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Technical considerations for choosing a metric for vehicle remote-sensing regulations

BACKGROUND

Motor vehicle emissions are a major source of air pollution in many megacities. Studies show that real-world emissions are often substantially higher than laboratory-certified levels when vehicles and engines are tested on a chassis or an engine dynamometer. Indeed, growing evidence indicates that chassis and engine dynamometer testing does not fully represent actual driving situations because of the limitations of driving cycles and test procedures, which allow for possible use of defeat devices or optimization of the vehicle for the test.[1]

There are a few real-world emissions measurement methods in use today. Among them are portable emissions measurement systems (PEMS) and remote sensing, and

1 Per Kågeson, *Cycle-beating and the EU test cycle for cars*, (European Federation for Transport and Environment: Brussels, 1998), http://www.transportenvironment.org/sites/te/files/media/T&E%2098-3_0.pdf; Giorgos Mellios, Stefan Hausberger, Mario Keller, Christos Samaras, Leonidas Ntziachristos, *Parameterisation of fuel consumption and CO_2 emissions of passenger cars and light commercial vehicles for modelling purposes*, (European Commission Joint Research Centre Technical Report EUR 24927 EN: Luxembourg, 2011), http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/22474/1/co2_report_jrc_format_final2.pdf; Dana Lowell, Fanta Kamakaté, *Urban off-cycle NO_x emissions from Euro IV/V trucks and buses*, (ICCT: Washington, DC, 2012), http://theicct.org/urban-cycle-nox-emissions-euro-ivv-trucks-and-buses; Yoann Bernard, John German, Aikaterini Kentroti, Rachel Muncrief, *Catching defeat devices: How systematic vehicle testing can determine the presence of suspicious emissions control strategies*, (ICCT: Washington, DC, 2019), https://theicct.org/publications/detecting-defeat-devices-201906.

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each has unique strengths and weaknesses.[2] PEMS, for example, can directly measure the on-road emissions of vehicles in broad, real-world driving conditions. But this technique is too time-consuming and expensive to be performed on a large number of vehicles. Remote sensing is a promising technology that measures exhaust emissions from on-road vehicles without interrupting traffic. Compared with PEMS, remote sensing can measure a large sample of vehicles in a short period of time at a far lower cost per vehicle. Further, it is difficult for vehicles to detect when they are being tested by remote sensing. However, unlike PEMS, which can measure a vehicle's emissions along several kilometers, remote sensing typically records a one-second snapshot of a vehicle's exhaust.

REMOTE SENSING IN REGULATION AND COMPLIANCE

While remote sensing has been widely used for research purposes since the 1990s, more recently, some countries have started to use it as a market surveillance tool to identify high-emitting vehicle groups and individual high emitters. The United States and China are leaders in remote sensing and are demonstrating how it can contribute to in-use compliance programs. In 2017, China's Ministry of Ecology and Environment released a national regulation for measuring pollutants from diesel vehicles using remote sensing. This is the first national-level remote-sensing regulation in the world. In it, emission limits on opacity, Ringelmann blackness, and nitrogen monoxide (NO) are set, and remote sensing is used to validate that vehicles are compliant with the standard. Specifically, the opacity and Ringelmann blackness limits are mandatory, while the NO concentration limit is used only for screening high-emitting vehicles. This is because remote sensing typically measures the ratio of concentration of the pollutant in the exhaust plume—e.g., NO to carbon dioxide (CO_2)—and there is not yet a legitimate way to accurately estimate NO concentration in tailpipe emissions from diesel vehicles. Thus, a major obstacle needs to be overcome before China and other countries can adopt an enforceable remote sensing NO emission concentration limit for diesel vehicles.

Still, an increasing number of governments are considering using remote sensing to enforce emission regulations for diesel vehicles. These include mainland China, Hong Kong, and South Korea. To improve the utility of remote sensing for vehicle in-use compliance programs, this paper explains the current lack of accuracy in estimating NO tailpipe concentrations in diesel vehicles and then discusses three options for choosing an alternative metric. Among the three options, we consider a fuel-specific metric to be the best approach for identifying high-emitters using available remote sensing technologies.

REMOTE SENSING BASICS

Broadly defined, remote-sensing technologies are emission-measurement systems that do not physically interact with the vehicles they test. The most common technique, called "open-path," uses absorption spectroscopy to measure pollutant concentrations in the exhaust plumes of in-use vehicles. A light source and detector are placed either beside or above a roadway. The instrument is oriented so that the light beam traverses

2 Yoann Bernard, Uwe Tietge, John German, Rachel Muncrief, *Determination of real-world emissions from passenger vehicles using remote sensing data*, (ICCT: Washington, DC, 2018), https://theicct.org/publications/real-world-emissions-using-remote-sensing-data.

the exhaust plumes of vehicles passing before being registered by the detector. Another technique is called "extractive" remote sensing. This method extracts a sample from the exhaust plume and measures it with lab-grade analyzers. Both methods estimate the concentration of pollutants relative to the concentration of CO_2 in the exhaust plume. Note that the different limitations and potential solutions described in this paper apply to both the "open-path" and "extractive" techniques.

Remote-sensing systems typically measure NO, carbon monoxide (CO), hydrocarbons (HC), and CO_2. Particulate matter (PM) emissions are indirectly derived from plume opacity. Nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ammonia (NH_3) emissions can also be measured using remote sensing.[3] Because the major pollutants have a similar dilution pattern in the air, their ratios to CO_2 can be considered sufficiently constant along the plume.

Emissions data is of limited value if it cannot be linked to information about the vehicle from which it originates. This includes how the vehicle is being operated at the time of the measurement. Remote-sensing systems therefore incorporate additional equipment to acquire some of this information. For example, a camera records an image of the vehicle's license plate number, which can be used to retrieve vehicle details such as make, model, fuel type, engine size, and emission standard from registration databases. Another device measures the speed and acceleration of the vehicle, which allows for estimation of the vehicle's engine load at the time of the emissions measurement. Finally, sensors measure ambient conditions such as wind, temperature, barometric pressure, and relative humidity.

APPLICATION AROUND THE WORLD

Remote-sensing technology has been widely used, with testing conducted in at least 27 countries. Programs in more than three-quarters of these 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 the on-road performance of various vehicle technologies. The next most-frequent use is for identifying individual high- or low-emitting vehicles or groups of high-emitting vehicles. Programs in some U.S. states, mainland China, Hong Kong, South Korea, Canada, Mexico, Austria, Iran, Bulgaria, Germany, Spain, and Denmark have used or plan to use remote sensing to identify individual high emitters. Such identification can be used to trigger early periodical technical inspection (PTI) and compliance actions, or to detect tampering.[4] Below are some examples of how remote sensing is used for motor vehicle emission control.

» In 2017, China created a national regulation for measuring emissions from diesel vehicles using remote sensing. It is the first national-level remote-sensing regulation in the world.[5] The standard replaced all local standards related to monitoring diesel

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3 Tim Dallmann, *Use of remote-sensing technology for vehicle emissions monitoring and control*, (ICCT: Washington, DC, 2018), http://www.theicct.org/publications/remote-sensing-briefing-dec2018.

4 Yoann Bernard, John German, Rachel Muncrief, *Worldwide use of remote sensing to measure motor vehicle emissions*, (ICCT: Washington, DC, 2019), http://www.theicct.org/publications/worldwide-use-remote-sensing-measure-motor-vehicle-emissions.

5 Zifei Yang, *Remote-sensing regulation for measuring exhaust pollutants from in-use diesel vehicles in China*, (ICCT: Washington, DC, 2018), http://www.theicct.org/publications/remote-sensing-regulation-measuring-exhaust-pollutants-use-diesel-vehicles-china.

exhaust emissions using remote sensing, and it applies to all diesel vehicles, including light-duty and heavy-duty vehicles. The regulation is a technical standard for test protocols with recommended limits for local agencies to follow if they currently have or decide to implement a remote-sensing program. This standard sets a limit for PM emissions through opacity and Ringelmann blackness (see Table 1). For NO, the limit is only used for screening high-emitting vehicles that are then subject to further inspection. A vehicle is considered non-compliant if it exceeds the limit for the same pollutant in two or more consecutive remote-sensing tests within 6 months. In cities that are implementing remote-sensing programs, vehicles that are found to be non-compliant with the opacity or Ringelmann blackness limits can be subject to a penalty and will be required to be repaired. The specifics depend on the region. For example, in Beijing, failure to pass remote-sensing standards will trigger a warning to the vehicle owner for immediate repair and subsequent confirmatory tests at an inspection and maintenance (I/M) facility. Owners receiving the warning are also given the opportunity to contest the test results. If the vehicle fails the confirmatory test after a repair, the owner is then subject to a penalty.

Table 1. Remote-sensing emission limits for diesel vehicles in China

Pollutant	Limits
Opacity*	30%
Ringelmann blackness**	Level I (20%)
NO***	1,500 parts per million (ppm)

Notes:
*Opacity is measured by the absorption percentage of green light (wavelength range 550 nanometers – 570 nanometers) going through the exhaust plume.
**Ringelmann blackness is an indicator of smoke density that compares the darkness of smoke with the Ringelmann scale. It has five levels of density. The levels are inferred from a grid of black lines on a white surface that, if viewed from a distance, merge into known shades of grey. Smoke Level 0 is represented by white, and Level 5 is represented by all black. Levels 1 (20%) to 4 (80%) are represented by 10-millimeter (mm) square grids drawn with 1-mm, 2.3-mm, 3.7-mm, and 5.5-mm-wide lines. Vehicle smoke is videotaped to determine its Ringelmann blackness.
***NO limit is only used for screening high-emitting vehicles.

» In Hong Kong, remote sensing has been used since 2014 as an enforcement tool for detecting high-emitting vehicles. But unlike the remote-sensing standard in mainland China, the regulation in Hong Kong only applies to gasoline and liquid petroleum gas (LPG) vehicles. Emission limits are set for NO, CO, and HC, in the unit of concentration. Two sets of remote-sensing equipment are placed with one-second distance between them.[6] A vehicle is considered non-compliant when emissions measured by both instruments exceed the established concentration limits. These limits were determined based on a large database of remote-sensing and chassis dynamometer tests (see the limits in Table 2).[7] The non-compliant vehicles are required to be repaired and tested at a designated test center within 12 working days. If not repaired, the vehicle license will be revoked and it will not be allowed on the road.

6 At 40 kilometers per hour, this would be about 10 meters.

7 Yuhan Huang, Bruce Organ, John L. Zhou, Nic C. Surawski, Guang Hong, Edward F.C. Chan, Yat Shing Yam, "Remote sensing of on-road vehicle emissions: Mechanism, applications and a case study from Hong Kong," *Atmospheric Environment* 182 (2018): 58–74. https://doi.org/10.1016/j.atmosenv.2018.03.035

Table 2. Remote-sensing emission limits for gasoline and LPG cars in Hong Kong

Emission Standard	NO (ppm)	CO(%)	HC (ppm)
Pre Euro	4,000	5	500
Euro 1	2,000	2	500
Euro 2	1,500	2	500
Euro 3	750	2	500
Euro 4	750	2	500
Euro 5	750	2	500
Euro 6	750	2	500

- In South Korea, remote sensing has been used to detect high-emitting vehicles since 2013, and 2–3 million vehicles per year are measured across 39 different locations. Only gasoline and LPG vehicles are subject to testing for HC, CO, and NO. The emission limits are set for tailpipe concentration, as well. When a vehicle is measured once as a high emitter, the owner receives a notice by mail, and it is suggested that the vehicle be checked. The second time the same vehicle is measured as a high emitter, the owner receives an order for improvement, The owner has to stop using the vehicle and get it repaired at a designated I/M facility within 15 days from the date of the order for improvement; otherwise, the owner will be subject to a fine. The cut-off point defining the high emitters found through remote-sensing measurements is defined as three times the standard limit applied during PTI.
- Remote sensing has been used in the United States for about 30 years. Although it was initially limited to research and fleet-emission monitoring, some states like Indiana, Massachusetts, Texas, and Virginia have introduced programs that seek to detect the worst-emitting vehicles and request their repair. If the vehicle's emissions under normal driving conditions are repeatedly above some defined cut-off points, the vehicle owner is notified. The cut-off points are higher for older vehicles and lower for newer vehicles, and they typically follow the tailpipe limit that applies during periodical inspection and maintenance under chassis dynamometer tests (i.e., IM240). Similar to Hong Kong and South Korea, none of the current remote-sensing programs in the United States are used to screen for high-emitting diesel vehicles. Some U.S. states also use remote sensing for its ability to identify individual low-emitting vehicles, called "clean screen" programs. Properly functioning vehicles measured with low emissions can be exempted from the next annual technical emissions inspection.
- In Europe, remote sensing is used for research activities, monitoring fleet emissions, and detecting vehicle tampering. There is currently no remote sensing program that supplements PTI.

In summary, the regulatory programs based on remote sensing in Hong Kong and South Korea only apply to gasoline and LPG vehicles, and the diesel remote-sensing regulation in China only includes NO limits to screen for high emitters.

OBSTACLES WHEN MEASURING DIESEL VEHICLE TAILPIPE POLLUTANT CONCENTRATIONS USING REMOTE SENSING

As discussed above, there is no mandatory NO limit for any diesel vehicle enforced by an in-use remote-sensing program in the world. This is because measuring the tailpipe concentration of pollutants using the current remote-sensing technology is not possible for diesel vehicles; the precise optical path length of the pollutant species through the exhaust plume is unknown, and the species disperse rapidly once exiting the exhaust pipe.

Tailpipe pollutant concentrations in diesel vehicles are currently estimated by the product of their measured ratios to CO_2 times an estimate of the tailpipe CO_2 concentration derived from the combustion equation. With gasoline and LPG engines, which both rely on the spark ignition of a premixed charge of air and fuel, combustion generally occurs in conditions close to the stoichiometric air-to-fuel ratio. This means that as long as the engine operates correctly, the CO_2 dry concentration at the tailpipe (that is, excluding water vapor) stays close to 15%. The simultaneous measurement of CO and HC also allows for a more accurate estimate of tailpipe pollutant concentrations by accounting for the fuel that has not completely burned to CO_2. However, in diesel engines, combustion is operated by compressed ignition of the fuel, and almost always this is under excess air conditions. Furthermore, the amount of excess air varies widely with different engine operation parameters and is related to the manufacturers' emission calibration and engine control strategies. This is a lean running condition that leads to excess oxygen in the exhaust. CO_2 concentration in the tailpipe of a diesel vehicle typically varies from 1% to 13% and, in rare cases during aftertreatment regeneration, it can be up to 15%.

The assumption in deriving tailpipe concentration using remote sensing is that all oxygen has been used to burn the fuel; consequently, there is no oxygen left in the exhaust and the CO_2 concentration is 15%.[8] As stated above, this condition is generally valid for spark-ignition engines (gasoline), but not at all for compression-ignition engines (diesel).

WHY POLLUTANT MASS EMISSION RATE MATTERS

Emission standards usually limit the mass of pollutant per unit of distance travelled (e.g., grams [g] per kilometer [km]) for light-duty vehicles and per unit of output of mechanical energy (e.g., g/kilowatt hour) for heavy-duty vehicles. These metrics are considered best suited to evaluate the environmental impact of an individual vehicle by assessing the mass of pollutant emitted while transporting persons or goods. But obtaining these metrics requires measuring the pollutant mass emission rate. A general formula for the pollutant mass emission rate is described below. It is proportional to the pollutant concentration, but also to the total exhaust mass flow.

$$\textit{Pollutant mass rate} = \mu \times \textit{Pollutant tailpipe concentration} \times \textit{Exhaust mass flow}$$

8 Huang et al., "Remote sensing of on-road vehicle emissions," 58-74. Additionally, pollutant ratios to CO_2 and fuel-specific emission factors do not rely on any assumptions regarding stoichiometric combustion.

In the equation, μ is the ratio between the densities of the pollutant and the total exhaust, and it mainly depends on the pollutant studied and the fuel used.

Expensive and time-consuming laboratory or PEMS testing requires a tight sample from the tailpipe to measure the exhaust mass flow. In contrast, exhaust mass flow data are not available from remote sensing. For PTI, the main constraints are cost and time per vehicle tested. These make it impractical to use a test capable of measuring emissions as accurately as during type-approval.[9] PTI does not seek to verify a vehicle's compliance with its type-approval limit, but rather to detect malfunctions. Most PTI tests therefore only require the measurement of tailpipe pollutant concentrations in order to indicate malfunctions.

Even though mass emissions are a function of tailpipe pollutant concentrations, as shown in the equation above, the main risk with using pollutant concentrations for assessing vehicles' pollutant emission levels is the lack of information about the mass flow of the pollutants. In particular, vehicles equipped with diesel engines tend to exhibit higher exhaust mass flow rates than most vehicles with gasoline engines when tested in similar conditions (e.g., same power demand). This is due to their need to run with a large excess of air.[10] In other words, even when there are similar tailpipe concentrations for gasoline and diesel vehicles, the diesel vehicles are emitting more mass emissions. That means that a testing scheme based on tailpipe pollutant concentration should at least adapt its thresholds depending on the engine technology.

ESTABLISHING EFFECTIVE LIMITS WHEN USING REMOTE SENSING

There are three possible options for improving the measurement of NO for diesel vehicles using remote sensing, and each is discussed below: (1) use a model to estimate the CO_2 concentration in the exhaust; (2) measure O_2 relative to CO_2 in the exhaust plume and then derive CO_2 concentrations; and (3) set regulatory limits in the metric of concentration ratios (NO relative to CO_2) or fuel-specific emission factors (g/kilogram [kg] of fuel burned). Among these options, we consider the CO_2- or fuel-specific metric to be the most appropriate approach for identifying high emitters using remote sensing, and it can be applied to both gasoline and diesel vehicles.

ESTIMATION OF THE CO_2 TAILPIPE CONCENTRATION FOR DIESEL

The first approach is to estimate the CO_2 concentration in the exhaust based on the vehicle's dynamics and characteristics. Some research institutes and remote sensing equipment suppliers are working toward this. The advantage is that if the CO_2 tailpipe concentration is estimated accurately enough, pollutant tailpipe concentration can be derived from the remote-sensing measurement of the pollutant-to-CO_2 ratio in the exhaust plume. However, the obvious disadvantage is that the pollutant tailpipe

9 The test requires a specific unit to sample the exhaust gas flow and a chassis-dynamometer loaded test. So far, the IM240 test used in the United States is the only known example. It allows for a direct comparison of the PTI test with the emission standard for type-approval.

10 Under the same power demand, a diesel engine would likely burn about 10% less fuel than a gasoline engine of the same size, due to better combustion efficiency. But that lower amount of fuel makes very little difference compared to the much higher exhaust flow mass from the diesel engine, which is mainly driven by the extra amount of fresh air needed for the combustion.

concentration estimation directly relies on the accuracy of the model used to estimate CO_2 tailpipe concentrations.

MEASUREMENT OF THE O_2-TO-CO_2 EXHAUST RATIO

The second approach is to measure the amount of O_2 relative to CO_2 in the exhaust plume, ideally close to the tailpipe. In this way, the air dilution ratio of the exhaust can be determined, and the emission concentration can be recalculated. Accurate measurement of O_2 relative to CO_2 would make pollutant concentration measurements from diesel engines possible in the same way it is for gasoline engines. However, there is currently no mature technology available to measure O_2 relative to CO_2. Some remote sensing equipment suppliers are working in this direction.[11]

If either of these two approaches became successful in estimating tailpipe concentrations, the current China remote-sensing diesel limit would need to be significantly tightened. That is because the currently used estimate is based on a gasoline-like CO_2 tailpipe concentration assumption that overestimates the real tailpipe concentration from diesels. Once the concentration is properly estimated, unless the limit is strongly adjusted downward, a diesel would be allowed to emit more pollutants by mass simply because its exhaust emissions are more diluted than its gasoline counterpart. A diesel that fails the current test would pass once the concentration is properly estimated, and this would weaken the current regulation. In addition, even if the CO_2 concentration could be estimated or measured accurately, vehicle manufacturers can perfectly control the dilution of diesel exhaust to the desired amount through calibration, and this might vary significantly from one vehicle to another. Vehicle manufacturers might be incentivized to increase the exhaust flow (e.g., use more fresh air), as this would lead to a lower tailpipe concentration. But it would not necessarily lead to lower pollutant mass emissions, and that is what really matters when assessing the impact on air quality.

ESTABLISHING CO_2- OR FUEL-SPECIFIC EMISSION LIMITS FOR REMOTE SENSING

The third approach is to use a more appropriate metric when setting thresholds for remote-sensing emissions measurements, i.e., a fuel-specific emission factor instead of a concentration limit. Fuel-specific or CO_2-specific emission factors are comparable metrics that can be measured accurately using current remote-sensing technologies. In addition, these ratios are good surrogates for a vehicle's emissions performance, and are indicators of what portion of the fuel burned ends up creating pollutants. This third method has been widely used for academic research purposes, and it can be used to build emissions inventories or to compare with data from existing inventories. The key is to determine how to set the cut-off points for remote sensing, given the reality that pollutant concentration is widely used for in-use vehicle PTI.

Figure 1 describes the measurement principle of remote sensing for a vehicle equipped with a spark-ignition engine operating at an ideal air-to-fuel ratio. Remote sensing measures the absorption of species in the exhaust plume, which is proportional to

11 Xuechun Yu, Current Status and Development Trend of Remote Sensing Technology for Vehicle Emissions in China, Dopler Eco-technologies Co., Limited presentation at Vehicle Emission Remote Sensing Symposium (Hong Kong), 2018, July 26.

the concentration along a given distance. Since species are known to disperse at approximately the same speed once they exit the tailpipe, the relative concentration of species can be calculated independently of the plume size. As discussed earlier, spark-ignition engines are expected to burn fuel and air in a close-to-ideal ratio, which means that the dry tailpipe CO_2 concentration will be approximately 15%. Tailpipe pollutant concentrations can then be estimated by multiplying the pollutant-to-CO_2 ratio by the tailpipe CO_2 concentration of 15%.

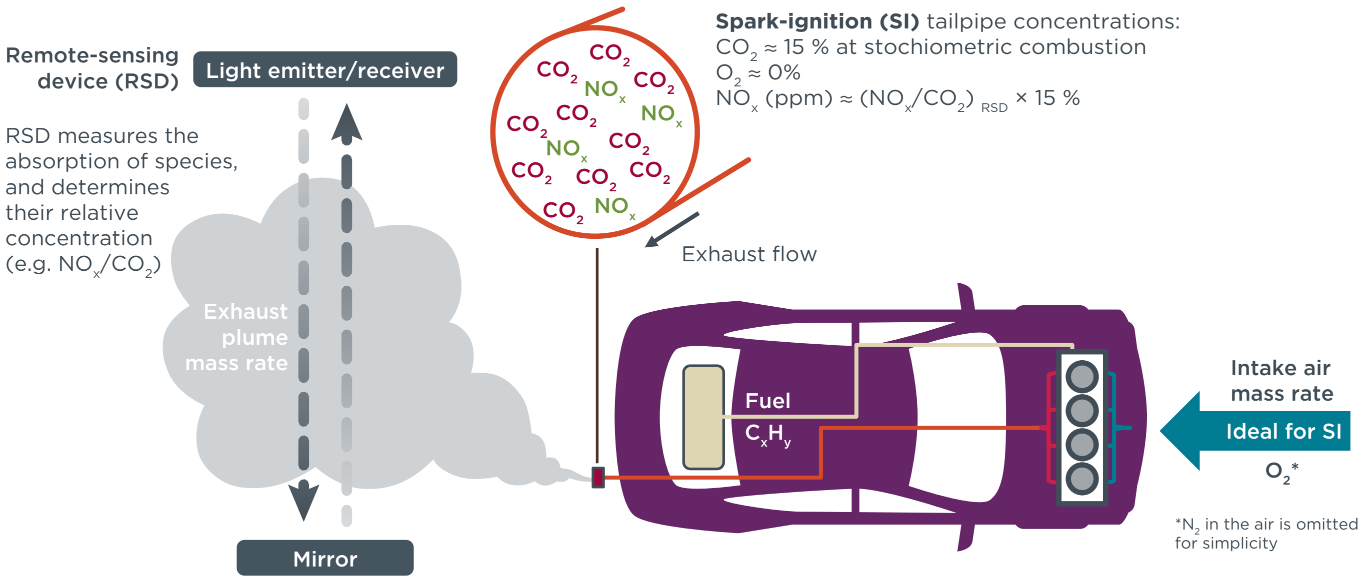

Figure 1. Exhaust emission measurement of a vehicle equipped with spark-ignition engine using a remote-sensing device

Figure 2 shows the emissions measurement of the exhaust plume of a diesel vehicle equipped with a compression-ignition engine. For identical CO_2 and pollutant mass emissions as in Figure 1, the excess amount of fresh air required for the (lean) combustion increases the exhaust flow rate and consequently decreases the concentration of pollutants. In both cases, the ratio of pollutants to CO_2 remains the same, independent of whether they are measured at the tailpipe or in the exhaust plume.

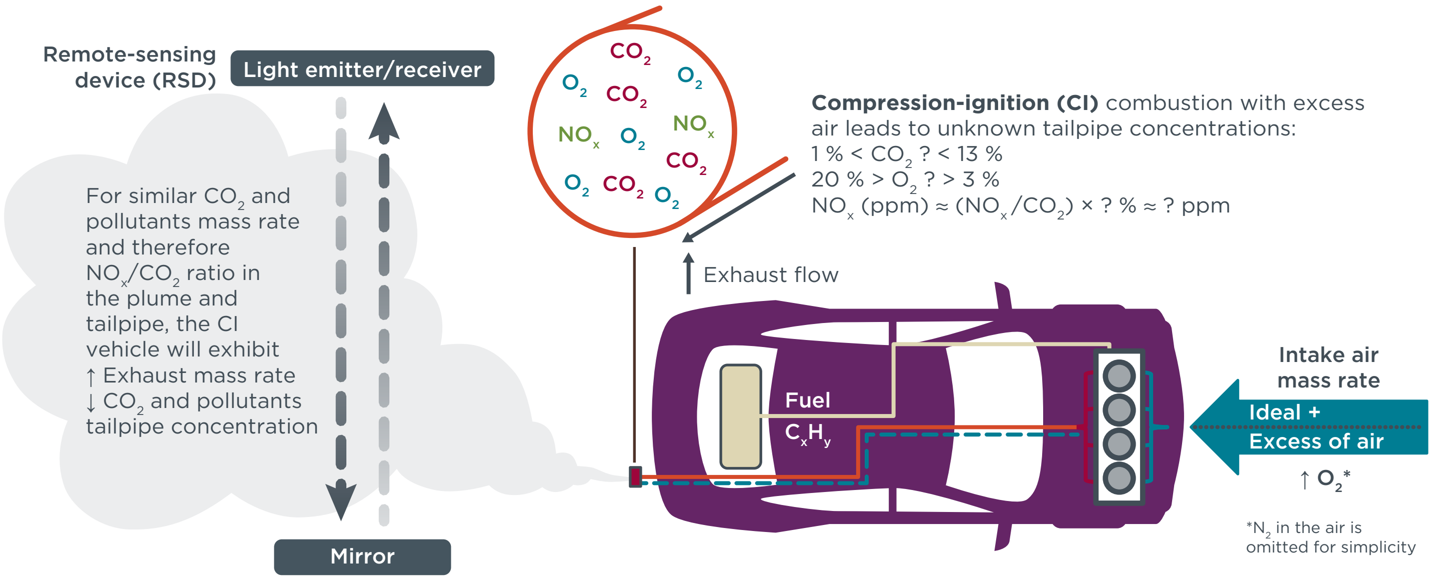

Figure 2. Exhaust emission measurement with a remote-sensing device of a vehicle equipped with compression-ignition engine

Note, however, that a single fuel- or CO_2-specific limit applied to both diesel and gasoline vehicles would not account for the reality that diesels are usually more efficient than gasoline vehicles with comparable technology. This typically means approximately 10% less CO_2 emissions and fuel use by diesel vehicles for a given power demand. While this difference can be considered as minor, the following section will discuss a possible solution that accounts for this difference. Still, the solution requires knowing additional information about the tested vehicle.

Advantages and disadvantages of the three possible solutions are summarized in Table 3.

Table 3. Advantages and disadvantages of three possible solutions for monitoring and enforcing pollutant limits for diesel engines.

Remote sensing metric	Advantages	Disadvantages
Estimate tailpipe CO_2 concentration	• Pollutant concentrations can be derived if tailpipe CO_2 is estimated accurately.	• Weakens existing tailpipe limits. It can only be an approximation, since original equipment manufacturers (OEMs) can control the dilution of diesel exhaust, and they do so in different ways.
Measure O_2 relative to CO_2 in the exhaust plume to determine tailpipe CO_2 concentration	• Pollutant concentrations can be calculated if O_2 relative to CO_2 is measured accurately.	• Weakens existing tailpipe limits. OEMs can control the dilution of diesel exhaust to meet the standards. • There is currently no mature technology to measure O_2 relative to CO_2.
Fuel-based metric	• Available with the current remote sensing technology. • Allows regulators to keep the stringency of existing standards.	• No direct comparison with PTI emission limits based on tailpipe concentration. • Does not account for differences in fuel economy/CO_2 emissions between vehicles.

THE STRONGEST OF THE THREE APPROACHES

Compared to the use of concentration, we consider a fuel-specific metric to be the best approach for identifying high-emitters. This is especially true when very little is known about the vehicle being tested, i.e., whether the vehicle is a gasoline or a diesel. But for the fuel-specific approach, more research is needed to determine an appropriate fuel-specific emission limit. Today, all remote sensing equipment wrongly calculates tailpipe concentration by assuming no dilution for diesel. To keep the stringency of current thresholds of 1,500 ppm in the Chinese remote-sensing regulation, we propose translating the current remote-sensing concentration limit into a fuel-specific emission factor. By using the assumption made by remote-sensing suppliers, the current 1,500 ppm tailpipe concentration means 32.3 g NO_x/kg of fuel burned for diesel and gasoline. A detailed calculation process for this conversion is included in the Appendix.

In the case of no pre-existing tailpipe concentration limits, a jurisdiction that wants to introduce a high-emitter in-use control program using remote sensing should define its own thresholds. For instance, a preliminary remote-sensing campaign could seek to determine cut-off points, for example at the 95th percentile of the fuel-specific emission range observed for each pollutant.

ESTABLISHING LIMITS BASED ON A DISTANCE-SPECIFIC ESTIMATE FOR LIGHT-DUTY VEHICLES

As discussed above, the method that uses a fuel-specific metric reaches its limit when vehicles with large differences in fuel economy need to be more precisely compared. All passenger vehicles with the same fuel type and emission standard are required to meet the same distance-specific emission limit, measured in grams per kilometer driven, for NO and other pollutants. Because these limits are set independently of each vehicle's fuel consumption, vehicles using less fuel and emitting less CO_2 will, all else being equal, have a higher pollutant-to-fuel ratio. A direct comparison of fuel-specific emissions would then tend to punish vehicles emitting low levels of CO_2 and reward vehicles with high CO_2 emissions.

To address this, an earlier paper developed a method for converting fuel-specific emissions to distance-specific emissions.[12] This method relies on proper estimation of the real-world fuel economy and CO_2 emissions of the specific vehicle passing by the remote-sensing device, using type-approval information and consumer reports of real-world fuel consumption. Fuel-specific results are averaged across multiple measurements and then normalized as it follows:

$$Pollutant(g/km) = mean\left(\frac{Pollutant\ (g)}{fuel\ (kg)}\right) \times \frac{fuel\ (kg)}{CO_2\ (g)} \times realworld\ CO_2\ (g/km)$$

This method allows users to define a limit that is specific to the vehicle model being measured. Having the same metric, this real-world distance-specific emissions measurement could be directly compared with the type-approval emission limit.

12 Yoann Bernard, Uwe Tietge, John German, & Rachel Muncrief, *Determination of real-world emissions from passenger vehicles using remote sensing data*, (ICCT: Washington, DC, 2018), https://www.theicct.org/sites/default/files/publications/TRUE_Remote_sensing_data_20180606.pdf

Finally, emission standards usually regulate NO_x and not just NO. For diesel vehicles, primary emissions of NO_2 are very variable and can make up as much as 50% of the NO_x.[13] Therefore, we recommend that future diesel remote-sensing regulations require the measurement of NO_2 in addition to NO.

CONCLUSIONS

Remote sensing measures the pollutant-to-CO_2 ratio in vehicle exhaust. It cannot currently be used to accurately estimate tailpipe pollutant concentrations for lean combustion vehicles, particularly diesel vehicles. Current remote-sensing equipment reports tailpipe concentration estimates by assuming nearly ideal combustion without excess air, but this is only typical for spark-ignition engines. As a consequence, some regulations, including the current Chinese regulation, define a limit based on the tailpipe NO concentration that is not mandatory.

This paper discussed three possible approaches to solve the problem: (1) estimate the CO_2 concentration in the exhaust based on vehicle characteristics; (2) measure O_2 relative to CO_2 in the exhaust; and (3) set the regulatory limits in the metric of concentration ratios (NO relative to CO_2) or fuel-specific emission factors (g/kg fuel).

For the first two, currently there are no mature technologies available to model the CO_2 concentration accurately or measure O_2 relative to CO_2. And if such solutions were to come, existing tailpipe limits would need to be significantly tightened for diesel, to avoid weakening the current emission limits. However, for the purpose of the identifying individual high emitters, a fuel-specific metric is appropriate and can be applied to both gasoline and diesel vehicles. In particular, it would be easy to revise the remote-sensing regulation in China with a fuel-specific metric, as it is better than the current definition in terms of concentration. The current NO tailpipe concentration limit of 1,500 ppm that was derived from lug-down test and European Stationary Cycle test data can be converted into an equivalent limit of 32.3 g of NO per kg fuel (eventually oxidized as NO_2). For LPG, this threshold could be adjusted to 34 g of NO per kg of fuel. To compare remote-sensing measurements with type-approval limits, a future solution could be to convert the fuel-specific results into distance-specific estimates. That can be done using real-world CO_2 data for each vehicle model, but it would require additional information about the vehicle being measured. However, the ongoing development of on-board fuel-consumption monitoring in Europe and remote on-board diagnostic regulation in the China VI standard is likely to open new ways to address the reporting of real-world fuel economy.

APPENDIX

CONVERTING THE CO_2 CONCENTRATION LIMIT INTO A FUEL-SPECIFIC EMISSION LIMIT

We take here as an example the current 1,500 ppm threshold for NO in China's remote-sensing regulation. To simplify, we give results for a non-oxygenated gasoline or

13 A diesel oxidation catalyst with especially low-mileage and a coated DPF can exhibit high NO_2/NO_x ratios.

diesel fuel that has a generic formula of CH_r, where r is the ratio of hydrogen to carbon molecules. A good approximation for the hydrogen-to-carbon ratio r in China is 1.86.[14]

For a complete combustion with an ideal proportion of air and fuel, the theoretical tailpipe concentration of CO_2 is given by:

$$CO_2 \text{ wet tailpipe concentration} = \frac{1}{4.76 + 1.44 \times r}$$

Removing the water vapor from the exhaust, the concentration on a dry basis as observed by remote sensing becomes:

$$CO_2 \text{ dry tailpipe concentration} = \frac{1}{4.76 + 0.94 \times r}$$

The NO to CO_2 concentration ratio expressed in mass ratio gives:

$$\frac{NO \text{ as } NO_2 \text{ mass } (g)}{CO_2 \text{ mass } (kg)} = \frac{NO \text{ concentration} \times MNO_2}{CO_2 \text{ concentration} \times MCO_2} \times 1000$$

Where:

MCO_2 is the molar mass of carbon dioxide equal to 44 g/mol
MNO_2 is the molar mass of nitrogen dioxide equal to 46 g/mol[15]

Finally, the mass of CO_2 emitted per mass of fuel burned is:

$$\frac{CO_2\,(g)}{Fuel\,(g)} = \frac{MCO_2\,(g/mol)}{MC(g/mol) + r \times MH(g/mol)}$$

Where:

MC is the molar mass of carbon equal to 12 g/mol
MH is the molar mass of hydrogen equal to 1 g/mol

The left column of Table A1 translates the NO tailpipe concentration limit of 1,500 ppm into the ratio of concentration relative to CO_2 as it is measured by remote sensing. That results in a NO / CO_2 limit of about 98 (ppm/%). It is then converted into pollutant to CO_2 mass ratio, which is around 10 g/kg. This metric was also proposed by researchers in Hong Kong who studied how to characterize diesel vehicle emissions and determine cut-off points using remote sensing. The researchers proposed NO-to-CO_2 thresholds depending on the certification standards, and they were around 57 (ppm/%) for Euro 4 and 23 (ppm/%) for Euro 5 high-emitters.[16]

The fuel-specific metric can be calculated from the pollutant ratio to CO_2. It has the advantage of accounting for measurement cases with significantly incomplete combustion; this is when part of the fuel is not entirely converted into CO_2 and instead generates significant amounts of CO and HC combustion residuals. Therefore, we recommend using fuel-specific thresholds, because these allow for a better

14 Administration of Quality Supervision, Inspection and Quarantine of China. Measurement methods of fuel consumption for light-duty vehicles. GB/T 19233-2008.

15 NO as NO_2 emissions use the NO_2 molar mass since all emitted NO will eventually oxidize into NO_2 in the atmosphere.

16 Yuhan Huang, Bruce Organ, John L. Zhou, Nic C. Surawski, Yat-shing Yam, Edward F.C. Chan, "Characterisation of diesel vehicle emissions and determination of remote sensing cutpoints for diesel high-emitters," *Environmental Pollution* 252 (Part A), 31–38, doi: 10.1016/j.envpol.2019.04.130

comparison of a vehicle's pollutant emissions (e.g., NO) against those of another vehicle independent of the other combustion by-products (e.g., CO).

For individual remote-sensing measurements, the fuel-specific NO emissions can be calculated as it follows:

$$\frac{NO\ as\ NO_2\ (g)}{Fuel\ (kg)} = \frac{MNO_2(g/mol) \times NO/CO_2\ concentration\ ratio}{1 + CO/CO_2\ concentration\ ratio + 6 \times HC/CO_2\ concentration\ ratio} \times \frac{1000}{MC(g/mol) + r \times MH(g/mol)}$$

The NO tailpipe concentration limit of 1,500 ppm converted into mass of oxidized NO_2 to fuel is around 32 (g/kg) for gasoline and diesel fuel.

LPG typically has a lower carbon content than gasoline or diesel fuel, and its hydrogen-to-carbon ratio *r* is around 2.62. This translates into 5% less CO_2 from the combustion of a given mass of LPG, while releasing 7% more energy. Therefore, the fuel-specific metric is not entirely adapted to compare gasoline and diesel fuel with LPG. For the latter, the limit should be set slightly higher at 34 gram NO per kg fuel.[17]

The right column of table A1 details the conversion from a tailpipe 1,500 ppm NO concentration to a CO_2-specific and fuel-specific metric.

Table A1. Conversion of tailpipe concentration limit into CO_2, fuel-specific and fuel energy-specific metrics for diesel, gasoline, and LPG fuels

	Diesel and gasoline	LPG
Current limit for NO tailpipe concentration (ppm)	1,500	1,500
NO limit reversed into NO/CO_2 limit (ppm/%) as remote sensing measures it	97.6	108.4
NO limit converted into NO as NO_2/CO_2 limit (g/kg)	10.2	11.3
NO limit converted into NO as NO_2/fuel limit (g/kg)	32.3	34.0

17 Alternatively, a single threshold of 0.7 grams of NO per megajoule of fuel energy content could be used across diesel, gasoline, and LPG fuels.