No. C 734
December 2022

Remote Sensing Measurements of Vehicle Emissions in Sarajevo

Field measurement campaign conducted in summer 2022

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Funded by: Click and add text
Photographer: Click and add text
Report number C 734
ISBN Click here to add ISBN no.
Edition Only available as PDF for individual printing

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This report has been reviewed and approved in accordance with IVL's audited and approved management system.

Preface

The Remote Sensing measurements in Sarajevo 2022 came about as a sub-project to IMPAQ-*Support to Bosnia and Hercegovina in Improving Air Quality and Air Management*. The project was funded by the Swedish International Development Cooperation Agency (SIDA), administrated through Swedish Environmental Protection Agency (SEPA) and executing parties were Swedish Environmental Research Institute (IVL) and OPUS RS. With the aim of improving air quality, a part of the IMPAQ project was to investigate the potential of and conditions for implementing a low emission zone in the capital of Bosnia and Hercegovina.

When the prerequisites for the low emission zone were examined, a need for more extensive and accurate traffic data was identified. As an addition to the original project, the remote sensing measurement campaign was initiated to gather real-life data on the composition of the vehicle fleet in Sarajevo and the fleets' emissions. The results from the measurement campaign have been highly valued and provided important insights for the preparations for the low emission zone.

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Acronyms

CNG	Compressed natural gas
CO	Carbon monoxide
CONOX	The first European project to merge data from RS measurements carried out in several European countries during the time period 2011-2017[1]
HC	Hydrocarbon
LPG	Liquefied petroleum gas
LCV	Light commercial vehicle
NH_3	Ammonia
NOx	Nitrogen oxide
NO_2	Nitrogen dioxide
PM	Particulate matter
PTI	Periodic Technical Inspection
PC	Passenger car
RSD	Remote sensing device

[1] Sjödin, Å., Borken-Kleefeld, J. Carslaw, D., Tate, J., Alt, G.-M., De la Fuente, J., Bernard, Y., Tietge, U., McClintock, P., Gentala, R., Vescio, N., Hausberger, S (2018) Real-driving emissions from diesel passenger cars measured by remote sensing and as compared with PEMS and chassis dynamometer measurements - CONOX Task 2 report. On behalf of the Federal Office of Environment, Switzerland. https://www.ivl.se/english/ivl/publications/publications/real-driving-emissions-from-diesel-passenger-cars-measured-by-remote-sensing-and-as-compared-with-pems-and-chassis-dynamometer-measurements---conox-task-2-report.html

Summary

With the goal of identifying the real-world emissions of PM, NO_x, HC and CO in Sarajevo, an intensive vehicle emission study was conducted in the summer of 2022 during a one-week test campaign. In total around 25,000 vehicle passages were recorded during the measurement, covering passenger cars PC, LCV, buses, trucks, and motorcycles.

Several key results and findings from our analysis:

- The one-week remote sensing pilot study in Sarajevo successfully recorded about 25,000 vehicle passages from which emission measurements of PM, NO_x, HC, and CO were made, split into different vehicle types (PC, LCV, trucks, buses, and motorcycles), fuel types (mainly diesel and petrol) and Euro standards (Euro 1-6).

- Data capture for heavy-duty trucks was less successful, due to less effective vehicle number plate identification (a well-known remote sensing (RS) shortcoming).

- As observed in many other recent European RS studies, the PM emissions from the Sarajevo vehicle fleet have been reduced substantially with increasing Euro standard (Euro 1 → Euro 6) for all vehicle types (on the order of 80-90%), whereas NO_x emissions from diesel vehicles have only been reduced on the order of ≈50%, despite the strict Euro standards.

- The emission performance of the Sarajevo vehicle fleet deviates from that of other European/EU fleets mainly for petrol cars, in which case emissions of PM, NO_x, HC and CO are substantially higher for older, pre-Euro 5 cars, compared to those in other European/EU cities where RS measurements have also been carried out.

- The latter observation raises the question of whether a lower quality petrol fuel is used in Sarajevo compared to the EU, e.g., with higher sulphur content poisoning the three-way catalyst.

- Euro 3, 4 and 5 diesel passenger cars contributed the most to emissions of NO_x, representing about 74% of all NO_x emissions, and about 63% of all passenger cars measured. Similarly, Euro 3 and Euro 4 diesel vehicles together are responsible for the greatest share of total PM emissions from all passenger cars, which are responsible of 74% of total PM emissions, with a share of only 40% of total measurements.

- The result of distance-specific emissions indicates that the latest Euro standard implementation step has significantly lowered real-world emissions of all measured pollutants (NO_x, PM, CO and HC) for petrol cars, and greatly reduced the emissions of PM, CO and HC for diesel cars, although NO_x emissions from diesel cars remain high.

- Future measurements should focus on heavy-duty, typically diesel fuelled, vehicles as their data capture were relatively low, while their relative contribution to NO_x remains high.

Sammanfattning

För att identifiera de verkliga utsläppen av partiklar, kväveoxider, kolväten och koldioxid i Sarajevo genomfördes en intensiv undersökning av fordonsutsläpp sommaren 2022 under en veckas testkampanj. Totalt registrerades cirka 25 000 fordonspassager under mätningen, som omfattade personbilar PC, LCV, bussar, lastbilar och motorcyklar.

Flera viktiga resultat och slutsatser från vår analys:

- Den fem dagar långa pilotstudien med fjärranalys i Sarajevo visade sig vara ganska framgångsrik, med ≈25 000 försök till utsläppsmätningar av PM, NOX, HC och CO, uppdelade på olika fordonstyper (PC, LCV, lastbilar, bussar och motorcyklar), bränsletyper (främst diesel och bensin) och Euro-standarder (Euro 1-6).

- Mätningarna av tunga lastbilar var mindre lyckade på grund av problemet med att fånga fordonets nummerplåtar med videokameran (en välkänd RS-brist).

- I likhet med vad som observerats i många andra nyligen genomförda europeiska RS-studier har partikelutsläppen från Sarajevos fordonsflotta minskat avsevärt med ökande Euronorm (Euro 1 Euro 6) för alla fordonstyper (i storleksordningen 80-90 %), medan NOX-utsläppen från dieselfordon endast har minskat i storleksordningen ≈50 %, trots de strikta Euronormerna.

- Utsläppsprestanda för fordonsflottan i Sarajevo avviker från andra fordonsflottor i Europa/EU främst när det gäller bensinbilar, där utsläppen av partiklar, NOX, HC och CO är betydligt högre för bilar från före Euro 5 i Sarajevo, dvs. äldre bilar, jämfört med andra städer i Europa/EU där fjärranalysmätningar har utförts.

- Den sistnämnda iakttagelsen ger upphov till frågan om det har använts (och fortfarande används) bensin av lägre kvalitet i Sarajevo än i EU, t.ex. med högre svavelhalt som förgiftar trevägskatalysatorn.

- Euro 3, 4 och 5 dieselfordon visade sig bidra till de största andelarna av de totala NO_x-utsläppen från alla personbilar med en total andel på cirka 74 % av alla NO_x-utsläpp, som tillsammans står för cirka 63 % av de totala mätningarna. På samma sätt står Euro 3- och Euro 4-dieselfordon tillsammans för den största andelen av de totala partikelutsläppen från alla personbilar, som står för 74 % av de totala partikelutsläppen, med en andel på endast 40 % av de totala mätningarna.

- Resultatet av de distansspecifika utsläppen visar att det senaste steget i genomförandet av Euronormen har lett till en betydande minskning av alla verkliga utsläpp (NO_x, PM, CO och HC) för bensinbilar, och även till en kraftig minskning av utsläppen av PM, CO och HC för dieselbilar, trots att NO_x-utsläppen för dieselbilar fortfarande ligger på en hög nivå.

- Framtida mätningar med fokus på tunga fordon rekommenderas med tanke på att dieselfordonens bidrag till NO_x fortfarande är stort, men att giltiga mätningar var begränsade.

1 Introduction

Road traffic is often the main source of poor air quality in urban areas. Although stricter exhaust requirements and improved exhaust cleaning technology in Europe have led to reduced emissions from petrol-powered vehicles, in particular since the early 1990s, problems with high emissions of nitrogen oxides (NO_X) and particulate matter (PM) from diesel vehicles remain. This is in part due to major shortcomings in EU exhaust legislation alongside historic deceptions perpetrated by car manufacturers (e.g. "dieselgate"). As a result, emissions during real-world driving in traffic are many times higher than in driving cycles used to set legal requirements. Consequently, air quality in European cities has not improved in proportion to increasingly toughened legal requirements. As a result, interest in measuring emissions in real traffic has increased sharply in recent years, both by national authorities and individual cities.

A comprehensive investigation of air pollutant emissions from traffic in real-world environments can help to better understand the impact of transport on urban air quality and to support regulations and techniques to mitigate future emissions. Remote sensing (RS) technology is a well-established technique to monitor real-driving traffic emissions and has been used extensively throughout the world. RS is well suited to measuring different types of pollutants, especially gaseous species. The data handling and processing of RS is also well-developed which makes it easy and efficient to apply for tests at different scales.

In this study, an intensive vehicle emission campaign was conducted with OPUS RS devices at four sites in Sarajevo in the summer of 2022 to measure air pollutant emissions from on-road traffic. The pollutants measured include gaseous species; oxides of nitrogen NO_X, nitrogen dioxide NO_2, hydrocarbon HC, and carbon monoxide CO, as well as particulate matter PM. Around 25,000 vehicle passages were recorded of which approximately 14,000 vehicles were analysed. These covered passenger cars (PC), light commercial vehicles (LCV), buses, trucks and motorcycles.

This report described the Sarajevo measurement campaign and summarized the main findings from the measurements, which started with an overview of measurement sites, RS technology and sample distribution. Emissions of NO_X, PM, CO and HC from passenger cars were analysed in terms of the fuel-specific and distance-specific emissions. The emissions of NO_X and PM from the Sarajevo measurement campaign were compared with corresponding results derived from the CONOX database from measurements carried out in Switzerland (sites Regensdorf and Gockhausen) and Italy (sites Madre Cabrini and Cilea) in the year of 2021.

In addition, distance-specific emissions were evaluated against the corresponding type-approved regulatory limits. Findings from the measurements of other type of vehicles, such as LCV, buses, trucks, and motorcycles were presented. The main findings are highlighted in the conclusion section and outlooks for future work are provided.

2 Overview of measurements

2.1 Measurement sites

The measurement campaign was carried out at four sites in Sarajevo city (Figure 1): site KSL012 (Longitude 18.329452°, Latitude 43.84063°), located on Kurta Schorka and near the intersection of Kurta Schorka and Laticka; site KSL03 (Longitude 18.365916°, Latitude 43.85169°), located on street Radenka Abazovica between Safeta Zajke and Dzemala Bijedica; site KSL09 (Longitude 18.39115° Latitude 43.85841°), located on street Hamdije Cemerlica near the intersection of Hamdije Cemerlica and Put zivota; and site BETANIJA (Longitude 18.407006°, Latitude 43.8717°), located on street Betanija at the intersection of between Alipasina and Betanija. (KSL012, KSL03, KSL09, and BETANIJA)

Site name	Number of measurements	Slope (%)
KSL012	6508	0.4
KSL03	4347	1.5
KSL09	4184	4.0
BETANIJA	10040	3.2

Figure 1. Map displaying the measurement sites and photos of the four sites with the placing of the remote sensing instrument at the roadside.

2.2 Remote sensing technology

The remote sensing instrument used for the measurements was provided by OPUS RSE (https://www.opusrse.com/technology/remote-sensing-device/) – see Figure 2. A brief description of how the measurement works is given below.

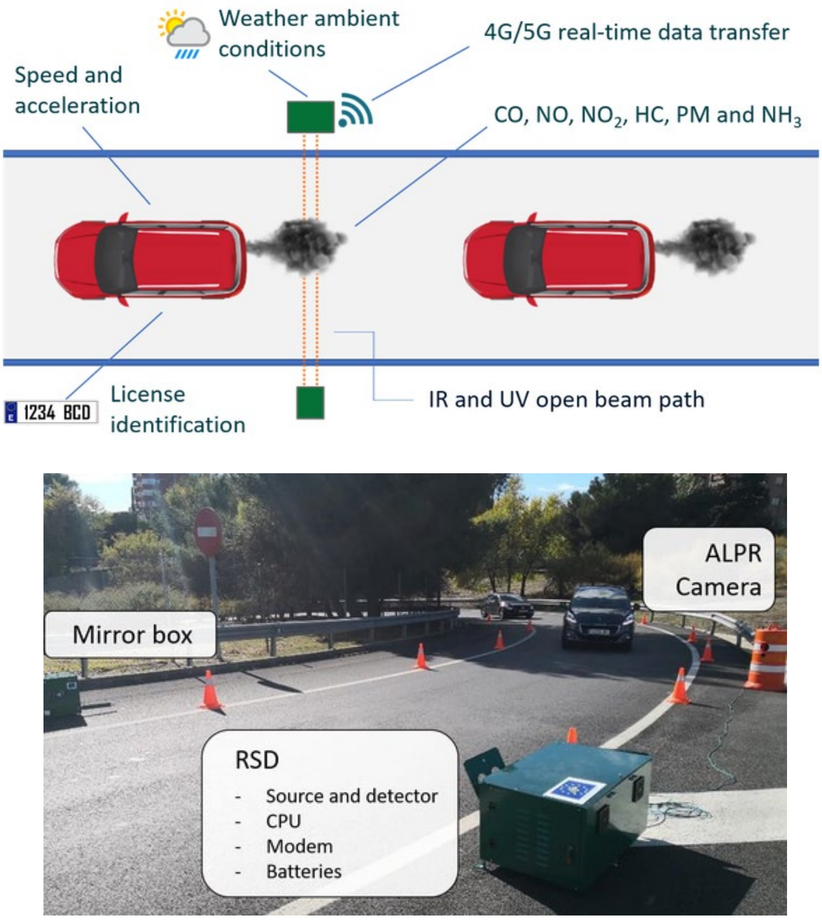


Figure 2. Remote sensing instrument used for the measurements.

The instrument used was an Opus AccuScan™ RSD5500, capable of measuring the raw exhaust concentrations of both NO and NO_2 (and thus their sum NO_x) together with CO, HC, PM (derived from an opacity measurement in the UV range) and CO_2.

Fixed (internal) gas cell calibration as well as audit calibrations of the instrument were made in regular intervals during each measurement day. The audit calibration was done by means of certified gas mixtures with known concentrations of NO, NO_2, CO, HC and CO_2. Since the measured emission rates are associated with the driving condition of the vehicle, the RSD5000 also measures speed and acceleration of each passing vehicle, which enables the possibility to express the driving condition as vehicle specific power (VSP), which is the engine power divided by the vehicle mass. Further, licence plate numbers were captured with a video camera connected to the RSD5500 instrument to retrieve vehicle information from the Sarajevo vehicle register, necessary for subsequent analysis.

2.3 Distribution of samples

There were 25,079 vehicle passages recorded in total, of which 15,409 (61.4%) were identified as passenger cars (PC), 1,787 (7.1%) were light commercial vehicles (LCV), 197 (0.8%) were buses, 134 (0.5%) were trucks, and 80 (0.3%) were motorcycles. For 7,472 (29.8%) records, the vehicles could not be identified. The measurements comprised of approximately 14,000 unique vehicles, as some vehicles were measured more than once (see Appendix table A1). The distribution of measurements for each group of vehicles by emission standard (Euro 1-6) is shown in Figure 3. The fuel used for PC was 77.4% diesel and 22.6% petrol. For LCV it was 85.3% diesel and 14.7% petrol, for buses 59% diesel and 41% with other type of fuel (such as CNG and LPG), for trucks 98% diesel and 2% petrol, and motorcycles were all petrol-powered. The measurements of heavy-duty trucks were less successful due to less effective vehicle license plate identification.

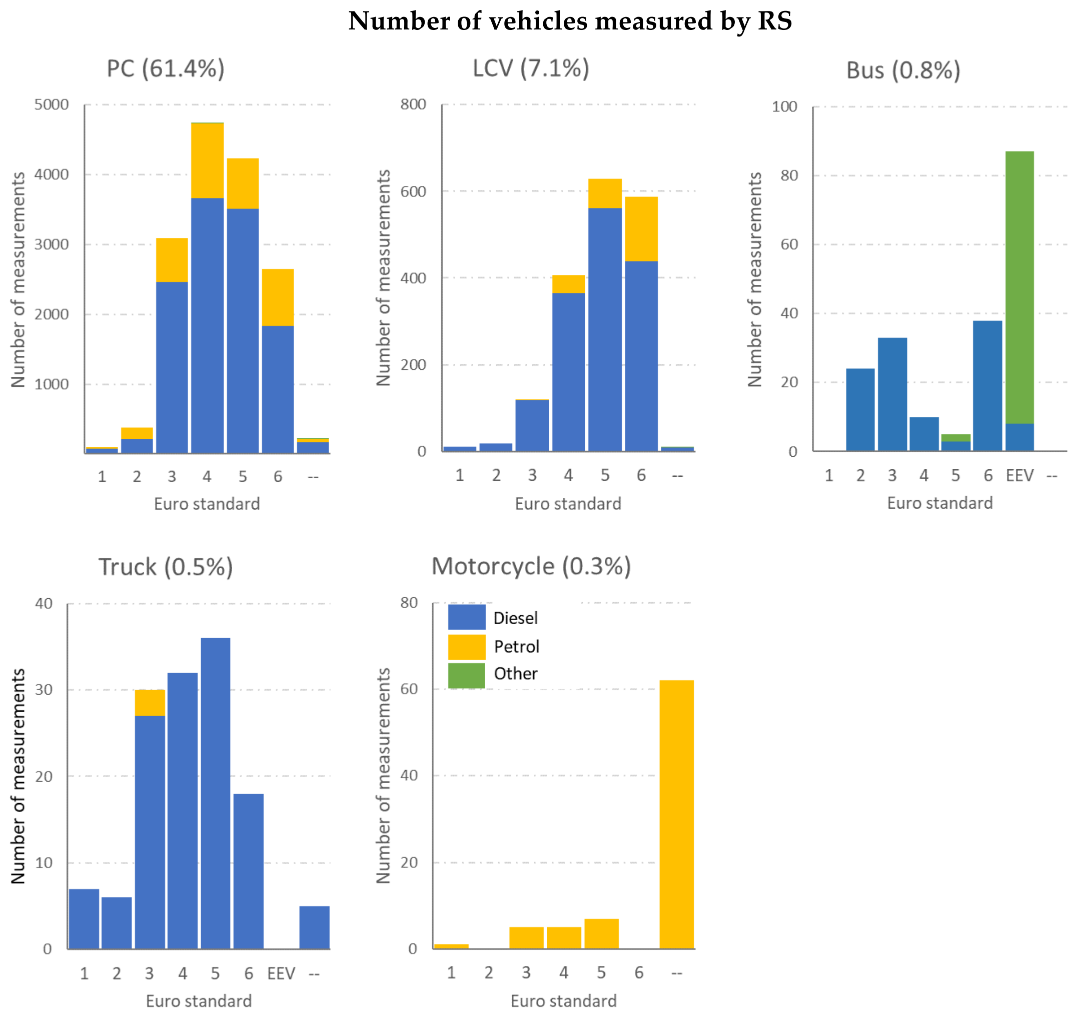


Figure 3. Number of remote sensing measurements by vehicle class, fuel type, and emission standard.

The distribution of total measurements at the four different sites is shown in Figure 4. 10040 records are from site BETANIJA, 6508 from KSL012, 4347 from KSL03 and 4184 from KSL09.

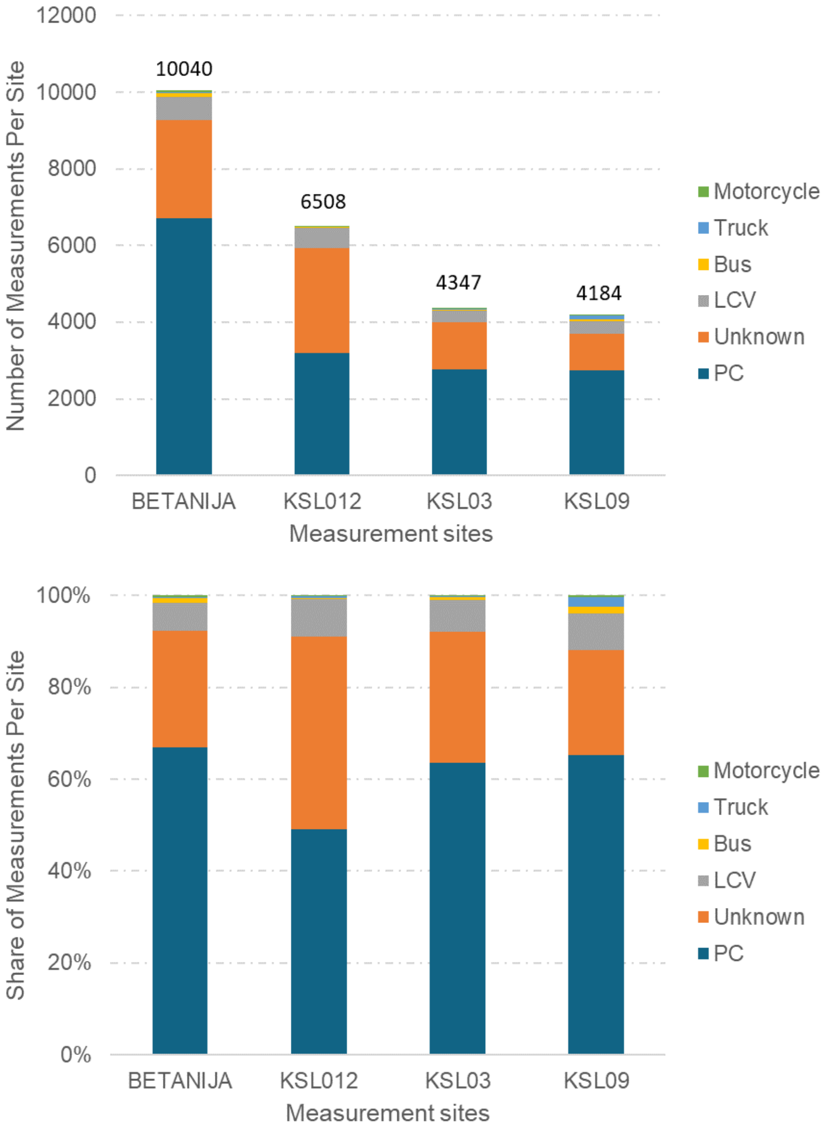


Figure 4. Number (upper) and share (bottom) of measurements per site by vehicle class

3 Results

3.1 Passenger cars

Of the 15,409 remote sensing measurements recorded for passenger cars, 11,928 cars were diesel-powered and 3,477 were petrol-powered. In this section, the fuel-specific emissions of PM, NO_X, NO_2, HC and CO are presented. The NO_X emission results from the Sarajevo measurement were compared with corresponding data retrieved from the CONOX database from measurements campaigns conducted in some European cities in Switzerland (sites Regensdorf and Gockhausen outside Zurich) and Italy (sites Madre Cabrini and Cilea) in the year of 2021. Distance-specific emissions of PM, NO_X, HC, and CO were also evaluated to compare to the legislative emission limits.

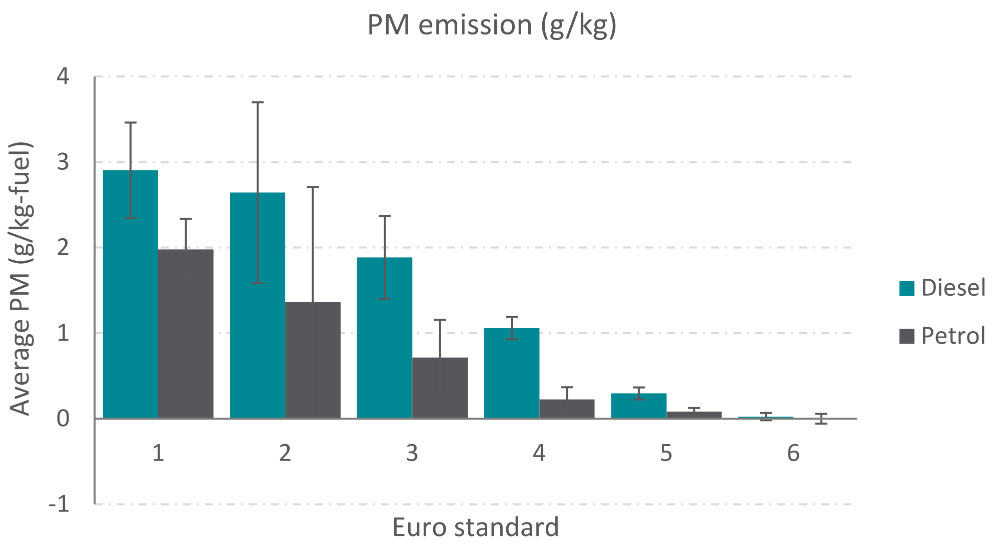
3.1.1 Fuel-specific emissions

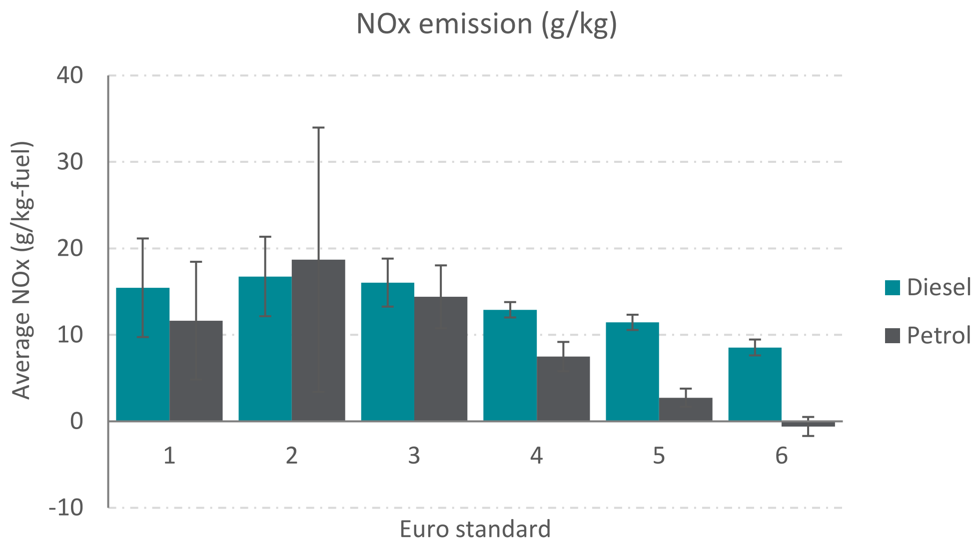
The valid numbers of remote sensing measurements for the emissions of PM, NO_X, NO_2, HC, and CO by fuel type and emission standard are summarized in Table 1. The most common vehicles were Euro 3, Euro 4, Euro 5 and Euro 6, and consisted of about 96% of all the diesel vehicles and 94% of all petrol vehicles. The averages (and 95% confidence interval of the mean) of the emissions from passenger cars were calculated by emission standard and fuel type, as the results illustrated in Figure 5. For PM, the average measured emission decreased from Euro 1 to Euro 6 for both diesel and petrol cars. The average PM emission for Euro 6 was 0.024 g/kg fuel for diesel vehicles, and -0.0005 g/kg fuel for petrol cars. Negative average values indicate the majority of the emissions measured were below the detection limit of the remote sensing instrument. Much lower PM emissions were observed for petrol cars compared to diesel cars for Euro 1-4, while for Euro 6 the difference between diesel and petrol vehicles was small. A large reduction can also be seen for NO_X emissions from Euro 2 (18 g/kg fuel) to Euro 6 (almost 0 g/kg fuel) for petrol vehicles, while for diesel vehicles the change is slower varying from around 17 g/kg fuel (Euro 2) to 8.5 g/kg fuel (Euro 6).

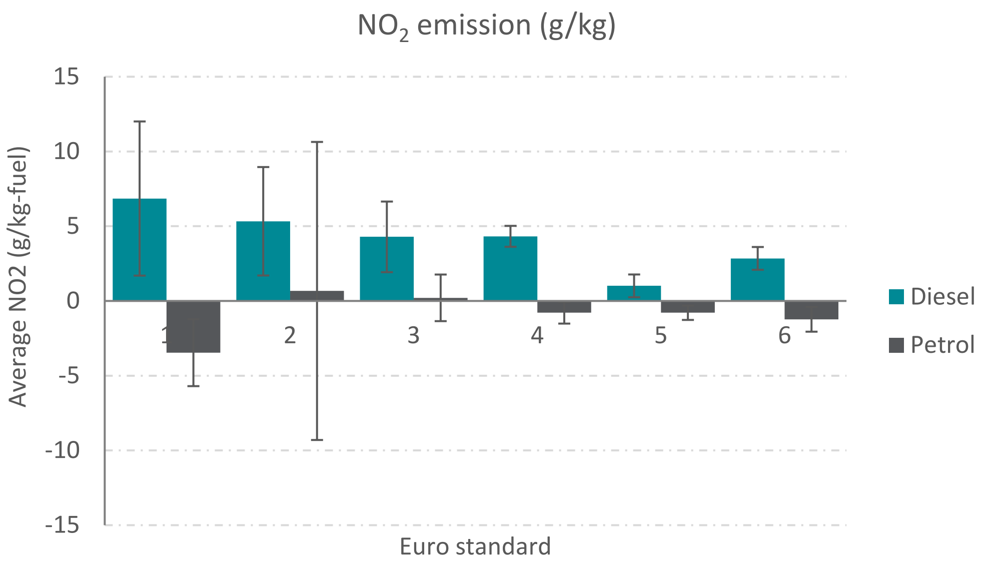
Higher emissions of HC and CO were measured for petrol cars compared to diesel cars. However, remarkable reductions were observed with increasing emission standard from Euro 1 to Euro 6 for petrol vehicles, with a reduction ratio of approximately 95% for CO and 96% for HC.

Table 1. Summary of the number of pollutant emission measurements for passenger cars by emission standard and fuel type (diesel and petrol).

Standard	Diesel counts (share)	Petrol counts (share)
Euro 1	73 (0.6%)	22 (0.6%)
Euro 2	217 (1.8%)	155 (4.5%)
Euro 3	2,459 (20.6%)	633 (18.2%)
Euro 4	3,661 (30.7%)	1,079 (31%)
Euro 5	3,516 (29.5%)	723 (20.8%)
Euro 6	1,831 (15.4%)	817 (23.5%)
Unknown --	171 (1.4%)	48 (1.4%)
Total	**11,928 (100%)**	**3,477 (100%)**


PM emission (g/kg)
Average PM (g/kg-fuel)
4
3
2
1
0
-1
1
2
3
4
5
6
Euro standard
Diesel
Petrol


NOx emission (g/kg)
Average NOx (g/kg-fuel)
40
30
20
10
0
-10
1
2
3
4
5
6
Euro standard
Diesel
Petrol


NO2 emission (g/kg)
Average NO2 (g/kg-fuel)
15
10
5
0
-5
-10
-15
2
3
4
5
6
Euro standard
Diesel
Petrol

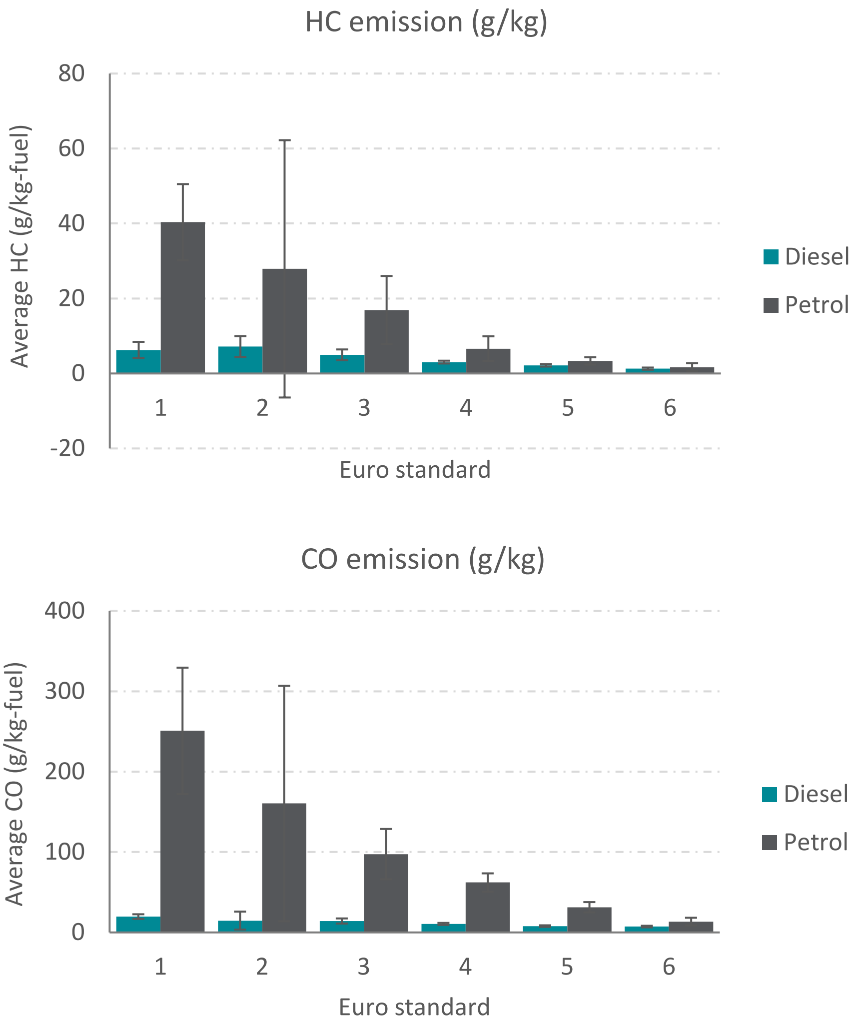


Figure 5. Average fuel specific PM, NO_x, NO_2, HC, and CO (gram per kilogram fuel) emissions from diesel and petrol passenger cars (PC) by emission standard. Whiskers represent the 95% confidence interval of the mean.

Figure 6 and Figure 7 show the average measured fuel-specific NO_x and PM emissions, respectively, of passenger cars in grams of pollutant emitted per kilogram of fuel burned (g/kg) by fuel type and emission standard. Included in these figures are the corresponding results derived from the CONOX database from measurements carried out in 2021 in Switzerland (sites Regensdorf and Gockhausen) and Italy (sites Madre Cabrini and Cilea). The number of measurements from both the Sarajevo and CONOX-2021 datasets are summarized in Table 2. In the CONOX datasets, Euro 6 includes Euro 6, Euro 6b, Euro 6c, and Euro 6d.

The most diesel and petrol vehicles in the CONOX datasets are Euro 6, accounting for approximately 55% of all diesel vehicles and 46% of all petrol vehicles, while for Sarajevo, the share of Euro 6 in the total number of vehicles is only 16% for diesel vehicles and 24% for petrol vehicles. Average emissions of NO_x for Euro 2, Euro 3, Euro 4 and Euro 5 petrol cars from the Sarajevo measurements were remarkably higher, by a factor of 1.5 - 3, compared to CONOX. For diesel cars, unlike for the petrol cars, the NO_x emissions measured in Sarajevo were about 20-30% lower than the average levels obtained from CONOX. This is true for most Euro standards (Euro 1-5), except for Euro 6, for which the average NO_x emission in Sarajevo was about 40% higher than according to the CONOX-2021 dataset.

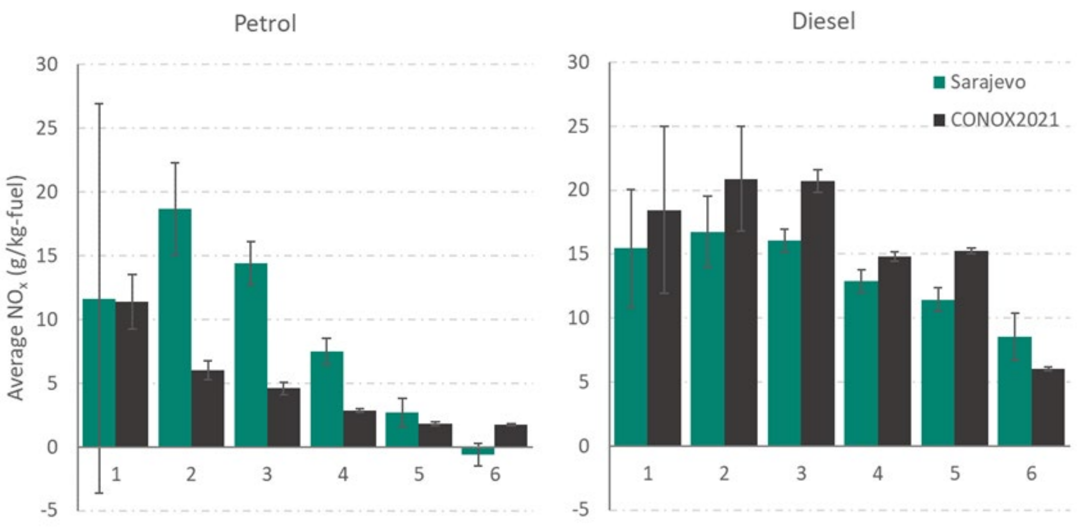


Figure 6. Average fuel-specific NO_x emissions from diesel and petrol passenger cars by emission standards for Sarajevo and CONOX database (2021). Whiskers represent the 95% confidence interval of the mean.

As seen in Figure 7, for petrol cars, PM emissions were substantially higher in Sarajevo for all Euro standards, especially prior to Euro 5, except for Euro 6 in which case the average emissions of both datasets were close to 0 g/kg, i.e., below the detection limit of the RS instrument. The average PM emissions for diesel cars in Sarajevo were higher than those of the CONOX dataset for all Euro standards except for Euro 6, but the differences were not statistically significant.

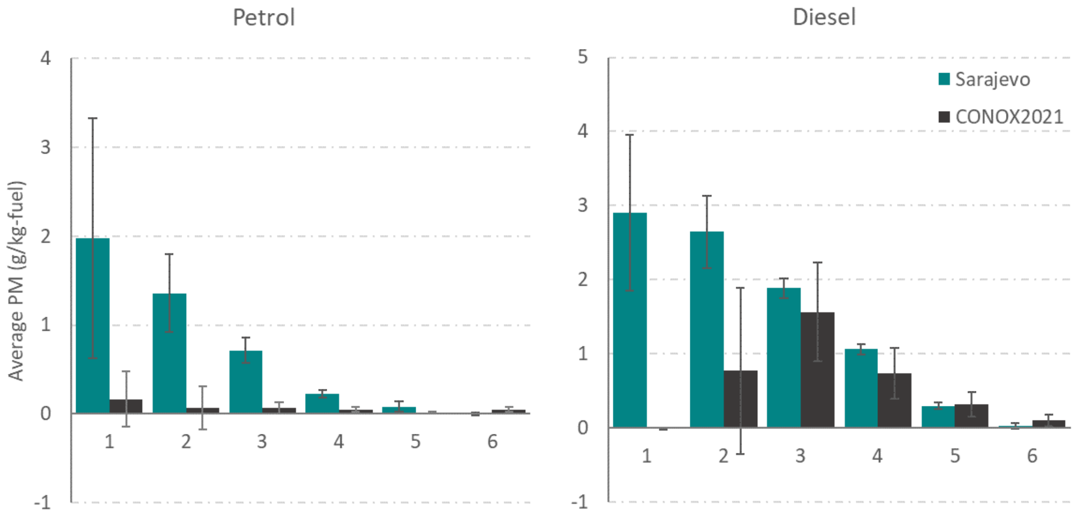


Figure 7. Average fuel-specific PM emissions from diesel and petrol passenger cars by emission standards for Sarajevo and CONOX database (measurements done in 2021). Whiskers represent the 95% confidence interval of the mean.

Table 2. Number of NO_x emission measurements of passenger cars by fuel type for the Sarajevo campaign and measurements done in 2021 from the CONOX database.

Emission Standard	Sarajevo		CONOX-2021	
	Diesel	Petrol	Diesel	Petrol
Euro 1	73	22	8	185
Euro 2	217	155	60	716
Euro 3	2459	633	693	1560
Euro 4	3661	1079	2822	8232
Euro 5	3516	723	8883	9336
Euro 6	1831	817	15127	17337
Total	**11757**	**3429**	**27593**	**37366**

Percentile distributions of NO_x and PM emissions of Euro 3, Euro 4, and Euro 5 petrol PCs from Sarajevo and CONOX were compared to investigate differences between the two datasets. The percentile distribution of NO_x emission for Euro 4 petrol cars is presented in Figure 8, see Appendix Figure S1 for equivalent Euro 3 and Euro 5 plots and Figure S2 for the percentile distribution of PM emissions for Euro 3, Euro 4 and Euro 5. The percentile distributions show that Sarajevo has a substantially higher number of high NO_x and PM emitting Euro 3, Euro 4 and Euro 5 petrol PCs compared to cities in western Europe.

Figure 9 shows the ten highest emitters for NO_x and PM with repeat measurements (vehicles measured three times or more by RS). Two vehicles were high emitters for both NO_x and PM emissions, as marked with red and blue circles in Figure 9.

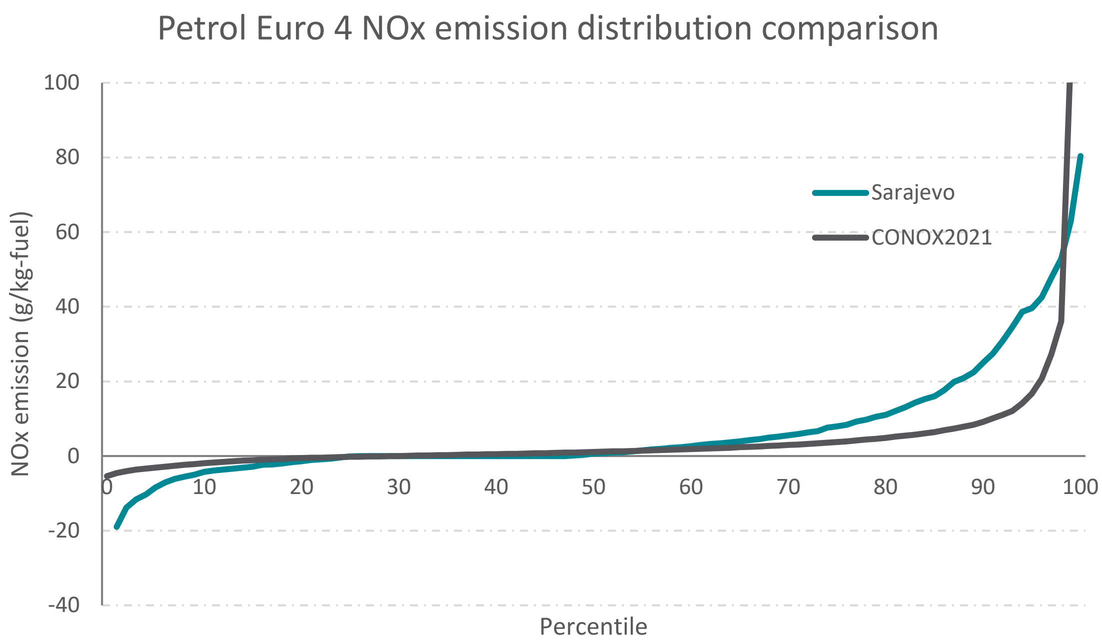
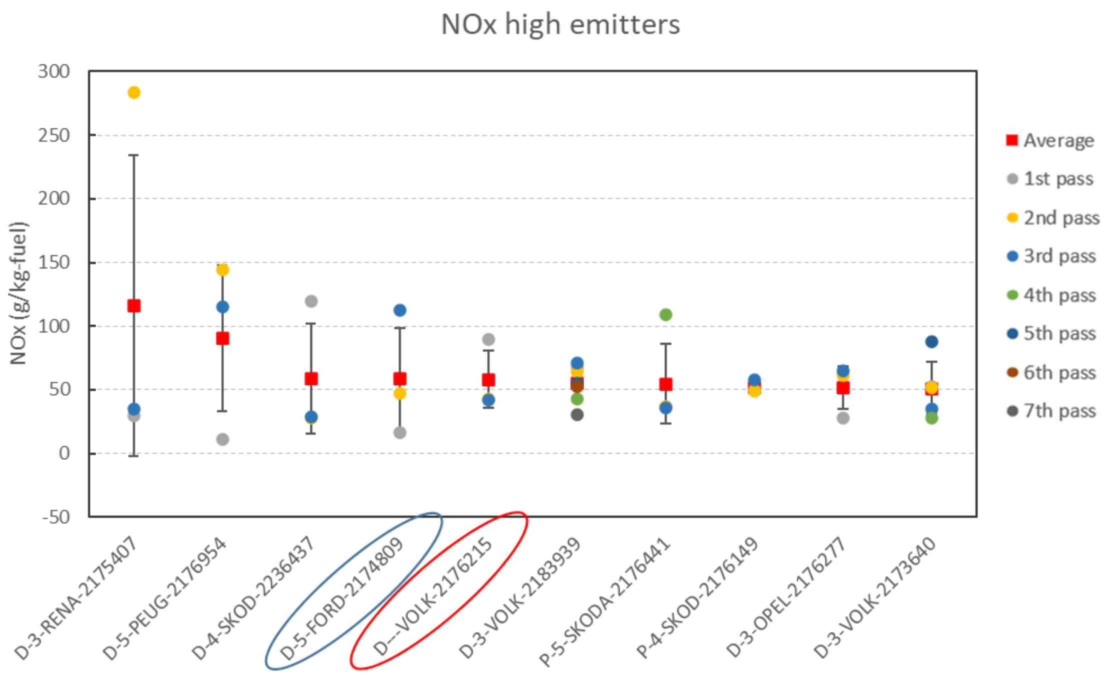


Figure 8. Percentile distribution of NO_x emissions measured from Euro 4 petrol passenger cars by comparing the Sarajevo campaign with CONOX datasets for measurements conducted in 2021.



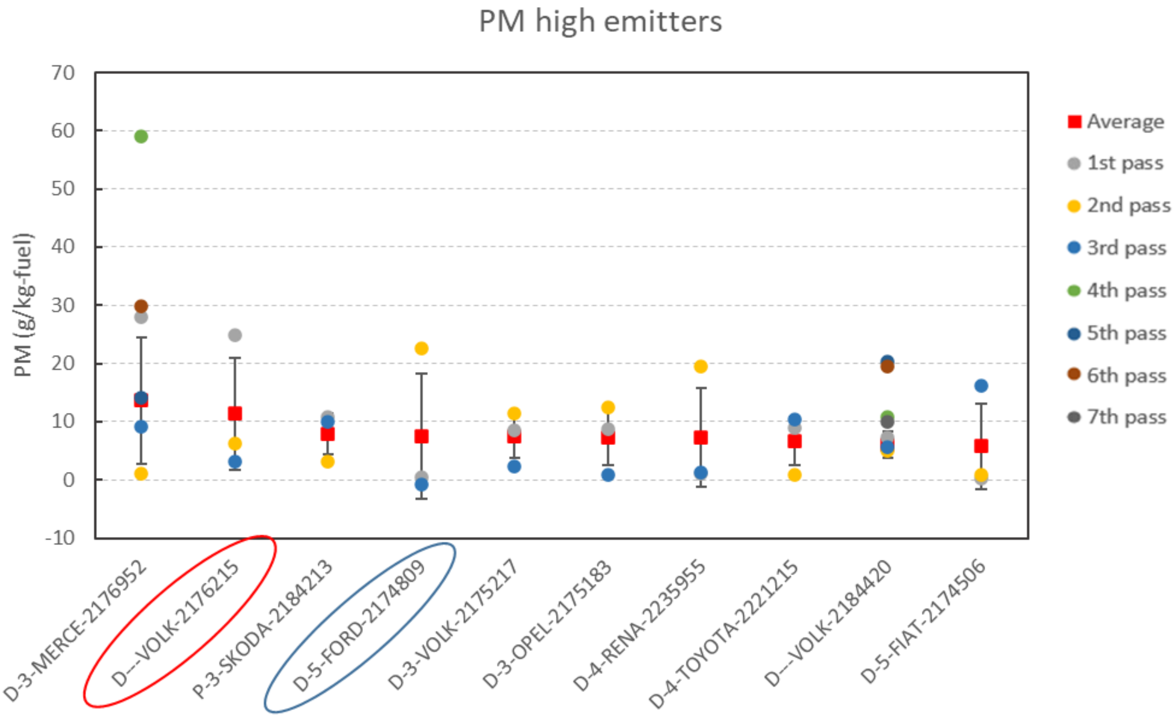


Figure 9. NO_x and PM emissions for the ten highest emitting passenger cars measured by the remote sensor 3 times or more, rank ordered by increasing average NO_x and PM emissions. For each vehicle the unique information is presented as "fuel type-Euro standard-maker-Vehicle unique ID", for example, P-3-SKODA-2184213 represents that the vehicle is petrol fuel, Euro 3 emission standard, vehicle maker is SKODA, and the Vehicle unique ID recorded with OPUS is 2174809. Error bars represent the standard deviations.

3.1.2 Distance-specific emissions

In addition to the fuel specific emissions of pollutants analysed above, the tailpipe pollutant concentration ratios were converted to distance-specific estimates in grams per kilometre (g/km), by combining the average pollutant emissions derived by RS with fuel consumption factors presented in Table 3.

Table 3. Fuel consumption factors for passenger cars.[2]

	Diesel PC	**Petrol PC**
	FC kg/km	FC kg/km
Euro 1	0.0504	0.0622
Euro 2	0.0576	0.058
Euro 3	0.0485	0.0597
Euro 4	0.0565	0.0575

[2] Borken-Kleefeld, J., Hausberger, S., McClintock, P., Tate, J., Carslaw, D., Bernard, Y., Sjödin, Å. (2018). Comparing emission rates derived from remote sensing with PEMS and chassis dynamometer tests - CONOX Task 1 report. IVL Report No. C 293. https://www.ivl.se/english/ivl/publications/publications/comparing-emission-rates-derived-from-remote-sensing-with-pems-and-chassis-dynamometer-tests---conox-task-1-report.html.

Euro 5	0.0512	0.0567
Euro 6	0.0512	0.0567

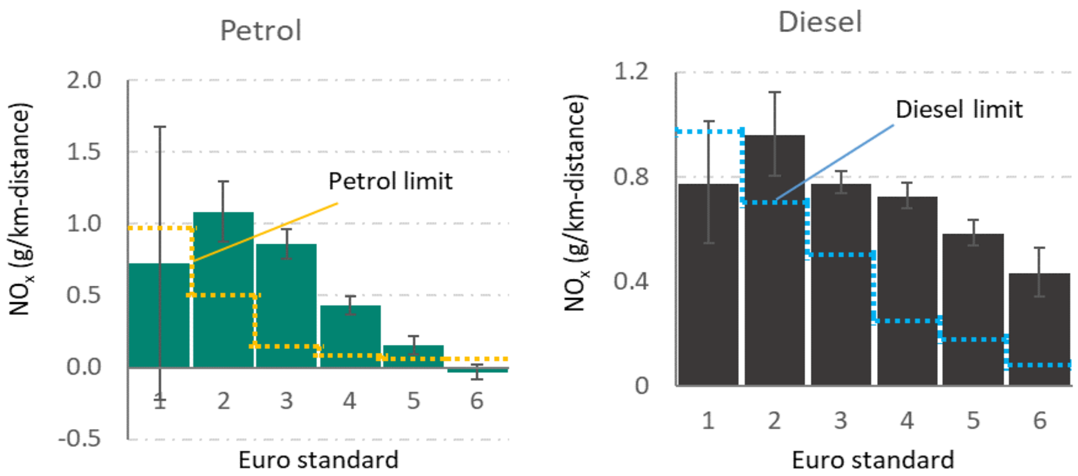
Figure 10 presents the average distance-specific NO_x, PM, CO and HC emissions by fuel type and emission standard for the Sarajevo measurements. The EU emission regulations for Euro 1 to Euro 6 for NO_x, PM, CO, and HC are summarized in Table 4.

The overall trend shows that the emissions of all pollutants (NO_x, PM, CO and HC) have decreased as the emission standard has increased for both petrol and diesel and cars. NO_x and PM emissions from petrol cars are lower than those from diesel cars, especially for the latest emission standards, Euro 5 and Euro 6. This is contrary to the emissions of CO and HC which have reduced more slowly or plateaued. In comparison to the EU emission regulation limits for each stage, the real-world NO_x and PM emissions from diesel passenger cars greatly exceed the regulatory limits for vehicle groups including Euro 2-Euro 5, which were found to have real-world emissions of NO_x and PM about 40% to 220%, and about 80% to 200%, respectively, higher than the respective laboratory type-approval limits. For petrol vehicles with emission standards prior to Euro 6, the real-world measured values were 2-6 times higher for NO_x emissions (excluding Euro 1), 2-6 times higher for CO emissions, and 2-5 times higher for HC emissions, than the laboratory type-approval limits, respectively. CO and HC emissions from diesel cars were found to be lower than the limits for all emission standards, with only Euro 3 and Euro 4 found to have slightly higher CO emissions than the limits. Figure 11 presents the estimated share of NO_x and PM emissions (by g/km) from PCs and the share of measurements by fuel type and Euro standard. The results indicate that Euro 3, Euro 4, and Euro 5 diesel vehicles contribute the highest shares of total NO_x emissions from all passenger cars with a total share about 74% of all NOx emissions, which together account for about 63% of total measurements. For petrol vehicles, Euro 3, Euro 4 and Euro 5 petrol vehicles make up 16% of the total measurements and they together only contribute 13% of the total NO_x. Similarly, Euro 3 and Euro 4 diesel vehicles together are responsible for the greatest share of total PM emissions from all passenger cars, which are responsible of 74% of total PM emissions, with a share of only 40% of total measurements.

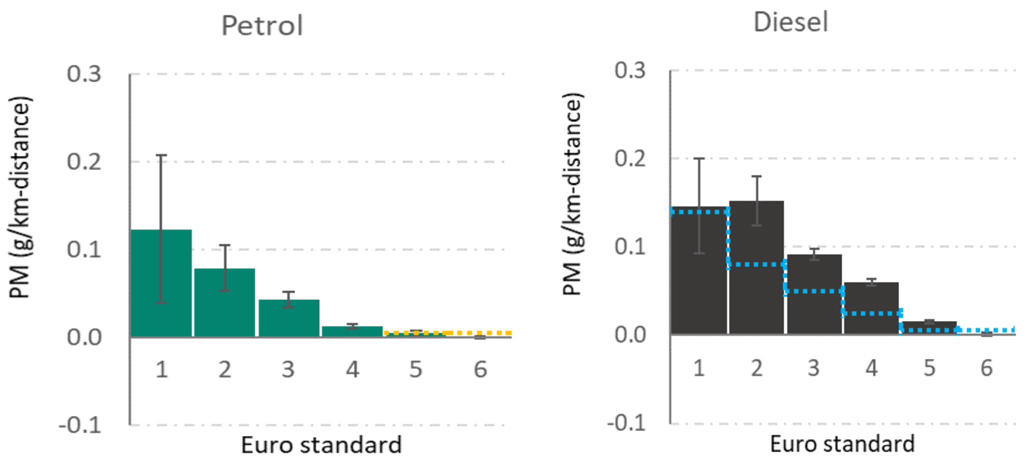
Euro 6 diesel and petrol cars were found to have lower real-world emissions of PM, CO, and HC than the regulation limits. For NO_x emissions, Euro 6 petrol cars were measured with an average level lower than the limit, while Euro 6 diesel vehicles had approximately 5 times higher emissions of NO_x than the regulation limit. This result indicates that the latest Euro 6 standard implementation step has significantly lowered real-world emissions of all regulated pollutants (NO_x, PM, CO and HC) for petrol cars and greatly reduced the emissions of the PM, CO and HC for diesel cars. NO_x emissions are the only exception, which remain high for diesel cars. Figure 11 shows that while Euro 6 petrol cars comprised 5% of all measurements, they produced negligible NO_x and PM emissions (with both levels under the detection limit of the RSD). Euro 6 diesel cars contributed approximately 9% and 0.4% of total NO_x and PM emissions, respectively, while comprising 12% of all measurements. Based on these findings, the replacement of previous Euro standard vehicles with Euro 6 vehicles will remarkably reduce the contribution of emissions from PCs to urban air pollution.

Table 4. EU emission standards for passenger cars (gram per kilometre, g/km). Data obtained from Emission Standards: Europe: Cars and Light Trucks (dieselnet.com)

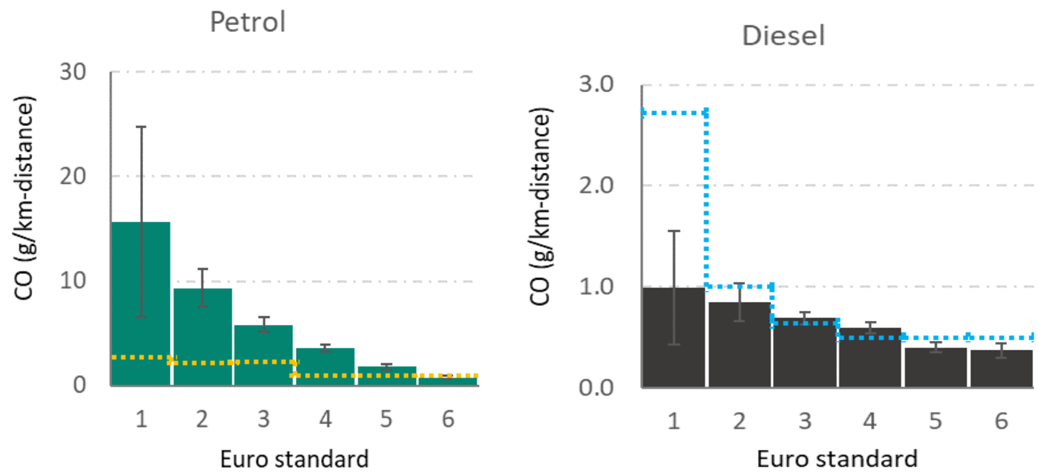
	NO_x (g/km)		PM (g/km)		CO (g/km)		HC (or HC+NO_x) (g/km)	
Standard	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Euro 1	0.97	0.97	0.14		2.72	2.72	0.97	0.97
Euro 2	0.7	0.5	0.08		1	2.2	0.7	0.5
Euro 3	0.5	0.15	0.05		0.64	2.3	0.56	0.2
Euro 4	0.25	0.08	0.25		0.5	1	0.3	0.1
Euro 5	0.18	0.06	0.005	0.005	0.5	1	0.23	0.1
Euro 6	0.08	0.06	0.005	0.005	0.5	1	0.17	0.1



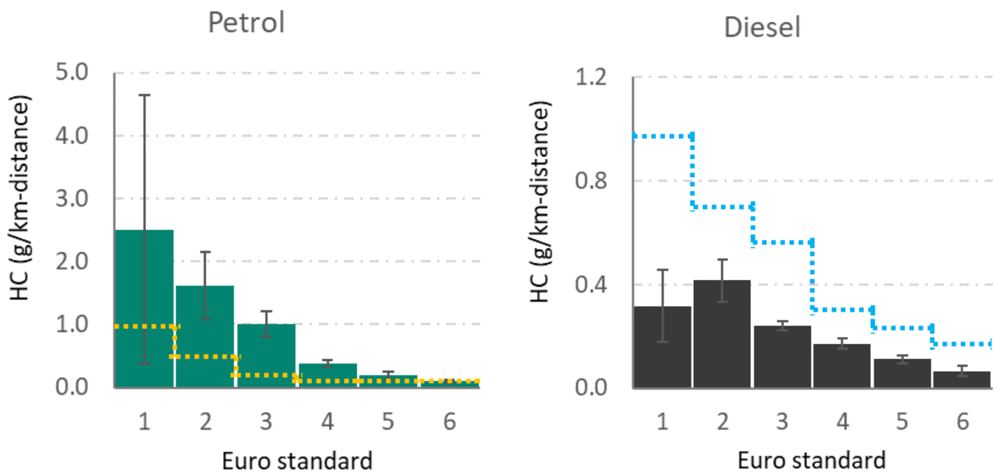
(a) NO_x emissions



(b) PM emissions



(c) CO emissions



(d) HC emissions

Figure 10. Average distance specific NO_x, PM, CO, and HC (gram per kilometre) emissions for diesel and petrol passenger cars by Euro standard. Whiskers represent the 95% confidence interval of the mean. Regulation limits for each emission substances are indicated with orange dash lines (petrol regulation limits) and blue dash lines (diesel regulation limits)

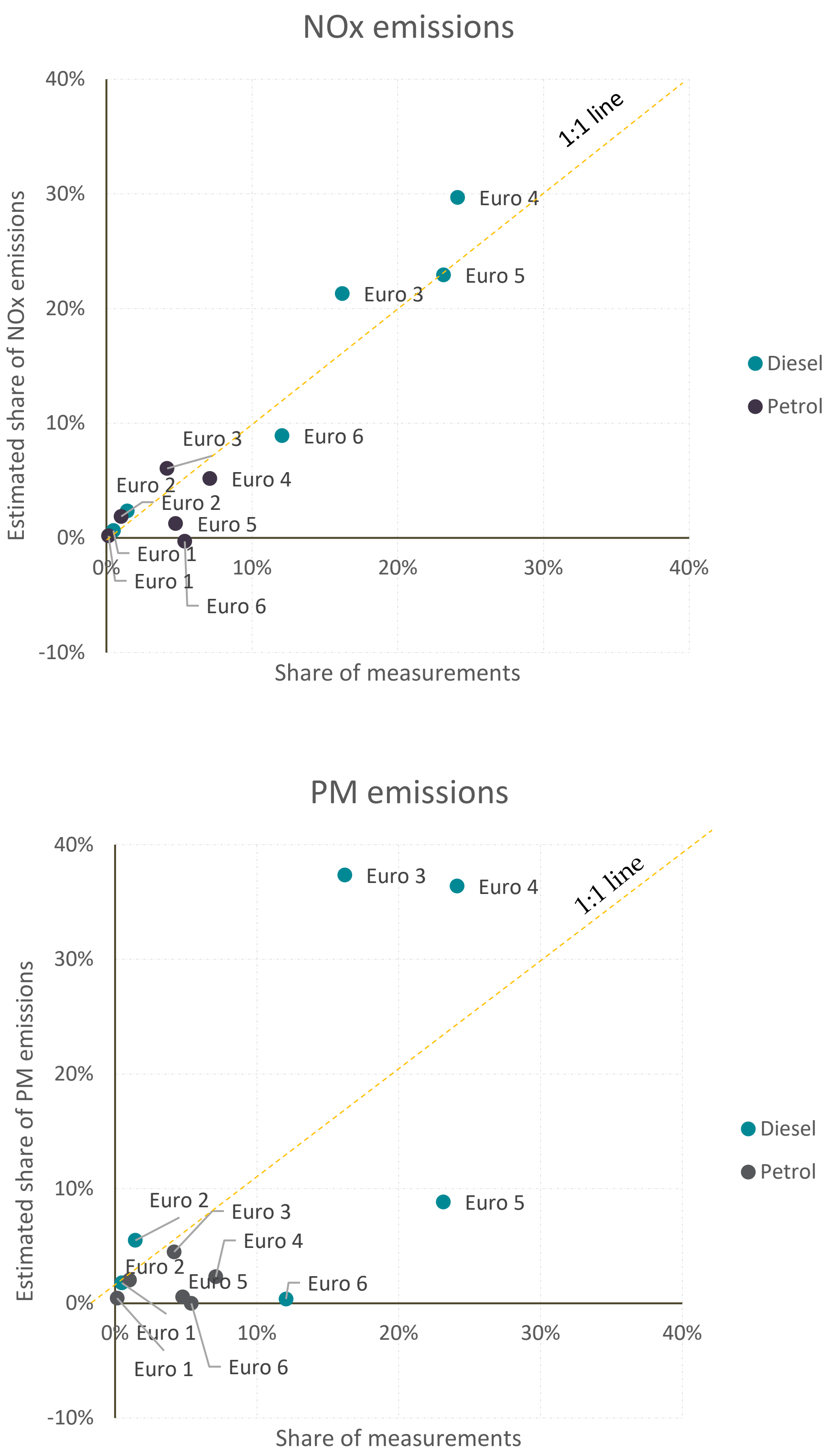


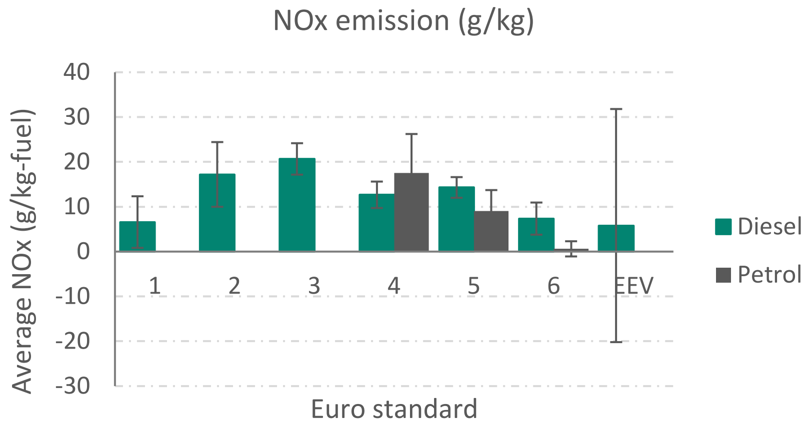
Figure 11. Share of measurements and estimated share of total NO_x and PM emissions (by distance-specific emissions) from passenger cars by Euro standard and fuel type.

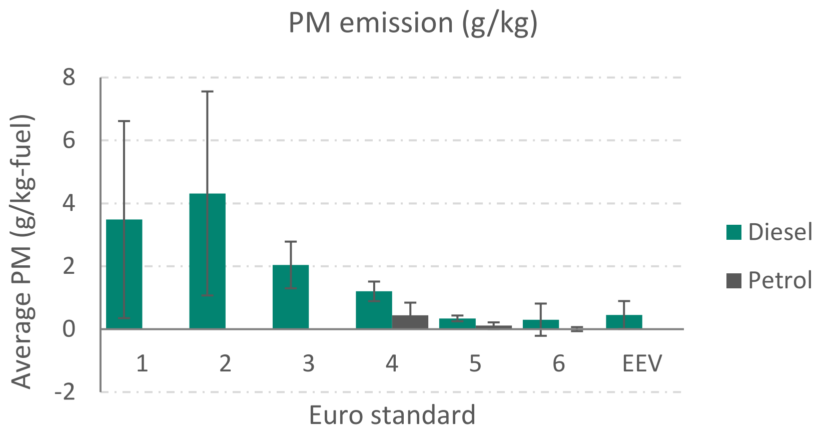
3.2 Light commercial vehicles

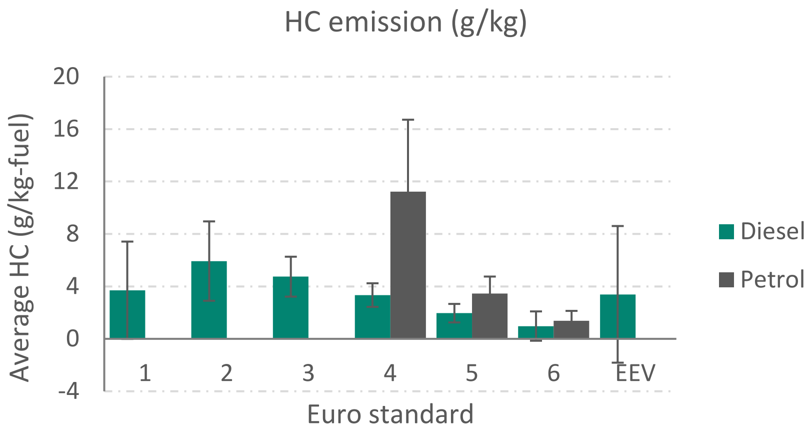
In total 1,787 measurements were obtained for LCV (7.1% of the total number of measurements), among which 1,524 (85%) were diesel-powered, 262 were petrol-powered, and one powered by other type of fuel. A summary of the number of measurements by fuel type and emission standard is shown in Table 5. Around 90% of all diesel-powered LCVs were type-approved to Euro 4, Euro 5 and Euro 6. Of all petrol-powered LCVs, 57% were type-approved to Euro 6, with Euro 4 and Euro5 constituting the remaining 42%. The average fuel-specific NO_x, PM, HC, and CO emissions are presented in Figure 12. For petrol LCVs only Euro 4, Euro 5 and Euro 6 were detected in the Sarajevo campaign, and for diesel LCVs the total attempted measurements of Euro 1, Euro 2 and EEV was less than 20, which was considered too small to draw a representative conclusion. By looking at the results of Euro 4, Euro 5 and Euro 6 LCVs with both fuel types, decreasing trends were shown for NO_x, PM, HC and CO emissions as the emission standard increased, especially for petrol vehicles, although the average CO emission increased for diesel vehicles.

Table 5. Number of measurements by fuel type and emission standard for LCV vehicles

Emission Standard	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6	EEV
Diesel	10	18	119	365	560	438	5
Petrol				42	68	150	







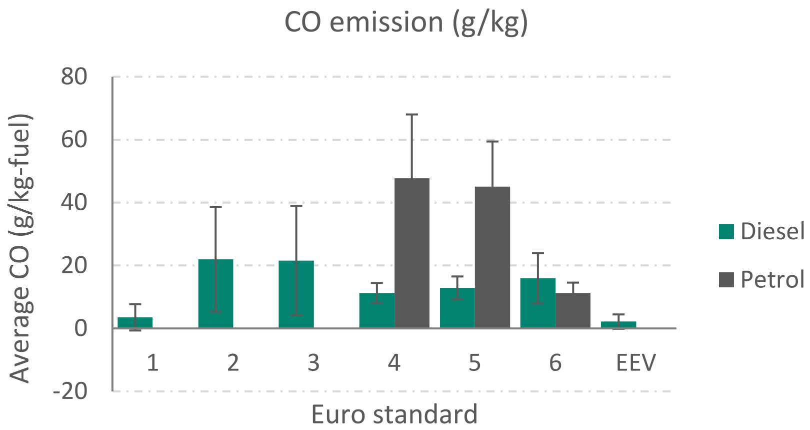


Figure 12. Average fuel specific NO_x, PM, HC, and CO emissions in gram pollutant per kilogram fuel (g/kg-fuel) burned of LCV by fuel type and emission standard.

3.3 Buses

This section presents findings for buses from the Sarajevo measurement campaign. 197 measurement records were identified as for buses (0.8% of total measurements), among which 116 (59%) buses were powered by diesel and 81 were powered by other types of fuel. For the diesel buses detected, the average fuel-specific emissions of NO_x and PM by emission standard are illustrated in Figure 13, with the valid number of measurements of each emission standard shown inside the base of each bar. Approximately 49% of the diesel buses were Euro 2 and Euro 3, 33% were Euro 6, 7% were EEV, and the remaining were Euro 4 and Euro 5. The average NO_x emission of Euro 6 diesel bus was 13 g/kg fuel, which was slightly lower (around 10%-65%) than the buses with older Euro standards from Euro 3 to Euro 5. In comparison to other Euro standard stages, a significantly lower average PM emission (about 0.02 g/kg fuel) was found for Euro 6 buses, which was up to 30 times lower than Euro 2 buses.

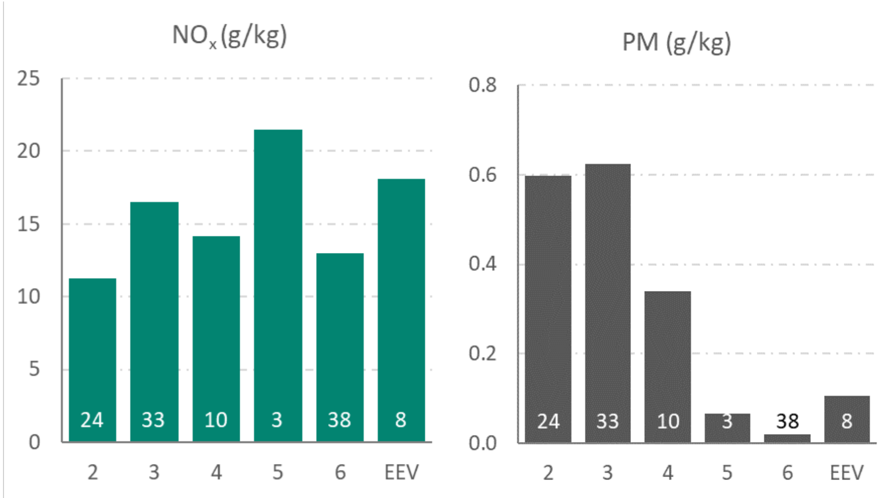


Figure 13. Average fuel specific NO_x, and PM emissions in g/kg fuel burned from diesel buses by emission standard. The number of measurements is shown inside of each bar.

3.4 Trucks

This section focuses on the emission measurements of trucks from the Sarajevo campaign. There are in total 134 measurements (0.5% of total measurements) obtained for trucks, among which 131 (98%) were diesel-powered and 3 were petrol-powered. The measurements of heavy-duty trucks were less successful, due to vehicle license plate capture, as previously stated. By reviewing a random sample of 300 photographs where license plates were not identified, about 13% could be manually identified as trucks, indicating the proportion of trucks initially identified was underestimated. Around 85% of all diesel trucks were Euro 3-6, with the remaining 15% made up of older emissions standards than Euro 3. The average fuel-specific emissions of NO_x and PM by emission standard from diesel trucks were shown in Figure 14. Despite the small sample, a significant reduction in both NO_x and PM emissions, especially for PM emission, can be seen for the trucks with the latest Euro 6 emission standards

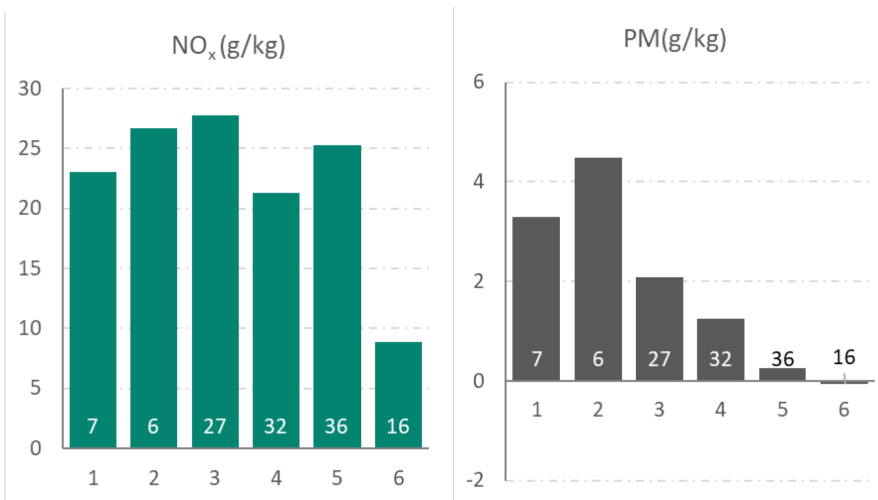


Figure 14. Average fuel specific NO_x, and PM emissions in g/kg fuel burned from diesel trucks by emission standard. The number of measurements is shown inside of each bar.

4 Conclusions and outlook

The one-week remote sensing pilot study in Sarajevo successfully recorded around 25,000 vehicle passages from which emission measurements of PM, NO_x, HC and CO were made, split into different vehicle types (PC, LCV, trucks, buses and motorcycles), fuel types (mainly diesel and petrol) and Euro standards (Euro 1-6).

Data capture for heavy-duty trucks was less successful, due to less effective vehicle number plate identification, which is a well-known limitation of remote sensing in this context. A higher capture rate could be achieved with a different positioning of the video camera, but due to other problems (e.g., elevated tailpipes, connected trailers affecting the exhaust plume) associated with measuring exhaust plumes from trucks, capture rates will always be lower than for light-duty vehicles.

As observed in many other recent European remote sensing studies, the PM emissions from the Sarajevo vehicle fleet have reduced substantially for all vehicle types (on the order of 80-90%), as Euro standards increase from Euro 1 to Euro 6. In contrast, NOx emissions from diesel vehicles have only reduced on the order of around 50%, despite the stricter Euro standards.

Euro 3 – 5 diesel passenger cars contributed 74% of all NO_x emissions from all passenger cars, while accounting for 63% of the number of all passenger cars measured. Similarly, Euro 3 and Euro 4 diesel cars together are responsible for 74% of total PM emissions from all passenger cars, while representing only 40% of all passenger cars measured.

The emission performance of the Sarajevo vehicle fleet deviates from that of other European fleets, mainly for petrol cars. Emissions of PM, NO_x, HC, and CO were substantially higher for pre-Euro 5 cars in Sarajevo, i.e., older cars, compared to those in other European cities where similar remote sensing measurements have also been performed. The main reason for this observation is the substantially higher share of high-emitting cars within the Sarajevo petrol car fleet.

The latter observation raises the question whether a lower quality of petrol fuel has been (and still is) used in Sarajevo than in the EU, e.g., with higher sulphur content poisoning the three-way catalyst, poor maintenance and /or tampering of the cars, possibly in combination with an inefficient inspection and maintenance program (PTI).

Based on the results from this study, the implementation of low emission zone which impose restrictions on pre-Euro 6 diesel vehicles would significantly reduce the contribution of air pollution emissions from road traffic.

Future measurements should also consider a focus on heavy-duty, typically diesel fuelled, vehicles as their data capture were relatively low, while their relative contribution to NO_x remains high.

Acknowledgements

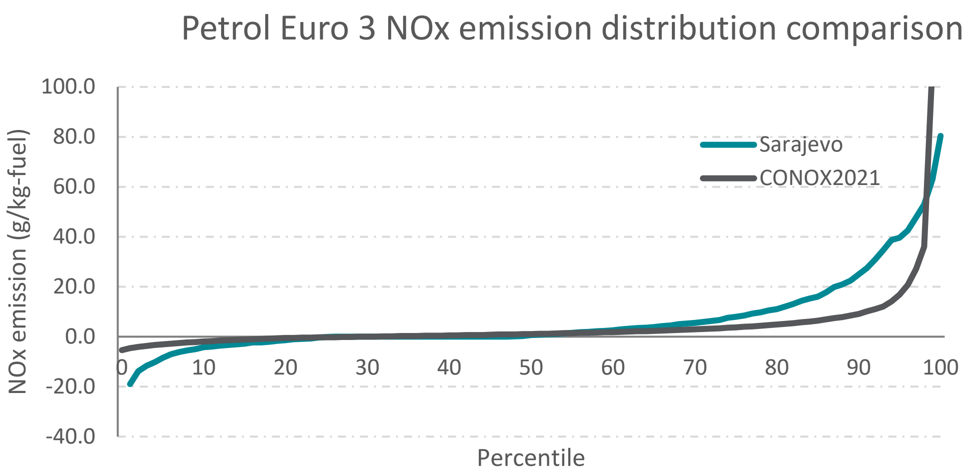
We gratefully acknowledge the support of Opus RSE for both providing valuable input regarding the selection of measurement sites in Sarajevo and making available their remote sensing instrumentation used for the measurements. We gratefully acknowledge our colleagues at the Ministry of Traffic and the Ministry of Spatial Planning, Civil Engineering and Environment at the Canton of Sarajevo for investigating/assessing/documenting many different locations in Sarajevo allowing us to select the most appropriate measurement sites for this study.

Appendix

Based on VehicleTechData_ID, 2080 vehicles (among which 1799 passenger cars) were measured twice, 376 vehicles (305 passenger cars) were measured three times and 87 vehicles (71 passenger cars) were measured four times, as summarized in the table below.

Table A1. Count of occurrences of VehicleTechData_ID and number of vehicles measured for all type of vehicles and for passenger cars.

Occurrences	1	2	3	4	5	6	7	8	9	10	11	12	17	Total
Count_all	11457	4160	1128	348	160	120	84	48	18	20	11	36	17	17607
Number of vehicles _all	11457	2080	376	87	32	20	12	6	2	2	1	3	1	14079
Count_PC	10263	3598	915	284	110	90	49	24	9	10	0	36	17	15405
Number of PCs	10263	1799	305	71	22	15	7	3	1	1	0	3	1	12491



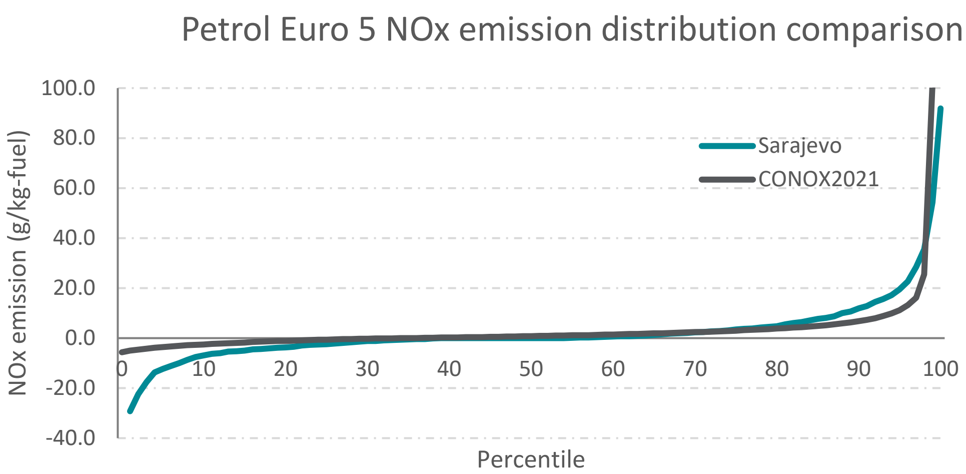
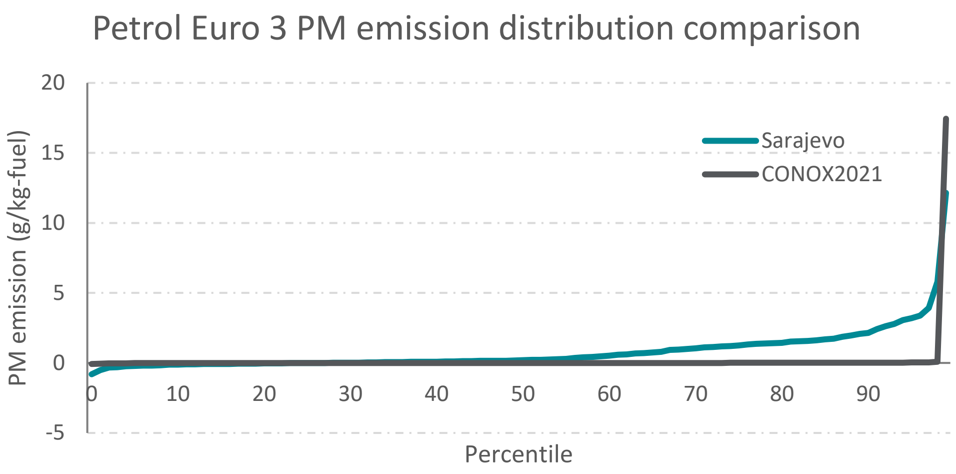
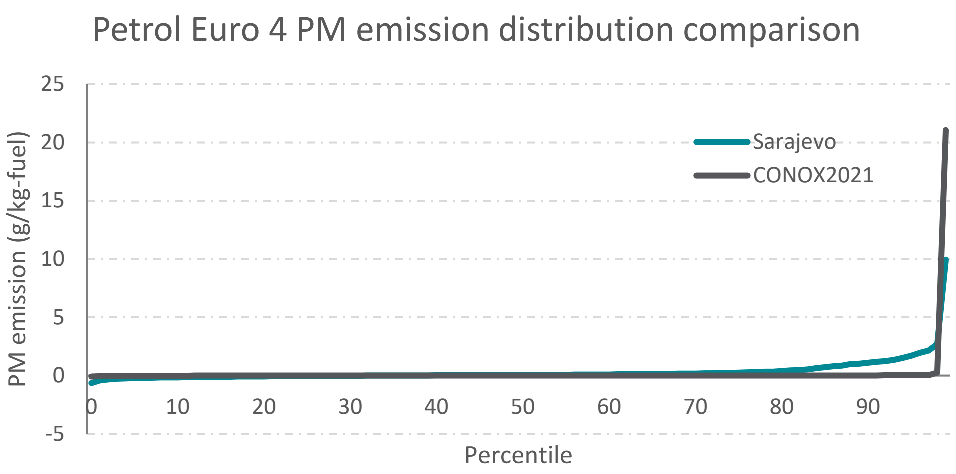


Figure S1. Percentile distribution of NO_x emissions measured from petrol passenger cars by comparing the Sarajevo campaign with CONOX datasets for measurements conducted in 2021.





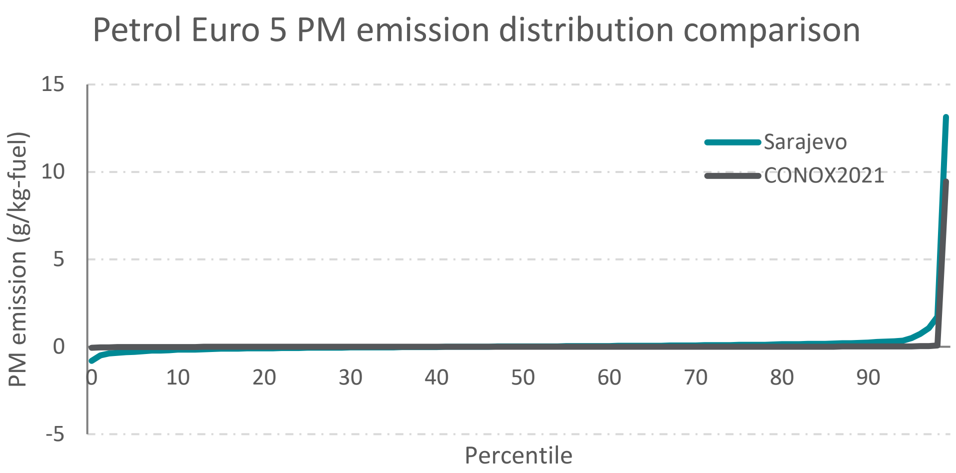


Figure S2. Percentile distribution of PM emissions measured from petrol passenger cars by comparing the Sarajevo campaign with CONOX datasets for measurements conducted in 2021.

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