Conference or Workshop Item:
Andrews, GE, Li, H, Hadavi, AS et al. (2015) RDE in Congested Traffic with Cold Start. In: 3rd International Conference Real Driving Emissions, 27-29 Oct 2015, Berlin, Germany.

RDE in Congested Traffic with Cold Start

Gordon E. Andrews, Hu Li, Basil Dahim, Ali S. Hadavi, Demitrios Savvidis, Ahmad Khalfan, Buland Dizayi and Alison S. Tomlin

Energy Research Institute

School of Chemical and Process Engineering

University of Leeds, Leeds, LS2 9JT, UK.

<profgeandrews@hotmail.com>

3rd International Conference on Real Driving Emissions 2015, 27 – 29 October 2015, Berlin, Germany

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Real Driving Emissions (RDE)

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 on the cold start issue as part of the RDE emissions problem.

Whether VW have ‘cheated’ and made the RDE worse than they would otherwise be 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.

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

Light-Duty Initiatives

Real-Driving Emissions (RDE)

Numerous reports have shown that in-use emissions from cars can be much higher than would be indicated by certification testing. For example more than half of the 14 Euro 6 diesel cars tested with SCR (selective catalytic reduction), LNT (lean NOx trap), or EGR (exhaust gas recirculation) systems had NOx emissions >6X higher than certified (2). Two cars, each with LNT or SCR systems, came in at ~25X higher than certified. In another study (3), of three such vehicles tested, the best (urea-SCR) was 3-4X higher, and the highest (EGR; and LNT+urea-SCR) were 5-7X the certified level in PEMS (portable emissions measurement system) testing. Even US Tier 3 light-duty diesel can show high in-use emissions (4), wherein two cars with either an LNT or SCR emitted 4-20X the Bin 5 allowable NOx, depending on route. Most SCR emissions were in the range of 10X. However, a third SCR vehicle had in-use emissions similar to the certification, demonstrating the feasibility of doing such. The investigators think engine calibrations, not additional hardware, can solve the problem of excessive NOx emissions.

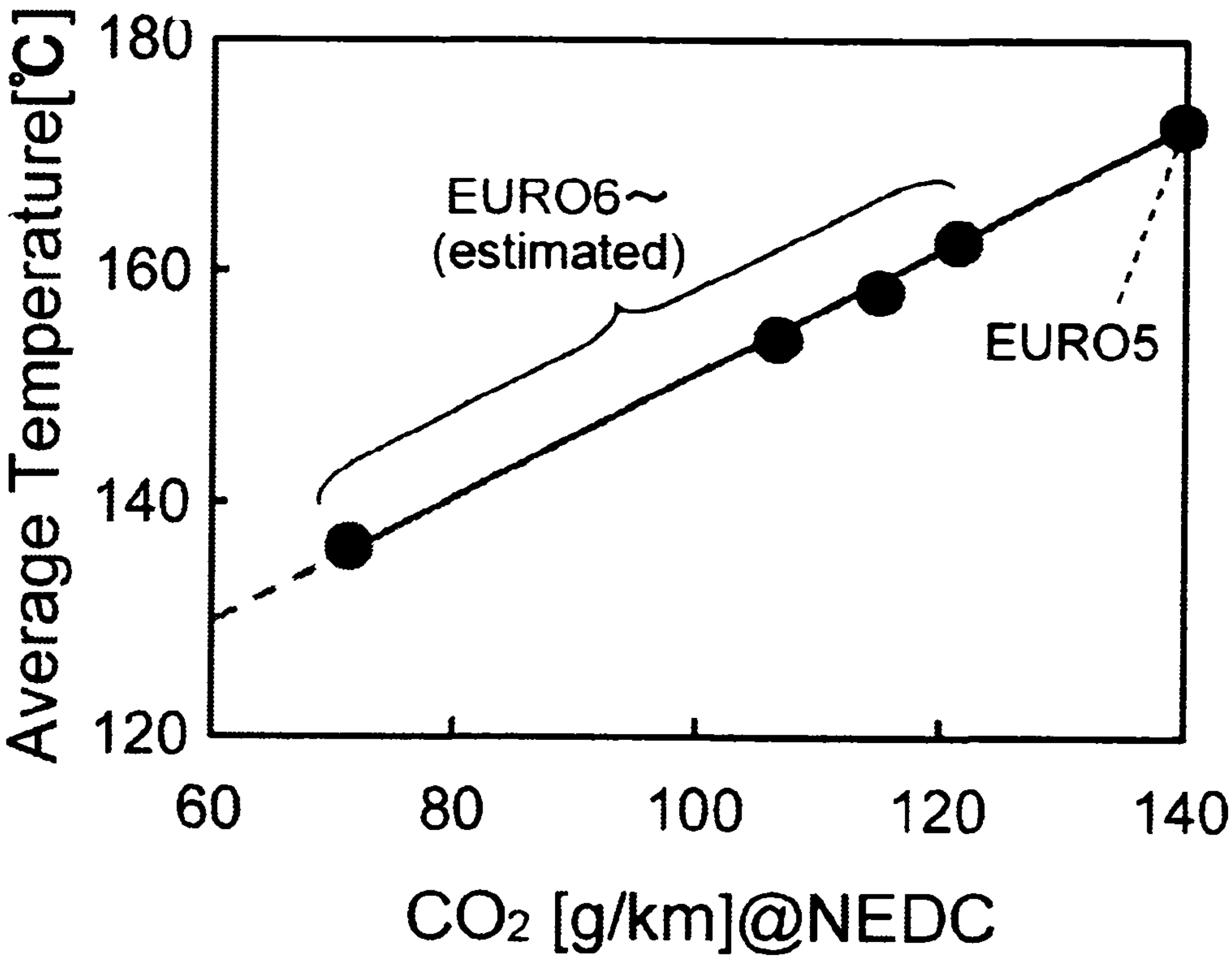
2. Mock, P and Franco, V. BOSMAL, 4th Int. Exhaust Emissions Symp. May 22, 2014. www.TheICCT.org
3. May, J. et al. Paper F2014-CET-058, 2014 FISITA Maastricht.
4. Thompson, G.J. et al. In use emission testing of LD Diesel vehicles in the US Int. Council on Clean Transportation www.TheICCT.org

This is the publication that suddenly made RDE a hot political issue – their findings were not new or published in a refereed publication!

Real Driving Emissions (RDE)
My research group on RDE at Leeds University have 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 RD and higher acceleration rates and more stop/starts.

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.
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.



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

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.
4. Traffic lights and road junctions
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.

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8. Cold start RDE for a HDD Euro 5
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1. Driver behaviour

This is probably the single most important factor in RDE – the test cycle is designed to eliminate the high variability in human drivers. Indeed for best test repeatability robot drivers are used.

In Leeds some years ago we carried out a 20 driver variability over a simply real world real traffic driving loop.

The drivers were instructed to obey the legal speed limit of 48kph maximum speed.

There were 3 sets of traffic lights at the junctions on this loop. Each driver drove 10 laps of the loop and the first was discarded from the data.

There was no cold start.

Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK

Driver behaviour Euro 1 TWC vehicle study 2004

	NEDC Euro 1	Max		Mean (20 drivers)		
		High	Low	High	Low	Ave.
CO_2 (g/km)	194	425	284	339	235	288
CO (g/km)	2.7	28.1	0.72	10.68	0.274	1.974
NO_X (g/km)	0.42	1.662	0.434	0.800	0.271	0.532
HC (g/km)	0.55	0.357	0.070	0.1998	0.055	0.108
Speed (km/h)	33.6	38.6	29.1	34.9	24.6	30.4
Acceleration (m/s^2)	1.06 Max	1.815	0.636	1.235	0.441	0.763
Deceleration (m/s^2)	-1.39 Max	-1.056	-0.274	-1.427	-0.575	-0.923
Throttle Position (%)		22.0	4.2	11.5	2.5	5.4
Positive Jerk (%/s)		26.9	7.17	21.93	3.83	7.21
Negative Jerk (%/s)		-7.86	-1.28	-18.03	-3.54	-8.81

Daham, B., Li, H., Andrews, G.E., Tate, J., Ropkins, K. and Margaret C Bell. 'Driver Variability Influences on Real World Emissions at a Road Junction using a PEMS'. **SAE Paper 2010-01-1072**, 2010. Also in SAE SP-2289 'Engine Emissions Measurement and Testing, 2010', p. 195-222. ISBN 978-0-7680-3424-0.

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

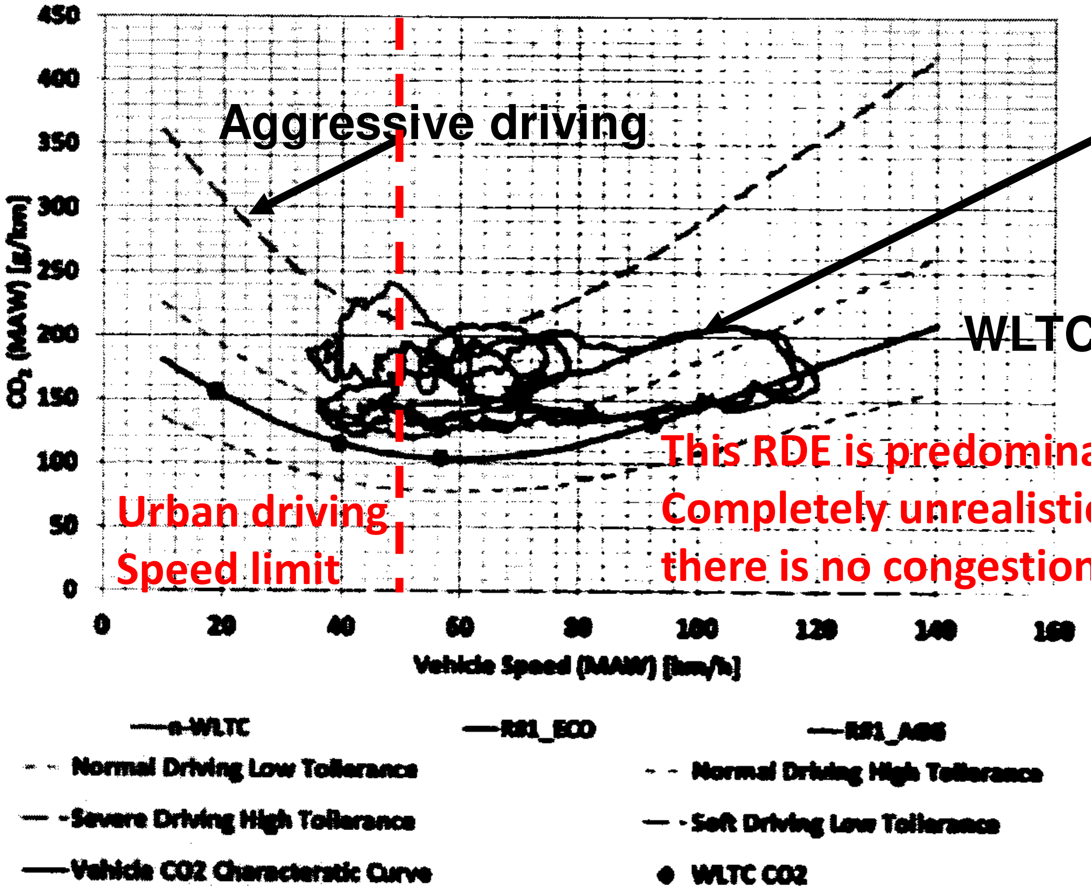

Figure 1. Representation of the Moving Average Window (MAW) approach to determining applicability of PEMS data from in-use emissions. Solid lines represent test data. Dashed lines represent two levels of tolerance or acceptability of the data. (8)

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

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2. Ambient Temperature

This is related to cold start effects as a cold start is defined in the NEDC as 25°C and this rarely occurs in the UK in RDE.

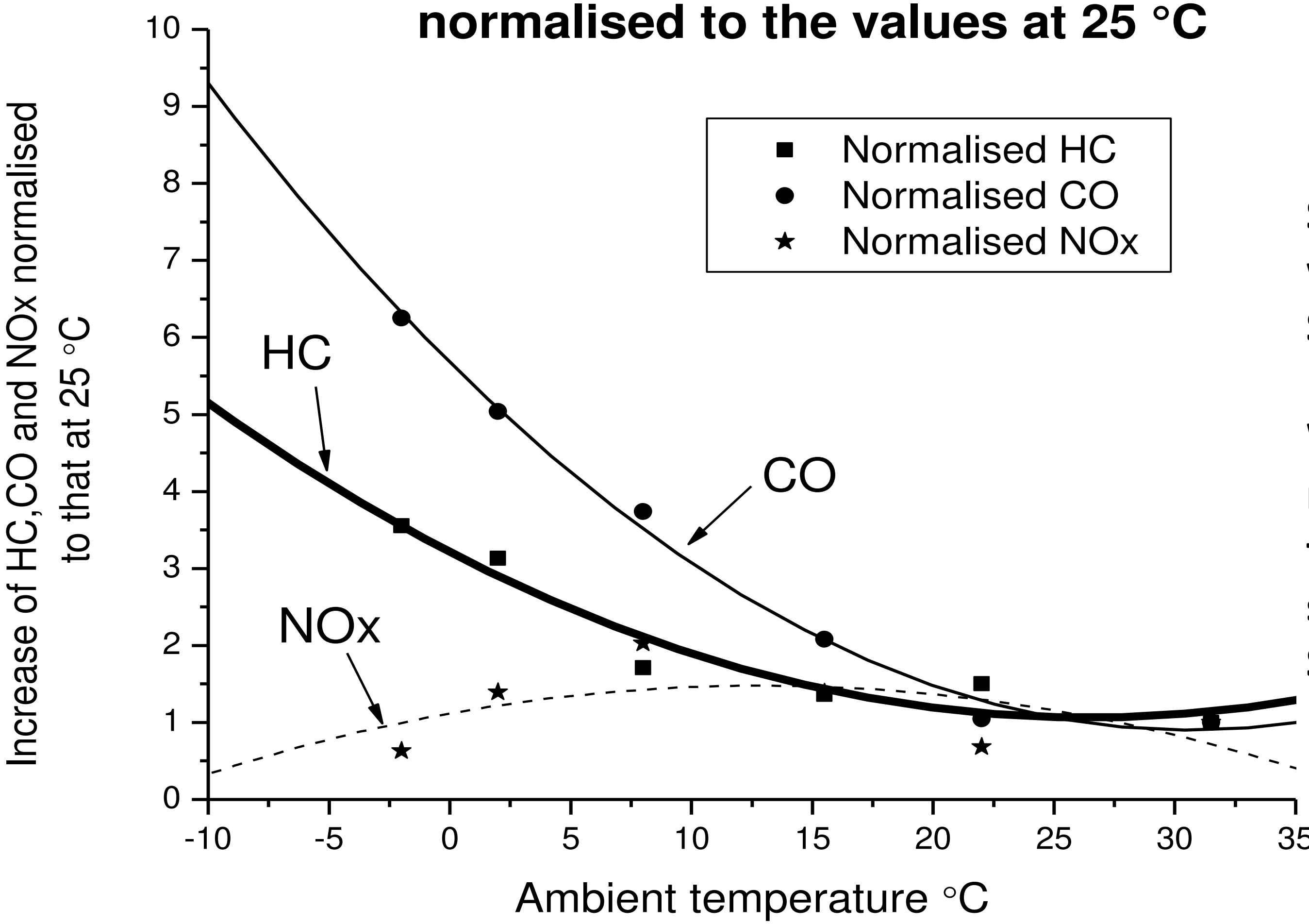
As a consequence the TWC light of time increases and the water and lube oil takes longer to warm up, which increases the fuel consumption and CO_2 emissions.

With diesels using deNOx catalysts and oxidation catalysts there will be a similar performance problem at temperatures <25°C, which is all part of the cold start effect.

The Leeds work was carried out in winter on days of different temperatures using the same RD loop with four left hand turns.

Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK

Fig.30 Relative increase of HC,CO and NOx normalised to the values at 25 °C



RDE with cold start
Euro 1
Simple loop driving with little traffic. Similar to NEDC Urban.

We also had similar results for congested traffic on a busy single lane road. SAE Paper 2005-01-1617

SAE 2004-01-2903

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3. Congested traffic in urban driving

low average speed
and more stop/starts – influence of other drivers.

Congestion is normally defined as:

Congestion = 1 – (Ave. Speed / legal speed limit)

The legal limit in urban driving is 48 kph for in the UK.

The average speed on the NEDC is 33.6 kph and is an average congestion of 30%. For the urban part only of the NEDC the average speed is 17.2 kph and congestion is 64% which is more reasonable. However, in our work congestion levels up to 80% have been observed and 95% in the worst congested parts of the route. Emissions are much higher than in the NEDC.

The new WLTP is little improvement as the average speed is too high, which is the main reason why it has been found to give lower emissions than on the NEDC for many vehicles.

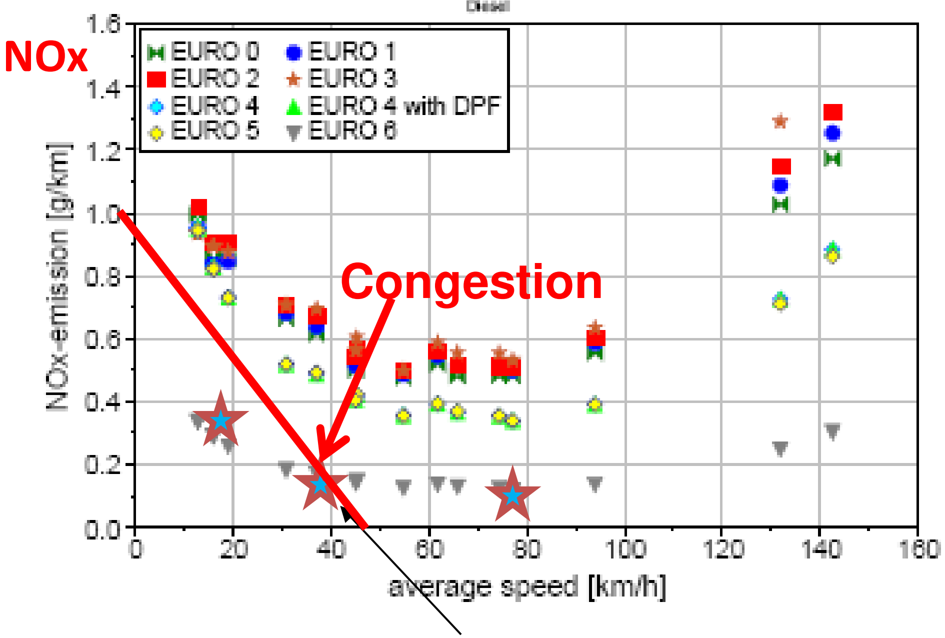
Features of congested roads:

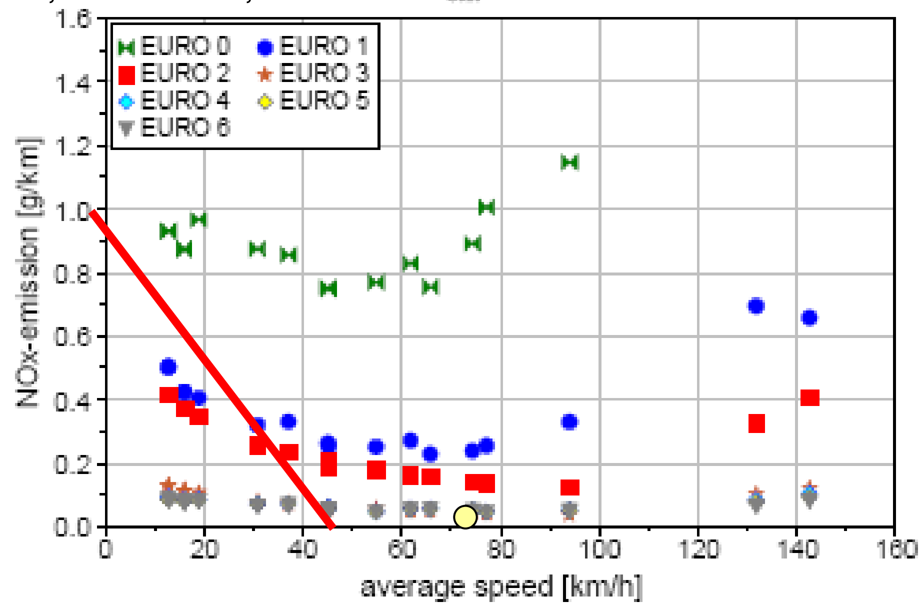
1. A high traffic flow
2. Frequent junctions on the route with traffic joining and leaving the main flow. Main flow stops to let in vehicles from the right or left, at the discretion of the drivers in the main flow. Each car joining causes main traffic to halt.
3. Traffic lights at major junctions and pedestrian crossings. All traffic now halts periodically. For high traffic flows it can take several stop/starts to get through. The process of starting and moving about 10m is very energy intensive with high emissions.
4. Traffic joining and leaving flows that can be comparable with the main flow.
5. Traffic mean velocity decreases as congestion increases.

Dr. Klaus-Dieter Schmidt, Head Engine Dev. FPT Moterenforschung AG Arbon, Switzerland.

Presentation on 'Technology of HD Euro VI Truck Engines & Future Trends Towards Improved Fuel Economy'. Leeds University CPD Diesel Particulates and NOx Emissions, May 2014.

Pkw **Diesel** Quelle: TU Graz, HBEFA 3, FPT Pkw **SI Petrol**





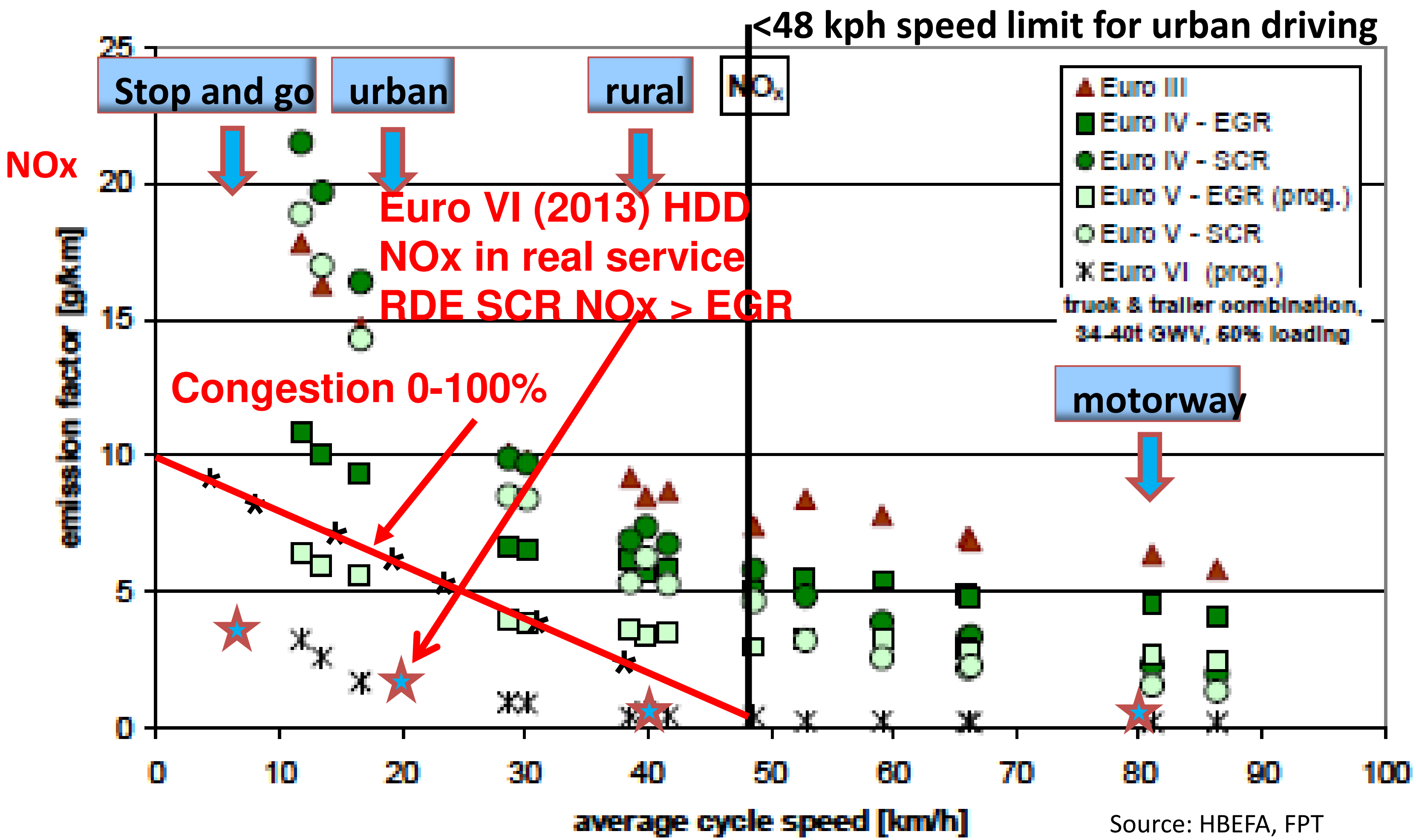
Euro VI NOx in real service

Euro VI Truck 40t

- One Euro VI truck emitts about the same NOx in g/km as one singe Euro 5/6 passenger car

Emissions increase at low speed in proportion to congestion for diesels and at a lower rate for SI vehicles. Euro 5 and 6 diesel more emissions with congestion

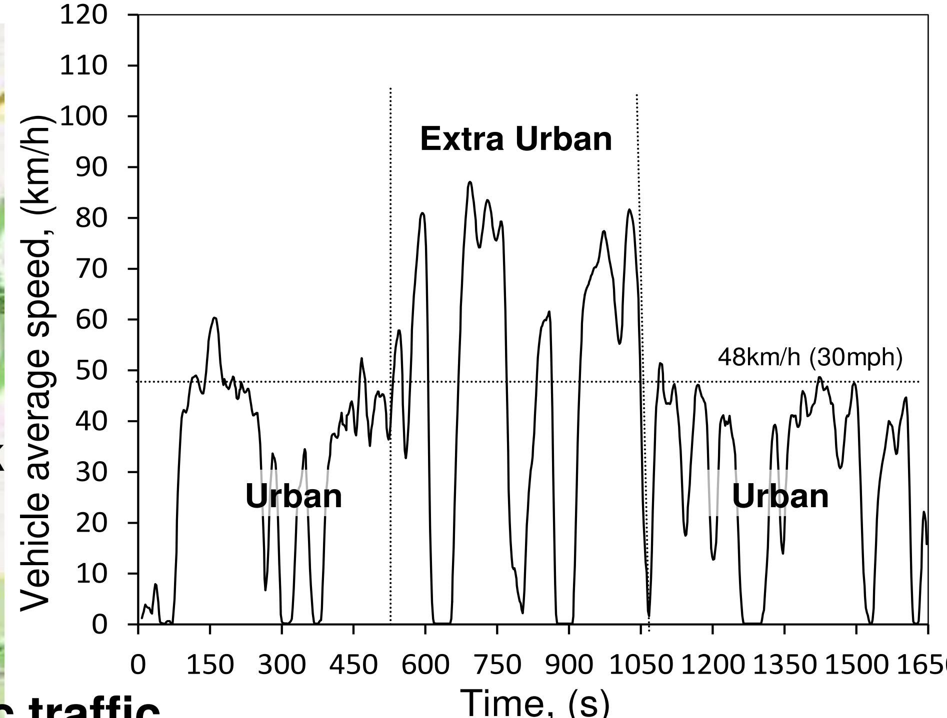
Lower speed = more congestion = more NOx pollution



Source: HBEFA, FPT

Dr. Klaus-Dieter Schmidt, Head of Engine Dev., FPT Moterenforschung AG Arbon, Switzerland. Presentation on 'Technology of HD Euro VI Truck Engines & Future Trends Towards Improved Fuel Economy'. Leeds University CPD Diesel Particulates and NOx Emissions, May 2014.

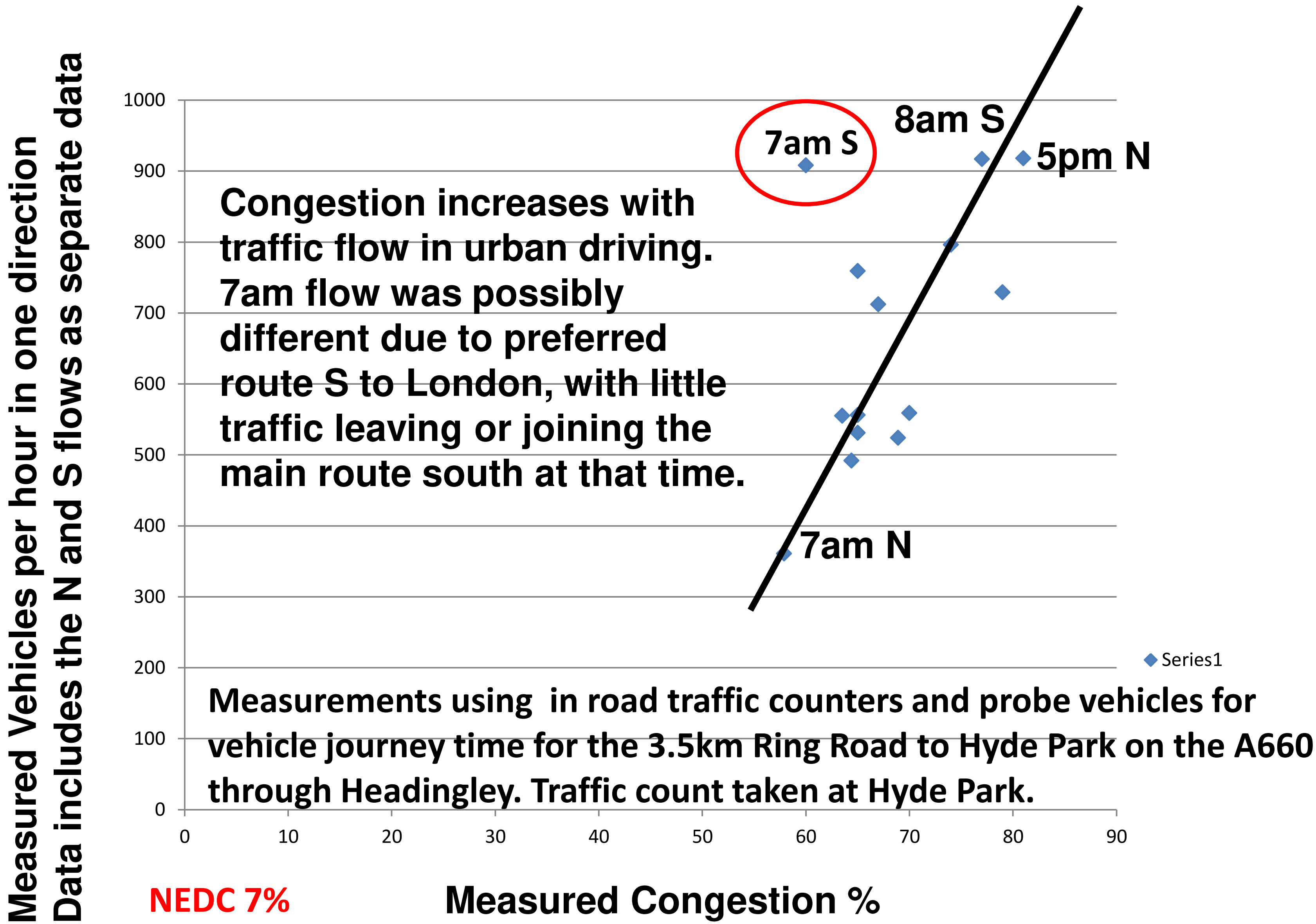
As part of a public enquiry over a trolley bus along the A660 traffic flow data have been measured between Ring Road and Hyde Park a distance of 3.5 km.

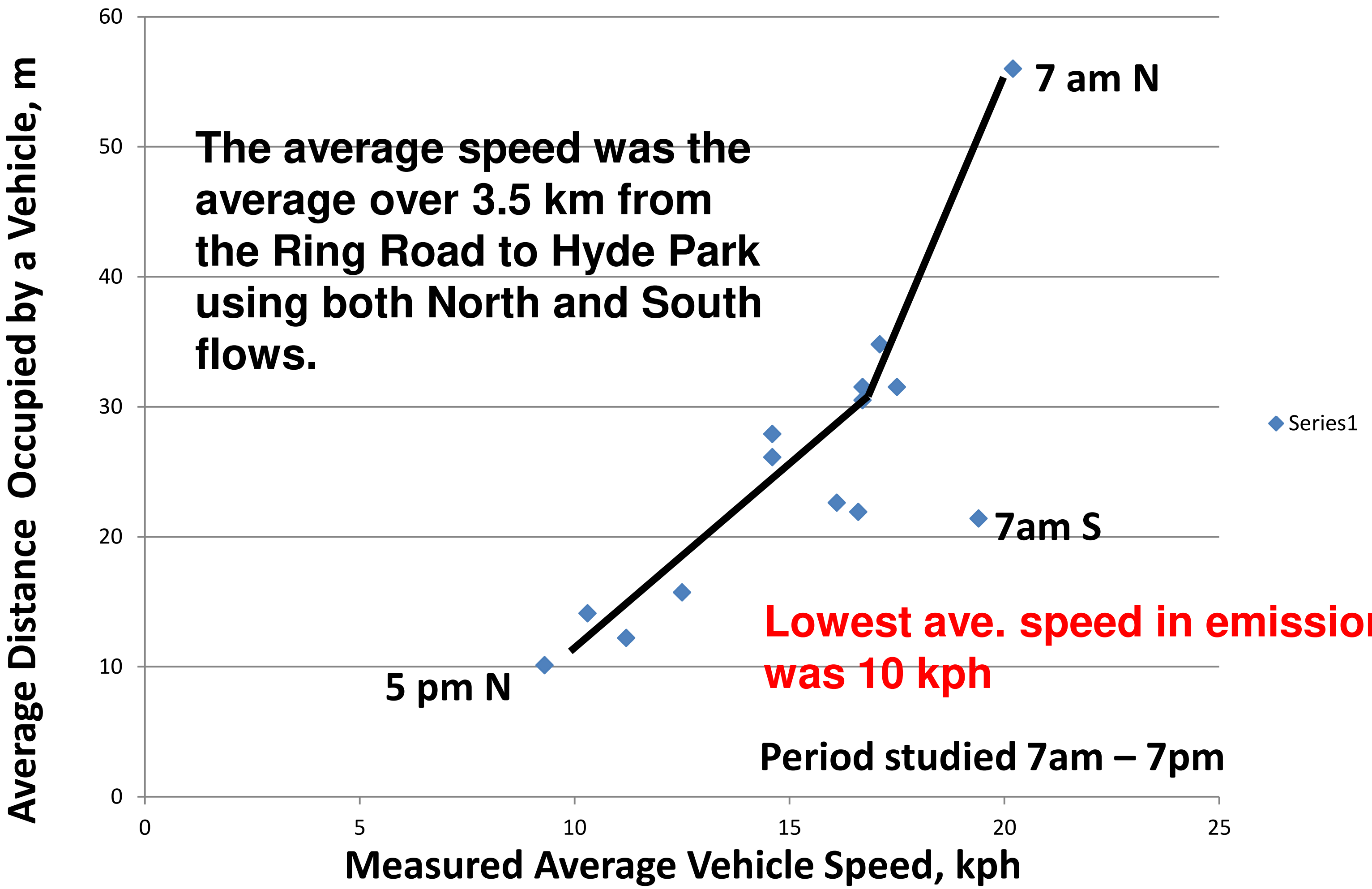


Typical midday light traffic

Leeds City Centre

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


Measured Vehicles per hour in one direction
Data includes the N and S flows as separate data
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
7am S
8am S
5pm N
7am N
Series1
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.
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.
NEDC 7%
Measured Congestion %



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.

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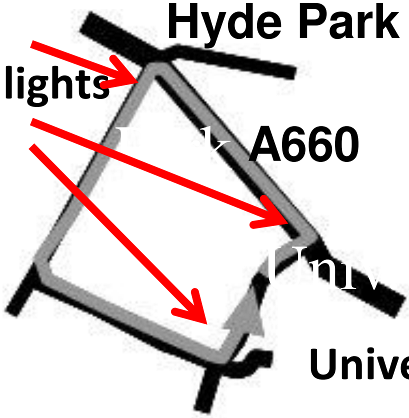
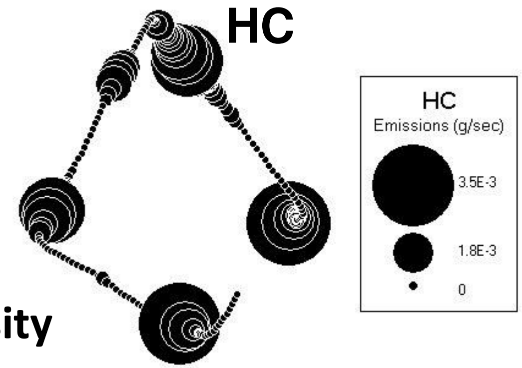
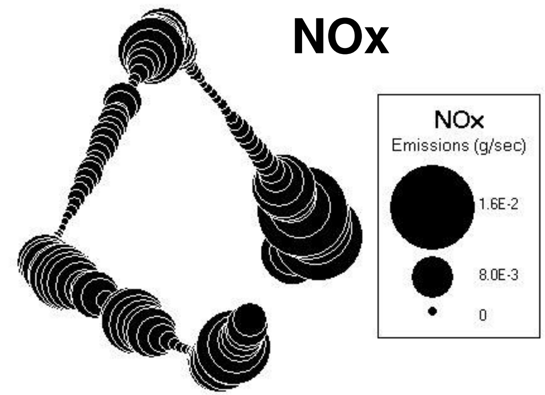
Example of emissions mapping using Horiba OBS g/s in a Ford Mondeo Euro 1 For Euro II – VI with lower emissions there are no significant emissions other than at junctions, so the effect of junctions is greater.



HC

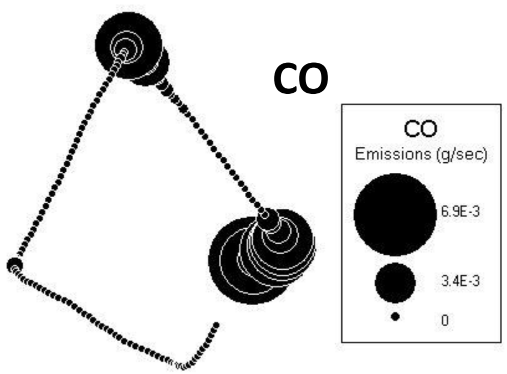


NOx

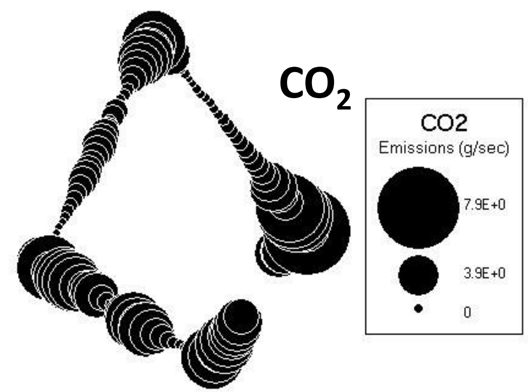


Pollution and CO_2 is predominantly at junctions for Euro 2 and increasingly so for Euro 4+

CO



CO_2



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

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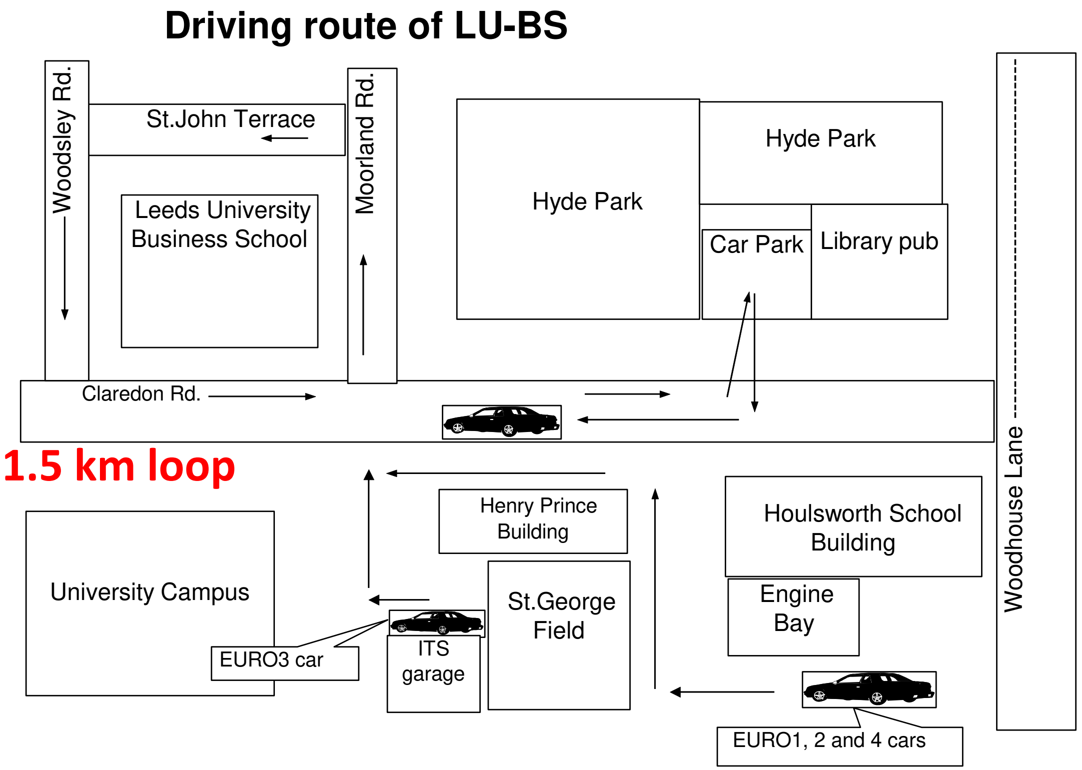
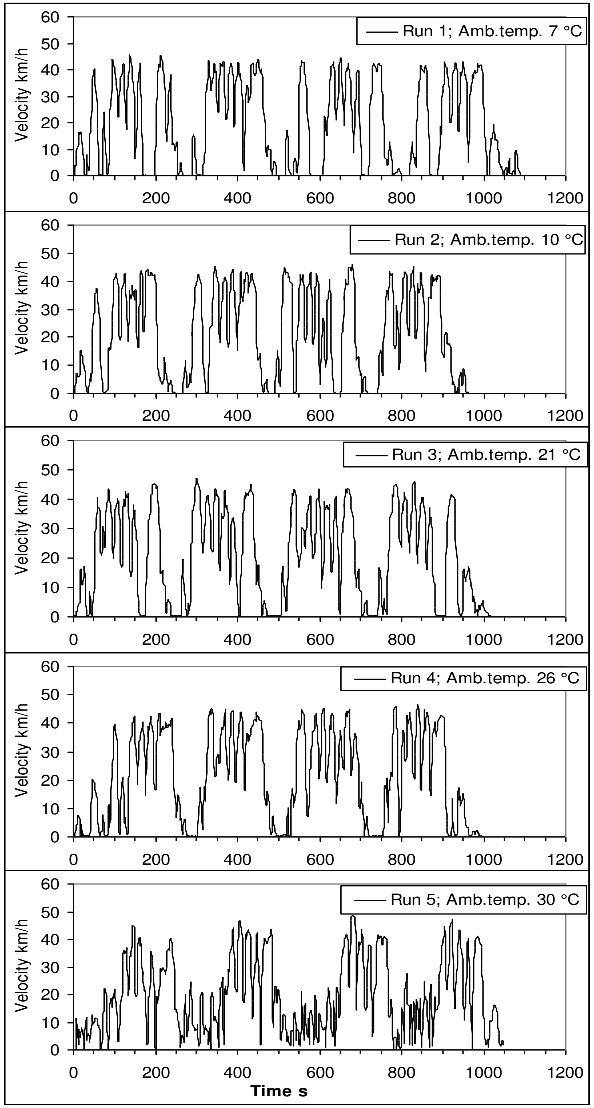
Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK

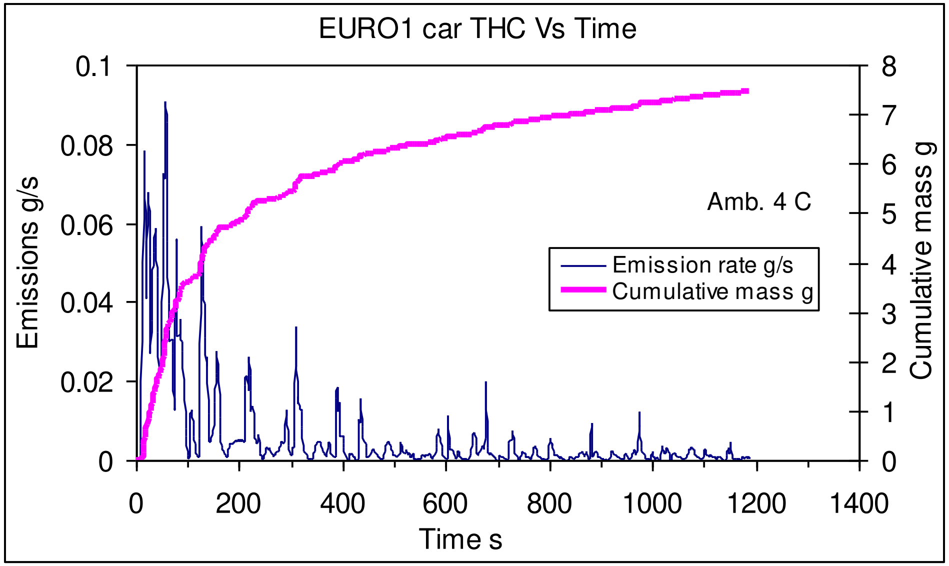
RDE in Congested Traffic with Cold Start

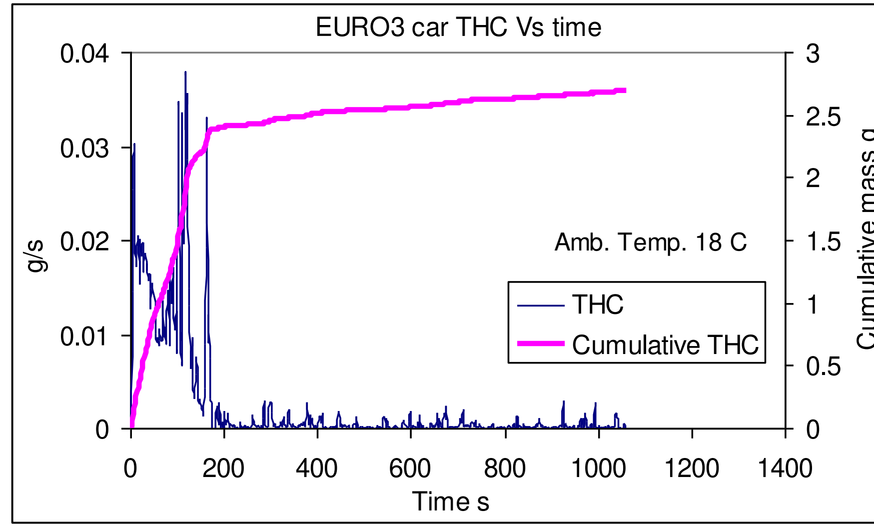


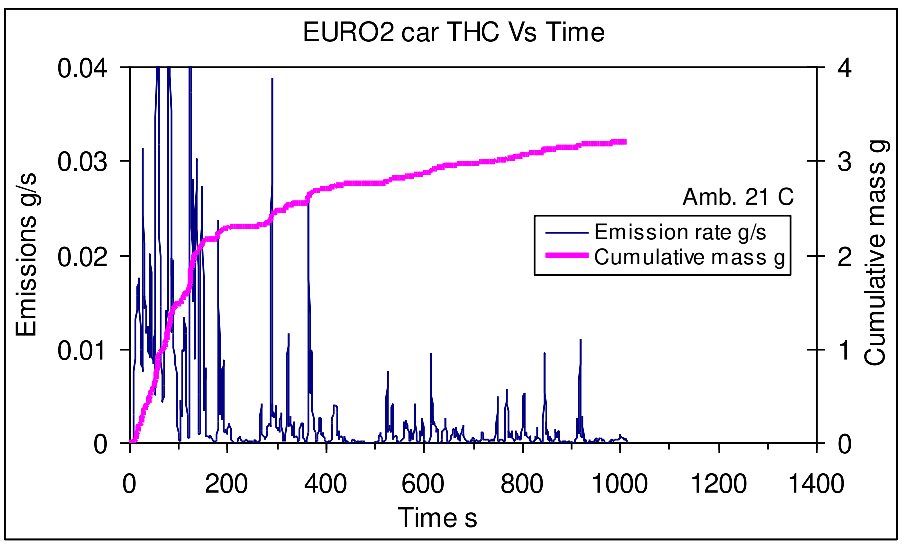


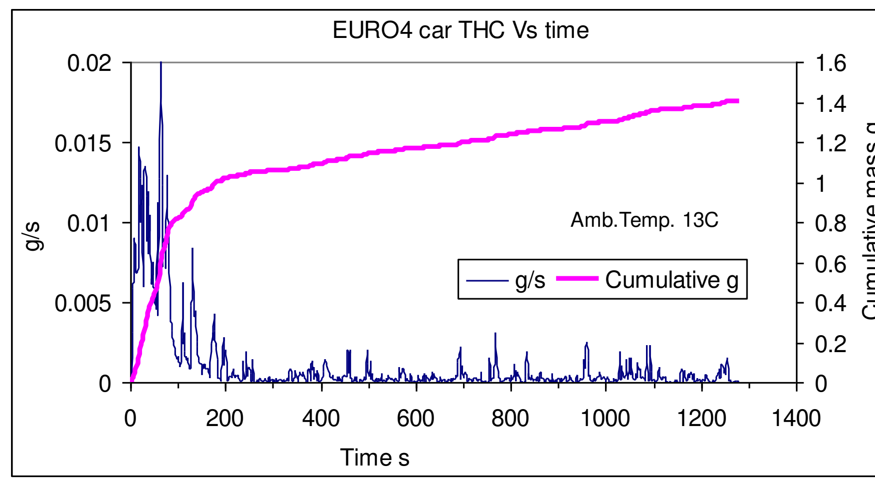
This is a simple loop real driving with cold start and was designed to be similar to the NEDC urban part. 5 repeat journeys are shown, which demonstrate the differences caused by different traffic conditions for the same driver. Four loops were driven as in the NEDC urban driving procedures.

Comparison of Euro 1-4 Vehicles for Urban Driving Real World THC Emissions with Cold Start



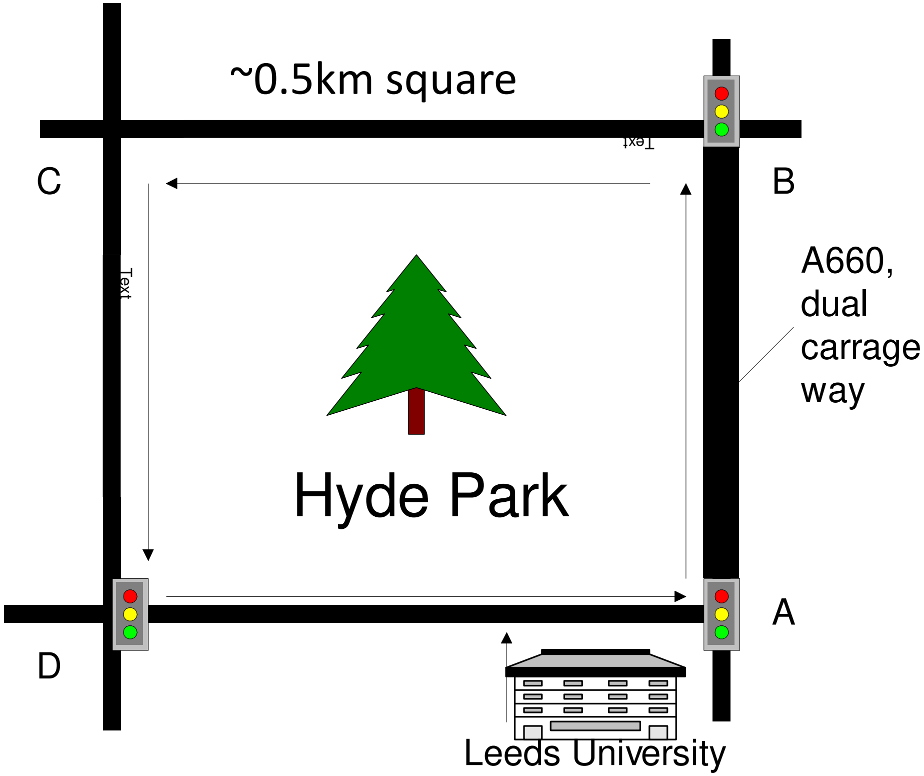






SAE Paper 2008-01-0754

HPL real world cold start driving route in Leeds



Cold start at Junction A

The junctions A, B and D have a set of pedestrian lights. This loop was used for the cold start tests. HPL-A refers to loop ADCBA and HP:=B refers to loop ABCDA

The HPL was a 1.96 km loop circuit, located in a busy residential area linked with major roads. AB was a dual carriage way on which the traffic Speed can be up to ~60 km/h and there are fewer traffic interferences. The other three sides were two-way single carriageways with more traffic variation and interferences. The legal speed limit on all the roads was 48 km/hr (30 mph). The present work was for legal driving only.

SAE 2012 – 01-0880

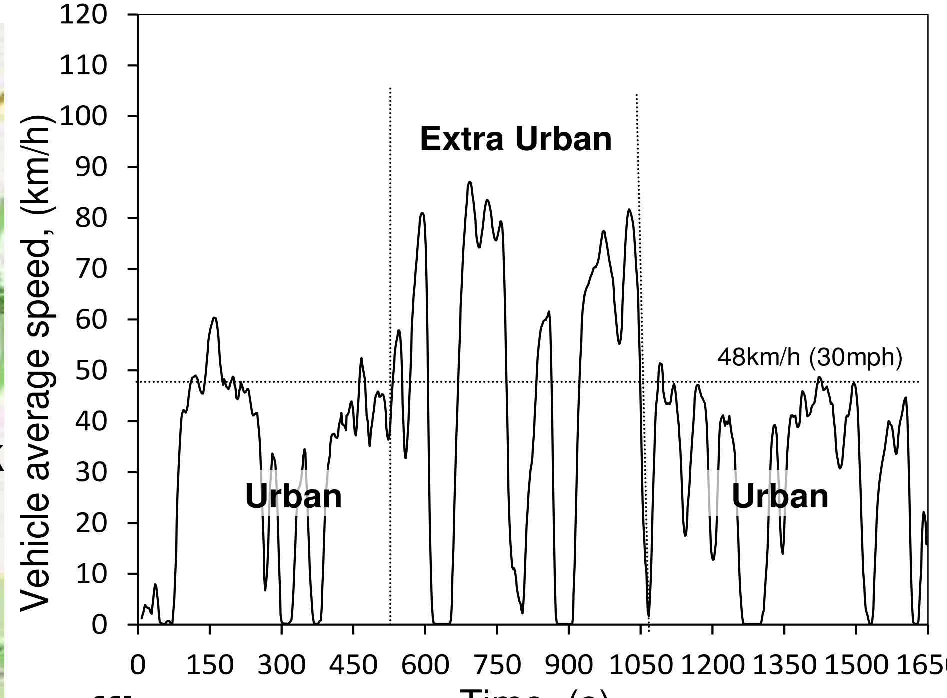
Average emissions for 4 HPLA loops – SI For Mondeo $\lambda=1$

	Euro 1	Euro 2	Euro 3	Euro 4	RDE E4 X NEDC
CO g/km HPLA	7.2	5.9	2.1	3.4	3.4
LUBS*				3.9	3.9
Euro	2.7	2.2	2.3	1.0	
HC g/km HPLA	0.7	0.58	0.49	0.29	2.9
LUBS*				0.35	3.5
Euro	0.55	0.29	0.2	0.1	
NOx g/km HPLA	1.1	0.51	0.44	0.15	1.9
LUBS*				0.14	1.8
Euro	0.42	0.21	0.15	0.08	

* SAE 2008-01-1307

A660 Single lane public traffic + Bus lane to Shaw Lane

Leeds City Centre



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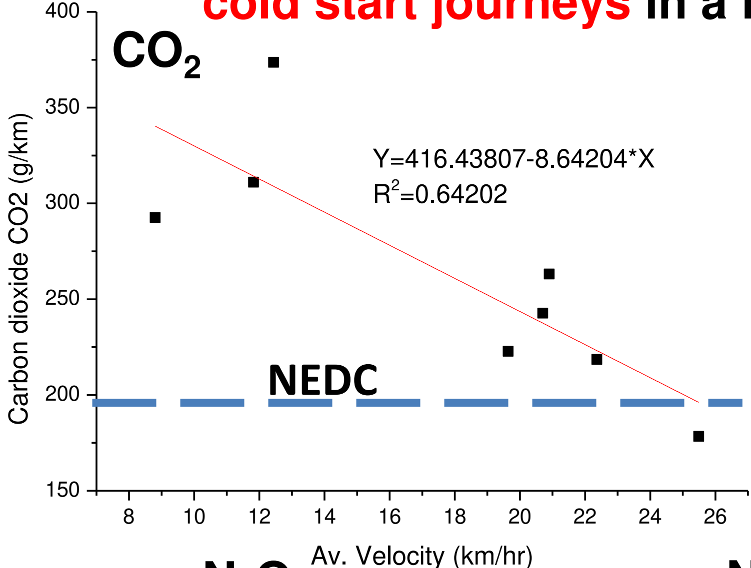
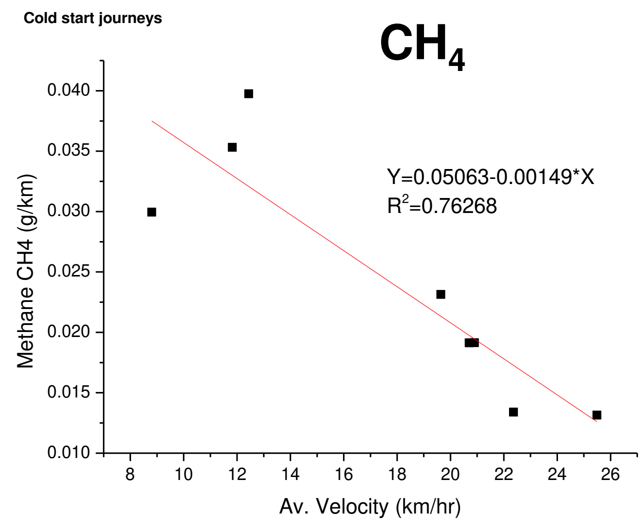
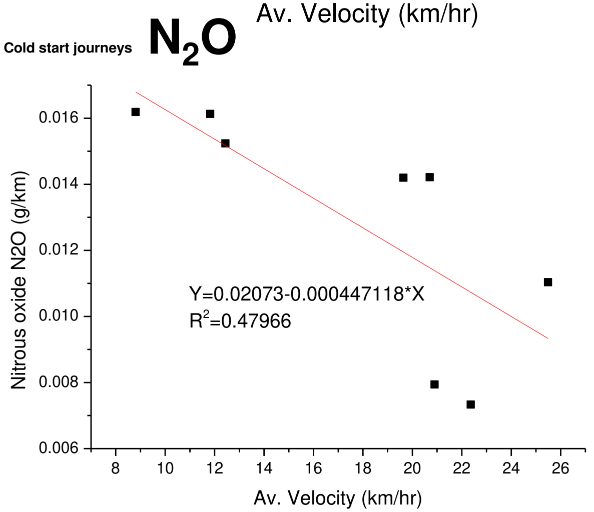
Influence of congestion on GHG emissions – CO_2. CH_4, N_2O for cold start journeys in a Euro 4 Ford Mondeo.







Note that the average speed is low due to congestion not due to steady state slow speed driving. High emissions at low speed are due to high congestion.

Khalfan, A., Li, H., and Andrews, G., "Cold Start SI Passenger Car Emissions from Real World Urban Congested Traffic," SAE Technical Paper 2015-01-1064, 2015, doi:10.4271/2015-01-1064.

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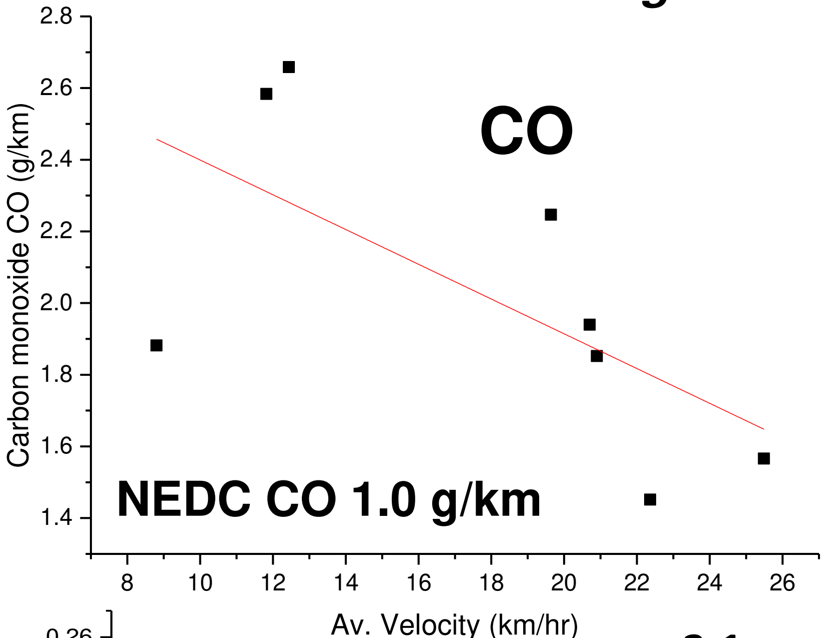
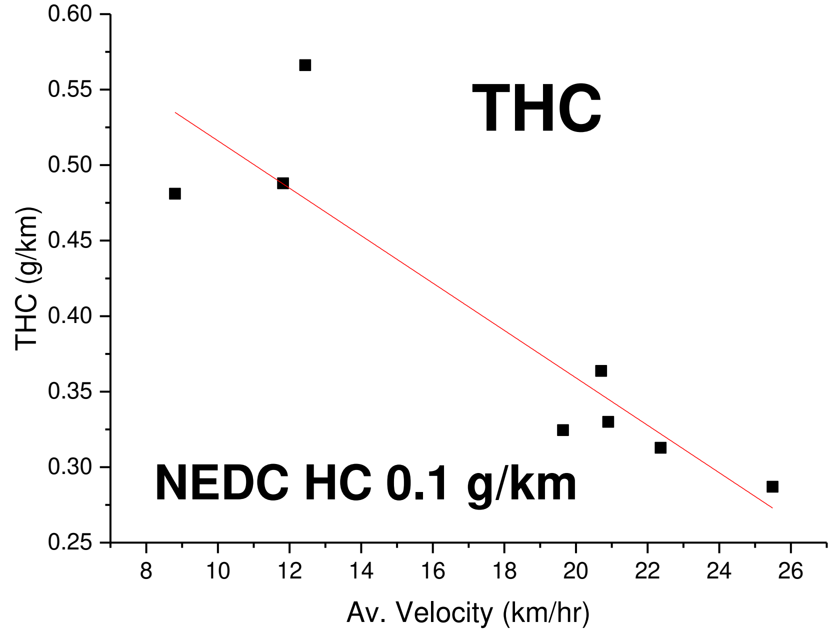
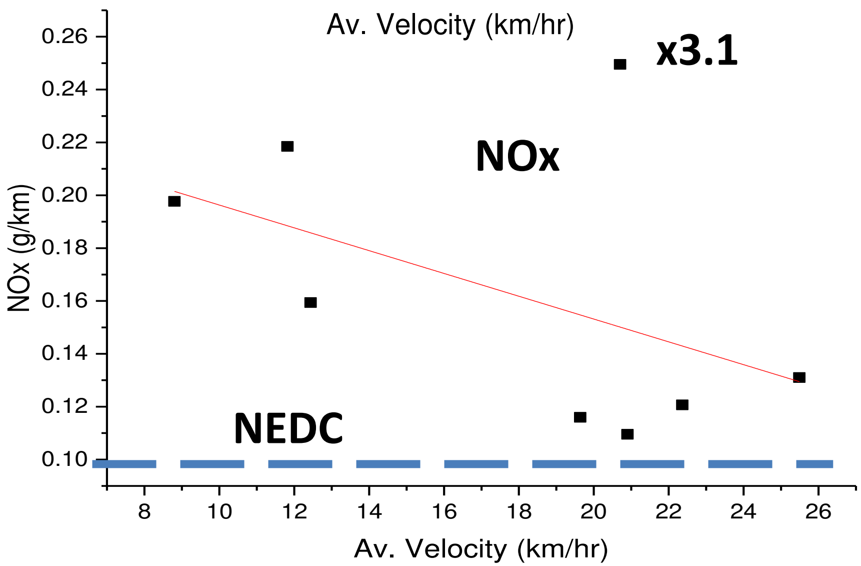
School of Chemical and Process Engineering, University of Leeds, UK

RDE in Congested Traffic with Cold Start





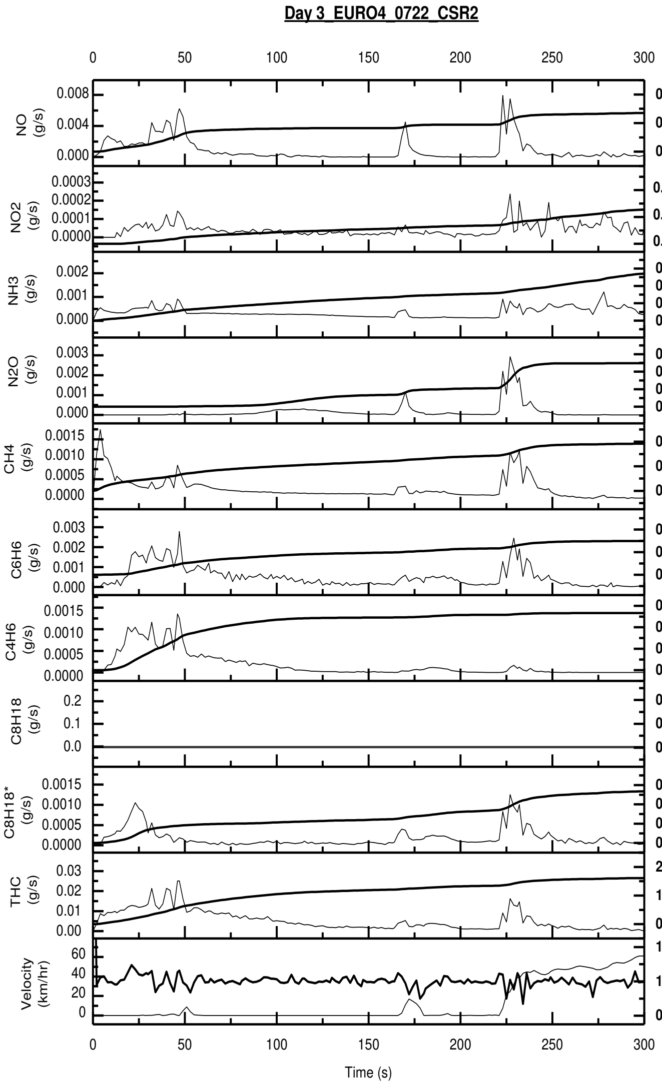


The variability at a given velocity is due to the different stop/start proportions for the same mean velocity. Lower emissions will occur where the peak velocity is higher but the idle periods are longer, for the same journey length.

Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK

RDE in Congested Traffic with Cold Start

Euro 4 Ford Mondeo



NO

NO_2

NH_3

N_2O

CH_4

Benzene

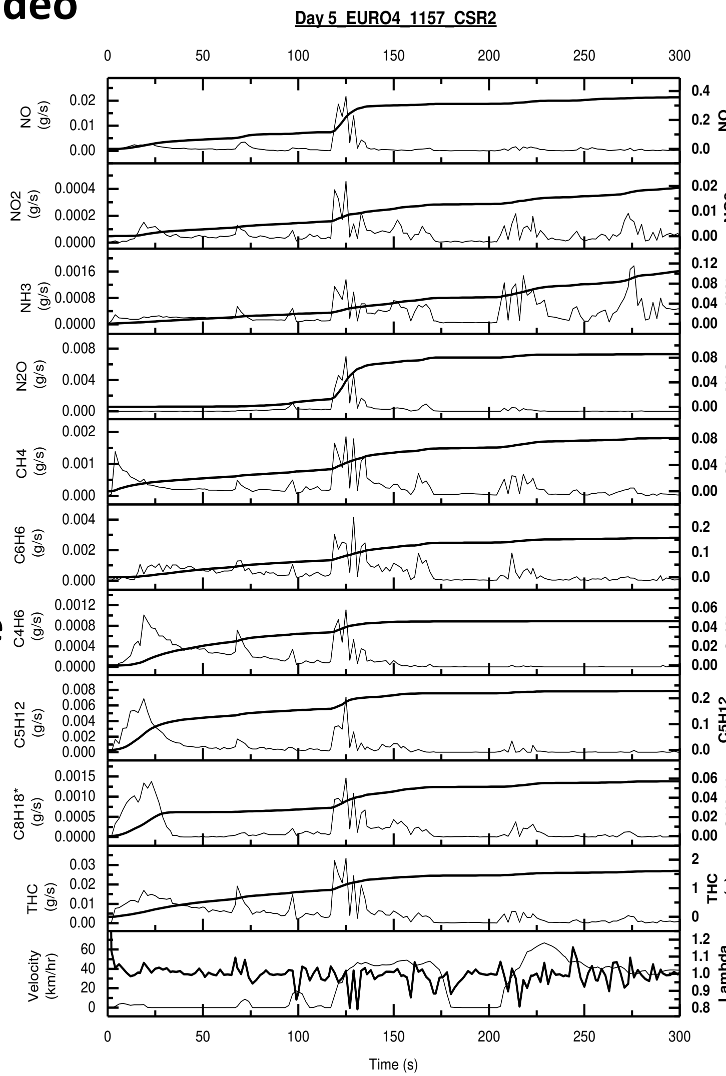
1,3 Butadiene

Hexane

isohexane

THC

Speed & λ



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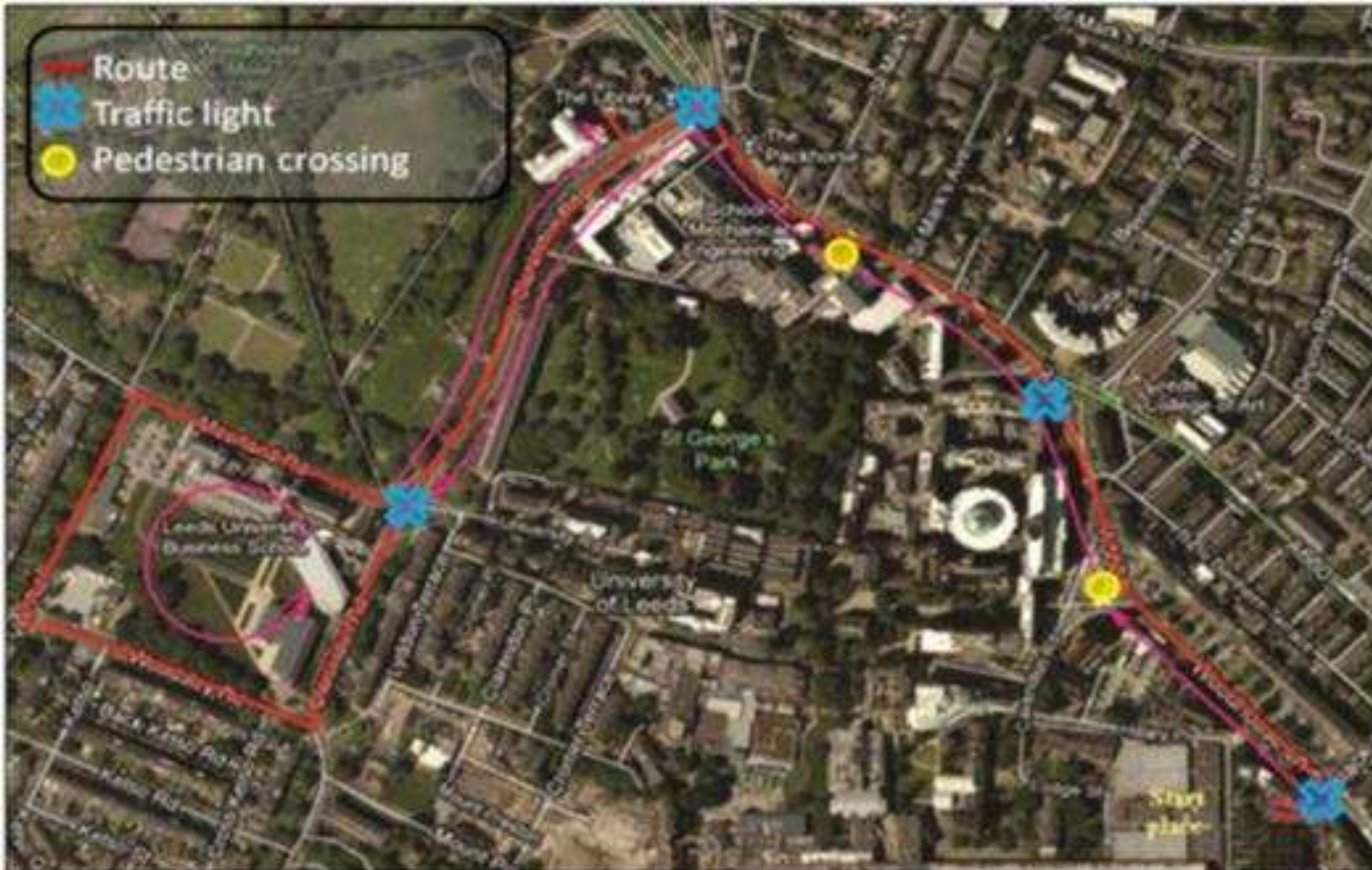
Diesel Cold Start into Congested Real World Traffic: Comparison of Diesel, B50, B100 for Gaseous Emissions.

Ali Hadavi, Grzegorz Przybyla, Hu Li and Gordon E. Andrews, ERI, U. Leeds, UK



SAE International 2013

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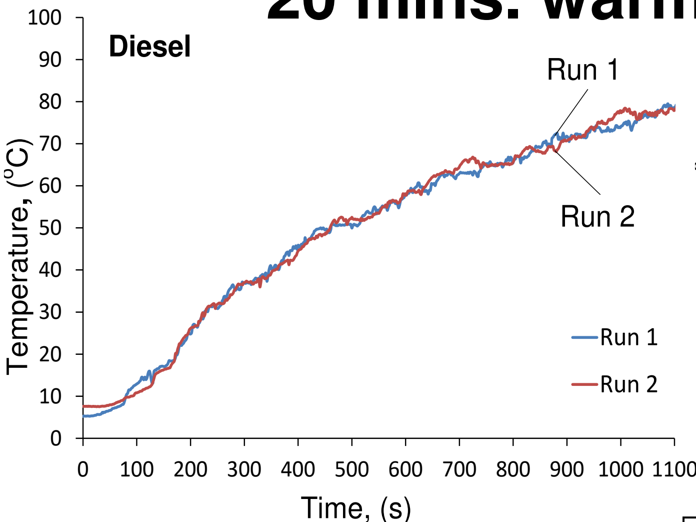
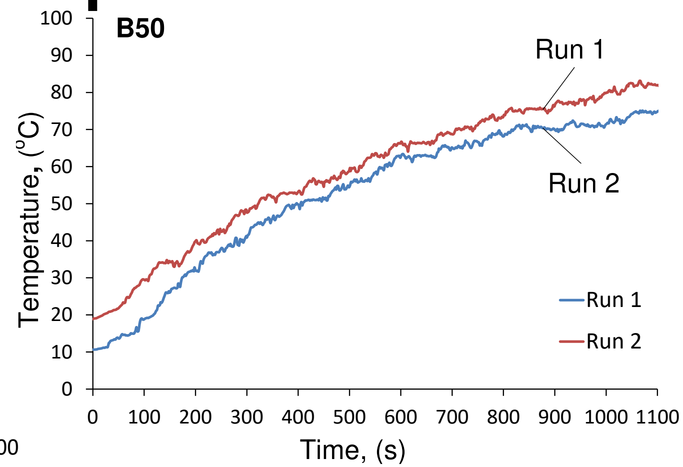
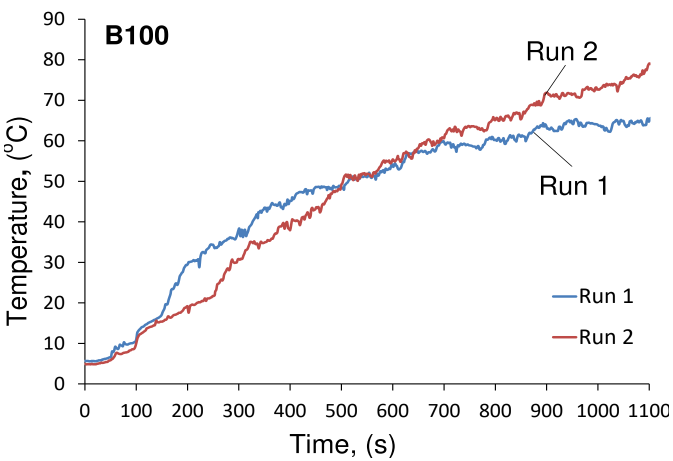
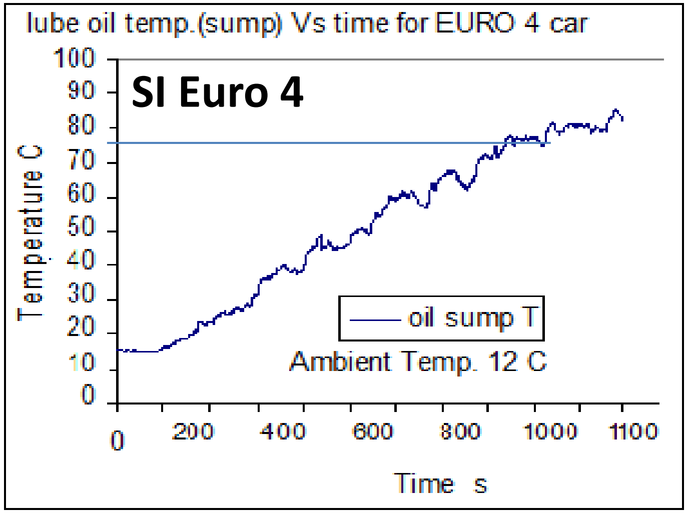
Warm up of the lubricating oil under real world cold start 20 mins. warm up for diesel and SI









Run	Time to raise lube oil by 60°C
D1	900s
D2	800s
B50-1	900s
B50-2	950s
B100-1	750s
B100-2	1000s
Petrol	950s

The variability was due to traffic differences not to the fuel or engine type.

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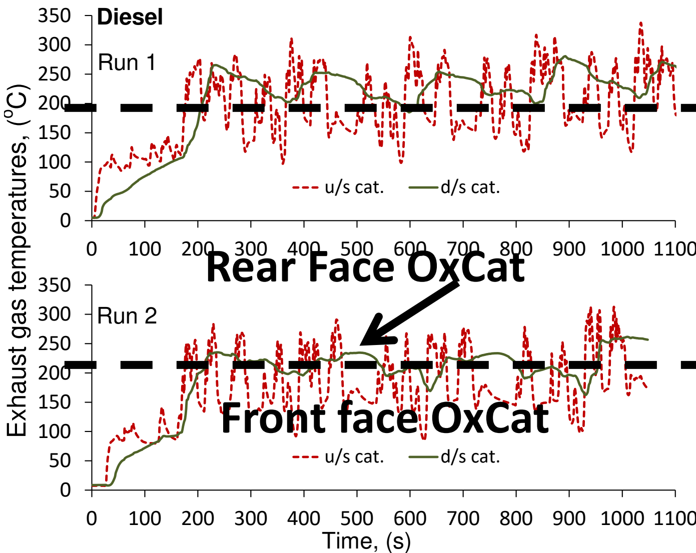
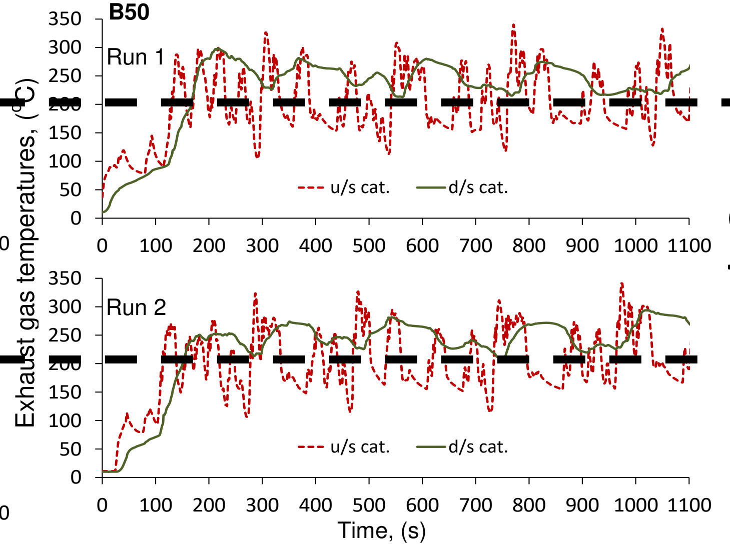
Diesel Cold Start into Congested Real World Traffic: Comparison of Diesel, B50, B100 for Gaseous Emissions.

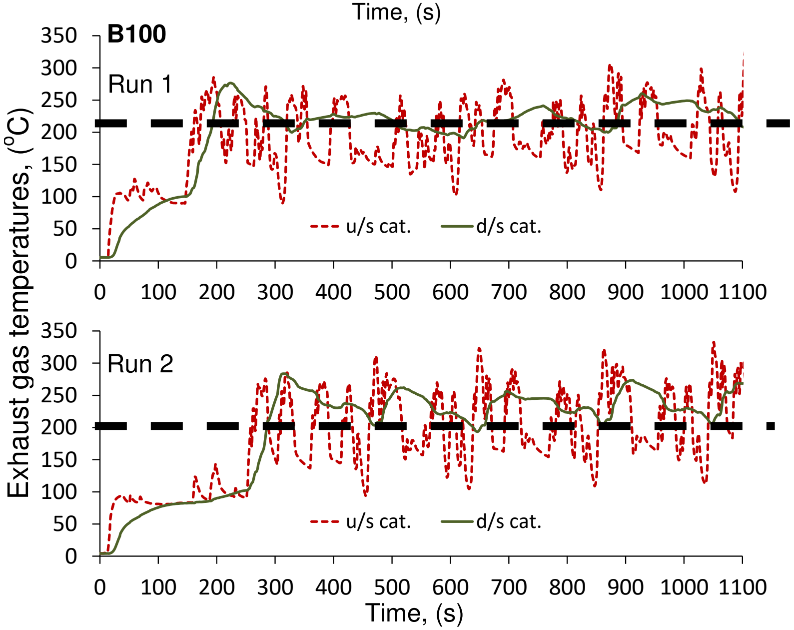
Ali Hadavi, Grzegorz Przybyla, Hu Li and Gordon E. Andrews, ERI, U10. Leeds, UK





SAE 2013-01-2528

Note that in a Euro 6 engine exhaust temperatures will be lower than this.



Run	Catalyst Time to 200°C	Vehicle time to 30 km/hr	CO Light off
D1	180s	180s	160s
D2	190s	200s	230s
B50-1	140s	120s	170s
B50-2	120s	50s (Cat at 100°C) 120s (2nd vel. Peak)	150s
B100-1	150s	160s	220s
B100-2	250s	260s	300s

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Powertrain, Fuels and Lubricants, Oct., Seoul,

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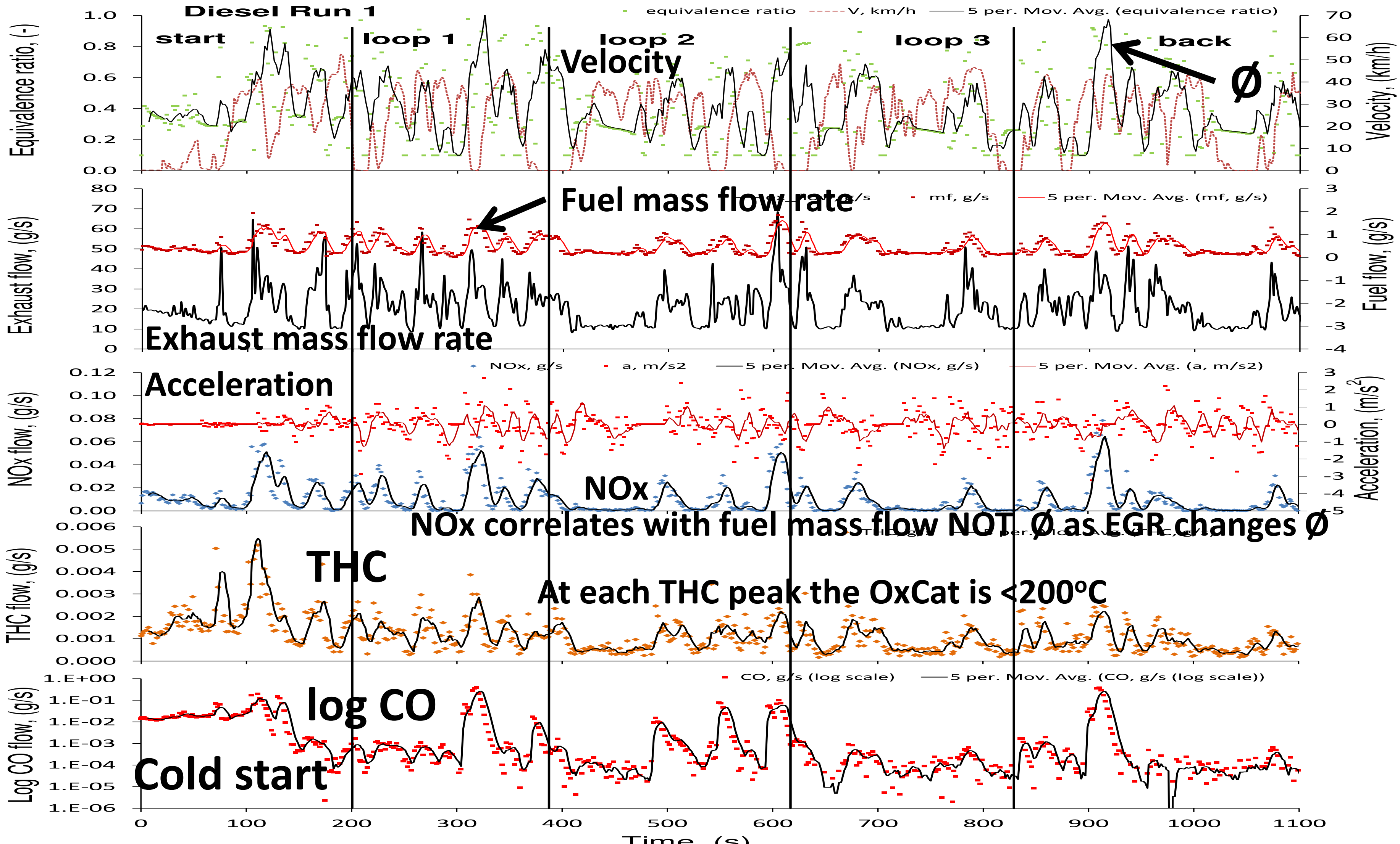

At each of these CO peaks the OxCat is below 200°C and the Ø is close to stoichiometric which increases CO

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Mean	Diesel Run1	Diesel Run2	B50 Run1	B50 Run 2	B100 Run1	B100 Run2	ECE urban test cycle
Ave. Acc, m/s^2	0.50	0.62	0.54	0.54	0.47	0.51	0.64
Max Acc m/s^2	3.41	4.91	2.99	3.8	2.98	4.94	0.74
Dec, m/s^2	-0.47	-0.57	-0.53	-0.56	-0.44	-0.50	-0.60
Max. Dec m/s^2	-2.87	-8.29	-4.7	-2.93	-3.22	-8.29	-0.74
V, km/h	20.4	17.3	22.0	20.4	18.3	19.9	17.2
Idle, %	26	38	19	24	30	32	28.6
Transients, %	27	26	32	30	28	22	44.8
Urban cruise <48 kph, %	46	32	47	46	41	45	26.6
High speed >48 kph, %	1	4	2	0	1	1	0
Congestion, %	53	63	51	54	58	54	64

Ali Hadavi, Grzegorz Przybyla, Hu Li and Gordon E. Andrews, ERI, U. Leeds, UK

Mean emissions for B100, B50 and diesel, g/km

	Diesel	B50	B100	Euro 3 Limit	RDE Factor
CO_2, g/km	318	261	312	172*	1.7
CO, g/km	2.2	2.6	2.7	0.8	3.1
THC+NOx, g/km	1.5	1.8	2.5	0.72	
THC, g/km	0.19	0.25	0.68	0.07	5.3
NO_x, g/km	1.29	1.59	1.78	0.65	2.4
NO, g/km	0.99	1.19	1.50	------------	
NO_2, g/km	0.30	0.39	0.27	------------	
NO_2/NO %	30%	33%	18%		
N_2O, g/km	0.20	0.04	0.07	------------	
Amb Temp., ^oC	6	11	5	------------	

The CO and THC are much higher than Euro 3 limit mainly due to the much longer cold start. NOx is higher due to the much higher acceleration rates and fuelling.

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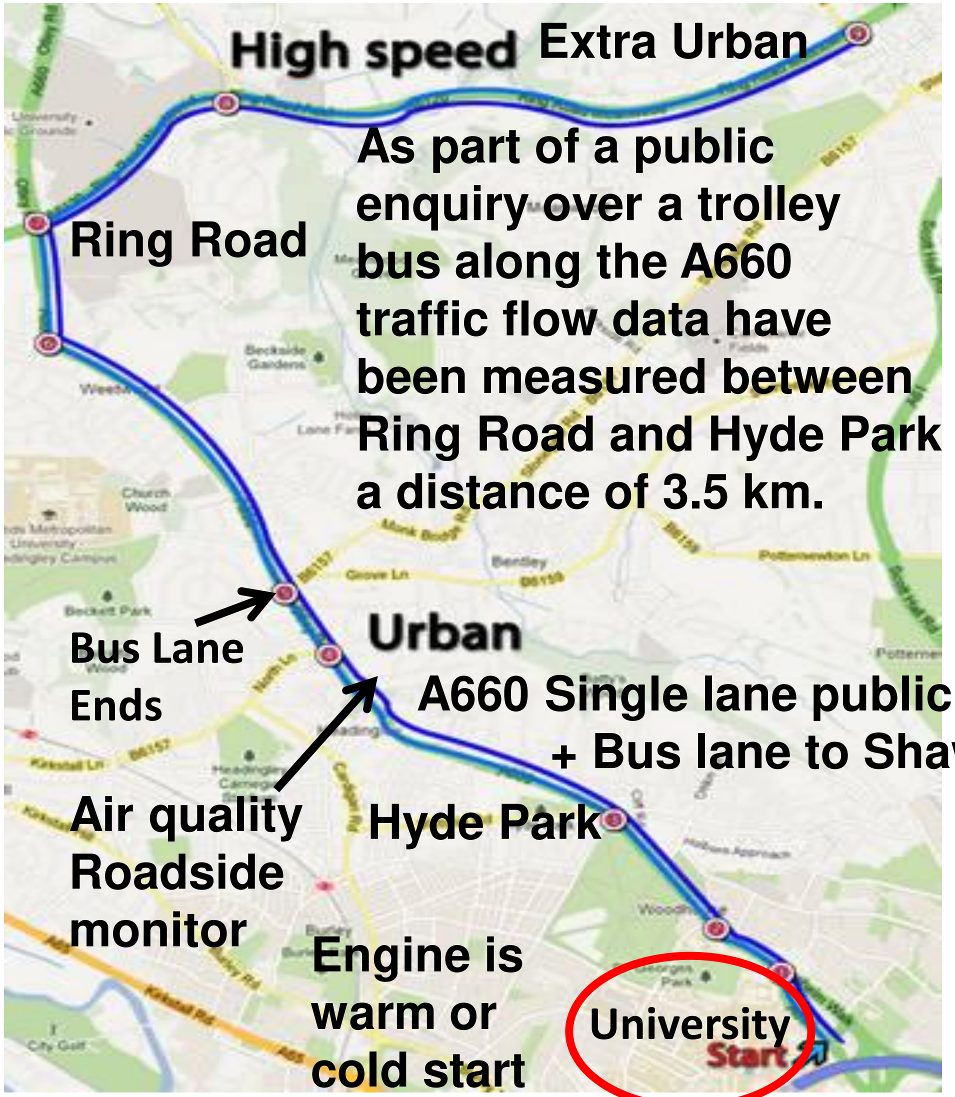
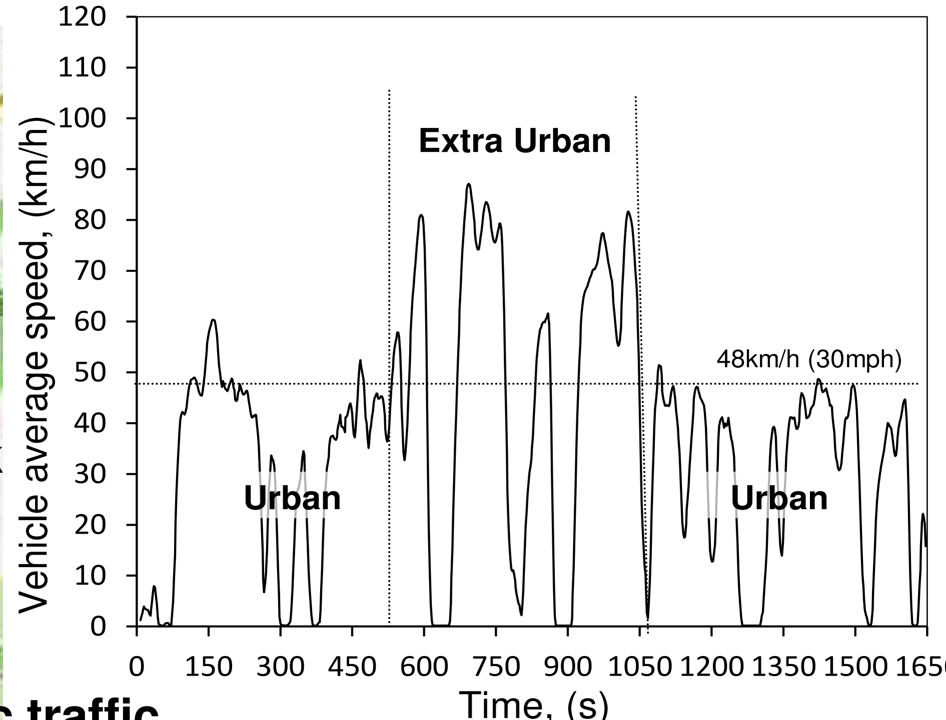
Journey average emissions of the most congested part in units of g/km

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)	



Leeds City Centre



Typical midday light traffic

The following results were for this complete journey with a fully warmed up catalyst undertaken after a cold start run.

Mean emissions for B100 and diesel, g/km

	B100			Diesel			Euro 3 Limit	RDE Factor
g/km	MEAN (5°C)	SD	SD/MEAN	MEAN (13°C)	SD	SD/MEAN		
CO_2	172.9	11.8	6.82%	173.6	5.9	3.37%	172	1.0
CO	0.067	0.011	16.59%	0.153	0.038	24.63%	0.8	0.2
THC+NOx	1.342	0.045	3.38%	2.004	0.593	29.61%	0.72	2.8
THC	0.194	0.034	17.29%	0.145	0.026	18.23%	0.07	2.1
NO_x	1.148	0.031	2.67%	1.858	0.567	30.51%	0.65	2.9
NO	0.695	0.045	6.46%	1.491	0.693	46.50%	--	
NO_2	0.454	0.065	14.35%	0.367	0.136	37.08%	-	
NO_2/NO	0.653			0.246				

CO is lower than diesel with B100 but THC are higher and NOx is lower.
NOx was higher than NEDC due to higher acc. which uses more power.

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

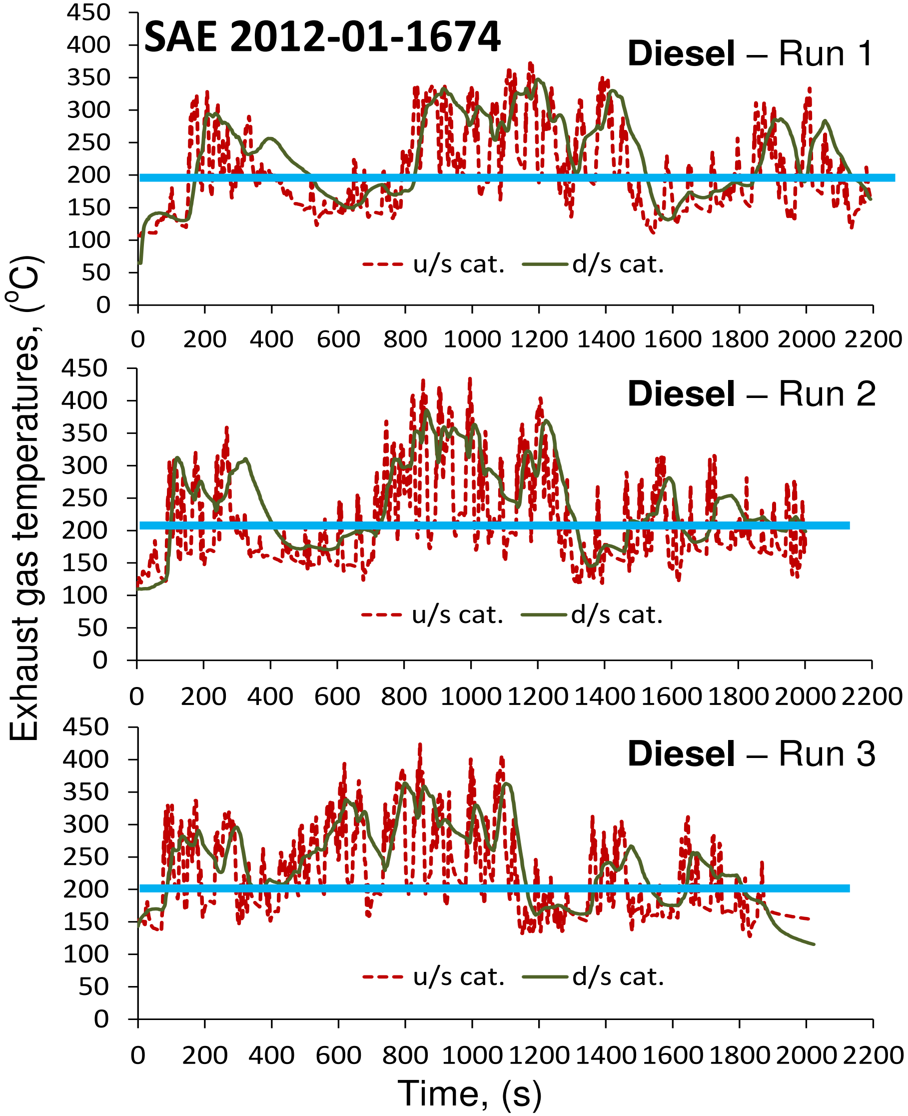
	B 100 Run1	B 100 Run2	B 100 Run3	B100 Ave.	Diesel Run1	Diesel Run2	Diesel Run3	Diesel Average	Euro 3 Limit
CO, g/km	0.297	0.501	0.396	0.398	0.189	0.112	0.144	0.148	0.8
THC, g/km	0.887	0.993	1.032	0.971	0.359	0.151	0.174	0.228	0.07
NO_x, g/km	3.87	4.926	2.320	3.705	2.988	1.891	2.536	2.472	0.65
CO_2, g/km	745	810	528	694	507	613	740	620	172
V_{mean}, km/h	5.54	7.09	9.13	7.25	6.35	5.09	5.40	5.61	

The RDE factor relative to the NEDC was 0.34 for CO , 3.3 for HC, 4.8 for NOx and 3.8 for CO_2 for the most congested part of the route through Headingley.

These results illustrate the advantage of diesel hybrids as operation in electric mode would always be done for these congested traffic conditions.

Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK

RDE in Congested Traffic with Cold Start 45



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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WHTC sequence as specified in ECE-R49

Cold test

soak

1. Test

2. Test

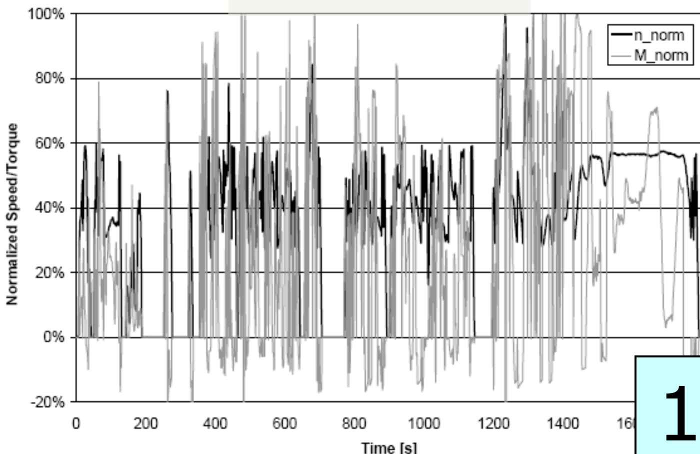


Figure 3:
WHTC test cycle

10 min

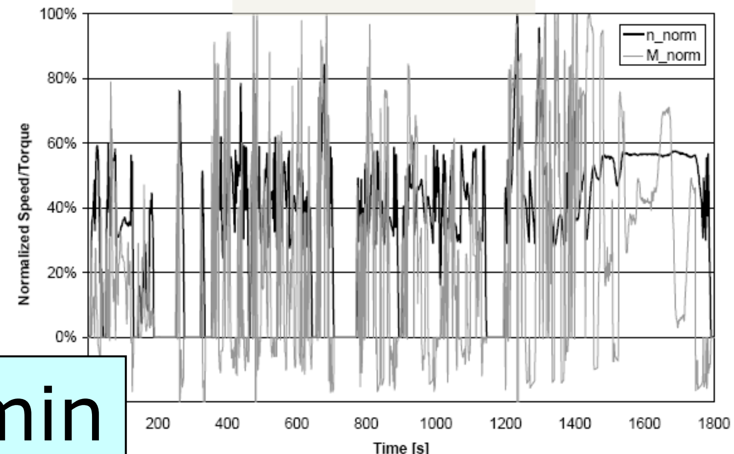


Figure 3:
WHTC test cycle

HDD cold start is not as significant as for passenger cars.

14%

86%

Weighting factor

What is the importance of cold start in the WHTC for HDD?

14% weighting to the cold start. 10min. soak with engine off then a repeat test. Is the second test truly a 'hot start' – depends on catalytic system thermal insulation. This cannot be too good or it will lead to overheating at maximum power conditions.

Current de-NOx catalytic systems for diesels are taking 200s to light off, so the city part of the test cycle emits raw emissions for most of the time.

Let the ratio of Test 1/Test 2 = y

Let the emissions of a pollutant in Test 2 =x

Then the weighted emissions are:

Total emissions = 0.14 yx + 0.86x

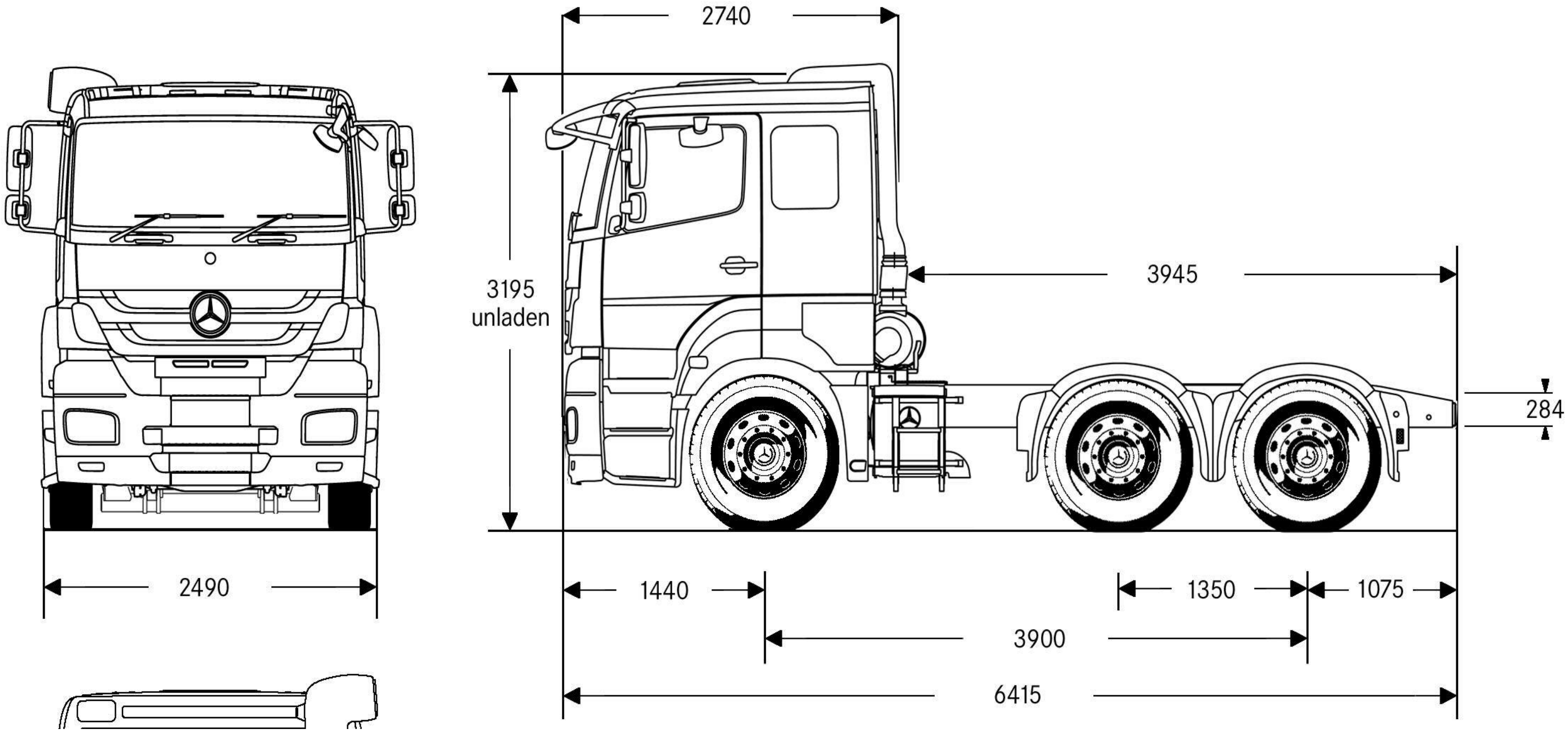
Proportion of Test1 of the total weighted emissions =

0.14yx / (0.14yx + 0.86x) = 0.14/(0.14 + 0.86/y)

Example: y = 10 then cold start is 62% of the total

y = 2 then cold start is 24.6% of the total

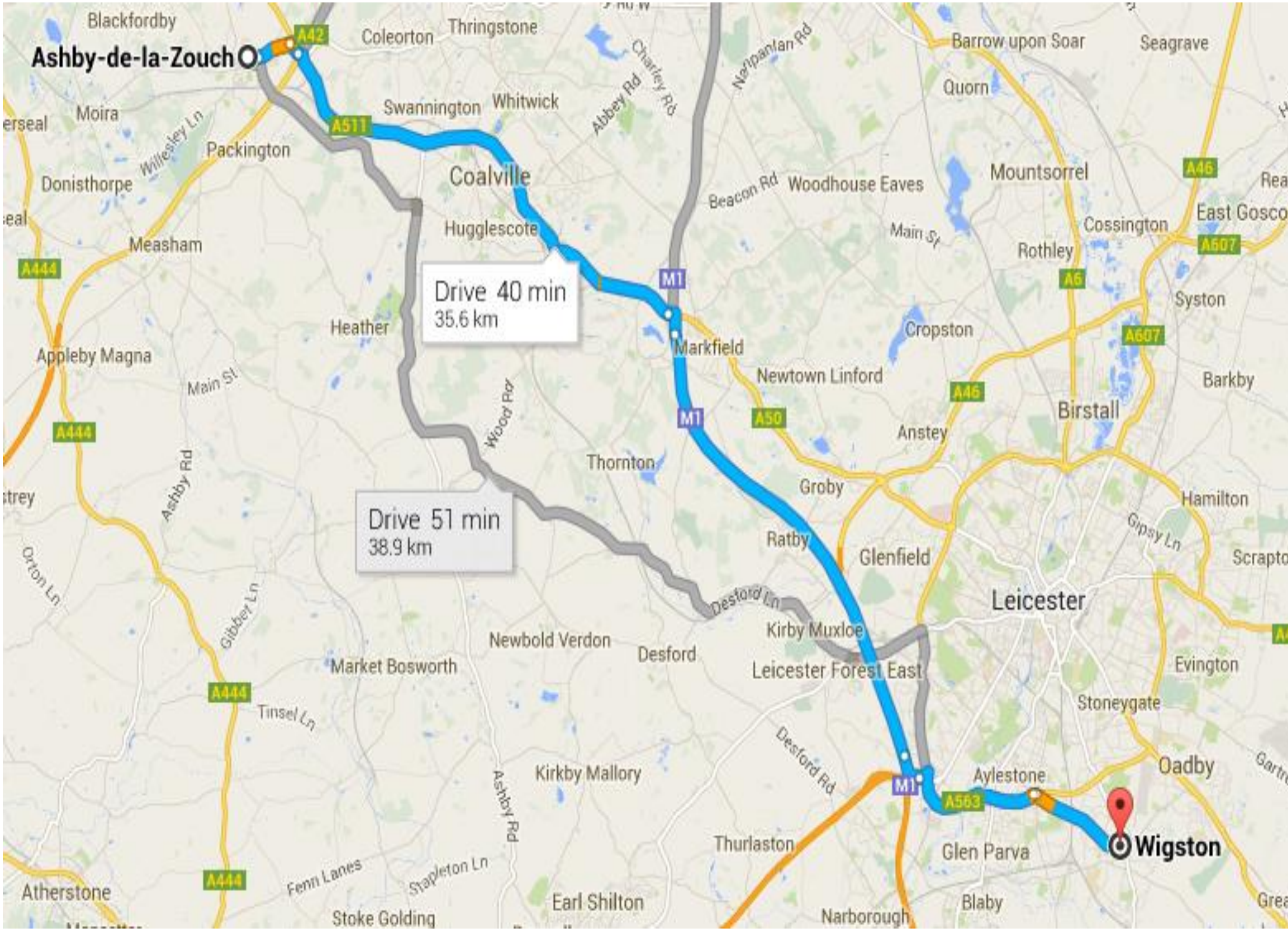
Clearly a good cold start performance is essential if NOx, HC and CO legislation is to be met for HDD vehicles.



Mercedes Benz AXOR-C6x2
Engine Mercedes-Benz OM457LA Euro V
Euro 5 with SCR deNOx
Unit injectors, TCIC, 4v/cyl.

Note that Euro V HDD did not have any cold start requirements to meet. The RDE are dominated by cold start issues

Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK



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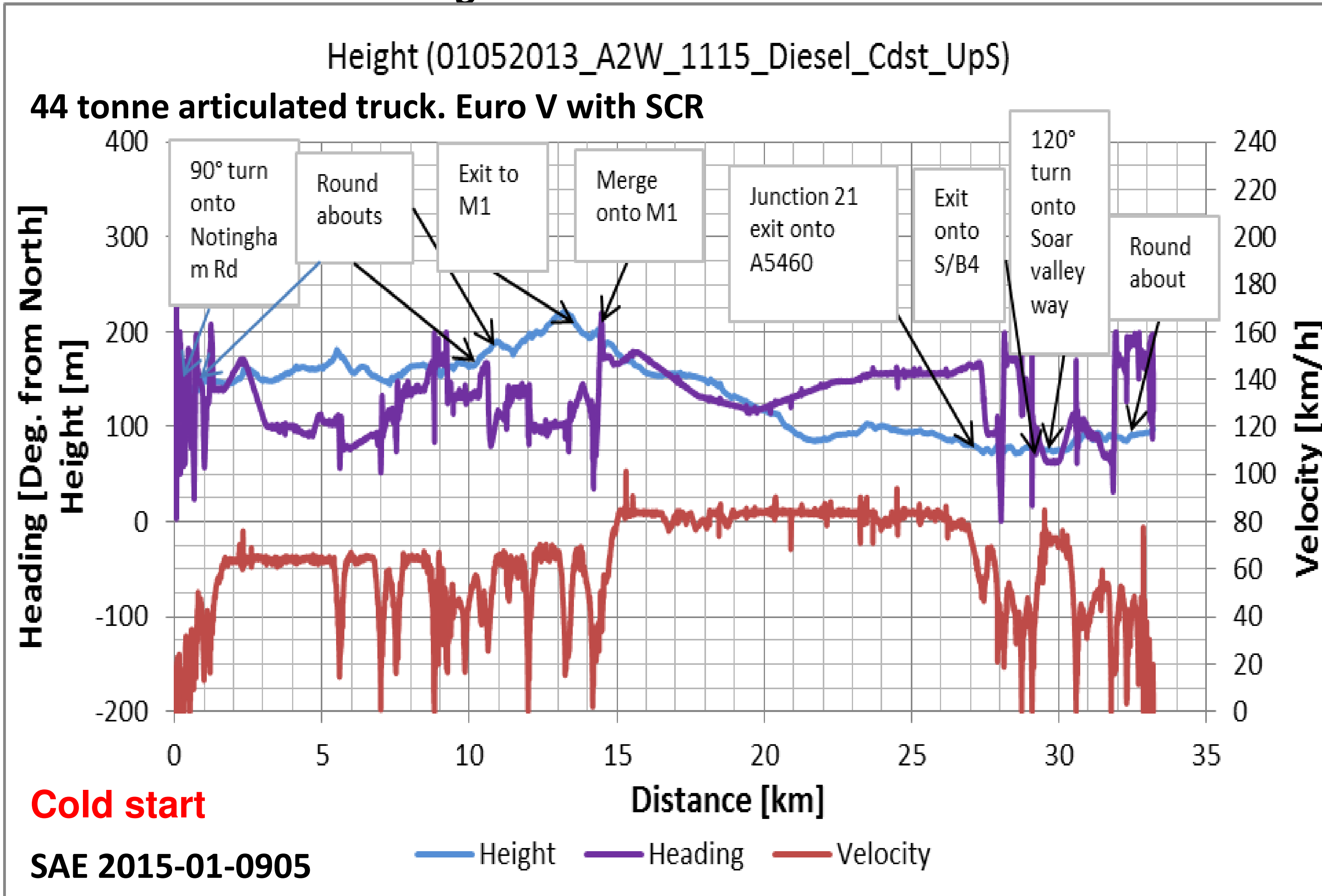
School of Chemical and Process Engineering, University of Leeds, UK

RDE in Congested Traffic with Cold Start



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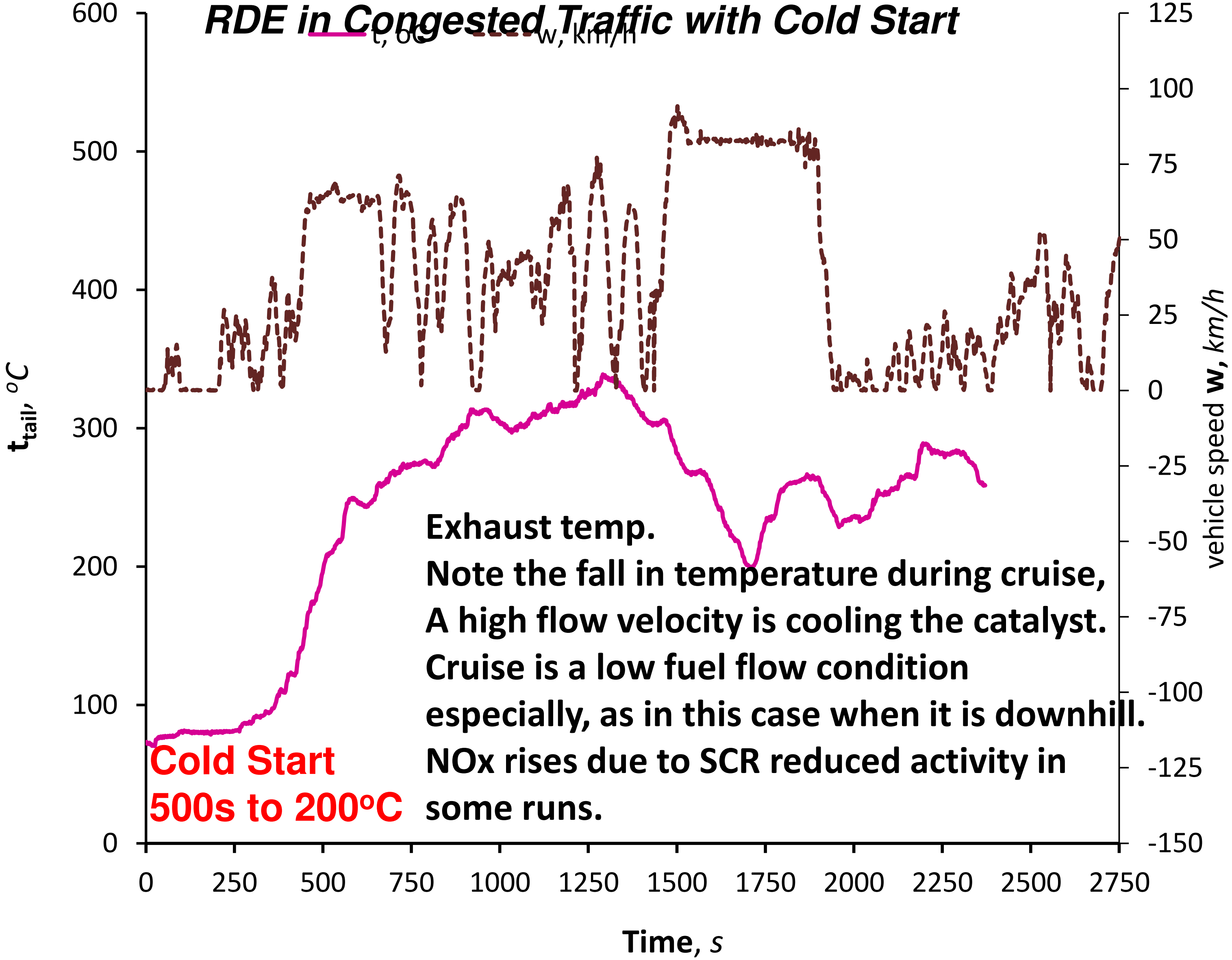

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School of Chemical and Process Engineering, University of Leeds, UK

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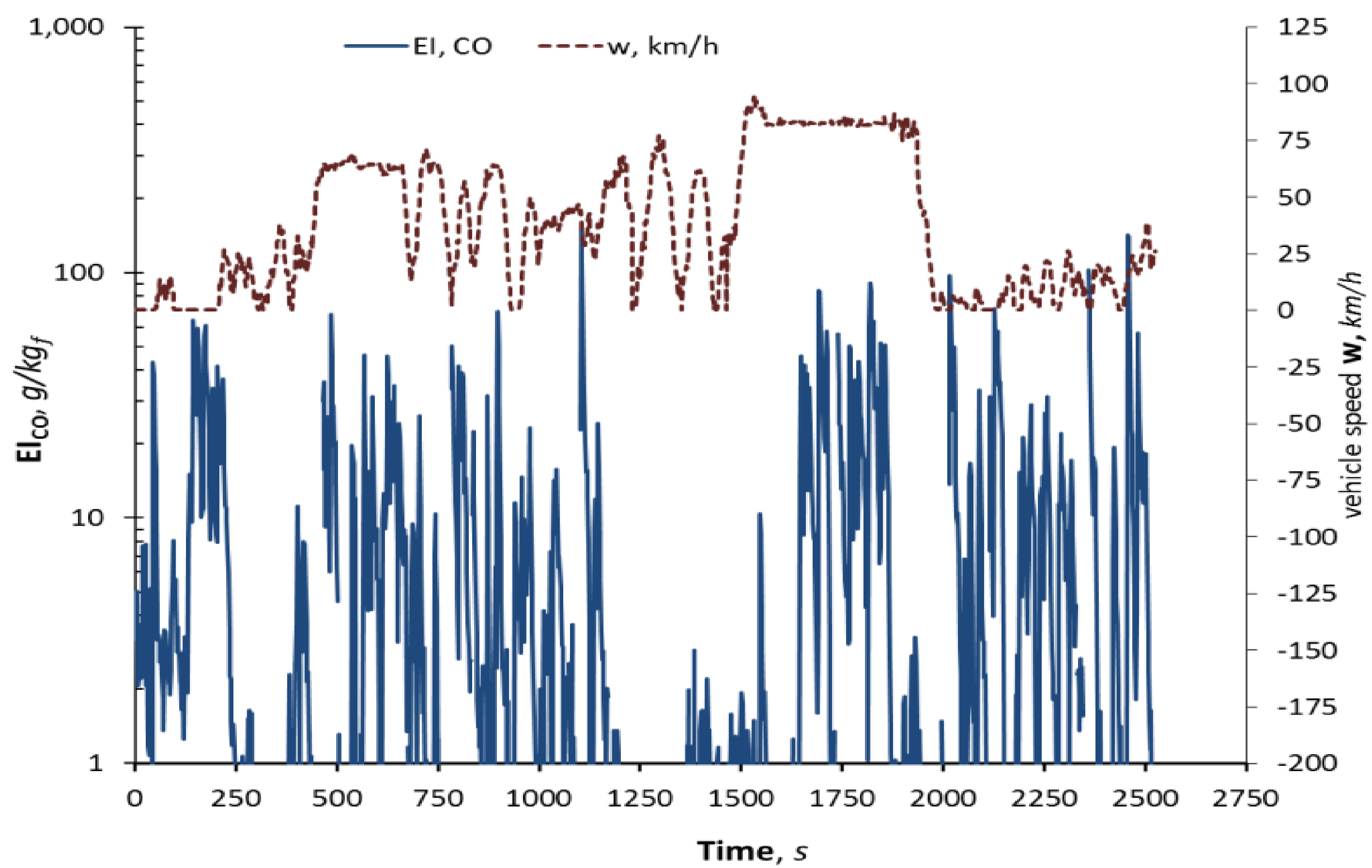
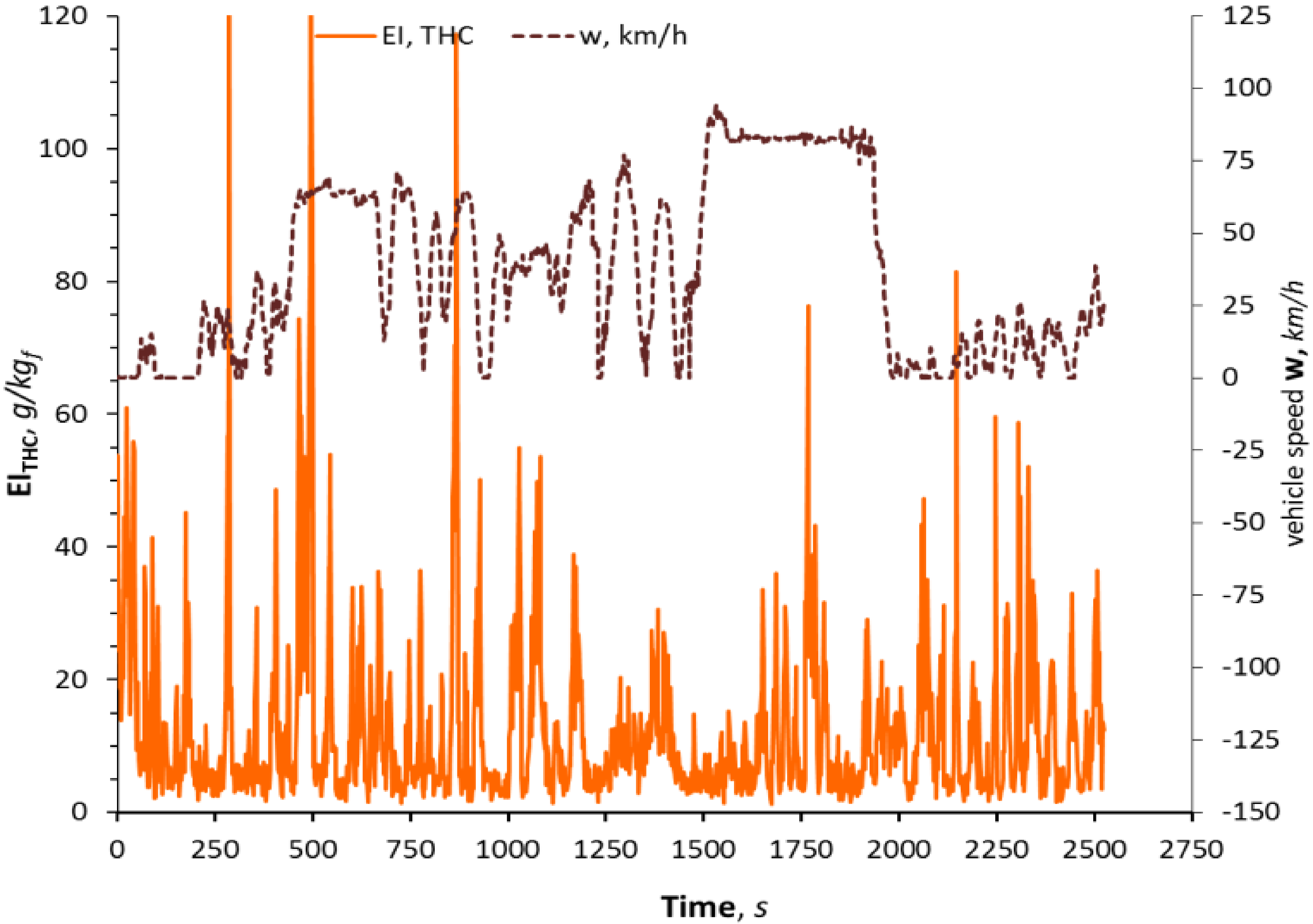


Fluctuations in CO over 2 order of magnitude of mass indicates an oxidation Catalyst going in and out of activity due to exhaust temperature fluctuations. Note high CO during motorway downhill cruise, where the catalyst cools. Similar effect for HC in the next slide.


EI, THC
w, km/h
0
20
40
60
80
100
120
EI_{THC}, g/kg_f
125
100
75
50
25
0
-25
-50
-75
-100
-125
-150
vehicle speed **w**, *km/h*
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
Time, *s*

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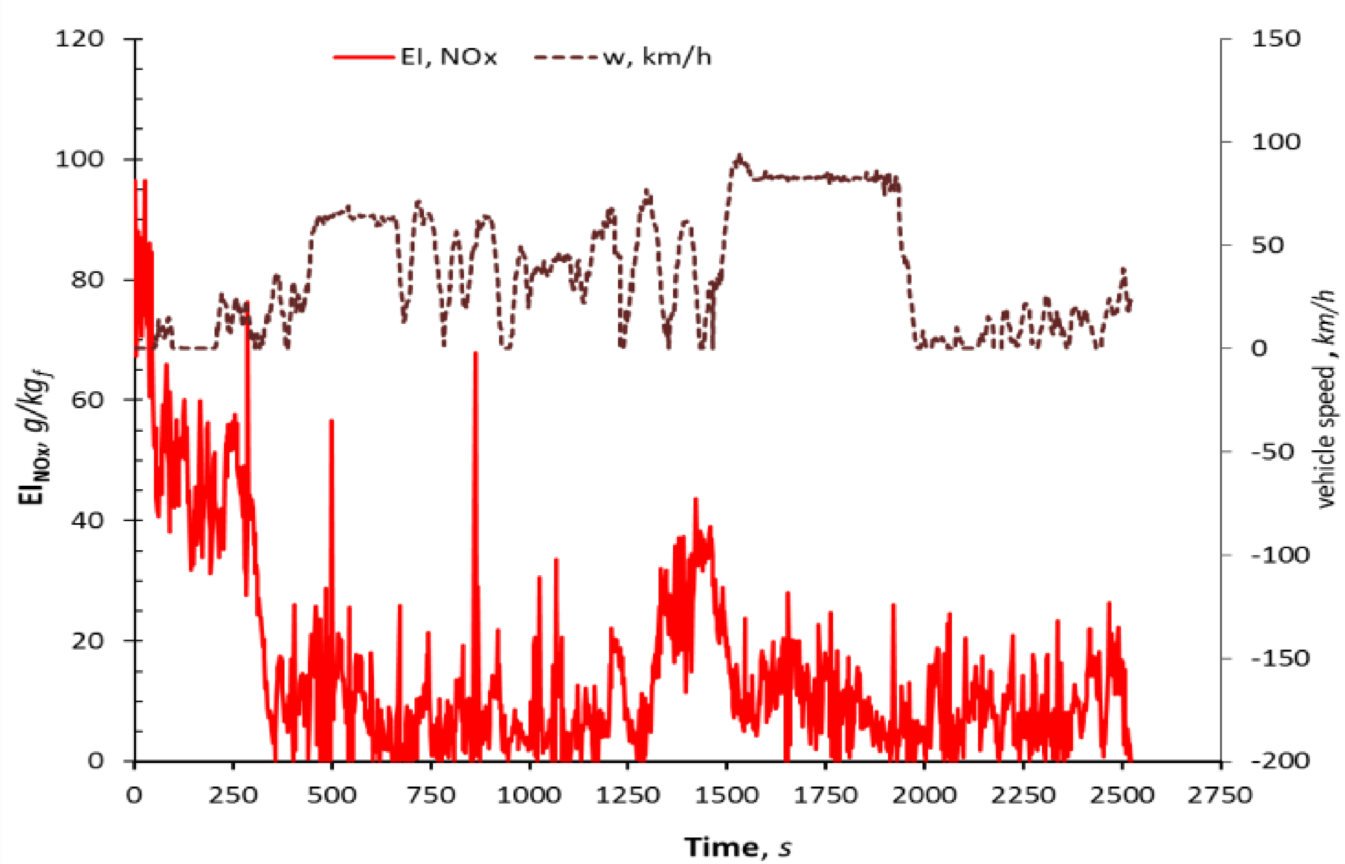
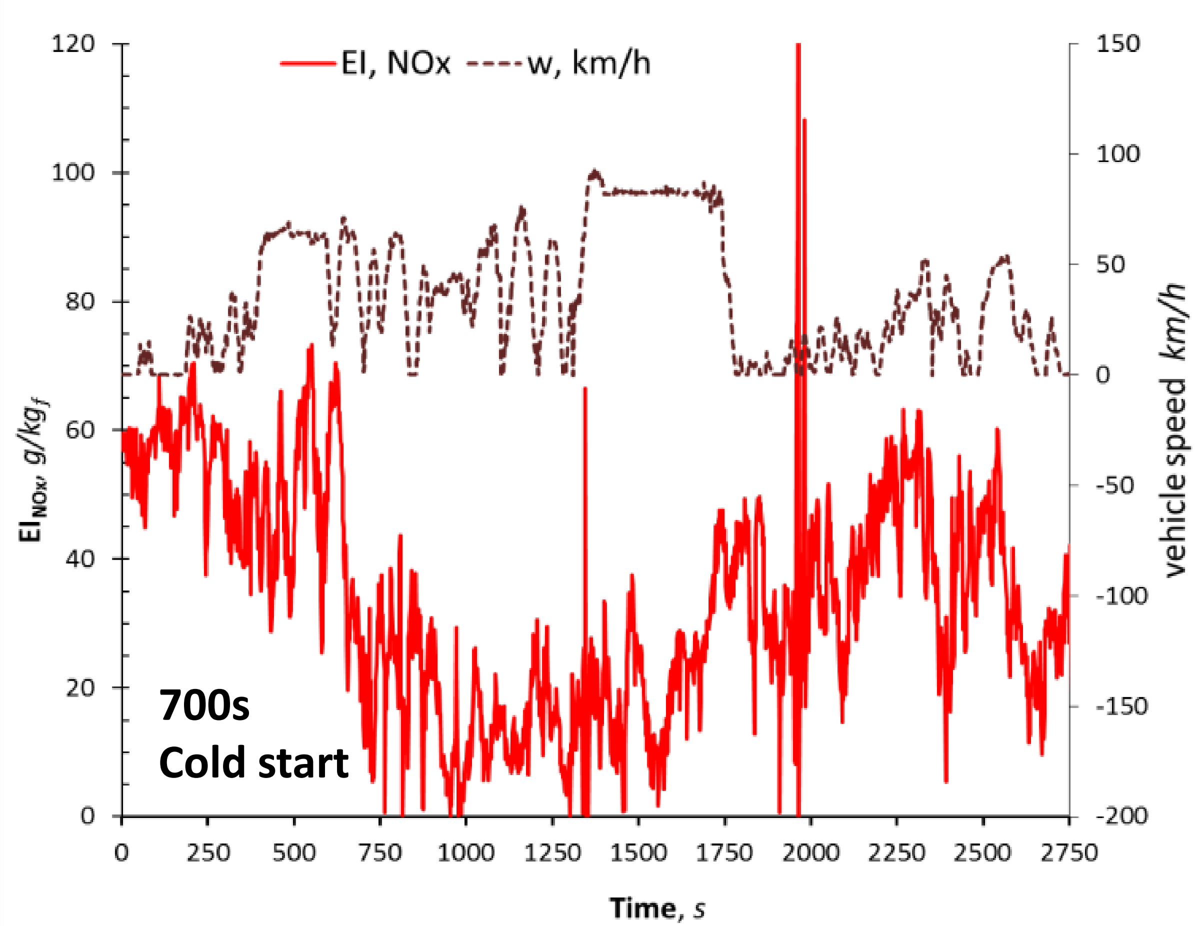
School of Chemical and Process Engineering, University of Leeds, UK

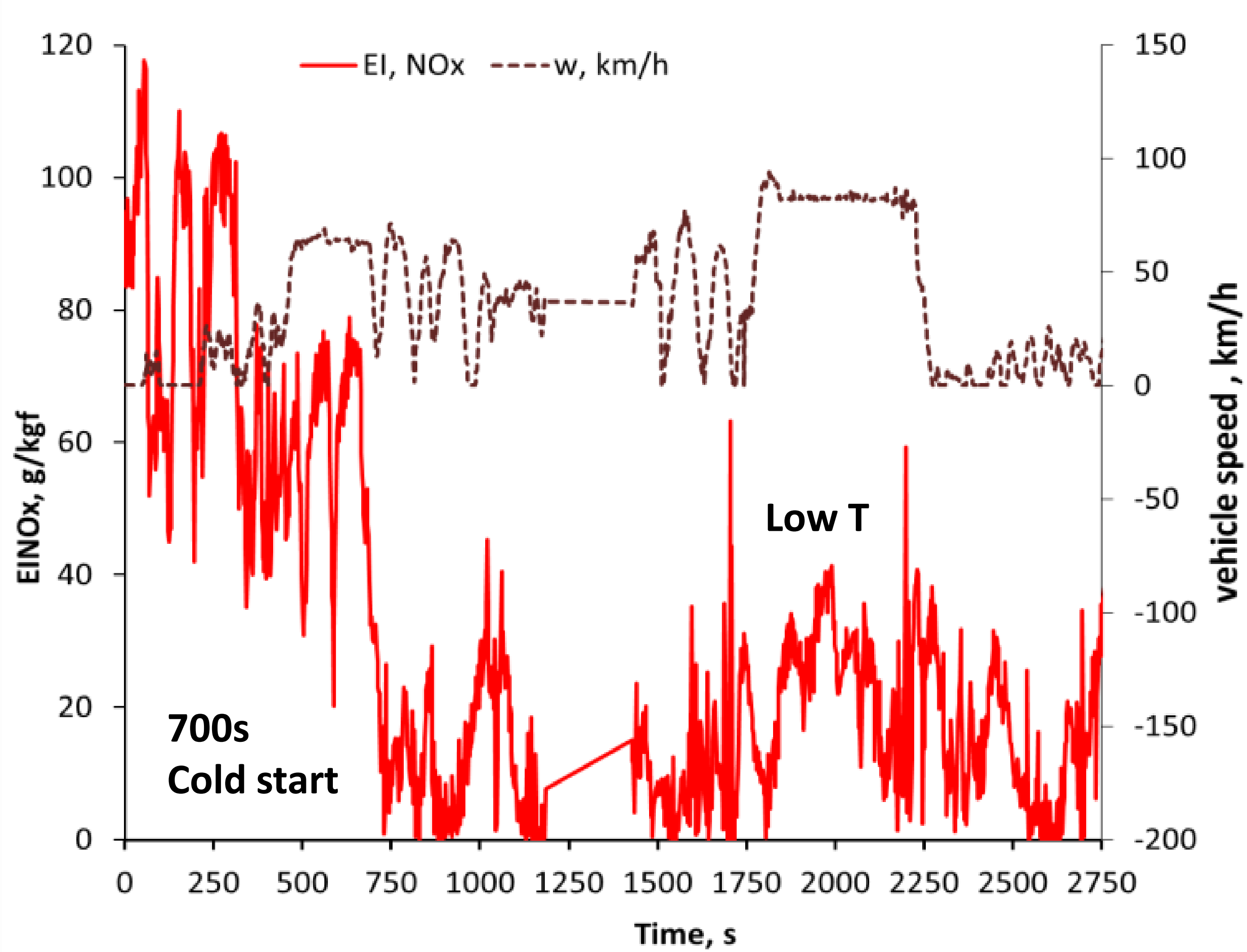
RDE in Congested Traffic with Cold Start



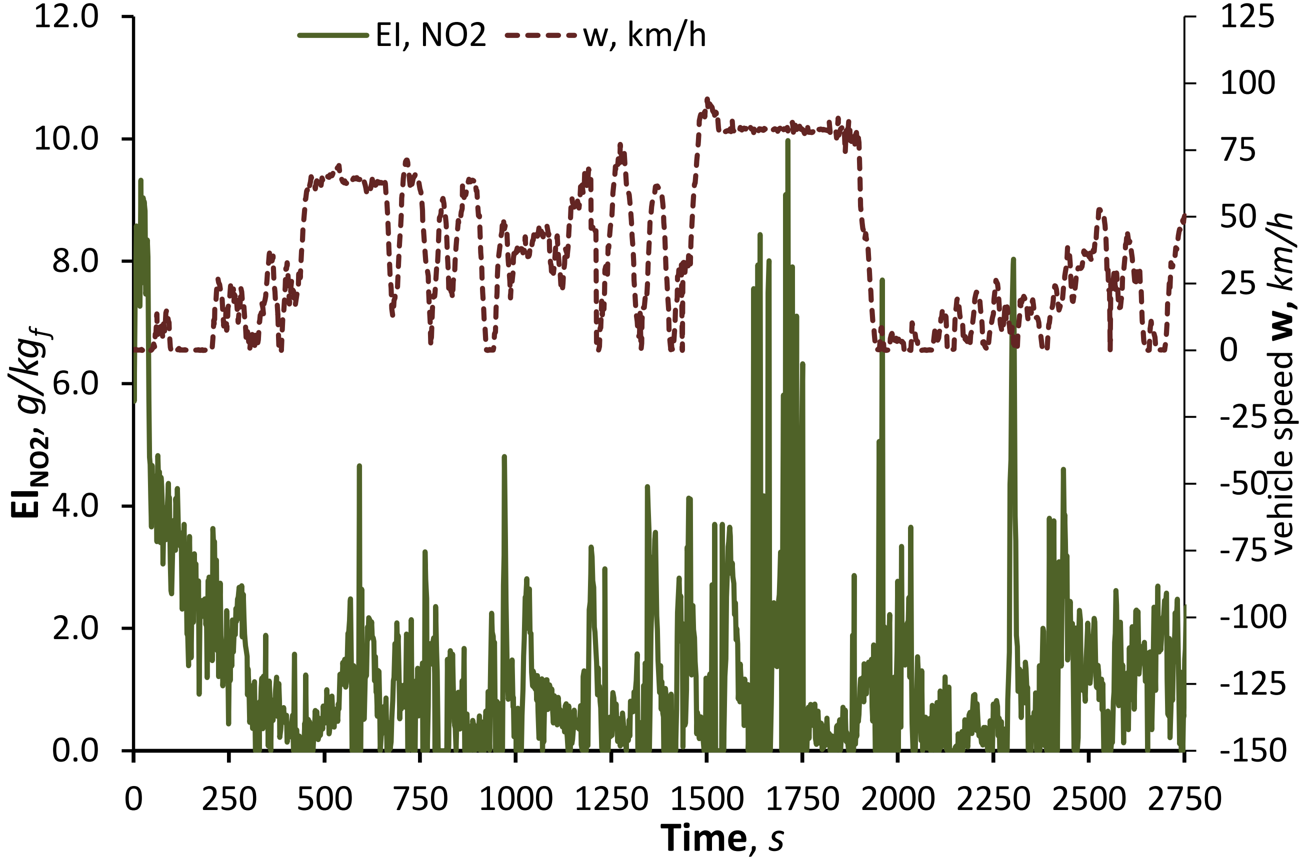
This is the NOx mass emission results from the ppm measurements in the previous slide. Clearly the deNOx efficiency is poor on this journey and the cold start effect is very clear over the first 300s. The spikes are likely to be due to inadequate Urea control and the rise in the mean NOx to inadequate catalyst temperature.



Several NOx mass emissions for different trips on the same journey are shown in this and the next slide.


EI, NOx
w, km/h
EINOx, g/kgf
vehicle speed , km/h
Time, s
700s
Cold start
Low T
120
100
80
60
40
20
0
150
100
50
0
-50
-100
-150
-200
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750

Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK



NO_2 emissions from the previous slide for total NOx
NO_2 also increases when the catalyst is at a low T during downhill cruise
Note cold start for NO_2 is 300s compared with 700s for NO due to the lower light off temperature for NO_2.

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School of Chemical and Process Engineering, University of Leeds, UK

Conclusions

1. RDE are strongly influenced by
   a) the driver actions; b) ambient temperature; c) traffic congestion
   d) road junctions and traffic lights; e) cold start
2. Both SI and diesel vehicles have all the above influences, but SI are also sensitive to quality of λ control.
3. The RDE multiplier was higher for cold start than hot start, as shown below.

Engine	Cold/Hot start	Loop/Road	CO_2	CO	HC	NOx
SI	Cold E4	Loop		3.3	3.3	1.9
SI	Cold E4	Road	1.0 – 1.4	1.4 – 2.6	3.0 - 5.5	1.4 – 3.1
SI	Cold E4	Congested	4.1	54	20	1.8
Diesel E3	Cold E3	Loop	1.7	3.1	5.3	2.4
Diesel E3	Cold E3	Congested	3.7	10.1	9.7	12.6
Diesel E3	Hot E3	Road	1.0	0.2	2.1	2.9
Diesel E3	Hot E3	Congested	3.8	0.34	3.3	4.8
Driver SI Variability	Hot E1 SI	Loop no traffic	2.2 – 1.2	10.4 -0.1	0.65 – 0.1	4.0 – 0.6

Conclusions (cont)

4. Catalysts light off time in RDE with cold start was a major factor in the high RDE. This light off time varied depending on the traffic conditions:

SI Euro 4 TWC 120 – 220s
Diesel E3 OxCat 150 – 300s
HDD EV SCR 300 – 700s

The worst case is the HDD SCR – where there has been no requirement at Euro V for cold start emission measurements. This is going to be a major area that has to be improved in HDD for the new test cycle.

5. Diesel exhaust catalyst, both oxcat and SCR exhibit cooling of the catalyst after encountering congested traffic after a high speed period and during cruise downhill where the high exhaust flow at low temperature cools the catalyst and reduces the NOx conversion.

6. To overcome these cold start effects, especially in diesel vehicles active heating of the exhaust is required and it is considered that direct combustion in the exhaust is the most effective way of doing this. Current burner designs are far from optimum for this purpose and better designs are required.

Acknowledgements

We would like to thank the UK EPSRC for supporting the early stages of this research and for providing the heated FTIR. This was through two large grants

LANTERN and RETEMM 2001 - 2008

More recent work has been through PhD students.

The recent HDD vehicle RDE diesel work was through a UK Department for Transport and Technology Strategy Board for supporting the research element within the project "Environmental and Performance Impact of Direct use of used cooking oil in 44 tonne trucks under real world driving conditions" which is part of the Low Carbon Truck Demonstration Trial." Thanks go to United Biscuits Midland Distribution Centre for the provision of a truck and general support and collaboration in field tests. Thanks also go to Bioltec System GmbH for advice and permission to use some technical information and Convert2Green for the provision of Ultra Biofuels for the tests.