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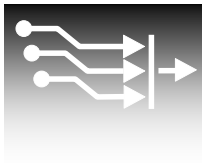
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# Sensor-based Particulate Measurement (Some Tall Tales from the Trenches)

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and Dave Miller<sup>3</sup>

7<sup>th</sup> International PEMS Conference and Workshop  
UCR, Riverside, California  
30<sup>th</sup>-31<sup>st</sup> March 2017



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## I & M Testing

Current generation routine stop-and-check and in-garage testing methods are approaching obsolescence because they are based on opacity which is

- Relatively insensitive to the finer PM produced by modern vehicles
- Cross-sensitive to by-products of some modern emission control systems, e.g.  $NO_2$  from SCRs

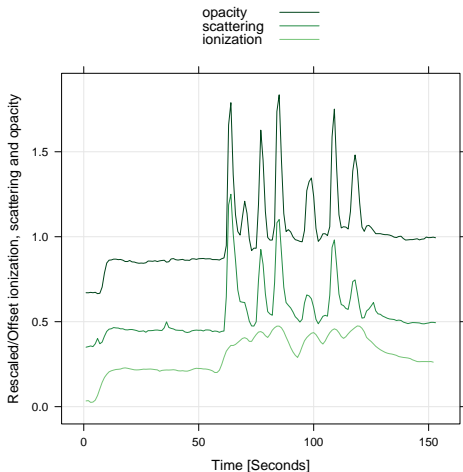
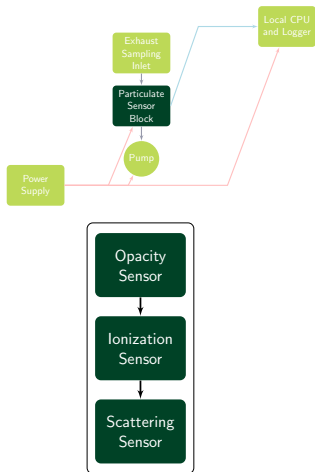
Various strategies have been employed to attempt to address the limitations of opacity but

- Most focus on replacing one single metric with one set of 'blind-spots' with another single metric with others
- Few address the practical issue of unit cost



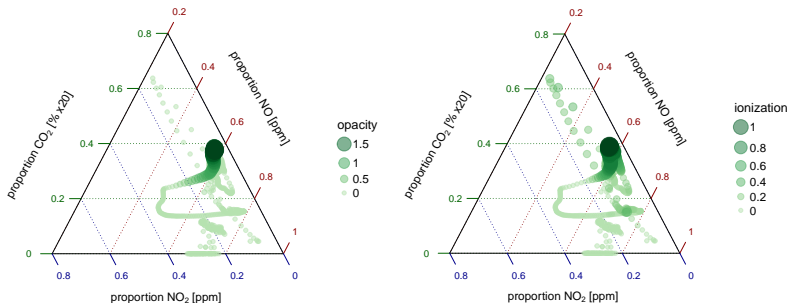
## A Sensory Array Measurement Strategy

# parSYNC<sup>®</sup> Sensor Module





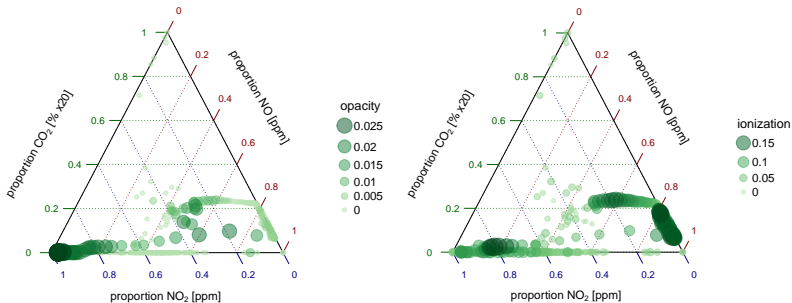
## An Older Dirtier Vehicle



PM emissions of this vehicle are relatively coarse/large  
(Note, opacity measure of PM stronger than ionization measure,  
1.5x comparing scales, but trends for both are highly similar)



## A Newer 'Cleaner' Vehicle



PM emissions of this vehicle are relatively fine/low  
*(Note, ionization lower but 6x opacity and trends are different)*  
But here SCR is also over-dosing/producing excess NO<sub>2</sub> which the  
opacity sensor is cross-sensitive to  
*(Note, the larger relative NO<sub>2</sub> contribution and the more  
pronounced opacity increase with increasing NO<sub>2</sub>)*



## Response Mapping

The current multiplex function (parSYNC\*) attempts to

- Map the cross/non-cross correlation behavior of individual sensors onto a reference method *robustly*
- Correct for the different time resolutions of the sensors and reference method

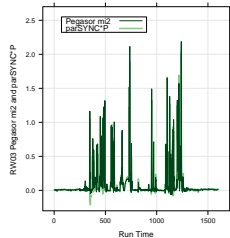
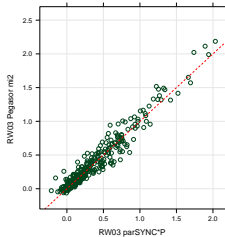
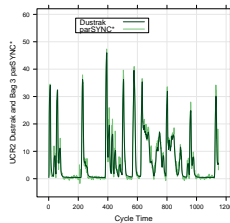
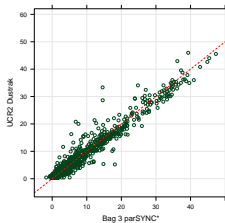
### Three Sensor Fit

$$\text{parSYNC}^* = [\text{REFERENCE}] = f(\text{parSYNC}1_{t=-1,0,1}) + f(\text{parSYNC}2_{t=-1,0,1}) + f(\text{parSYNC}3_{t=-1,0,1})$$



## Validation of Mapping

- DUSTRAK and Pegasor sensor maps, parSYNC\* and parSYNC\*P
- Blind testing on replicate runs
- Both three sensor maps
- Both  $R > 0.95$







## A Serious Caveat

At this stage, this all looks very promising

- 1 Buy yourself a sensor (or bundle of sensors)
- 2 Run it (or them) alongside a reference method to make a calibration dataset
- 3 Model the dataset and, if you get a good calibration, you are good to go, right?

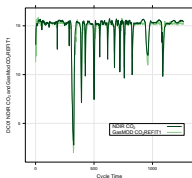
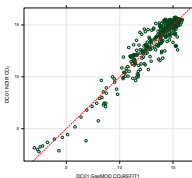
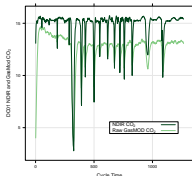
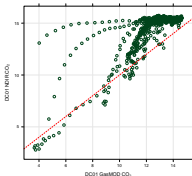
*Unfortunately, it is not that simple...*



# A 'Bad' Map

### One Sensor Fit

$$\text{GasMOD CO}_2\text{REFIT1} = [\text{NDIR}] = f(\text{GasMOD CO}_{2,t=-1,0,1})$$



## Raw sensor comparison

- Here both sensor response time and changing exhaust water content are affecting agreement

## REFIT1 comparison

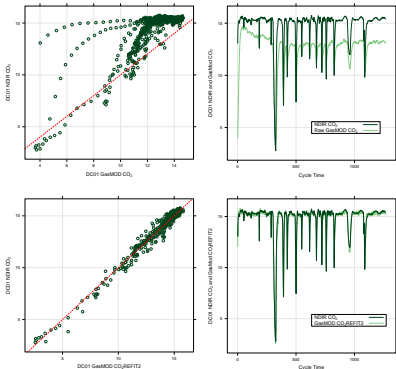
- Here fit looks good and blind testing with same vehicle will seem to confirm that
- But can you spot what REFIT1 is actually doing?



# A Better Map

### Multi Sensor (Multi-Parameter) Fit

$$\text{GasMOD } CO_2\text{REFIT2} = [\text{NDIR}] = f(\text{GasMOD } CO_{2,t=-1,0,1}) + f(H_2O, \text{temperature}_{t=-1,0,1})$$



### Raw sensor comparison

- Same start point as REFIT1

### REFIT2 comparison

- The fit statistics are not that much better than REFIT1
- BUT this tracks changing water content and temperature
- So it tracks rather than suppresses features above 15%



## Before/After Repair Comparison

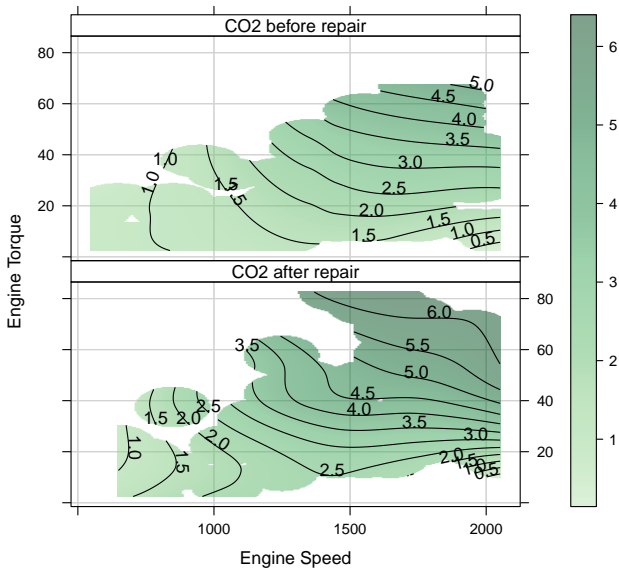
Another option is to compare vehicle emissions before and after a repair

- This is perhaps the most informative option
  - Vehicles independently identified as faulty - *so this is real-world*
  - Garage inspection of failure - *so problem is confirmed and characterized*
  - Vehicles then repaired - *so emission monitoring at start and end of this process means both failures and repairs can be investigated*
- But logistically it is the most challenging and, typically, it is also the most time-consuming

The following examples show dynamometer drive cycle and SNAP test emissions from one vehicle, identified as faulty by OBD codes, before and after the associated repair

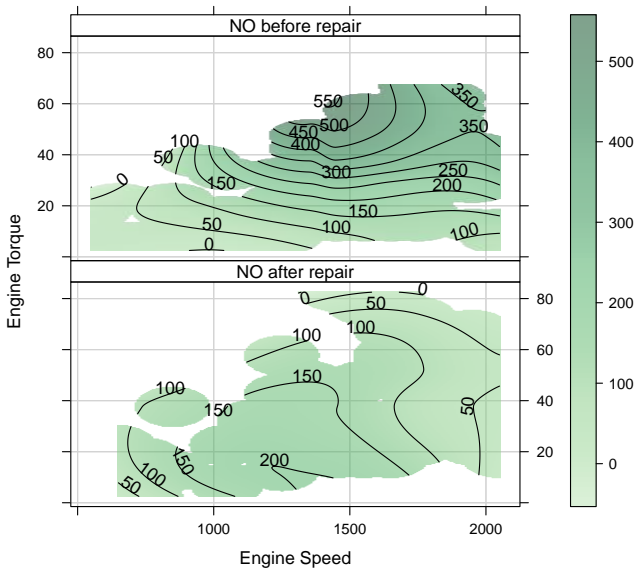


## CO<sub>2</sub> Before/After Repair





# NO Before/After Repair

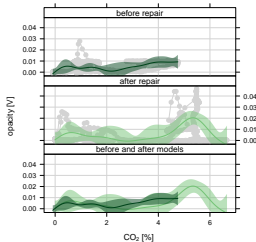
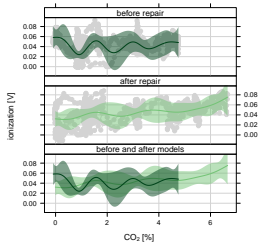
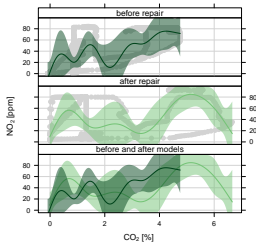
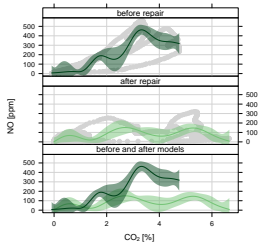




## More On-board Metrics

We are looking to develop a range of 'on-board' metrics and diagnostics because a tester will need standalone information from a test unit

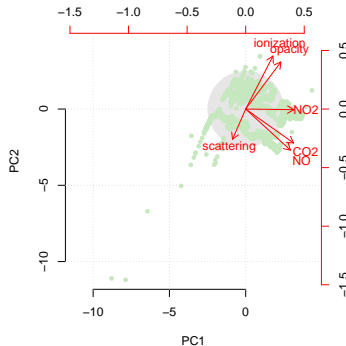
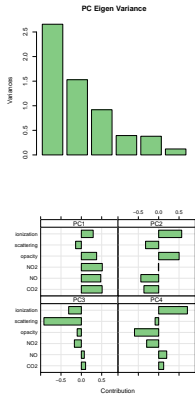
*(By the way, good repair or bad?)*





## More Data Analysis

We have only just begun looking at the data we have



*Above, a preliminary PCA of one vehicle, showing, amongst other things, extreme outliers amongst the scattering measurements*

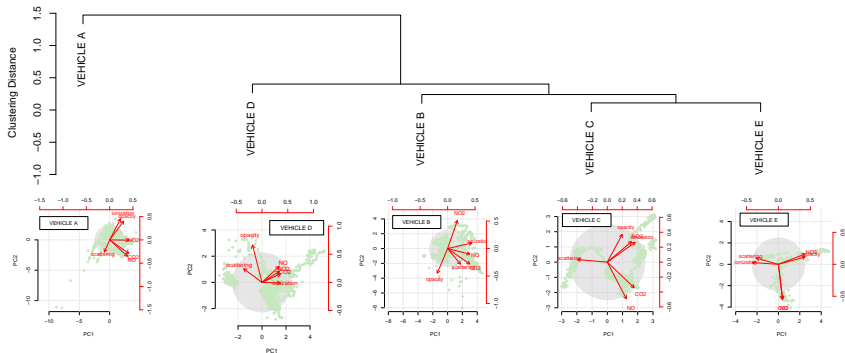




Next Steps

## (Hopefully) More Sampling

We are seeing interesting trends in the data we have...



*...but we really need more if we want to make the work robust*



### Thank You

We gratefully acknowledge the contributes of many others who anonymously contributed vehicles, equipment, labor and parallel data

Without your input this work would not have been possible

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Andrew Burnette - [andrew.burnette@infowedge.com](mailto:andrew.burnette@infowedge.com)

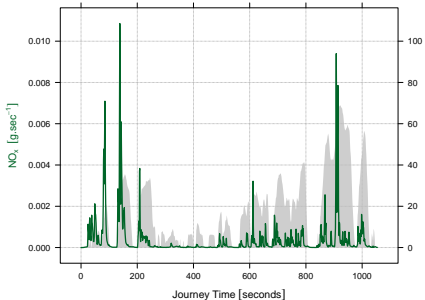
Dave Miller - [davidmiller@3datx.com](mailto:davidmiller@3datx.com)



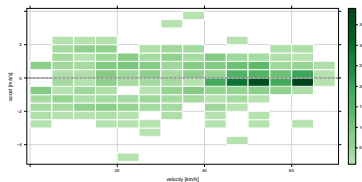
## Acknowledgments

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Data analysis carried out in R and pems.utils



Vehicle Speed [miles.hr<sup>-1</sup>]



pems.utils R package

(<https://sites.google.com/site/karloppkins/rpackages/pems>)