Real World Driving Emissions in Congested Traffic

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presented by

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The Guardian, Friday 5th May, 2017 p. 4

Minister's Plan to Tackle Diesel Pollution

Levels of NO_2, primarily from diesel traffic, have been at illegal levels in almost 90% of urban areas in the UK since 2010.

The government has been repeatedly defeated in the UK courts over its failure to have an effective policy to address this issue.

Last week (End April 2017) a high court judge said the continued delays were a "significant threat to public health". He ordered the publication of the new air quality plan by Tuesday 2nd May 2017.

It was published on Friday 5th May to general derision for its ineffectiveness – no money to scrap Euro 3 – 5 diesels.

NO_2 causes 23,500 of the 40,000 premature deaths from dirty air each year (*the rest are mainly due to fine particulates $PM_{2.5}$)* according to the government's own data.

Councils will also be supported in retrofitting old buses with deNOx systems and electrification - *a very few councils in a limited scheme*.

Balancing Regulations and Customer Expectations in Future Powertrains, Fuel, Lubricants, and Vehicle Systems.
Executive Panel Discussion, SAE 2016 International Powertrains, Fuels and Lubricants Meeting, October 25, 2016, Baltimore
Meeting the Challenges Ahead, Tim Johnson, Corning, JohnsonTV@Corning.com

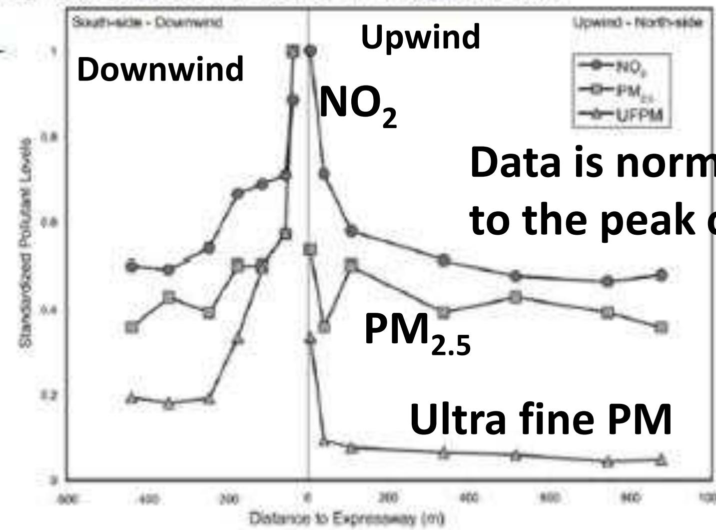
Toxic pollution is present on our highways.

Levels are 2-5X ambient, and 40% of city populations are exposed.

These are predictions NOT measurements

~40-45% of the populations of Los Angeles (shown) and Toronto (probably most cities) lives within heavy traffic zones.

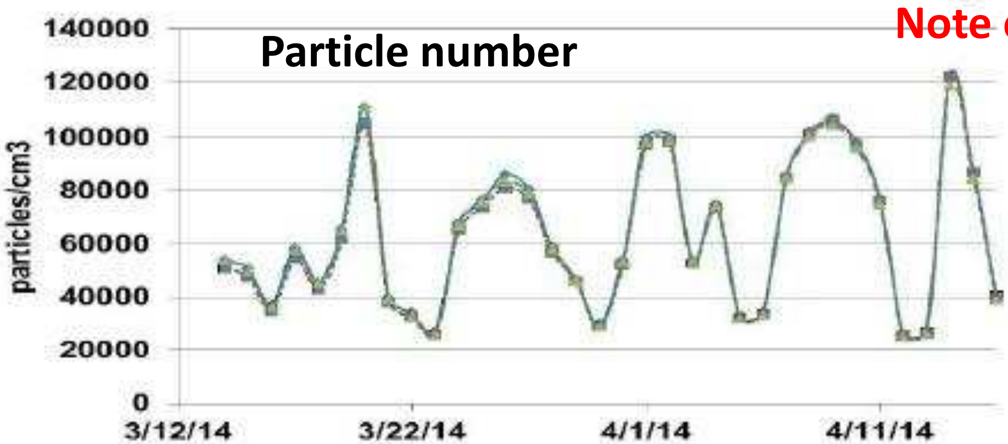
HEI Traffic Review 2010



Data is normalised to the peak conc.

Toxic NO_2 and particulate concentrations are 2-5X background levels on the highway. Toronto 2008

Note effect of road is 200m each side



- Location 15m from I-710 in Carson City, CA at SCAQMD monitoring site. Downwind data.

TSI, poster ETH NP conf 6/14

The A660 Clarendon Road junction by the University

Roadside particle number monitoring

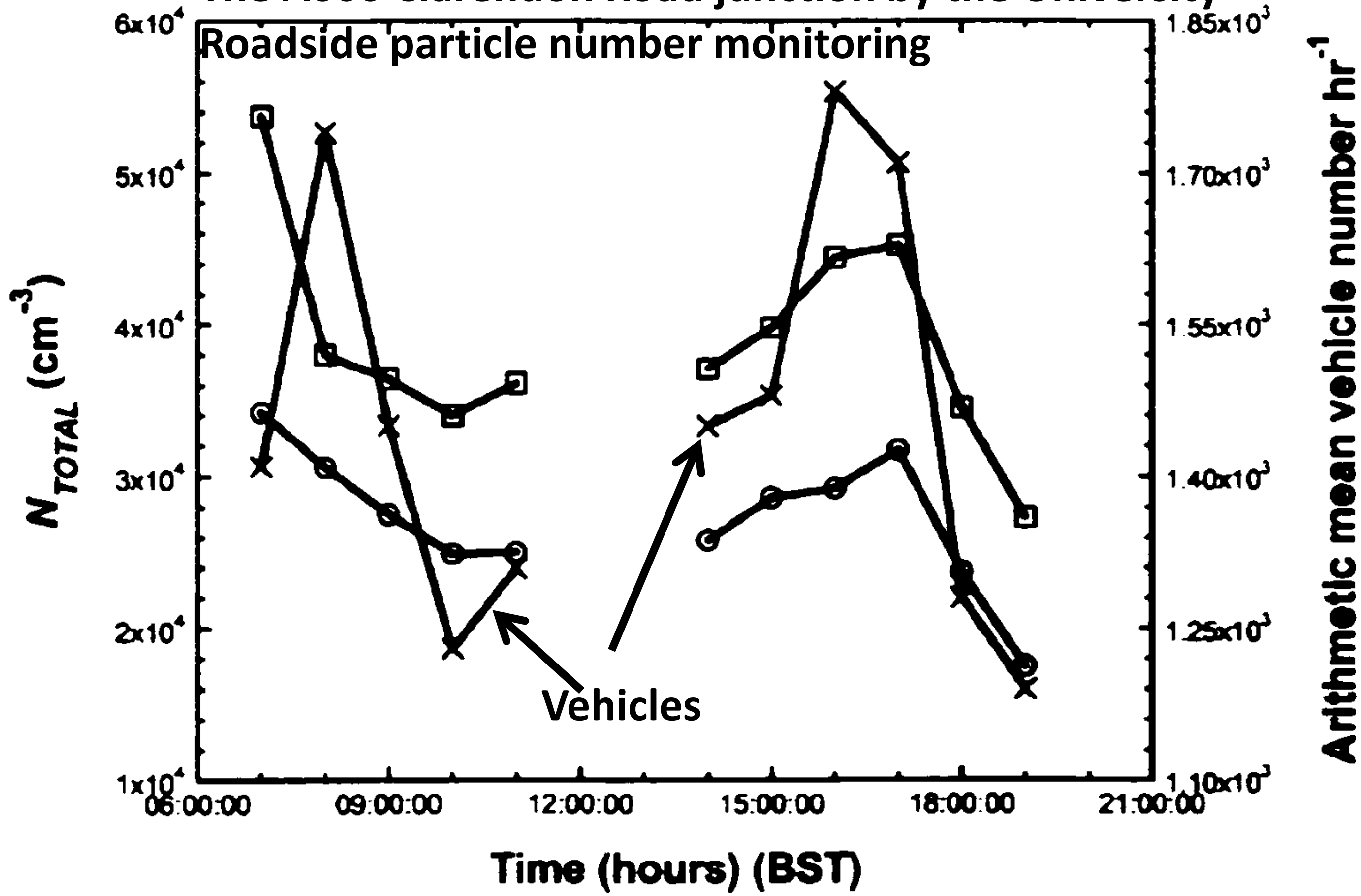
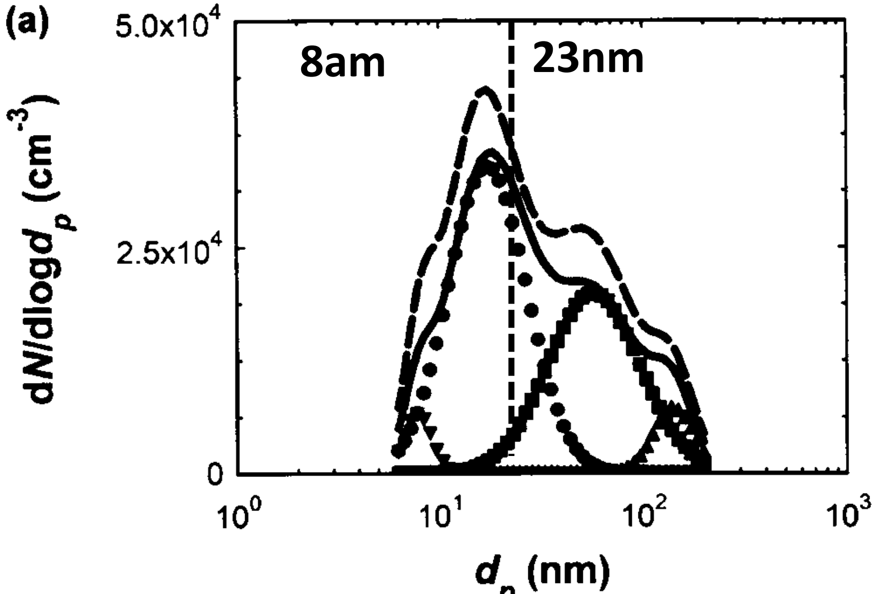


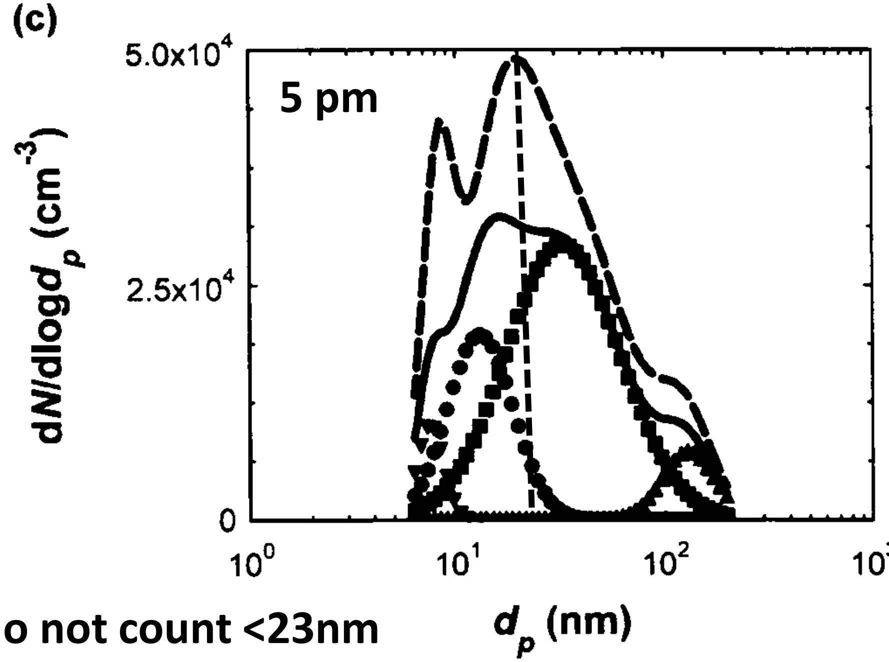
Fig. 1 The daily traffic flow at the sampling site and the arithmetic mean and median total particle concentrations (–□– arithmetic mean total number concentration (particles cm^{-3}); –○– median total number concentration (particles cm^{-3}); and, –×– arithmetic mean total number of vehicles h^{-1}).

Lingard et al. (inc. G.E. Andrews) J. Environ. Monitoring 2006, 8, 1203-1218.

Vehicle count peaks at 1750/h at 4&5pm and 8am. In evening particle number peaks with peak traffic load.

Lingard et al. (inc. G.E. Andrews) J. Environ. Monitoring 2006, 8, 1203-1218.





EU PN regs do not count <23nm

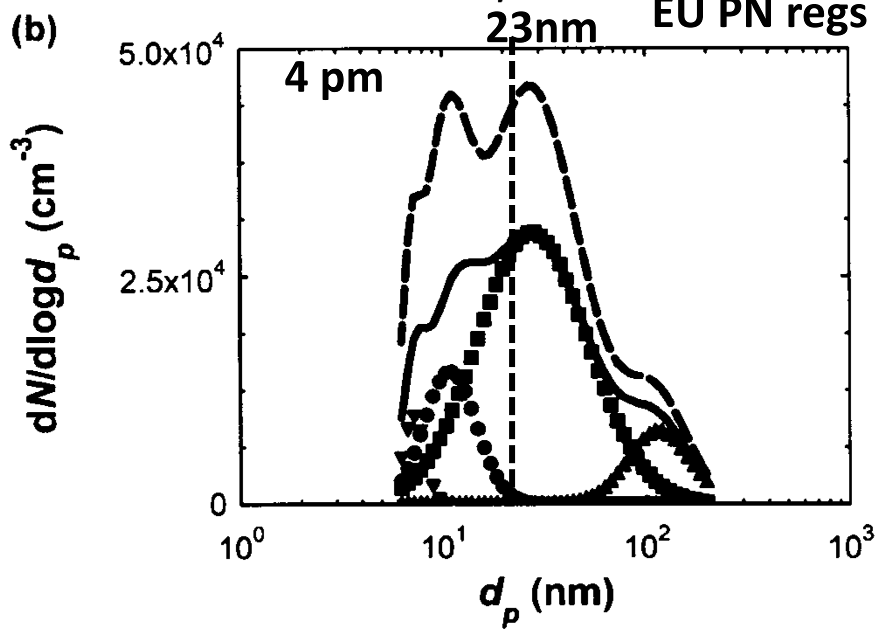


Fig. 5 The particle size distribution of urban airborne roadside particulates at (a) 08:00 hrs; (b) 16:00 hrs; and, (c) 17:00 hrs, based on the output form the R-Mix fitting procedure (-- fitted arithmetic mean log-normal distribution; — fitted median log-normal distribution, including the fitted component modes: ▼ mode I; ● mode II; ■ mode III and ▲ mode IV).

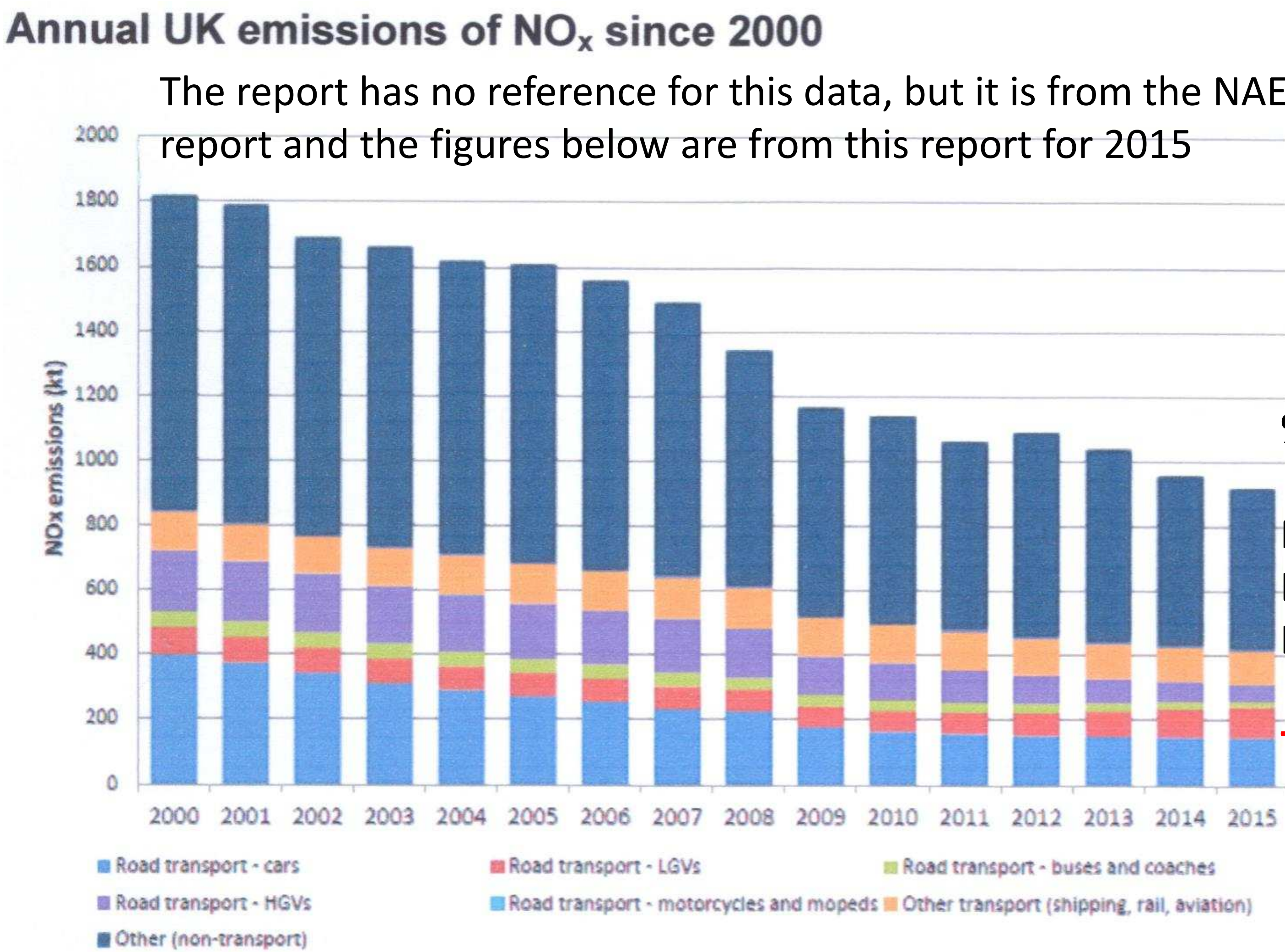
Roadside particle size distribution has A nuclei peak at ~10-20nm and a larger Peak at 30 -50 nm.
SI engines emit in the former size and Diesels in the latter size, typically.

Dept. for Environment, Food and Rural Affairs and Department of Transport May 5th 2017

Improving air quality in the UK: tackling nitrogen dioxide in our towns and cities

Draft UK Air Quality Plan for tackling nitrogen dioxide.

The report has no reference for this data, but it is from the NAEI 2017 report and the figures below are from this report for 2015



% total emissions 2015

Passenger cars 16%

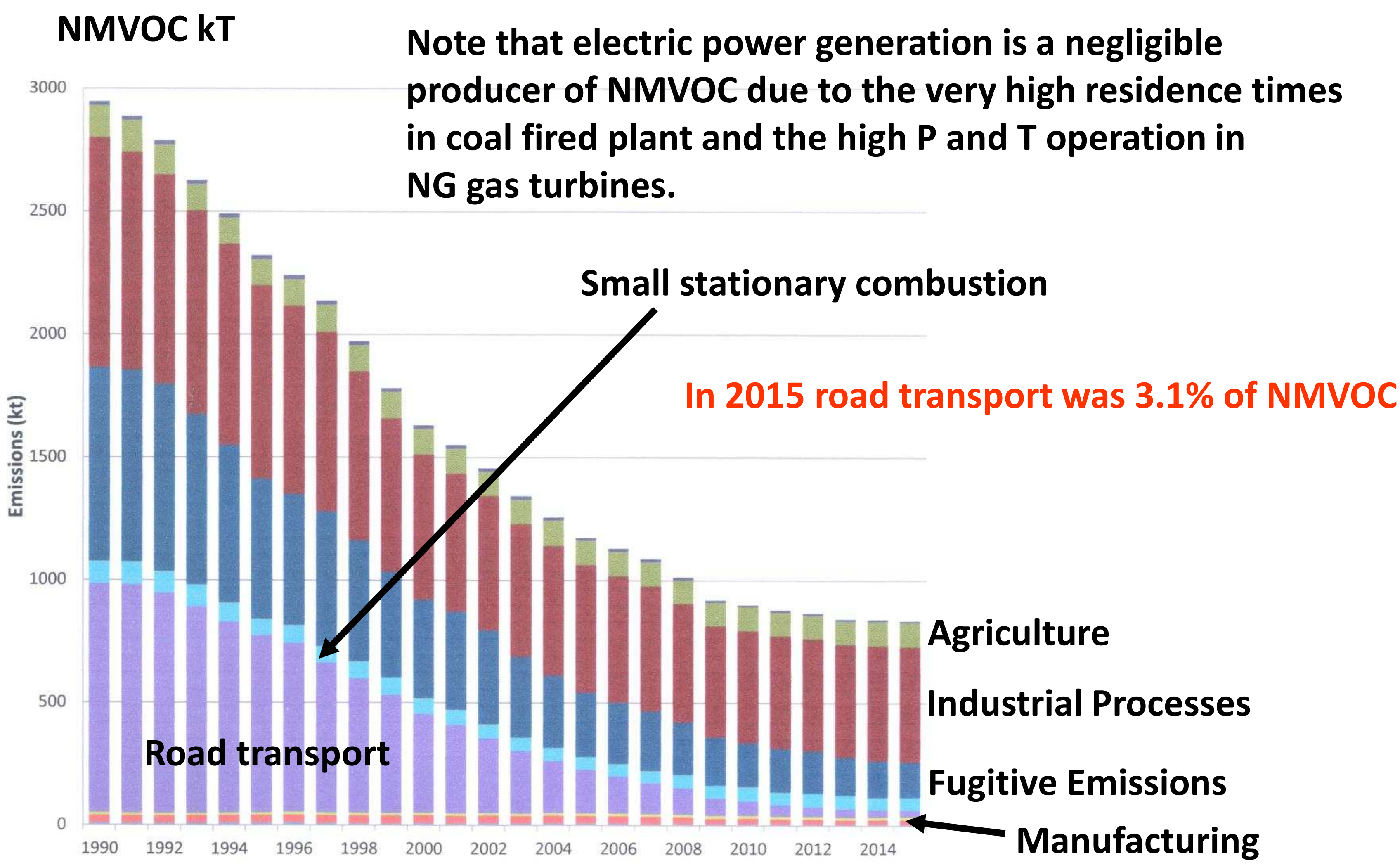
Light duty 10%

Heavy duty + buses = 8%

Total road transport = 34%

UK Informative Inventory Report (1990 to 2015) from the UK National Atmospheric Emissions Inventory (NAEI) Programme. March 2017. Wakeling et al. Ricardo Energy & Environment

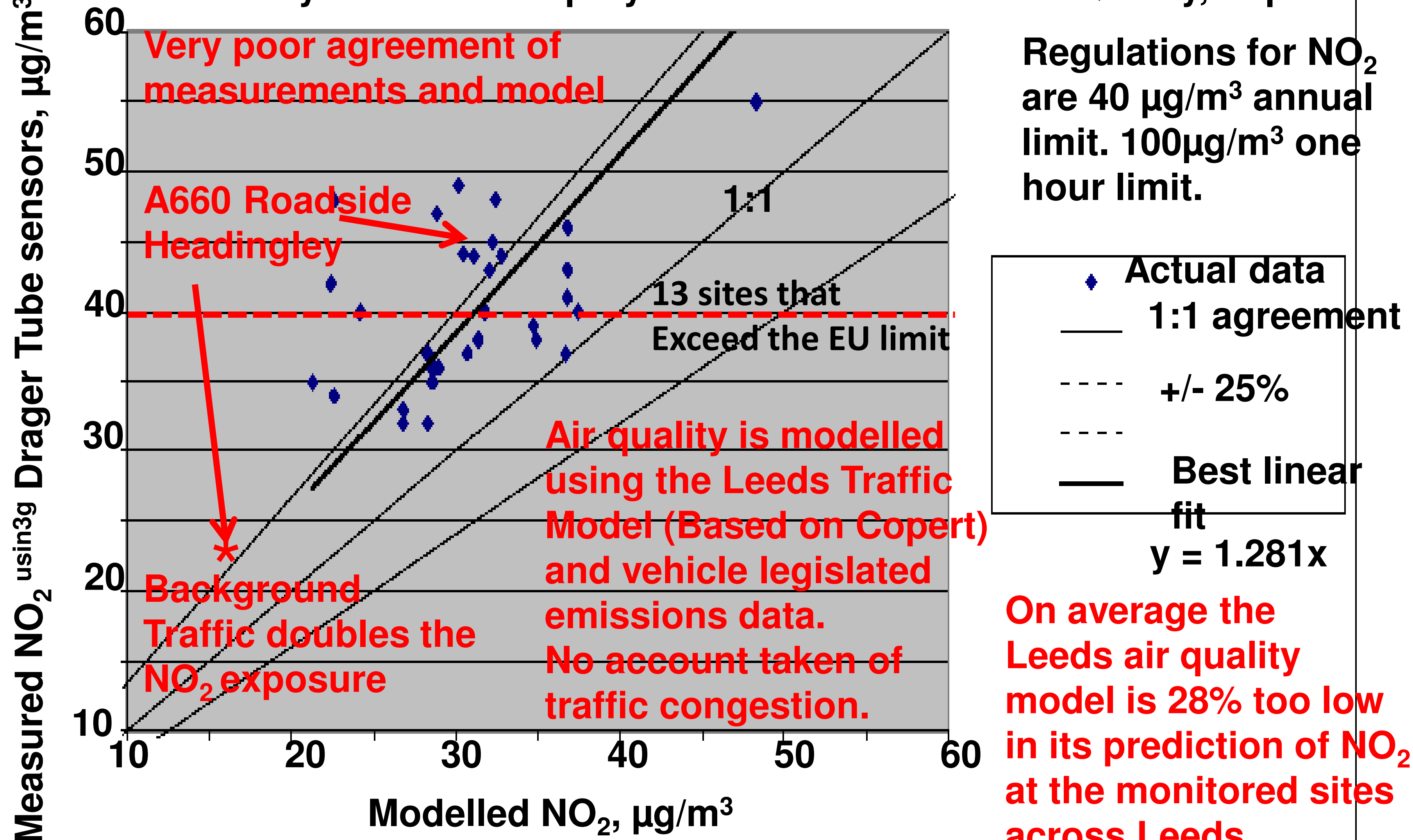
Figure ES.1-2 Total UK Emissions by Source Sectors of Non-Methane Volatile Organic Compounds (NMVOCs), 1990-2015.



Ahmad Khalfan, Gordon E. Andrews, Hu Li University of Leeds, UK

Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start

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



Note that the modelled air quality data only predicts 1 exceedance

SAE 2016-01-2326

The City of Leeds air quality data in 2009 shows a legislated roadside monitor by the test road in this work with an annual average of 45 μg/m^3 and a background sample close to the same location, but away from the road, of 22 μg/m^3.

This is a 23 μg/m^3 increase due to the road traffic.

If 34% of the background NO_x is from road transport as in the UK emissions audits for 2015, then 7 μg/m^3 of the background NO_x is from road transport.

If we assume that all the increase in NO_x at the roadside is due to road transport emissions then the total road transport NOx is 30 μg/m^3 which is 67% of the roadside NO_x.

It is vary rare to have the above combination of measurements and most estimates of transport contribution to roadside NO_x is via modelling.

Dept. for Environment, Food and Rural Affairs and Department of Transport May 5th 2017
Improving air quality in the UK: tackling nitrogen dioxide in our towns and cities
Draft UK Air Quality Plan for tackling nitrogen dioxide.

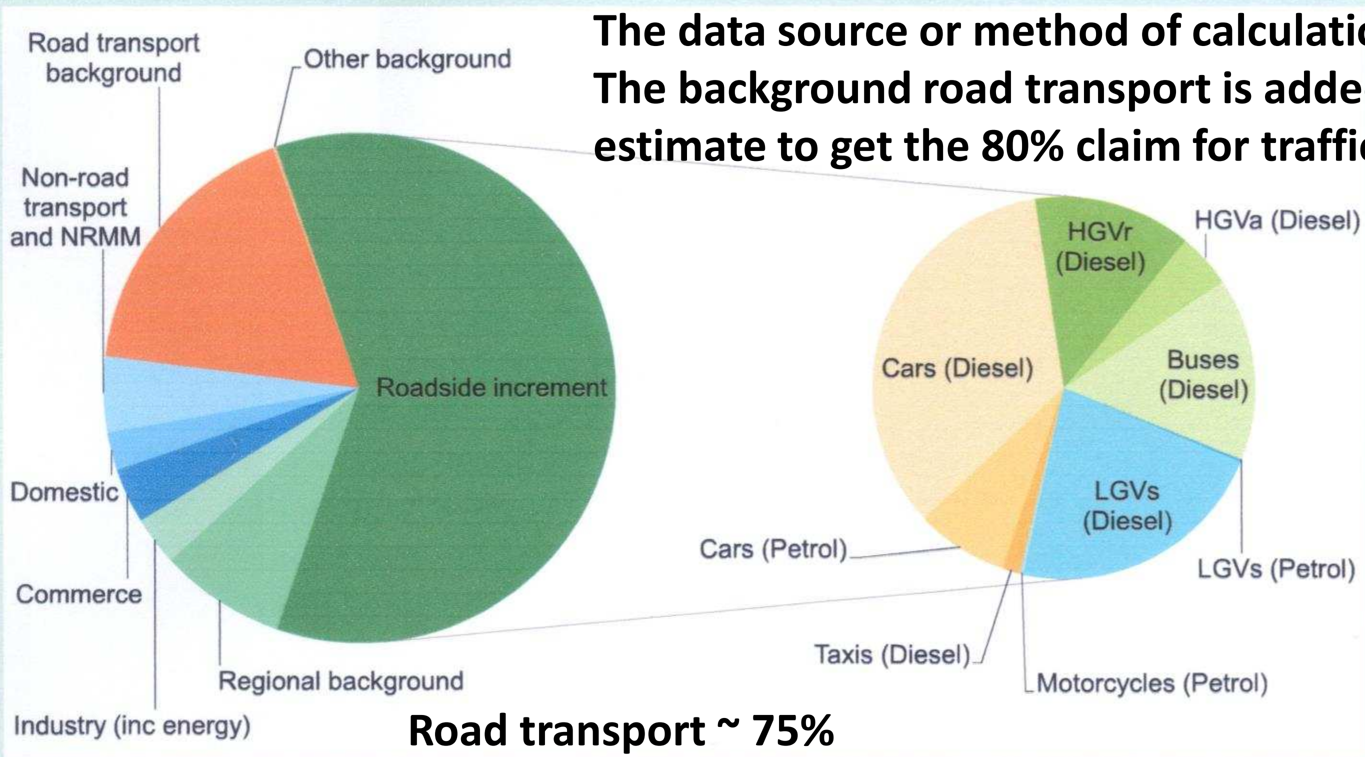
14. Although non-transport sources of NO_x are considerable contributors (Figure 2) road transport is responsible for some 80% of NO_x concentrations at roadside, with diesel vehicles the largest source in these local areas of greatest concern (Figures 3a; 3b and 3c).[11] This is due to both the significant growth in vehicle numbers, particularly diesel vehicles, and improvements in real world testing showing that laboratory test-based **Emission standards have not delivered expected reductions under real world driving conditions. (see also Section6) Ref. 12**

Ref. 12 DfT (2016) Vehicle Emissions Testing Programme report www.gov.uk/government/publications/vehicle-emissions-testing-programme-conclusions

Note that there is no reference for the statement that 'some 80% of NO_x concentrations at the roadside, with diesel vehicles as the largest source in these areas of greatest concern.' Note 11 refers to NO_x and NO_2 differences. It is not a reference for the statement.
In 2015 the NAEI for NO_x was 34% from road transport and of this only 16% was from passenger cars. However, transport will obviously contribute more to roadside pollution but the 80% figure needs details of the calculation.

Dept. for Environment, Food and Rural Affairs and Department of Transport May 5th 2017
Improving air quality in the UK: tackling nitrogen dioxide in our towns and cities
Draft UK Air Quality Plan for tackling nitrogen dioxide.

Figure 3a: Breakdown of UK national average NO_x roadside concentration into sources, 2015



The data source or method of calculation was not given. The background road transport is added to the roadside estimate to get the 80% claim for traffic contribution.

Road transport ~ 75%

Note: The 'Roadside increment' in the large pie chart is the estimate of the proportion of NO_x roadside concentrations contributed by local traffic, which is shown in greater detail in the smaller pie chart. NRMM = Non-Road Mobile Machinery; LGV = Light Goods Vehicles; HGVr = Rigid Heavy Goods Vehicles; HGVa = Articulated Heavy Goods Vehicles.

The NAEI details how the overall contribution to NOx from transport is based on real world measurements and diesel emissions are above the std. – but based on pre Euro 4 data in the main.

< how this estimate was made is not referenced.

In spite of the uncertainty of where the data comes from for the contribution of diesels to roadside air quality, the press has picked up on these numbers.

Diesels contributing 80% to roadside NO_2 have been quoted in newspapers.

The Mayor of London, Sadiq Khan, has quoted the diesel as contributing 90% to roadside NO_x emissions. He uses this figure to demand that the diesel be banned in London and urges the UK Government to bring forward the date when diesel engines will not be allowed for sale.

This data comes from modelling air quality and there is little work on measuring roadside emissions and also measuring the background NO_x in the same location but away from the influence of the road.

Contents

Passenger Car Test Cycles and Real World Driving

Vehicle emissions up to Euro 6d have been based on regulated test cycles. Initially the USA, Europe and Japan had different test cycles and the NEDC was used in Europe from Euro 3 in 2000 to Euro 6 and the WLTC has taken over from Euro 6d onwards.

The drive to change to the WLTC was the concern that the NEDC was not representative of real world driving and emissions compliance with this test cycle had not resulted in equivalent improvements in air quality. The development of Real Drive Emissions RDE legislation in Euro 6d has the same origins, with improved air quality as the goal.

However, the aim of test cycles was to compare a Ford car with a VW car with a Honda on the same quantitative basis using test procedures that were accurate to 1% or better.

It was always known that these test cycles were not representative of real world driving – both NEDC and FTP75 were known in the 1990s not to be representative of real world driving – but they were better than steady state testing, which was the testing basis prior to these cycles.

Summary of RDE limits for Urban Driving

Distance > 16km (Impractical as data shows typical urban journeys are much shorter than this)

Share of total RDE distance = 29-44% (Minimum Total 36 – 55 km)

Average speed 15 – 40 kph (Equivalent to 17 - 69% Congestion) **Peak <60kph**

Stops and Idle 6- 30% and individual stops <300s

Acc x Vel <0.136 V + 14.44 (For the allowed speed range in urban driving this is 16.4 - 19.9 m^2/s^3 [kW /tonne], this is how aggressive Urban drivers are eliminated)

Cold Start

Ave. speed 15 – 40 kph (as for hot start)

Max speed - < 60 kph (This is also unrealistic as it will cause catalysts to light off very quickly and is an illegal speed in UK urban areas (max. 48 kph and 32 kph in many areas)

Idling after first ignition <15s

Cold start stop < 90s

To comply with these cold start limitations you cannot cold start into congested traffic, but this is reality in major cities with houses alongside major commuter routes.

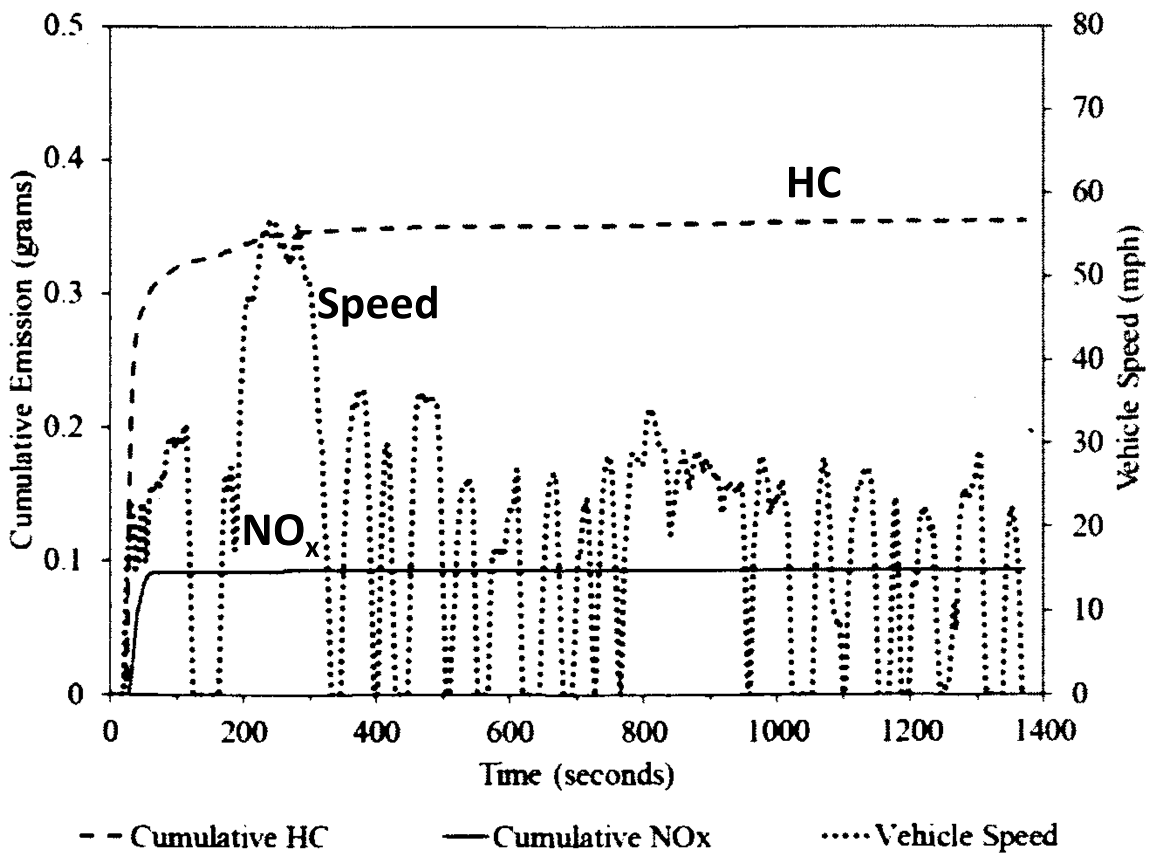
A key feature of these limits is there is no specific requirements for common road events such as traffic light junctions, right and left hand turns, traffic merging events etc. In our experience emissions occur at specific road events and are near zero in between, once the catalyst is hot.

Pham, A. and Jeftic, M. CARB SAE 2018-01-0428

Characterization of gaseous emissions from blended plug in hybrid electric vehicles

During high power cold starts.

FIGURE 5 Cumulative FTP HC and NOx emission for a SULEV vehicle.



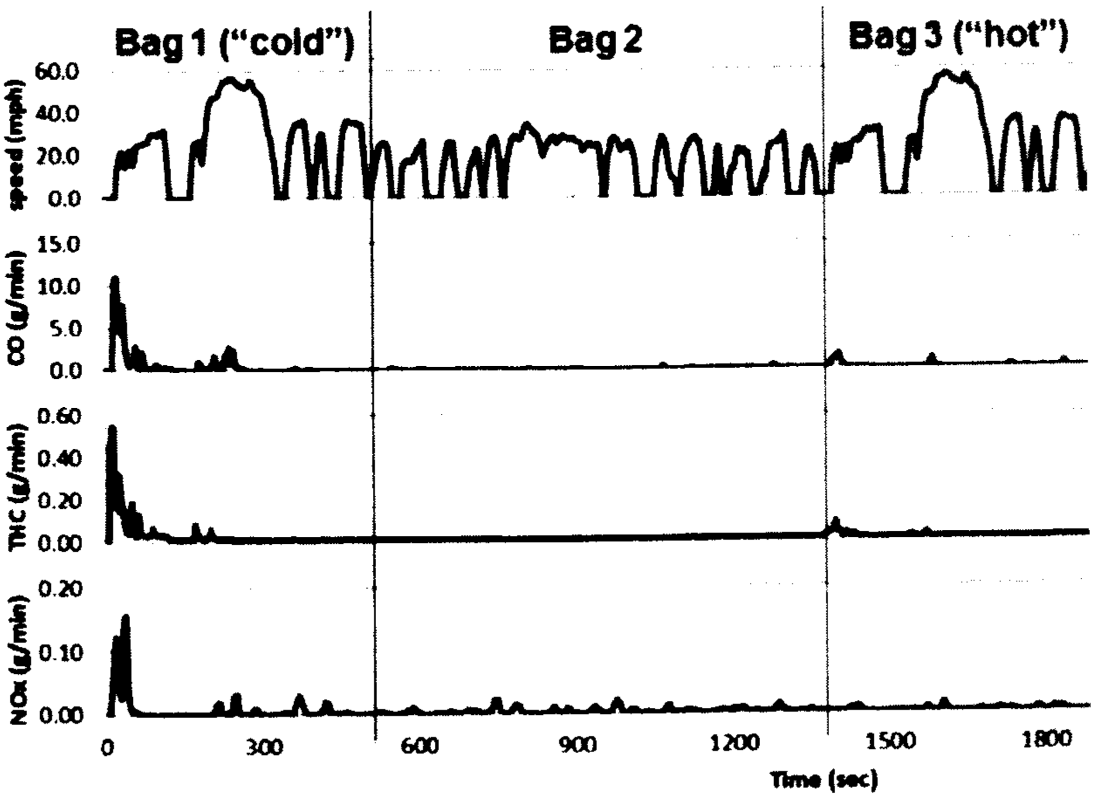
Ford Fusion Energi
LEV II SULEV
7.6 kWh battery
2L engine
1784 kg

90% of HC and 98% of NO_x emitted in the first 120s cold start of the test. Most of this emitted in the first 50s.

Pihi, J. et al. Oak Ridge NL SAE 2018-01-1264

Development of a cold start fuel penalty metric for evaluating the impact of fuel compsition changes on SI engine emissions control.

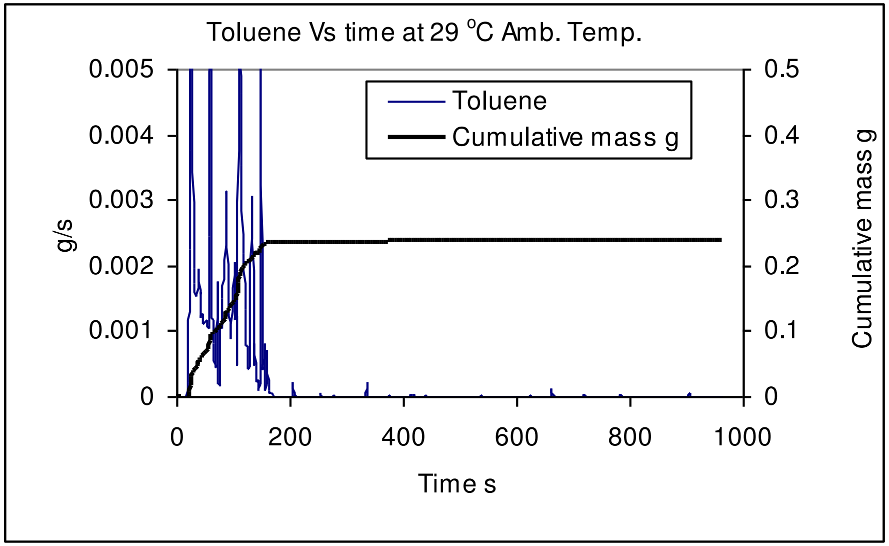
FIGURE 1 FTP time traces for vehicle speed and regulated gaseous emissions. Data were produced using the Ford Focus ST.

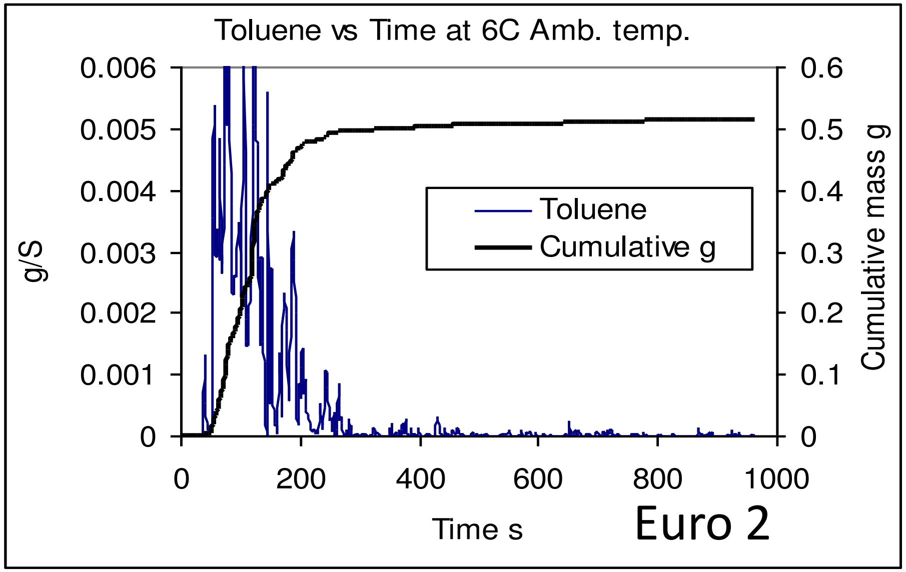


Ford Focus ST 2013
2L, GDI turbo

FTP 75
Most of emissions during cold start over first 100s.

Toluene emissions as a function of warm up and ambient temperature

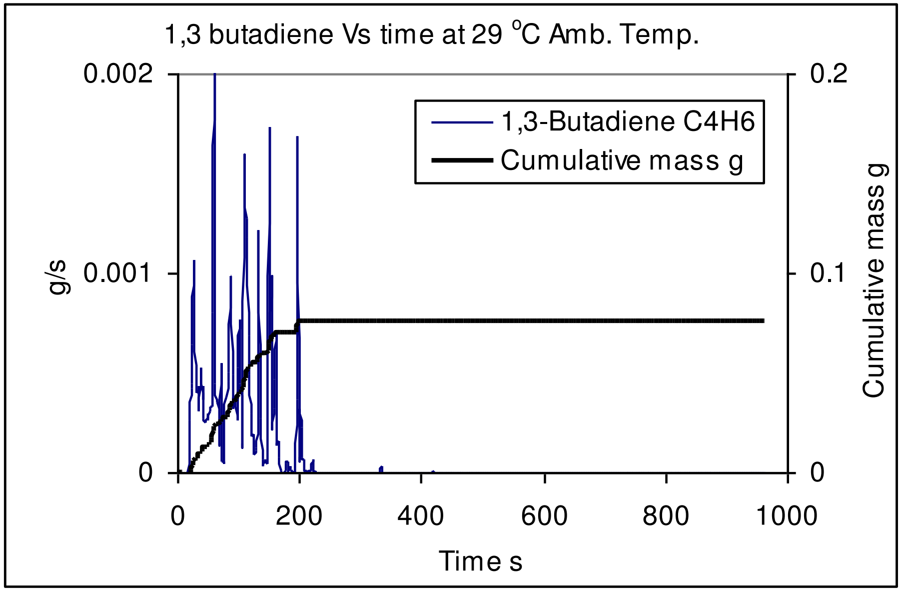


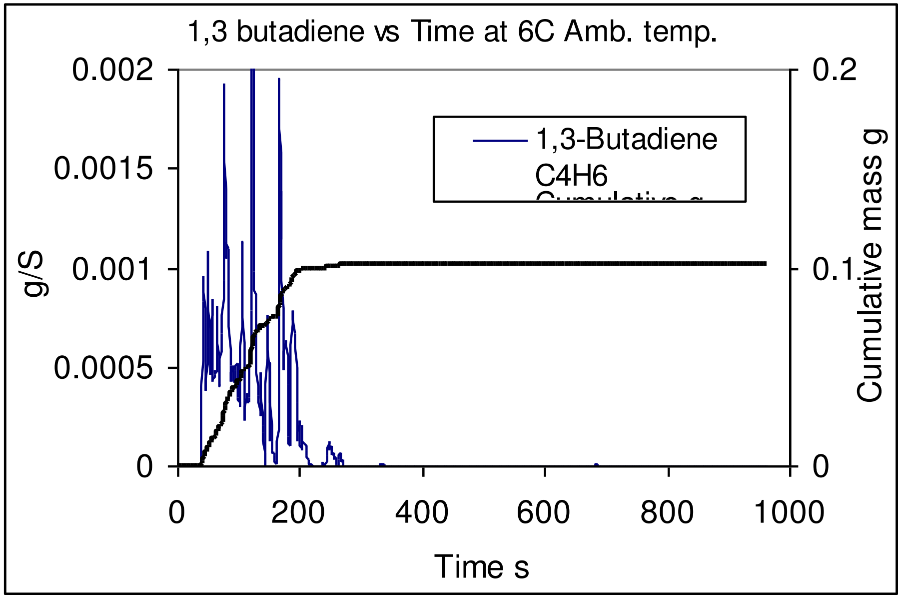


The toluene emissions show the classic cold start effect that was expected. No toluene emissions after ~150s at 29°C and very low levels after ~250s at 6°C cold start.

SAE Paper 2008-01-1303.

1,3 butadiene emissions as a function of warm up and ambient temperature





Classic cold start Emissions results for 1,3-butadiene.
TWC light of times of ~200s.
No detectable emissions after the catalyst was hot.

SAE Paper 2008-01-1303.

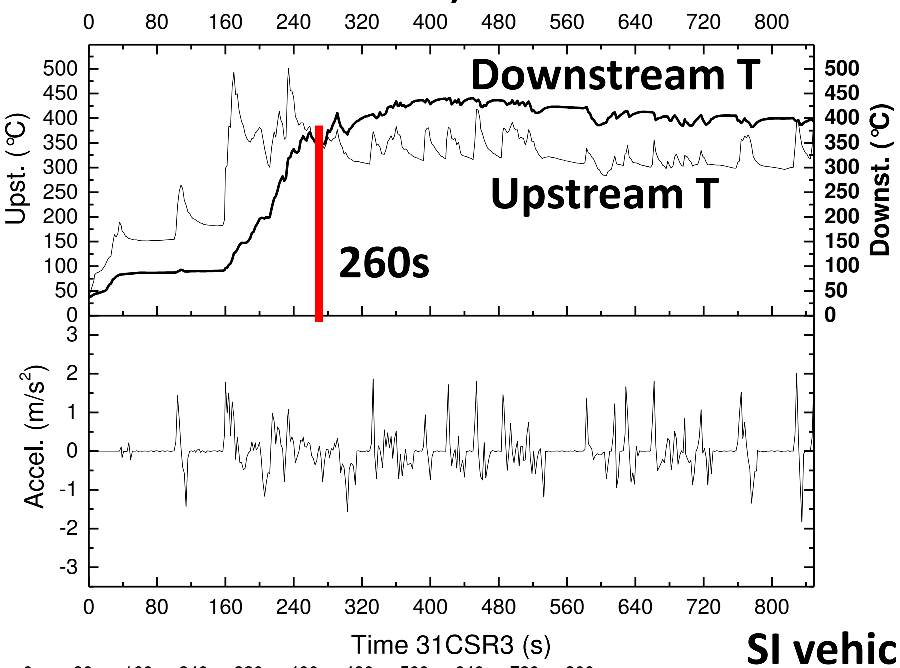
The impact of the long journey distances in RDE is to dilute the cold start emissions.

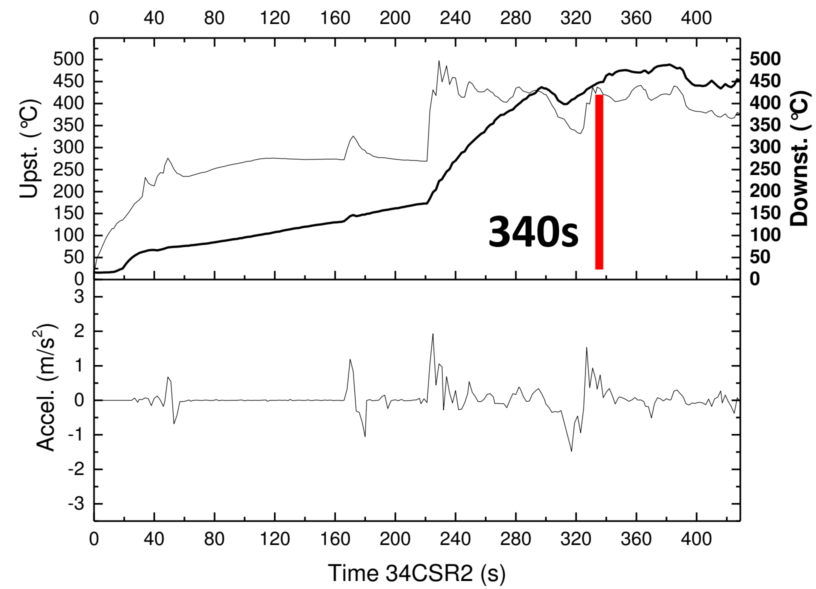
In modern vehicles, as I have just shown, the CO, HC and NO_x are mainly emitted in the cold start. For TWC SI vehicles with the catalyst hot there are no further emissions in the rest of the journey.

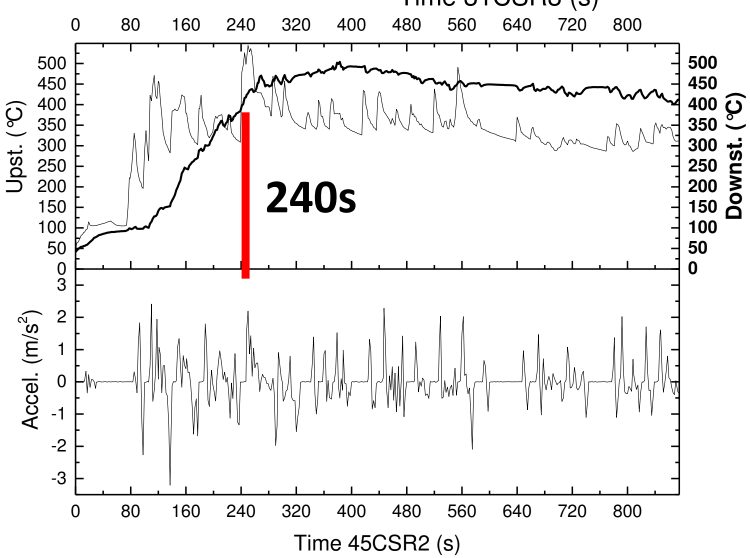
The net result is that the cold start emissions are the same, but the whole journey emissions decrease on a per km basis as the length of the journey increases. For those who live in the urban area where the cold start occurs, the emissions are the same.

For CO_2 the vehicle will continue to use fuel and the longer distance may have some relevance in representing the average CO_2 emissions.

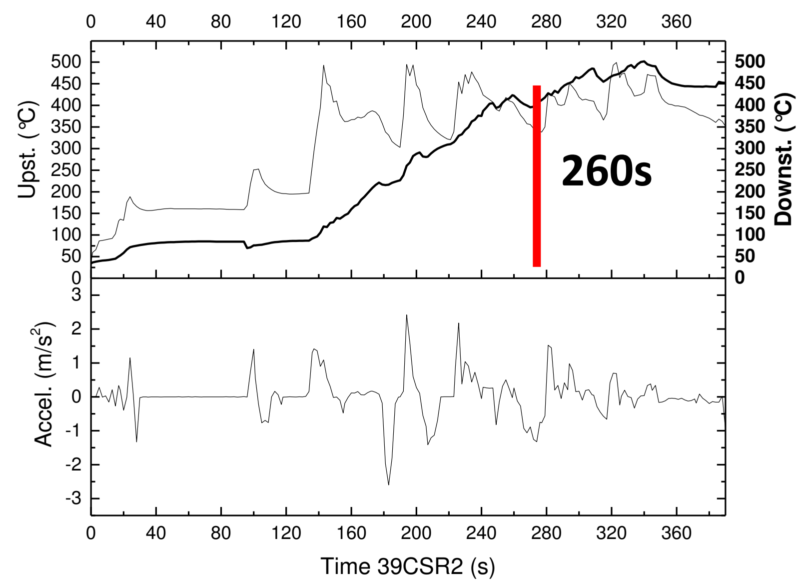
For diesels there can be other emissions on the journey as the engine out HC and CO are too low to heat the catalyst and so the catalyst can cool if it meets congested traffic or a downhill portion of the journey where the engine motors. In both cases the catalyst de-lights and there is a new cold start.







SI vehicles have high engine out CO and HC. Catalyst is heated by their heat release at the TWC



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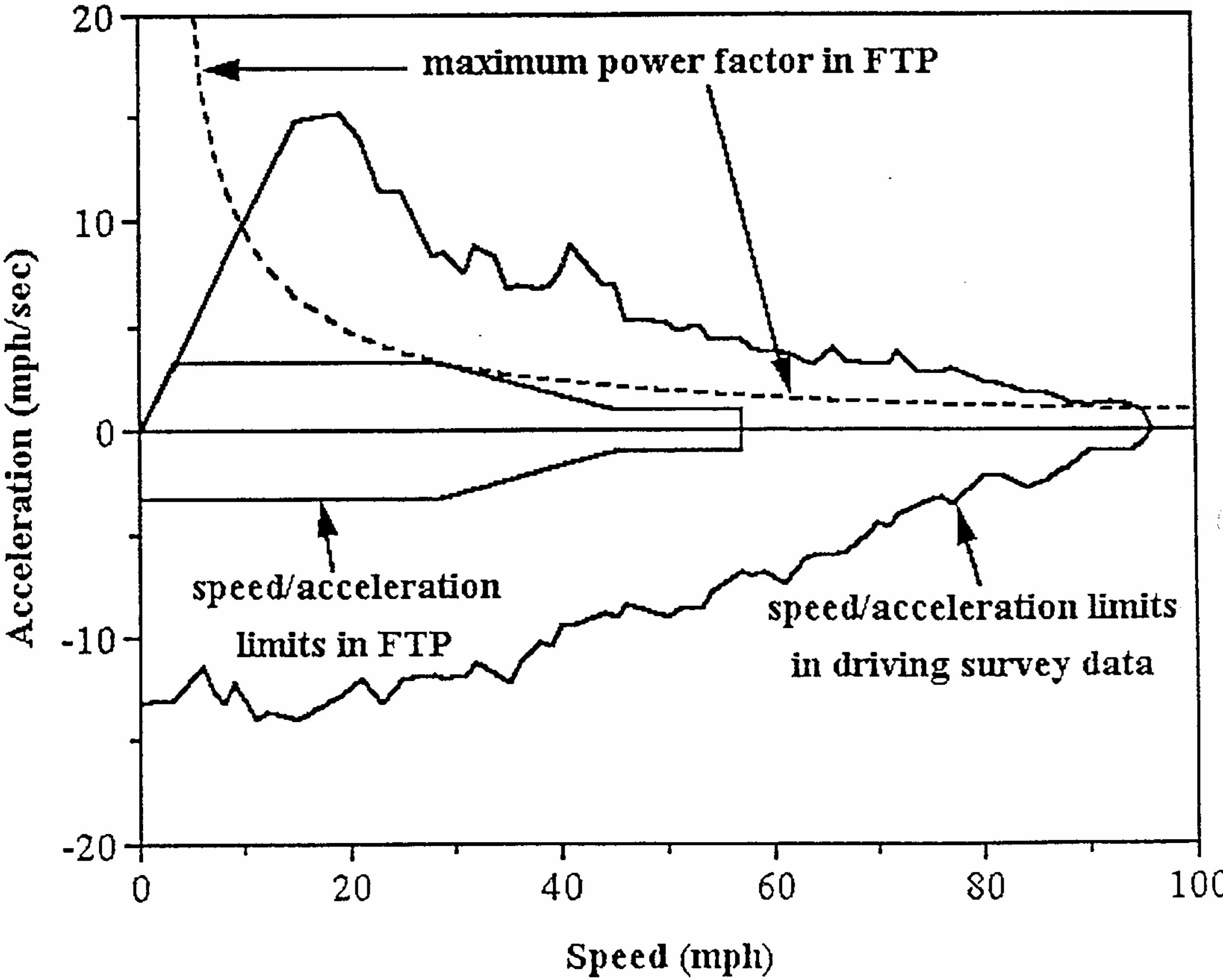
Test Cycle	NEDC	FTP	JC09	WLTC	RDE Urban	Leeds Work
Mean Vel. kph	33.6	31.5	24.4	46.5	15 - 40	5–26
Congest.	30%	34%	49%	3%	17-69%	46 - 90%
Max. Acc. m/s^2	1.0	1.5	1.7	1.7		2.2–2.8
Mean Acc m/s^2	0.59	0.50	0.42	0.41		0.35-0.51
Dist., km	11	12	8.2	23.3	>16km 29-44%	5
No. Acc. from idle /km	1.3	1.5	1.5	0.4		1.4 - 7
Idle %	23.7	17.6	28.7	12.6	6 - 30	20 - 57

In congested traffic real world driving mean speeds are lower that in test cycles and RDE limits, peak acceleration and deceleration rates are higher than on test cycles, idle proportion is higher than on WLTC and typical RDE and the number of stop/starts are greater.

Real World Emissions 1995, CRC

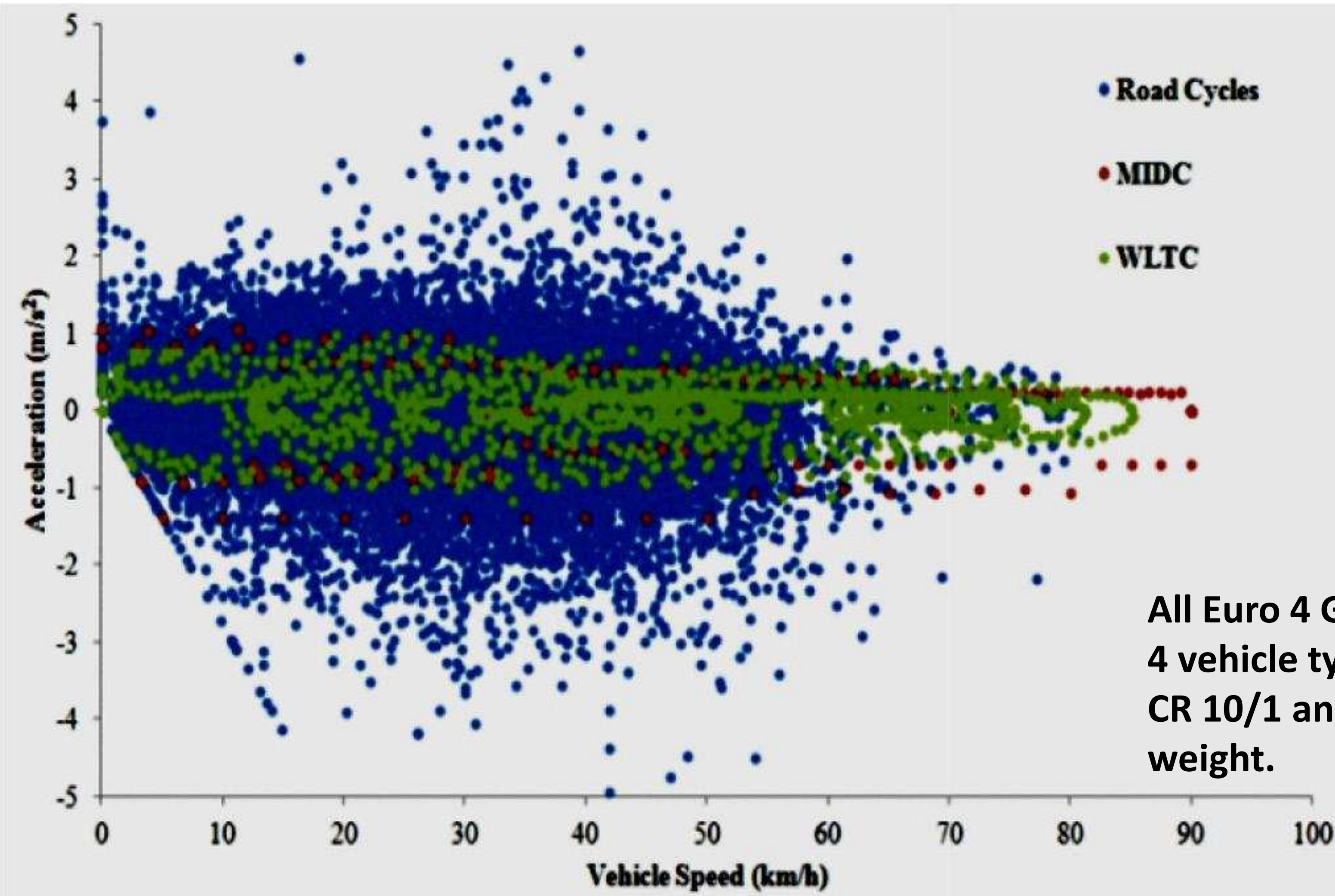
Figure A.11. FTP driving compared to real-world driving in the three-parameter driving d[illegible]a



The FTP test cycle does not have acceleration rates that are representative of the real world.
The ECE test cycle has even lower acceleration rates.

Pathak, S., Singh, Y., sood, V., and Channiwala, S., "On-Road Vehicle Driving and Energy Requirements and Impact on Unregulated Exhaust Emissions under Urban Driving Conditions,"

***SAE Int. J. Engines* 10(4):2017, doi:10.4271/2017-01-1013. CSIR India + SV NIT**



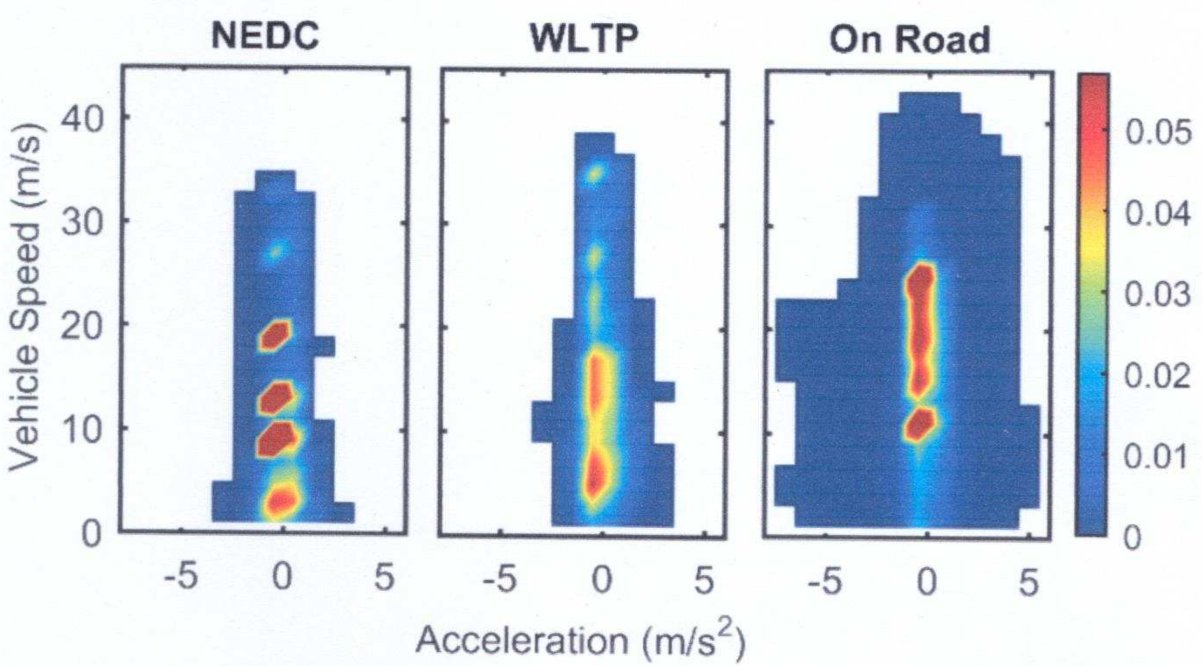
All Euro 4 Gasoline
4 vehicle types, all ~1L
CR 10/1 and 850kg kerb weight.

R. Burke, Analysis of Diesel Passenger Car On-road and over Standard Cycles., U. Bath Powertrain & Vehicle Research Centre, PVR.

IMechE Real Driving Emissions: The impact on Engineers 31st Oct. 2017

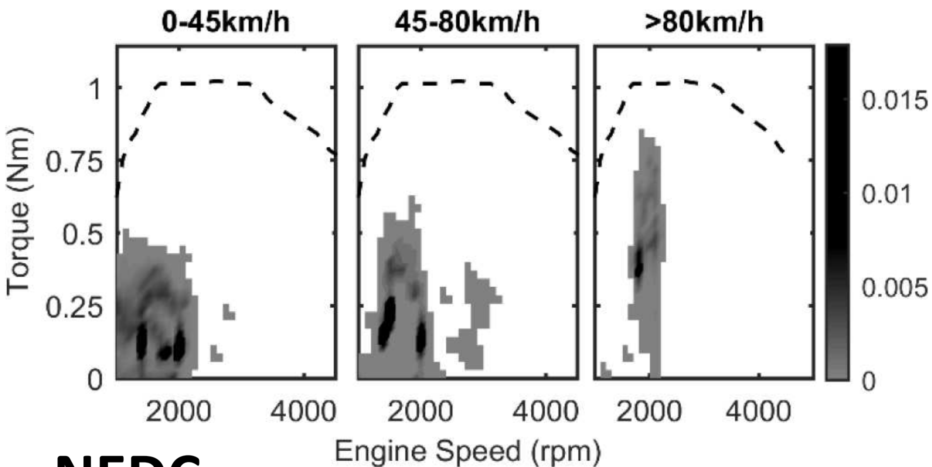
Transient Differences

- Quantification of the transient differences between on-road and standard CD cycles
- Acceleration vs. vehicle speed
  - Wider range of accelerations in WLTC/on-road
  - Narrow hot spots for on-road/NEDC due to steady speed conditions

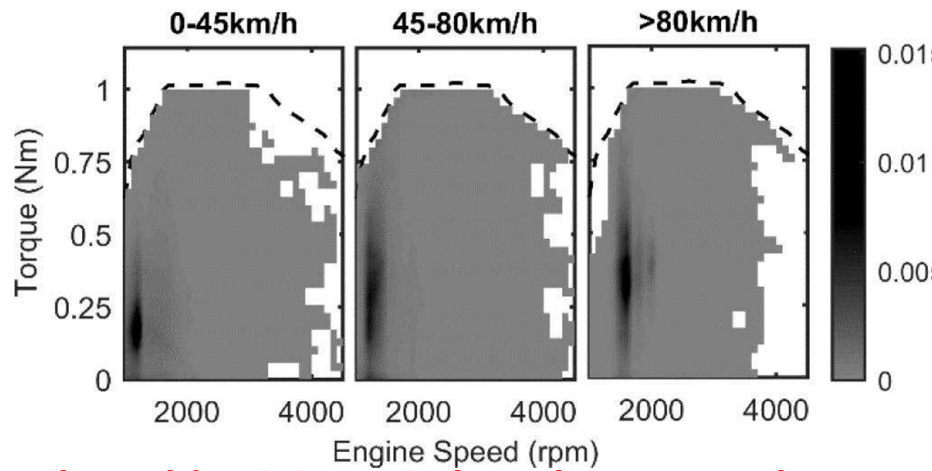


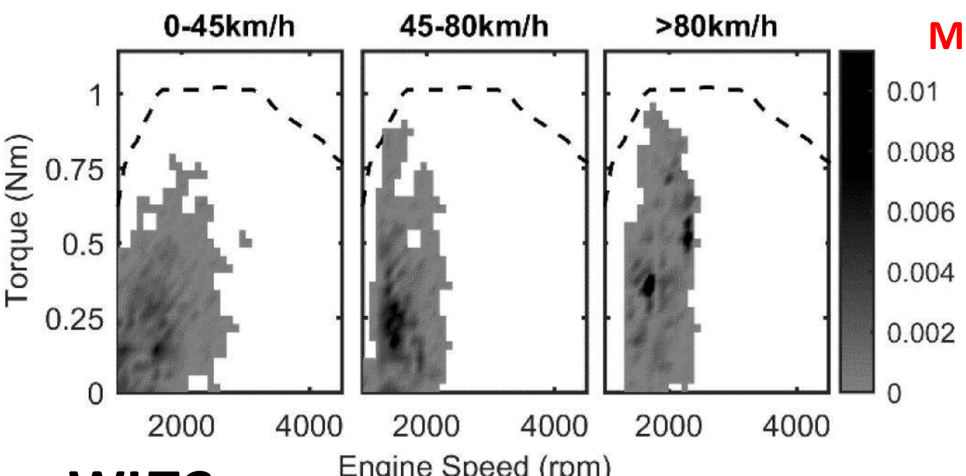
Chappell, E., Burke, R., Lu, P., Gee, M. et al., "Analysis of a Diesel Passenger Car Behavior On-road and over Certification Duty Cycles," *SAE Int. J. Engines* 9(4):2016, doi:10.4271/2016-01-2328. U. Bath + Shell

Diesel vehicle 2014 2.0L. Aftertreatment – DOC + DPF + SCR.



NEDC





WLTC

Real World Driving Trip length Mean 44 km

Max. 208 km. Ave. trip speed 39 kph max. 88 kph

It is obvious from the plots that the on-road driving has covered a much broader region of the speed torque map with the most notable differences being:

1. The low speed/high torque region
2. Engine speeds above 2500rpm

These two regions are not visited during NEDC and only briefly during the WLTC cycle.

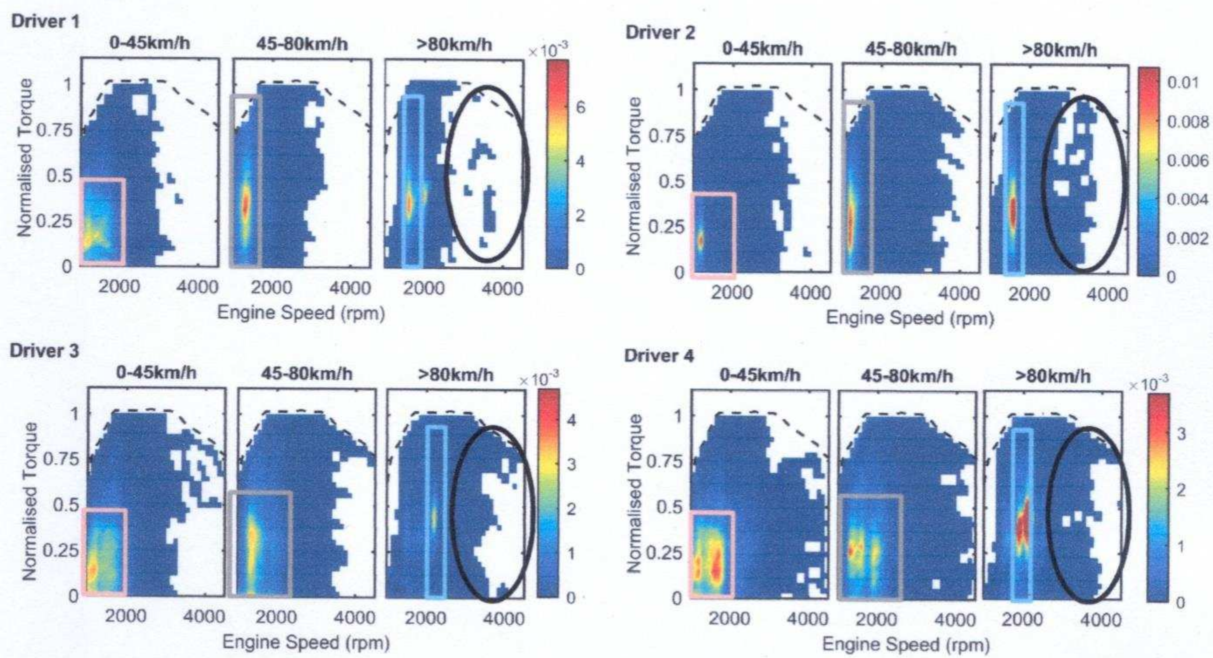
R. Burke, Analysis of Diesel Passenger Car On-road and over Standard Cycles., U. Bath Powertrain & Vehicle Research Centre, PVR.

IMechE Real Driving Emissions: The impact on Engineers 31st Oct. 2017

Driver-to-driver variation

- "Driver" = "Driver/Route combination

- Similar concentration of points for all drivers at low vehicle speeds <45km/h
- Drivers 1 and 2 use lower speed range but wider torque range 45-80km/h
- High vehicle speed:
  - Most common operating points are similar
  - Drivers 3 and 4 use higher speed range more often

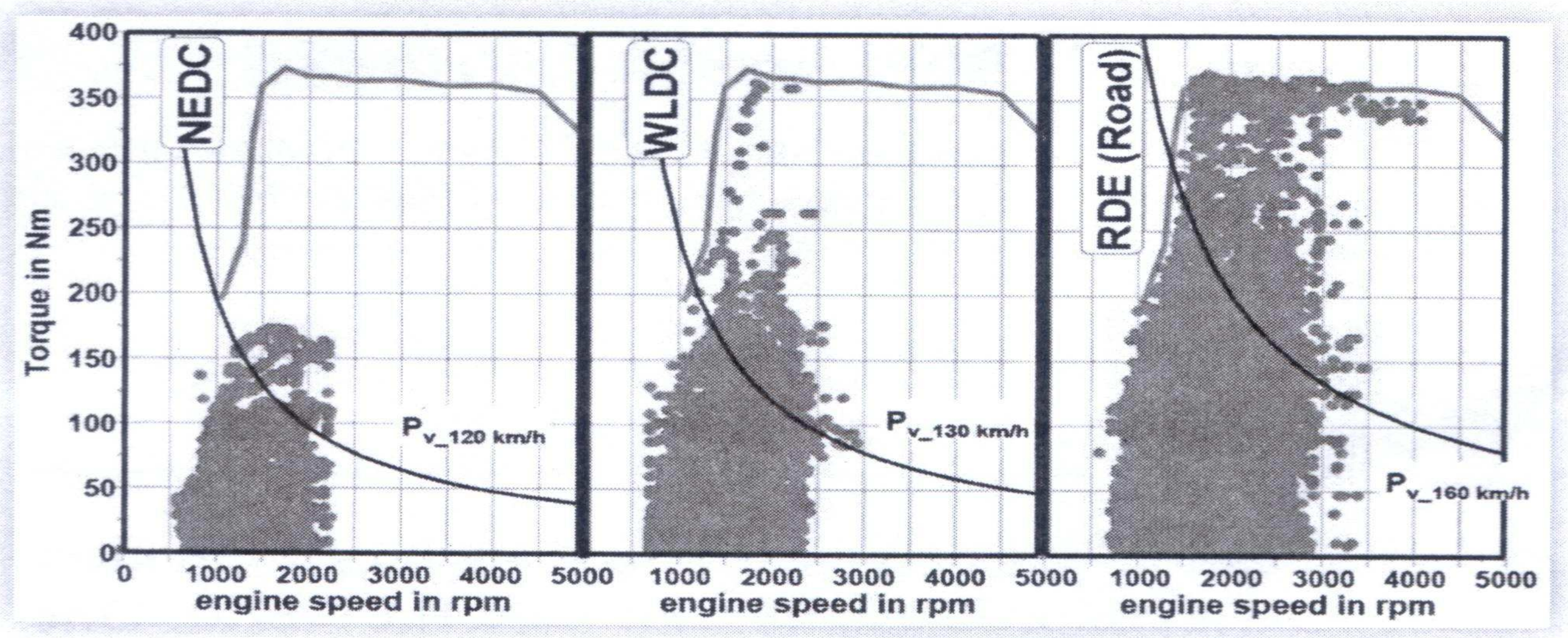


Predetermined vehicle speed/gear shift test cannot capture driver-to-driver variations

Dost, T. and Getziaff, J. West Saxon Univ., Denmark. SAE 2018-01-0378

Cylinder Individually Gas Exchange Controlling:A method for improved efficiency of turbocharged SI engines.

FIGURE 2 Load distribution in the engine map of a middle class passenger car (Audi A5 Model 2016) under the various exhaust gas regulations [3]. Engine facts: 2,0 l 4 Cylinder SI Engine with Direct Injection and Turbocharging, 185 kW, 370 Nm



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Driving route and test cycle

LU-UDTC: Leeds University Urban Driving Test Cycle

Fig.4 Driving route of LU-UDTC

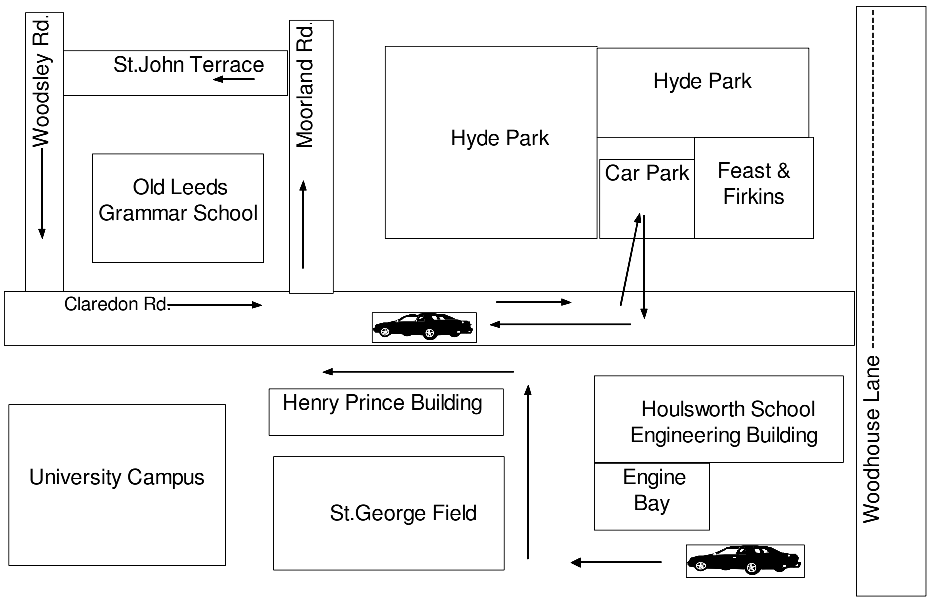
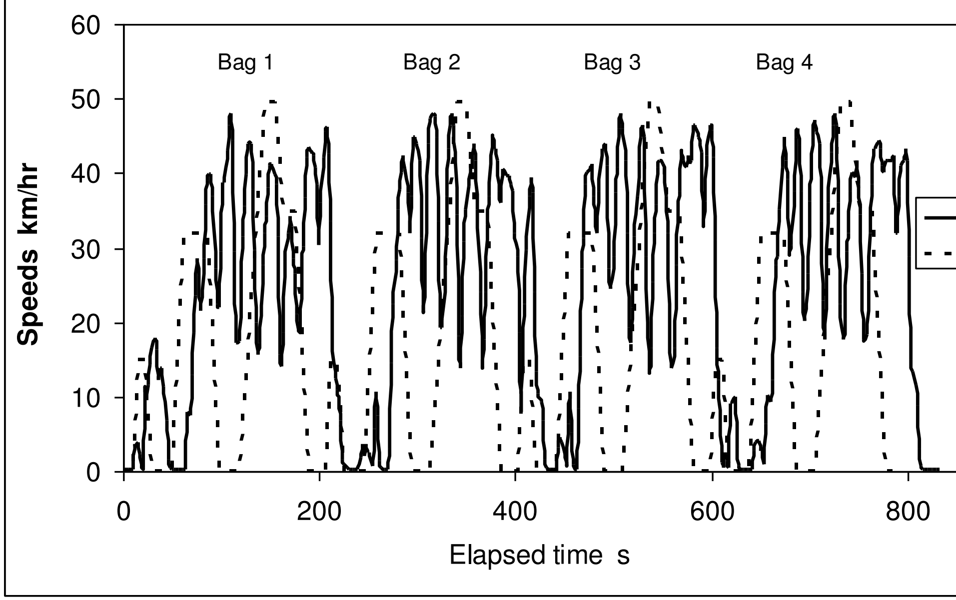


Fig.5 Typical profile for LU-UDTC driving mode



SAE 2004-01-2903 Hu Li and Andrews G.E. U. Leeds

Average emissions for 4 HPLA loops – SI For Mondeo λ=1

	Euro 1	Euro 2	Euro 3	Euro 4	E4 X NEDC
CO g/km HPLA	7.2 X2.7	5.9 X2.7	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 x2.6	0.51 X2.4	0.44 X2.9	0.15	1.9
LUBS*				0.14	1.8
Euro	0.42	0.21	0.15	0.08	

* SAE 2008-01-1307

SAE Paper 2012-01-0880

Comparison with the urban real world driving circuit

(SAE 2005-01-0676)

Influence of speed control bumps for 30mph zone

	Bumps g/km	Urban circuit	Euro 1 g/km
CO_2	607 X3.4	365	180
CO	5.4	9.9	2.7
NO_x	3.6 X 8.6	1.3	0.42
THC	1.02	1.2	0.55

SAE 2005-01-1620 Hu Li and Andrews G.E., U. Leeds

% Change in toxic emissions

	Smooth Run	With Humps	% Change
Toluene	2 mg/km	14 mg/km	600
Formaldehyde	6 mg/km	14 mg/km	133
Acetaldehyde	1 mg/km	2 mg.km	100
1,3 Butadiene	3 mg/km	21 mg/km	600
Benzene	13 mg/km	52 mg/km	300

These results for toxic air pollutants show a greater influence than for the 148% average increase in THC, some of the toxic HCs were increased by more than twice the average.

SAE 2005-01-1620 Hu Li and Andrews G.E. U. Leeds

James Wylie, JM, Technology to Meet Diesel Eu6d Standards
13th Integer Emissions Summit & AdBlue Forum Europe 2017, Dresden, 29 Jun

Euro 6 Technology Can Significantly Reduce Real World NOx

A number of tested diesel vehicles already meet Euro 6d in the real world on EA Cycle

OEM	Model	Model Year	Engine (L)	Power (bhp)	EQUA EF	OEM	Model	Model Year	Engine (L)	Power (bhp)	EQUA EF
Audi	A5	2014	2.0	161	1.0	Audi	A4	2014	2.0	148	2.1
Audi	Q2	2016	2.0	150	1.0	Audi	A6	2016	2.0	197	2.1
Mercedes	E-Class	2016	2.0	194	1.0	BMW	3 Series	2016	2.0	161	2.1
Seat	Alhambra	2015	2.0	150	1.0	Ford	Fiesta	2015	1.5	94	2.1
Skoda	Superb	2016	2.0	148	1.0	Jaguar	XE	2016	2.0	178	2.1
VW	Golf SV	2015	2.0	148	1.0	Jaguar	XF	2015	3.0	296	2.1
VW	Passat	2016	1.6	118	1.0	Land Rover	R R Evoque	2016	2.0	179	2.1
VW	Scirocco	2015	2.0	148	1.0	BMW	Mini One	2015	1.5	116	2.1
VW	Tiguan	2016	2.0	150	1.0	Skoda	Octavia	2016	2.0	191	2.1
VW	Tiguan	2016	2.0	240	1.0	Skoda	Superb	2016	1.6	118	2.1
VW	Touran	2016	1.6	108	1.0	VW	CC	2016	2.0	190	2.1
Audi	A3	2016	2.0	150	1.5	VW	Golf	2016	1.6	110	2.1
Volvo	S60	2016	2.0	148	1.5						

JM Source: EQUA index by Emissions Analytics (EA) http://equaindex.com/download/6980/ 9

Euro 6d are the first generation of diesel to have to comply with RDE legislation and WLTC and they so comply as shown above and some also meet the 2021 requirement for equal emissions to the WLTC. The modern diesel this year is not a cause of urban pollution.

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1. Roadside NO_x exceedances of EU air quality standards and the legal requirement to reduce real world traffic emissions.
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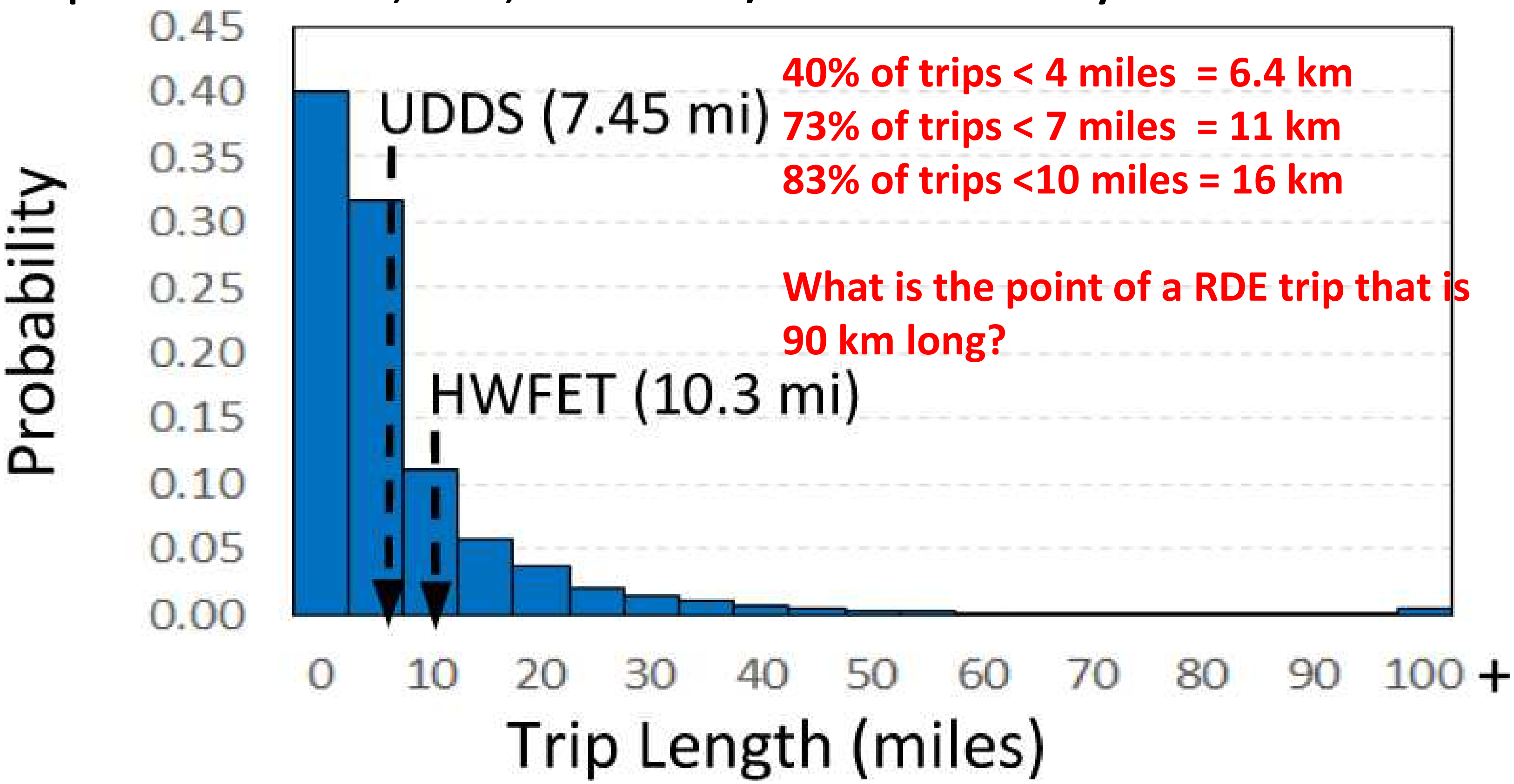
Laberteaux, K. and Hamza, K., "A Study of Greenhouse Gas Emissions Reduction Opportunity in Light-Duty Vehicles by Analyzing Real Driving Patterns," SAE Technical Paper 2017-01-1162, 2017, doi:10.4271/2017-01-1162. Toyota



All 2910 monitored vehicles in the CHTS data set (from all over California, monitored for approximately. one week, including weekdays and weekends), with their recorded trips (total 65,652 trips), as well as several standard drive cycles [28] such as UDDS, HWFET, NYC, LA92 and US06. A histogram of the trip lengths in the data set is shown in Fig. 2, with the values for UDDS and HWFET marked.

M.Andre, SAE Paper 890874
Paris traffic journeys
68% <5km

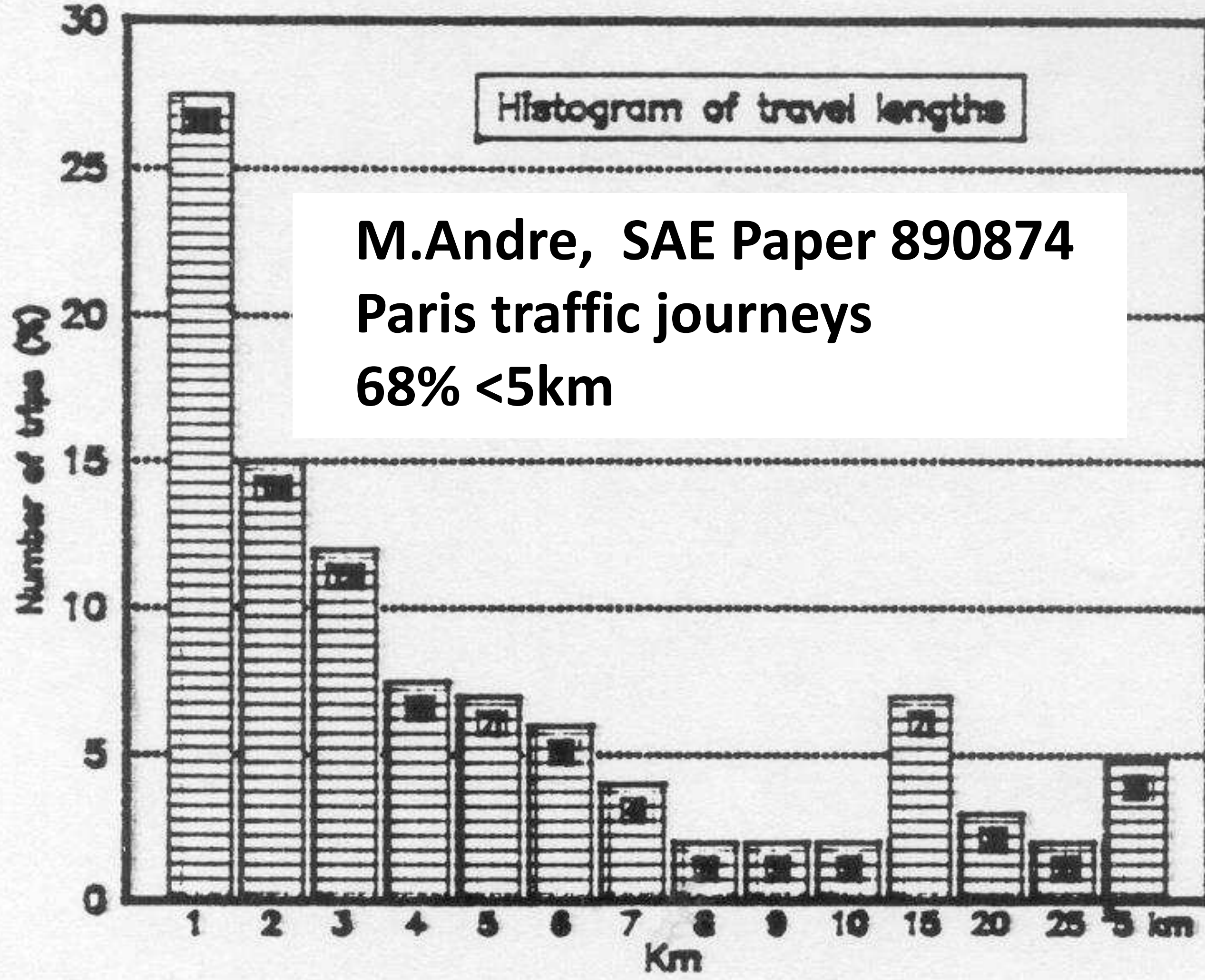
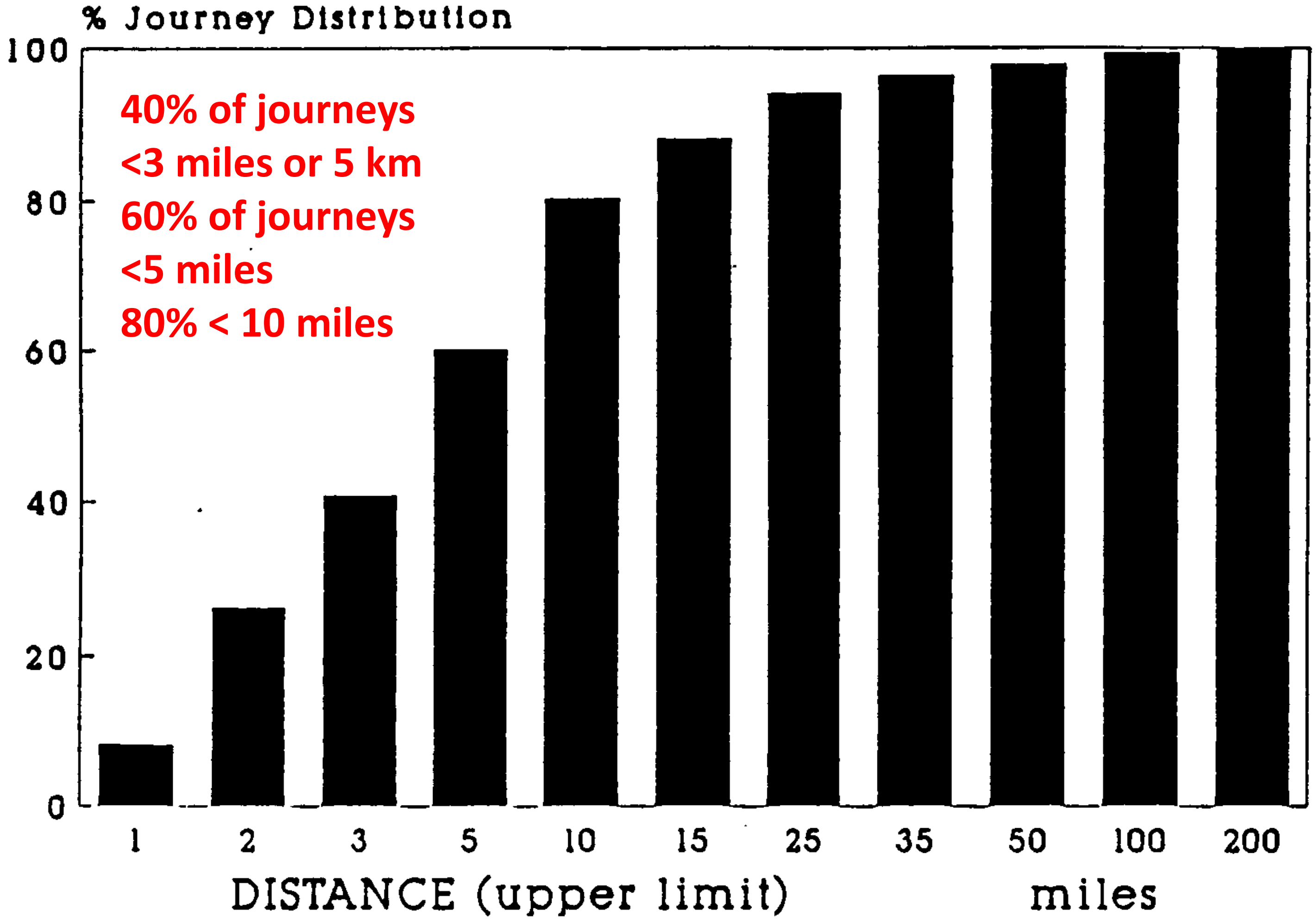


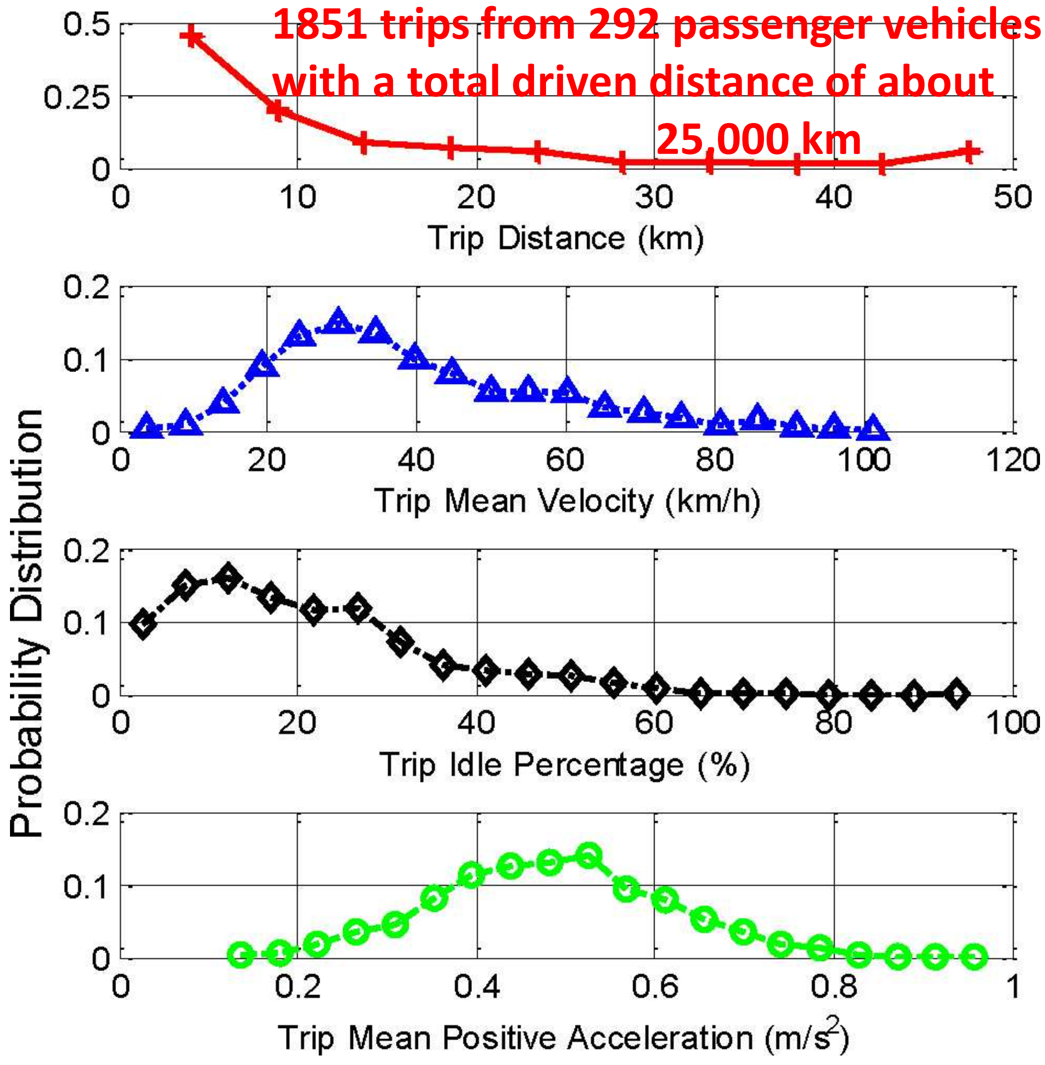
FIG. (2.2)
Histograms of travel lengths and instant speeds.

CAR JOURNEY DISTRIBUTION BY DISTANCE



Ref:1985/86 National Travel Survey (DOT)

Liu, Z., Ivanco, A., and Filipi, Z., "Impacts of Real-World Driving and Driver Aggressiveness on Fuel Consumption of 48V Mild Hybrid Vehicle," *SAE Int. J. Alt. Power.* 5(2):2016, doi:10.4271/2016-01-1166. Clemson-ICAR,Clemson Univ. , Greenville, South Carolina, USA.



50% of journeys <5km

RDE unrepresentative of real world driving, as the distance driven is excessively high.

Most common journey average speed is 30 kph (OK for RDE)

Most common idle is 10% and Idle proportions 10 – 30% are common (RDE 6-30% so in agreement)

National Renewable Energy Laboratory. Transportation Secure Data Center: www.nrel.gov/tsdc. 2001-2002.

UK Informative Inventory Report (1990 to 2015) from the UK National Atmospheric Emissions Inventory (NAEI) Programme. March 2017. Wakeling et al. Ricardo Energy & Environment p.139

Table 3-17 Average Traffic Speeds in Great Britain

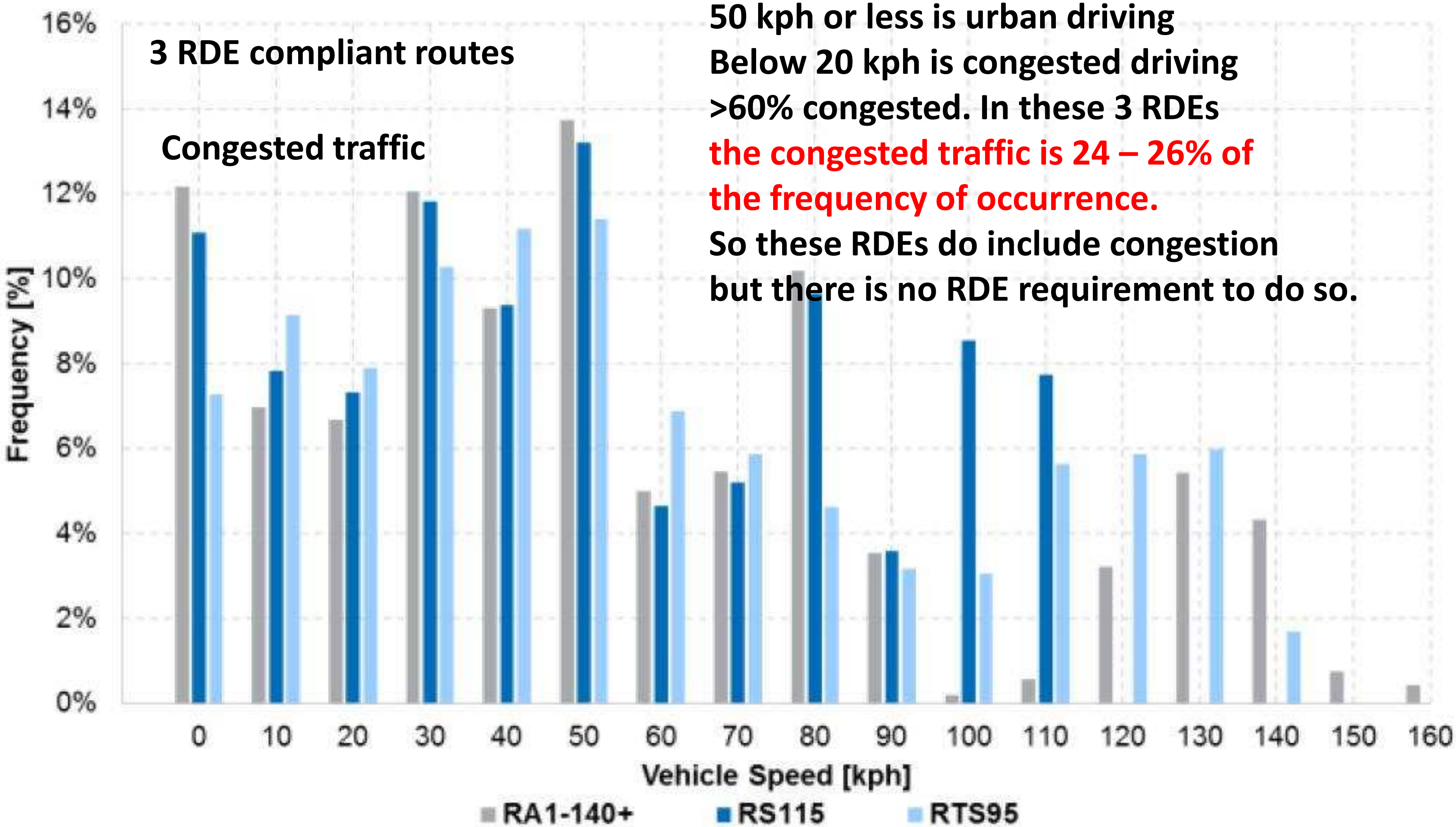
Road Type		Cars & LGV (kph)	HGV (kph)	Buses (kph)
Urban Roads				
Central London	Major principal roads	16	16	16
	Major trunk roads	24	24	16
	Minor roads	16	16	16
Inner London	Major principal roads	21	21	24
	Major trunk roads	32	32	24
	Minor roads	20	20	20
Outer London	Major principal roads	31	31	32
	Major trunk roads	46	46	32
	Minor roads	29	29	29
	Motorways	108	87	87
Conurbation	Major principal roads	31	31	24
	Major trunk roads	38	37	24
	Minor roads	30	30	30
	Motorways	97	82	82
Urban	Major principal roads	36	36	32
	Major trunk roads	53	52	32
	Minor roads	35	34	29
	Motorways	97	82	82
Rural Roads				
Rural single carriageway	Major roads	77	72	71
	Minor roads	61	62	62
Rural dual carriageway		111	90	93
Rural motorway		113	90	95

16 kph is a 67% Congestion

RDE Urban mean 15-40 kph with peak of 60 kph Central London 16 kph The range is Realistic but 40 kph will give lower emissions.

Auld, A., Ward, A., Mustafa, K., and Hansen, B., "Assessment of Light Duty Diesel After-Treatment Technology Targeting Beyond Euro 6d Emissions Levels,"

SAE Int. J. Engines **10(4):2017, doi:10.4271/2017-01-0978. Ricardo UK Ltd.**



3 RDE compliant routes

Congested traffic

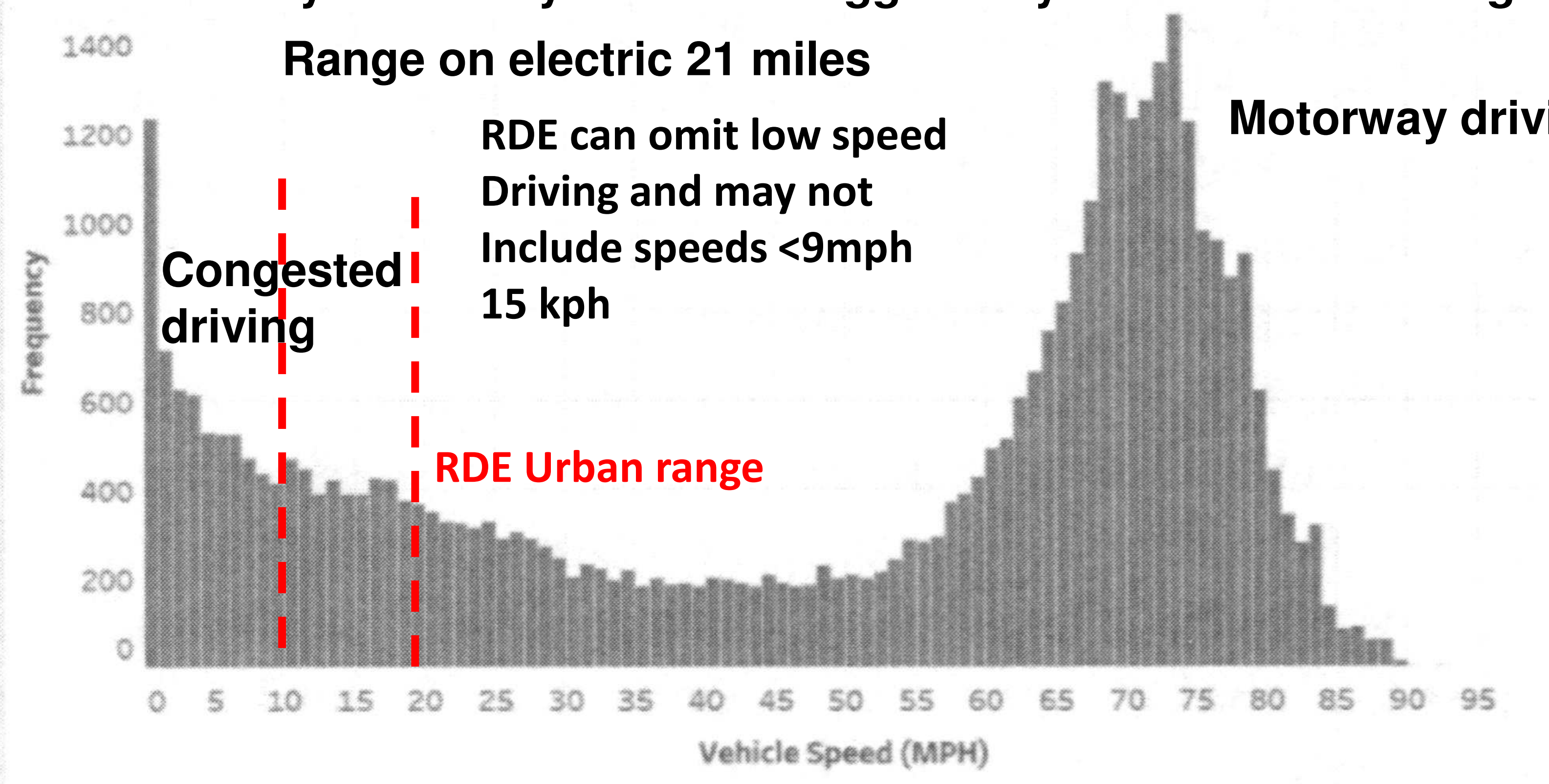
50 kph or less is urban driving
Below 20 kph is congested driving
>60% congested. In these 3 RDEs
the congested traffic is 24 – 26% of
the frequency of occurrence.
So these RDEs do include congestion
but there is no RDE requirement to do so.

Meroux, D Ford Motor Co. + Tal, G. Univ. Cal. Davis SAE 2018-01-0670

Policies to maximise fuel economy of plug in hybrids in a rental fleet.

FIGURE 2 Histogram of vehicle speeds aggregated by minute

U, Cal. – Davis has 13 model year 2017 Ford Fusion Energi SE sedans – a motor Pool for use by University staff. Use logged May 2017. Time at idle ignored.



Implications of these journey length, speed and idle surveys. - 1

The objective of undertaking real world emissions is to explain why levels are higher than on test cycles and give rise to high roadside emissions in cities.

All the roadside monitors in the UK that exceed EU air quality standards are located at the roadside in large cities and these all experience congested traffic. Indeed if the Leeds Headingley site is investigated on the Web it show peak emissions in the morning and evening rush hours, when congestion is at its greatest.

As congested traffic is low speed and high traffic density and commuting journeys are short distances but long in time, the representative real world driving cycle would be about 5km long with speeds < 30 kph, which is the Leeds A660 Headingley test cycle used in my research group.

To keep with the UK proportions of rural and motorway (37% urban, 44% rural and 19% motorway), would then require a total journey length of about 14 km, very similar to the NEDC. It is not clear why such long journeys are required on the RDE.

Implications of these journey length, speed and idle surveys. - 2

If the RDE does not adequately reflect congested traffic urban driving, where the air pollution hot spots occur, then the technology to meet the RDE requirements may have little impact on air quality in large cities, where the air quality problems are.

It may be a more viable test for fuel consumption, although the relative weightings for urban, rural and motorway are inappropirate for the UK.

However, the problem with an RDE that does not address the air quality problem is that the engine technology required for this may not be developed. Stop/start control and freewheeling or sailing technologies for example have a greater benefit in congested traffic with a lot of idle and acceleration/decelerations. Also energy storage to give supercharger boost gives a bigger benefit in congested traffic, as does parallel and series hybrids. Hybrid engines have little benefit in motorway driving compared with urban driving. In this way the RDE cycle may deflect engine development away from the technologies most beneficial for urban congested traffic driving.

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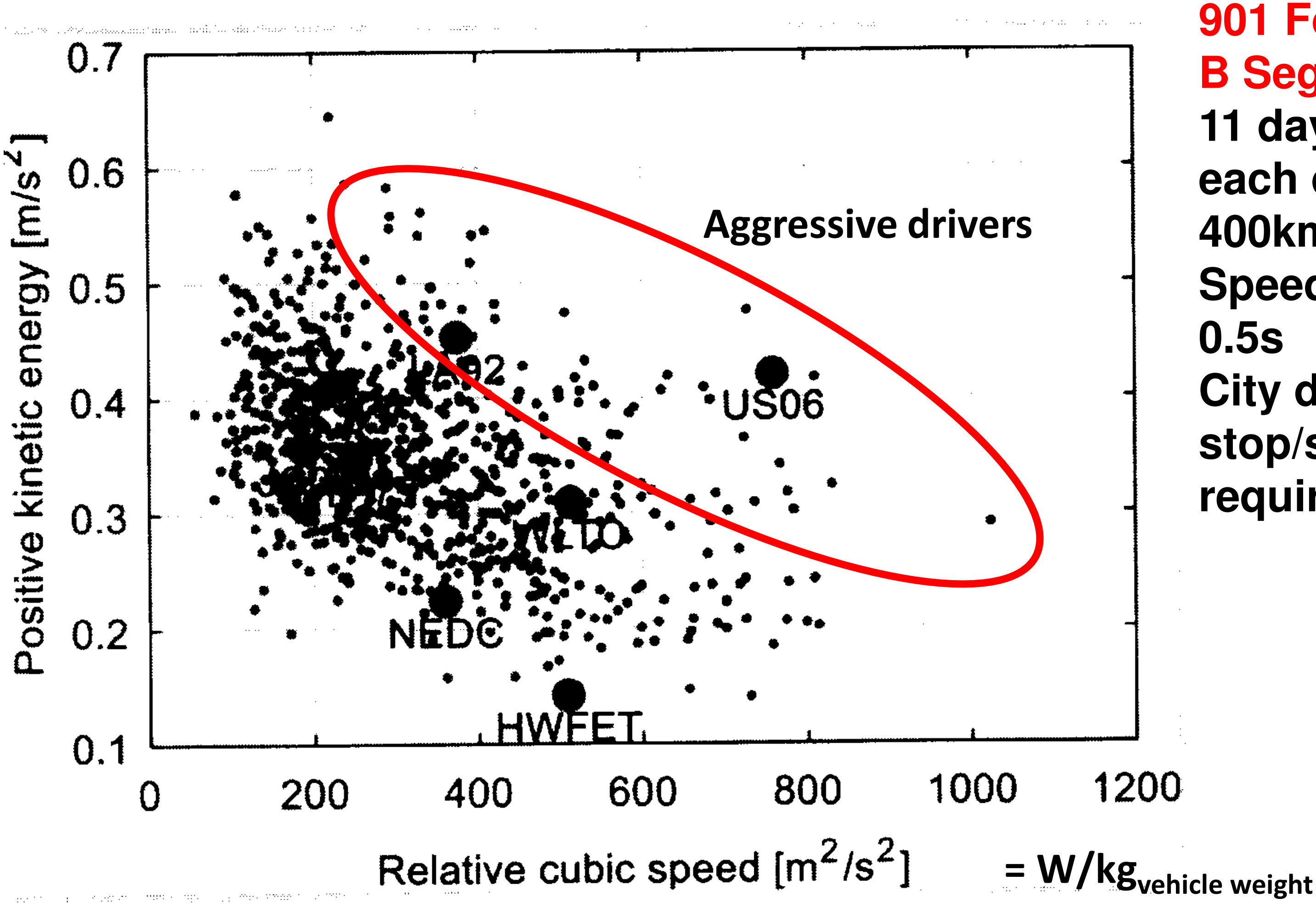
Cho, B. and Kees, D. Ford Motor Co., Shah, N. AVL, d'Urbal, V. ALTEN. SAE 2018-01-0644

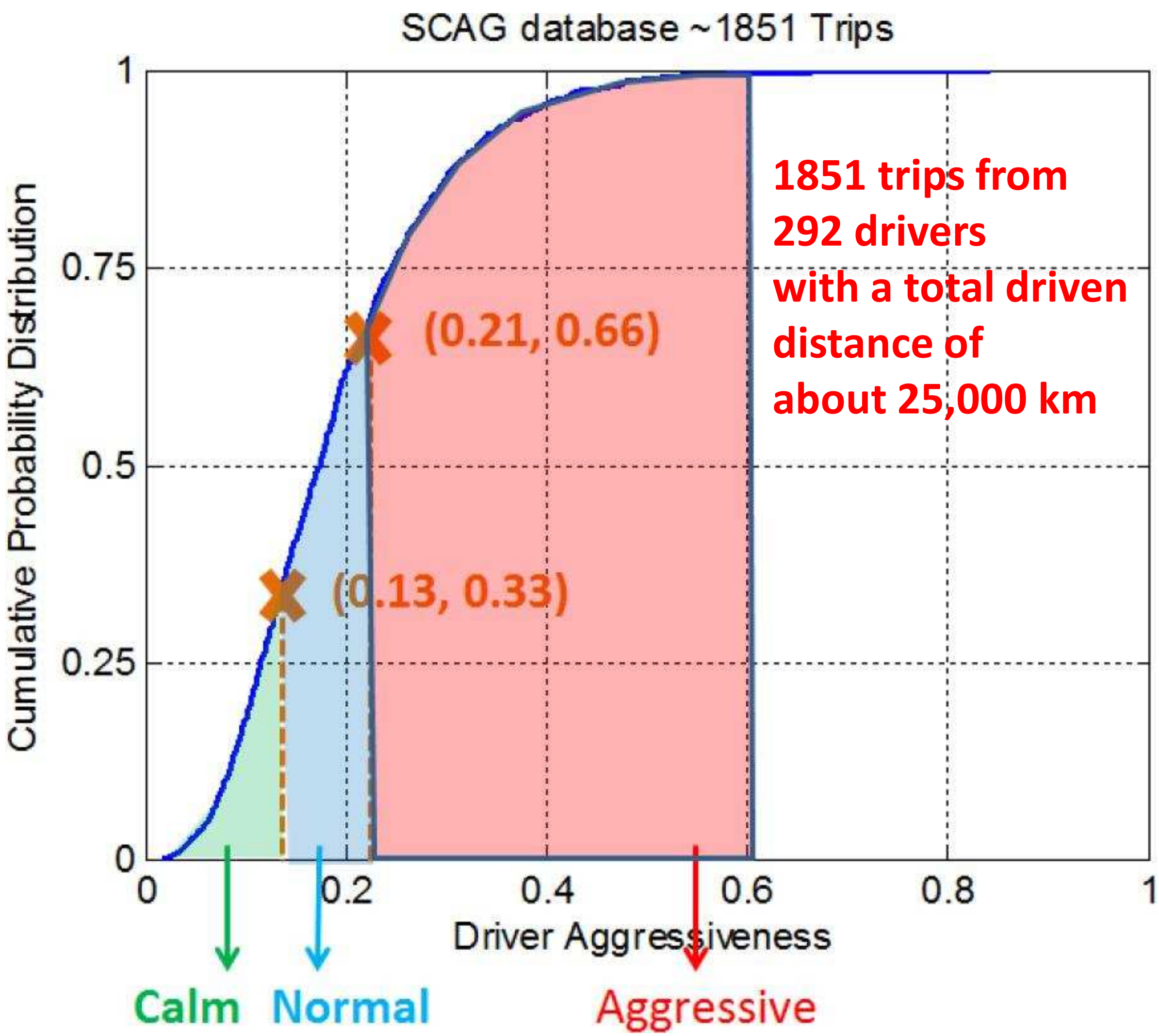
A methodology of Real-World Fuel Consumption Estimation: Pt 1 Drive Cycles

IGURE 2 Relative cubic speed and positive kinetic energy



901 Ford vehicles
B Segment Gasoline
11 days of data with each driver doing 400km on average.
Speed logged every 0.5s
City driving has more stop/starts which requires more energy.

Liu, Z., Ivanco, A., and Filipi, Z., "Impacts of Real-World Driving and Driver Aggressiveness on Fuel Consumption of 48V Mild Hybrid Vehicle," *SAE Int. J. Alt. Power.* 5(2):2016, doi:10.4271/2016-01-1166. Clemson-ICAR,Clemson Univ. , Greenville, South Carolina, USA.



~30% of drivers are aggressive Drivers

This is a complex method to characterise aggressive driving. If the throttle position is monitored then the rate of change of throttle position is a better measure. However, in the absence of this vehicle acceleration rates is simpler. Also aggressive drivers exceed speed limits. perhaps power demand is a good enough measure – vel x acc. Using the second differential of power in the definition is a recipe for signal noise!

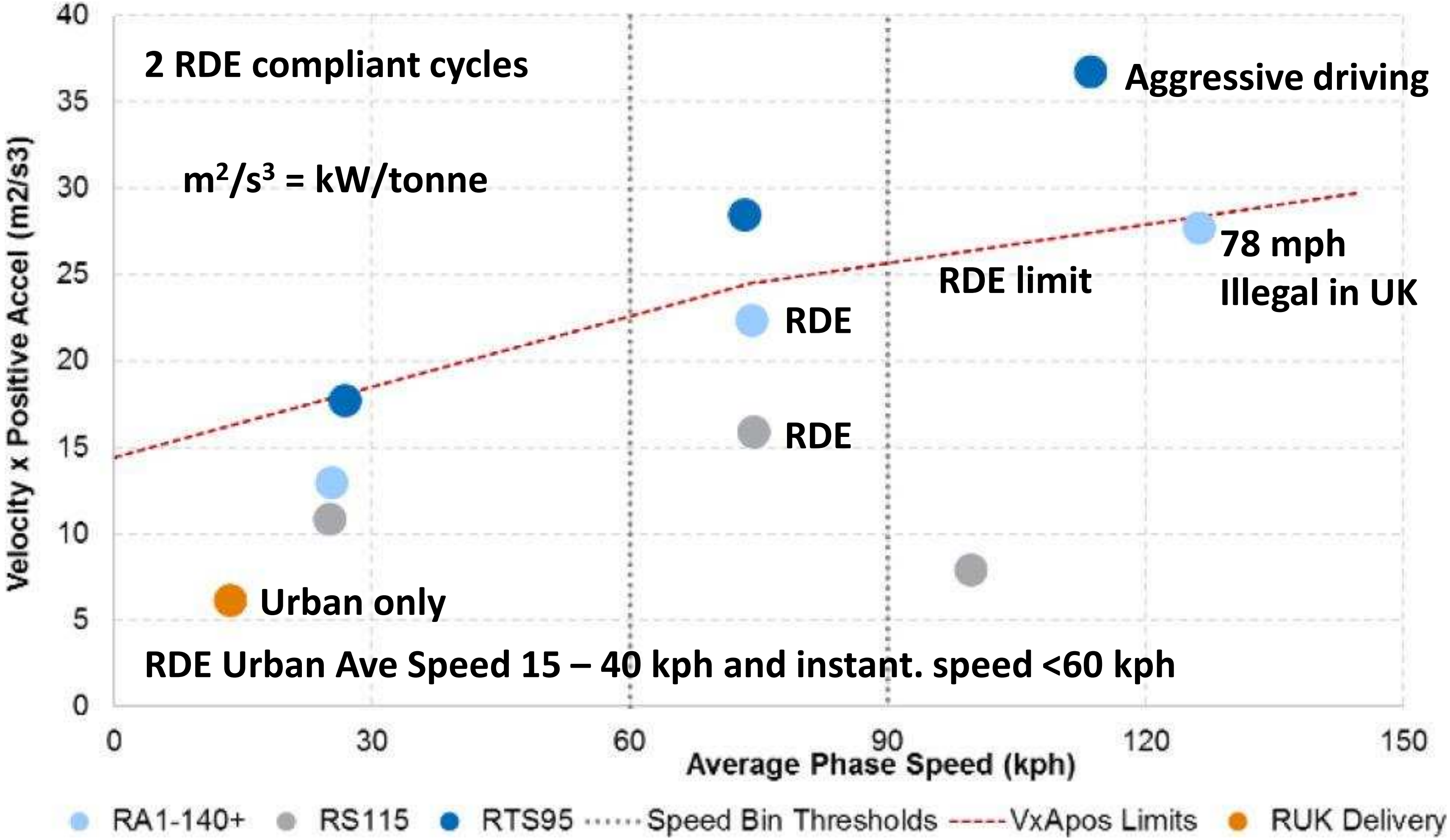
Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK

Driver behaviour Euro 1 TWC vehicle study 2004

	NEDC Euro 1	Max		Mean (20 drivers)		
		High Agressive	Low	High Mean of 9	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.

Auld, A., Ward, A., Mustafa, K., and Hansen, B., "Assessment of Light Duty Diesel After-Treatment Technology Targeting Beyond Euro 6d Emissions Levels,"
SAE Int. J. Engines 10(4):2017, doi:10.4271/2017-01-0978. Ricardo UK Ltd.



Contents

From BOSMAL presentation at the 3rd Int. RDE Conf. Berlin 2015
This will be a Chinese city with population of several million. Four lane highway with all four Lanes 90% congested at peak commuting times. I have seen scenes like this in Hefei China at Peak times where the average velocity was 6kph. Yet the RDE proposals ignore congestion!


This is the Leeds A660 outside Weetwood Hall
at 8.15am. Traffic queues from city centre to
beyond the outer Ring Road, a distance of over
6 km. Part of this route is the subject of our work
on emissions in congested traffic.
At peak times like this, the road has 1000 vehicles
per hour per lane.

Measurement of Congestion

Congestion is measured as:

Congestion% =[1–{Ave. Vel./48 kph (the legal urban limit)}]%

Ave. Velocity / vph = Ave. road distance per vehicle.

To measure congestion probe vehicles in the traffic are require, which may also be measuring the tailpipe emissions, as in this work. A distance in the traffic is driven at different times of the day (so that different traffic flows are experienced) and the distance divided by the time taken is the average journey speed. It is nothing to do with a vehicle travelling smoothly at a low velocity.

The City of Leeds, Yorkshire, England

UKs Third largest city

Population 800,000

Region 2.5M (Bradford, Wakefield, Harrogate, York, Skipton, Keighley, Barnsley,)

Leeds Jobs 500,000

City Centre Jobs 100,000

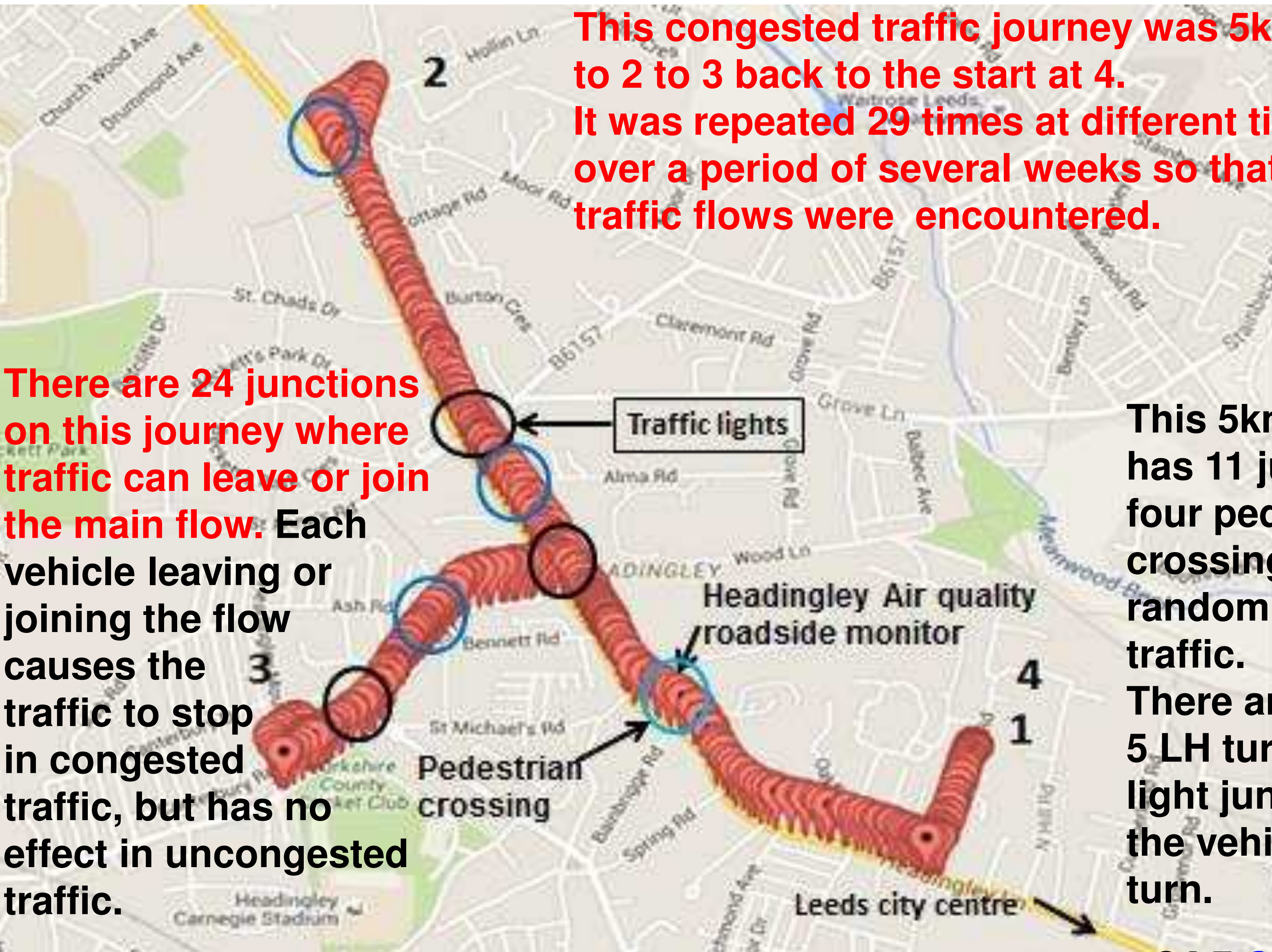
70,000 students and 10,000 staff in 3 Universities

Leeds is one of Europe's cities that has never met the EU air quality standards on NO_x and the road studied is one of the most congested in the UK and Europe. It is the main commuting route into the city from the north.

The congested traffic at peak times is 5km long

Ahmad Khalfan, Gordon E. Andrews, Hu Li, School of Chemical and Process Engineering, Univ. of Leeds, UK

Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start



This congested traffic journey was 5km long from 1 to 2 to 3 back to the start at 4.
It was repeated 29 times at different times of the day over a period of several weeks so that different traffic flows were encountered.

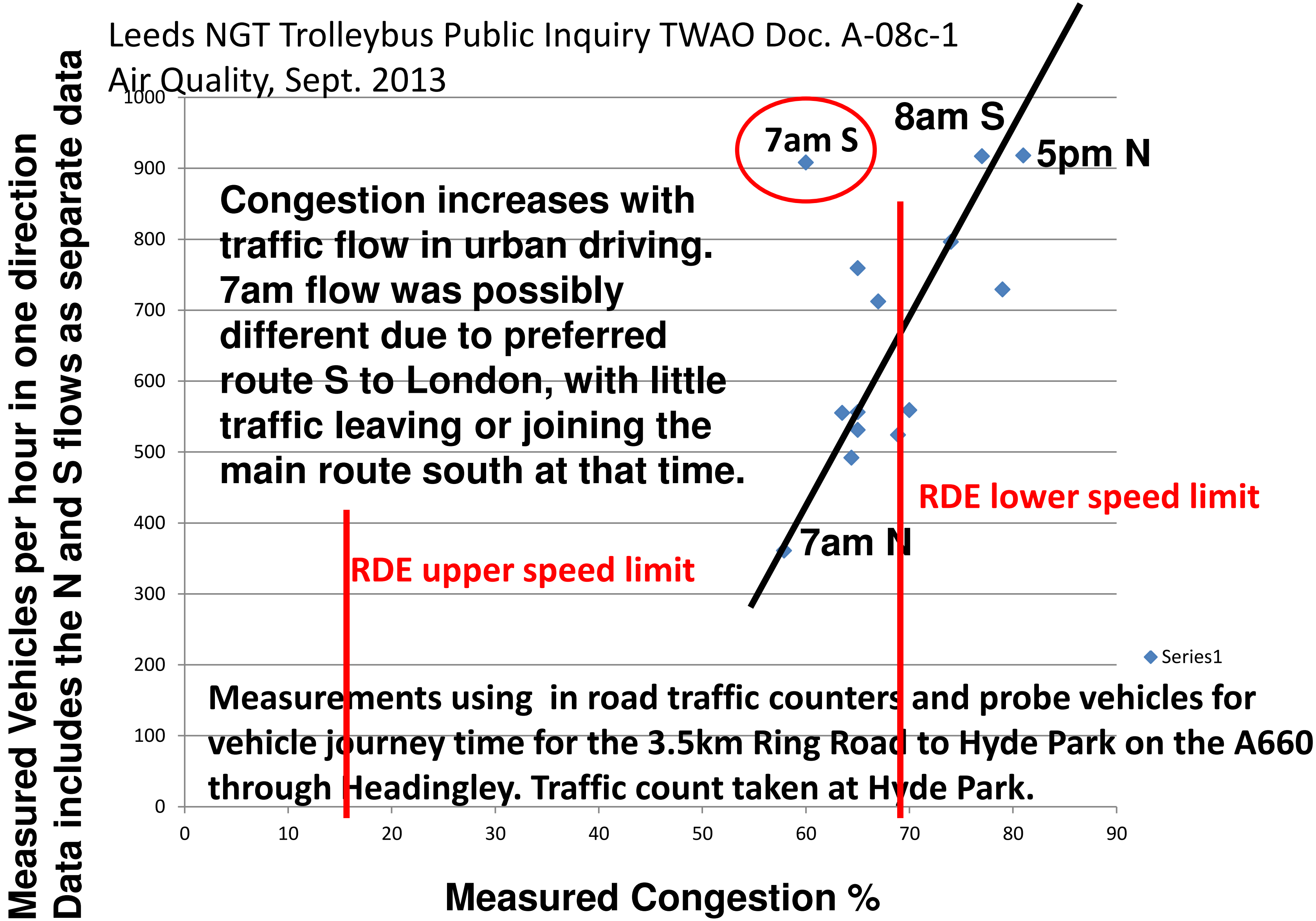
There are 24 junctions on this journey where traffic can leave or join the main flow. Each vehicle leaving or joining the flow causes the traffic to stop in congested traffic, but has no effect in uncongested traffic.

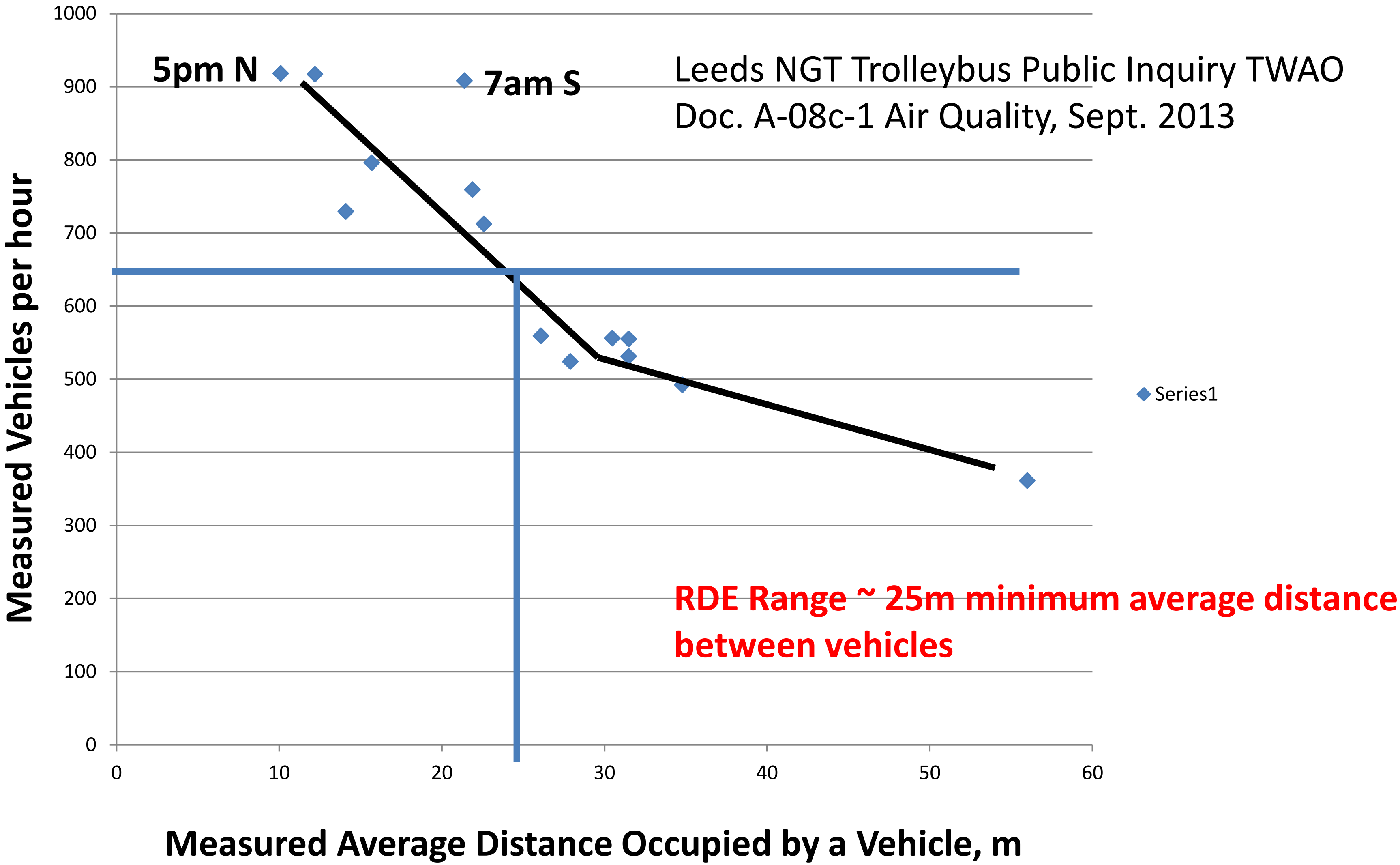
This 5km loop journey has 11 junctions and four pedestrian crossings that cause random stops to the traffic.
There are 3 RH turns, 5 LH turns and 3 traffic light junctions where the vehicle does not turn.

SAE 2016-01-2326

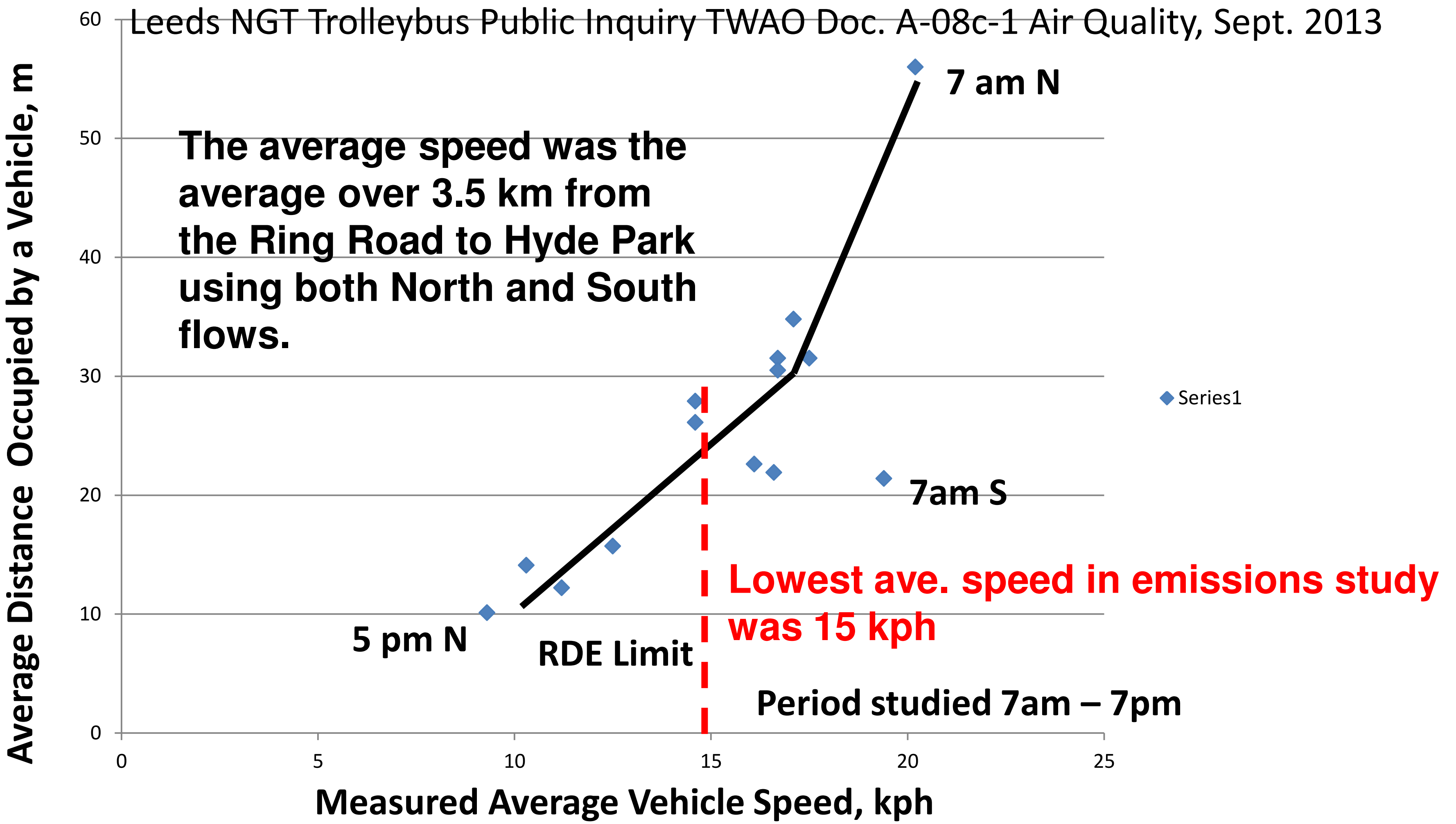
Features of congested roads:

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. 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 flows that can be comparable with the main flow.
5. Traffic mean velocity decreases as congestion increases.


Leeds NGT Trolleybus Public Inquiry TWAO Doc. A-08c-1
Air Quality, Sept. 2013
7am S
8am S
5pm N
7am N
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.
RDE lower speed limit
RDE upper speed limit
Series1
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.
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
Measured Vehicles per hour in one direction
Data includes the N and S flows as separate data
Measured Congestion %


5pm N
7am S
Leeds NGT Trolleybus Public Inquiry TWAO
Doc. A-08c-1 Air Quality, Sept. 2013
RDE Range ~ 25m minimum average distance between vehicles
Measured Vehicles per hour
Measured Average Distance Occupied by a Vehicle, m
Series1
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60

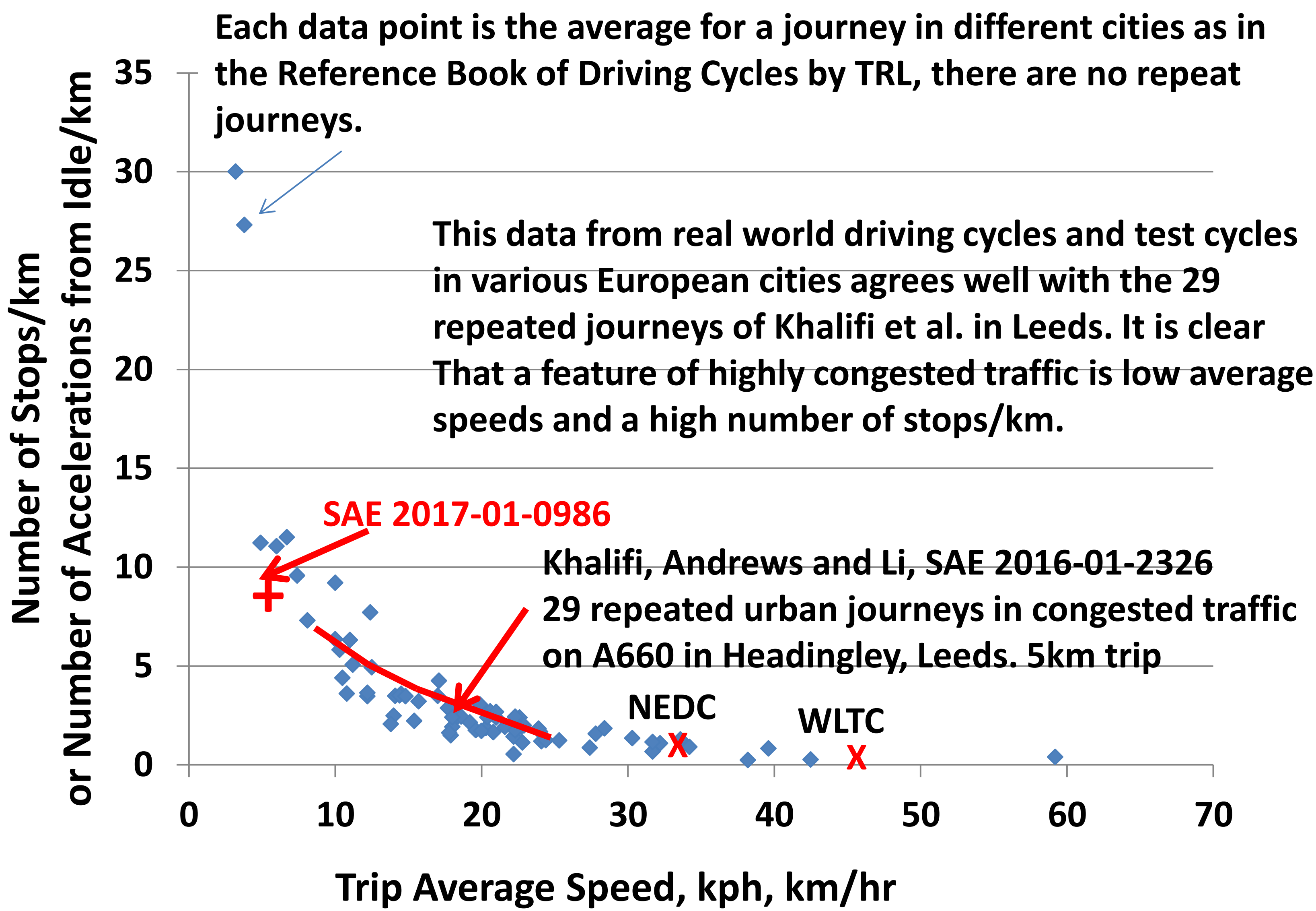
Professor Gordon E. Andrews, Energy Research Institute, University of Leeds, UK.
Real World Diesel and SI Engine Gaseous Emissions



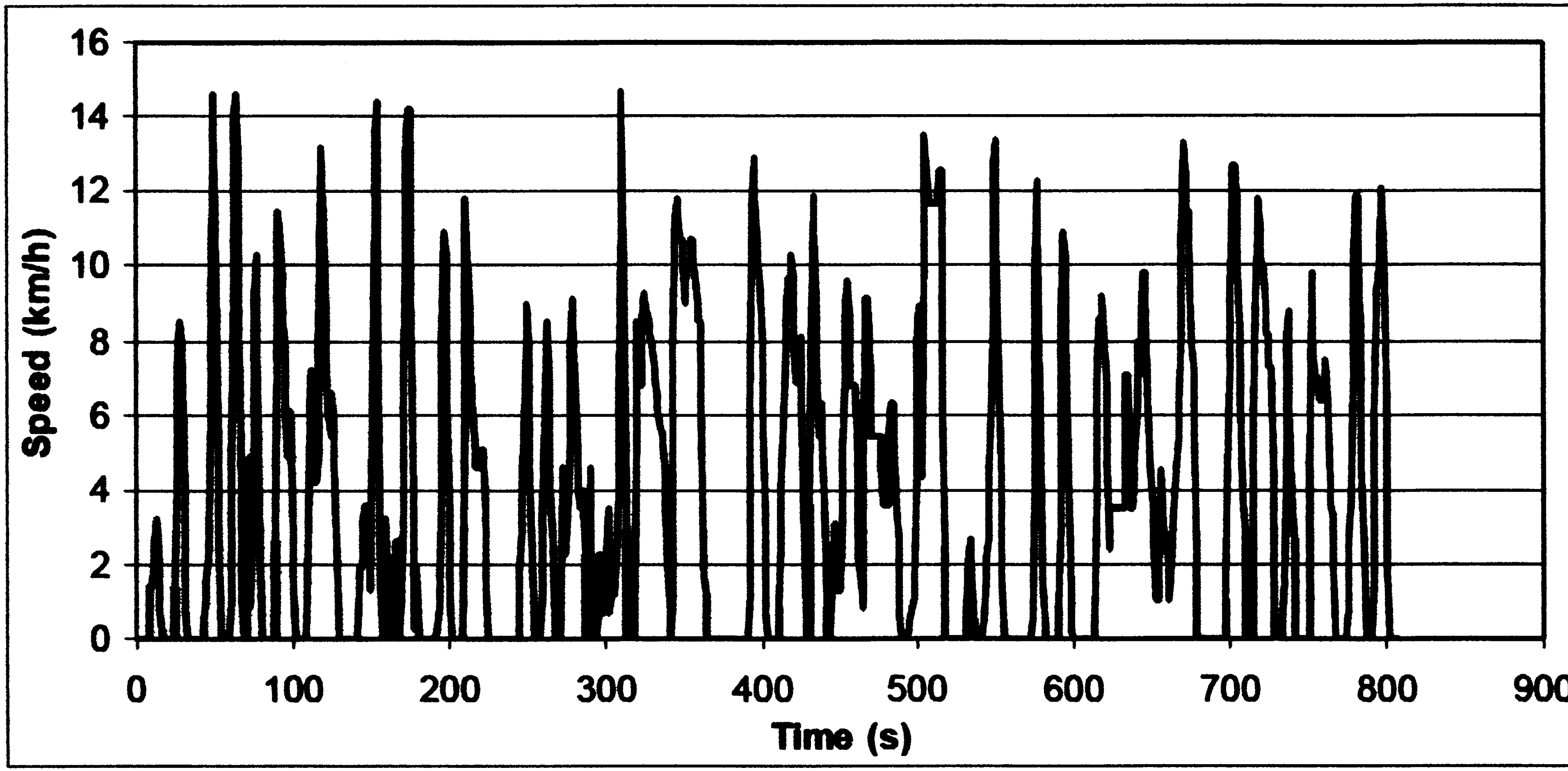
Another definition of congestion is when the journey time is half the normal time congestion Is 100% and the above results show that the A660 is congested for all times of the day.

4th Int. Exhaust Emissions Symposium 22-23 May 2014, BOSMAL, Bielsko-Biala, Poland

Barlow, T.J., Latham, S., McCrae, I.S. and Boulter, P.G., 2009. A Reference Book of Driving Cycles for use in the Measurement of Road Vehicle Emissions v. 3. TRL Project Report PPR 354 for Dept. Transport, June 2009.

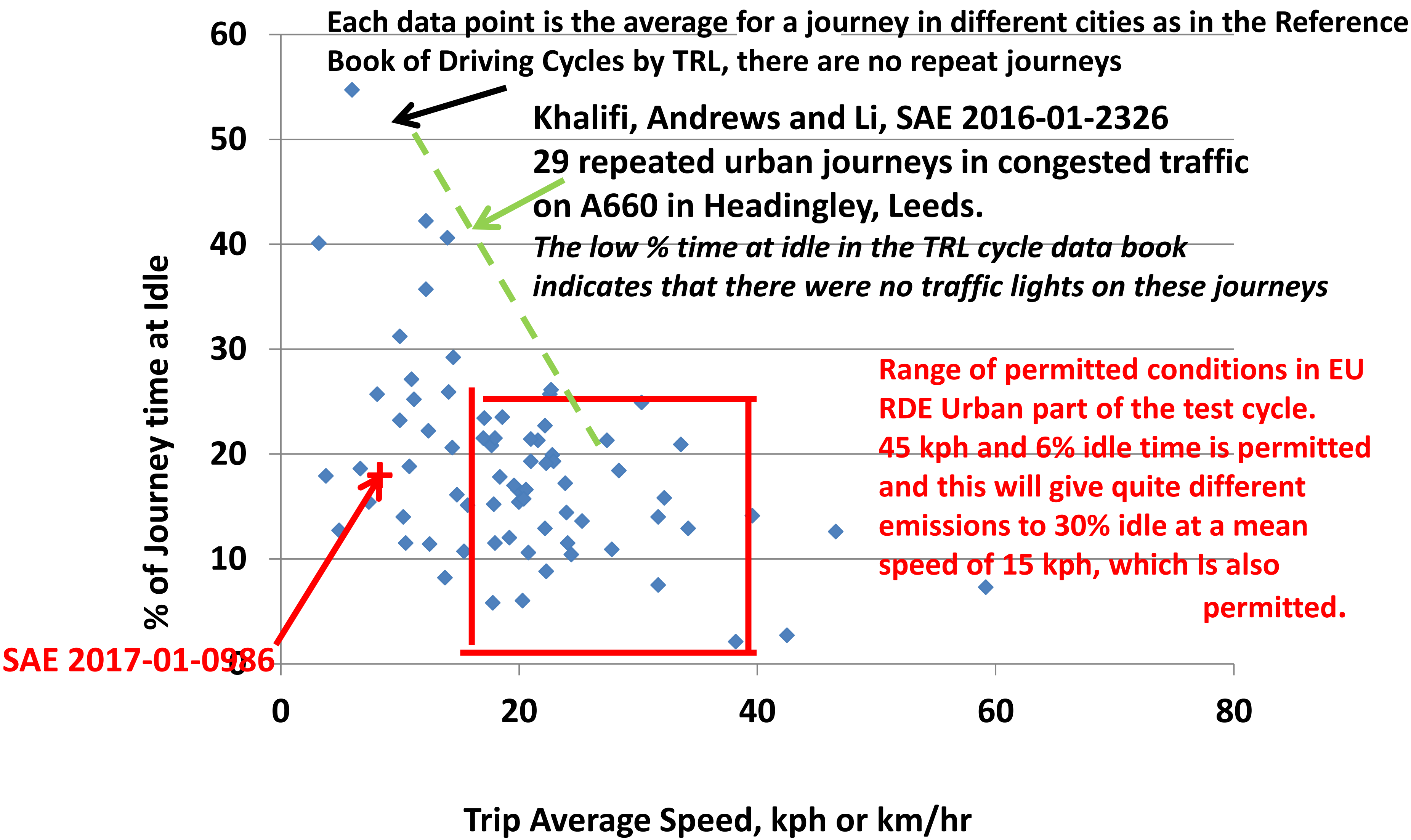


Barlow, T.J., Latham, S., McCrae, I.S. and Boulter, P.G., A reference book of driving cycles for use in the measurement of road vehicle emissions. v. 3. June 2009. Dept. for Transport.

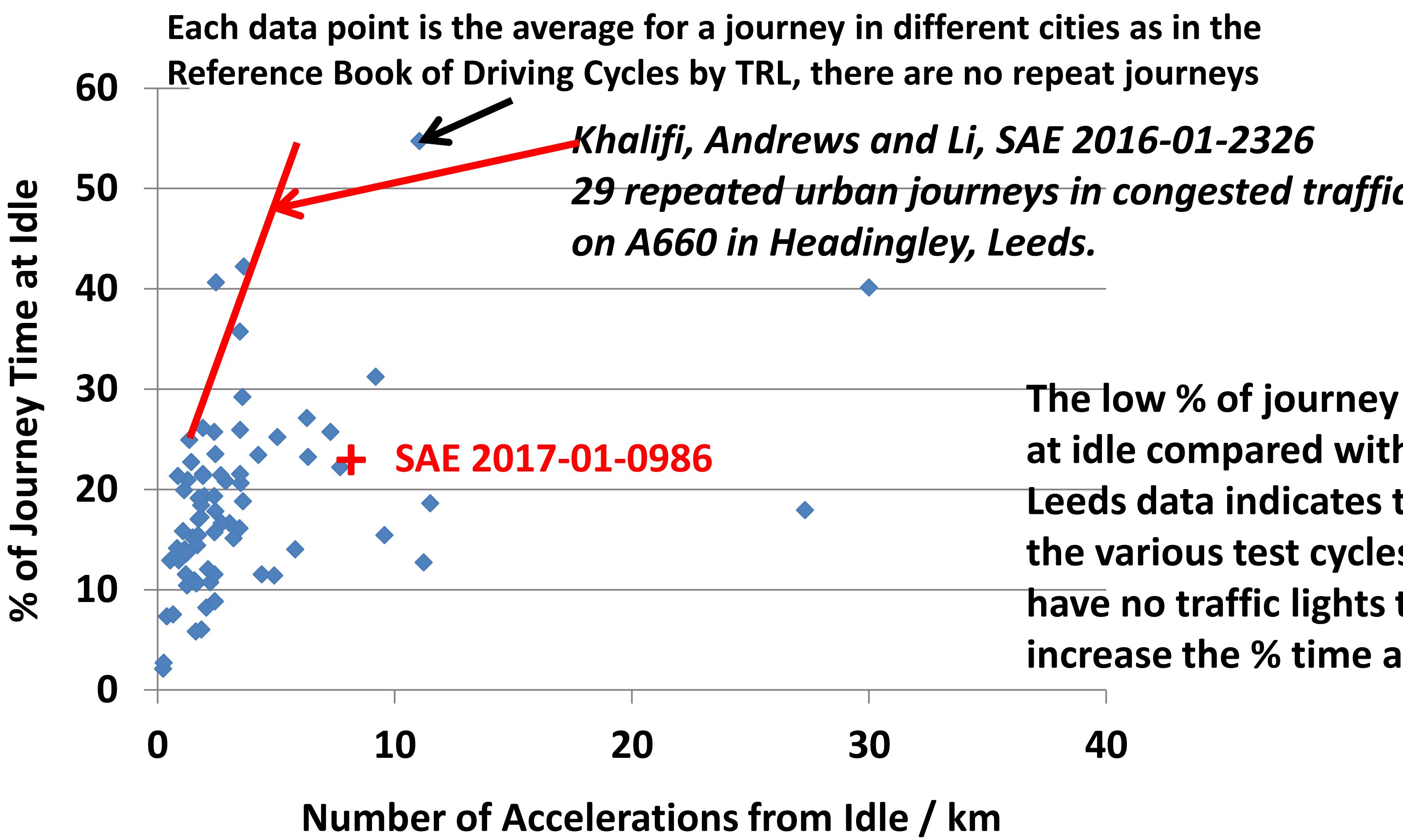


INRETS urbainlent1: Distance 0.844km, ave. trip speed 3.8 kph, ave. driving Speed 4.6 kph. Idle 17.9% (Leeds data indicates 60% idle for this speed). Stops/km 27.3, accelerations/km 53.3. This cycle also has no traffic light on Red as the % idle would be longer if this occurred. Probably >1000 cars/hr/lane

Barlow, T.J., Latham, S., McCrae, I.S. and Boulter, P.G., 2009. A Reference Book of Driving Cycles for use in the Measurement of Road Vehicle Emissions v. 3. TRL Project Report PPR 354 for Dept. Transport, June 2009.



Barlow, T.J., Latham, S., McCrae, I.S. and Boulter, P.G., 2009. A Reference Book of Driving Cycles for use in the Measurement of Road Vehicle Emissions v. 3. TRL Project Report PPR 354 for Dept. Transport, June 2009.

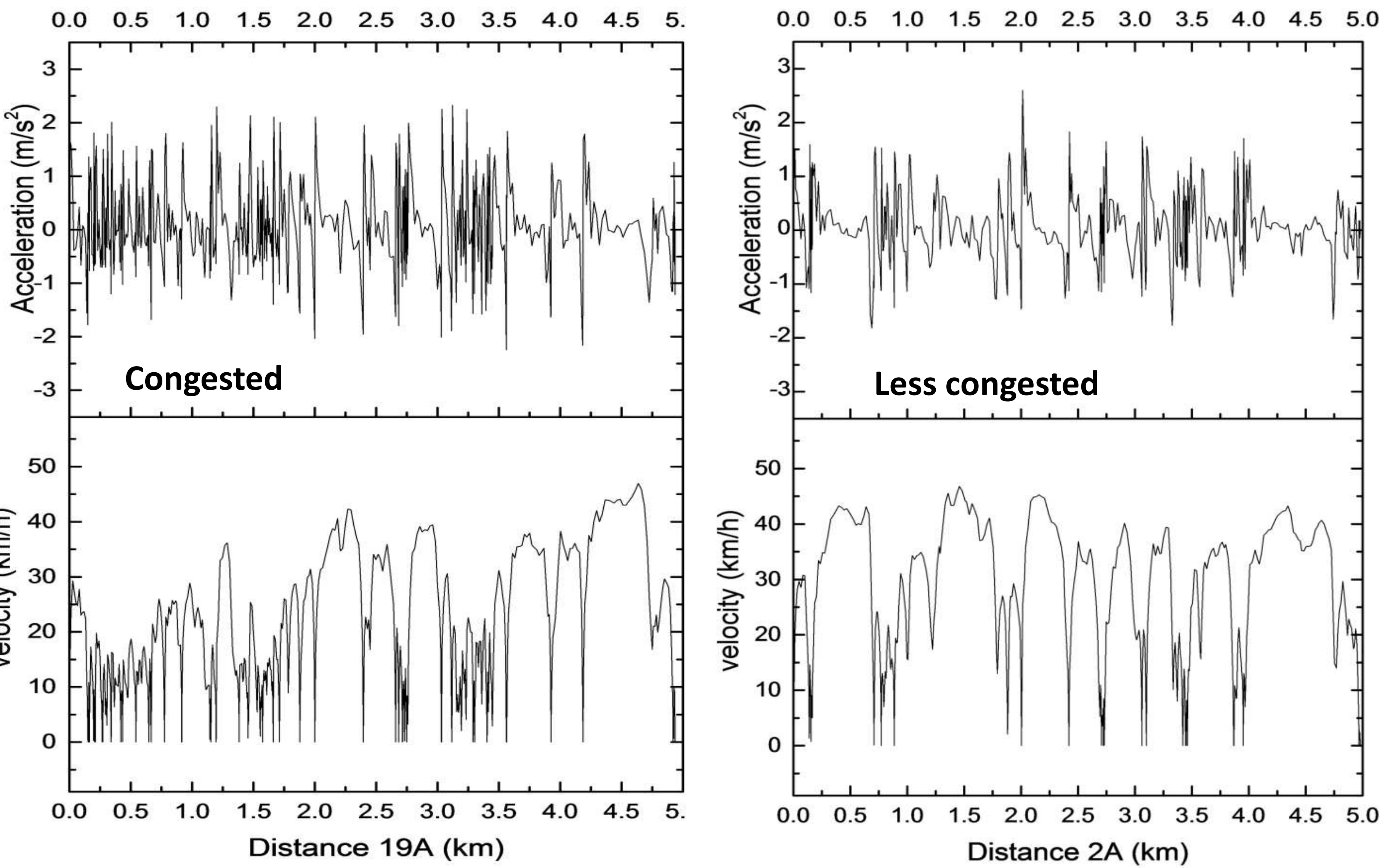


The low % of journey time at idle compared with the Leeds data indicates that the various test cycles have no traffic lights that increase the % time at idle.

Contents

Khalfan, A., Andrews, G.E. and Li, H. *Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start*I SAE 2017 SAE2017-01-2388

Khalfan, A., Andrews, G.E. and Li, H. ***Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start*****l SAE 2017 SAE2017-01-2388.**



Vehicle: Ford Mondeo – Euro 4

PEMS: Gasmet FTIR with heated sample lines, pumps and filters. Calibrated by manufacturer for 60 species including all relevant species for emissions, including:

NO, NO_2, HCN, N_20, NH_3

$CO_{2,}$ CH_4, N_2O

All the VOC of importance in ozone formation

Horiba OBS 1 used for exhaust mass flow measurements.

Fuel mass flow by Max-meter (a micro-liquid level mass flow meter).

Fuel mass flow also derived from the exhaust mass flow flow and the lambda probe reading or the A/F by carbon balance.

Vehicle Specific Power (VSP) is often reduced to the velocity x acceleration term in m^2/s^3

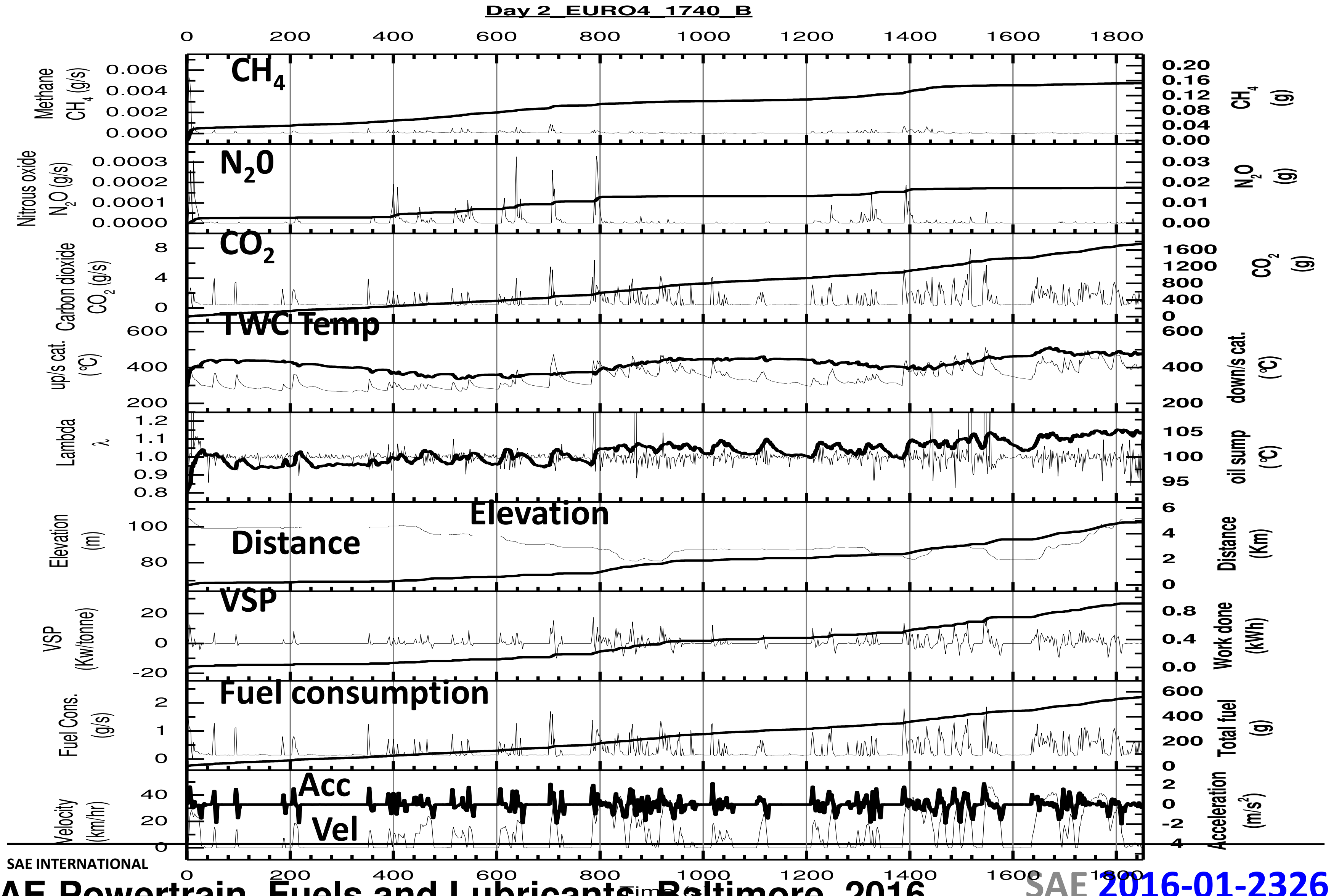
Papers that use this often do not tell the reader that these units are W/kg or kW/tonne, which if the weight of the vehicle is taken into account enables the power output of the vehicle to be determined.

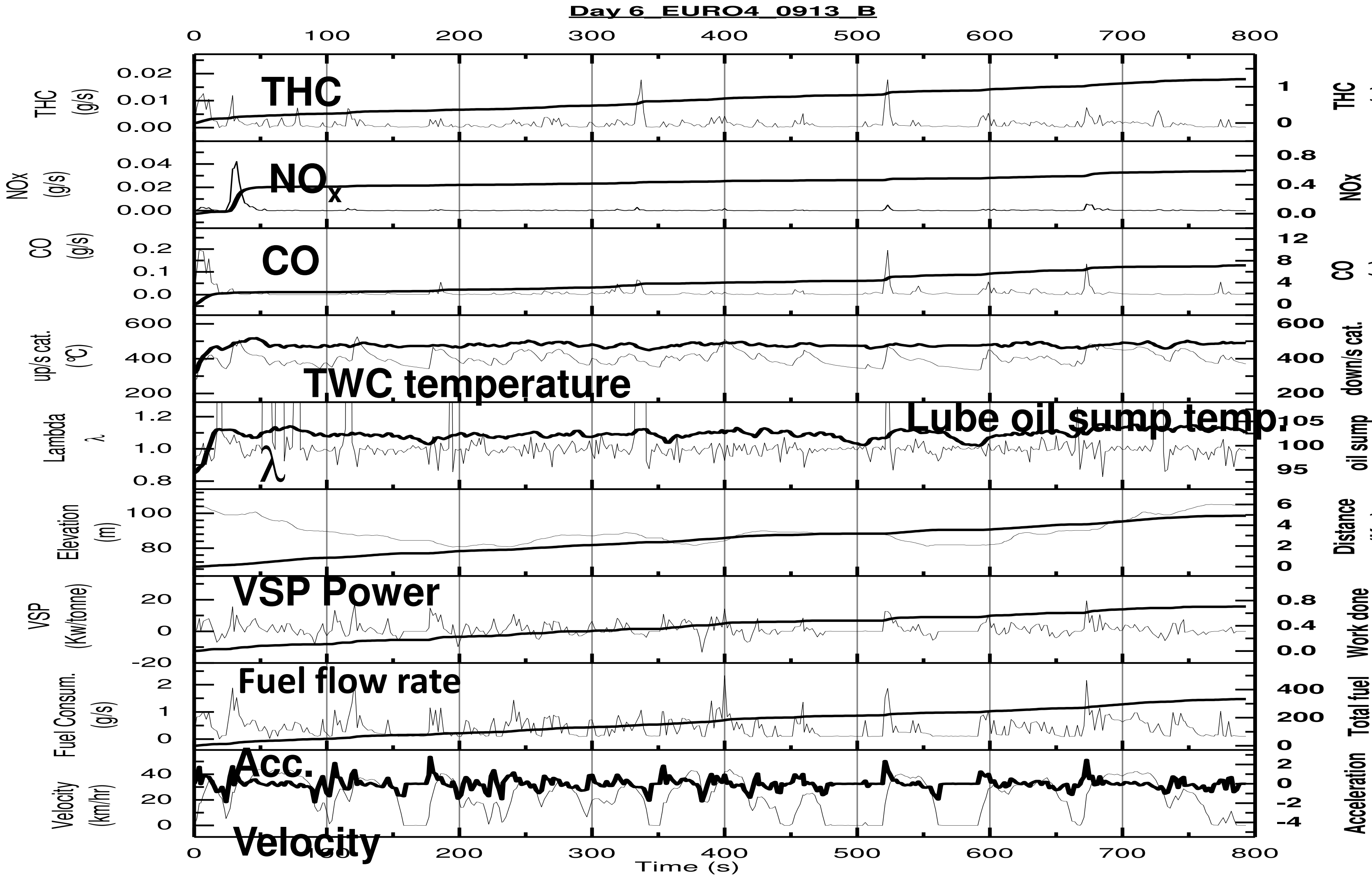
Note: $W/kg = J/skg = Nm/skg = kgm^2/s^3kg = m^2/s^3$

VSP and kW power output can be calculated on line by the PEMS system and you can put emissions into different power bins, as required under RDE legislation.

Thermal Eff. = VSP x Vehicle weight (tonnes) / fuel flow x CV

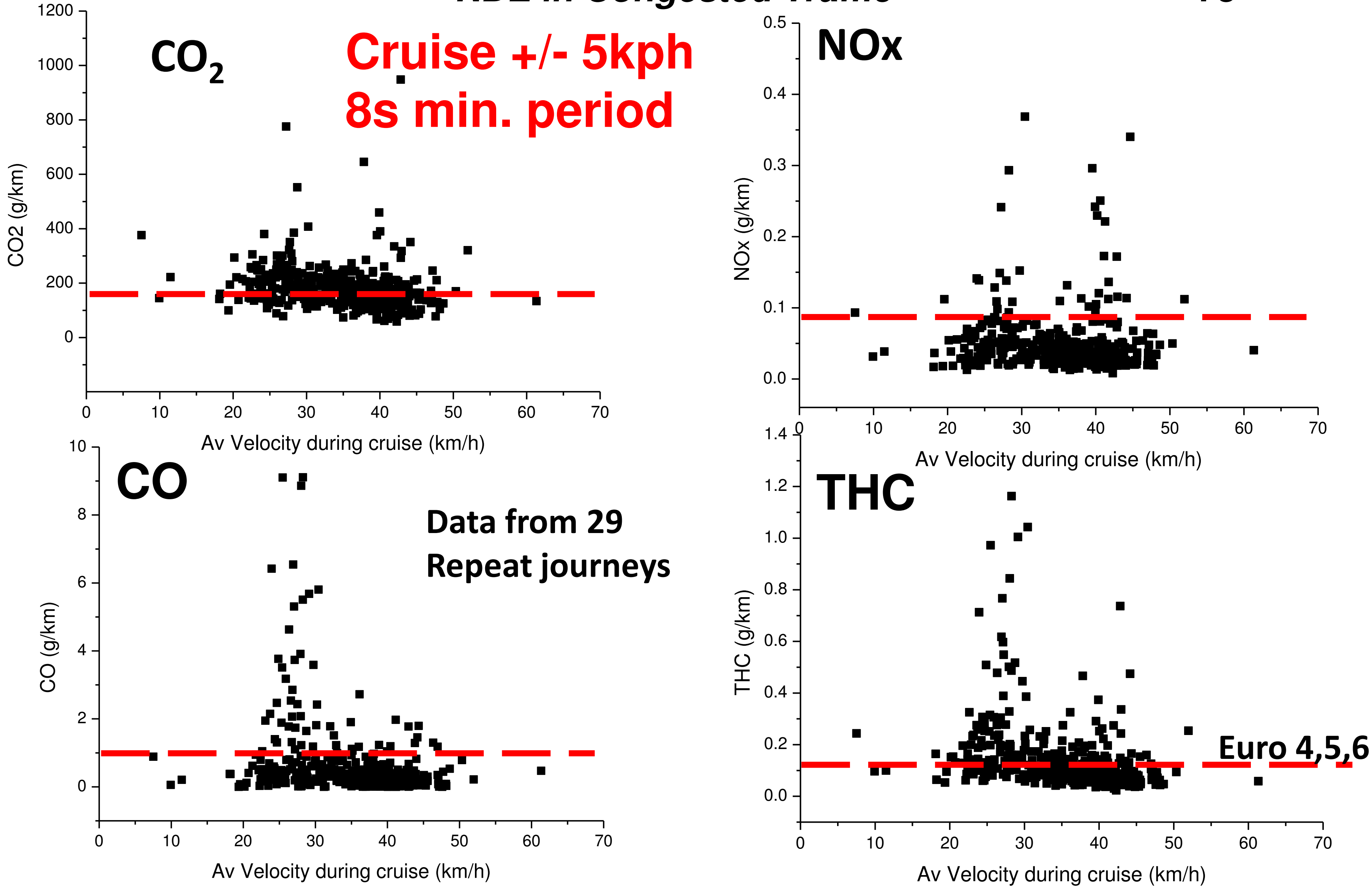
This enables the on-road thermal efficiency to be determined.


Day 2_EURO4_1740_B
CH4
N20
CO2
TWC Temp
Elevation
Distance
VSP
Fuel consumption
Acc
Vel
Methane CH4 (g/s)
Nitrous oxide N2O (g/s)
Carbon dioxide CO2 (g/s)
up/s cat. (°C)
Lambda λ
Elevation (m)
VSP (Kw/tonne)
Fuel Cons. (g/s)
Velocity (km/hr)
CH4 (g)
N2O (g)
CO2 (g)
down/s cat. (°C)
oil sump (°C)
Distance (Km)
Work done (kWh)
Total fuel (g)
Acceleration (m/s2)
Time (s)


Day 6_EURO4_0913_B
THC
NOx
CO
TWC temperature
Lube oil sump temp.
λ
VSP Power
Fuel flow rate
Acc.
Velocity
THC (g/s)
NOx (g/s)
CO (g/s)
up/s cat. (°C)
Lambda λ
Elevation (m)
VSP (Kw/tonne)
Fuel Consum. (g/s)
Velocity (km/hr)
THC (g)
NOx (g)
CO (g)
down/s cat. (°C)
oil sump (°C)
Distance (Km)
Work done (kWh)
Total fuel (g)
Acceleration (m/s²)
Time (s)

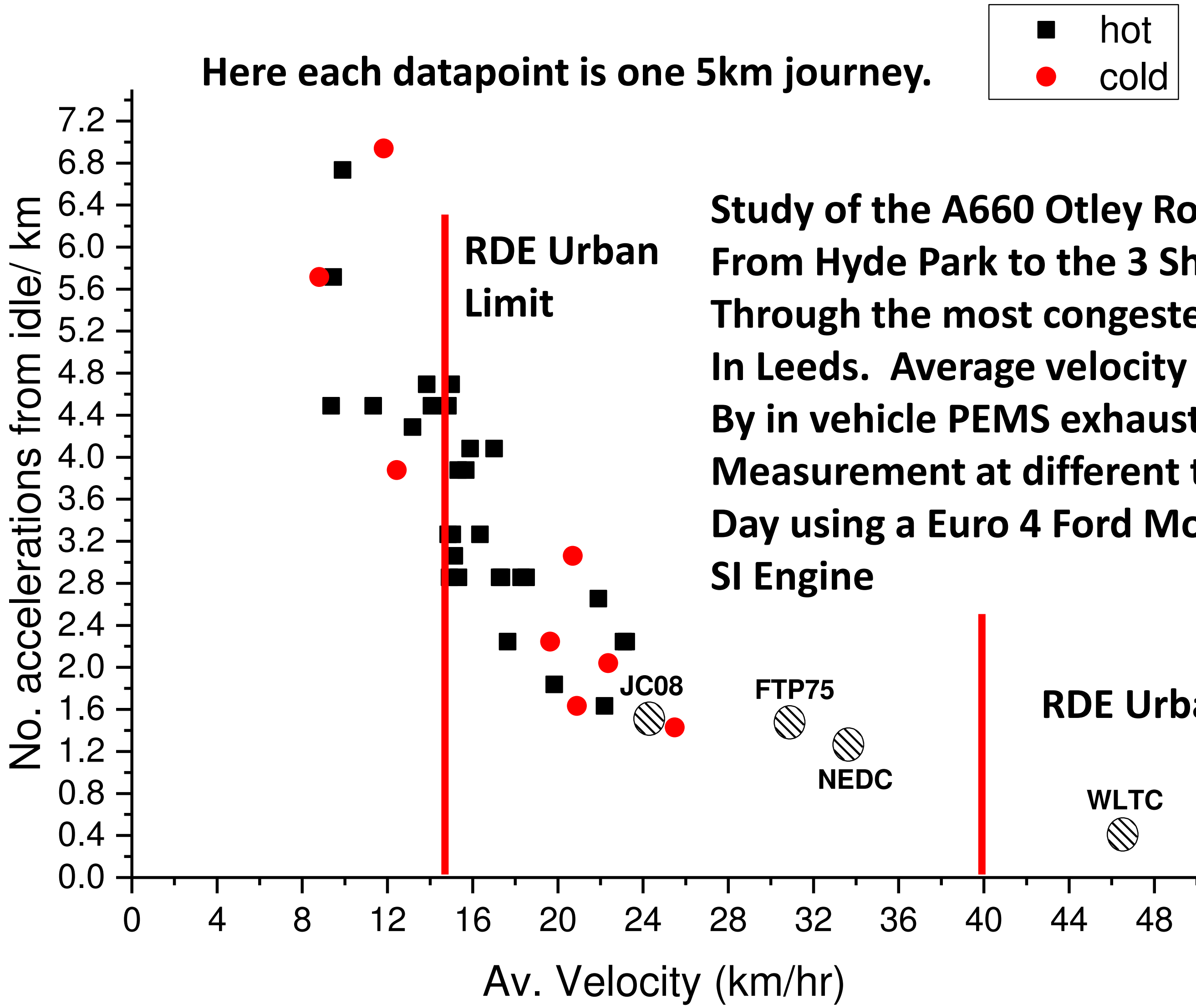
Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK

RDE in Congested Traffic **73**



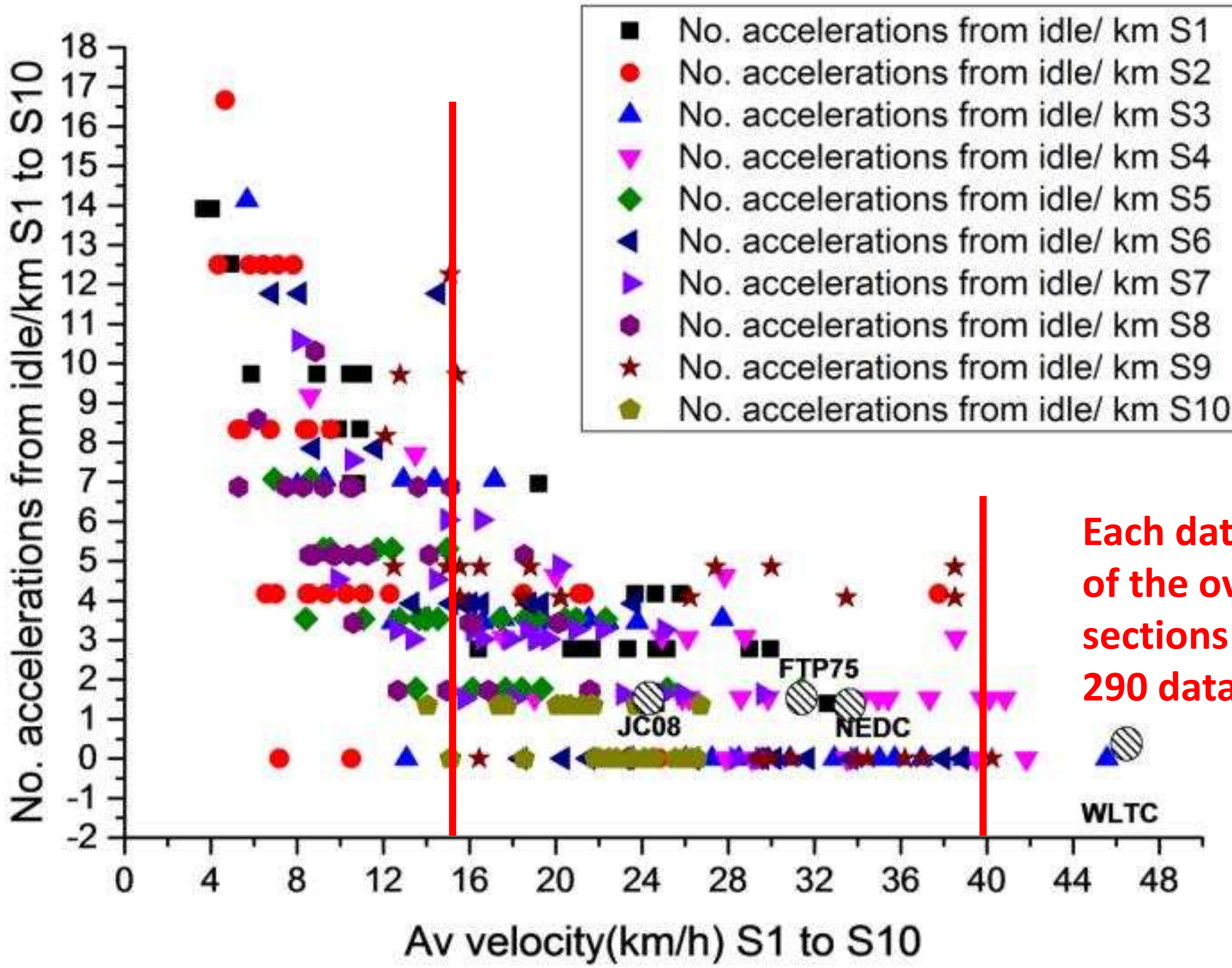
Khalfan, A., Andrews, G.E. and Li, H. *Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start*l SAE 2016-01-2326.

Here each datapoint is one 5km journey.



Study of the A660 Otley Road in Leeds
From Hyde Park to the 3 Shoes Pub
Through the most congested traffic
In Leeds. Average velocity varied
By in vehicle PEMS exhaust sample
Measurement at different times ot the
Day using a Euro 4 Ford Mondeo.
SI Engine

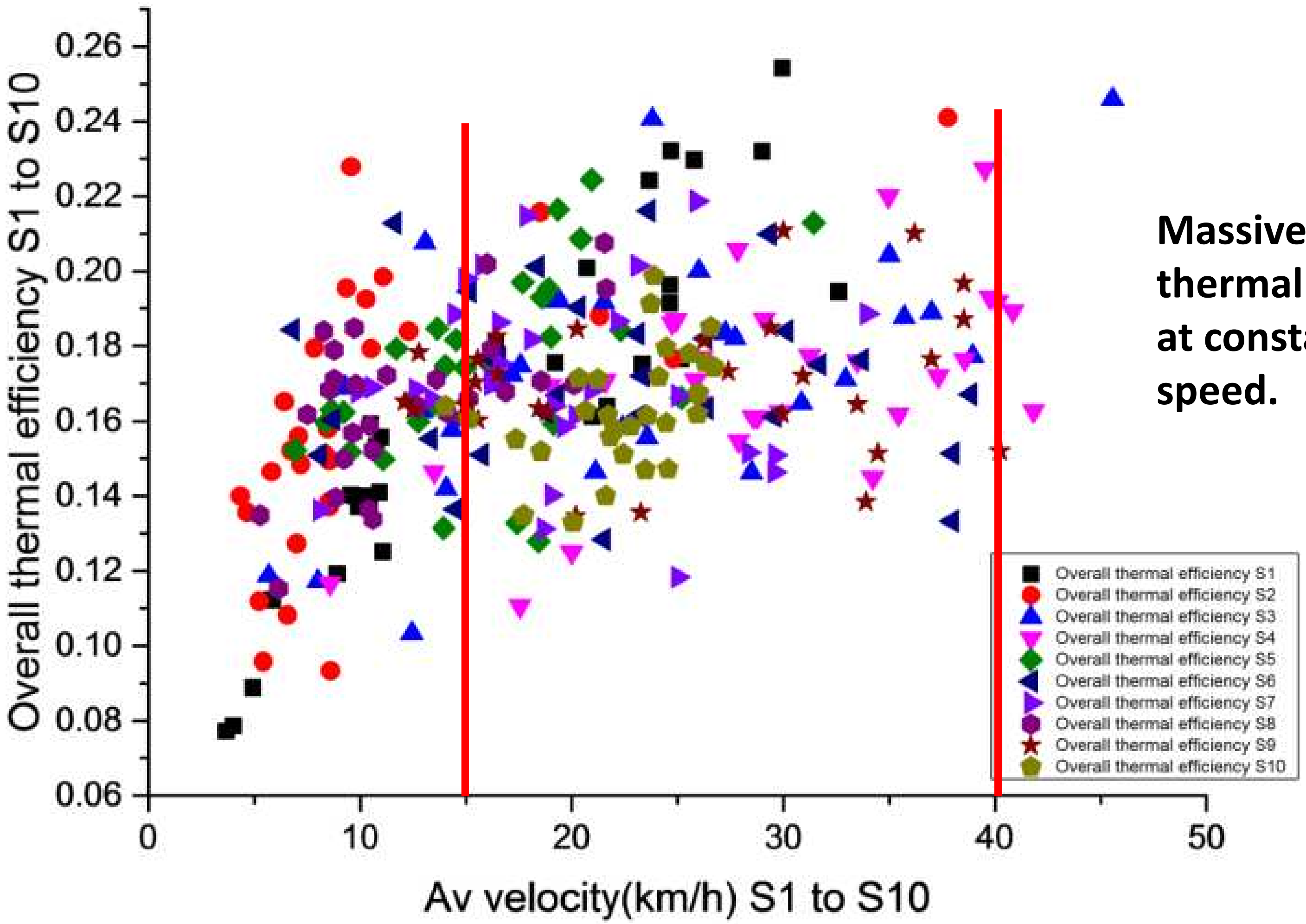
Khalfan, A., Andrews, G.E. and Li, H. *Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start* SAE 2017 SAE2017-01-2388



Each data point is one section of the overall journey, 10 sections in the journey
290 data points, all hot start.

Khalfan, A., Andrews, G.E. and Li, H. *Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start*l SAE 2017 SAE2017-01-2388

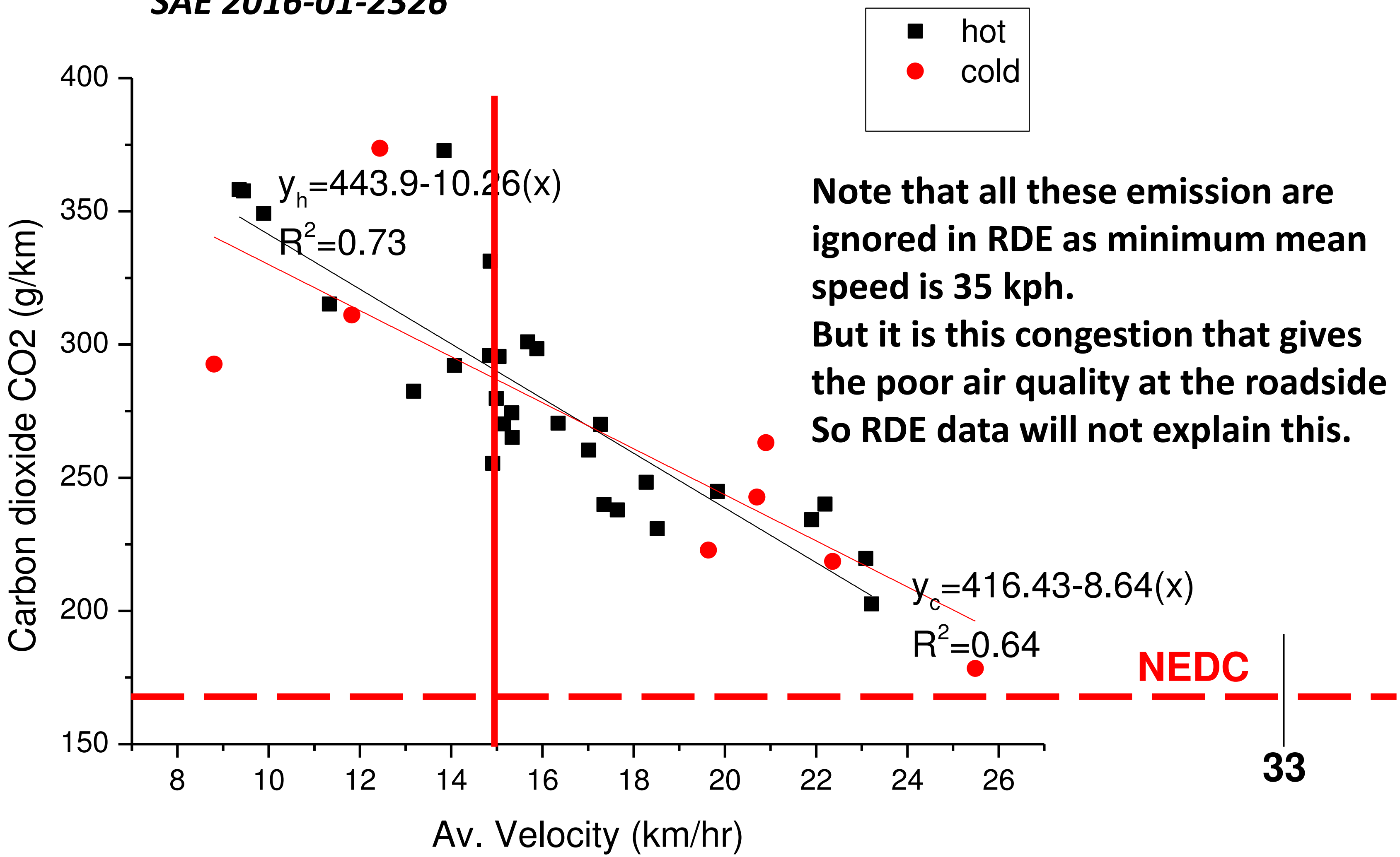
Thermal efficiency = VPS kW/tonne x wt Vehicle/ fuel kW



Massive range of thermal efficiency at constant mean speed.

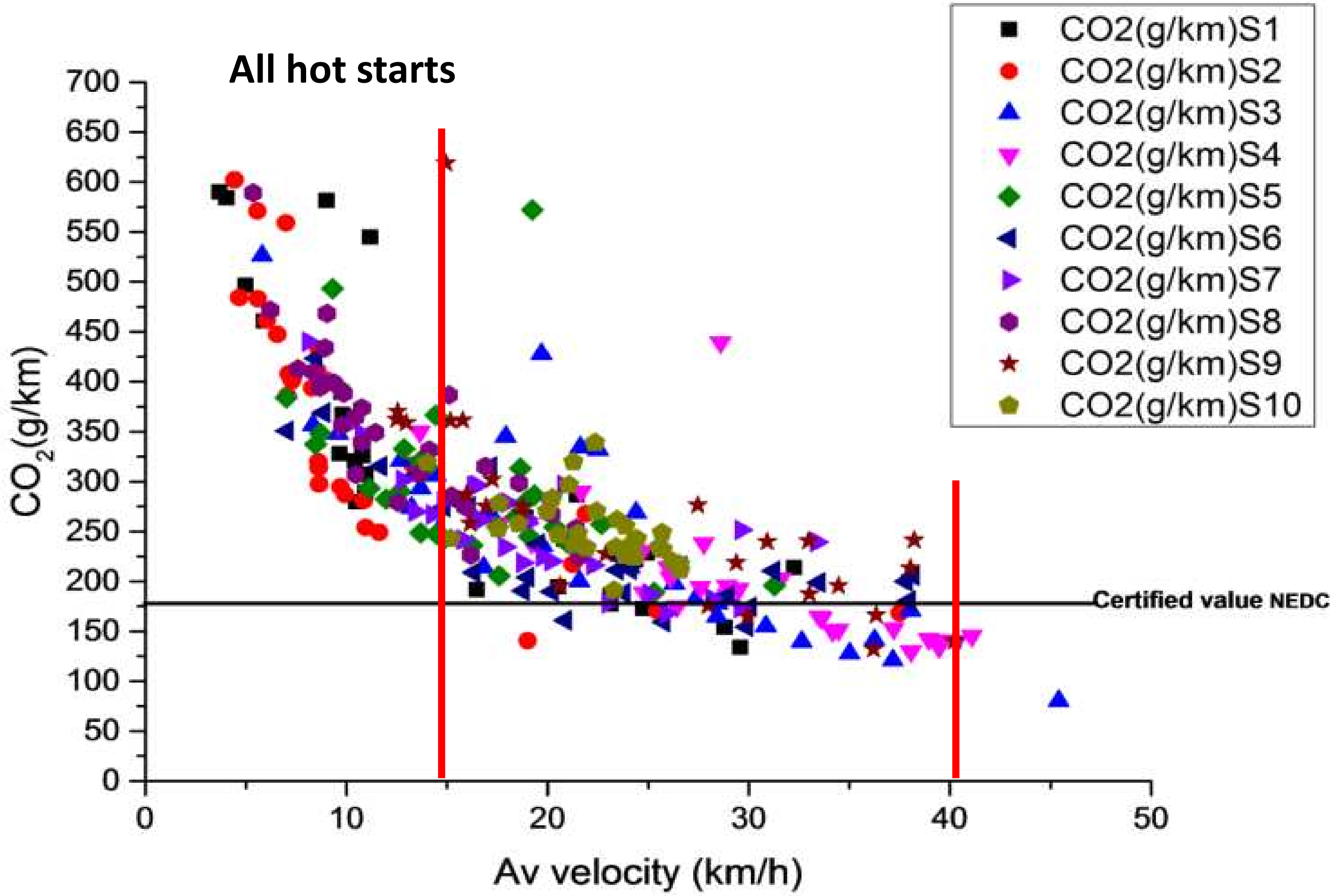
Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK

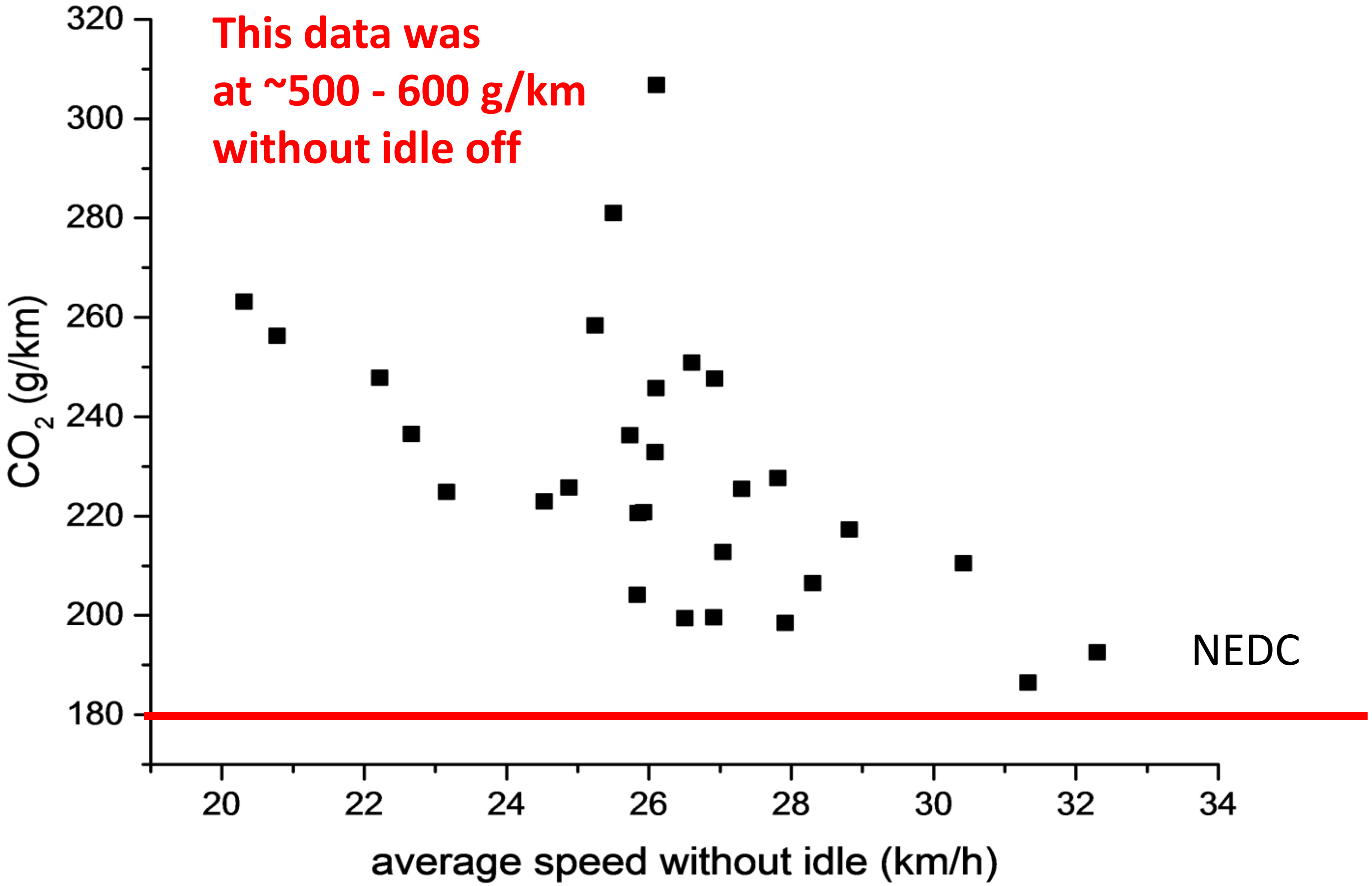
SAE 2016-01-2326



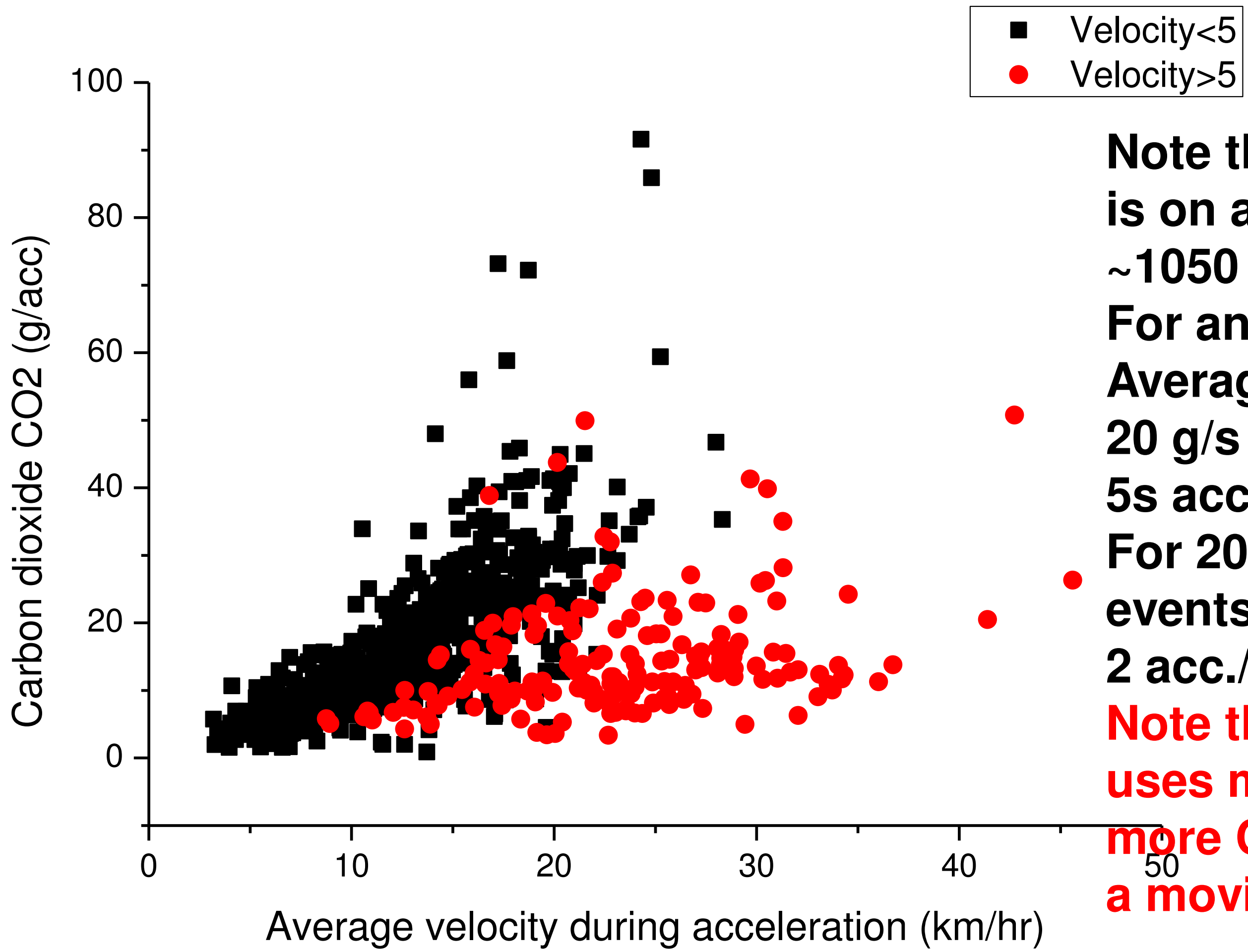
Note that all these emission are ignored in RDE as minimum mean speed is 35 kph.
But it is this congestion that gives the poor air quality at the roadside
So RDE data will not explain this.

Khalfan, A., Andrews, G.E. and Li, H. ***Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start*****. SAE 2017-01-2388**





Congested traffic data presented earlier in the course. Here the fuel consumed during idle and its CO_2 have been deducted from the journey average CO_2. Also the speed has been increased to deduct the time spent at idle from the total journey time. These are now much lower CO_2 for the congested traffic parts of the journey. Thus engine off at idle will give a significant reduction in congested city traffic.



Note that 95 g/km over the NEDC is on average 0.89 g/s or ~1050 g in total.
For an acceleration at 15 kph Average speed this is about 20 g/s per acc. and for a typical 5s acc.event is 100 g per acc.
For 2020 CO_2 this is ~21 acc. events from Idle, or about 2 acc./km

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

What is the fuel requirement to accelerate the vehicle from idle?

Assume an acceleration to 2 m/s^2,vehicle mass was 1440 kg.

Force = mass x acc. = 2.88 KN

Work = Force x distance (typical acc. event occurs over 50m)

Work = 2.88 KN x 50m = 144KNm = 144KJ

The typical acceleration event takes 10s, thus the power is 14.4KW

Fuel mass flow to give 14.4 KW?

Assume CV 43 MJ.kg and engine efficiency at low powers of 20%

Fuel flow = 0.0144/(0.2 x 43) = 1.7 g/s

In this work the peak fuel consumption for the acceleration events varied from 1-2 g/s so these estimates are reasonable.

1.7 g/s gives about 5g/s of CO_2 and with 29 acc. /1000s each lasting 10s this is 1450g CO_2.

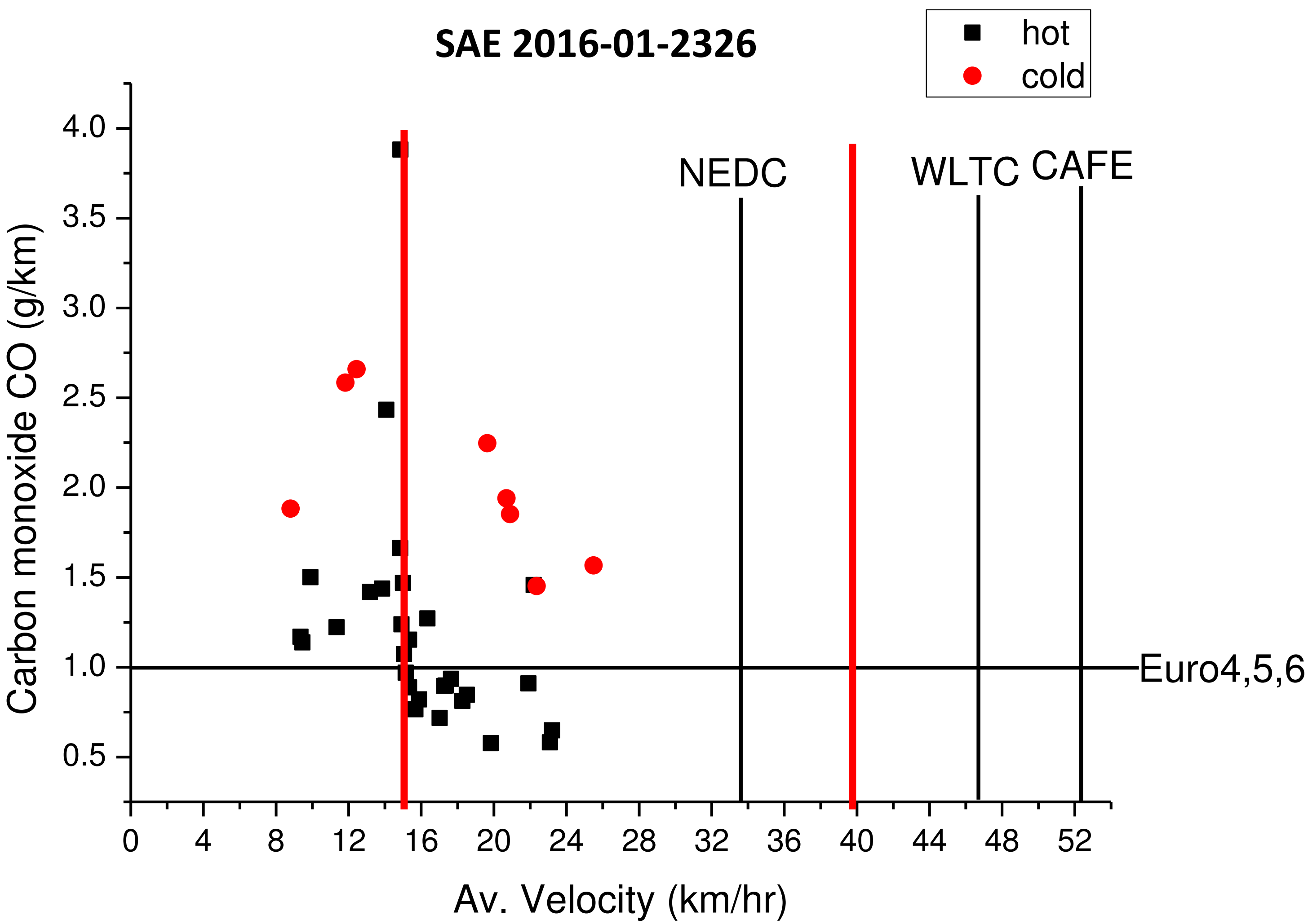
What is the fuel requirement to accelerate the vehicle from idle?

The above simple analysis of the energy required to move the vehicle from idle with an acceleration of 2 m/s^2 agrees with the measurements in this work.

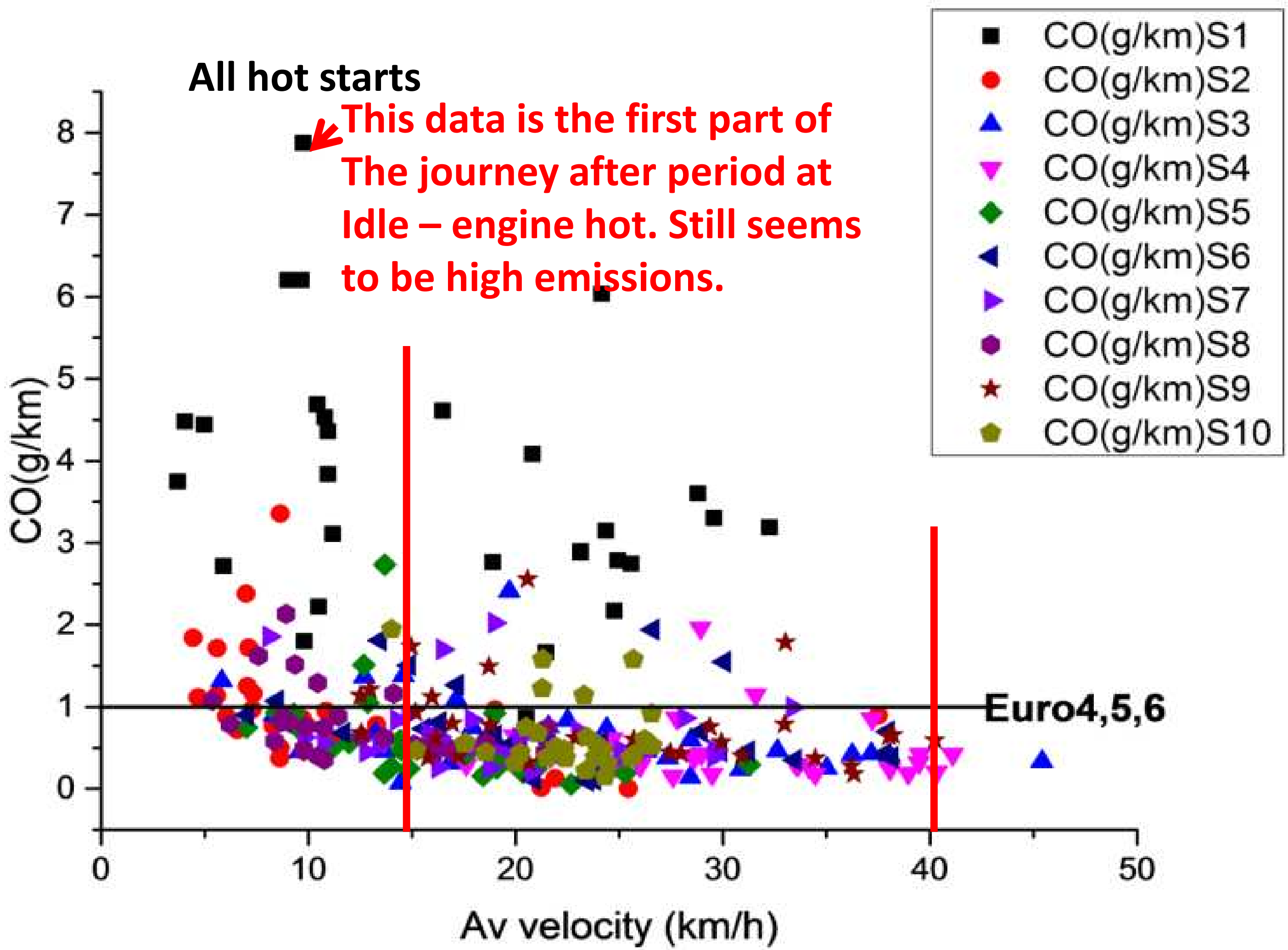
For the average 29 acceleration events per 1000s and 2.75 km drive distance this fuel consumption gives 530 g_{CO2}/km.

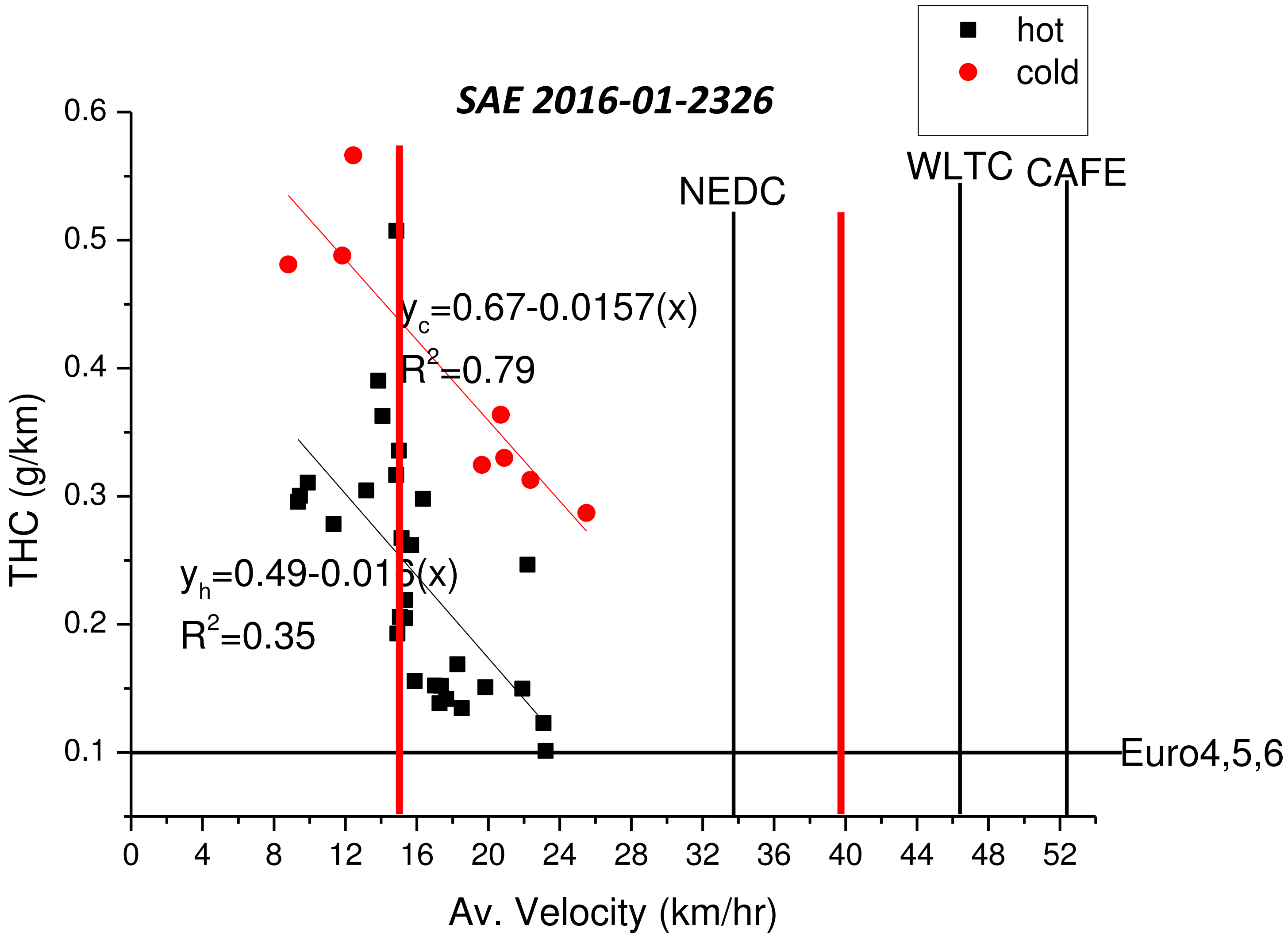
Thus it can be seen that the reason that the present congested traffic driving has such large CO_2 emissions is the generation of large numbers of acceleration events from idle.

Clearly, if these accelerations can be done by an electric motor, then a hybrid vehicle will have a major CO_2 saving under these driving conditions. Also if the deceleration can be achieved with energy recuperation that the impact of congested driving on CO_2 emissions will be reduced.

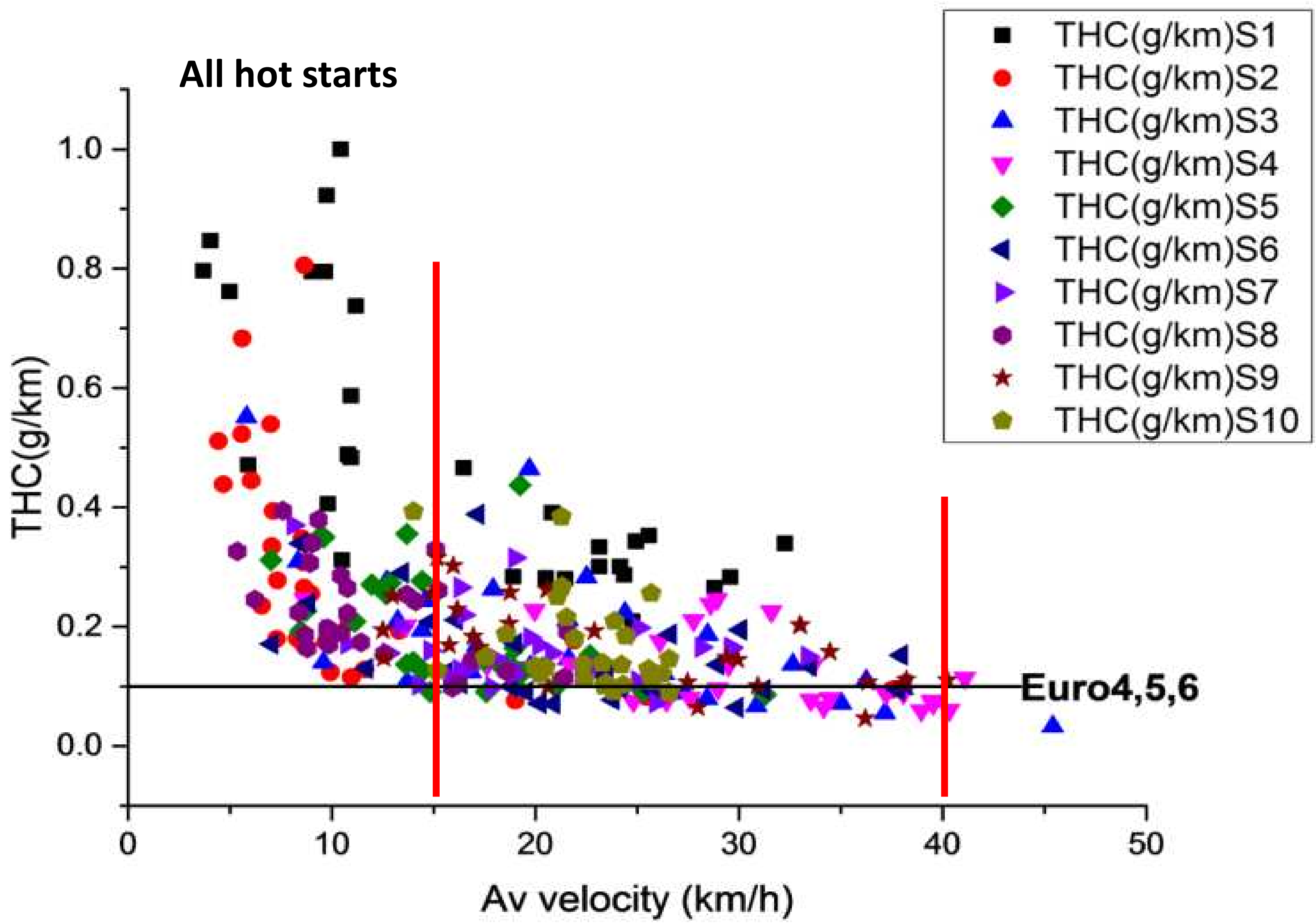

SAE 2016-01-2326
hot
cold
Carbon monoxide CO (g/km)
Av. Velocity (km/hr)
NEDC
WLTC
CAFE
Euro4,5,6
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
4
8
12
16
20
24
28
32
36
40
44
48
52

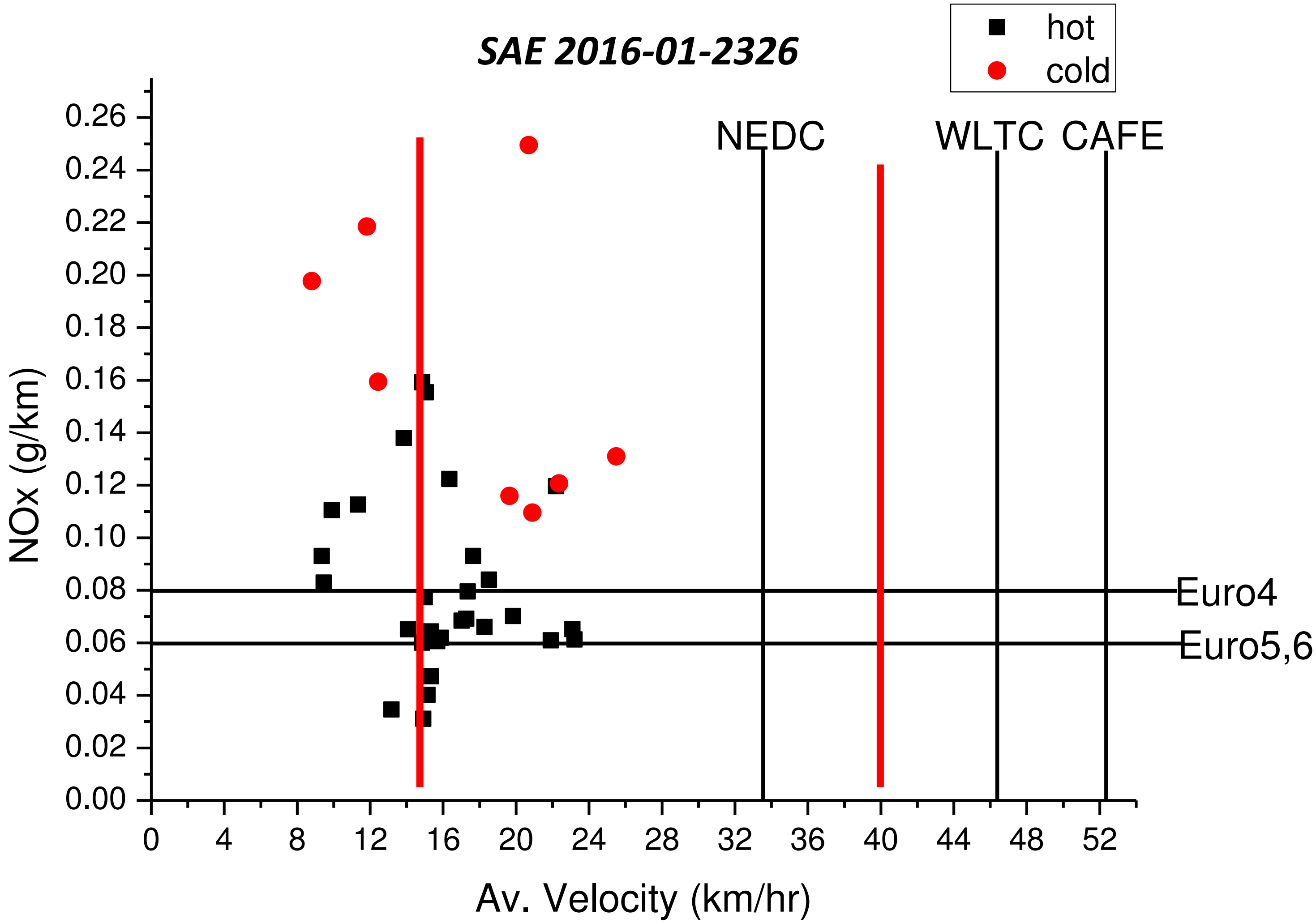
Khalfan, A., Andrews, G.E. and Li, H. *Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start*. SAE International SAE2017-01-2388



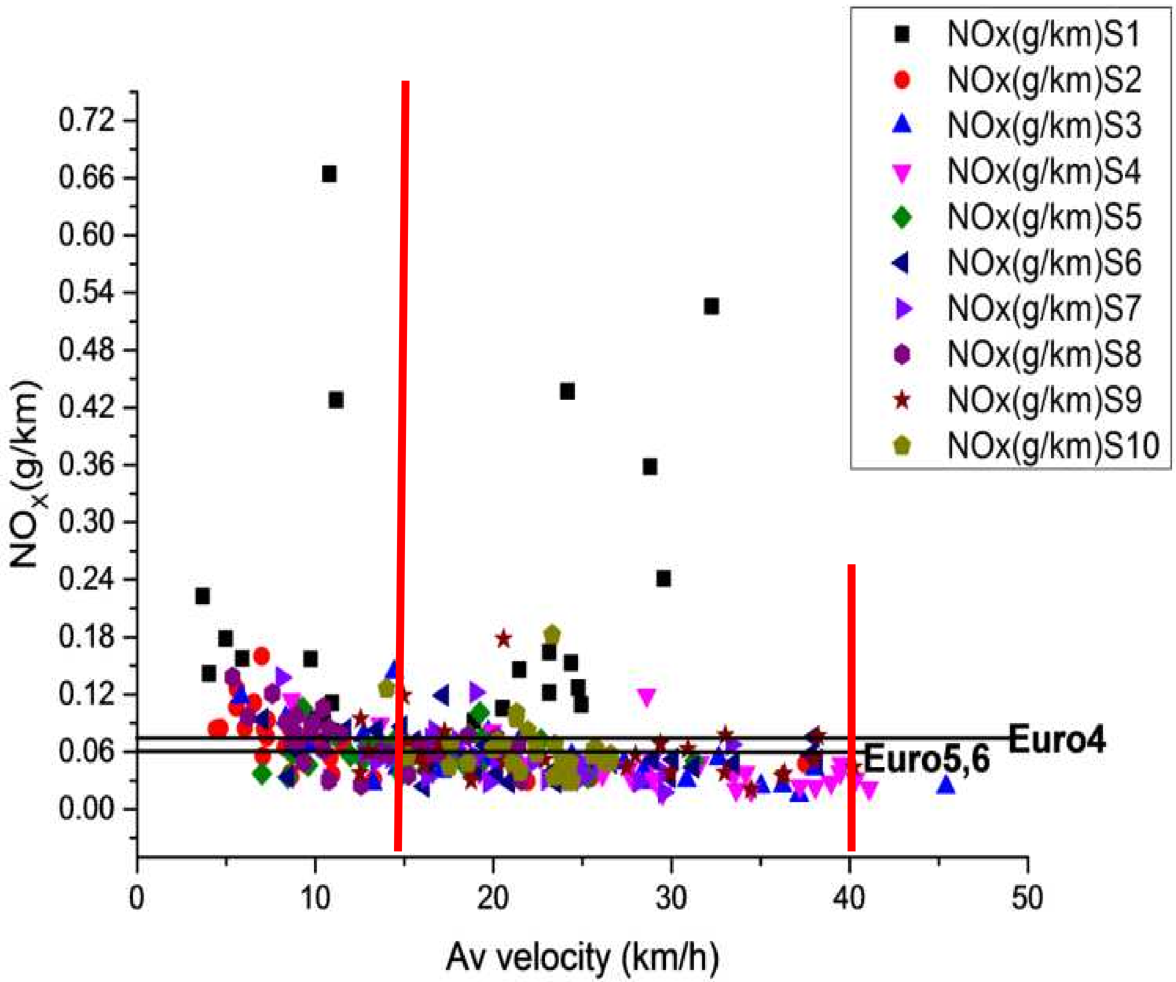

SAE 2016-01-2326
hot
cold
0.6
0.5
0.4
0.3
0.2
0.1
THC (g/km)
0
4
8
12
16
20
24
28
32
36
40
44
48
52
Av. Velocity (km/hr)
NEDC
WLTC
CAFE
Euro4,5,6
y_c=0.67-0.0157(x)
R^2=0.79
y_h=0.49-0.016(x)
R^2=0.35

Khalfan, A., Andrews, G.E. and Li, H. *Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start*. SAE International SAE2017-01-2388

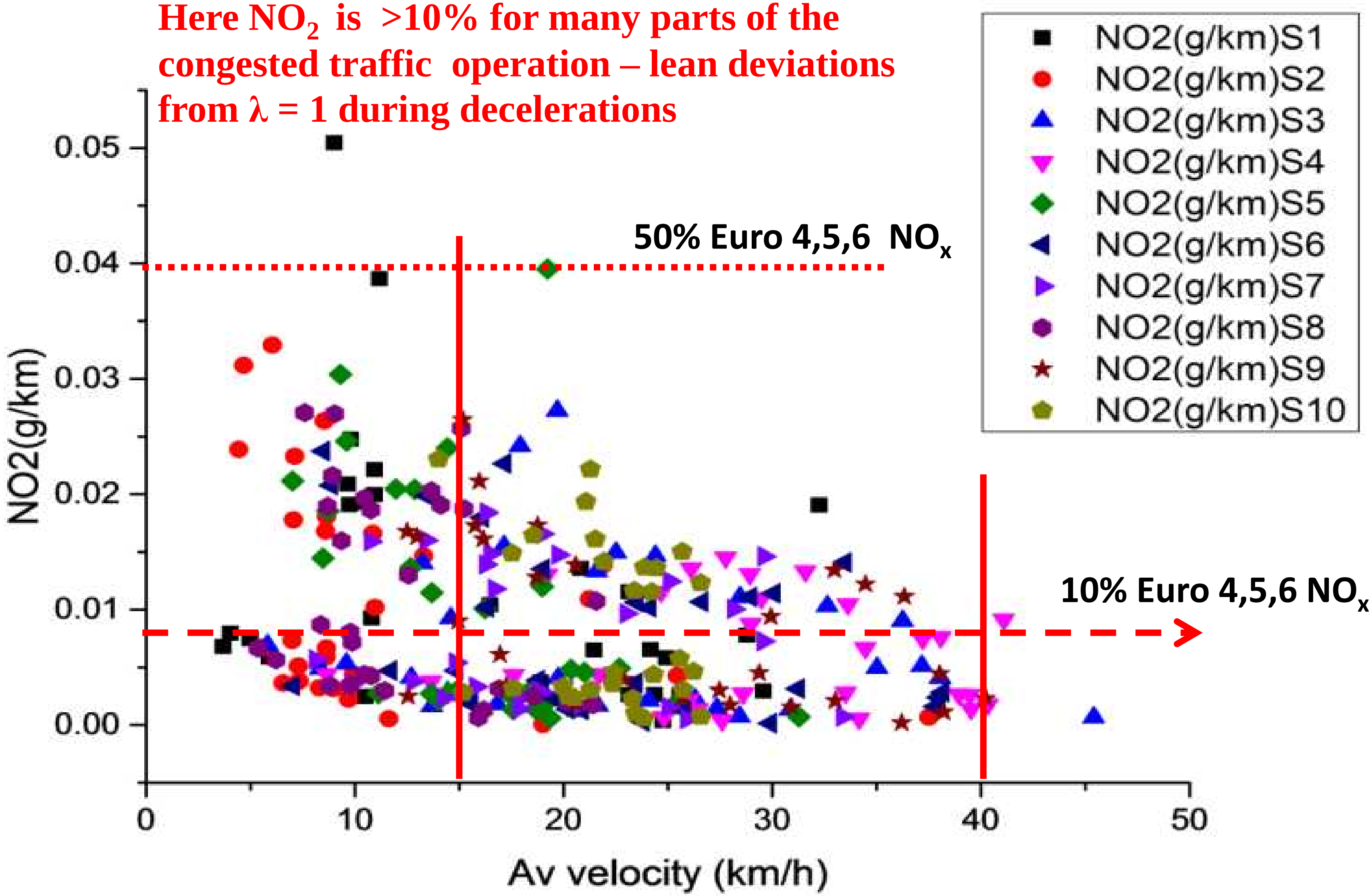



SAE 2016-01-2326
hot
cold
NEDC
WLTC
CAFE
Euro4
Euro5,6
NOx (g/km)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0
4
8
12
16
20
24
28
32
36
40
44
48
52
Av. Velocity (km/hr)

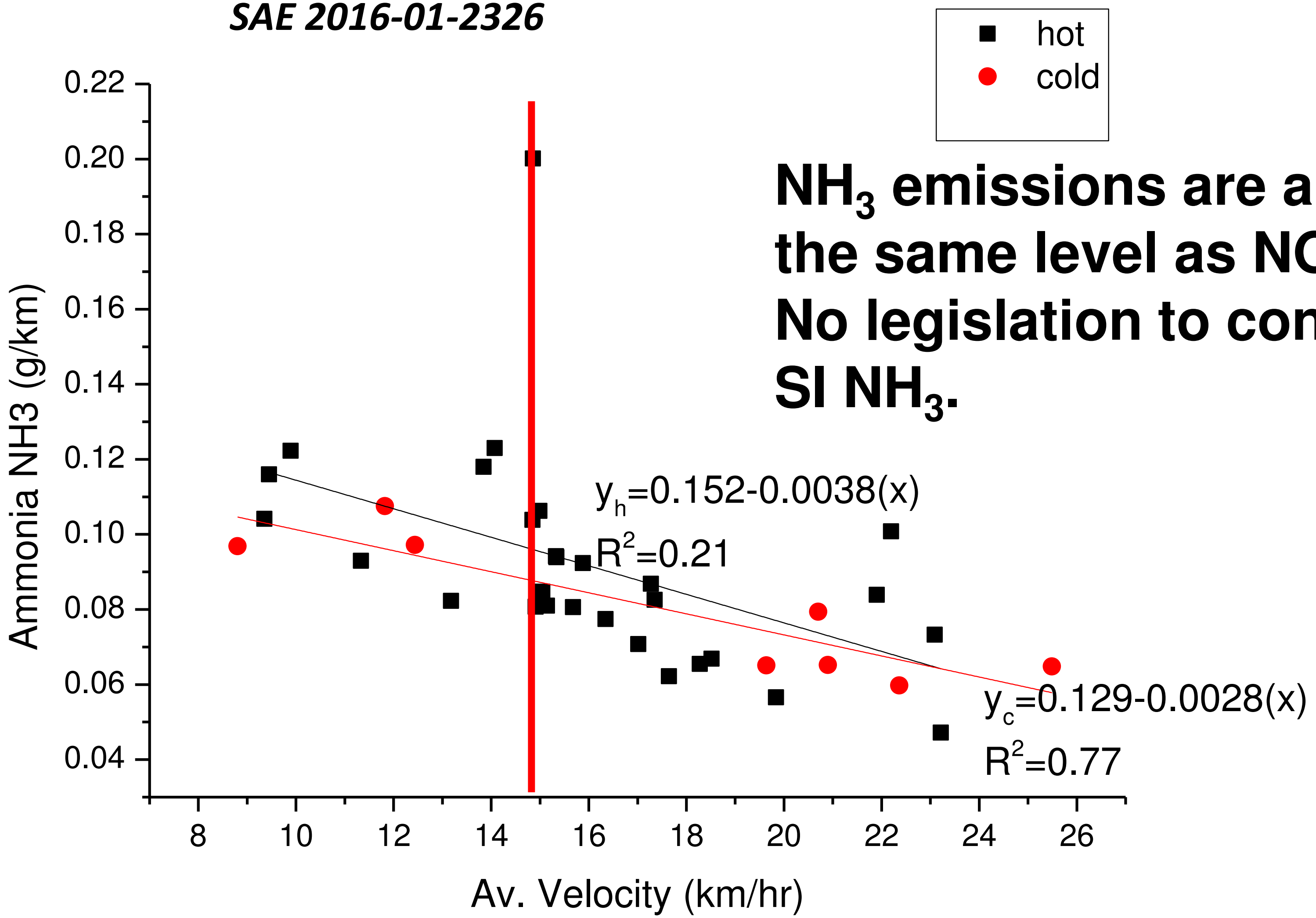
Khalfan, A., Andrews, G.E. and Li, H. ***Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start*****. SAE International SAE2017-01-2388**



Normally a SI engine at λ = 1 has negligible NO_2
Here NO_2 is >10% for many parts of the congested traffic operation – lean deviations from λ = 1 during decelerations

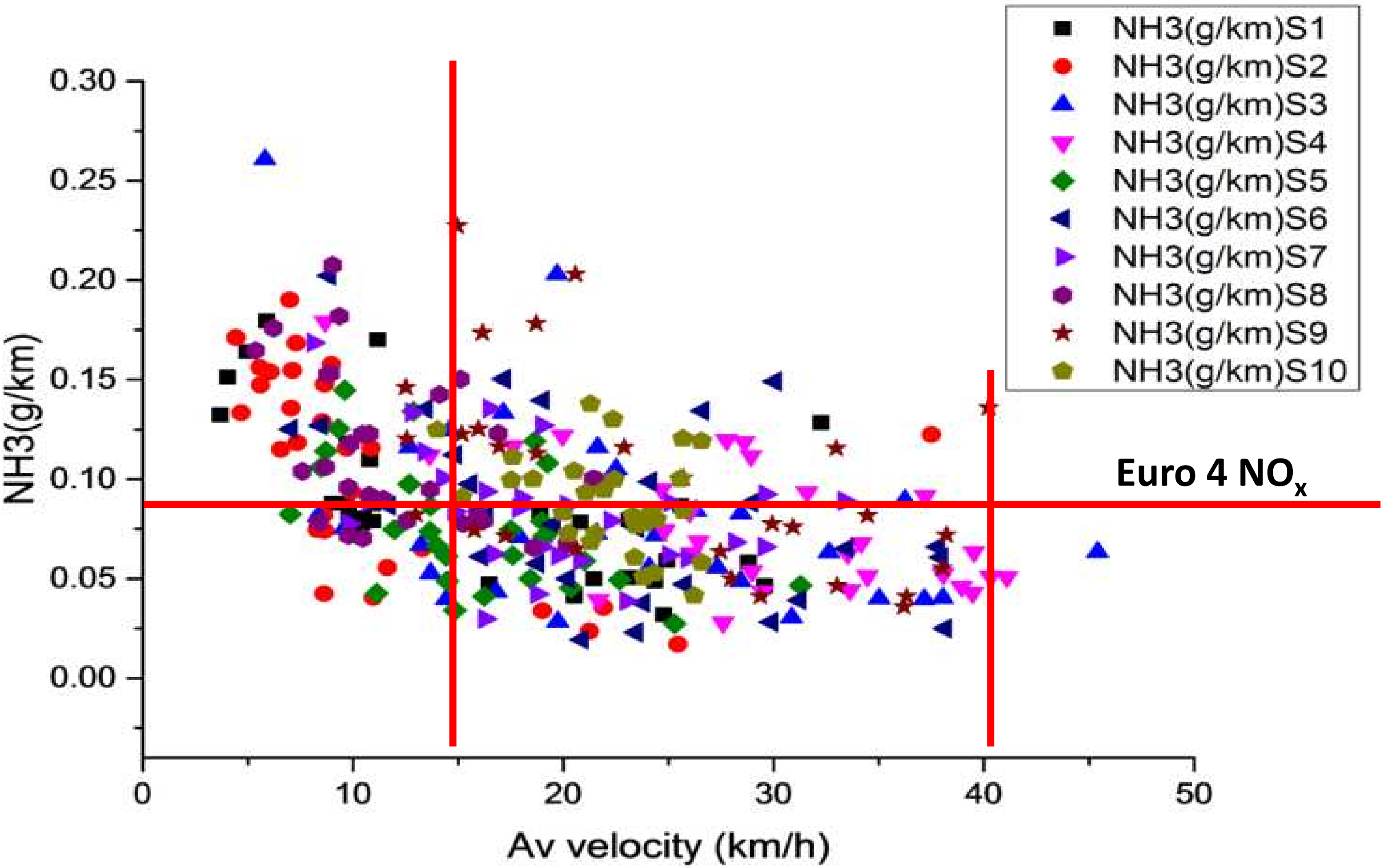


SAE 2016-01-2326



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

Khalfan, A., Andrews, G.E. and Li, H. *Real Driving Emissions in Congested Traffic: A Comparison of Cold and Hot Start*. SAE International SAE2017-01-2388



Contents

1. Roadside NO_x exceedances of EU air quality standards and the legal requirement to reduce real world traffic emissions.
2. RDE, WLTC and comments on the RDE boundaries and cold start
3. Comparison of tests cycles with RDE and the present real world driving urban journey.
4. Previous Leeds work on real world emissions that shows higher emissions than on the test cycle.
5. What is the typical urban driving distance and speed?
6. Aggressive drivers
7. Congested traffic: comparison of the Leeds A660 route with other urban driving routes.
8. Congested traffic: emissions results
9. Conclusions

Conclusions

1. Roadside air quality measurements all show exceedances of European air quality standards for NO_x. They are all located on the roadside where at peak commuting times the road is highly congested. The A660 north from Leeds is one such road and has highly congested traffic in the morning and evening rush hour traffic. The traffic load is about 1000 vehicles per hour at this time.
2. The emissions per journey can be expressed as an average for the journey and the mean journey speed is a good corelator..
3. The limits of the RDE exclude journeys with average speeds below 15 kph, but these are quite common in congested traffic, with journey speeds as low as 5 kph for the highest congestion.
4. Individual journeys can be split into shorter sections of about 200m length so as to expand the number of journeys.
5. Air quality in cities could benefit by including low speed congestion in the RDE by lowering the lowest journey speed to 5 kph or eliminating the lower speed limit.
6. The elimination of aggressive drivers from the RDE is not justified as they are part of the real world driving emissions problem.