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WORLDWIDE USE OF REMOTE SENSING TO MEASURE MOTOR VEHICLE EMISSIONS

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INTRODUCTION

Development and use of remote vehicle emissions sensing has been growing in recent years. Early systems were pioneered by the University of Denver, funded initially by the Colorado Office of Energy Conservation and later by the California Air Resources Board (CARB) in the late 1980s. In the past decade, use of remote sensing has increased dramatically, especially in China.

Vehicle remote sensing technologies are emission-measurement systems that do not physically interact with the vehicle undergoing testing. Unlike testing using chassis dynamometers or portable emission measurement system (PEMS), where vehicle tailpipe emissions are directly measured, remote sensing measures pollutant concentrations in a vehicle's exhaust plume via spectroscopy as the vehicle drives through a light beam or, alternatively, extracts a sample from the exhaust plume to measure with pollutant analyzers. The first method is much more prevalent and is the primary focus of this paper. Throughout this paper we refer to the first method as "open path" remote sensing and the second as "extractive" remote sensing.

This paper details the current state of remote sensing technology, research, and deployment around the world, with a particular focus on evaluating barriers to its widespread deployment.

APPLICATIONS OF REMOTE SENSING DATA

Conceptually, remote sensing technology is in certain respects the opposite of laboratory and PEMS testing (see Figure 1). Laboratory and PEMS testing can collect massive amounts of emissions data on a single vehicle, but the testing is too time-consuming and expensive to perform on large numbers of vehicles. The snapshot of the exhaust plume content collected by open path remote sensing from a passing vehicle is equivalent to about one second's worth of emissions data,[1] but thousands of vehicles can be measured in a single day. Combined with the nonintrusive nature of remote sensing, as the vehicle does not detect that it is being tested, remote sensing is a particularly suitable solution for market surveillance. With enough measurements, remote sensing can be used to statistically quantify the emissions of individual vehicle models, evaluate the impacts of environmental and driving conditions, monitor older as well as newer vehicles, and track the effects of aging, deterioration, malfunctions, and recalls.

Remote sensing is potentially the best option for:

» Determination of granular fleetwide emissions factors to assist local governments in policymaking decisions, such as the establishment of vehicle restriction measures such as low-emissions zones, or vehicle bans, or the development of vehicle scrappage and renewal programs.

» Development of emissions factors to use as inputs in determining emissions inventories.

» Monitoring of overall fleet emission trends.

» Identification of high-emitting vehicle groups for market surveillance and follow-up regulatory compliance activities.

» Utilization of real-world vehicle emissions data to inform new customer purchase decisions.

1 Certain extractive remote sensing techniques may collect hundreds of seconds of data while gathering data on fewer vehicles per day.

» Identification of individual low-emitting vehicles, for a "clean screen" program whereby properly functioning vehicles can bypass annual technical inspections.[2]

» Identification of individual high-emitting vehicles for triggering early technical inspections or for tampering detection.

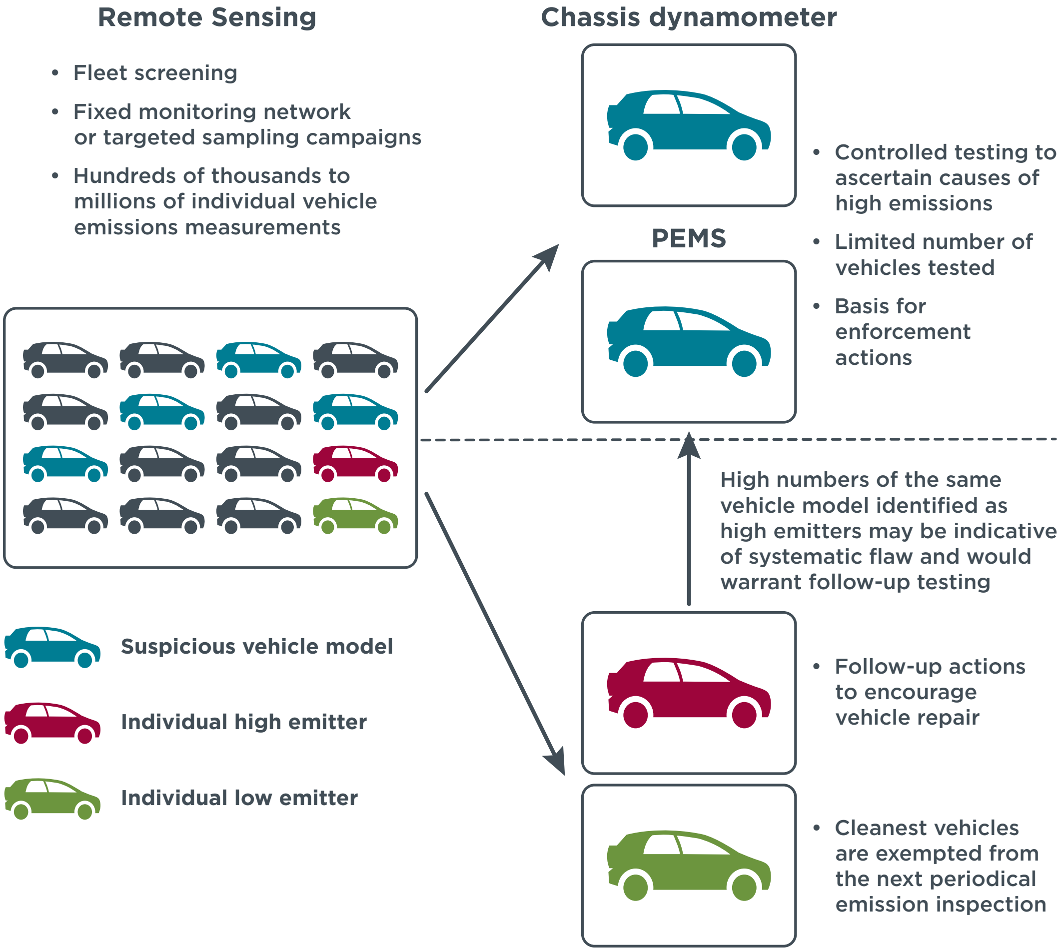

Figure 1: Possible applications of vehicle remote sensing in an enhanced vehicle emissions control program.

REMOTE SENSING EMISSIONS MEASUREMENT METHODS

The two main types of remote sensing technologies are described below.

Open path systems (see Figure 2): A light source and light detector are placed either at the side of or above a roadway, and the light source is reflected back by a mirror or reflective strip on the other side. The light absorbed by the exhaust plume as the light passes through is measured and correlated to the concentration of certain pollutants in the exhaust plume. The pollutant concentration as measured before the vehicle crosses the light beam is taken as background pollution and subtracted from the measurement. The system also includes speed and acceleration detectors and a license plate camera. All systems currently use infrared and ultraviolet light sources through arc lamp, such as xenon, or lasers. The use of lasers as the light source can increase the sampling rate

2 The ability to identify individual vehicle emissions could also be used in the future to identify and allow clean vehicles to enter a low-emission zone without charge.

along an individual exhaust plume from about 100 times per second to more than 10,000 times per second, potentially improving speed and accuracy.[3]

Either light source can theoretically be used in either configuration (Figure 2), although it is more common for the overhead system to employ a laser light source and the cross-road system to employ an arc lamp source. Overhead systems work similarly to cross-road systems and are capable of conducting measurements at sites with multiple lanes as well as collecting measurements from any vehicle independently of exhaust stack height. Cross-road systems must be positioned in line with the height of the exhaust stack.

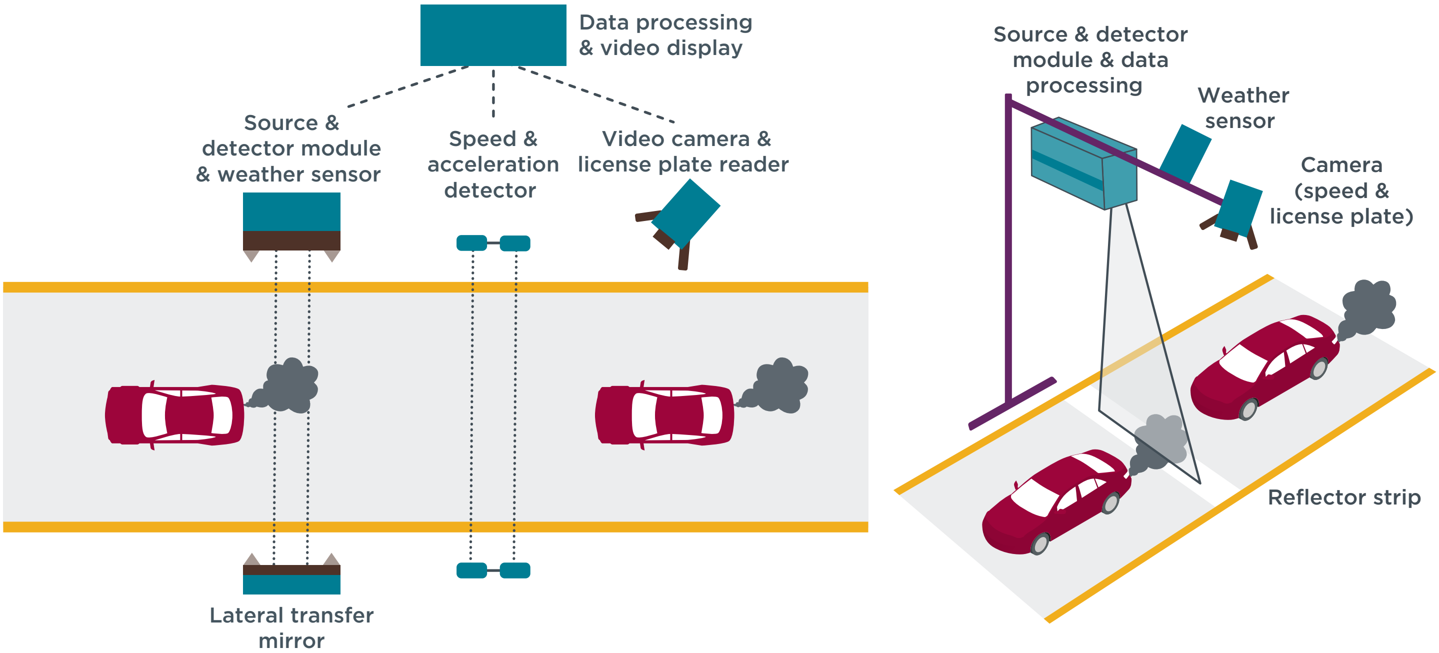

Figure 2: Schematic setup of the three units of the remote sensing device. Left, setup for cross-road remote sensing: the light source with the reflecting mirror at the other side of the road and the light detector, the speed and acceleration detectors, and the plate number recorder. Right, setup for top-down remote sensing system.

Note: Figure modified from Jens Borken-Kleefeld and Tim Dallmann, Remote Sensing of Motor Vehicle Exhaust Emissions (ICCT, February 2018), https://www.theicct.org/sites/default/files/publications/Remote-sensing-emissions_ICCT-White-Paper_01022018_vF_rev.pdf.

Extractive systems (Figure 3a and Figure 3b): Extractive remote sensing captures a portion of the target vehicle exhaust plume and directs that exhaust to pollutant analyzers to measure exhaust concentrations. An advantage is that the precision of the pollutant measurement is limited only by the complexity of the analyzers. However, extractive remote sensing systems can measure fewer vehicles in a given amount of time than open path systems, depending on the sampling technique selected.

3 Note that the laser's faster **exhaust** sampling rate may not yield useful improvements **of the vehicle fleet sampling rate** if remote sensing devices using arc lamps are fast enough to measure every vehicle that goes by.

Multiple techniques have been devised for capturing the exhaust, including:

1. Exhaust plume chaser (Figure 3a): A vehicle equipped with on-board emission analyzers chases vehicles while sampling the air behind them. A portion of the target vehicle exhaust plume is captured using a sampling line with its inlet on the exterior of the chase vehicle. This exhaust sample is routed to pollutant analyzers to measure exhaust concentrations.

2. Stationary air sampling (Figure 3b): The air in the vicinity of the exhaust's plume is actively aspirated. The measurement method is similar to the plume chaser, except that target vehicles drive past a fixed sampling location with sampling inlets placed in close proximity to the tailpipes/exhaust stacks of passing vehicles. The schematic in Figure 3b is a stationary air sampling system optimized for heavy-duty vehicles.

Figure 3a: Schematic setup of a plume chaser installed in vehicle measuring the exhaust emissions from the truck in front

Figure 3b: Schematic setup of a stationary air sampling system.

REMOTE SENSING MANUFACTURERS AND CAPABILITIES

The first open path cross-road arc lamp systems were pioneered by Gary Bishop and Donald Stedman of the University of Denver, funded initially by the Colorado Office of Energy Conservation and later by the California Air Resources Board in the late 1980s.[4] The original system, called the Fuel Efficiency Automotive Test (FEAT), was used to identify gasoline vehicles with high carbon monoxide (CO) emissions for repair, with the goal of both reducing in-use emissions and improving fuel efficiency. The systems were later commercialized by Envirotest and more recently by OPUS Group under the brand AccuScan.[5] The RSD 5000 is the latest remote sensing device from OPUS. It adds nitrogen dioxide (NO_2) to pollutants detected by the earlier RS 4600 device—nitrogen monoxide (NO), CO, carbon dioxide (CO_2),[6] hydrocarbons (HC), and opacity. While laser-based analyzers have been used for 20 years for on-road remote sensing,[7] a relatively recent innovation is the EDAR instrument commercialized by HEAT. This system uses a laser light source along with reflective strips placed in or on the road surface to enable top-down open path remote sensing. In addition, the EDAR system has the capability to scan a two-dimensional image of the exhaust plume. This has the potential to allow for an absolute measurement of each pollutant, as compared with measuring each pollutant as a ratio to CO_2. This particular laser-based system also has the ability to measure exhaust gas temperature.

4 Donald H. Stedman et al., "On-Road CO Remote Sensing in the Los Angeles Basin" (California Air Resources Board, 1989), https://ww3.arb.ca.gov/research/apr/past/a932-189.pdf.

5 Envirotest is now a subsidiary of OPUS providing testing services in the US while the operational hub in Europe is Opus Remote Sensing Europe (OpusRSE) in Madrid.

6 Note that while open path remote sensing measures CO_2 absorption, it is not necessarily able to quantify CO_2 emissions or fuel consumption. Typically the CO_2 value is used so that the other pollutants can be reported on a fuel-specific basis.

7 D.D. Nelson, M.S. Zahniser, J.B. McManus, C.E. Kolb, J.L. Jiménez, "A Tunable Diode Laser System for the Remote Sensing of On-Road Vehicle Emissions," *Applied Physics B* 67, no. 4 (October 1, 1998): 433–41, https://doi.org/10.1007/s003400050527.

While China started using remote sensing much later than the United States, Chinese authorities now test far more vehicles with remote sensing than any other country. Domestic manufacturers have developed to supply this market. These manufacturers include Environmental Technology Consultants (ETC) in Hong Kong, which makes a battery-powered portable arc lamp system,[8] and Dopler,[9] which offers roadside and overhead laser-light systems in China. Anhui Baolong[10] has an overhead arc lamp system installed in many locations in China.[11] Note that the overhead remote sensing equipment from Dopler and Baolong monitor CO, CO_2, HC, and NO, but not NO_2.

Extractive remote sensing systems are less widely available than open path systems. While there are no commercialized systems readily available on the market, regulatory and academic researchers have created their own systems. Researchers from the University of California, Berkeley, have used the extractive measurement technique to characterize the benefits of various emissions control technologies for trucks in the Port of Oakland.[12] CARB has developed and used a system called the Portable Emissions Acquisition System (PEAQS).[13] PEAQS captures a portion of the emissions from passing heavy-duty vehicles and calculates a fuel-specific emissions snapshot, or the amount of pollutant per unit of fuel burned, for total NO_x and black carbon, which is a large fraction of diesel particulate emissions. The University of Denver had earlier developed a similar principle, the On-road Heavy-duty Monitoring System (OHMS), that used a portable shed to improve the capture and analysis of fuel-specific emissions.[14] In Europe, the University of Münster[15] and the Czech Technical University[16] have developed stationary extractive sampling systems that capture a portion of the exhaust plume of passing vehicles.

CARB has also developed a plume chasing system. The agency equipped a zero-emission vehicle with plume-chasing capabilities to measure CO, NO_x, and particulate matter (PM) from light-duty gasoline vehicles as well as heavy-duty diesel trucks.[17] The University Heidelberg developed a plume chaser to identify trucks that use illegal systems to deactivate NO_x emission controls.[18] The University of Birmingham developed a special configuration of its Mobile Air Monitoring Laboratory (MAML) operated as a

8 "Remote Sensing System," ETC Remote sensing system, accessed April 3, 2019, http://etc-rs.com/product.html.

9 "多普勒环保科技有限公司," [Dopler Environmental Technology Co., Ltd.], Dopler Eco Technologies Co. Ltd., accessed April 3, 2019, http://www.dopler.com.cn/productsd.php?tid=3&id=49.

10 "Baolong Dedicated to Vehicle Emissions Remote Sensing for Clean Air," Tsinghua Holdings, accessed April 3, 2019, http://subsites.chinadaily.com.cn/thhc/2017-08/21/c_100754.htm.

11 Other Chinese remote-sensing suppliers are Nanjing Xinyuanjian, Beijing Huaqing, Changsha Shijie, Anhui Qingyu, Hebei Xianhe, Guangzhou Yunjing, Tianjin Shengwei, Tianjin Tongyang, Zhejiang Univ. Mingquan, Runcheng Tech, Shenzhen Anche, Shantou Shengfei'er and Dongruan Group.

12 Chelsea V. Preble et al., "Effects of Particle Filters and Selective Catalytic Reduction on Heavy-Duty Diesel Drayage Truck Emissions at the Port of Oakland," *Environmental Science & Technology* 49, no. 14 (July 21, 2015): 8864–71, https://doi.org/10.1021/acs.est.5b01117.

13 Jeremy D. Smith et al., "Quantification of HD In-Use Vehicles Using the Portable Emissions AcQuisition System (PEAQS)" (28th CRC Real world emissions workshop: California Air Resources Board, March 18, 2018), https://www.nctcog.org/nctcg/media/Transportation/Present/JeremySmith_CARBCRC_Presentation.pdf.

14 Gary A. Bishop and Molly J. Haugen, "Investigate the Durability of Diesel Engine Emission Controls," (University of Denver, March 2018), http://www.feat.biochem.du.edu/assets/reports/DU_CARB_OHMS_Final_Report_v8.pdf.

15 Christian Peitzmeier et al., "Real-World Vehicle Emissions as Measured by in Situ Analysis of Exhaust Plumes," *Environmental Science and Pollution Research* 24, no. 29 (October 2017): 23279–89, https://doi.org/10.1007/s11356-017-9941-1.

16 Michal Vojtíšek, Jan Skácel, and Vít Beránek, "Roadside Measurement of PM/PN Emissions from Individual Vehicles in Prague," 2018, 23.

17 Seong Suk Park et al., "Emission Factors for High-Emitting Vehicles Based on On-Road Measurements of Individual Vehicle Exhaust with a Mobile Measurement Platform," *Journal of the Air & Waste Management Association* 61, no. 10 (October 1, 2011): 1046–56, https://doi.org/10.1080/10473289.2011.595981.

18 D. Pöhler and T. Engel, "Bestimmung von LKW NO_x Emissionen [Real Driving Emissions] Auf Tiroler Autobahnen Und Potenziellen Abgasmanipulationen" [Determination of truck real driving NO_x emissions on Tyrolean motorways and potential emissions manipulation] (Institut für Umweltphysik, Universität Heidelberg, November 5, 2018).

car chaser called SNIFFER.[19] Other plume chaser solutions are being used for research applications in China,[20] Finland,[21] Slovenia,[22] and Mexico.[23]

Table 1 summarizes the main open path and extractive remote sensing technologies and manufacturers.

Table 1: Main remote sensing technologies and manufacturers.

Type	Position	Provider / Inventor	Equipment name	Measurement	Measures
Open path	Cross-road	University of Denver	FEAT	Arc lamp light beam with mirror reflector	CO, HC, CO_2, NO, NO_2, NH_3, SO_2, opacity
	Cross-road	Opus	RSD 4600 and older	Arc lamp light beam with mirror reflector	CO, HC, CO_2, NO, opacity
			RSD 5000		CO, HC, CO_2, NO, NO_2, NH_3, opacity
	Cross-road	Environmental Technology Consultants	R-series S650	Arc lamp light beam with mirror reflector	CO, CO_2, HC, NO, NO_2
	Cross-road; Overhead	Dopler Eco Technologies	DPL7000 Series	Laser light beam with mirror reflector	CO, CO_2, HC, NO, opacity
	Overhead	HEAT LLC	EDAR	Laser curtain with strip reflector	CO, total and speciated HC, CO_2, NO, NO_2, opacity
	Overhead	Anhui Baolong		Arc lamp light beam with mirror reflector	CO, CO_2, HC, NO, opacity
Extractive	Overhead sampling	University of California, Berkeley		Exhaust plume sample	CH_4, NO, NO_2, NH_3 BC, PM, PN, PN size,
	Overhead sampling	CARB	Portable Emissions Acquisition System (PEAQS)	Exhaust plume sample	Black carbon and NO_x
	Overhead sampling in Shed	University of Denver	OHMS	Exhaust plume sample	CO, CO_2, HC, NO, NO_2, N_2O, PM, PN, Black Carbon
	Roadside sampling	Czech Technical University		Exhaust plume sample	CO, CO_2, NO_x, PM, PN
	Roadside sampling	University of Münster		Exhaust plume sample	NO_x, CO_2, PN
	Plume chaser	University of Heidelberg	ICAD	Exhaust plume sample	NO, NO_2, CO_2
	Plume chaser	University of Birmingham	SNIFFER	Exhaust plume sample	NO, NO_2, CO_2
	Plume chaser	CARB	Mobile Measurement Platform (MMP)	Exhaust plume sample	CO, CO_2, HC, NO_x, PM, PN, Black Carbon

19 Karl Ropkins et al., "Evaluation of EDAR Vehicle Emissions Remote Sensing Technology," *Science of The Total Environment* 609 (December 2017): 1464–74, https://doi.org/10.1016/j.scitotenv.2017.07.137.

20 Xing Wang et al., "On-Road Diesel Vehicle Emission Factors for Nitrogen Oxides and Black Carbon in Two Chinese Cities," *Atmospheric Environment* 46 (January 1, 2012): 45–55, https://doi.org/10.1016/j.atmosenv.2011.10.033.

21 Liisa Pirjola et al., "Physical and Chemical Characterization of Real-World Particle Number and Mass Emissions from City Buses in Finland," *Environmental Science & Technology* 50, no. 1 (January 5, 2016): 294–304, https://doi.org/10.1021/acs.est.5b04105.

22 I. Ježek et al., "Black Carbon, Particle Number Concentration and Nitrogen Oxide Emission Factors of Random In-Use Vehicles Measured with the on-Road Chasing Method," *Atmospheric Chemistry and Physics* 15, no. 19 (October 5, 2015): 11011–26, https://doi.org/10.5194/acp-15-11011-2015.

23 Miguel Zavala et al., "Emission Factors of Black Carbon and Co-Pollutants from Diesel Vehicles in Mexico City," *Atmospheric Chemistry and Physics* 17, no. 24 (December 22, 2017): 15293–305, https://doi.org/10.5194/acp-17-15293-2017.

METHODOLOGY

To detail the current state of remote sensing technology, research, and deployment around the world, information on worldwide remote sensing activities was gathered. The information comes mainly from the results of a survey we initiated in September 2018 and was supplemented by additional information to which the ICCT has access, such as in-house databases and published literature.

The ICCT sent surveys to all organizations that we were aware might be working on remote sensing around the world. This included remote sensing equipment providers, researchers, and city, state, and country governments and authorities. All 28 questionnaires were completed and returned. In some cases, surveys were followed up by email or phone interviews to clarify responses. The survey responses included remote sensing technologies used, purposes of the testing, pollutants measured, types of vehicles targeted, number of vehicles tested, cities in which testing was conducted, testing conditions, vehicle information collected, and current challenges for the use of remote sensing (see detailed survey questions in Appendix A). We asked survey respondents to focus on remote sensing work since 2010 to capture the most recent developments.

WORLDWIDE REMOTE SENSING SUMMARY

DATA COLLECTION LOCATIONS AND ACTIVITIES

Figure 4 presents countries where remote sensing data collection has taken place since 2010 based on our findings. Data has been collected from all continents except Antarctica, with more than 1 million measurements per year collected in China, the United States, Hong Kong, and Korea, and more than 1 million measurements since 2010 in India. In Europe, data collection activities have been mostly in western countries—with more than 1 million measurements since 2010 in Spain—and northern countries. There also have been a few activities in Bulgaria, the Czech Republic, and Slovenia. Ghana is the only African country were remote sensing was found.

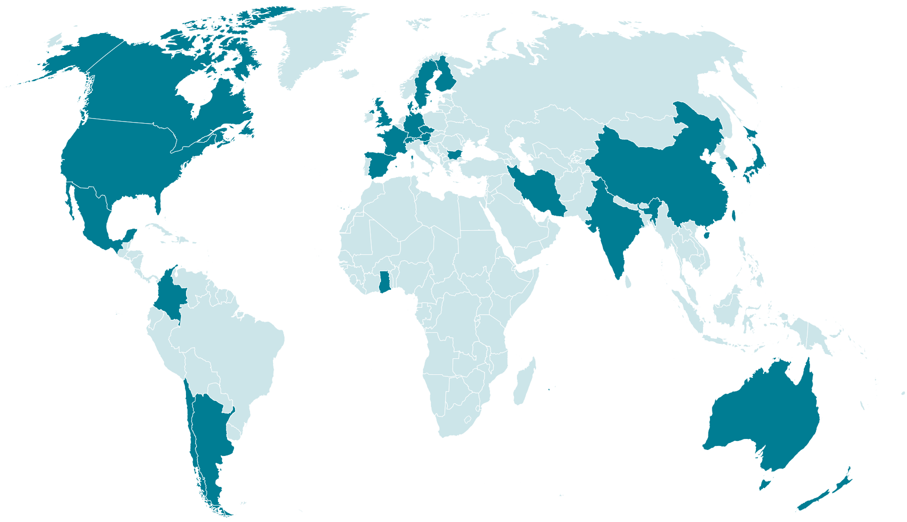

Figure 4: Countries where remote sensing has been used since 2010 in dark blue.

Table 2 presents an overview by country that includes the remote sensing technology used, the types of vehicles measured, the application that was the focus of the work, and the range of individual measurements since 2010.

Table 2: Overview of the different remote sensing technologies, type of vehicles measured, and programs that took place in different countries since 2010.

Country	Technology				Type of vehicles measured					Use of remote-sensing					Number of individual measurements since 2010
Argentina	C				PC	LCV	HDV	MC			MO				10,000 - 100,000
Australia	C				PC	LCV	HDV			R	MO				10,000 - 100,000
Austria	C				PC	LCV	HDV			R	MO	H			10,000 - 100,000
Bulgaria	C				PC	LCV	HDV	MC			MO	H			10,000 - 100,000
Canada	C	O	A		PC	LCV	HDV			R	MO	H		MS	10,000 - 100,000
Chile	C				PC	LCV	HDV	MC			MO				10,000 - 100,000
China	C	O		S	PC	LCV	HDV			R		H			>1,000,000
Colombia	C				PC	LCV	HDV	MC			MO				10,000 - 100,000
Czech Republic			A		PC	LCV	HDV	MC	OFF	R					10,000 - 100,000
Denmark	C				PC	LCV	HDV			R	MO	H			10,000 - 100,000
Finland				S			HDV			R					<10,000
France	C	O			PC	LCV	HDV	MC		R	MO				100,000 - 1,000,000
Germany	C		A	S	PC	LCV	HDV	MC		R	MO	H		MS	10,000 - 100,000
Ghana	C				PC	LCV	HDV	MC		R	MO				10,000 - 100,000
Hong Kong	C				PC	LCV	HDV			R	MO	H		MS	>1,000,000
India	C				PC	LCV	HDV	MC		R	MO				>1,000,000
Iran	C				PC	LCV	HDV			R	MO	H			10,000 - 100,000
Japan	C				PC	LCV	HDV	MC			MO				100,000 - 1,000,000
Korea	C				PC							H			>1,000,000
Mexico	C		A	S	PC	LCV	HDV	MC		R	MO	H	L		100,000 - 1,000,000
New Zealand	C				PC	LCV	HDV								100,000 - 1,000,000
Slovenia				S	PC	LCV	HDV			R					<10,000
Spain	C				PC	LCV	HDV	MC		R	MO	H			>1,000,000
Sweden	C		A		PC	LCV	HDV			R	MO				10,000 - 100,000
Switzerland	C				PC	LCV	HDV	MC		R	MO			MS	100,000 - 1,000,000
UK	C	O		S	PC	LCV	HDV	MC		R	MO			MS	100,000 - 1,000,000
USA	C	O	A	S	PC	LCV	HDV	MC	OFF	R	MO	H	L	MS	>1,000,000

C: Cross-road (open path) system
O: Overhead (open path) system
A: Extractive air sampling at a fixed location
S: Extractive air sampling from a car (plume chaser or sniffer)
PC: Passenger Car
LCV: Light-commercial vehicles, such as vans and pickup trucks
HDV: Heavy-duty vehicles
MC: Motorcycles
OFF: Off-road equipment
R: Research
MO: Monitoring of fleet emissions
H: Identification of individual high emitters for inspections or tampering
L: Identification of individual low emitters for a “clean screen” program
MS: Identifying groups of high emitting vehicles for market surveillance

POLLUTANTS MEASURED

The pollutants measured varied across the different remote sensing testing programs. The large majority measured nitrogen oxide (NO), HC, and CO_2 while more than half the programs measured NO_2, CO, and some measure of particulates. Total particulate matter based on opacity was the most commonly measured indicator of PM. Only campaigns using extractive techniques were able to measure black carbon, particulate number, and/or particulate size distribution. Other pollutants that were measured less frequently include ammonia (NH_3), sulfur dioxide (SO_2), nitrous oxide (N_2O), and methane (CH_4).

REMOTE SENSING TECHNOLOGY USE

Open path systems were by far the most widely and commonly used. Cross-road system configurations were used by 24 of the 27 countries in which remote sensing was deployed, while the overhead configuration was used in 5 of the 27. Five countries employed both configurations. Note that in the majority of cases, the cross-road systems used arc lamps, and the overhead systems, lasers. In China there were also overhead systems using arc lamps and cross-road systems with lasers.

Programs in seven countries used extractive sampling from a car, or exhaust plume chaser, and six used extractive sampling at a stationary location.

APPLICATIONS OF REMOTE SENSING DATA

Programs in more than three-quarters of countries used data from remote sensing to monitor fleet emissions. Slightly less than three-quarters of the countries used the data for research, such as determining emissions control deterioration rates and evaluating on-road performance of various vehicle technologies.

The next most-frequent use was identifying individual high- or low-emitting vehicles or groups of high-emitting vehicles. Programs in some U.S. states, China, Hong Kong, Korea, Canada, Mexico, Austria, Iran, Bulgaria, Germany, Spain, and Denmark used or planned to use remote sensing to identify individual high emitters for triggering early periodical technical Inspections or for tampering detection. Programs in the U.S. states of Virginia, Colorado, Ohio, and a recent project in the city of Nashville in Tennessee also used remote sensing to identify individual low emitters for a "clean screen" program, in which low-emitting vehicles are exempted from periodic technical inspections

Even less common were programs that used remote sensing to inform regulatory compliance. Programs in the United States,[24] Hong Kong, Canada, Switzerland, Germany, and the United Kingdom used remote sensing data to demonstrate the feasibility of identifying groups of high-emitting vehicles for market surveillance. High-emitting groups of vehicles identified by remote sensing can be subject to further compliance testing and potential enforcement actions.

CHINA: SUMMARY OF ACTIVITIES

Activities in China are of particular interest because of the extensive amount of remote sensing data that is being gathered and the potential applications for it. Remote sensing activities in China focused primarily on detection of individual high-emitting vehicles.[25] China has had the largest amount of remote sensing activity in the world since 2017 with close to 260 permanent open path systems recording about 38 million vehicle

24 Carl Fulper et al., "Remote Sensing Data (RSD) From the State of Colorado: 'Real-World' Emission Analysis on Newer Vehicles," 2017, 20.

25 Zifei Yang, "Remote-Sensing Regulation for Measuring Exhaust Pollutants from In-Use Diesel Vehicles in China" (ICCT, September 19, 2017), https://www.theicct.org/sites/default/files/publications/China-diesel-remote-sensing_ICCT-policy-update_19092017_vF.pdf.

measurements during 2017 alone.[26] Most of the remote sensing campaigns were in the Jing-Jin-Ji region, which is the densely populated area surrounding Beijing, Tianjin, and Hebei and used a total of 126 systems as of late 2017. Beijing, Tianjin, and 26 other cities in China were required to establish remote sensing platforms by the end of 2017.[27] At that time, 22 out of 31 provinces in China were using remote sensing (detailed in Appendix B). More recently, Sichuan province installed remote sensing units in the city of Chengdu.[28] According to the Three-Year Action Plan on Winning the Battle for Blue Sky, China's State Council put in place a requirement to extend the establishment of remote sensing platforms in the Jing-Jin-Ji area to the other key regions of the Yangtze River Delta and Fen-Wei Plain by the end of 2018.[29] By the end of 2018, more than 560 remote sensing units were in active use across China in 23 provinces.

Figure 5 shows the locations of remote sensing activities in China as of late 2018. Appendix B details the number of measurements in 2017 by province and whether select cities are subject to mandatory monitoring.

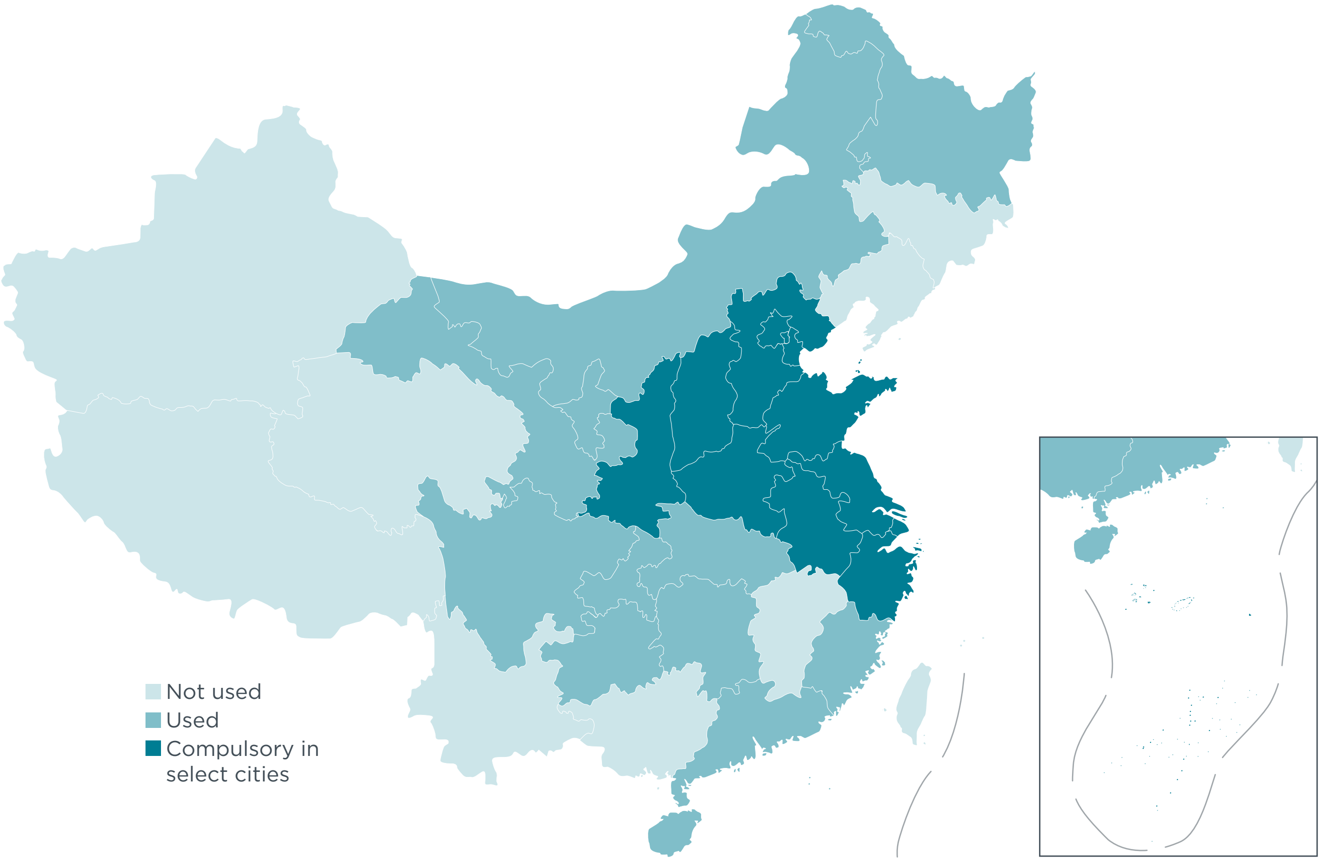

Figure 5: Location of remote sensing activities across China by the end of 2018. More information can be found in Appendix B.

26 MEE, "China Vehicle Environmental Management Annual Report 2018," 2018, http://www.vecc.org.cn/180601/1-1P601164953.pdf.

27 MEE, "关于印发《京津冀及周边地区2017年大气污染防治工作方案》的通知," [2017 Jing-Jin-Ji Air Pollution Prevention and Control Plan], March 23, 2017, http://dqhj.mee.gov.cn/dtxx/201703/t20170323_408663.shtml.

28 Chengdu EPB, "成都市机动车遥感监测平台及 '黑烟车'抓拍系统介绍," [Chengdu Motor Vehicle Remote Sensing Monitoring Platform and 'Black Smoke Vehicle' Capture System], 2019, http://www.move2019.org/assets/doc/presentation/13%20D2A%20%E6%88%90%E9%83%BD%E9%BB%91%E7%83%9F%E8%BD%A6%E4%B8%8E%E9%81%A5%E6%84%9FV1.pdf.

29 China State Council, "国务院关于印发打赢蓝天保卫战三年行动计划的通知（国发〔2018〕22号," [Three-Year Action Plan on Winning the Battle for Blue Sky], June 27, 2018, http://www.gov.cn/zhengce/content/2018-07/03/content_5303158.htm.

UNITED STATES: SUMMARY OF ACTIVITIES

Remote sensing activities in the United States are also significant. The University of Denver was an early pioneer in remote sensing activities with the FEAT system, and U.S.-based organizations have developed a number of measurement techniques using both open path and extractive sampling, including OPUS, EDAR, OHMS, and PEAQS.

Remote sensing campaigns have been conducted in 19 states and Washington, DC, as illustrated in Figure 6 and detailed in Appendix C. The figure shows which U.S. states use remote sensing, differentiated by program objectives. Currently, the most active states on remote sensing are California, using open path and extractive sampling, and Colorado and Virginia, using the open path method. Each state is gathering several million remote sensing measurements per year.

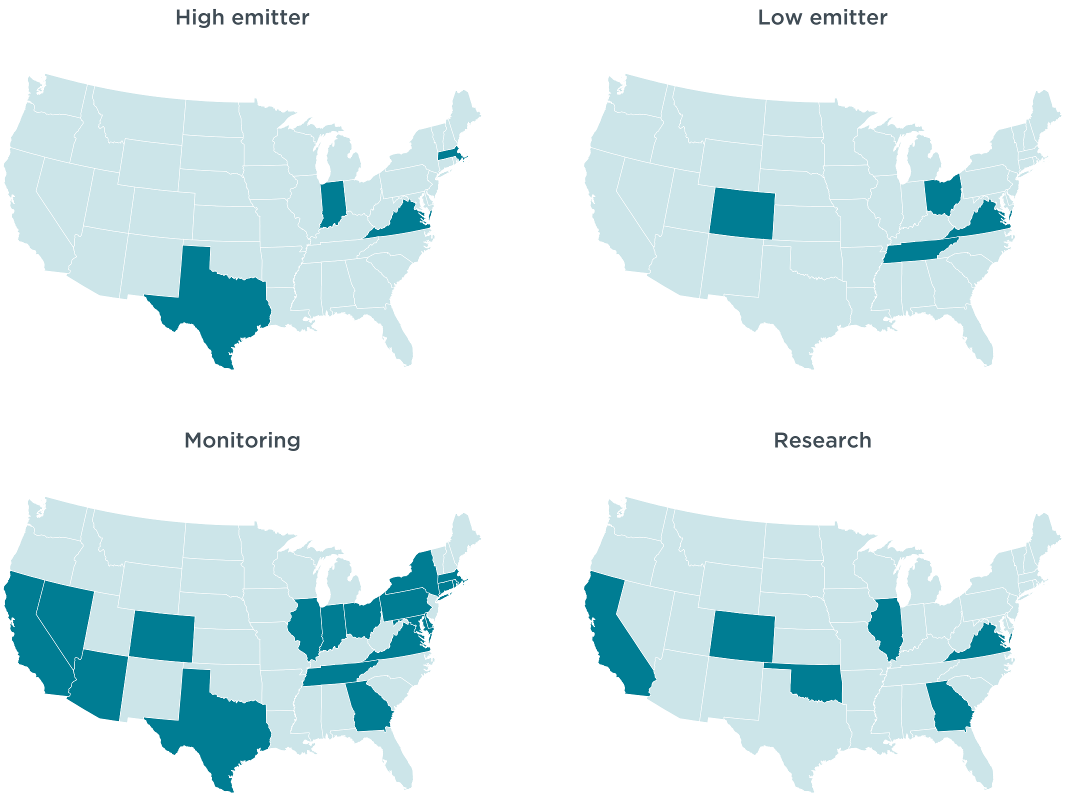

Figure 6: Map of U.S. states using remote sensing, by program use. More information can be found in Appendix C.

EUROPE: SUMMARY OF ACTIVITES

While remote sensing in Europe started in the early 1990s for research purposes in Sweden[30] and the United Kingdom, Europe has historically lagged behind China and the United States in extensively deploying and pioneering new uses of remote sensing. This has recently changed, and Western Europe is rapidly accelerating remote sensing measurements and expanding the uses of remote sensing. Since 2010, the vast majority of projects employed cross-road open path systems, although recent

30 Åke Sjödin, "On-Road Emission Performance of Late-Model TWC-Cars as Measured by Remote Sensing," *Air & Waste* 44, no. 4 (April 1994): 397–404, https://doi.org/10.1080/1073161X.1994.10467261.

projects in England, Scotland[31] and France[32] used the overhead configuration. In 2016, the Bundesamt für Umwelt (Switzerland's Federal Office for the Environment) funded the CONOX project to compile remote sensing findings from Switzerland, Sweden, the United Kingdom, France, and Spain since 2011 to build a European remote sensing database. In 2018, multiple reports were published leveraging the more than 700,000 measurements from the CONOX database.[33, 34, 35] The Real Urban Emissions initiative (TRUE) and others have continued to build up the database with hundreds of thousands of new records being taken in 2018 alone, including more than 100,000 in London and more than 200,000 in Paris.

Since 2017, Spain and Denmark have been running pilot programs using cross-road open path remote sensing to detect high-emitting vehicles. These programs specifically target the identification of trucks that use illegal devices to turn off their emission control systems, also known as Adblue killer or SCR emulator. In Germany, a plume chaser system was developed and demonstrated for use as a high-emitter screening tool. Researchers in Finland[36] and Slovenia[37] have used plume chasers to study emissions of vehicles including black carbon and fine particulates. In the United Kingdom, overhead open path remote sensing measurements were compared with results from PEMS and a plume chaser. The comparison showed that remote sensing provided a representative measurement of vehicle emissions under real-world conditions.[38] Research to further develop extractive road-side sampling was conducted in Germany and the Czech Republic. Finally, as Sofia, Bulgaria, began remote sensing, authorities deployed signs that instantly told drivers when their emissions were too high, generating headlines that helped to publicize the benefits of remote sensing.

CURRENT CHALLENGES FOR THE USE OF REMOTE SENSING

While remote sensing is already an extremely useful technology, there are still a number of barriers to maximizing its potential and achieving wider deployment. There are various challenges for hardware and measurement accuracy, such as road configuration, weather conditions, and lack of a tailpipe concentration estimate for lean combustion engines. Access to license plate and vehicle registration information is often limited, and data analysis methods have not been standardized. Other challenges include logistics for collecting data and cost. These barriers are described in more detail below.

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31 "Real Time Vehicle Emissions Pilot Project, March 2017," West Lothian Civic Centre, December 5, 2017, https://www.westlothian.gov.uk/article/23026/Real-Time-Vehicle-Emissions-pilot-project-March-2017.

32 "Paris Working with TRUE Initiative to Evaluate Real-World Vehicle Emissions," The Real Urban Emissions Initiative, accessed March 19, 2019, https://www.trueinitiative.org/blog/2018/september/paris-working-with-true-initiative-to-evaluate-real-world-vehicle-emissions?author=Tim+Dallmann.

33 Jens Borken-Kleefeld et al., "Comparing Emission Rates Derived from Remote Sensing with PEMS and Chassis Dynamometer Tests—CONOX Task 1 Report" (Federal Office for the Environment, Switzerland, May 2018), https://www.ivl.se/download/18.2aa26978160972788071cd7b/1529408235244/comparing-emission-rates-derived-from-remote-sensing-with-pems-and-chassis-dynamometer-tests-conox-task1-report.pdf.

34 Å Sjödin et al., "Real-Driving Emissions from Diesel Passenger Cars Measured by Remote Sensing and as Compared with PEMS and Chassis Dynamometer Measurements—CONOX Task 2 Report" (Federal Office for the Environment, Switzerland, May 2018), https://www.ivl.se/download/18.2aa26978160972788071cd79/1529407789751/real-driving-emissions-from-diesel-passengers-cars-measured-by-remote-sensing-and-as-compared-with-pems-and-chassis-dynamometer-measurements-conox-task-2-r.pdf.

35 Jens Borken-Kleefeld et al., "Contribution of Vehicle Remote Sensing to In-Service/Real Driving Emissions Monitoring—CONOX Task 3 Report" (Federal Office for the Environment, Switzerland, May 2018), https://www.ivl.se/download/18.2aa26978160972788071cd7b/1529408235244/comparing-emission-rates-derived-from-remote-sensing-with-pems-and-chassis-dynamometer-tests-conox-task1-report.pdf.

36 Pirjola et al., "Physical and Chemical Characterization of Real-World Particle Number and Mass Emissions from City Buses in Finland." Environmental Science & Technology, 50 (2016): 294-304 https://pubs.acs.org/doi/full/10.1021/acs.est.5b04105

37 Ježek et al., "Black Carbon, Particle Number Concentration and Nitrogen Oxide Emission Factors of Random in-Use Vehicles Measured with the on-Road Chasing Method." Atmospheric Chemistry and Physics, 15 (2015): 11011-11026 https://www.atmos-chem-phys.net/15/11011/2015/

38 Karl Ropkins et al., "Evaluation of EDAR Vehicle Emissions Remote Sensing Technology," Science of The Total Environment 609 (December 2017): 1464–74, https://doi.org/10.1016/j.scitotenv.2017.07.137.

Hardware and measurement

- Harsh weather conditions such as snow, rain, fog, and strong wind may increase the proportion of invalid records for open path systems.
- Congested traffic limits the rate of measured vehicles.
- Measuring on multi-lane roads using cross-road and extractive systems is difficult and is preferably done with the use of an overhead system.
- While open path systems have proven effective at determining significant decreases in PM emissions, such as from a diesel vehicle with or without diesel particulate filter, it is more challenging for these systems to determine absolute PM emissions, especially at lower emission rates. This limitation is important because particle number emissions could be high even when mass emissions are low.
- High vehicle speeds create a safety issue if staff are required to be on site and can increase the proportion of invalid records because of faster dilution of the exhaust plume.
- Estimation of tailpipe concentration for lean combustion engines, such as diesel engines, cannot be estimated accurately by open path systems,[39] as the exhaust dilution rate is unknown. This may complicate the use of remote-sensing to replace stationary emission inspection whose testing protocol usually define thresholds based on tailpipe concentration. Alternatively, these limits could be replaced by thresholds relative to fuel or CO_2.
- Most open path remote sensing technologies report pollutant measurements as a ratio relative to fuel or CO_2. Absolute measurement of emission rates, which are claimed to be available in some open path remote sensing technologies, would be preferred to measuring pollutants relative to fuel or CO_2.
- There is a lack of standardized validation testing for remote sensing technologies available on the market.
- Some permanent installations using fixed light-reflecting devices require regular monitoring and maintenance.[40] Also, not every manufacturer has developed permanent installations.

Data availability and analysis

- Automatic license-plate recognition is a well-developed technology but may still require the need for occasional manual data entry.
- In some countries, such as China, the license plate number alone is not sufficient to identify a vehicle. The license plate color code is also needed and increases the complexity of vehicle identification.
- Access to vehicle registration information is required to identify the vehicle specifications from the license plate. This access is usually controlled by local

39 The future addition of O_2 measurement to open path systems would solve this problem.
40 Some manufacturers provide an automated replacement of the light-reflecting device.

authorities, which may have restrictions regarding data access. Even when access to vehicle information is granted, approval may be time-consuming and costly.

» In most regions it is not possible to obtain real-time vehicle information, thereby limiting applications that would benefit from real-time emissions information.
» A critical amount of remote sensing data must be measured at different sites under different conditions to reach statistical confidence in the results.
» There is a lag between the time a new model is introduced for sale and the time when enough of the vehicles are on the road to generate sufficient data to analyze.
» Longitudinal data sets are needed for market surveillance and assessment of emissions technology deterioration, as well as repairs and recalls of individual vehicles.
» There is a lack of standardized data handling and analysis.
» There are numerous challenges relating to cleaning, storing, compiling, validating, and normalizing the large quantities of raw data that result from remote sensing campaigns.

Logistics and cost

» There is a lack of regulatory provisions and official guidance for remote sensing in some countries.
» Permits are needed to set up the equipment and may be difficult to obtain in certain countries.
» Road traffic-management issues can limit possible sampling sites and may require help from local authorities and police.
» The cost of deployment of remote sensing on a per-vehicle basis can be high, especially for short duration campaigns or extractive systems, depending on the technology used and the project scope.
» There are a limited number of commercial equipment providers of remote sensing except for China, limiting market competitiveness.
» There are three prevalent business models that remote sensing companies use—a pay-for-service model in which the company provides a turnkey project with little hands-on involvement by the customer, a leasing model in which the equipment is leased and the customer is trained to run the equipment in-house, and an equipment-purchase model in which the capital equipment is purchased and testing is conducted in-house. Not all service providers offer all three options. The pay-for-service model may result in higher long-term costs compared with a model in which the capital equipment is purchased and testing is conducted in-house.

CONCLUSIONS AND RECOMMENDATIONS

Remote sensing of vehicle emissions is being used in a number of countries around the world. Most of the applications have focused on research and overall fleet emission trends. In some countries, remote sensing is moving into identification of high-emitting vehicle groups for market surveillance and identification of individual high- and low-emitting vehicles to assist with periodic vehicle emission inspections. The United States and China are leaders in remote sensing deployment and are demonstrating how remote sensing can contribute to identification of and enforcement against high-emitting vehicles. Recently there has been a significant increase in the use of and interest in remote sensing in the European Union.

Still, the deployment of remote sensing is at a relatively early stage compared with the need to comprehensively track real-world emissions on a continuous and granular basis. There are multiple opportunities to increase the use of remote sensing data. Countries and regions should ideally explore ways to reduce barriers to remote sensing, such as improving equipment and data analysis, as well as decreasing the cost and addressing other logistical hurdles. Recommendations for ways to lower remote sensing barriers include:

1. Independent validation of the various technologies available on the market, to better understand the respective technologies and their strengths and limitations.
2. Development of national and international centralized databases on vehicles' registration data, accessible quickly and at low cost while respecting privacy concerns.
3. Continued development of open path technologies to allow unmanned operation to reduce staff safety issues, avoid interruption of traffic, and lower operating costs.[41]
4. Improvement of the durability and reduction of the maintenance cost of permanent installations.
5. Extending the scope of measured gases. It is particularly important to measure the oxygen-to-CO_2 ratio to accurately estimate tailpipe emissions concentration of lean combustion engines. Expanded and improved monitoring of particulate and NO_2 emissions is also important.
6. Further development of systems that can measure the absolute amount of pollutants in the exhaust plume, rather than measuring a fraction of the plume and calculating pollutant measurements relative to fuel or CO_2.
7. Combining open path and extractive sampling technologies in ways that complement each other and take advantage of the benefits of each.
8. Devising and improving methods to use real-world remote sensing to enhance emission factors used for air quality modeling and other applications and compare with emissions standards, such as converting fuel- or CO_2-specific emissions into distance-specific emissions.
9. Scaling up the amount of remote sensing and number of measurement sites to increase the proportion of the in-use fleet that is regularly measured.

41 Some systems are already developed for unmanned operation.

APPENDIX A: QUESTIONS OF THE SURVEY

1. Are you currently using remote-sensing (RS)?

- ☐ Yes
- ☐ No

2. If yes, for what purpose(s)? (check all that apply)

- ☐ Research activities
- ☐ Monitoring of fleet's emissions
- ☐ Identification of individual high emitters for triggering early periodical technical inspections

or for tampering detection?

- ☐ Identification of individual low emitters for a "clean screen" program?
- ☐ Identification of group of high emitting vehicles for market surveillance?

3. Which RS technology have you used? (check all that apply)

- ☐ Cross-road (open path) systems (e.g. FEAT, OPUS, ETC)
- ☐ Overhead (open path) systems (e.g. EDAR, ETC)
- ☐ Active air sampling at a fixed location (OHMS, PEAQS)
- ☐ Active air sampling from a car, also called exhaust plume chaser
- ☐ Other (Please specify)

4. Which pollutants have you measured with RS? (check all that apply)

- ☐ Nitrogen-monoxides (NO)
- ☐ Nitrogen-dioxides (NO_2)
- ☐ Total hydrocarbons (THC)
- ☐ Methane (CH_4)
- ☐ Carbon-monoxide (CO)
- ☐ Particulate Matter (PM)
- ☐ Particulate Number (PN)
- ☐ Ammonia (NH_3)
- ☐ Other (Please specify)

5. What vehicle type(s) are you targeting in your remote sensing applications (check all that apply)

- ☐ Passenger cars
- ☐ Light-commercial vehicles
- ☐ Heavy-duty vehicles (trucks, buses)
- ☐ Motorcycles
- ☐ Non-road vehicles (locomotives, ships, tractors, snowmobiles, etc.)
- ☐ Other (Please specify)

6. What software have you used for managing and analyzing RS data?

7. What is the current size of your RS database?

- ☐ < 1,000
- ☐ < 10,000
- ☐ < 100,000
- ☐ < 1,000,000
- ☐ > 1,000,000

8. How often do you conduct remote-sensing testing campaigns?

- ☐ Always (permanent installation)
- ☐ More than once a year
- ☐ Around once a year
- ☐ Less than once a year

9. What city or cities have you conducted remote sensing in since 2010?

10. Which information is typically available in your RS database for "emission information"? (check all that apply)

☐ NO/CO_2	☐ Total NO	☐ NO concentration	☐ Exhaust temperature
☐ HC/CO_2	☐ Total NO_2	☐ NO_2 concentration	☐ Other (Please specify)
☐ CO/CO_2	☐ Total HC	☐ HC concentration	
☐ PM/CO_2	☐ Total CO	☐ CO concentration	
☐ PN/CO_2	☐ Total PM	☐ PM concentration	
☐ NO_2/CO_2	☐ Total PN	☐ PN concentration	
☐ O_2/CO_2	☐ Total O_2	☐ O_2 concentration	
☐ NH_3/CO_2	☐ Total CO_2	☐ CO_2 concentration	
	☐ Total NH_3	☐ NH_3 concentration	

11. Which information is typically available in your RS database for "testing conditions?" (check all that apply)

☐ Date	☐ Site Latitude	☐ Ambient relative humidity
☐ Universal Time Clock offset	☐ Site Longitude	☐ Ambient pressure
☐ Vehicle speed	☐ Site Altitude	☐ Wind speed
☐ Vehicle acceleration	☐ Ambient temperature	☐ Wind direction
☐ Validity of the speed/ acceleration measurement	☐ Direction of the road	
☐ Road grade	☐ Vehicle specific power	
☐ Other (Please specify)		

12. Which information is typically available in your RS database "vehicle information?" (check all that apply)

☐ Date of registration	☐ Engine displacement	☐ Mass
☐ Category	☐ Type-approval CO_2 or fuel consumption	☐ License plate
☐ Fuel type	☐ Model name	☐ Mileage
☐ Emission standard	☐ Model year	☐ Emissions control
☐ Manufacturer	☐ Maximum power	☐ Powertrain technology
☐ Other (Please specify)		

13. In your opinion, what are the current challenges for the use of remote sensing for your activities?

APPENDIX B: CHINESE PROVINCES USING REMOTE-SENSING

Provinces using RS in 2018	Number of measurements in 2017	Compulsory in select cities in 2017	Compulsory in select cities in 2018
Anhui	170,064		✓
Beijing	12,161,900	✓	✓
Chongqing	104,000		
Fujian	3,032,145		
Gansu	7,127,362		
Guangdong	680,235		
Guizhou	320,900		
Hainan	4,368		
Hebei	4,635,126	✓	✓
Heilongjiang	910,000		
Henan	861,258	✓	✓
Hubei	598,000		
Hunan	131,200		
Inner Mongolia	153,962		
Jiangsu	1,951,000		✓
Ningxia	131,144		
Shandong	3,621,592	✓	✓
Shanghai	105,000		✓
Shaanxi	400,000		✓
Shanxi	48,719	✓	✓
Sichuan	– *		
Tianjin	950,000	✓	✓
Zhejiang	724,000		✓

*Sichuan began measuring in 2018.

APPENDIX C: REMOTE SENSING PROGRAMS IN U.S. STATES

States	Monitoring	Research	High emitter	Low emitter
Arizona	✓			
California	✓	✓		
Colorado	✓	✓		✓
Connecticut	✓			
DC	✓			
Delaware	✓			
Georgia	✓	✓		
Illinois	✓	✓		
Indiana	✓		✓	
Maryland	✓			
Massachusetts	✓		✓	
Nevada	✓			
New York	✓			
Ohio	✓			✓
Oklahoma		✓		
Pennsylvania	✓			
Rhode Island	✓			
Tennessee	✓			✓
Texas	✓		✓	
Virginia	✓	✓	✓	✓