Shaohua Hu[3], Shishan Hu[3], Liem Pham[2], Heejung Jung[2]

[1]Minnesota State University, Mankato
[2]University of California, Riverside
[3]California Air Resources Board

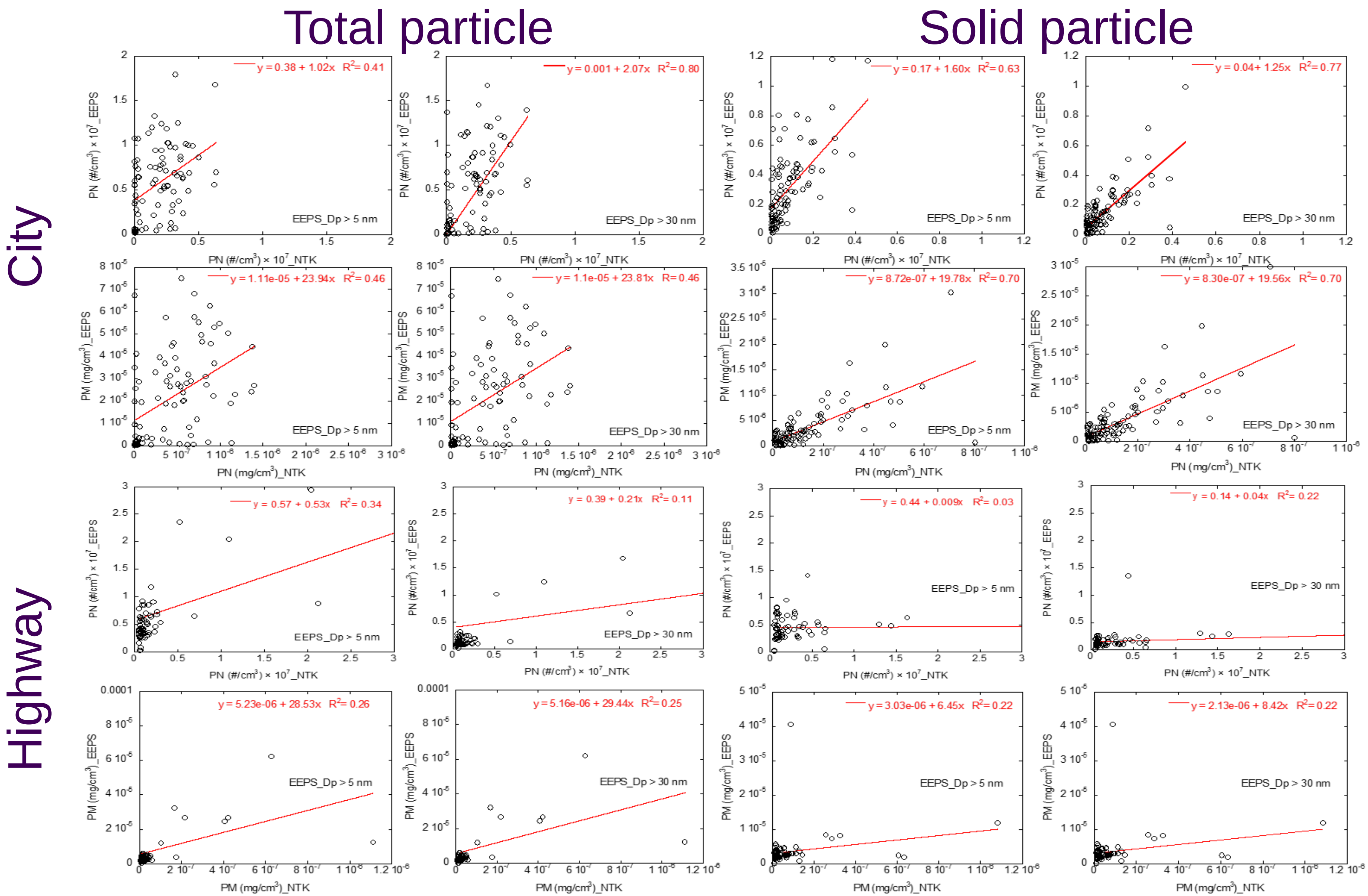
2017 Cambridge Particle Meeting, 23 June 2017

Minnesota State University Mankato

Non-ignition events during RPM=0



Example linear correlations between EEPS and NTK



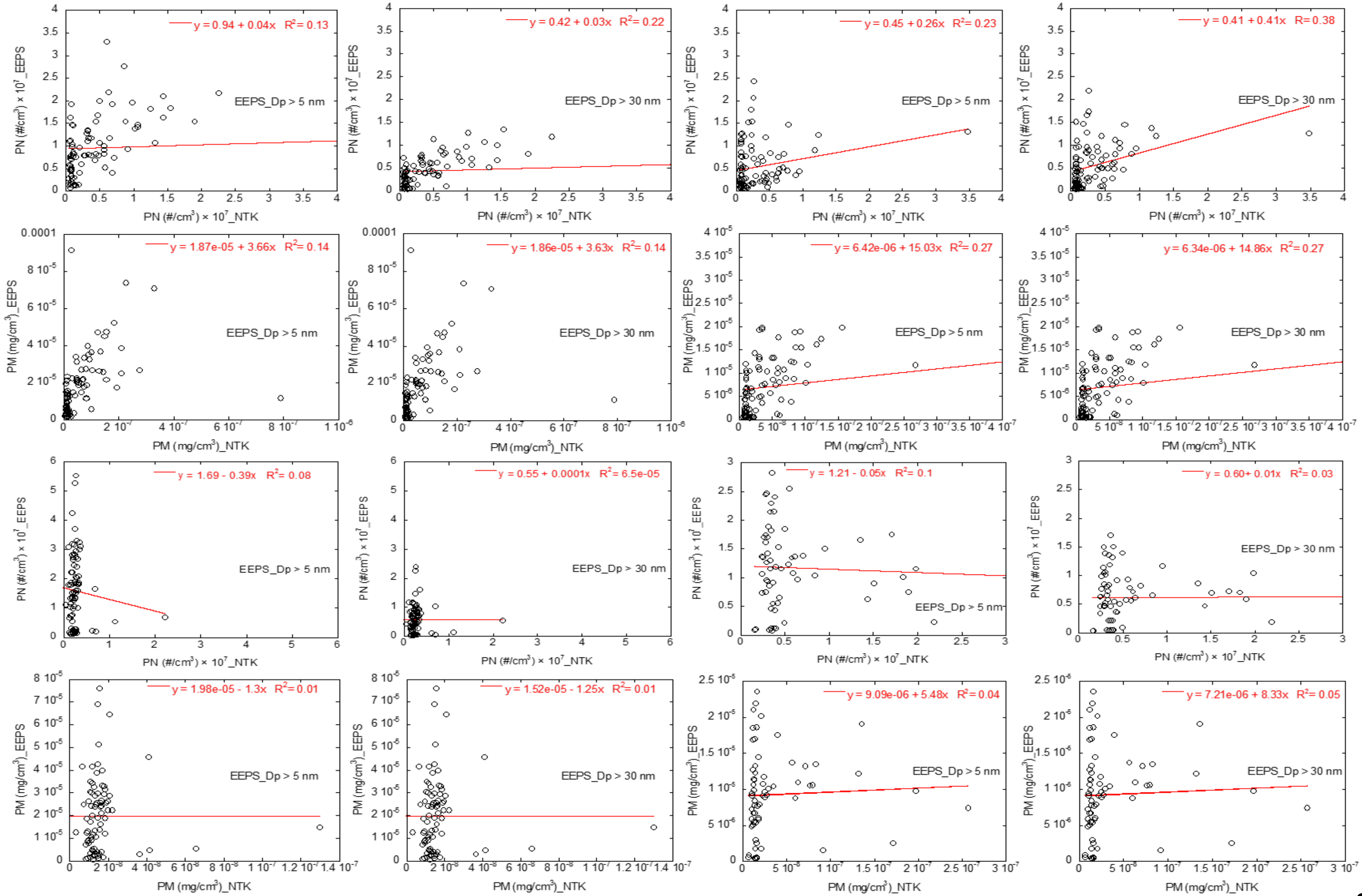
Linear correlation between EEPS and NTK for Sonata

Total particle

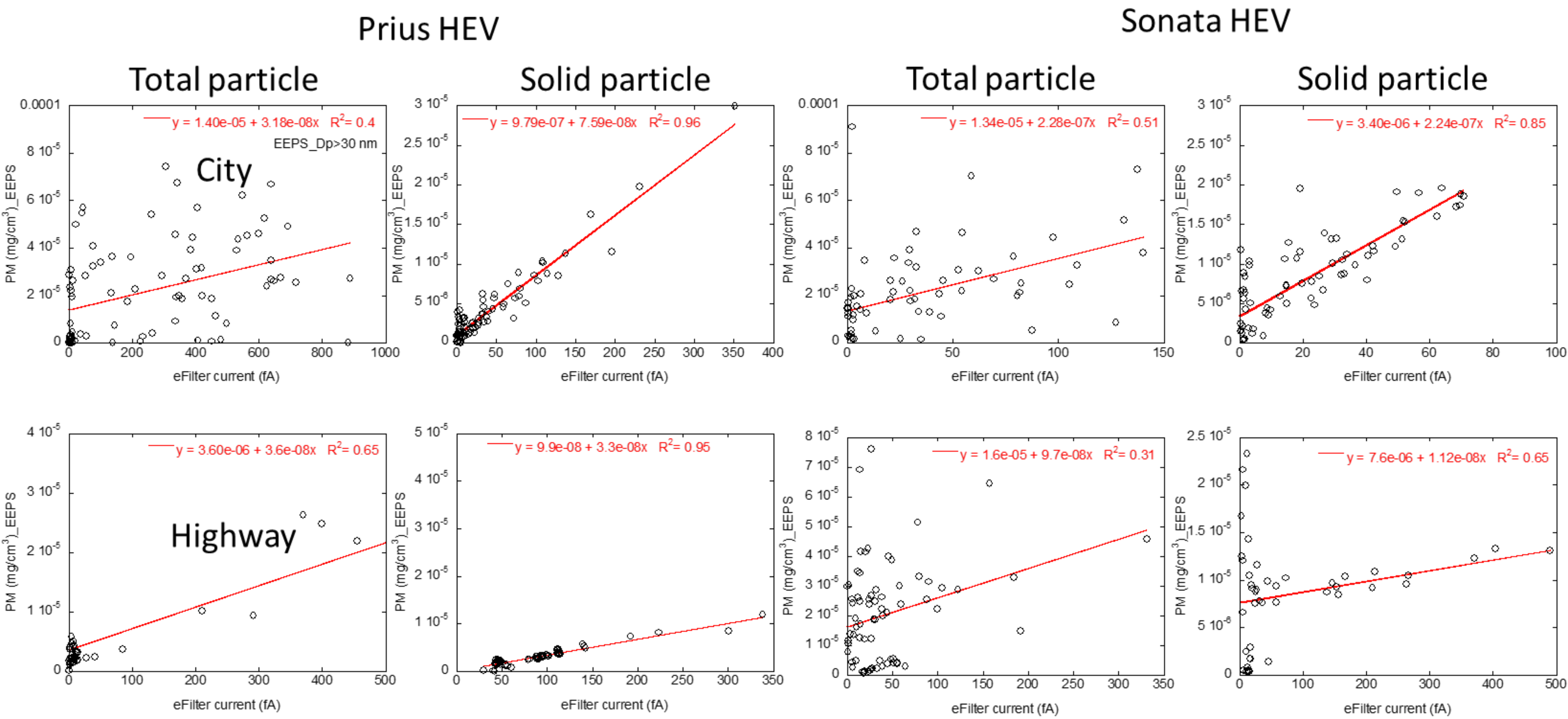
Solid particle

City

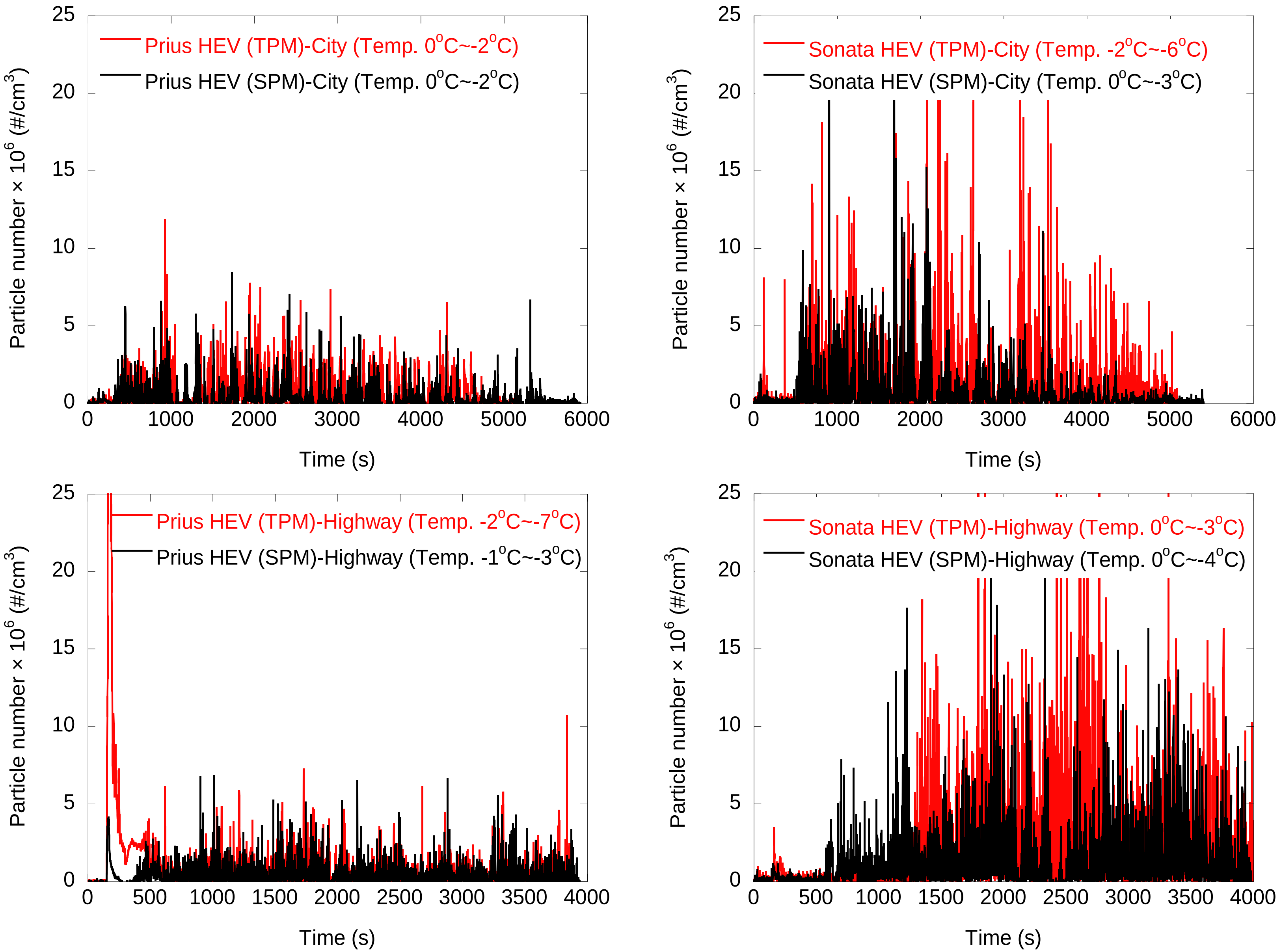
Highway



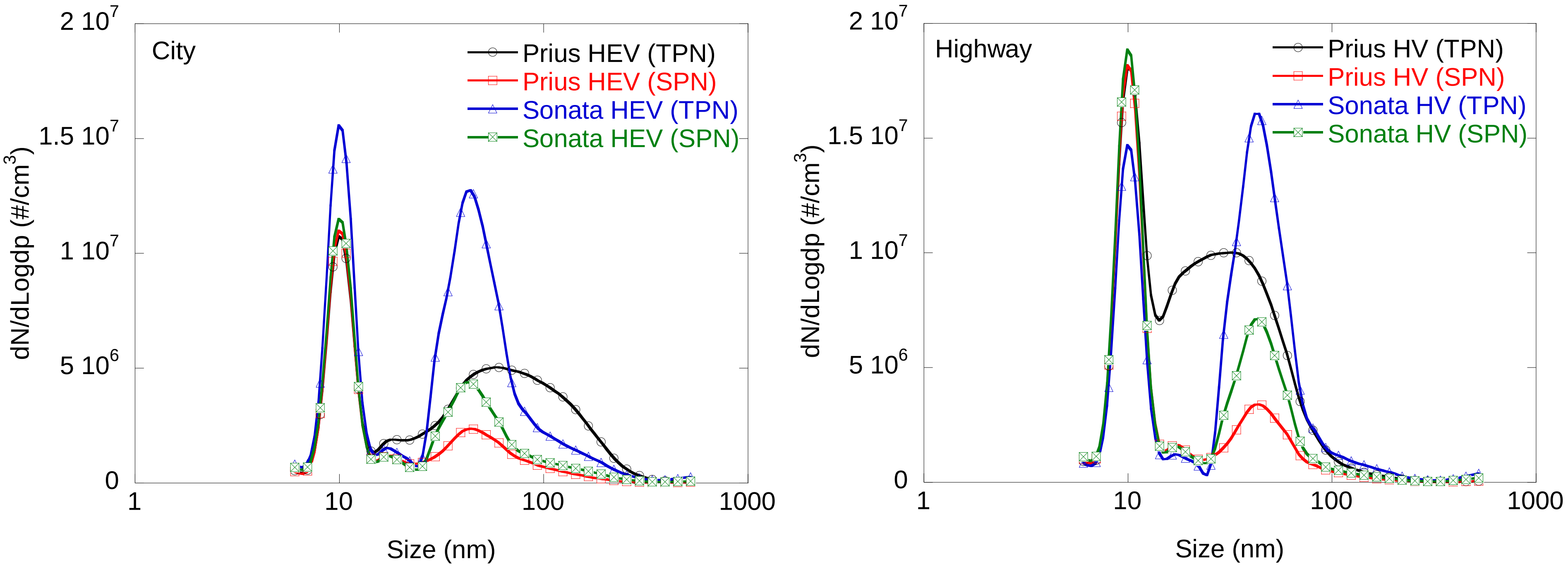
Linear correlation between EEPS and e-Filter



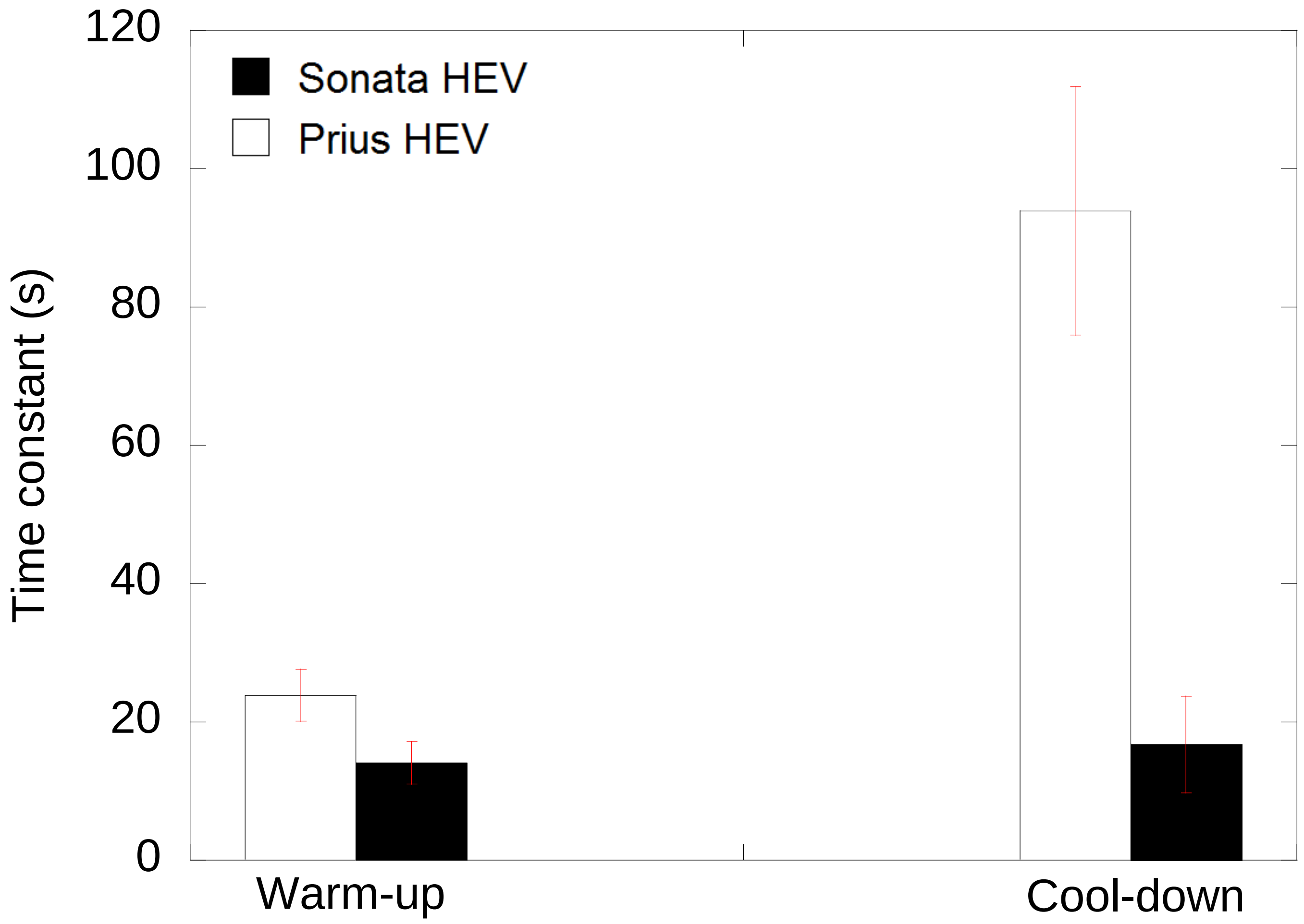
PM number (EEPS)



Particle size distribution



Time constant for cool down and warm-up



ntroduction

Vhat is the Advanced Clean Cars program?

n 2012, the California Air Resources Board (ARB) adopted the Advanced Clean Cars (ACC) rogram, a comprehensive set of standards for new vehicles in California through model year 025. This historic program, developed in coordination with the United States (U.S.) nvironmental Protection Agency (EPA) and National Highway Traffic Safety Administration NHTSA), combined the control of smog-causing (criteria) pollutants and greenhouse gas GHG) emissions into a single coordinated set of requirements for model years 2015 through 025 and assured the development of environmentally superior passenger cars and other ehicles that will continue to deliver the performance, utility, and safety vehicle owners have ome to expect all while saving the consumer money through significant fuel savings. The omponents of the ACC program are the Low-Emission Vehicle III (LEV III) regulations that educe criteria pollutants and GHG emissions from light- and medium-duty vehicles and the ero-emission vehicle (ZEV) regulation, which requires manufacturers to produce an increasing umber of pure ZEVs (meaning battery electric and fuel cell electric vehicles) and plug-in hybrid ectric vehicles (PHEV) in the 2018 through 2025 model years. When fully implemented, new ehicles are expected to emit 34 percent fewer GHG emissions and 75 percent fewer smog-orming emissions than today's vehicles.

ehicles and transportation fuels are the dominant sources of carbon emissions in California. CC is an integral part of California's ambitious long-term requirements to reduce the State's npact on climate change and improve ambient air quality. The vehicle programs are a critical