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Real World SI Vehicle Emissions in Low Speed Congested Traffic

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5th International Exhaust Emissions Symposium 2016, 19-20 May, 2016, BOSMAL, Bielsko-Biala, Poland

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Real Driving Emissions (RDE) - 1

The current appalling press regarding RDE shows a lack of understanding of the issue and an industry that has not got its voice across to the public.

The VW issue in the press has been more about vehicles with higher emissions in RDE than on test cycles, which has been the situation since emissions regulations came in and applies equally well to SI engines as diesel, as I will show in this lecture.

Whether VW have ‘cheated’ and made the RDE worse relative to the test cycle, is a separate issue, but the RDE would have been higher than on the test cycle irrespective of any RDE calibrations that were different to those on the test cycle.

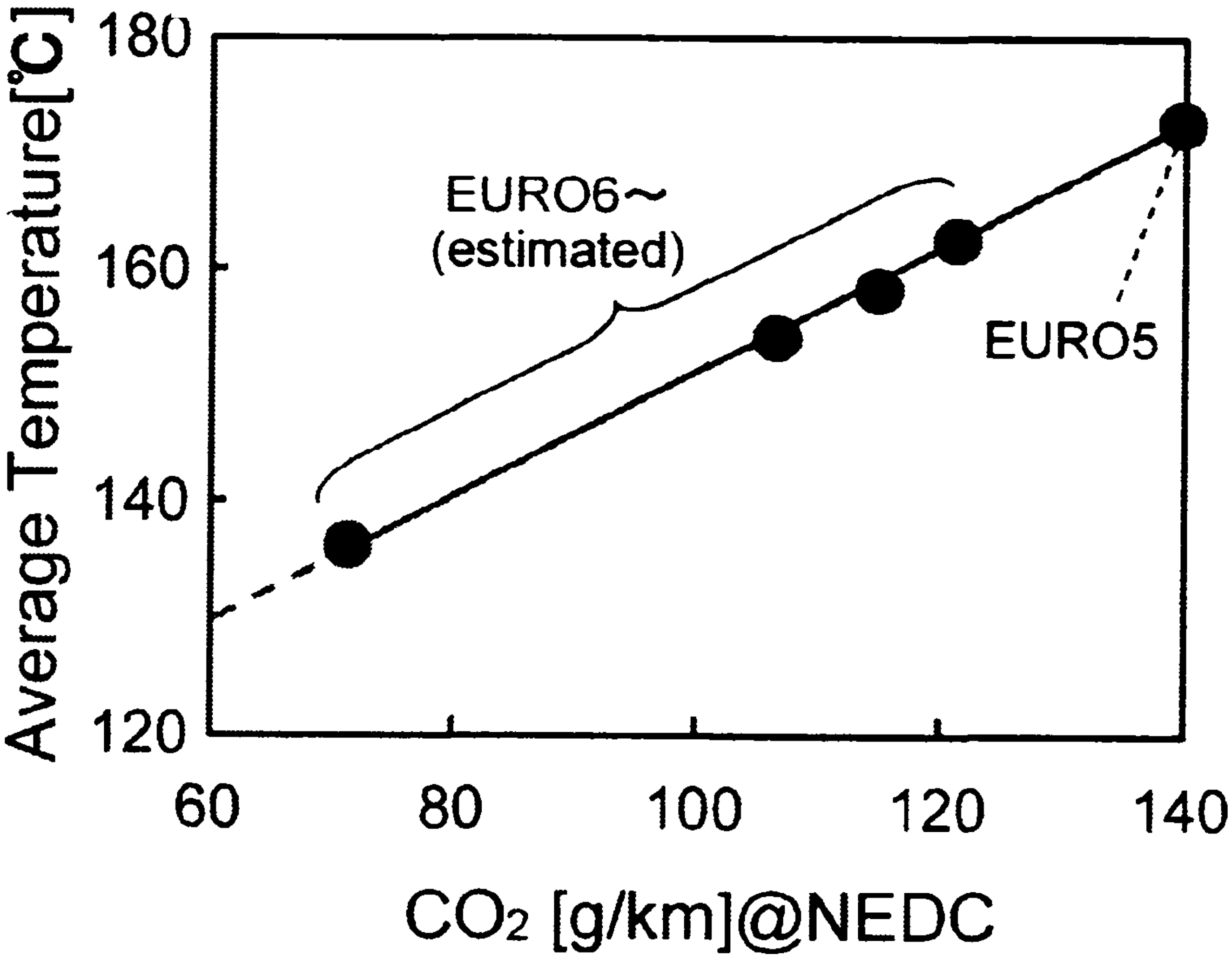
It is my view that congested traffic is a key feature of RDE.

Real Driving Emissions (RDE) - 2

My research group on RDE at Leeds University have over the last 12 years published over 40 SAE papers on RDE and why they are higher than on test cycles.

RDE higher than on test cycles applies to all vehicles SI and diesel and for SI vehicles the RDE effect is closely related to longer cold start in RDE and higher acceleration rates and more stop/starts, as I will show in this presentation.

Modern Euro 6 diesels with particle filters have no real world issues with PM emissions and yet SI engines without a particle trap are now emitting more PM in RDE than diesels with particle traps fitted.
The major RDE effect for diesels is on NOx and CO_2 and with catalysts to control NOx, either NSR or Urea SCR, the catalyst has to be above about 200°C to be active and the lower temperatures of diesel exhausts make this difficult, as I will illustrate for a HDD truck RDE journey.



Future low CO_2 vehicles will have lower exhaust temperatures due to more TC and associated leaner diesel engine operation.

deNOx catalyst for lean burn require T>200°C for light off. RD temperatures are lower than on test cycles and so NOx emissions will be higher.

Tsukamoto, Y. et al., Development of new concept catalyst for low CO_2 emissions Diesel engine using NOx adsorption at low temperatures. Toyota. SAE 2012-01-0370

Prediction of Urban Air Quality in Europe -1

There are relatively few experimentally based air quality measurements in Europe and in UK cities. One per city is quite common.

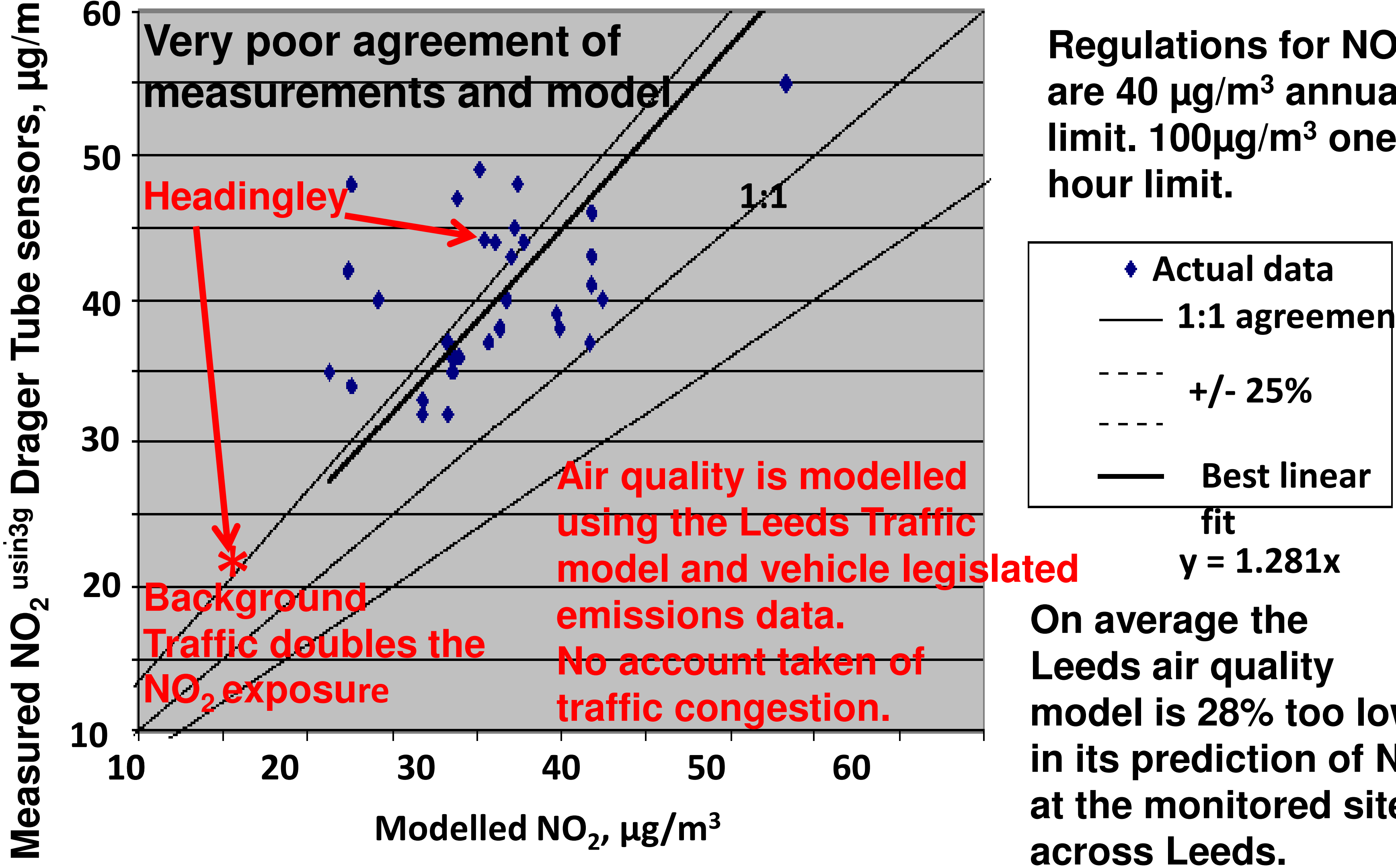
In Leeds the entire Leeds air quality is measured by the official government funded site at ONE location in the centre of Leeds. This is about 20m from a busy slip road leading to the Leeds Inner Ring Road. Concentrations elsewhere are based on the Leeds air quality model.

The city council has additional roadside measurement locations and one of these is in Headingley on the A660, on the congested route used in this study. This is a site that frequently exceeds European regulations on NOx and PM and this study investigates the pollution from triffic passing this site using a probe vehicle in the traffic flow with PEMS.

Predictions of air quality relating to traffic rely on three inputs:

1. **Traffic modelling for traffic flows and mean travel time.**
2. **The UK national database for the age of registered vehicles in Leeds**
3. **The certified emissions per vehicle according to its age – using the NEDC test cycle.**
4. **Although there is a procedure agreed in the UK to take into account cold start in situations where they may be significant, this is often ignored for Euro 3 onwards and was ignored in the Leeds model.**

Leeds NGT Trolleybus Public Inquiry TWAO Doc. A-08c-1 Air Quality, Sept. 2013



Very poor agreement of measurements and model

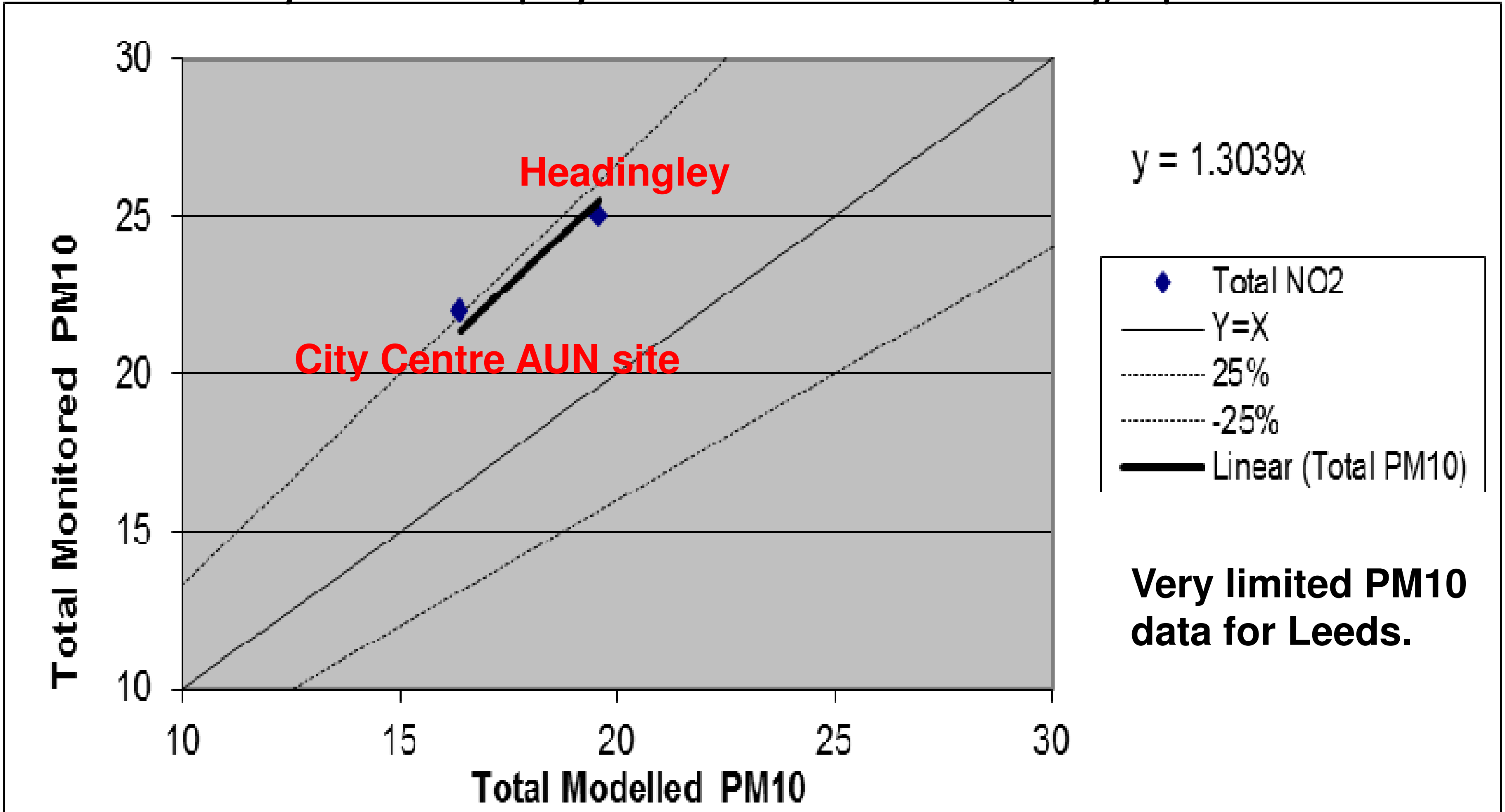
Background Traffic doubles the NO_2 exposure

Air quality is modelled using the Leeds Traffic model and vehicle legislated emissions data.
No account taken of traffic congestion.

Regulations for NO_2 are 40 µg/m³ annual limit. 100µg/m³ one hour limit.

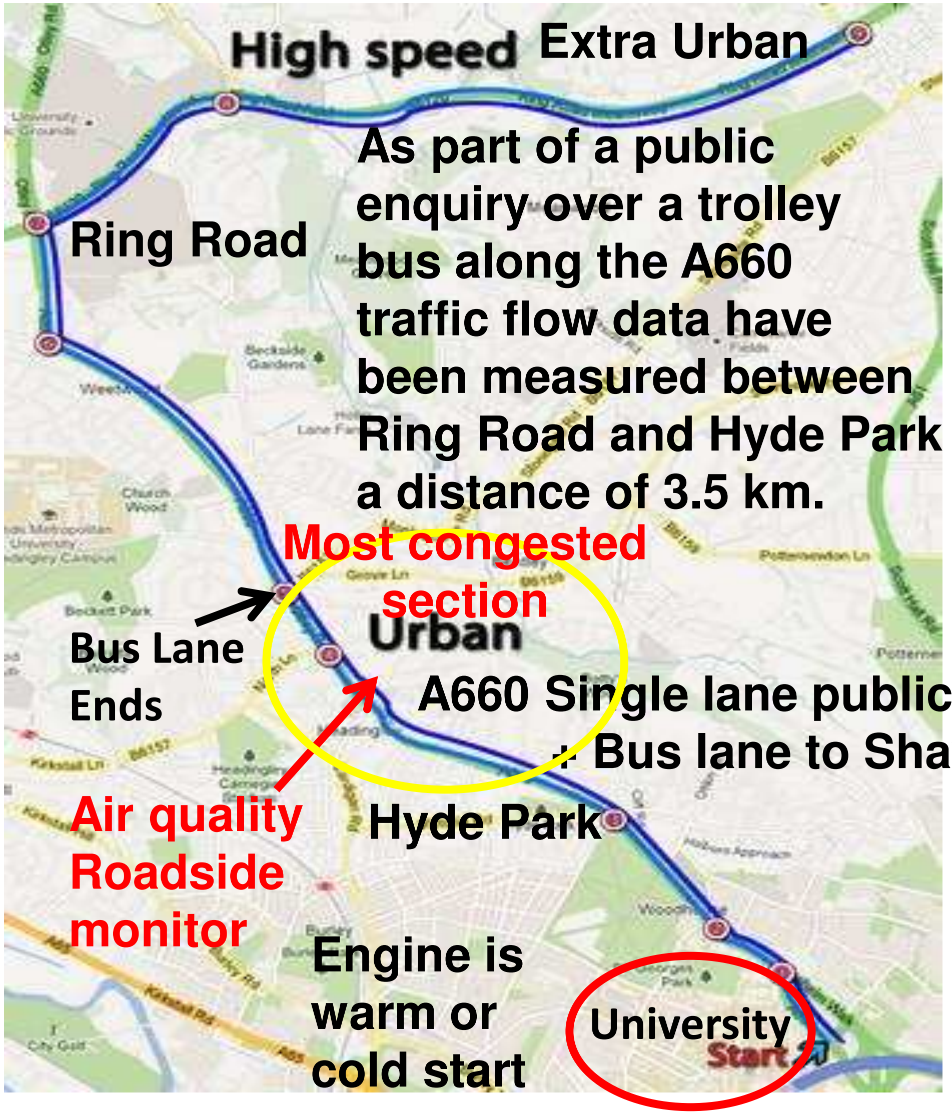
On average the Leeds air quality model is 28% too low in its prediction of NO_2 at the monitored sites across Leeds.

Leeds NGT Trolleybus Public Inquiry TWAO Doc. A-08c-1 Air Quality, Sept. 2013



Very limited PM10 data for Leeds.

Very poor agreement between air quality modelling and measurements for PM10. This is because the model used PM for traffic from the legislated test cycles and emissions in congested traffic are higher.



As part of a public enquiry over a trolley bus along the A660 traffic flow data have been measured between Ring Road and Hyde Park a distance of 3.5 km.

Most congested section

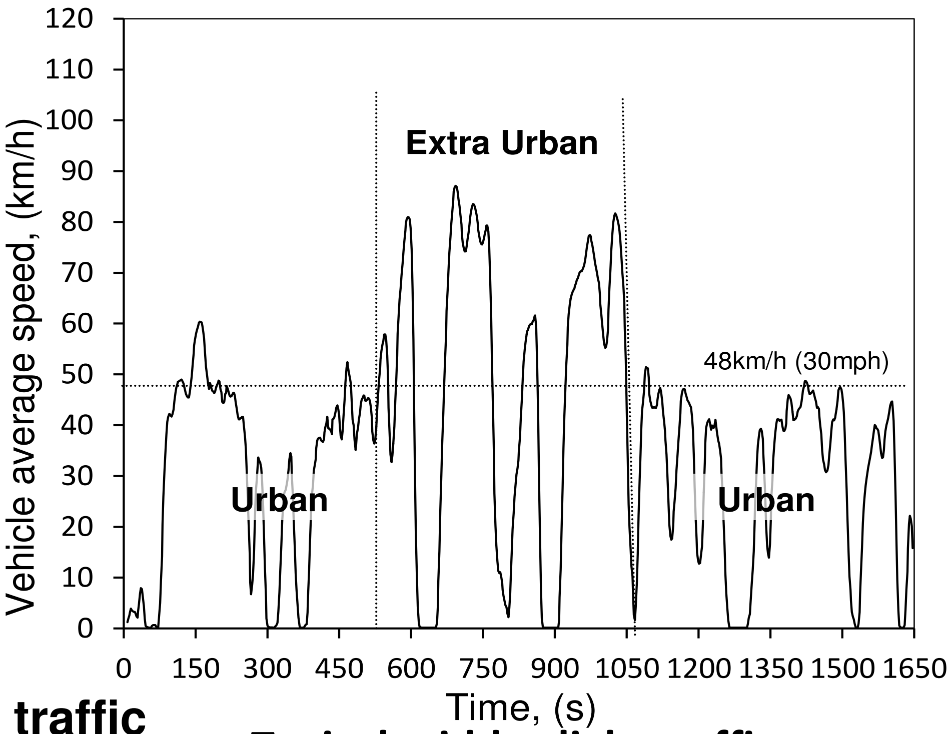
Bus Lane Ends

A660 Single lane public traffic + Bus lane to Shaw Lane

Air quality Roadside monitor

Engine is warm or cold start

Leeds City Centre



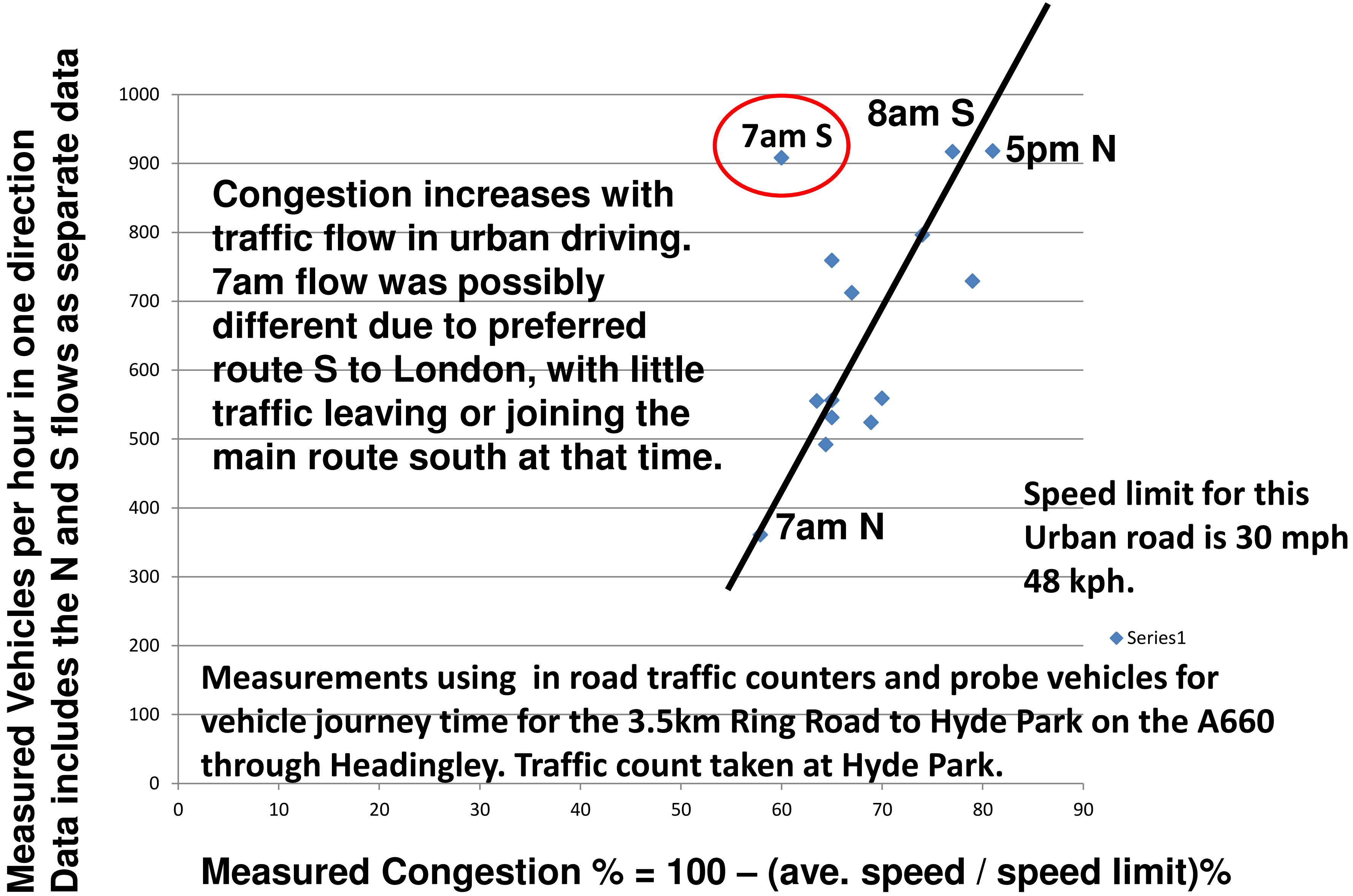
Typical midday light traffic

The Leeds A660 road has traffic monitoring and modelling by the City plus has an air quality monitoring station at the roadside in Headingley.

Journey times monitored between Ring Road and Hyde Park

SAE Paper 2012-01-1674

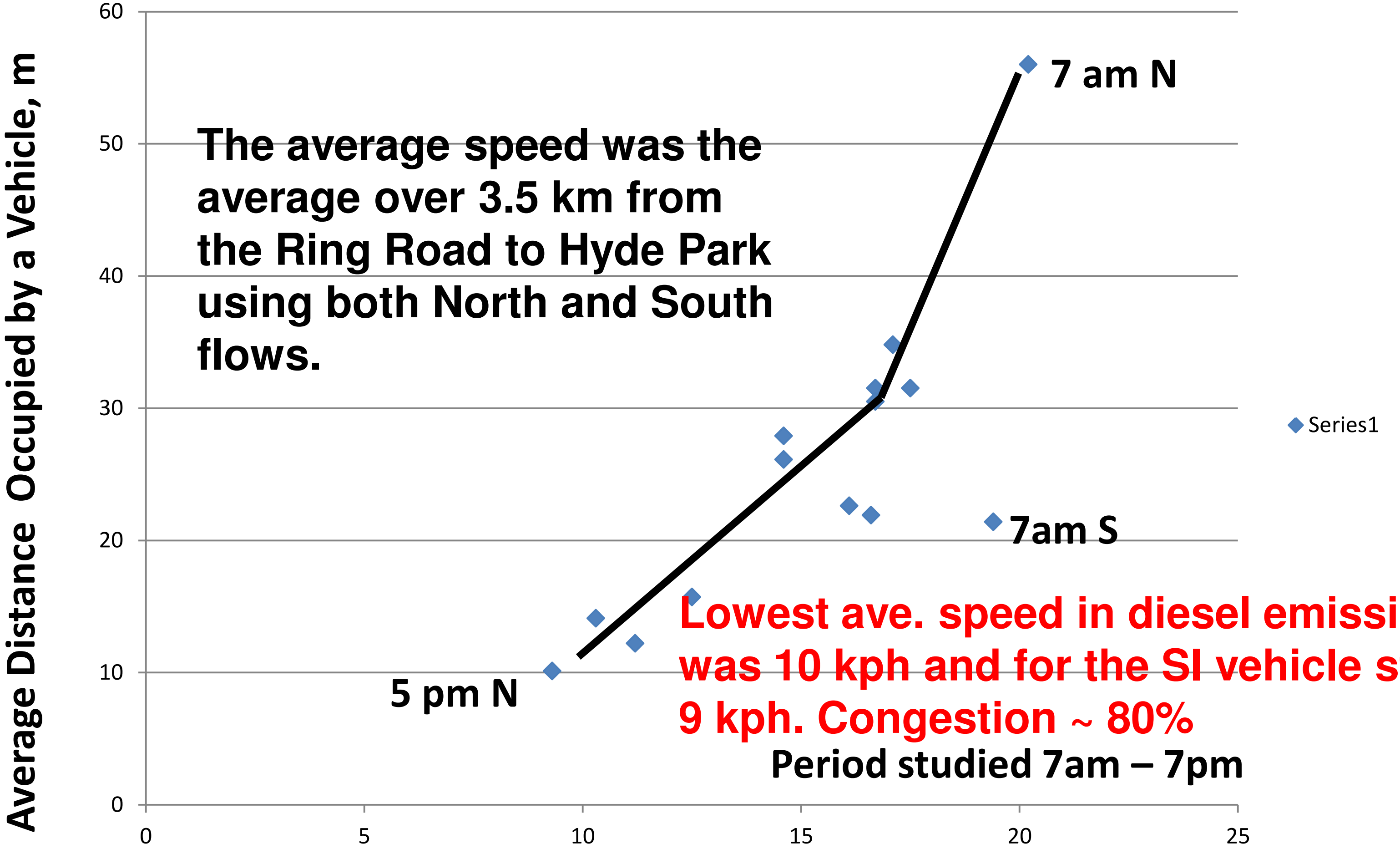
Real World Emissions SI Emissions in Congested Traffic



Congestion increases with traffic flow in urban driving. 7am flow was possibly different due to preferred route S to London, with little traffic leaving or joining the main route south at that time.

Speed limit for this Urban road is 30 mph 48 kph.

Measurements using in road traffic counters and probe vehicles for vehicle journey time for the 3.5km Ring Road to Hyde Park on the A660 through Headingley. Traffic count taken at Hyde Park.



The average speed was the average over 3.5 km from the Ring Road to Hyde Park using both North and South flows.

Lowest ave. speed in diesel emissions study was 10 kph and for the SI vehicle study was 9 kph. Congestion ~ 80%

Period studied 7am – 7pm

Measured Average Vehicle Speed, kph (3.5km distance /time taken)
Probe vehicles used to determine the journey time.

Another definition of congestion is when the journey time is half the normal time congestion Is 100% and the above results show that the A660 is congested for all times of the day.

Euro 3 Diesel Van SAE Paper 2012-01-1674 and SAE 2013-01-2528

	B100			Diesel			Euro 3 Limit	RDE x Euro Limit
	MEAN (5°C)	SD	SD/ MEAN	MEAN (13°C)	SD	SD/ MEAN		
CO$_2$, g/km	172.9	11.8	6.82%	173.6	5.9	3.37%	172*	
CO, g/km	0.067	0.01	16.59%	0.153	0.04	24.63%	0.8	0.2
THC+NOx, g/km	1.342	0.04	3.38%	2.004	0.59	29.61%	0.72	2.8
THC, g/km	0.194	0.03	17.29%	0.145	0.03	18.23%	0.07	2.1
NO$_x$, g/km	1.148	0.03	2.67%	1.858	0.57	30.51%	0.65	2.9
NO, g/km	0.695	0.04	6.46%	1.491	0.69	46.50%	-----------	
NO$_2$, g/km	0.454	0.07	14.35%	0.367	0.14	37.08%	-----------	
NO$_2$/NO	65%			25%				

Journey average emissions of the most congested part in units of g/km

SAE 2013-01-2528

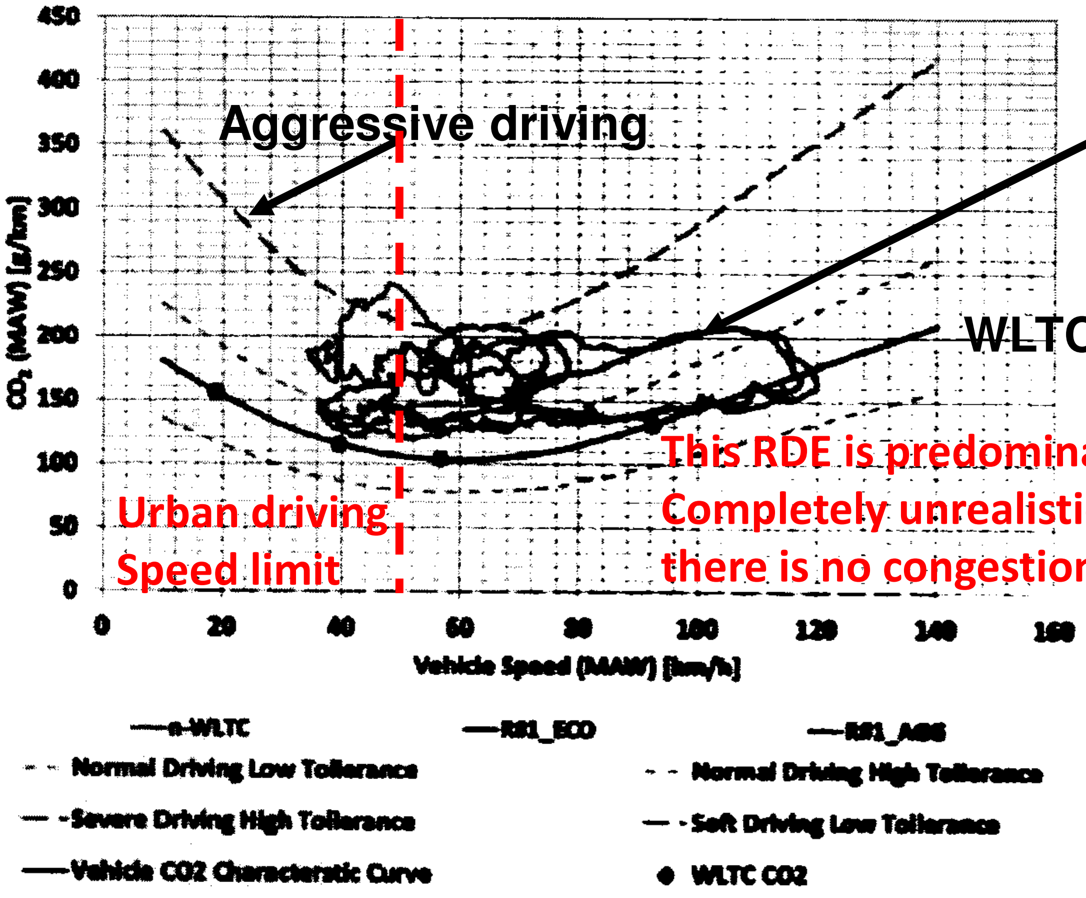
Fuel	Diesel Run1	Diesel Run2	B50 Run1	B50 Run2	B100 Run1	B100 Run2	Euro 3 Limit	RDE Factor
CO, g/km	8.7	6.3	7.0	5.5	8.2	12.9	0.8	10.1
THC, g/km	0.72	0.64	0.69	0.47	1.46	2.78	0.07	9.7 (D)
NO_x, g/km	4.0	3.5	3.3	2.9	4.2	5.2	0.65	12.6
CO_2, g/km	737	1189	579	543	789	942	172	3.7
V_{mean}, km/h	6.8	4.5	7.6	7.7	6.6	5.4	17.2 (Urban)	

In this paper this most congested part of the route was Investigated for a SI Vehicle – Euro4

Diesel Particulate and NOx Emissions 2015

Prof. Gordon E. Andrews, Energy Research Institute, U. Leeds, UK

Tim Johnson, Review of Vehicular Emissions Trends, SAE Int. J. Engines 7(3) 2015, Corning Inc. doi:10.4271/2015-01-0993 SAE Paper 2015-01-0993



This RDE is predominantly extra-urban. Completely unrealistic for the UK as there is no congestion.

Figure 1. Representation of the Moving Average Window (MAW) approach to determining applicability of PEMS data from in-use emissions. Solid lines represent test data. Dashed lines represent two levels of tolerance or acceptability of the data. (8)

8. Vlachos, T. et al. In use emissions testing with PEMS in the current and future European vehicle Emissions legislation: Overview underlying Principles and expected benefits. SAE Int. J. Commer. Veh. 7(1):199-215 Doi:10.427/2014-01-1549. SAE Paper 2014-01-1549

Comparison of congestion simulated in test cycles

This assumes a regulated speed of 30 mph or 48.3kph for urban driving

Test Cycle	NEDC	FTP	CAFE	JC09	WLTC	RDE	This work
Mean Vel. kph	33.6	31.5	52.3	24.4	46.5	30 - 110[1]	5 – 26
Congestion	30%	34%	0%	49%	3%	0%	90% - 46%
Max. Acc. m/s^2	1.0	1.5		1.7	1.7	1.5[2]	2.2 – 2.8
Distance, km	11	12		8.2	23.3	~80-90[1]	5
No. Acc. From Idle / km	1.3	1.5		1.5	0.4	~0.2[1]	1.2 - 7

RDE in congested traffic involves lower speeds, higher accelerations and many more accelerations from idle than on any legislated test cycle WLTC will have lower emissions than NEDC due to higher speeds and proposals for RDE ignore congested driving completely

[1] RDE Examples from S. Hausberger et al. TU Graz, 3rd Conf. RDE, Berlin, Oct. 2015.

[2] J. Merks et al. U. Poznaz, 3rd RDE, Berlin, Oct. 2015

The air quality exceedances for PM and NO_2 in cities is based on local monitoring stations close to roads with congested traffic e.g. Marylebone Road in London and Headingley in Leeds. It is the local congested traffic that is the problem and as I have shown, none of the test cycles or so called improved test cycles address this issue and it is totally ignored in the proposals for RDE testing.

In congested traffic the average speed is low, peak accelerations are high and the number of accelerations from idle/km is much higher than on any test cycle. These are the reasons for real world driving causing poor air quality in cities and these conditions are ignored in WLTC and RDE proposals. Thus these new test procedures will not address the issue of real world driving and poor urban air quality.

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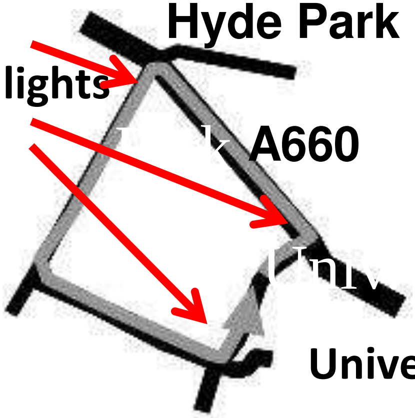
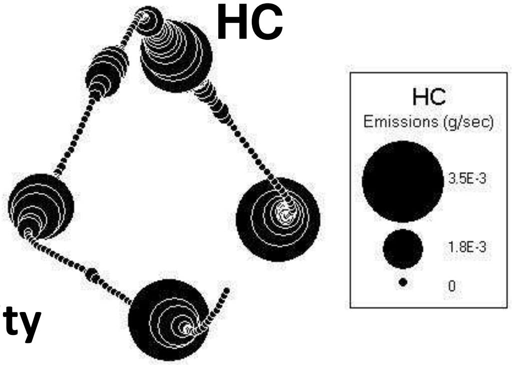
Factors that influence RDE – both SI and Diesel

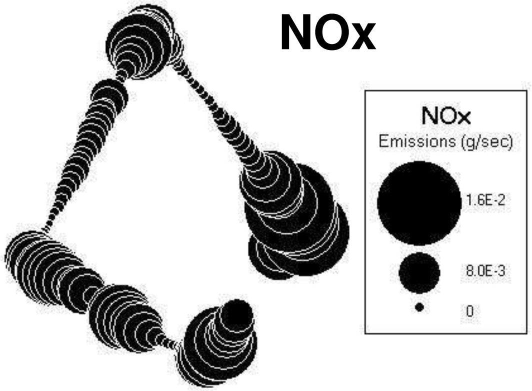
1. Driver behaviour – aggressive drivers – high acc./decel
2. Ambient temperature – affects catalyst light off and water and lube oil warm-up times, related to cold start.
3. Congested traffic in urban driving – low average speed and more stop/starts – influence of other drivers – this is the main topic of this presentation.
4. Traffic lights and road junctions – most emissions in urban areas occur at these real driving events.
5. Cold start in RDE is longer than on test cycles and often occurs in congested traffic.
6. Diesels have an additional problem that the catalyst can cool down after it has lit off – cruise and reaching congested traffic after a period of high speed driving. This will be shown for SCR and has previously been shown for oxidation catalysts.

Example of emissions mapping using Horiba OBS g/s in a Ford Mondeo Euro 1

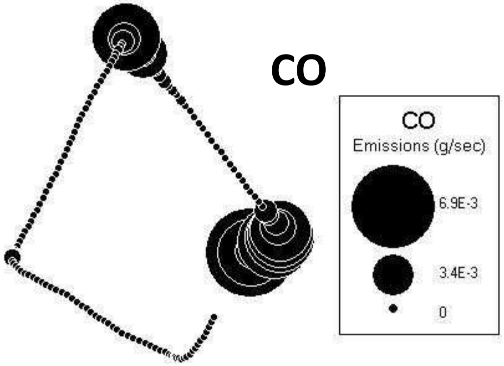
For Euro II – VI with lower emissions there are no significant emissions other than at junctions, so the effect of junctions is greater.

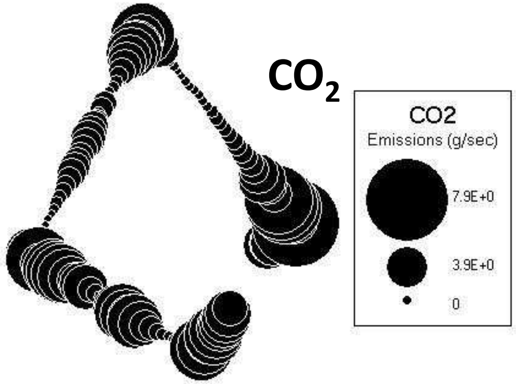






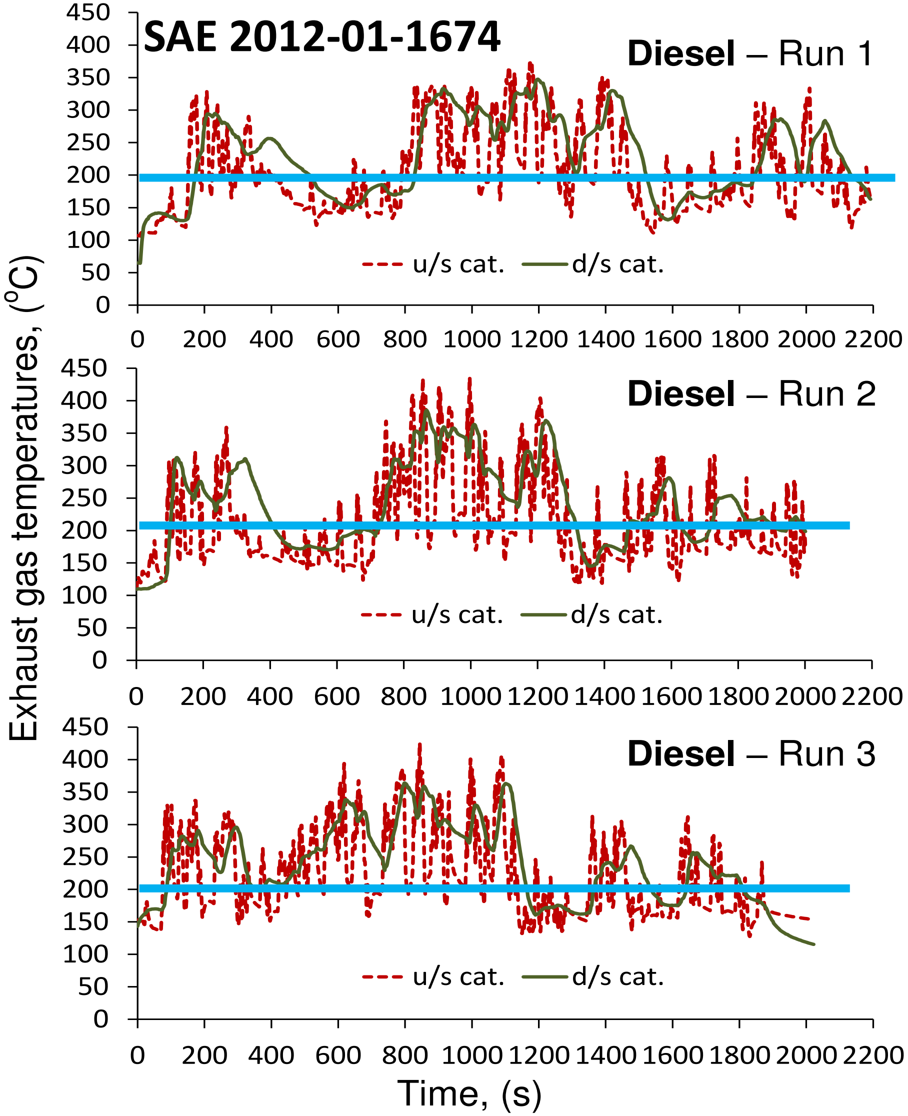
Pollution and CO_2 is predominantly at junctions for Euro 2 and increasingly so for Euro 4+





Junctions are the most important influence of congested traffic driving in urban locations. There are no junctions in the NEDC!

RDE in Congested Traffic with Cold Start



The present work was not designed to include a cold start, the time at the start of the test while instruments and data loggers were set up was sufficiently long for catalyst cooling to occur.

The low oxidation catalyst temperatures at the start of the test resulted in high CO and HC emissions during the subsequent warm up period.

For most of the journeys the catalyst temperature was well above 200°C.

However, there were times when the catalyst cooled down to around 150°C in congested traffic, where CO and HC increased.

This is a different catalyst behavior to that in SI vehicles operating at λ=1 as the exhaust temperature are higher and there is greater heat release at the catalyst due to CO and HC oxidation.

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PEMS – Temet FTIR (Gasmet) with Horiba OBS pitot tube exhaust mass flow measurements and gas sampling.

Racelogic GPS for velocity and acceleration measurements

Cold start and hot start emissions compared for the same test journey.

Congestion varied by testing at different times of the day with different traffic loadings.

29 hot start trips and 8 cold start – total journeys 37

Same driver for all journeys.

Ford Mondeo Euro 4 vehicle

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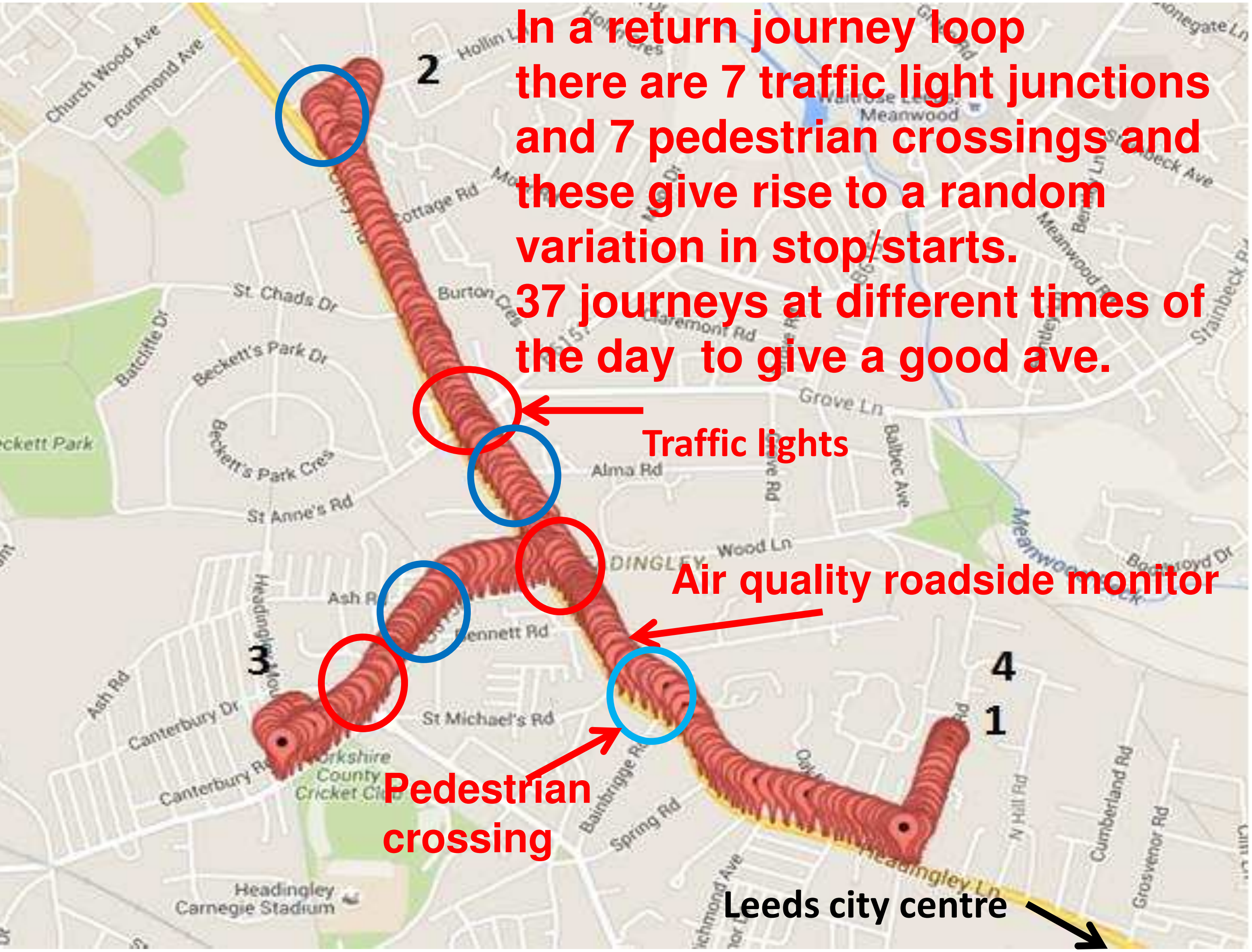

In a return journey loop there are 7 traffic light junctions and 7 pedestrian crossings and these give rise to a random variation in stop/starts.
37 journeys at different times of the day to give a good ave.

**Single lane traffic flow in each direction.
Peak traffic flows 1000 vehicles/hour**

Each journey was a loop so outward and inward driving in the same journey.

There was a total of 20 junctions in each direction where vehicles could leave or join the main flow.

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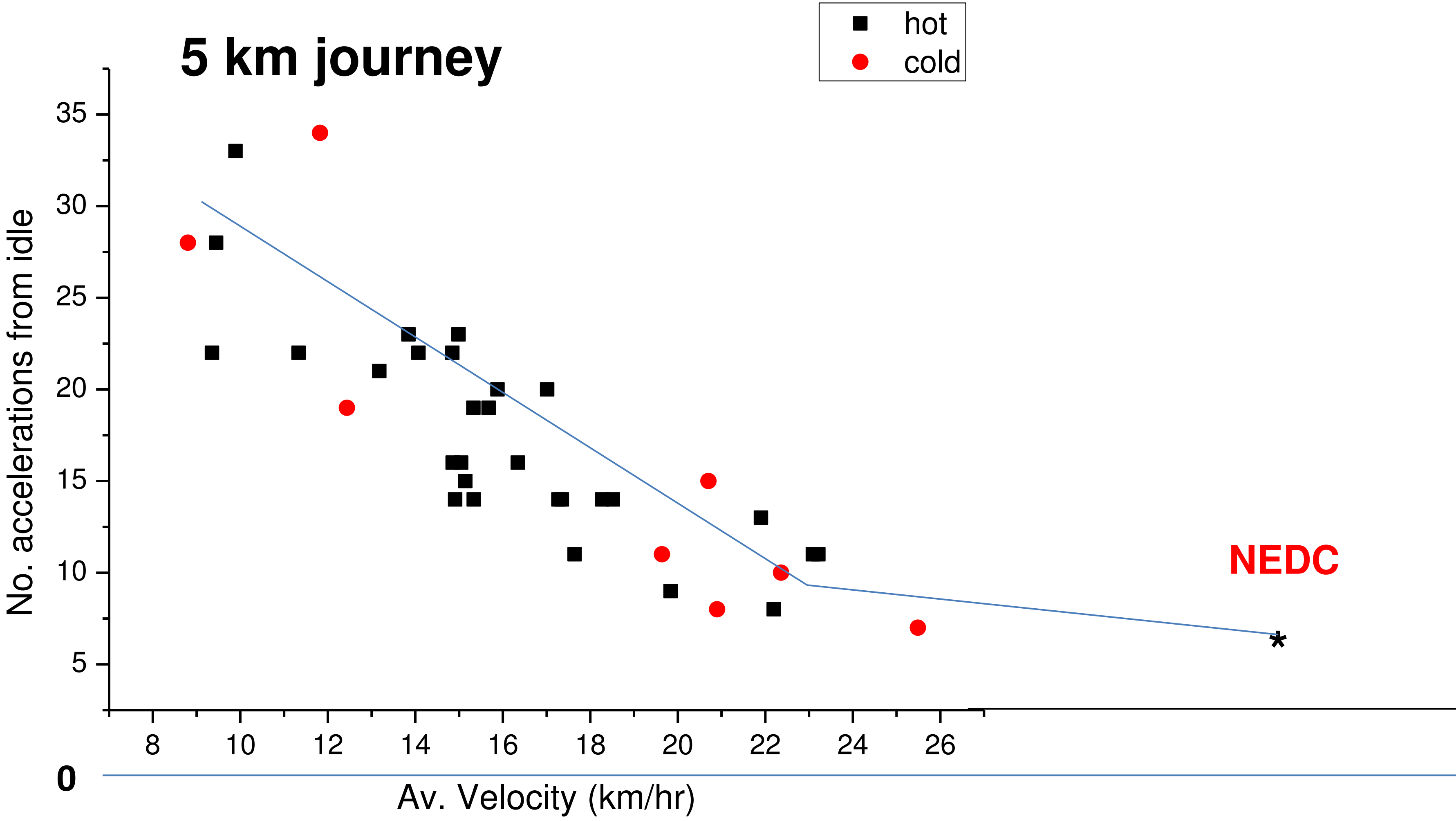
5 km journey
■ hot
● cold
No. accelerations from idle
35
30
25
20
15
10
5
0
8
10
12
14
16
18
20
22
24
26
Av. Velocity (km/hr)
NEDC
*

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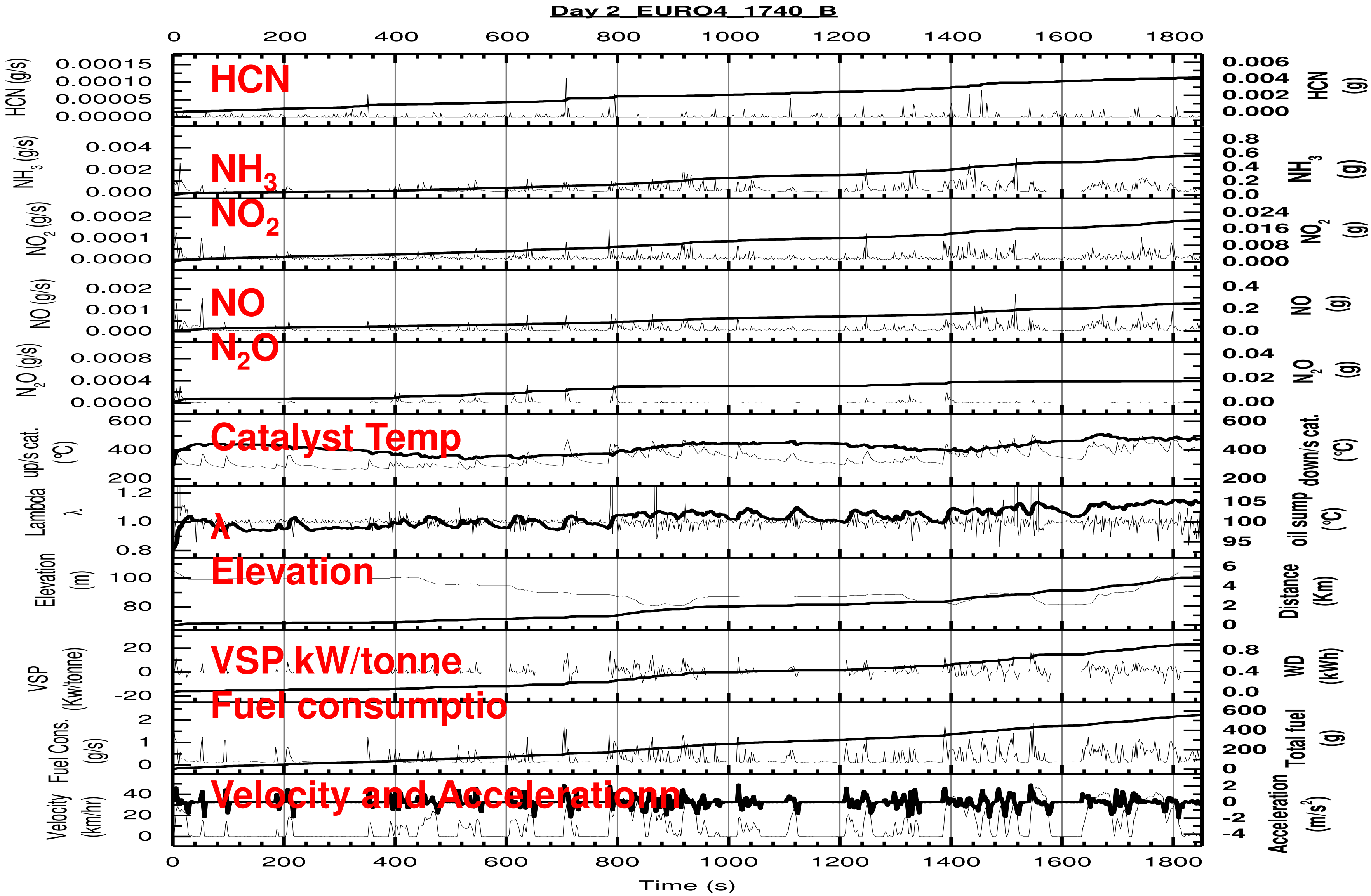
RDE in Congested Traffic



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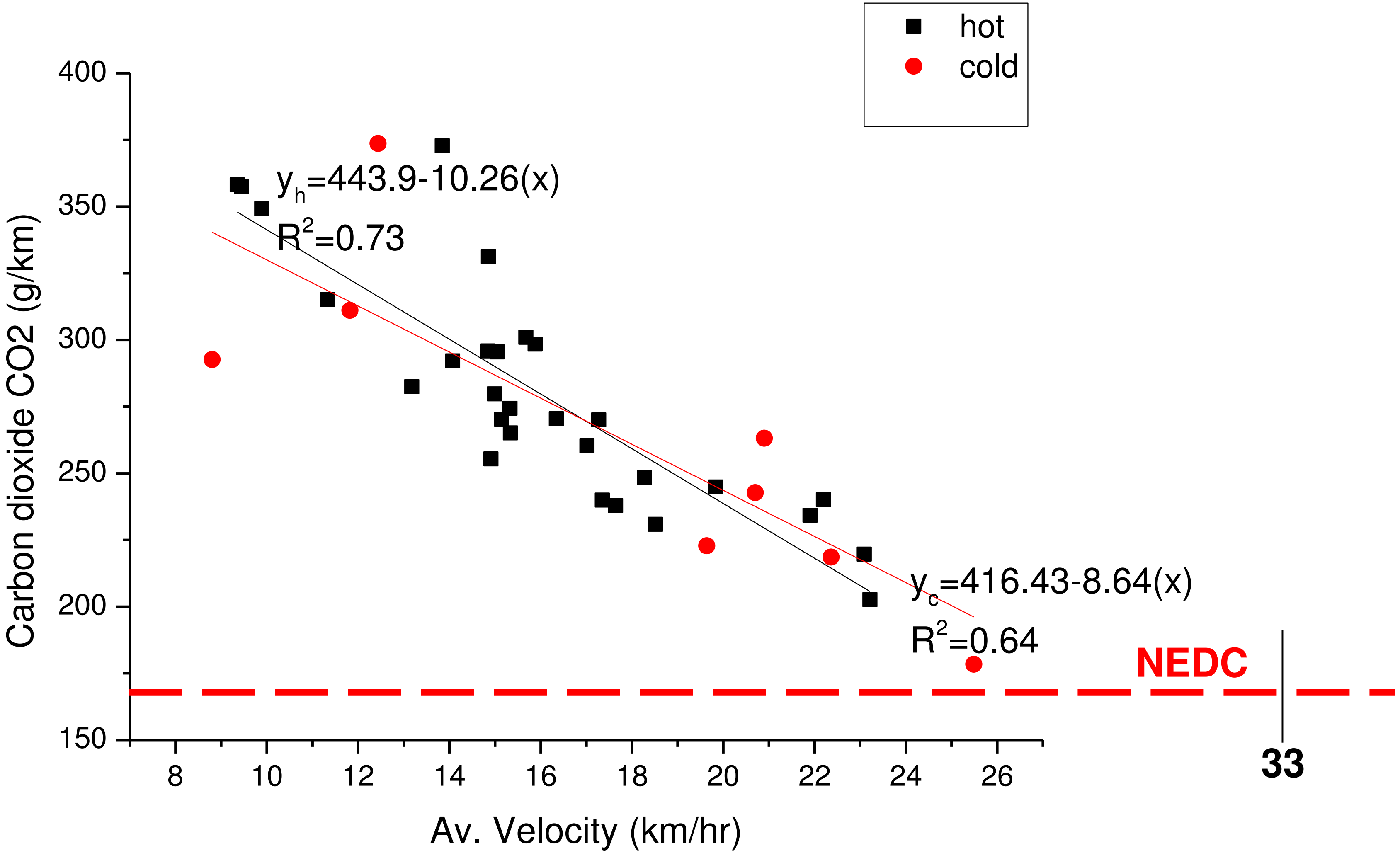
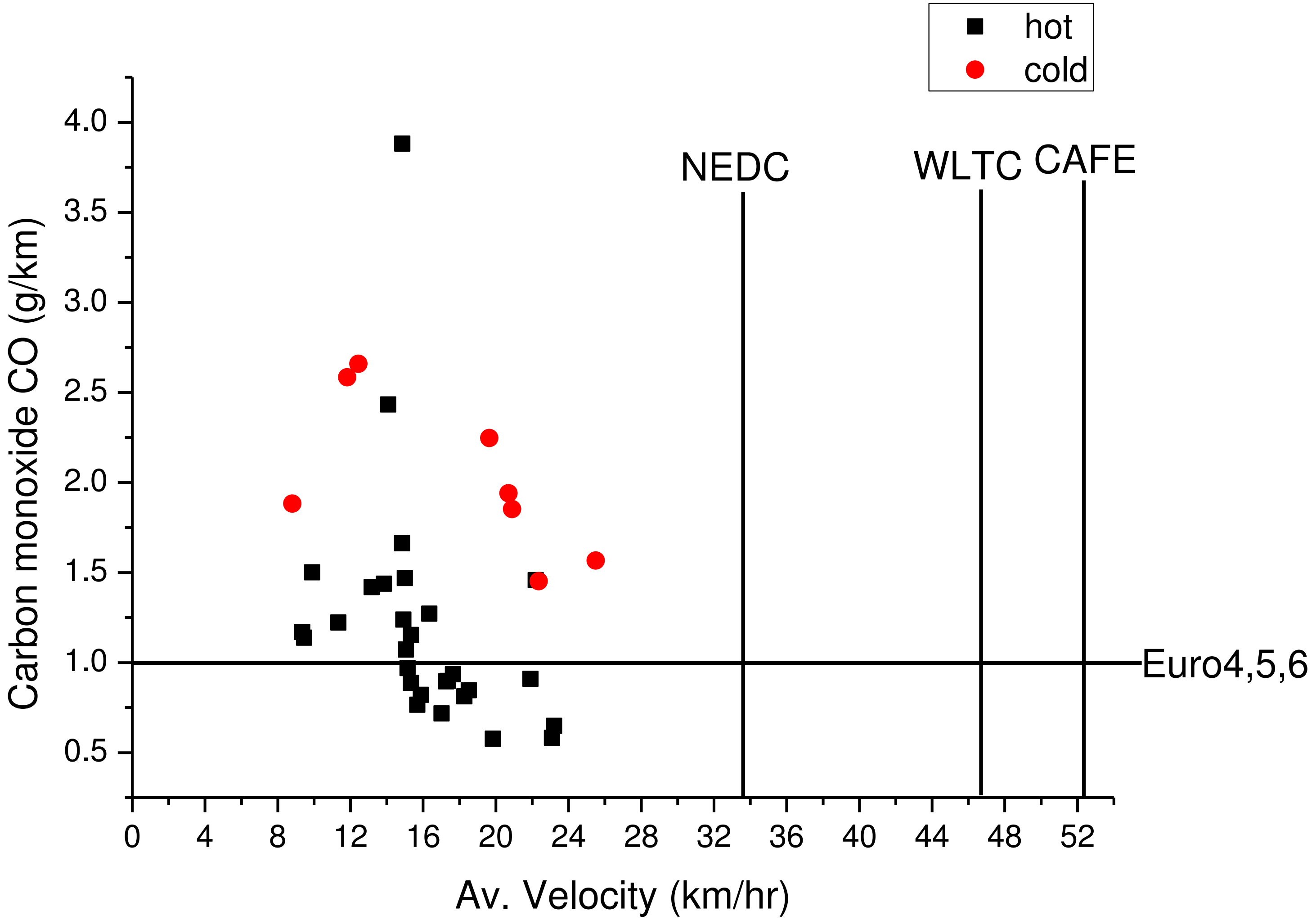
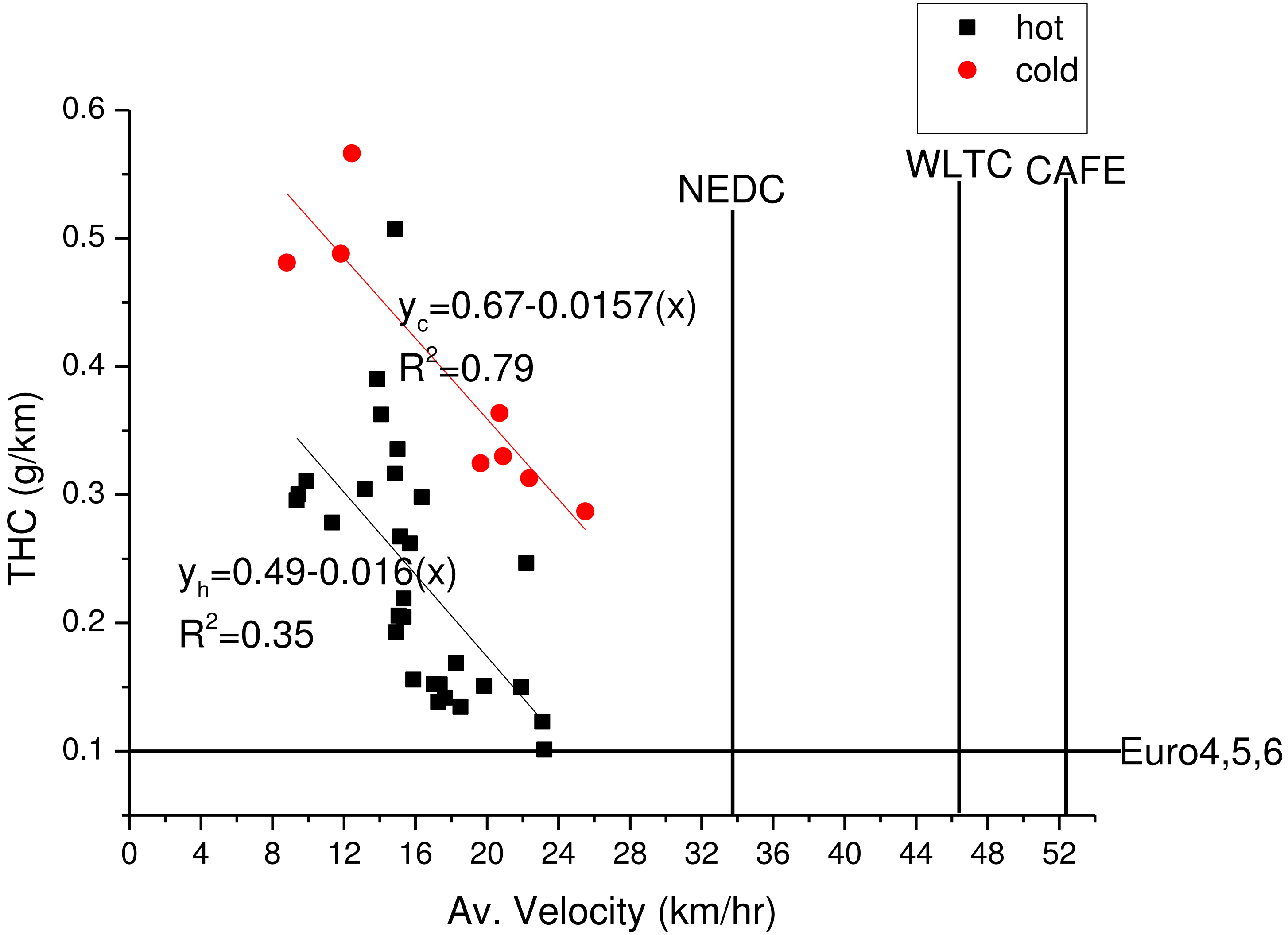
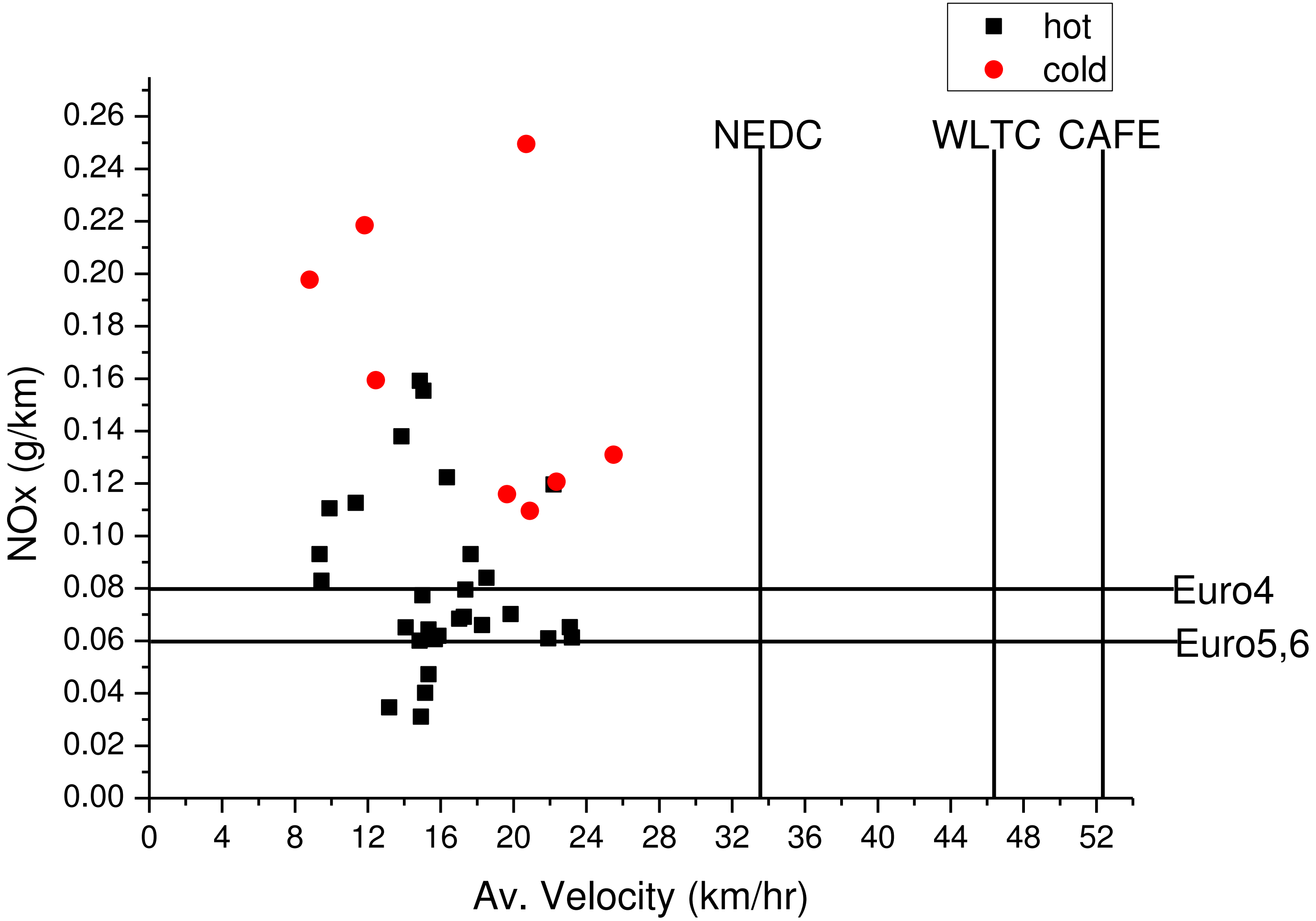
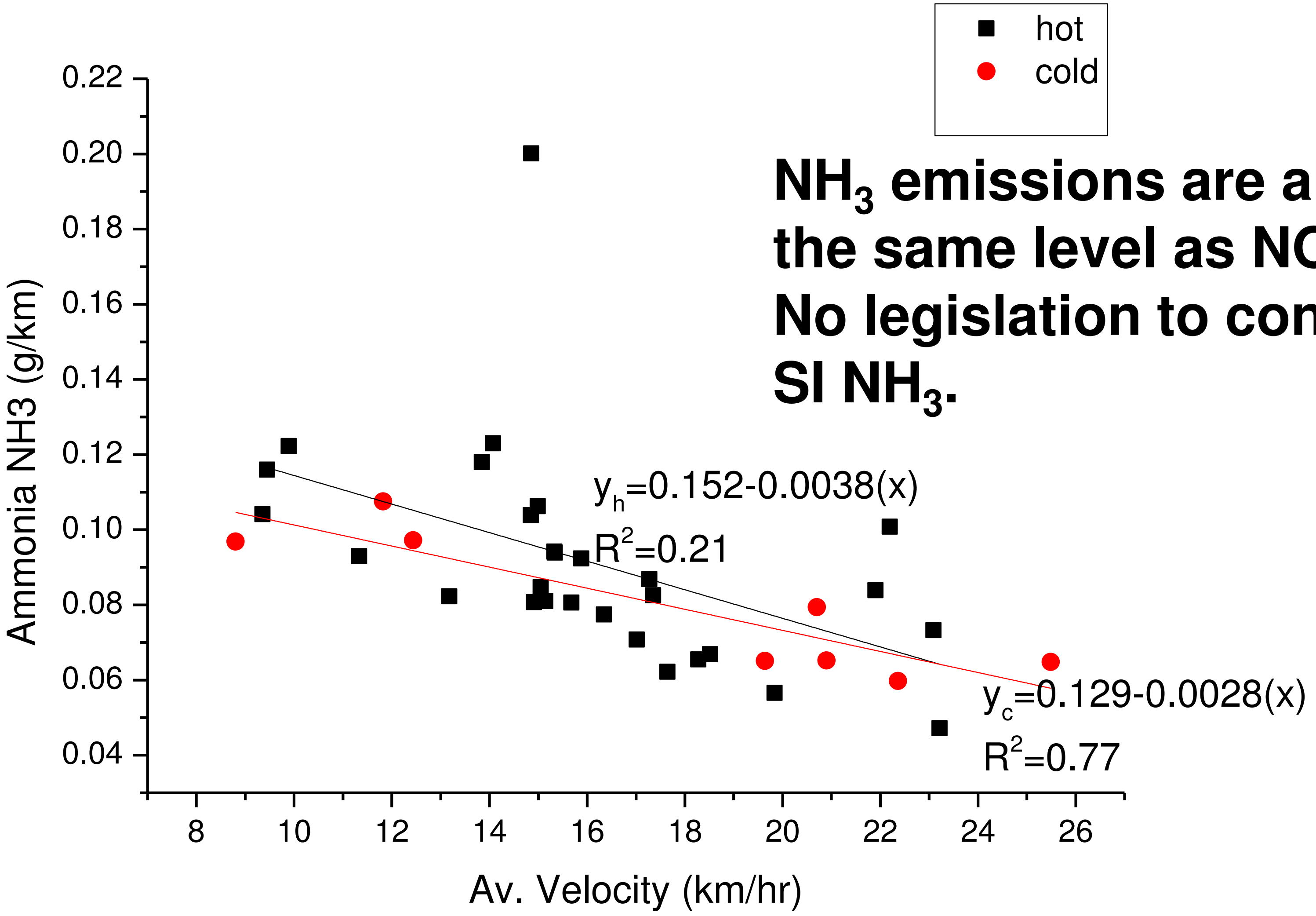

hot
cold
Carbon dioxide CO2 (g/km)
400
350
300
250
200
150
8
10
12
14
16
18
20
22
24
26
Av. Velocity (km/hr)
y_h=443.9-10.26(x)
R^2=0.73
y_c=416.43-8.64(x)
R^2=0.64
NEDC
33


■ hot
● cold
Carbon monoxide CO (g/km)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
NEDC
WLTC
CAFE
Euro4,5,6
0
4
8
12
16
20
24
28
32
36
40
44
48
52
Av. Velocity (km/hr)


hot
cold
0.6
0.5
0.4
0.3
0.2
0.1
THC (g/km)
NEDC
WLTC
CAFE
Euro4,5,6
y_c=0.67-0.0157(x)
R²=0.79
y_h=0.49-0.016(x)
R²=0.35
0
4
8
12
16
20
24
28
32
36
40
44
48
52
Av. Velocity (km/hr)


■ hot
● cold
NEDC
WLTC
CAFE
Euro4
Euro5,6
NOx (g/km)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0
4
8
12
16
20
24
28
32
36
40
44
48
52
Av. Velocity (km/hr)



NH_3 emissions are about the same level as NOx. No legislation to control SI NH_3.

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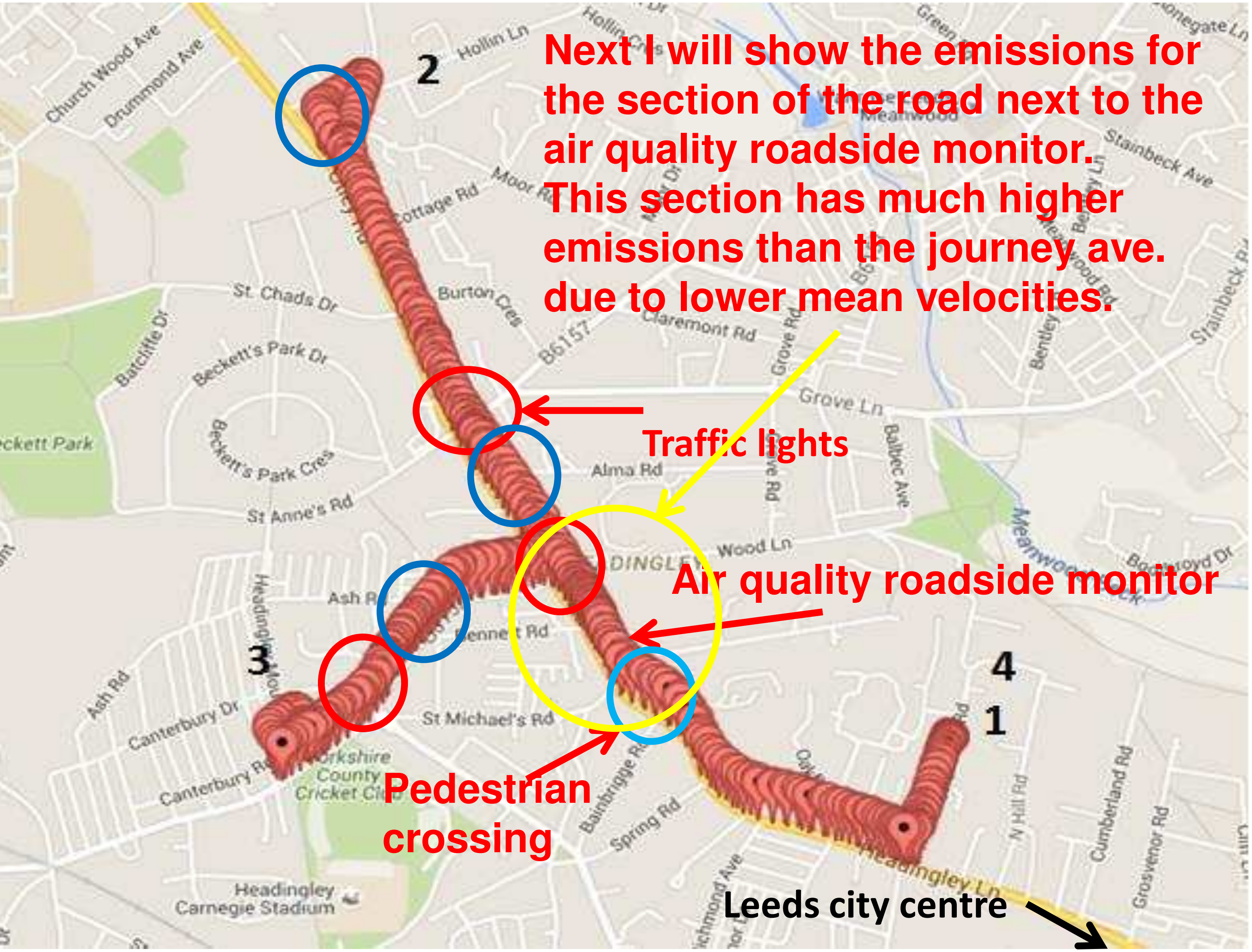
10. Individual acceleration events v. mean vel. In acc.
11. Individual constant velocity (cruise) sections of the journey
12. Conclusions



Next I will show the emissions for the section of the road next to the air quality roadside monitor. This section has much higher emissions than the journey ave. due to lower mean velocities.

Traffic lights

Air quality roadside monitor

Pedestrian crossing

Single lane traffic flow in each direction.
Peak traffic flows 1000 vehicles/hour

Each journey was a loop so outward and inward driving in the same journey.

There was a total of 20 junctions in each direction where vehicles could leave or join the main flow.

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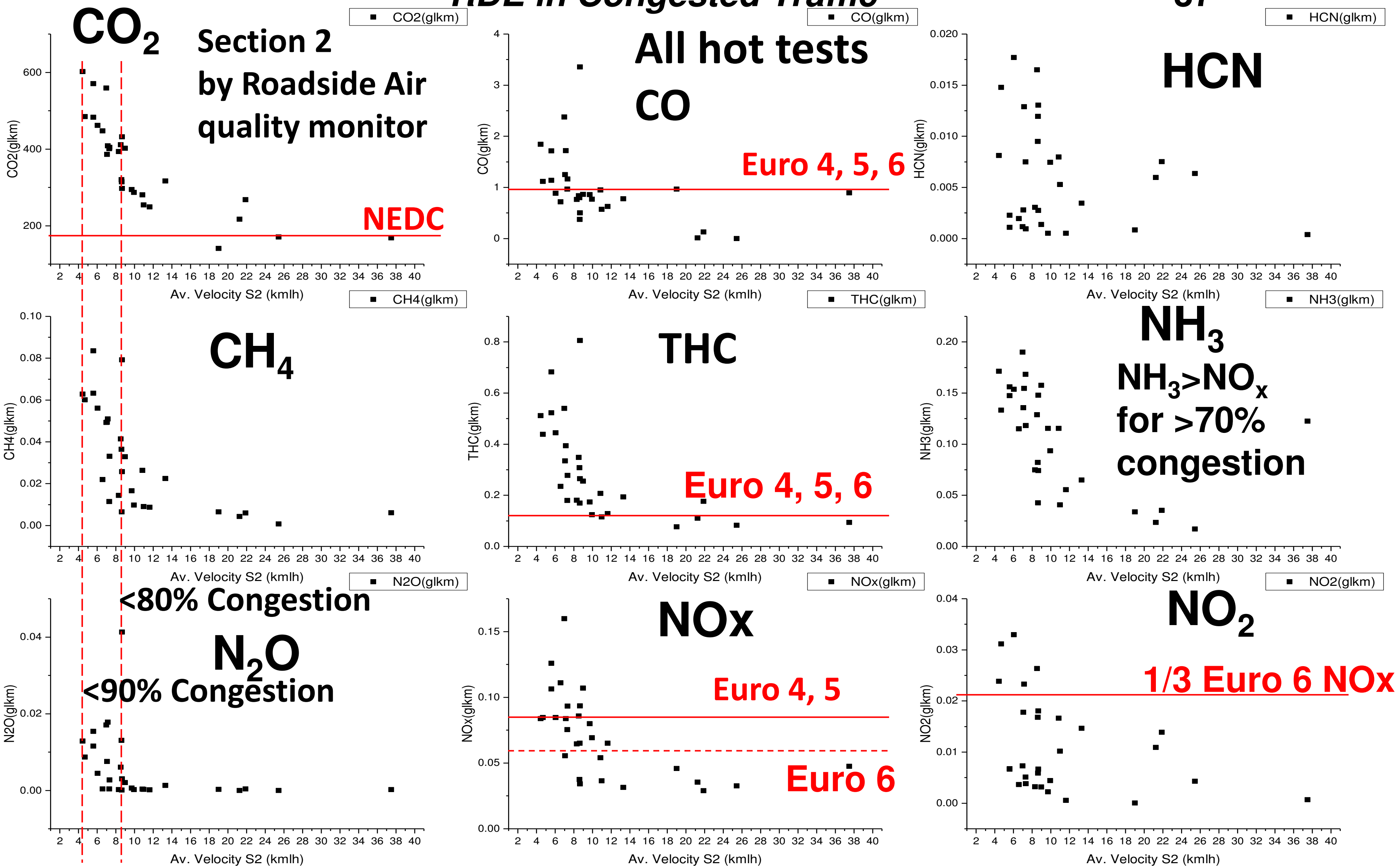
RDE in Congested Traffic



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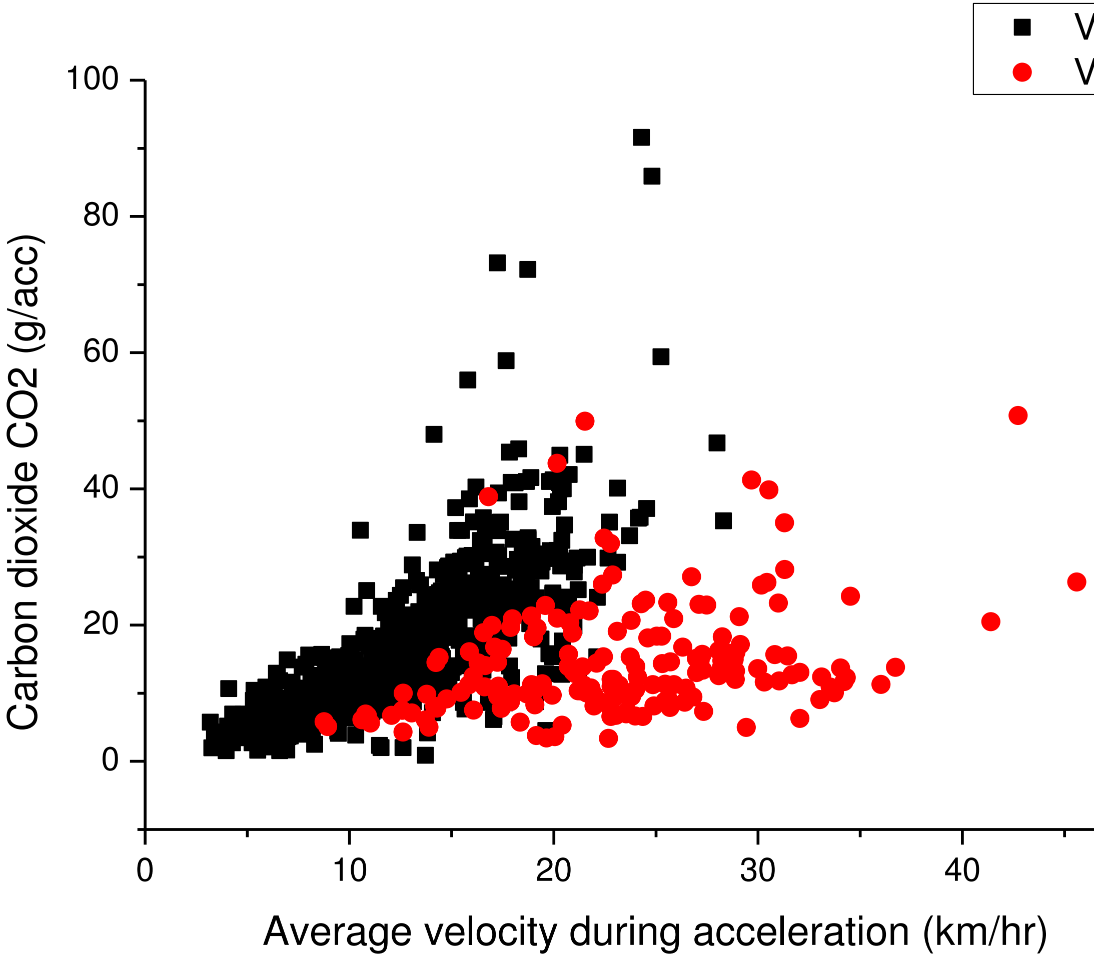
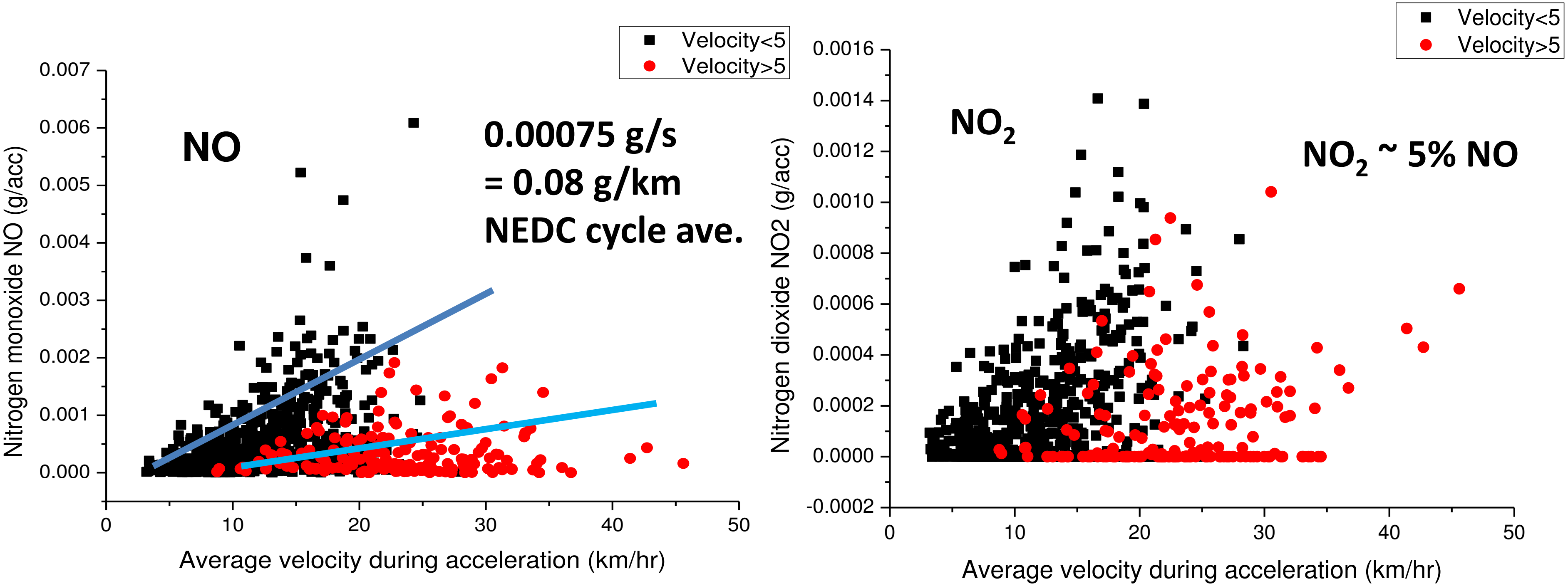


Note that 95 g/km over the NEDC is on average 0.89 g/s or ~1050 g in total.
This is 21 acceleration events From Idle.

Note that acceleration from idle uses much more fuel and emits more CO_2 than acceleration from a moving vehicle.

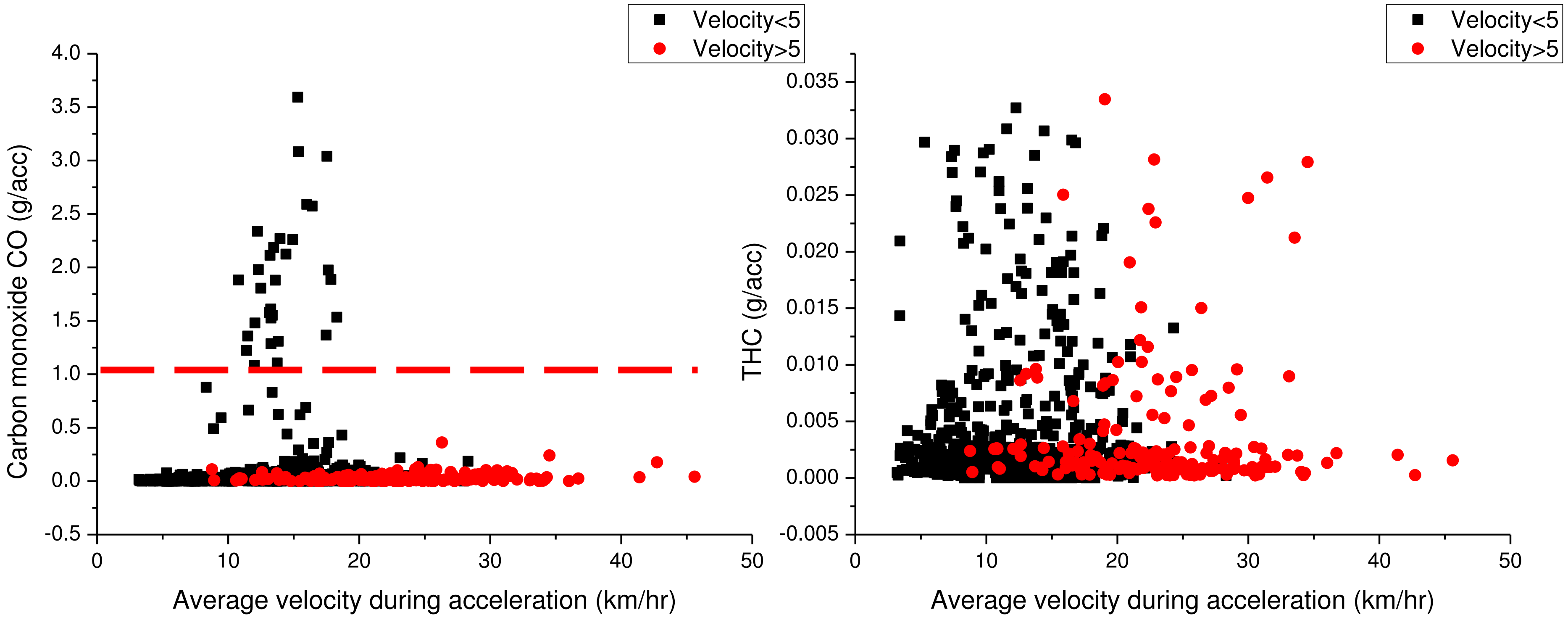


0.00075 g/s = 0.08 g/km NEDC cycle ave.

NO$_2$ ~ 5% NO

High acceleration has higher NOx emissions due to higher power used. Acceleration from idle has higher NOx due to higher power requirement. Congested traffic has a high number of acceleration events from idle. Variation in NOx emission rate for the same average velocity in the acceleration was very large ~ x10. It is possible to accelerate hard without generating large NOx emissions.

RDE in Congested Traffic



NEDC limit 1 g/km = 0.093 g/s averaged across the test cycle. X>10 of this rate has been measured In medium acceleration events.

NEDC limit g/km = 0.0093 g/s ave. most acc. are below this but some are very high THC emissions.

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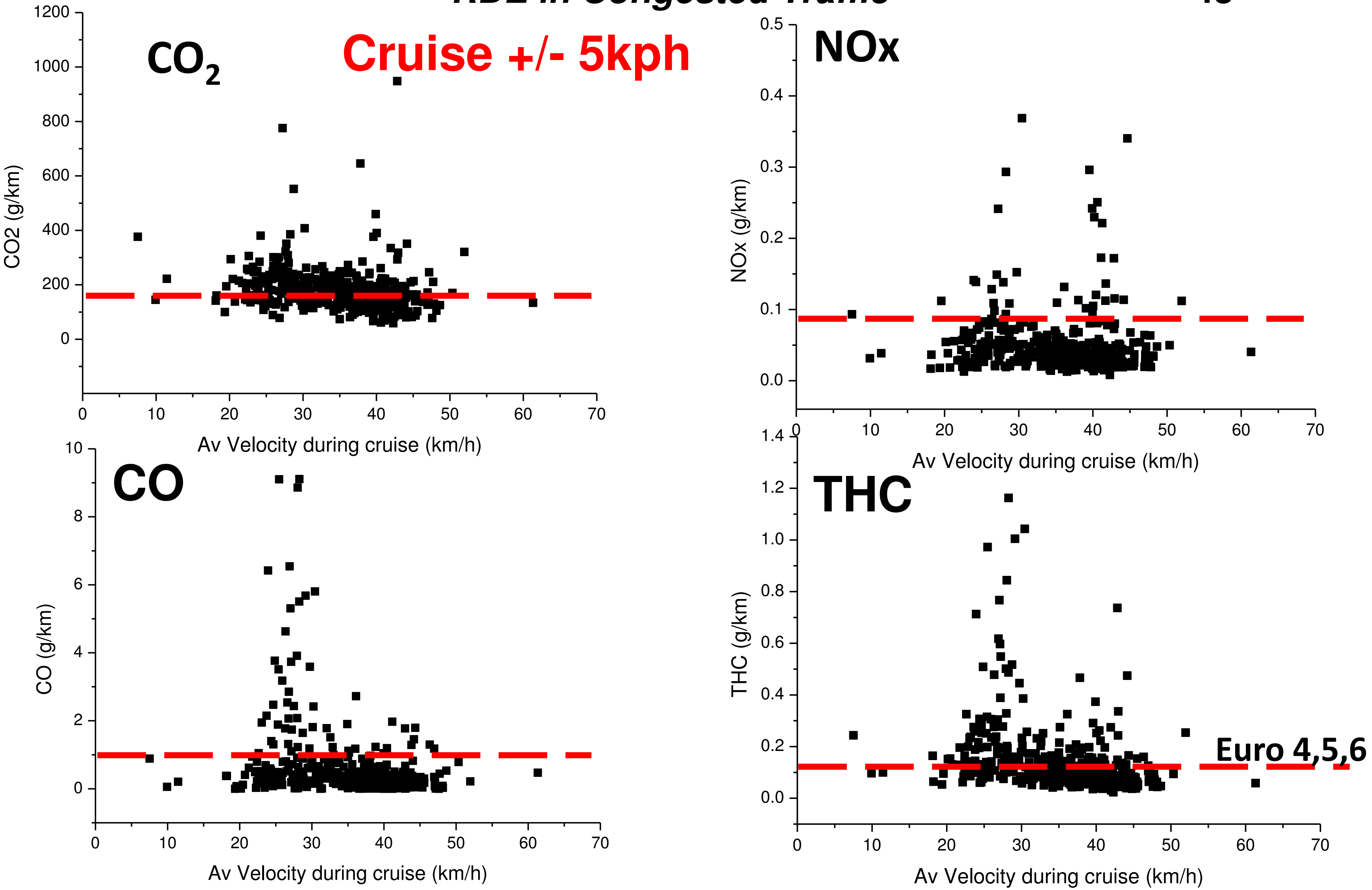
RDE in Congested Traffic

Cruise +/- 5kph



Cruise emissions at nominal constant velocity (cruise) scatter around the values for the NEDC.

Cruise criteria is constant velocity at +/- 5kph for >8s

CO_2 has much of the data above the NEDC value

NOx and CO and mainly below the NEDC limit

THC mainly above the NEDC limit.

It may be that the +/- 5 kph is too large for the constant velocity assumption to be valid.

However, the wide variation in nominal constant velocity in a journey with no trend in emissions may indicate that the short duration cruise emissions are influenced by the preceding acceleration or deceleration

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Conclusions

1. Air quality exceedances in cities occur at local roadside mesurements stations.
2. Existing test cycles have low levels of congested driving and the WLTC and proposed RDE have even lower congestion than the NEDC
3. In congested traffic for diesels the lower temperature can cause the catalyst not to work. This is very significant for Urea SRC where the low average speed gives low temperatures and low activity of the NOx removal.
4. Congested traffic has a high number of accelerations from Idle and these stop/start event cause pollution.
5. In congested traffic emissions may be x ~10 of the limit.

Acknowledgements

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