Remote sensing of motor vehicle emissions in Seoul

Lead authors: Liuhanzi Yang, Ruoxi Wu, Yoann Bernard, Tim Dallmann, Uwe Tietge (ICCT)

Contributing authors: Sunggi Shin, Il-woong Yang (Korea Environment Corporation)
Dongjun Ha, Beunsoo Park, Songjae Yang, Jinyoung Song (Seoul Metropolitan Government)

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FIA Foundation and the International Council on Clean Transportation (ICCT) have established The Real Urban Emissions (TRUE) Initiative. The TRUE initiative seeks to supply cities with data regarding the real-world emissions of their vehicle fleets and equip them with technical information that can be used for strategic decision making. TRUE will use a combination of measurement techniques to produce a granular picture of the on-road emissions of the entire vehicle fleet by make, model, and model year.

INTRODUCTION

Remote sensing is a promising technology that can measure vehicle emissions during normal, on-road operation and at relatively low cost. More than 27 countries around the world have carried out remote sensing campaigns to measure motor vehicle emissions (Bernard et al., 2019). Since 2013, South Korea has measured emissions from on-road vehicles using remote sensing equipment as part of their periodic inspection to identify high-emitting vehicles. Every year, the emissions of 2 million to 3 million vehicles are measured across 42 different locations in 21 cities.[1] Gasoline and liquefied petroleum gas (LPG) vehicles are subject to testing for tailpipe emissions of hydrocarbons (HC), carbon monoxide (CO), and nitrogen monoxide (NO). Owners of non-compliant vehicles identified by remote sensing are required to get the high-emitting vehicles checked or repaired at a designated inspection and maintenance facility.

With the aim of reducing emissions from in-use vehicles and improving urban air quality, Seoul, Incheon, and 17 cities in the Gyeonggi Province established low-emission zone programs in 2012. Beginning in 2020, 13 additional cities throughout the Gyeonggi province implemented low-emission zone (LEZ) programs. Light-duty diesel vehicles registered in the capital area with an emissions classification of Grade 5 that were manufactured before 2002 or 2005 (depending on size) are banned from entering the low-emission zone. As a further step, Seoul established a Green Transport Zone in which all diesel and gasoline Grade 5 vehicles are banned from entering the zone as of December 1, 2019 (Seoul Metropolitan Government, 2019).

This study analyzes remote sensing data collected in Seoul to provide policy recommendations for Seoul's Green Transport Zone program and other measures that can improve the air quality in the city. Similar work was previously undertaken by the ICCT to evaluate the potential emissions benefit of the LEZ policy in Paris through 2030. We conclude with implications of the remote sensing data analysis for the timing and stringency of the Paris LEZ and provide policy recommendations for the design of LEZs in other cities around the world (Bernard et al., 2020).

1 Locations include Seoul (11 sites) and Gyeonnggi-do (13 sites) in the Capital Area, four sites in other metropolitan areas, and three sites in air quality control areas located in cities with populations over 500,000.

This project is carried out in collaboration with Seoul Metropolitan Government and Korea Environment Corporation (K-eco). The paper is organized as follows: we first provide information related to vehicle emission standards in South Korea, remote sensing applications in South Korea, and the Green Transport Zone policy in Seoul. The next section describes the remote sensing testing campaign in Seoul, the instrumentations that were used, and the data processing and analysis methodology. The following sections present the characteristics of the sampled fleet and the emission results from light-duty vehicles. The final section provides policy recommendations for the next stage of Seoul's Green Transport Zone Program and for better air quality in Seoul.

BACKGROUND

EMISSION STANDARDS IN SOUTH KOREA

For light-duty vehicles (LDVs) in South Korea, emissions standards equivalent to those in the European Union or United States apply, depending on the vehicle application and type of fuel used. Emissions standards for light-duty gasoline vehicles follow the standards established by the California Air Resources Board (CARB). In 2009, South Korea adopted CARB's Non-Methane Organic Gases (NMOG) Fleet Average System (FAS) for gasoline-fueled vehicles, meaning a car manufacturers fleet, as opposed to individual models, are required to meet a prescribed level of NMOG emissions. South Korea has also adopted CARB's Low-emission Vehicle III program standards, with certification levels functionally equivalent to CARB's low-emission vehicle (LEV), ultra-low-emission vehicle (ULEV), super ultra-low emission vehicle (SULEV) and zero-emission vehicle (ZEV) levels. For light-duty diesel vehicles, the European standards apply. Starting from September 2014, light-duty diesel vehicles are subject to Euro 6 regulations and, since October 2017, new vehicle types are certified to Euro 6d-TEMP, and include on-road certification testing requirements. Figure 1 presents the non-methane organic gas (NMOG) and NO_x emission limits for light-duty gasoline and diesel vehicles in United States, European Union, and South Korea. For all heavy-duty vehicles, South Korea implemented Euro VI HD engine emission standards in January 2014, one year later than Europe.

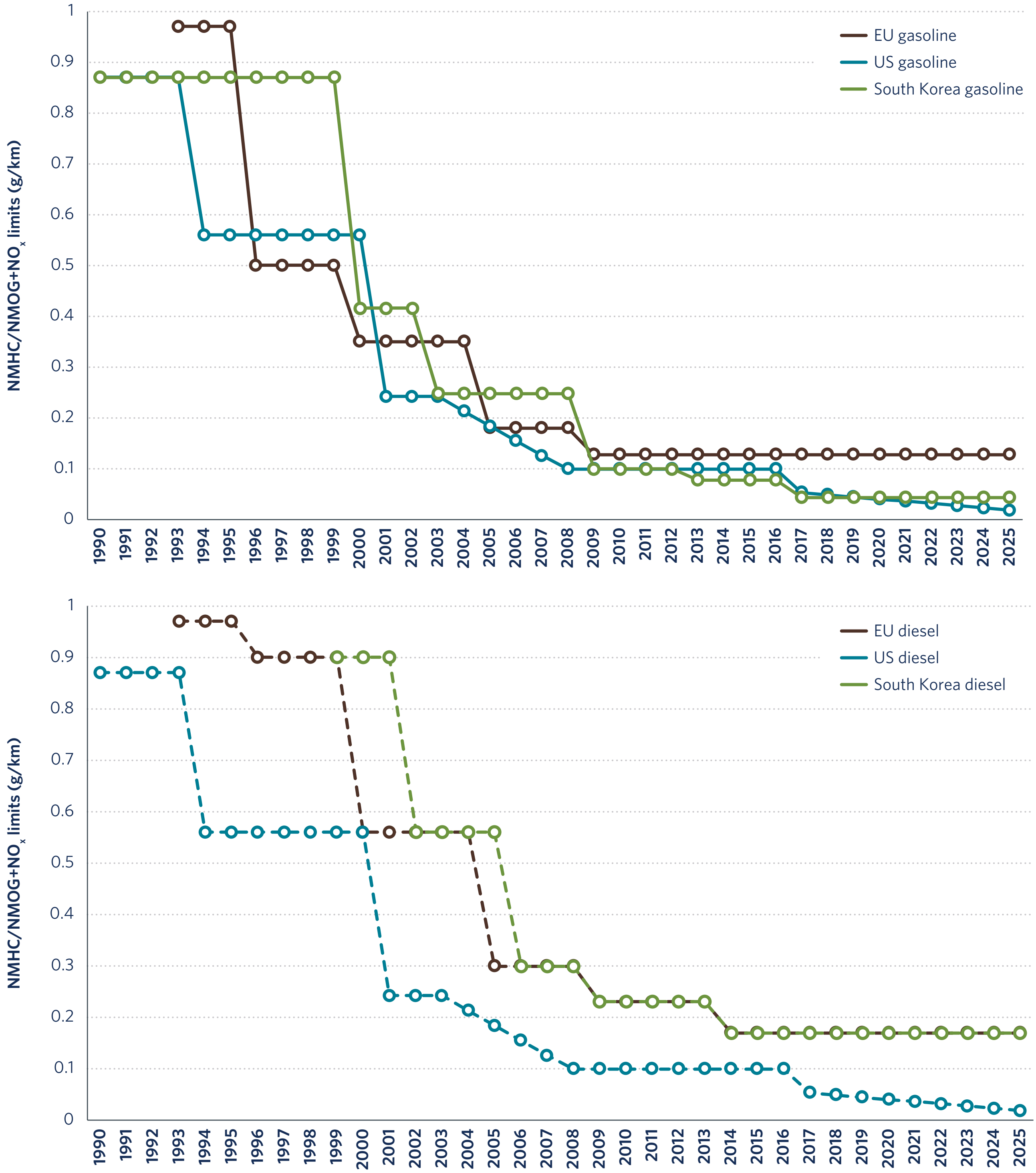

Figure 1. NMOG and NO$_x$ emission limits for light-duty gasoline and diesel vehicles in United States, European Union, and South Korea.

Table 1. Definitions of vehicle emission grades in South Korea.

Grade	Vehicle type	Emission level	Fuel type	Minimum implementation date
1	Light-duty vehicle (LDV)	Zero emission vehicle	Electric and fuel cell	-
		Super ultra-low emission vehicle	Gasoline and liquefied petroleum gas (LPG) (Including hybrid)	Jan 1st, 2016 (Standard 6), Jan 1st, 2016 (Standard 5), Jan 1st, 2013 (Standard 3), Jan 1st, 2009 (Standard 3)
	Heavy-duty vehicle (HDV)	Zero emission vehicle	Electric·and fuel cell	-
		Euro-VI and above	Gasoline hybrid	Dec 1st, 2016
			LPG hybrid	
2	LDV	Ultra-low emission vehicle	Gasoline and LPG (Including hybrid)	Jan 1st, 2016 (Standard 4), Jan 1st, 2016 (Standard 3), Jan 1st, 2016 (Standard 2) Jan 1st, 2013 (Standard 2), Jan 1st, 2009 (Standard 2) Jan 1st, 2006
		Low emission vehicle (LEV II & III)	Gasoline and LPG	Jan 1st, 2016 (Standard 1) Jan 1st, 2013 (Standard 1), Jan 1st, 2009 (Standard 1)
	HDV	Euro-VI	Gasoline and LPG	Jan 1st, 2016 (LPG) Jan 1st, 2013 (Gasoline)
			Diesel hybrid	Jan 1st, 2014
3	LDV	Low emission vehicle (LEV I)	Gasoline and LPG	Jan 1st, 2003
		Euro-6d-temp and above	Diesel	Sep 1st, 2017
		Euro-6	Diesel (Including hybrid)	Jan 1st, 2014
		Tier 1	Gasoline and LPG	Jan 1st, 2000
		Euro-5	Diesel	Sep 1st, 2009
	HDV	Euro-V	Gasoline and LPG	Jan 1st, 2009
		Euro-VI	Diesel	Jan 1st, 2014
		Euro-IV	Gasoline and LPG	Jan 1st, 2006
		Euro-V	Diesel	Sep 1st, 2009
4	LDV	-	Gasoline and LPG	Jan 1st, 1988 (Equipped with three-way catalyst)
		Euro-4	Diesel	Jan 1st, 2006
	HDV	Euro-III	Gasoline and LPG	Jul 1st, 2002
		Euro-IV	Diesel	Jan 1st, 2006
5	LDV	-	Gasoline and LPG	Before 1987 (Unequipped with three-way catalyst)
		Before Euro-3	Diesel	Before Jan 1st, 2006*
	HDV	Euro-II	Gasoline and LPG	Before Jan 1st, 2000
		Euro-III	Diesel	Jul 1st, 2002

*For some vehicle types there is a two-year grace period.

Vehicles in South Korea are classified into five grades according to certified emission standard and fuel type, with Grade 1 being the cleanest and Grade 5 being the dirtiest. Diesel vehicles are excluded from Grade 1 and Grade 2, with the exception of diesel hybrid heavy-duty vehicles. For example, the newest Euro 6 diesel LDVs are classified as a Grade 3 vehicle in South Korea. The aim of this classification is to identify a vehicle's emissions levels in order to support in-use emissions control programs. The LEZ program in 30 cities and the Green Transport Zone program in Seoul use the grading system to restrict the access of high-emitting vehicles to some locations in the city. Table 1 presents the definition of vehicle emission grades in South Korea.

In South Korea, more than three quarters of the vehicles are Grade 2 and Grade 3. Grade 1 vehicles accounted for less than 10% of the total fleet (see Figure 2).

REMOTE SENSING APPLICATIONS IN SOUTH KOREA

South Korea has measured the emissions of in-use vehicles using remote sensing devices (RSDs) as part of periodic inspection programs since 2013. The Korea Environment Corporation, an environmental service organization attached to the Ministry of Environment, is in responsible for operating remote sensing equipment in South Korea.

The South Korean remote sensing program measures the emissions of 2 million to 3 million vehicles per year across 39 different locations. While the emissions of all vehicles passing the RSD equipment are measured, only gasoline and liquefied petroleum gas (LPG) vehicles are subject to in-use emission limits. For these vehicles, emission limits for tailpipe concentrations of HC, CO, and NO are based on vehicle type and the year of manufacture (see Table A1 and Table A2 in the appendix). When a vehicle's emissions exceed these limits, defined as three times the standard limit applied during periodic technical inspection, it is classified as a high emitter and a notification is sent to the owner, suggesting that the vehicle be checked. If the same vehicle is observed to exceed RSD emission limits for a second time in a year, the owner receives an order for improvement. The owner is required to stop using the vehicle and get it repaired at a designated inspection and maintenance facility within 15 days from the date

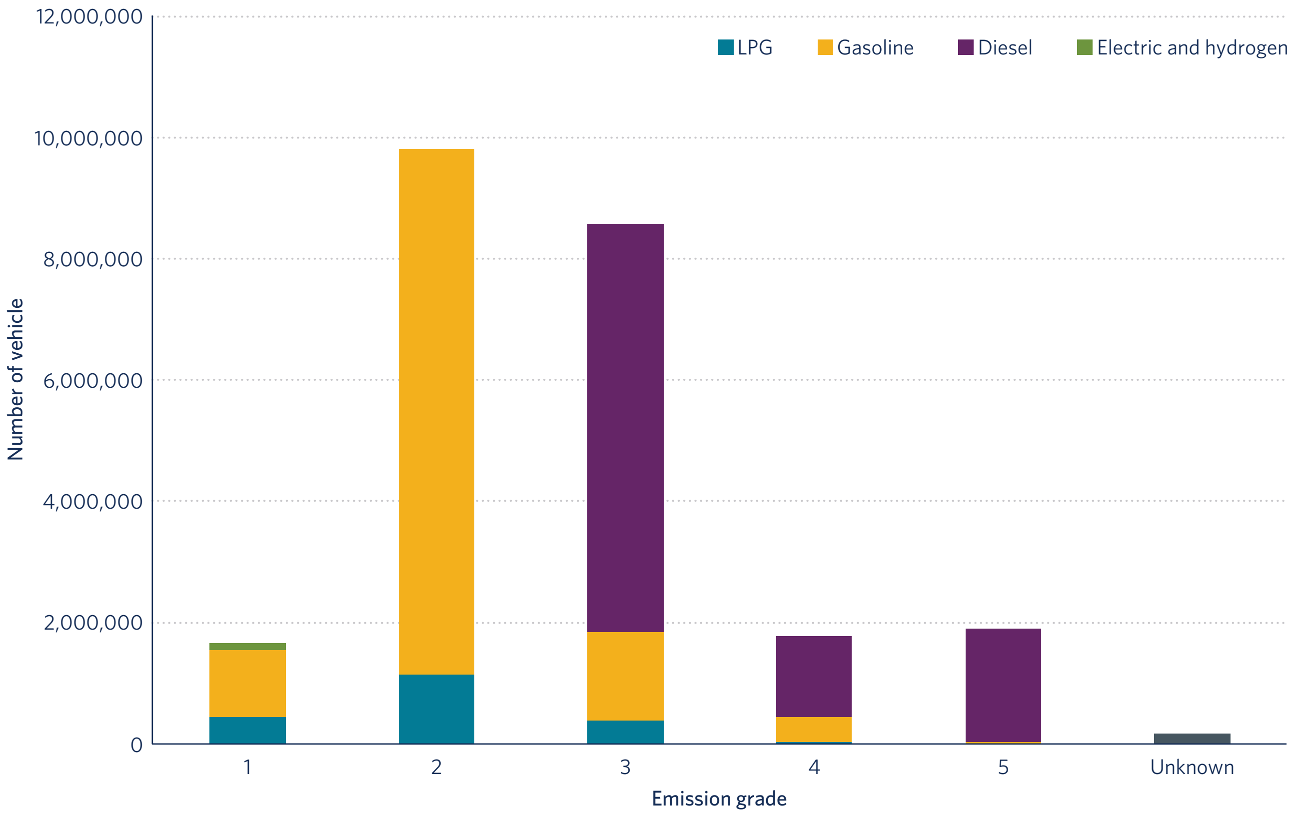

Figure 2. Number of vehicles in South Korea by emission grade. Data are as of May 31, 2020. Source: K-eco (2020).

of the order for improvement; otherwise, the owner will be subject to a fine.

Remote sensing devices can efficiently screen high-emitting vehicles while avoiding traffic jams and the risk of accidents caused by on-road inspections of forced stops. The measurement data from RSDs are used to identify high emitting vehicles, evaluate the current status of vehicle emissions, and shape vehicle emission control policies in South Korea.

In 2017, an unmanned fixed RSD was installed in Seoul to address staff safety issues and increase measurement efficiency. There are currently three unmanned measurement sites, one in Seoul and two sites in the Gyeonggi Province. K-eco plans to increase the number of fixed unmanned RSDs used and eventually operate only fixed unmanned devices.

Table 2 gives an overview of remote sensing records collected in South Korea since 2013.

GREEN TRANSPORT ZONE PROGRAM IN SEOUL

While older Grade 5 vehicles account for only 10.6% of all the registered vehicles nationwide, they are responsible for 53.4% of total $PM_{2.5}$ emissions from on-road vehicles (C40 cities, 2020). Since 2012, Seoul has restricted the use of Grade 5 diesel vehicles registered in the capital area within its low-emission zone. Seoul's low-emission zone covers the entire city of Seoul and its neighboring metropolitan area, including the city of Incheon and most of Gyeonggi Province. After a six-month pilot program in 2019, Seoul officially banned all Grade 5 gasoline and diesel vehicles registered in or outside of the capital area from entering the Green Transport Zone from December 1, 2019. The Green Transport Zone covers the 16.7 square kilometers of the city center within the historic city walls (see Figure 3). Forty-five gateways in and out of the zone are fitted with surveillance cameras to enforce the restrictions with real-time data collection. Any person driving a Grade 5 vehicle inside this area is subject to a fine of 100,000 won (approximately $82) for a first-time violation and 200,000 won for those who violate the ban over three times a day. Exceptions are made for vehicles equipped with a diesel particulate filter, emergency vehicles, and cars belonging to a person with a disability permit (C40 cities, 2020). Table 3 presents a summary of the Low Emission Zone and Green Transport Zone programs in Seoul. Seoul plans to expand the Green Transport Zone to include Gangnam and Yeouido and restrict all diesel vehicles from entering Seoul in 2050. (Seoul Metropolitan Government, 2021). Seoul is also developing a long-term climate action plan to reach carbon neutrality by 2050. To achieve this goal, Seoul is considering limiting new vehicle registrations to only electric and hydrogen starting in 2035 (C40 cities, 2020).

Table 2. Overview of the data collection in South Korea

Year		2013	2014	2015	2016	2017	2018	2019	2020
Number of remote sensing instruments		4	4	6	6	6	6	6	6
Number of records	**Gasoline**	357,917	382,008	391,763	413,877	411,602	508,371	649,403	660,404
	LPG	174,306	155,582	158,183	166,823	176,600	199,383	186,306	168,082
	Diesel	369,798	424,233	471,211	516,697	488,408	591,771	690,788	780,960
	Compressed natural gas	4,474	1,632	873	1,004	1,289	3,808	1,399	1,045
Measurement site		Capital area[a]	Capital area and five metropolitan cities[b]				Capital area, five metropolitan cities, and Air Quality Control area[c]		Capital area

[a] Capital area: Seoul, Incheon, Gyeonggi-do Province
[b] Five metropolitan cities: Busan, Ulsan, Daegu, Gwangju, Daejeon
[c] Air quality control area: Changwon, Gimhae, Pohang, Jeonju, Cheonan, Chungju.

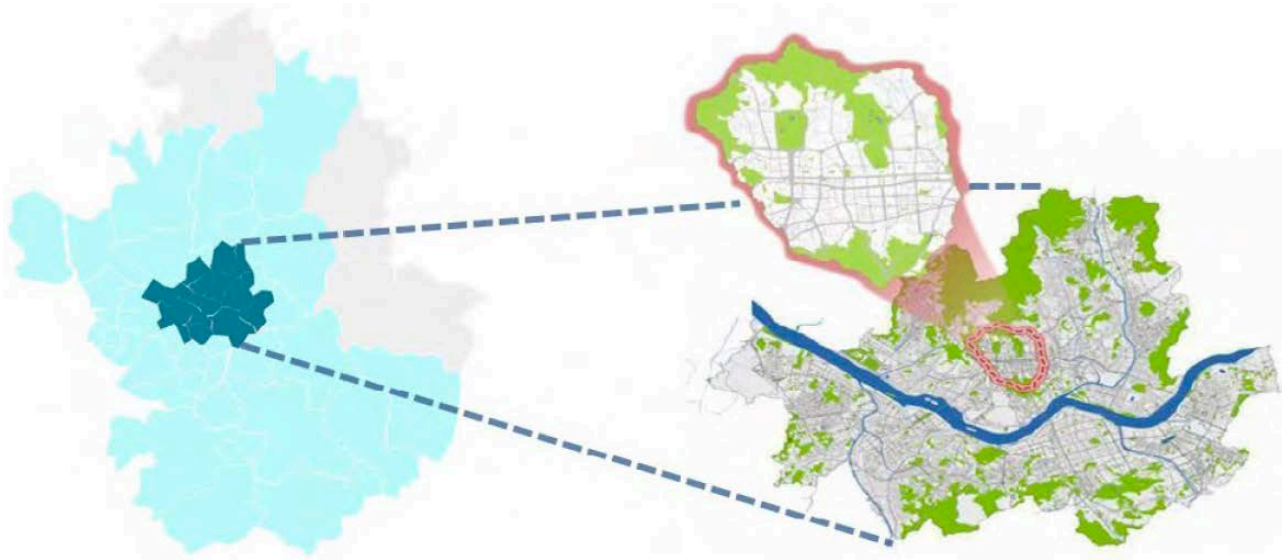

Figure 3. Location of Green Transportation Zone in Seoul Metropolitan area. (Source: C40 cities)

Table 3. Seoul's Low Emission Zone and Green Transport Zone (source: C40 cities)

	Low Emission Zone	Green Transport Zone
Vehicle	Grade 5 diesel LDVs registered in the capital area	Grade 5 diesel and gasoline LDVs registered anywhere
Area	The entire area of Seoul and neighboring metropolitan area	16.7 square kilometer city center within the city walls
Operation	24 hours (365 days)	6am–9pm (365 days)
Fine	200,000 won (approximately $166) per violation per month (regardless of the number of violations)	100,000 won (approximately $82) per violation per day; 200,000 won if over three violations in a day.

SEOUL REMOTE SENSING STUDY OVERVIEW

REMOTE SENSING INSTRUMENTATION

The RSDs used in the Seoul remote sensing study were the RSD4600 and RSD5000 models from Opus AccuScan. Each record from the RSD5000 consists of 100 measurements of the exhaust plume of a vehicle in 0.5 seconds but each record of RSD4600 is 50 measurements during the same time period. The RSD5000 models were upgraded to measure NO_2 but the NO_2 results were not certified in 2019 when the measurements were taken.

AnRSD consists of three components: a device which measures pollutants in the exhaust plumb and records speed and acceleration, a device that collects data on ambient conditions such as temperature, humidity, and wind speeds, and equipment to operate the measurement device and collect measurement data. The data collected is transferred to K-eco's monitoring system every 5 seconds.

The fixed RSD normally runs from 7am to 8pm each day except for regular maintenance and quality control tests by an authorized institution. In Seoul, there is one unmanned fixed RSD at Naegok IC (see Figure 4).

The location of each RS measurement site is presented in Figure 5. K-eco operated the RSD at sites with the following characteristics:

Southern end of Dongho Bridge | **Unmanned fixed RSD at Naegok IC**

Figure 4. RSD5000 remote sensing device deployed at the Southern end of Dongho bridge and Naegok IC

- Single lane roads to prevent interference from non-target vehicle exhaust plumes.
- Steady traffic flow to provide sufficient sampling rates and to avoid sampling disruptions during periods of congestion.
- Slight upward slope or locations where vehicles are under acceleration to provide sufficient engine load.
- Sufficient distance from residential areas to limit measurements of cold engines.
- Adequate space to set up instrumentation and ensure operator safety without disrupting traffic flows.

DATA COLLECTION SUMMARY

For this study, we analyzed the remote sensing data collected at 11 sites in Seoul from January 2019 to December 2019, comprised of 748,418 records. Table 4 presents an overview of the remote sensing data collected at each site. The locations of the remote sensing campaign sites in Seoul are not within the Green Transport Zone.

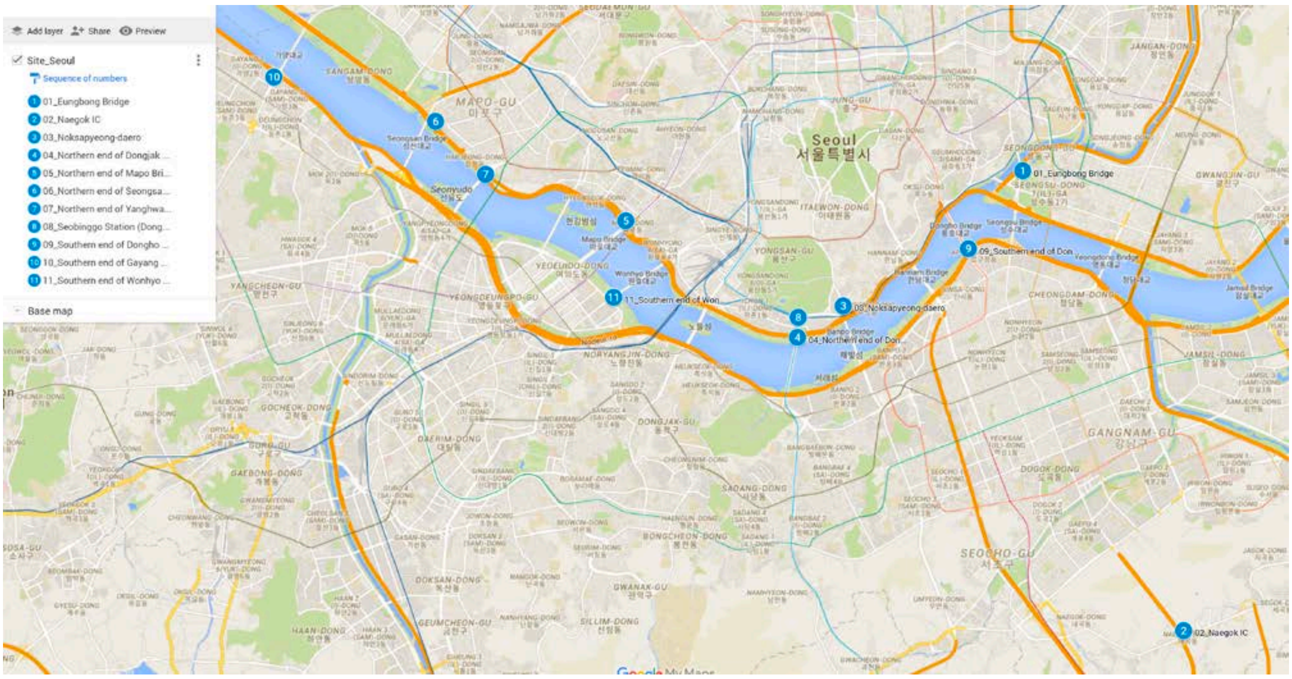

Figure 5. Measurement sites in Seoul
(Source: Google Maps, https://www.google.com/maps/d/edit?mid=1qdRMlOwLTh2zNAJuF2pjW9YZ-vxep68L&usp=sharing)

Table 4. Overview of the data collection of the Seoul remote sensing study

Site ID	Site name	Road type	Vehicle size	Number of valid records
1	Eungbong Bridge	Urban road	heavy	79
			light	5,848
2	Naegok IC (Unmanned)	Urban road	heavy	1,701
			light	452,383
3	Noksapyeong-daero	Urban road	heavy	438
			light	16,133
4	Northern end of Dongjak Bridge	Motorway	heavy	51
			light	13,985
5	Northern end of Mapo Bridge	Motorway	heavy	236
			light	20,232
6	Northern end of Seongsan Bridge	Motorway	heavy	382
			light	32,677
7	Northern end of Yanghwa Bridge	Motorway	heavy	772
			light	76,101
8	Seobinggo Station (Dongjak Bridge)	Urban road	heavy	299
			light	30,223
9	Southern end of Dongho Bridge	Motorway	heavy	299
			light	45,300
10	Southern end of Gayang Bridge	Motorway	heavy	258
			light	17,543
11	Southern end of Wonhyo Bridge	Urban road	heavy	455
			light	33,023
Total				**748,418**

DATA PROCESSING AND ANALYSIS

A complete database of Seoul remote sensing records was provided to K-eco, including vehicle emissions data, operating conditions, and ambient weather conditions. For this analysis, the RSD data was uploaded to K-eco's Comprehensive Information System for Vehicle Emissions (MECAR) server via the website (mecar.or.kr). The MECAR decompress the RSD data and runs an automatic license-plate recognition program. The list of recognized plate numbers is sent to Korea Transportation Safety Authority's server to get information on the vehicles such as model, category, model year, and inspection and maintenance test (loaded test) results. Finally, MECAR matches the RSD data with the information on each vehicle.

The following criteria are applied to filter data that are used for data analysis in the following section:

- The RSD records are valid
- The interval from a previous vehicle's record is longer than 2 seconds
- Acceleration is larger than 0

- Vehicle Specific Power ranges from 3 kW/ton to 22 kW/ton[2]
- Estimated tailpipe CO + CO_2 concentration is less than 21%
- Estimated tailpipe CO_2 concentration is less than 16%
- Estimated tailpipe HC concentration is less than 20,000ppm
- Estimated tailpipe NO concentration is less than 7,000ppm
- The number of measurement samples in each record is larger than 10
- The vehicle information is available

The RSD5000 remote sensing instrument used in this study measures the intensity of ultraviolet (UV) smoke, or the smoke factor, of the plume as a proxy for particulate matter emissions. The smoke factor is a ratio of exhaust opacity to the amount of fuel burned at the time of measurement. The smoke factor is measured in the UV smoke using frequencies providing the greatest sensitivity to the particulate mass fraction. The amount of fuel burned is formulated by adding the measurements of the carbon-based gases of the exhaust. The interaction of the remote sensing light beam with exhaust particles is complex and dependent on several factors, including the physical and chemical characteristics of the exhaust particulate matter. These factors can vary considerably across vehicles in a fleet and even for individual vehicles across operating modes. While the opacity measurement gives some information about particulate matter emissions, it is fundamentally different than methods used to quantify particulate matter mass and particle number emissions in regulatory certification and compliance testing.

Data processing and statistical analysis were performed following standardized methods described in Bernard et al. (2018). In the following sections, we present a characterization of the sampled vehicle fleet, detailed emission results for LDVs, and an evaluation of the emissions of diesel vehicles retrofitted with a diesel particulate filter (DPF).

2 Vehicle specific power (VSP) is a one-dimensional measure for engine load, depending on speed, acceleration, and driving resistances. Jiménez (1999) suggest a range of 3 kW/ton–22 kW/ton, just below the maximal VSP in the U.S. Federal Test Procedure (FTP). The VSP in the New European Driving Cycle (NEDC) ranges up to 29 kW/ton when highway driving is included; therefore, a range similar to the U.S. FTP is applied in South Korea as normal driving operation.

CHARACTERISTICS OF THE SAMPLED FLEET

Figure 6 shows the characteristics of the vehicle fleet sampled in the Seoul remote sensing study by vehicle category. Vehicles are classified into four categories: light-duty passenger vehicles, light-duty trucks, heavy-duty passenger vehicles, and heavy-duty trucks. Vehicle size (light and heavy duty) are classified based on gross vehicle weight. If a gross vehicle weight of a vehicle is less than 3500 kg, it is considered a light-duty vehicle. Otherwise, it is considered as a heavy-duty vehicle. Vehicle type is classified based on the function of the vehicle (passenger or freight). Light passenger vehicles were the overwhelming majority (92.6%) of vehicles observed during the measurement campaign. In the following sections, we focus on the analysis of light-duty passenger vehicles.

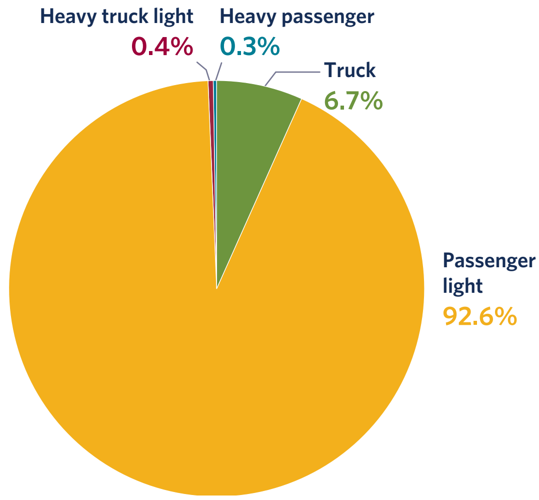

Figure 6. Characteristics of the vehicle fleet sampled in this study by vehicle type.

Figure 7 presents the characteristics of the light-duty vehicles sampled in this study by emission grade and fuel type. Around 80% of the light-duty vehicle fleet sampled are Grade 2 and Grade 3 vehicles, which is consistent with the vehicle fleet composition of Seoul (see Figure 2). The emission grade of some vehicles cannot be obtained from the vehicle information database, so they are labeled in the figure as Grade X.[3] More than 88% of Grade 2 vehicles were powered by gasoline engines, with the remaining 12% powered by LPG engines. Of the Grade 3 vehicles, 84% were powered by diesel engines, while the

3 The vehicle grading database was established in 2019, so some vehicles are lacking a grade in the vehicle information database in this study.

remainder were powered by gasoline engines (13%) and LPG engines (3%). Diesel LDVs dominated the Grade 3 vehicles, due to the fact that the newest diesel LDVs—Euro 6 and 5 diesels—are classified as Grade 3. In this study, we focus the analysis of diesel and gasoline LDVs.

Figure 8 shows the speed, acceleration, vehicle specific power (VSP), and ambient temperature distributions measured in the remote sensing test. The speed, acceleration, and VSP generally follow a bell-shaped distribution, with median values of 37.7km/h, 0.8m/s², and 11.4 kW/ton, respectively. In this testing campaign, two types of RSD, the RSD 4600 and the RSD 5000, were used. Among them, only RSD 5000 reports ambient temperature so Figure 8 (d) presents the ambient temperature distribution collected by the RSD 5000. The median value of the ambient temperature is 15 °C. There are several peaks in the temperature distribution due to the fact that the dataset covers all of 2019 from January through December.

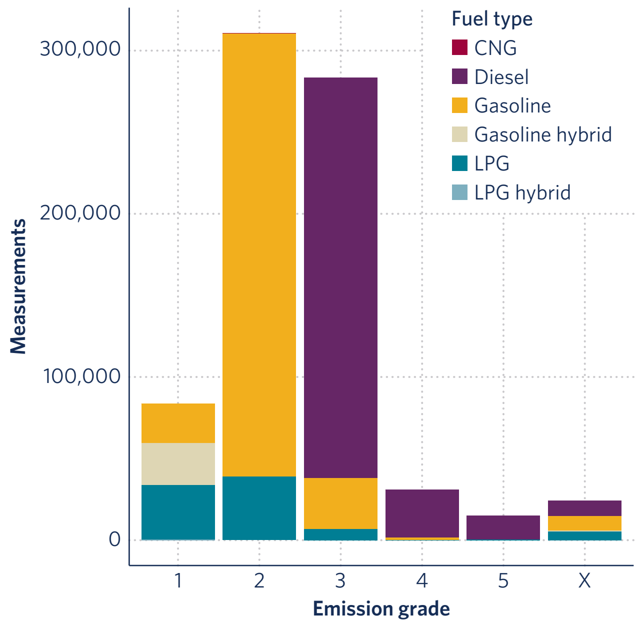

Figure 7. Characteristics of the light-duty vehicles sampled by emission grade and fuel type.

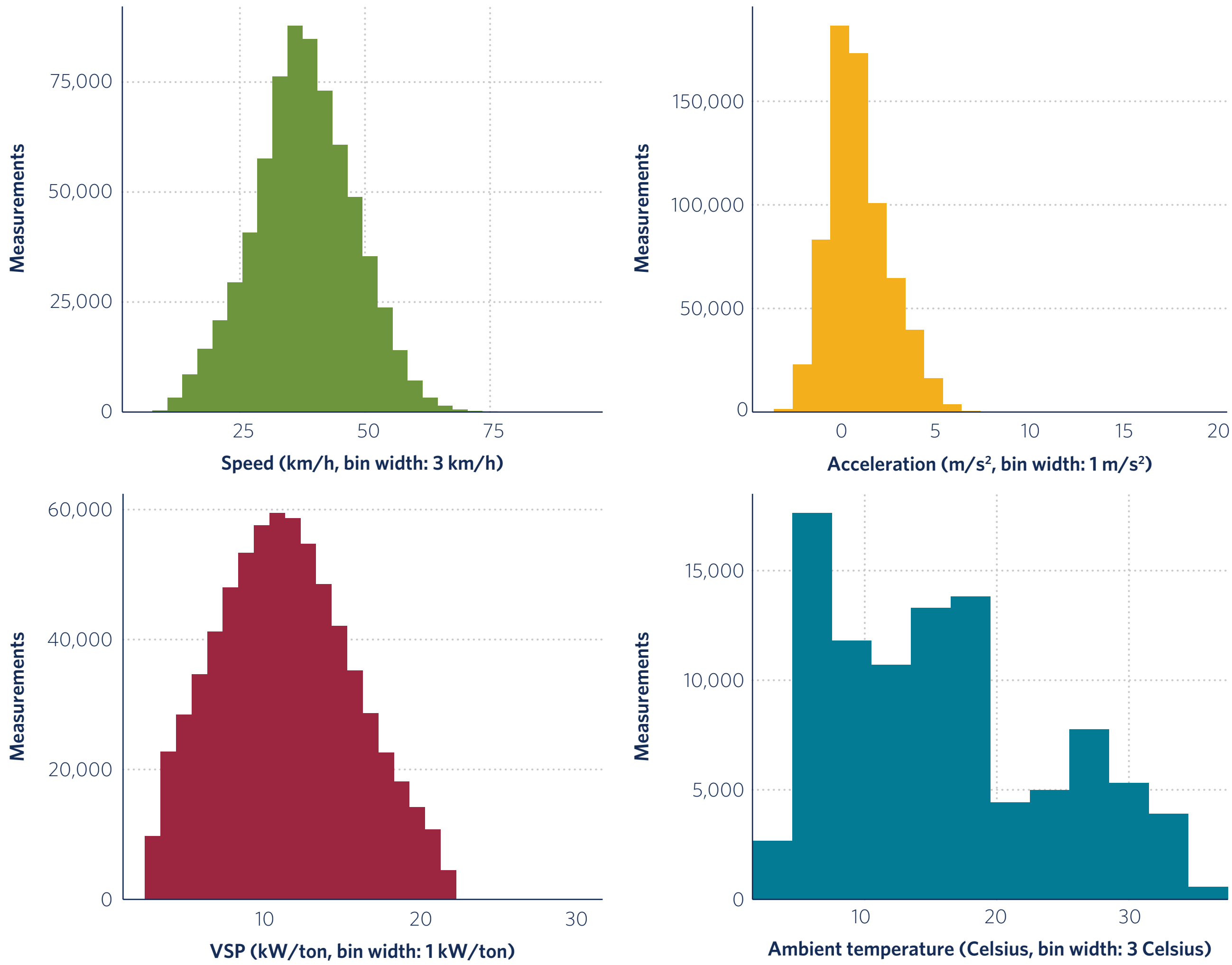

Figure 8. (a) Speed, (b) acceleration, (c) VSP, and (d) ambient temperature distributions of the sampled vehicles.

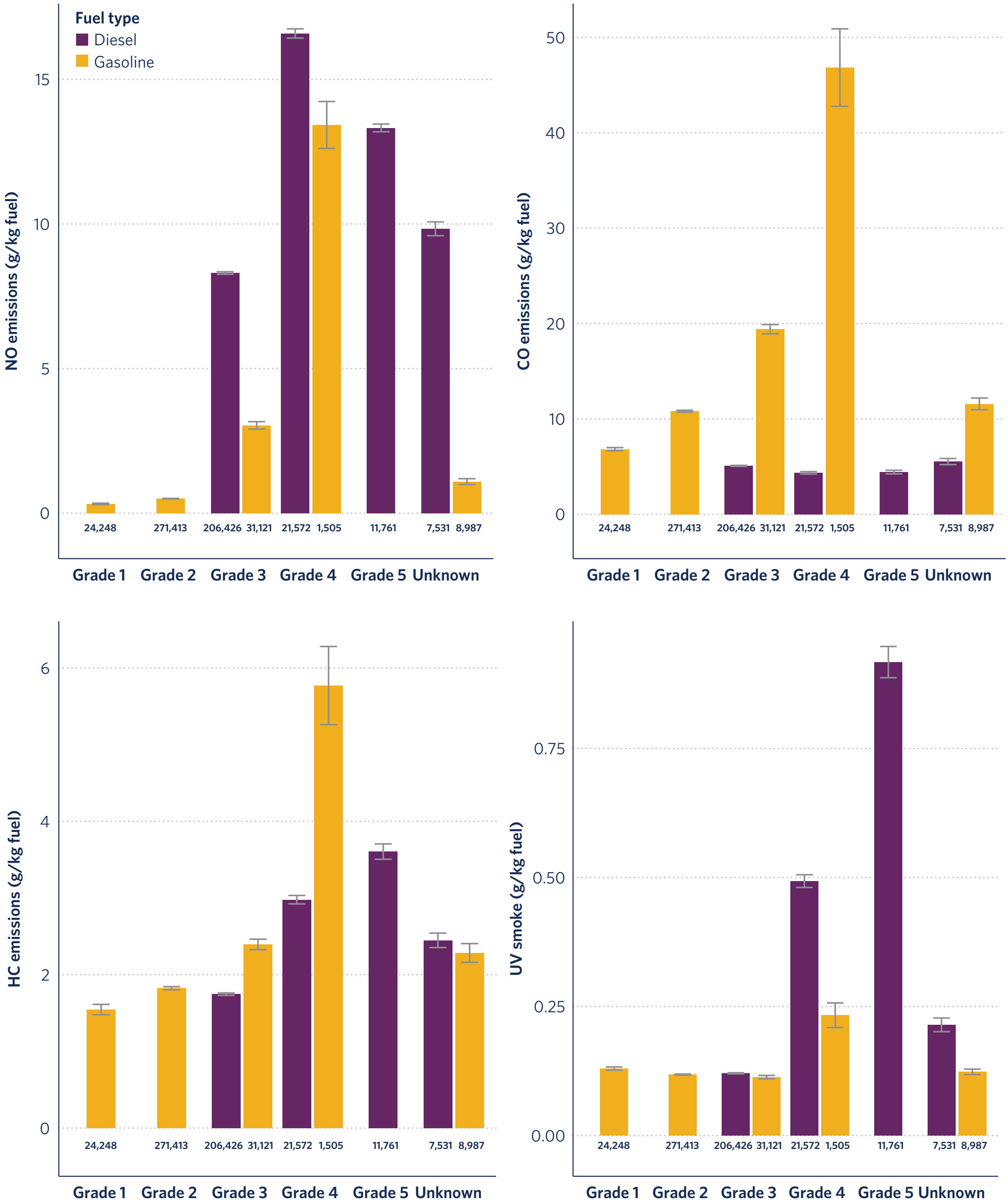

Figure 9. NO, CO, HC, and UV smoke from light-duty passenger vehicles by emission grade and fuel type. Error bars indicate the 95% confidence interval. The number of measurements is presented at the bottom of each bar.

LIGHT-DUTY PASSENGER VEHICLE EMISSIONS

This section presents emissions results of light-duty passenger vehicles, which are the predominant vehicle type in the Seoul remote sensing study. NO, CO, HC, and UV emissions are considered.

Figure 9 shows the average fuel-specific NO, CO, HC, and UV smoke from light-duty passenger vehicles by emission grade and fuel type. For gasoline LDVs, emissions increase as the emission grades increase. The CO and HC emissions from diesel light-duty passenger vehicles are relatively low, which is in line with the expectation that diesel engines typically have low CO and HC emissions. The NO emissions from Grade 4 diesel LDVs are relatively high and are even higher than NO emissions from their Grade 5 counterparts. It should be noted that diesel NOx is expected to be higher because primary NO_2 was not measured in Korea. Based our previous analysis, NOx emissions are about 10%-35% higher than NO emissions.

UV smoke from diesel passenger LDVs decline significantly as emission standards improve. This is due to the fact that Grade 3 diesel LDVs (Euro 5 and Euro 6) are equipped with DPFs by manufacturers. It is worth noting that NO emissions of Grade 3 gasoline LDVs are still one third of those of Grade 3 diesel LDVs, even though Grade 3 gasoline LDVs are about one decade older than Grade 3 diesel LDVs.

Some of the Grade 5 diesel vehicles in Seoul are retrofitted with DPFs. We evaluated the performance of retrofitted DPFs by comparing the UV smoke of retrofitted vehicles with vehicles without a DPF and with a DPF originally installed (see Figure 10). UV smoke, used as a proxy for particulate matter emissions, from DPF-retrofitted Grade 5 diesel LDVs are 37% lower than Grade 5 diesel LDVs without DPF, but are still 4.2 times higher than Grade 3 diesel LDVs with a DPF originally equipped. This implies that there are considerable differences in the efficiency of retrofitted and original DPFs. For diesel LDVs with an originally-equipped DPF, the average UV smoke are in line with those from gasoline LDVs, which indicates that the original DPFs are working effectively on the road to reduce the particle emissions from diesel engines.

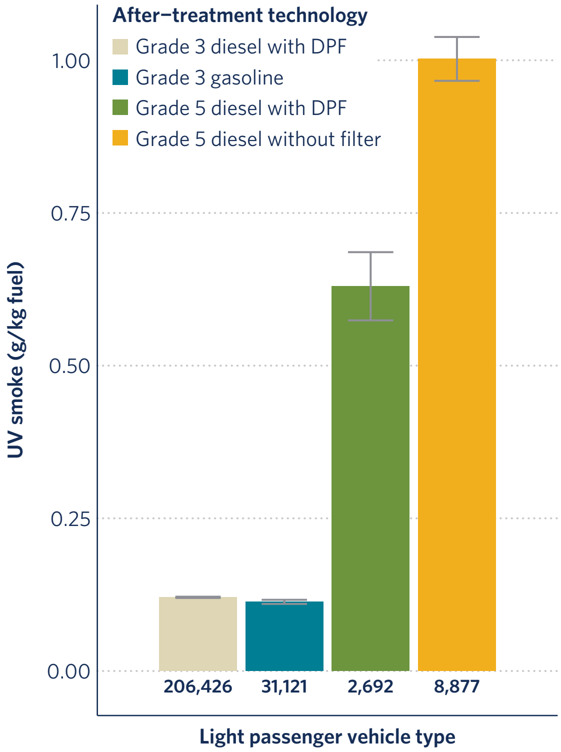

Figure 10. UV smoke from Grade 5 DPF-retrofitted diesel LDVs, compared with Grade 5 diesel LDVs without filters and Grade 3 diesel and gasoline LDVs. Error bars indicate the 95% confidence interval.

EMISSIONS BY MODEL YEAR

Figure 11 presents how NO, CO, HC, and UV smoke from light-duty diesel and gasoline passenger vehicles change over model year. For gasoline LDVs, NO, CO, and HC emissions gradually decrease as the model year increase. Significant declines in NO, CO, and HC emissions can be observed starting in model year 2000, when South Korea adopted the Tier 1 emission standard. For diesel LDVs, NO emissions from diesel LDVs are still high prior to Euro 6-equivelant standards being introduced in 2014. After these standards were introduced, and especially when the real-driving emission testing requirements took into effect in 2017, NO emissions from diesel LDVs started to decrease. However, real-world diesel NO remains significantly higher than NO from gasoline vehicles of the same model year. UV smoke from diesel LDVs which are model year 2012 or newer are at the same level as gasoline LDVs. This is because that Euro 5b introduced a particle number limit in September 2011 and, since then, diesel LDVs are typically installed with a DPF.

Figure 11. Average NO, CO, HC, and UV smoke from light-duty passenger vehicles, by fuel type and model year.

CONCLUSIONS AND POLICY RECOMMENDATIONS

In this study, we analyzed the real-world emissions data collected by remote sensing in Seoul in 2019. The testing campaign was conducted at 11 sites in the city of Seoul, and the in-use emissions of more than 740,000 vehicles were measured. The sampled fleet was mostly comprised of light-duty passenger vehicles, including cars and vans.

Our analysis found that real-world NO emissions from Grade 4 diesel LDVs are comparable or even higher than Grade 5 diesel LDVs. Currently, Grade 5 vehicles are banned from entering the Green Transport Zone in Seoul to reduce emissions from vehicles used in the area and improve urban air quality. Our analysis indicates that emissions from Grade 4 vehicles are not lower than those from Grade 5 and should be banned from the Green Transport Zone as well. In addition, results from this study indicate that UV smoke from Grade 5 diesel LDVs retrofitted with a DPF are 37% lower than those without DPF, but this reduction efficiency is much lower than expected. Therefore, we recommend that the Seoul Metropolitan Government should consider polices to encourage the retirement of the older vehicle fleet rather than encouraging retrofitting the vehicles with DPFs. By retiring Grade 5 diesel vehicles and expanding driving ban to include Grade 4 vehicles, UV smoke and NO_x emissions from in-use diesel vehicles would be significantly reduced and would further improve the urban air quality in Seoul. Additional analysis on emission reduction and air quality benefits is highly recommended to evaluate the impact of the suggested ban on Grade 4 vehicles and the retirement of older vehicles.

APPENDIX

Tables A1 and A2 present the remote sensing emission limits for in-use economy cars and passenger vehicles in South Korea.

Table A1. Remote sensing limits for economy cars (engine displacement <1,000 cc).

Manufacture year	Gasoline			LPG, CNG		
	CO (%)	HC (ppm)	NO_x (ppm)	CO (%)	HC (ppm)	NO_x (ppm)
Up to December 31, 1997	12.60	3,270	6,330	16.38	4,230	7,590
January 1, 1998 to December 31, 2000	7.20	1,170	5,400	9.36	1,500	6,480
January 1, 2001 to December 31, 2003	3.60	630	4,920	4.68	810	5,880
January 1, 2004 and newer	3.00	540	3,720	3.90	690	4,470

Table A2. Remote sensing limits for passenger vehicles (engine displacement >= 1,000 cc).

Manufacture year	Vehicle weight (kg)	Gasoline			LPG, CNG		
		CO (%)	HC (ppm)	NOx (ppm)	CO (%)	HC (ppm)	NOx (ppm)
January 1, 1988 to December 31, 1997	Up to 1000	5.49	630	5,400	7.14	819	6,480
	1000–1,200	4.41	510	4,320	5.73	663	5,184
	1200–1,400	3.63	420	3,570	4.71	546	4,284
	1400–1600	3.24	390	3,150	4.20	507	3,780
	1600 -1800	2.82	360	2,760	3.66	468	3,312
	1800–2000	2.61	330	2,520	3.39	429	3,024
	2000 and up	2.37	300	2,280	3.09	390	2,736
January 1, 1998 to December 30, 2000	Up to 1000	3.00	540	4,200	3.90	702	5,040
	1000–1,200	2.43	450	3,360	3.15	585	4,032
	1200–1,400	2.01	360	2,790	2.61	468	3,348
	1400–1600	1.80	330	2,460	2.34	429	2,952
	1600–1800	1.59	300	2,160	2.07	390	2,592
	1800–2000	1.47	270	1,980	1.92	351	2,376
	2000 and up	1.35	240	1,800	1.77	312	2,160
January 1, 2001 to December 30, 2005 (for LPG: January 1, 2001 to December 31, 2003)	Up to 1000	2.31	420	3,300	3.00	540	3,960
	1000 ~ 1,200	1.86	330	2,610	2.43	420	3,120
	1200 ~ 1,400	1.56	300	2,160	2.04	360	2,580
	1400 ~1600	1.38	270	1,890	1.80	330	2,190
	1600 ~ 1800	1.23	240	1,650	1.59	300	1,920
	1800 ~ 2000	1.14	210	1,500	1.47	270	1,740
	2000 and up	1.05	180	1,350	1.38	240	1,590
January 1, 2006 and newer (for LPG: January 1, 2004 and newer)	Up to 1000	2.31	420	3,090	3.00	540	3,720
	1000 ~ 1,200	1.86	330	2,490	2.43	420	3,000
	1200 ~ 1,400	1.56	300	2,070	2.04	390	2,490
	1400 ~1600	1.38	270	1,830	1.80	360	2,190
	1600 ~ 1800	1.23	240	1,590	1.59	300	1,920
	1800 ~ 2000	1.14	210	1,470	1.47	270	1,770
	2000 and up	1.05	180	1,320	1.38	240	1,590

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TRUE—The Real Urban Emissions Initiative
FIA Foundation, 60 Trafalgar Square, London WC2N 5DS, United Kingdom
For more information contact: **true@fiafoundation.org**
@TRUE_Emissions
www.trueinitiative.org