Real world CO_2 and NO_x emissions from 149 Euro 5 and 6 diesel, gasoline and hybrid passenger cars

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Abstract

In this study CO_2 and NO_x emissions from 149 Euro 5 and 6 diesel, gasoline and hybrid passenger cars were compared using a Portable Emissions Measurement System (PEMS). The models sampled accounted for 56% of all passenger cars sold in Europe in 2016. We found gasoline vehicles had CO_2 emissions 13 – 66% higher than diesel. During urban driving, the average CO_2 emission factor was 210.5 (sd. 47) g km^{-1} for gasoline and 170.2 (sd. 34) g km^{-1} for diesel. Half the gasoline vehicles tested were Gasoline Direct Injection (GDI). Euro 6 GDI engines <1.4ℓ delivered ~17% CO_2 reduction compared to Port Fuel Injection (PFI). Gasoline vehicles delivered an 86 - 96% reduction in NO_x emissions compared to diesel cars. The average urban NO_x emission from Euro 6 diesel vehicles 0.44 (sd. 0.44) g km^{-1} was 11 times higher than for gasoline 0.04 (sd. 0.04) g km^{-1}. We also analysed two gasoline-electric hybrids which out-performed both gasoline and diesel for NO_x and CO_2. We conclude action is required to mitigate the public health risk created by excessive NO_x emissions from modern diesel vehicles. Replacing diesel with gasoline would incur a substantial CO_2 penalty, however greater uptake of hybrid vehicles would likely reduce both CO_2 and

NO_x emissions. Discrimination of vehicles on the basis of Euro standard is arbitrary and incentives should promote vehicles with the lowest real-world emissions of both NO_x and CO_2.

Keywords

Real-world emissions; PEMS; Passenger cars; GDI; NO_x; CO_2;

1 Introduction

Whilst passenger car emissions have improved with successive legislation there is substantial evidence of the growing discrepancy between type approval limits and real driving emissions (RDE) for both nitrogen oxides (NO_x) and carbon dioxide (CO_2) (Carslaw et al., 2011; Fontaras et al., 2017; Franco et al., 2014; Kågeson, 1998; O'Driscoll et al., 2016; Weiss et al., 2012). This creates the need for Portable Emissions Measurement (PEMS) studies to provide a true picture of real world emissions (Collins et al., 2007; Frey et al., 2003; Kousoulidou et al., 2013; Rubino et al., 2007; Weiss et al., 2011).

There is also a growing body of evidence relating to the adverse health effects of air pollution (COMEAP, 2010; EEA, 2015; RCP, 2016; WHO, 2016, 2013). Across Europe many major cities are unable to meet the annual mean concentration limit for nitrogen dioxide (NO_2), set for the protection of human health. Exceedances of the limit value occur mostly at roadside locations; this is largely attributed to the failure of the EU type approval procedure to reduce real world emissions, particularly NO_x from diesel vehicles (Beevers et al., 2012; Degraeuwe et al., 2015; DfT, 2016a; Franco et al., 2014). With an aim to address this the EU have introduced (from September 2017) a real driving component to the type approval process, Euro 6d-TEMP (EC, 2016).

CO_2 is the dominant greenhouse gas (GHG) causing global warming, which has severe impacts on climate, people and ecosystems around the world (IPCC, 2014). An international consensus has grown around the need to reduce emissions of GHGs though international summits such as the Paris Climate Accord (CCC, 2016). After the energy sector, the transport sector is the biggest emitter of GHGs in the European Union (EU), and more than two thirds of transport emissions come from road transport, making road transport responsible for ~20% of all GHG emissions in the EU (Europa, 2017). The EU is committed to reducing CO_2 emissions from road transport by introduction of fleet average CO_2 targets that aim to deliver a 40% decrease in emissions from new cars between 2005 and 2021. The current fleet average target of 130 g km^{-1} was introduced in 2015. Technological advancements in engine fuel efficiency have reduced vehicle CO_2 emissions but rising demand for fuel has outweighed fuel economy improvements. As a result, transportation is the only major sector in the EU for which greenhouse gas emissions continue to rise (CCC, 2015; Fontaras et al., 2017).

In Europe, the most prevalent passenger car fuels are diesel and gasoline. Differences between the two fuels and associated engines in energy density, combustion processes and after treatment technologies result in different exhaust compositions. Comparatively speaking, gasoline vehicles produce 20 - 30% more CO_2, whilst diesel vehicles emit many times more NO_x (Moody and Tate, 2017; Suzuki and Matsumoto, 2004; Weiss et al., 2012).

‘Dieselisation’ of the European passenger fleet began in the mid-1980’s, driven by improvements in fuel economy and supposed environmental benefits. Throughout the 2000’s, government incentives promoted sales of diesel vehicles leading to a peak in EU passenger car sales of 52% in 2015 (ICCT, 2016). Recent trends in sales indicate the 2015 Volkswagen scandal along with evidence of the health effects relating to air pollution from diesel vehicles have caused consumers to move away from diesel (FT, 2016) (see supporting information). Total annual car sales continue to rise, and whilst some consumers are opting for alternative fuel vehicles instead of diesel, the majority are switching back to gasoline (SMMT, 2017).

In the UK over half of all alternative fuel vehicles sold are gasoline- electric hybrids. Previous studies have found average emissions from two Euro 5 Toyota Prius gasoline-electric vehicles were (0.009 ± 0.005 g NO_x km^{-1}) and (136 ± 21 g CO_2 km^{-1}) (Wu et al., 2015) with fuel economy savings of 40 – 60% compared to an equivalent conventional gasoline vehicle (Fontaras et al., 2008).

In this study, we compare the real-world emissions of NO_x and CO_2 from 149 Euro 5 and 6 diesel, gasoline and hybrid passenger cars and 2 gasoline-electric hybrids. We analyse and compare the real world CO_2, NO_x and primary NO_2 emissions and how these relate to type approval limits and manufacturer's official estimates. We investigate the CO_2 savings delivered by Gasoline Direct Injection (GDI) engines, and compare urban and motorway emissions. We also extend the discussion to the significance of cold start emissions in the supporting information. Our aim is to present an accurate representation of CO_2 and NO_x emissions from the current Euro 5 and 6 European fleet in order to inform policies that protect both air quality and climate change objectives.

2 Materials and Methods

PEMS measurements of 149 vehicles were conducted in the Greater London area between 2012 -2016. The test fleet contained 37 Gasoline Euro 5 (G5), 35 Gasoline Euro 6 (G6), 36 Diesel Euro 5 (D5), 39 Diesel Euro 6 (D6), 1 Euro 5 Hybrid (H5) and

1 Euro 6 Hybrid (H6) vehicle(s). The models sampled accounted for 56% of all passenger cars sold in Europe in 2016 and included vehicles made by 27 manufacturers.

2.1 Test vehicles

The goal of this study was to provide a broad characterisation of the fleet, as opposed to identifying issues specific to a manufacturer, therefore vehicles were anonymised and assigned a vehicle ID. The characteristics of the vehicles are provided in the supporting information.

Engine displacements of the test fleet followed the wider European trend, with diesel engines being larger and gasoline engines smaller. The average engine displacement was 1.9 ℓ for diesel and 1.5 ℓ for gasoline. The distribution of engine sizes in the test fleet was representative of the UK and European fleet (see supporting information). As engine displacement relates closely to CO_2 emissions, the vehicles were split into categories for analysis as follows; <1.4 ℓ = Extra Small [XS], 1.4 ℓ - ≤1.55 ℓ = Small [S], 1.55 ℓ - ≤2ℓ = Medium [M] and >2 ℓ = Large [L].

The most represented euro car segments in the test fleet were B (Small), C (Lower Medium), D (Upper Medium) and H (SUV). Segments B, C, D and H are the most common in the passenger car market, in the UK in 2015 they made up 83% of new vehicles registered (SMMT, 2015).

Vehicles in the test fleet had relatively low start mileages with an average of 4105 (standard deviation, sd. 3000) km. Therefore, deterioration of the emissions control systems as a result of ageing, usually observed after ~50,000km (Borken-Kleefeld and Chen, 2015), is not a factor in this study. As it is too early for substantial evidence of emissions degradation from Euro 5 and 6 vehicles, it cannot be assumed emissions stated in this study will remain constant over the lifetime of the vehicle (Chen and Borken-Kleefeld, 2016). Some of the vehicles have driven less than 3000 km and may not have fully de-greened, however, these are representative of vehicles on European roads. The vehicles in the test fleet include Euro 6 classified vehicles manufactured from 2013 – 2016. The Euro 6 regulations are currently undergoing rapid changes, and vehicle manufacturers are likely to be modifying vehicles in response. As a result, the real-world performance of Euro 6 vehicles has become a moving target, again however, this sample can still be seen as representative of vehicles currently on the road.

2.1.1 After treatment

All gasoline vehicles in the test fleet were fitted with three-way catalysts (TWCs) which control NO_x, carbon monoxide (CO) and hydrocarbon emissions. All diesel vehicles were fitted with a Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF) and Exhaust Gas Recirculation (EGR), as are all diesel cars Euro 5 or after (BMVI, 2016; DfT, 2016a). The D6 vehicles had a mixture of NO_x aftertreatments, 7 used only EGR, 19 used EGR + Lean NO_x Trap (LNT), and 13 used EGR + Selective Catalytic Reduction (SCR). This reflects the 2014 sales mix (ICCT, 2015). All three abatement technologies were previously found to reduce diesel NO_x emissions to a similar degree (O’Driscoll et al., 2016).

Half of the vehicles in the test fleet were equipped with fuel saving stop-start technology. 60% of new cars sold in Europe have stop-start technology (Gross, 2015). It is thought to deliver fuel savings of between 3-5%, making any potential benefit within the natural variability of PEMS measurements (Bishop et al., 2007), and therefore not an explicit consideration explicitly in this study.

2.1.2 Gasoline Direct Injection (GDI)

From 2009 to 2014 the GDI deployment rate in Europe rose from 10% to 38% (Wolfram et al., 2016). Forty two percent of the gasoline vehicles in the test fleet were equipped with GDI engines, and these tended to be smaller vehicles (B and C segment). The GDI share of the market has increased rapidly in recent years, and now makes up almost half of new gasoline vehicles sold. Studies have found GDI engines deliver fuel consumption savings of between 3 - 14.5% compared with Port Fuel Injection (PFI) engines (Chan et al., 2012; Saliba et al., 2017). However, GDIs have higher emissions of particulates (both mass and number) and a higher number of the ultrafine particles most associated with health effects (Liang et al., 2012; Peckham et al., 2011; Wang et al., 2014). The particle number (PN) limit and RDE emissions type approval testing required for the Euro 6d-TEMP emissions standard (September 2017) will require manufactures to address the issue of GDI engine PN. New technologies, including Gasoline Particulate Filters (GPFs) have been found to significantly reduce both particulate matter mass (PM) and PN emissions from GDIs (Czerwinski et al., 2017; Saliba et al., 2017). GDI engines without a GPF have been found to have higher particulate emissions than a diesel vehicle with a DPF (Liang et al., 2012). Neither PM nor PN were measured in this study.

2.1.3 Hybrid vehicles

A limited sample of 2 gasoline- electric hybrids were also analysed for comparison, one Euro 5, one Euro 6. Both had 1.8 ℓ gasoline engines.

2.2 Test route and trip section extraction

The test route was comprised of urban and motorway driving over an average distance of 83 km. For each vehicle, an urban and motorway section of 16 km was extracted for comparison (Table 1). A lack of repeatability is often a criticism of PEMS measurements as vehicle emissions are highly sensitive to driving style (Durbin et al., 2008; Huang et al., 2013). It is therefore important to ensure the characteristics of the trips being compared are as consistent as possible. Here this was done by extracting sections of the trip for each vehicle with similar distance, duration, average speed, range of speed, time spent idle, Vehicle Specific Power (VSP, calculated using the equation found in the supporting information), Relative Positive Acceleration (RPA) and the 95th percentile of the product of speed and positive acceleration ($v.a_{pos}\_[95]$) (see supporting information).

Table 1. Motorway and urban cycle characteristics

	Duration [s]	**Distance [km]**	**Average speed [km h^{-1}]**	**% idle***
Urban	2368 (sd**. 105)	16.1 (sd. 0.1)	24.5 (sd. 1.1)	17.9 (sd. 3.1)
Motorway	580 (sd. 10)	16.1 (sd. 0.1)	99.8 (sd. 1.5)	0.02 (sd. 0.1)

*Vehicle speed < 0.5 ms^{-1}, acceleration between ± 0.1 ms^{-2}

** sd = standard deviation

The start and end point of each trip did not differ in altitude by more than 100 m and the altitude of the entire test was between 0 to 700 m. The dynamic characteristics of the extracted urban and motorway sections were compliant with the requirements of the RDE type approval test detailed in Annex IIIA of Regulation (EU) 2017/1151. This study differs from (EU) 2017/1151 in that the urban and motorway sections are not just defined by vehicle speed. Urban sections were extracted from measurements made on A, B or C roads (in the UK) with a speed limit of 50 km h^{-1} (30 mph). Motorway sections were extracted from continuous measurements made on M roads (UK) with a speed limit of 110 km h^{-1} (70 mph). A rural section is not included at it was not possible to extract continuous 16 km sections in the rural speed range. Not binning by speed ensured results reflected emissions exactly as they occurred during real world driving. Here, such section extraction was to standardize measurement conditions rather than normalisation using e.g. (EU) 2017/1151 prescribed methods. These tools have been shown to apply different corrections to real world test data (Heijne et al., 2016).

Figure 1 shows the speed distribution, VSP distribution, $v.a_{pos}$_[95] and RPA of the urban and motorway sections. In each plot the data falls into distinct groups, indicating consistency between the tests.

Figure 1(a) shows the speed distributions of each section compared to the current type approval drive cycle (New European Drive Cycle, NEDC) and the new Worldwide harmonized Light vehicles Test Procedure (WLTP). Urban sections (light grey) contain speeds within the range 0 - 50 km h^{-1}, motorway sections (dark grey) contain mostly speeds > 75 km h^{-1}.

VSP is an instantaneous measure of a vehicles power per unit mass as a function of speed, acceleration/deceleration and road gradient (see supporting information). Figure 1(b) is a frequency diagram of the instantaneous VSP for urban and motorway sections. Urban sections were characterised by lower speeds and had a lower range of VSP, whereas the peak frequency for motorway sections was higher in speed and VSP. The height of the peaks reflects the duration of the different sections, urban sections were on average 4 times longer than motorway.

$v.a_{pos}$_[95] is the metric for assessing the maximum dynamic boundary conditions in (EU) 2017/1151 (see supporting information). An RDE test trip is valid if $v.a_{pos}$_[95] is below a certain value. These values are proportional to speed and are marked by dashed diagonal lines on Figure 1(c). All data points fell below these lines showing trips in this study met the v.a_{pos}_[95] RDE dynamic boundary conditions.

RPA is the metric for assessing the minimum dynamic boundary conditions in (EU) 2017/1151 (see supporting information). An RDE test trip is valid if it has RPA above a certain value. Again these values are proportional to speed and are marked by dashed diagonal lines on Figure 1(d). All data points fell above these lines showing trips in this study met the RDE dynamic boundary conditions.

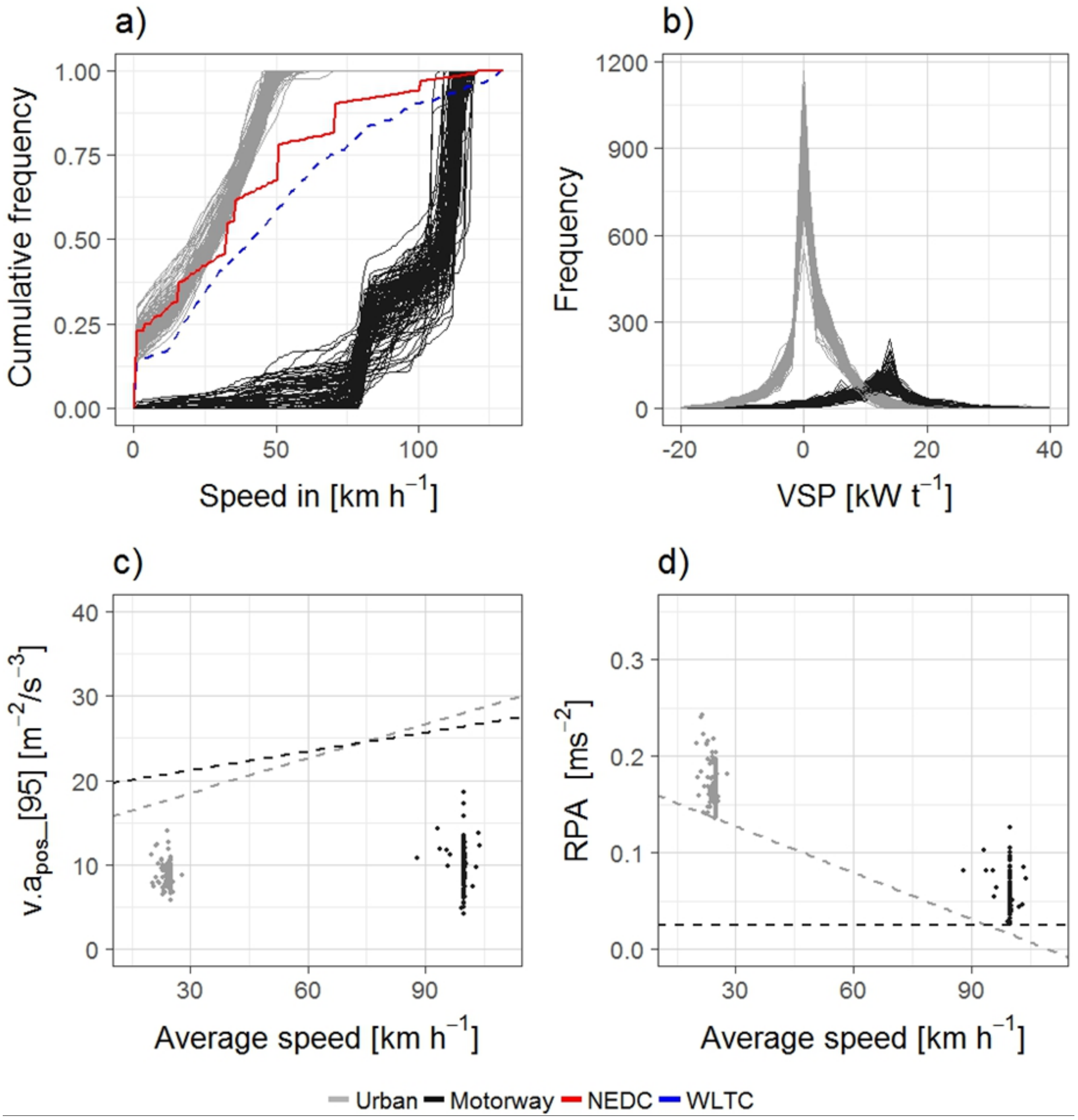

Figure 1. Urban and motorway sections characteristics (a) cumulative speed distribution (b) VSP frequency (c) validation of v.a$_{pos}$_[95] by speed (points must be below dashed line for trip to be valid) (d) validation of RPA by speed (points must be above dashed line for points to be valid)

2.2.1 Ambient temperature

Ambient temperatures ranged between 3 – 30°C and the study average ambient temperature was 15.3 (sd. 5.9) °C. This is within the “normal range” for Europe (EC, 1998). Previous studies have found NO_x emissions increase at lower ambient temperatures (DfT, 2016a; Kwon et al., 2017). The main reason for higher NO_x emissions at lower ambient temperature is due to engine control strategies that disable the EGR at low temperature. This is to prevent condensation in the EGR, which would be damaging (TNO, 2016) We found some correlation between NO_x emissions and ambient temperature for Euro 5 vehicles. However, we have not corrected for ambient temperature as the range of temperatures were evenly represented in tests for each vehicle category, ensuring comparisons were fair (see supporting information). We aimed to accurately represent real world European driving emissions, and as such needed to cover a range of temperatures to be representative. In this study urban and motorway sections were part way through the test and therefore did not include cold start emissions. For an illustration of a cold start see the supporting information.

2.3 PEMS measurements

PEMS measurements were performed by Emissions Analytics using a SEMTECH-DS (Sensors Inc., USA) following exactly the procedures detailed in O'Driscoll et al, (2016). The instrumentation (PEMS analysers, and exhaust flow meters), PEMS installation procedures, ambient conditions, altitude and elevation gain were compliant with the RDE type approval test detailed in Annex IIIA of Regulation (EU) 2017/1151. An optional requirement of additional chassis dynamometer testing to validate the PEMS was not performed for these tests. The PEMS analysers were calibrated at the beginning, middle and end of each trip and a correction for analyser drift was applied using the PEMS manufacturer's software. For a description of the data analysis methods see the supporting information.

3 Results and Discussion

3.1 CO_2 emissions

Figure 2 compares CO_2 emissions from gasoline (GDI and PFI) and diesel vehicles by engine size for urban and motorway sections. There was no significant difference in CO_2 emissions between Euro 5 and Euro 6 technology vehicles. Gasoline CO_2 emissions were consistently higher than diesel. The increase in average CO_2 emissions from gasoline to diesel ranged between 13 – 66%, with the CO_2 differences between gasoline and diesel being larger for larger engine displacements and was higher for urban driving sections.

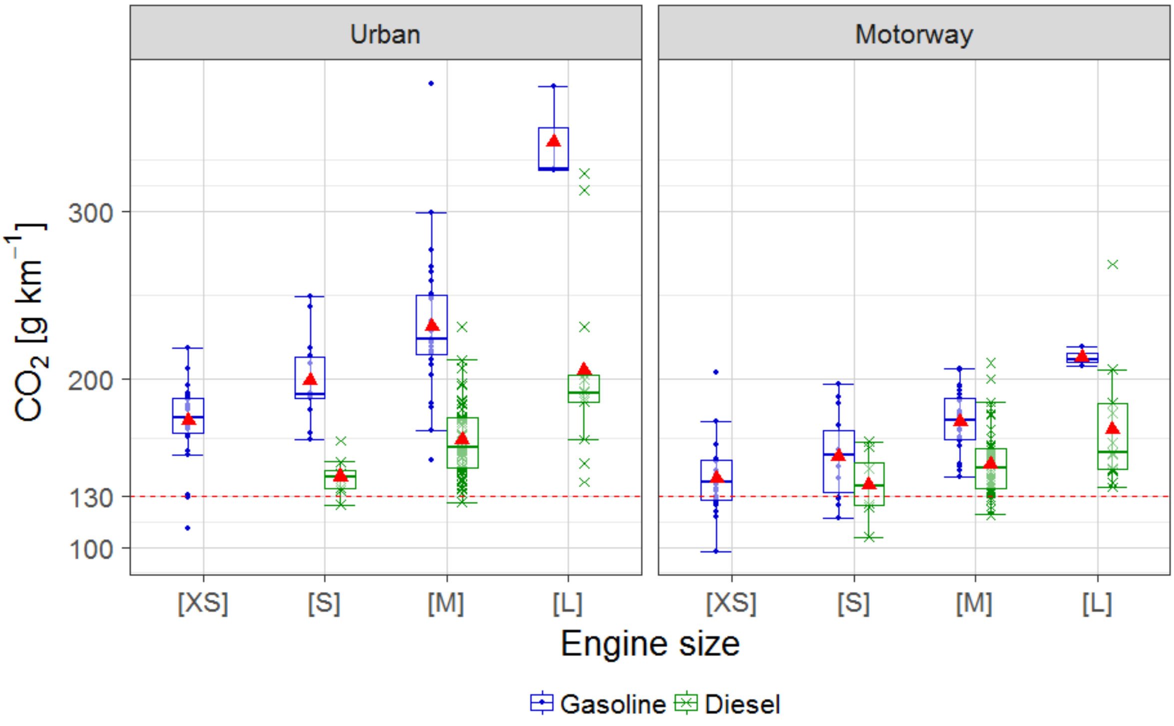

Figure 2. Urban and motorway CO_2 emissions by engine displacement (dashed line = 130 g CO_2 km^{-1} fleet target limit, red triangle = mean, central line in boxplot = median, top and bottom of box = 1st and 3rd quartile, whiskers = 1.5 * interquartile range)

The average quoted in Table 2 is weighted by the size distribution of gasoline and diesel engines in the UK fleet using 2015 new car sales data (see supporting information). This size distribution has stayed relatively constant over the last 20 years (DfT, 2016b). The same trend was found for vehicle weight, see supporting information for further detail.

	[XS]	**[S]**	**[M]**	**[L]**	**UK weighted average**	**Average % increase from manufacture's official estimates**
CO_2 [g km^{-1}]						
			URBAN			
Gasoline	175.2 (sd. 23.3)	199.2 (sd. 25.2)	231.5 (sd.42.3)	340.9 (sd. 28.6)	210.5 (sd. 47)	61 (sd. 28)%
Diesel	-	141.9 (sd.11.6)	163.4 (sd. 21.6)	205.1 (sd. 55.1)	170.2 (sd. 34)	41 (sd. 18)%
			MOTORWAY			
Gasoline	140.6 (sd. 20.3)	154.3 (sd. 24.9)	174.4 (sd. 17.9)	213.0 (sd.6.0)	160.2 (sd. 29)	23 (sd. 17)%
Diesel	-	137.1 (sd. 19.8)	149.0 (sd. 18.9)	170.0 (sd. 36.4)	152.3 (sd. 22)	27 (sd. 15)%
Increase from diesel to gasoline						
Urban	-	40%	42%	66%	24%	
Motorway	-	13%	17%	25%	5%	

sd = standard deviation

Table 2. Average CO_2 emission by engine displacement, sections and fuel in [g km^{-1}]

CO_2 emissions increased with engine size, and to a greater extent for gasoline vehicles, indicating CO_2 savings could be made by downsizing gasoline engines. However, the majority of gasoline engines are already small, [L] engines account for only 7% of the EU gasoline fleet. Engine size should be considered as consumers switch away from diesel to gasoline. If an [M] diesel is replaced with an [M] gasoline our results indicate the increase in urban CO_2 emissions would be 42%. Replacing an [M] diesel with an [S] gasoline would result in a 22% increase. Even by switching to an [XS] gasoline there is still an increase of 7%.

Table 2 lists by how many percent real-world CO_2 emissions exceeded the manufacturer's official estimates. The average urban percentage exceedance was higher for gasoline vehicles (+61%) than diesel vehicles (+41%). These results agree with previous studies that found wide discrepancies between official reported CO_2 values and CO_2 emissions inferred from real world fuel consumption (Fontaras and Samaras, 2010; T & E, 2015), which have shown increases from around 10% in 2002 to around 40% in 2014 (CCC, 2015). Our results show this trend has continued particularly for gasoline vehicles. This is because (as shown in Figure 1) the test cycles are not fully representative of driving condition in the real world.

Only 4 vehicles (2 diesel, 2 gasoline) had real-world CO_2 emissions below the 2015 fleet average target of 130 g CO_2 km^{-1} during urban driving. 23 vehicles (10 diesel, 13 gasoline) achieved the fleet average target during motorway driving. The average urban percentage exceedance of the CO_2 target was +31% for diesel and +62% for gasoline.

When comparing gasoline and diesel vehicles it is important to consider vehicle utility. The average diesel car in the UK travels 65% further annually than the average gasoline car (DfT, 2015). Across Europe increases in annual vehicle mileage and the number of vehicles on the road have resulted in yearly increases in total vehicle kilometres driven. This increase in activity has outweighed savings from fuel economy improvements, much of which come from diesel vehicles. A gradual switch from diesel to gasoline would incur a substantial CO_2 penalty, hampering already ambitious climate change commitments.

3.1.1 CO_2 emissions from GDI engines

As 60% of the GDI engines were Euro 6, to compare GDI to PFI we focused only on Euro 6 vehicles. Forty percent of the G6 GDI engines in the study were [XS] and this is where the biggest CO_2 reductions occurred relative to PFI engines (Figure 3). For urban driving the average CO_2 emission from [XS] GDI gasoline engines was 151.0 (sd. 29.5) g km^{-1}. This was 17% below the average for [XS] PFIs. However, it was still higher than the average urban emission for [S] diesel engines. For motorway sections the [XS] GDIs had an average of 129.8 (sd. 19.3) g km^{-1} representing an 18% reduction compared to the [XS] PFIs. For [S] engines, no significant CO_2 benefit was found for GDI compared to PFI engines and for [M] engines during urban driving CO_2 emissions from GDI engines were on average 15% higher. There were no [L] GDI engines in the test fleet.

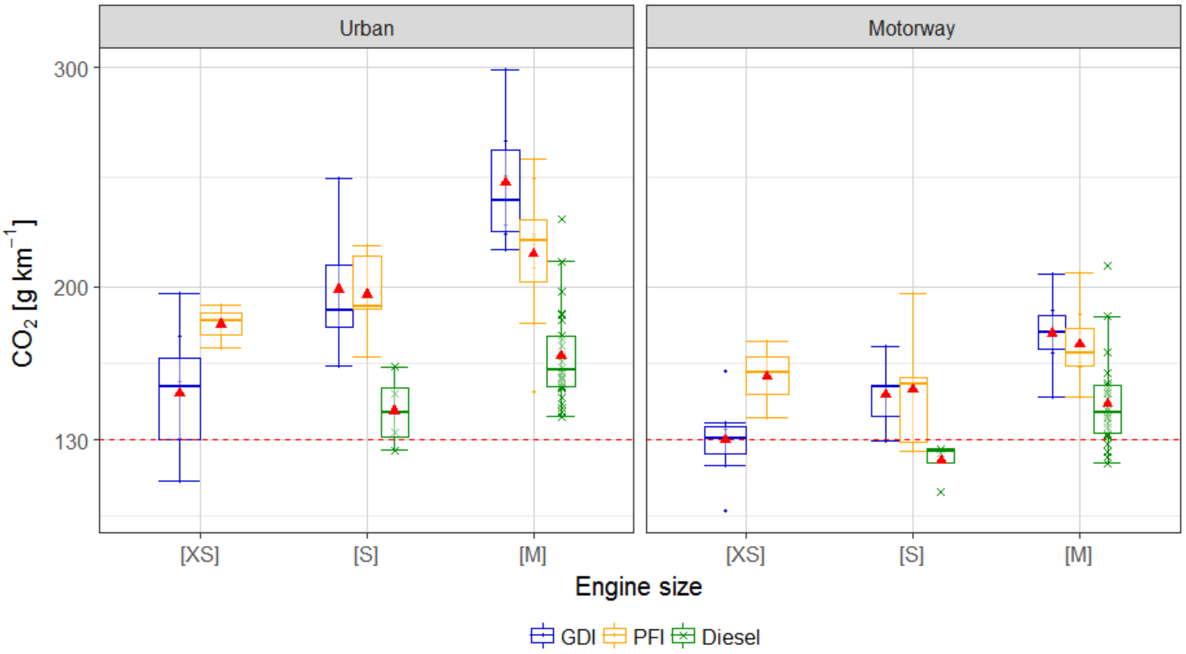

Figure 3. GDI, PFI and diesel Euro 6 urban and motorway CO_2 emissions by engine displacement (dashed line 130 g CO_2 km^{-1} limit, red triangle mean)

Whilst these results are promising, there are still questions concerning GDI cold start emissions and the prevalence of ultra-fine particles in exhaust gases. Further work is needed to evaluate real-world PN and PM emissions from GDI engines. Caution is required to avoid repeating the mistake made in the expansion of diesel vehicle sales, where technologies were pushed forward for a climate change benefit before air quality implications were fully understood.

3.2 NO_x emissions

There was a much greater divergence between gasoline and diesel when comparing NO_x emissions. The highest CO_2 emissions measured were 4 times the lowest. The highest NO_x emission measured was over 4000 times the lowest, although it should also be noted that there was significant variation within the vehicle categories. Unlike CO_2, significant improvement in NO_x emissions between Euro 5 and Euro 6 was found

(Figure 4). This indicates that any CO_2 efficiency improvements were offset by NO_x abatement strategies. Unlike CO_2 emissions, which uniformly increased with engine size, there was no uniform relationship between engine size and NO_x (see supporting information).

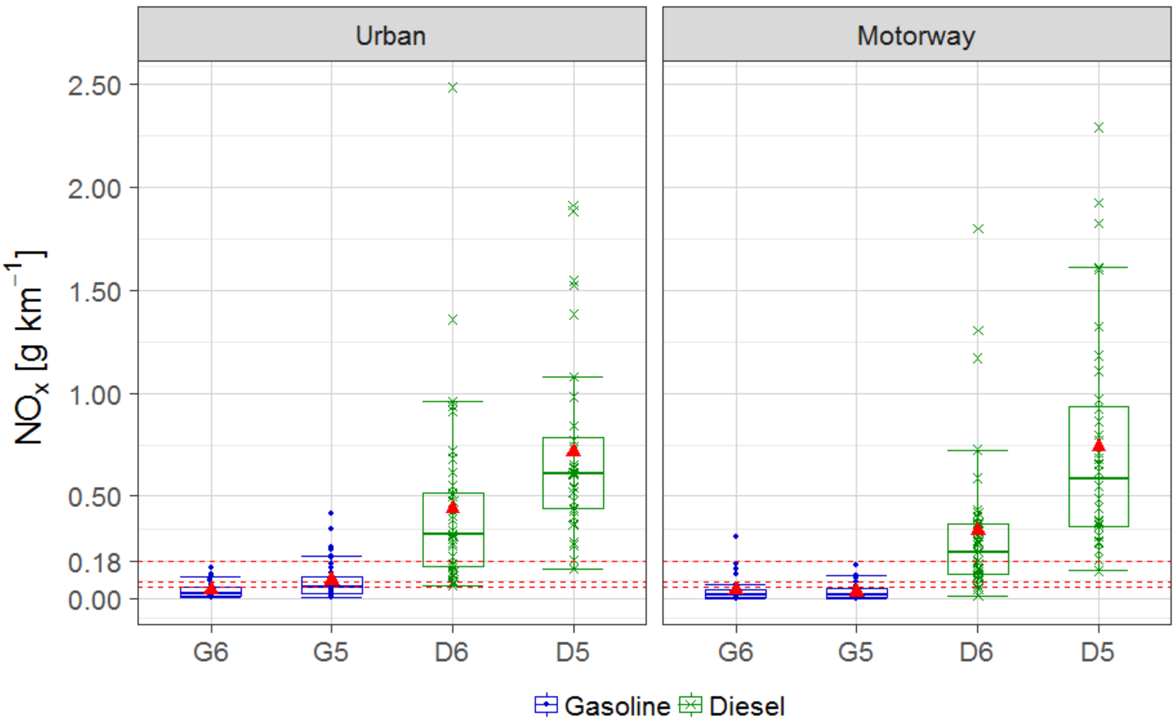

Figure 4. Urban and motorway NO_x emissions by vehicle category (red dashed line = type approval limits, D5 limit (0.18 g km^{-1}) is labelled, below is the D6 limit (0.08 g km^{-1}) and below that gasoline limit (0.06 g km^{-1} for G5 and G6), red triangle = mean)

In Figure 4 the dashed horizontal lines represent the type approval limits for each category. The majority of gasoline vehicles met the gasoline type approval limit during RDE, with the exception of G5 urban sections. In contrast, the majority of diesel vehicles met neither the diesel Euro 5 nor the diesel Euro 6 limit. sd = standard deviation

Table **3** lists the ratio of average NO_x emissions from each vehicle category to the relevant type approval limit. The urban ratio of real world to type approval limit increased between D5 and D6. This has been the case for diesel vehicles with successive euro standards (Franco et al., 2014; Weiss et al., 2011). The same observation has been made for CO_2 (Fontaras and Samaras, 2010). However, for diesel vehicles, the ratio between type approval and real world emissions is many times smaller for CO_2 than for NO_x.

sd = standard deviation

Table **3** lists the reduction in average NO_x emissions between diesel and gasoline vehicles. For urban driving the average D6 NO_x emission was 11 times the G6 average.

The mean NO_x emission for diesel vehicles was higher than the median (Figure 4) indicating a few high polluting vehicles had a substantial effect on the group mean. Removing these high polluting vehicles would deliver a NO_x benefit (O'Driscoll et al., 2016). Removing the worst 5 vehicles from the D6 sample reduced the average NO_x emissions by 30%.

NO_x [g km^{-1}]					**Reduction from diesel to gasoline**	
	G6	**G5**	**D6**	**D5**	**Euro 6**	**Euro 5**
Urban	0.04 (sd. 0.04)	0.09 (sd. 0.1)	0.44 (sd. 0.44)	0.72 (sd. 0.45)	91%	86%
Motorway	0.04 (sd. 0.06)	0.03 (sd. 0.04)	0.33 (sd. 0.36)	0.74 (sd. 0.54)	88%	96%
Ratio to relevant type approval limit						
Urban	x 0.7	x 1.5	x 5.5	x 4		
Motorway	x 0.7	x 0.5	x 4.1	x 4.1		

sd = standard deviation

Table 3. Mean NO_x emission by sections and category in [g km^{-1}]

D6 vehicles emitted 55% and 39% less NO_x than D5 vehicles for motorway and urban driving, respectively. For gasoline vehicles the major improvement in NO_x was in urban driving with a reduction of 56% achieved by G6s compared to G5s.

Of the 39 D6 vehicles in the study, 6 had one section (either urban or motorway) with emissions lower than the Euro 6 diesel type approval limit. No diesel vehicle met the type approval limit for both the urban and motorway sections. For the worst D6 vehicle (D6.3.0b), NO_x emissions were 31 times the type approval limit in the urban section. Urban G5 vehicles were the only gasoline category for which average NO_x emissions exceeded the gasoline type approval limit. Of the 37 G5 vehicles, 6 (16%) had urban section emissions in excess of the Euro 5 diesel type approval limit (0.18 g km^{-1}).

The variability in real world emissions from different vehicles with the same Euro standard demonstrates that the European emissions type approval process is not effective. The introduction of the RDE test procedure in September 2017 (EC, 2015) is an attempt to address this, though it will have no impact on the millions of vehicles already in circulation. Ultra-Low Emission Zones (ULEZ), such as that being introduced in London 2019, will discriminate by Euro standard. However, our results show that discriminating on the basis of real world emissions would be more effective. For example, 16% of the G5 vehicles exceeded the Euro 5 diesel type approval limit but will be allowed in the London ULEZ, as will all Euro 6 diesel cars. Five percent of D6 vehicles met the Euro 6 diesel type approval limit during urban driving, but many had emissions far in exceedance of it, with emissions being 5.5 times higher on average ranging to as much as 31 times higher.

3.2.1 NO_2 emissions

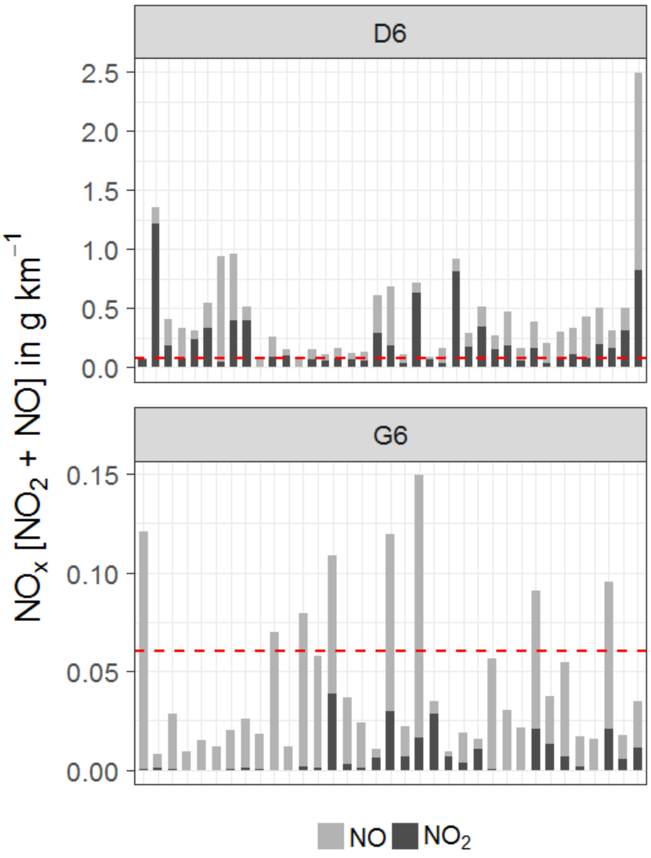

Figure 5. NO_x in g km^{-1} as NO and NO_2 components for Euro 6 urban sections (each bar represents an individual vehicle, red dashed line = NO_x type approval)

The proportion of NO_x emitted directly as nitrogen dioxide (NO_2) is referred to as primary NO_2 or fNO_2. There is no type approval limit for NO_2, only the combination NO and NO_2 (NO_x). At roadside locations the amount of NO_2 emitted directly from the exhaust becomes a dominant source of ambient concentrations, causing exceedances of the Air Quality Limit Value at the roadside (Alvarez et al., 2008; Carslaw, 2005; Degraeuwe et al., 2015; O'Driscoll et al., 2016). fNO_2 is higher from modern diesel vehicles due to the presence of oxidising catalysts in emissions control devices that oxidise NO to NO_2 (Giuseppe Madia et al., 2002).

Figure 5 shows the total NO_x emissions from urban sections of Euro 6 gasoline and diesel vehicles separated into the component parts of NO (light grey) and NO_2 (dark grey). Vehicles are arranged in order of increasing engine displacement along the x axis. Figure 5 shows clearly the contrast in composition in NO_x emissions between diesel and gasoline vehicles. A large proportion of diesel NO_x emissions (42 (sd. 19)% for D5, 46 (sd. 23)% for D6) were emitted directly as primary NO_2. In contrast, fNO_2 for gasoline vehicles is approximately half that for diesels (27 (sd. 26)% for G5, 17 (sd. 22)% for G6).

As with total NO_x, gasoline provided a 92-97% reduction in NO_2. Average D6 NO_2 emissions were 30 times the average G6 for urban sections. The average D6 urban emission (0.22 (sd. 0.26) g NO_2 km^{-1}) was 2.7 times the Euro 6 type approval limit for total NO_x. While the new RDE test procedure is likely to reduce overall NO_x emissions, it will not specifically address higher fNO_2 from diesel vehicles (O'Driscoll et al., 2016).

It should be noted that NO_2 emissions from G6 vehicles were within the error range for the PEMS system used. Whilst this may affect the accuracy of exact emissions measurements, it can be concluded that primary NO_2 emissions from Euro 6 gasoline vehicles are not an issue of concern.

3.3 Gasoline-electric hybrids

In this study the hybrids were the best overall performing group. Average urban CO_2 emissions were 117.4 (sd. 12.4) g km^{-1}. This was the lowest in the entire study and the only group with an average below the fleet target 130 g km^{-1}. Average motorway CO_2 emissions were 150.9 (sd. 36.3) g km^{-1}, which is similar to the average for [M] gasoline vehicles. This indicates that hybrid technology, which makes use of kinetic energy recovery, is much more effective in urban driving when there are regular vehicle accelerations and decelerations. Whilst these results indicate hybrids have an important role to play in reducing CO_2 emissions it is important to note with hybrid vehicles full lifecycle CO_2 emissions need to be considered, including the energy intensive production of the batteries used in hybrid and electric vehicles (Samaras and Meisterling, 2008).

The hybrids tested had the lowest measured emissions of NO_x. Both Euro 5 and Euro 6 hybrids had average urban NO_x emissions of 0.002 (sd. 0.000) g km^{-1}. This was 20 times lower than the G6 average and within the error range for the PEMS system used. Hybrid motorway emissions were similarly low and NO_2 emissions were negligible.

Whilst the sample size is limited, our results are in agreement with Zhang et al. (2015) and Wu et al., (2015). Further work is needed to expand the sample size and include other hybrid technologies. The wide variability in emissions from vehicles of the same technology group and limitation of the sample size in this study should be stated when quoting these results. These results relate only to gasoline – electric hybrid vehicles.

Our conclusions cannot be extended to other technologies such as diesel or plug-in hybrids.

4 Conclusions

A reduction in real world NO_x and CO_2 emissions is essential for the protection of human and environmental health. Our study confirms that diesel vehicles deliver a substantial CO_2 reduction relative to gasoline of between 11 - 40%. However, our results also show that the emissions type approval process has been ineffective and that D5 and D6 urban NO_x emissions are 300% and 450% higher than the emissions standard, respectively. This has contributed to slower reduction in NO_2 concentrations in cities (Beevers et al., 2012) and poses a significant risk to human health (COMEAP, 2010). Gasoline vehicles achieved an 86 – 96% reduction in NO_x relative to diesel and GDI engines reduced CO_2 emissions by between 9 – 12% compared with PFI.

These results are indicative of the air quality / climate change trade-off between gasoline and diesel vehicles. Gasoline- electric hybrid vehicles had low emissions of both CO_2 and NO_x, though further measurements are needed given the limited sample size in this study. Greater uptake of hybrid vehicles would ensure the consumer move away from diesel did not incur a CO_2 penalty.

Given what is now known about defeat devices and real-world emissions, discrimination on the basis of Euro standard can almost be seen as arbitrary. Incentives and rewards should be created for vehicles (both gasoline and diesel) with acceptable real-world emissions for both NO_x and CO_2. This idea is soon to be adopted in London and Paris with the launch in Autumn 2017 of the ‘cleaner vehicle checker’ (Greater London Authority (GLA), 2017).

For both G5 and D6 vehicles, NO_x emissions were higher during urban driving than motorway, by 200% for G5 and 30% for D6. A key consideration for air quality pollutants is public exposure. Therefore the location of the NO_x emissions is relevant as well as the total amount. The increase in NO_x emissions during urban driving (where public exposure is highest) has negative implications for public health. CO_2 emissions were also higher during urban driving. Whilst in theory it is the total mass of CO_2 and not the location of emission that is relevant, heightened urban emissions also have negative implications for climate change goals because more vehicle kilometres are driven on urban roads than motorways; in Great Britain 40% of passenger car kilometres are urban, 40% rural and only 20% motorway (DfT, 2014).

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6 References

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