

Guidance note about on-road vehicle emissions remote sensing

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1.1 Background and objectives

On-road vehicle remote sensing (RS) has great appeal. The exhaust emissions from thousands of vehicles can be scanned within a single day under “real-driving” with minimal interference to driving. RS has been used to monitor the effectiveness of emission standards, to cross-check inspection and maintenance programs, and to identify high emitters, among others. However, not all promises hold true, and others require careful execution and interpretation.

The ICCT has commissioned this guidance document to inform policymakers on good practices of vehicle RS. The main objective of the paper is to educate policymakers on different RS applications, to reflect upon their results, interpretation, and possible limitations, and to identify the most relevant literature sources for further reading.

A detailed literature review of the results or the effectiveness of different RS programs worldwide is not intended, nor to compare the cost effectiveness of RS programs with vehicle emission control policies.

1.2 Introduction

Vehicles are in many countries important sources of air pollution both at local and national scales. Therefore vehicle emissions are regulated – new vehicles have to comply with vehicles exhaust emission standards and in-use vehicles often need to pass inspections at regular intervals. However, vehicle emissions under real-driving can differ significantly from laboratory results. To measure vehicle emissions various techniques have been employed (Robin Smit, Ntziachristos, and Boulter 2010; Franco et al. 2013). These can be categorized as follows:

Single vehicle emission measurements interrupting the driving:

- Pullover of vehicles followed by immediate on-site inspection;
- Test-center or laboratory emission testing over predetermined cycles.

Single vehicle emission measurements not interrupting the driving:

- Remote sensing – measurement of individual vehicles passing by optical sensors;
- Vehicle chasing experiments – a laboratory vehicle follows vehicles sampling their exhaust plume.

Single vehicle emission measurements after vehicle conditioning:

- PEMS (Portable Equipment Measurement System) – equipping a (test) vehicle with a portable gas analyser, and measuring emission rates during the driving.

Fleet emission measurements not interrupting the driving:

- Tunnel measurements – not resolved for single vehicles, but for vehicle classes;
- Measurement of ambient concentrations at roadsides – not resolved for single vehicles, but for vehicle classes.
- Measurement of concentration differences in ambient air masses - not resolved for single vehicles, but for vehicle classes.

In the following we concentrate on vehicle RS as one technique for the monitoring on-road emissions. We briefly review key operating principles of (optical) RS, and discuss typical applications. The final section provides recommendations and a list for further reading.

1.3 Vehicle remote sensing

1.3.1 Operating principles

Vehicle RS is a non-intrusive technique to determine the concentration of certain pollutants in situ. Measured is the attenuation of light by its exhaust plume when a vehicle crosses the beam. The stronger the attenuation in a specific wavelength, the higher is the concentration of a particular absorbent. The concentration difference relative to the measured background concentration is ascribed to the vehicle that has just passed.

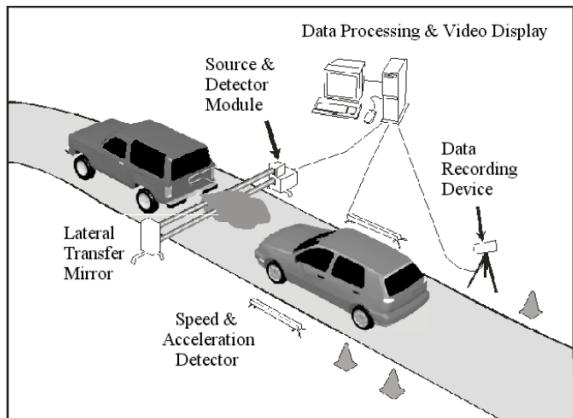


Fig. 1: Schematic set-up of on-road vehicle emission RS (McClintock 2007). Copyright © 2007 Envirotest Systems. Reprinted with permission by Envirotest Systems.

Fig. 1 provides a sketch of the instrumentation: A vehicle crosses the instrument's beam during pass-by, and the pollutant concentrations (increments) are sampled. Each valid record is the average over 10-100 concentration measurements within 0.5 seconds. If certain quality parameters are met, the average concentration increment is retained. The instrument is regularly calibrated against a puff of gas of known concentrations. The measurements are usually performed during daytime, when traffic is most intense but the system operates also well at night. A dry, non-dusty road is needed, meaning a small limitation for operating conditions. For recommendations on a careful system set-up and quality assurance consult the extensive US EPA guidance (US EPA 2002).

The increment in the instantaneous CO₂ concentration is directly proportional to the carbon contents of the fuel burnt, and thus to the amount of fuel consumed. This way one can determine (instantaneous) emission factors in gram pollutant per kg fuel for each vehicle measured.

Instantaneous speed and acceleration of the vehicle are measured slightly upstream of the emission measurement. This is matched to the recorded concentrations and used as information about the engine load leading to the emissions.

The technique has been developed in the late 1980's by D. Stedman and collaborators at the University of Denver (G. A. Bishop et al. 1989) and has been further developed until today.

1.3.2 Vehicle technical information

Vehicle license plates are recorded and registration data are accessed to obtain information on the vehicle itself e.g. its emission classification or model year, engine power, vehicle weight, last technical inspection etc., and to be able to contact the owner in case of a high emission measurement. Thus, detailed information about the composition of the fleet actually driving on-road (as opposed to the stock of vehicles registered) is recorded with the same measurement. This is in turn very valuable empirical input data about the frequency distribution of vehicle types and ages and of the on-road fleet, which is not often available for the specific site otherwise. However, this must be considered a by-product and could also be obtained without emission measurements. Again, the more representative the measurement site(s) and the vehicles captured the more useful the traffic information in describing the vehicle population in a larger area.

1.3.3 Suitable traffic conditions & measurement set-up

To obtain remote sensing emissions measurements that are representative of normal on-road urban driving and equivalent dynamometer test driving cycles, a few provisions should be respected, for instance (McClintock 2012):

- The measured concentration increments can only be ascribed to individual vehicles, when they are clearly separable; therefore, single lane traffic is often preferred;
- Free-flowing traffic is preferred, steady acceleration would be optimal. Sites where vehicles accelerate from a stop sign or light are good;
- The engine should be under load, hence a positive acceleration or some small road gradient are desirable;

- Low probability for cold-start vehicles to exclude false detection of high emitters;
- The ratio of engine power to speed is sufficient to provide readable exhaust plumes for most vehicles.

The site characteristics determine the driving conditions that can be observed and the vehicles passing. For emission factor and inventory purposes it is often advisable to measure at several sites to cover a wider range of driving conditions and a broader section of the fleet in the area under investigation. For applications such as a cross-check on I/M performance, high emitter screening and clean screening, it is better if all the traffic is centered within the VSP range that dominates the emissions from the comparative I/M test.

When conducting research e.g. on the effects of temperature or aggressive driving, the above restrictions do not necessarily apply: The purpose determines the suitability of the site(s).

As VSP influences the emission level, comparing measurements across different sites care should account for the different driving conditions and fleet selection, cf. e.g. (C. Mazzoleni, China, and Salvadori 2011).

1.3.4 Pollutants covered by RS

Advances in measurement technique have expanded the scope of pollutants that can be directly measured through optical RS. Devices routinely measure CO₂, CO, HC as propane equivalents, NO, and opacity. Latest RS devices also measure NO₂, NH₃ and SO₂ (e.g. (Gary A. Bishop et al. 2012). In particular the simultaneous measurement of NO and NO₂ is highly desirable for an accurate determination of total NO_x emissions from diesel vehicles with modern after-treatment devices.

RS measures opacity in the IR and UV wavelengths. The UV channel has been calibrated for black carbon particulate from unfiltered diesel engine exhaust. The IR channel is responsive primarily to black carbon. The combination of UV and IR can be used to differentiate black smoke from blue or white smoke (oil or cool-

ant). Thus, an RS device can measure the standard set of regulated air pollutants simultaneously.

1.3.5 Vehicle categories covered by RS

The technique is not limited to a certain vehicle category. But for practical reasons mostly vehicles with horizontal tailpipes within a few dozen centimeters above ground have been measured, meaning light duty vehicles have been most extensively measured around the globe (Gary A. Bishop and Stedman 2008; Carslaw et al. 2011; Claudio Mazzoleni et al. 2004; Zhang, Bishop, and Stedman 1994). Results for LDVs are therefore the focus of this review. Nonetheless there have also been measurements of heavy-duty trucks and buses (Burgard et al. 2006; Yanowitz, McCormick, and Graboski 2000), motorcycles and motor-rikshas as well as snowmobiles (Ray et al. 2013), various off-road machines and aircraft (Popp, Bishop, and Stedman 1999).

1.3.6 Quality assurance and uncertainties

An accurate measurement needs proper adjustment of the instrument's light path and the exhaust plume of the vehicle. As it is a differential measurement, it is important that the values taken as 'background concentration' are valid and not affected by the emissions of the vehicle under investigation. Further, the exhaust gases sampled result from combustion about 1 to 25 meters earlier, depending on the vehicle's speed (Jiménez 1999). However, speed and acceleration (i.e., the load points associated with this emission rate) are measured over a fixed distance before the emissions are measured. If hence the driving on approach is unsteady, the measured speed and acceleration may not be representative of the operating mode at the time the measured emissions were generated. The typical accuracy of modern RS devices is given in Table 1.

	Calibration gas	Measurement
CO	$\pm 10\%$	$\pm 0.25\% \text{ CO}$
HC (as propane)	$\pm 15\%$	$\pm 250 \text{ ppm}$
NO	$\pm 15\%$	$\pm 250 \text{ ppm}$
speed		$\pm 1.0 \text{ mph}/\pm 1.6 \text{ km/h}$
acceleration		$\pm 0.5 \text{ mph}/\pm 0.8 \text{ km/h}$

Table 1: Typical accuracy limits for modern RS devices (McClintock 2011). Copyright © 2011 Envirotest Systems. Reprinted with permission by Envirotest Systems.

Negative values result from measurement noise and an inaccurate determination of the background concentration, and appear more frequently for modern, very clean vehicles. They have to be included and not rounded to zero (McClintock 2012).

1.3.7 Strengths and limitations

On-road RS can provide several hundred valid measurements per hour. The great advantage is that they are taken from actual fleets under real-driving conditions. *With its large sample size RS can provide very accurate results on fleet averages.* To the extent that statistics allow the results can further be differentiated e.g. by vehicle category and fuel type, emission control stage and model year, and even driving conditions (vehicle specific power (VSP) or speed-acceleration combinations). Fig. 2 shows an example for average NO_x emission rates from diesel cars in the UK as a function of model year and engine load. Clearly, NO_x unit emissions increase strongly at higher engine loads. Note, that the maximum VSP for the urban part of the European emission certification cycle NEDC is 12 kW per ton. The higher emission rates in Fig. 2 appear thus at the edge or outside the NEDC homologation cycle, from model year 2000 (or Euro 3 standard) onwards, see also (Rhys-Tyler and Bell 2012). That illustrates the known phenomenon of increased ‘off-cycle’ emissions without signifying a malfunctioning of the vehicle, e.g. (US EPA 2002, 22).

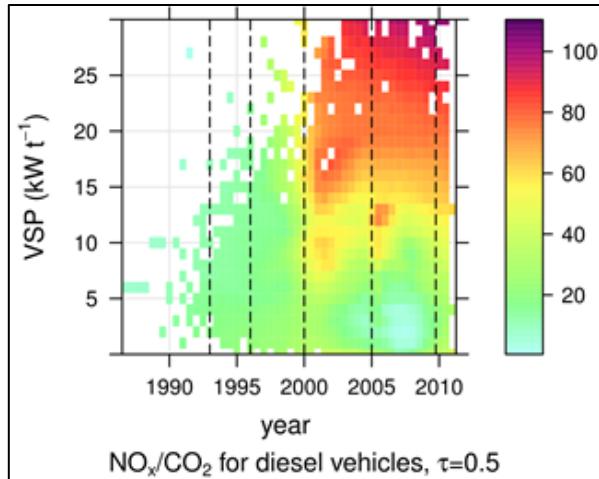


Fig. 2: Mean NO_x unit emissions as function of model year and engine load (VSP) for diesel cars measured during seven RS campaigns in the UK between 2007 and 2010 (Carslaw et al. 2013). Dashed lines indicate the introduction dates of Euro 1 to Euro 5 standards. Copyright © 2013 by Elsevier. Reprinted with permission by Elsevier.

RS can offer coarse statements about an individual vehicle’s emission rate adequate for screening purposes when on-road measurements are suitably qualified. Each individual vehicle is usually measured only once or a few times under somewhat variable driving conditions, and few are measured more than ten times. Vehicle emissions vary with driving mode, hence care needs to be taken to site the RS devices where driving behavior is stable and predictable and VSP can be used to estimate engine load, e.g. freeway on-ramps. Properly functioning modern light duty vehicles very rarely exhibit high emissions. However, malfunctioning or broken vehicles can have inherently variable high emissions as has been illustrated in repeated FTP tests (Gary A. Bishop, Stedman, and Ashbaugh 1996). For these high emitters a few instantaneous records may not be sufficient to accurately characterize their general emission behavior. However, when their emission level is several times above fleet average the likelihood for malfunctioning is high. With only one or two RS measurements, extra information is desirable to increase confidence in the assessment of an individual vehicle’s emissions and to decrease false detections. For instance, RS results are often combined

with a so-called high- or low-emitter index, that is itself based on mass sampling over entire cycles from I/M tests (to be explained below). Such combined information can in turn be used to lower the cut-off threshold capturing more high emitters without increasing false detection rates.

Due to the limitations in its normal set-up ***RS measurements can provide an important but not complete picture of vehicle emissions:***

- RS excludes emissions from idling or during deceleration when there is insufficient exhaust to measure;
- The usual RS set-up is focused to measure emissions from (usually light duty) vehicles at moderate VSP. In consequence, the emission factors derived may not be representative for emissions e.g. under highway driving conditions;
- The RS is set-up to measure hot exhaust emissions from the vehicles. This means that emissions from cold start are deliberately excluded. As modern vehicles have quite low hot emissions, cold start excess emissions can be a significant source particularly in urban areas and under cold ambient temperatures;
- RS can provide qualitative information about evaporative HC high emitters. When substantial HC within a vehicle plume does not correlate well with CO₂ the plume probably contains HC from an evaporative source (St.Denis and Roeschen 2012).
- RS does not provide information on non-exhaust PM emissions, for example from tyre and break wear;
- When comparing with emissions measured over test cycles like the US-FTP or the European NEDC, care must be taken to compare only similar ranges for engine operation (VSP) and to weigh the respective operation ranges properly. Otherwise (high) off-cycle emissions might distort the comparison.

The vehicle information obtained from license plate readings is often limited to vehicles within a certain jurisdiction, i.e. information about ve-

hicles from outside often disregarded. Yet this is only an administrative problem; when overcome it could yield further interesting information e.g. comparing the emission levels of vehicles subject to different regulatory regimes.

These limitations require a careful set-up of the measurements, careful data analysis and cautious interpretation. The following section discusses some typical RS applications.

1.4 Remote sensing applications

The following applications are brought forward as particularly suitable for vehicle RS techniques:

1. Fleet emission monitoring
2. Cross-check on I/M performance
3. Cross-check on OBD performance
4. High emitter screening
5. Clean screening

1.4.1 Fleet average emission measurement

RS can be used to measure the average emissions from the fleet driving. This measurement can be used to analyze e.g. to what extent an expected emission reduction from tightened exhaust emission standards translates into a change in on-road emissions.

Short-term measurements can inform (within the limits mentioned above) about the average CO, HC, NO (and possibly NO₂, and NH₃) unit emissions of the fleet (of light duty vehicles) actually driving, and about average unit emissions per model year.

With comparable measurements over several years this can be used to analyze the development of average fleet emissions over time, and thus of the effectiveness of successive emission standards, to analyze the change of unit emissions with vehicle age, the turnover of the fleet, and also the change of vehicle mileage with age (in the region of the measurement site).

All this information is very useful for a comparison with the average emission factors as well as fleet composition assumed in an emission in-

ventory or an emission model. Thus results can help with calibration of the model and inventory for the time periods measured.

Monitoring progress over model years and control stages

Fig. 3 illustrates how important measurements of on-road emissions can be; plotted are the concentration of NO_x over CO₂ from passengers cars over manufacturing year from recent RSD measurements in the UK (Carslaw et al. 2011). About 20'000 diesel and 50'000 gasoline cars were measured during seven campaigns at various urban sites in the UK between 2007 and 2010. Directly measured was NO, this is translated to NO_x by assuming literature shares of primary NO₂, particularly relevant for diesel cars. In this cross-section of the fleet clearly newer than 1990 model years of gasoline cars have successively lower unit emissions. In other words, the older the gasoline car, the higher is its NO_x emission rate.

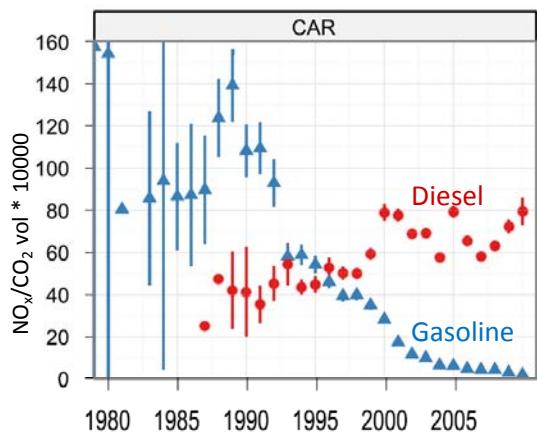


Fig. 3: NO_x emission factors of gasoline (blue triangles) and diesel (red dots) passenger cars by manufacturing year from RS in the UK (Carslaw et al. 2011). The high standard deviation for model years <1988 is because of low sample size. In addition older vehicles have been subject to deterioration due to usage as compared to younger vehicles. Copyright © 2011 by Elsevier. Reprinted with permission by Elsevier.

In stark contrast, NO_x unit emissions from more modern diesel cars are at least as high if not higher compared to older diesel car model years. This behavior is unexpected as emission standards have been tightened not only for

gasoline but also for diesel cars in the European Union, and as all diesel cars have been shown to really have lower NO_x emissions over the homologation cycle (NEDC).

High NO_x unit emissions from modern diesel cars were also obtained by RS in Zurich, by PEMS measurements on random routes and by off-cycle chassis dynamometer tests (Borken-Kleefeld 2012; Hausberger et al. 2009; Weiss et al. 2011). All measurements point to a significant discrepancy of NO_x emission control under test cycle and on-road driving conditions for diesel cars. Together with the strong increase of diesel cars in Europe the failing control of their NO_x emission is made responsible for persistent non-compliance with NO₂ ambient air quality standards at many road sites (EEA 2012).

This example shows that a monitoring of actual on-road emissions (by whatever means) is important for effective air quality policies. This is even more important when the homologation test cycle of new vehicles or technical inspections tests of existing vehicles are known to differ significantly from real-world driving conditions.

Monitoring progress in the fleet

The change of average emissions of the rolling fleet depends on the unit emissions of each vehicle class (can be monitored as above), on the fleet turnover, i.e. the share of new vehicles with progressively lower unit emissions added and of old vehicles with higher unit emissions retired, and the respective mileage of the different vehicles. With on-road measurements these factors can be recorded at the same time i.e. the real average on-road emission factor can actually be measured directly for the vehicle category under investigation.

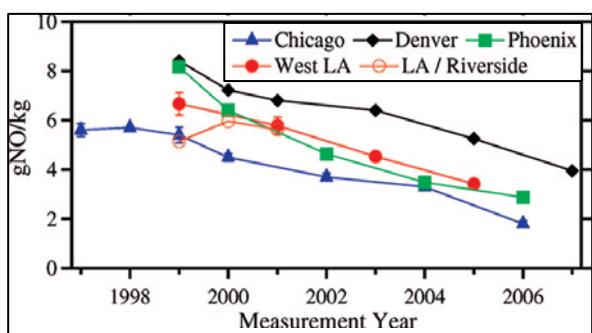


Fig. 4: Average fuel specific on-road NO emission factor from RSD campaigns in Chicago, Denver, Phoenix, and Los Angeles (all USA) against year of measurement (Gary A. Bishop and Stedman 2008). Copyright © 2008 by American Chemical Society. Reprinted with permission by American Chemical Society.

Fig. 4 shows results from a decade of on-road vehicle RS emission measurements at various cities in the US. (Gary A. Bishop and Stedman 2008) clearly document decreasing fleet average emissions. Differences between the sites are explained by a different fleet composition (newer vs. older cars, share of light trucks and diesel vehicles), different fleet ages, varying driving conditions (notably acceleration and road gradient), and other smaller factors.

Such on-road measurements provide a reality check for e.g. inventories and emission models. However, for a representative assessment for a larger area several sites with different fleet and driving characteristics need to be viewed together.

Conversion to gram pollutant per kilometer

A sample of several thousand emission records from remote sensing usually covers a considerable range of driving conditions in terms of VSP or speed-acceleration pairs. The mean results are therefore comparable to results from a driving cycle. However, limit values and emission factors measured on chassis dynamometers are usually expressed in the unit gram pollutant per kilometer. To convert average measured on-road emission rates to this unit requires knowledge of the average fuel economy over a comparable driving cycle.

1.4.2 Cross-check on I/M and OBD performance

RS has been used to evaluate the performance of inspection and maintenance (I/M) programs, notably in the US. The US EPA has issued an extensive best practice guidance document that is not repeated here (US EPA 2002). It is a special case of an analysis of the impact of a measure by comparing emissions either before and after the measure (in this case the introduction of an I/M scheme), or by comparing vehicles subjected and not subjected to the measure.

Similarly, on-board diagnostics (OBD)¹ can be considered as a technical measure, and comparing emissions of vehicles before and after its introduction (under comparable driving situations) is another (relatively) straightforward application of a fleet monitoring using on-road RS.

1.4.3 High emitter identification

On-road RS has also been used to filter out those vehicles with highest absolute emissions in the (light-duty) fleet. These are mostly older vehicles or vehicles with dysfunctional after-treatment. Fig. 5 shows how e.g. 90% of mean CO emissions readings are very low for modern light-duty vehicles, yet that emission rates increase with vehicle age. This is to be expected as earlier models had generally higher allowed emission rates than newer models, and there has been additional ageing and related performance deterioration. The frequency of high emitters among newer models is much lower; however as there is a much larger number of newer model vehicles they are a significant source of excess emissions (discussed further in conjunction with Fig. 6).

Emissions are also strongly correlated with odometer. Certain active vehicles such as taxis, shuttle buses and delivery vehicles are more likely to become high emitters at a younger age

¹ OBD stands for on-board diagnostics, and refers to the capability of a vehicle to diagnose and report on malfunctioning e.g. of the emission controls. Advanced OBD has been mandatory for cars sold in the US since 1996, in the European Union since 2001 (gasoline) and 2004 (diesel).

and to have a greater emissions impact because of their high mileage.

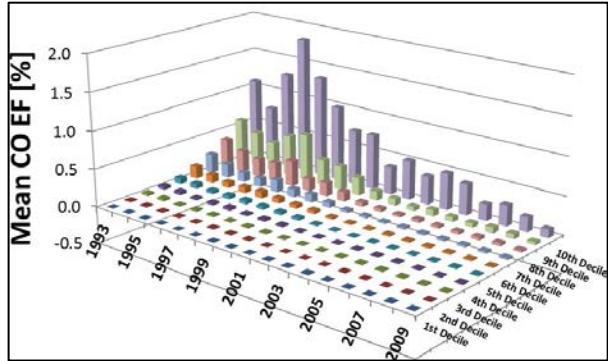


Fig. 5: Mean CO emission rate differentiated by model year and decile for RS measurements in Southern Michigan in 2010 (C. Mazzoleni, China, and Salvadori 2011). Example for the skewness of the distribution. Copyright © 2013 by Coordinating Research Council (CRC). Reprinted with permission by CRC.

Normally functioning vehicles also have occasionally high instantaneous emissions e.g. at load changes but this does not make them permanent high-emitters. Therefore, to prevent false detection additional filters are needed. The particular problem is to conclude from a 0.5 seconds' measurement of instantaneous emissions on the general emission behavior of a vehicle under all sorts of different driving conditions. The following additional filters are recommended to identify vehicles with excessive emissions:

- Consider only records with moderate speeds and moderate positive acceleration, or for a VSP² within the range of the emission test cycle, e.g. in the range of 3-22 kW t⁻¹ for the US FTP and the European NEDC

² VSP: Vehicle specific power is a one-dimensional measure for engine load, depending on speed, acceleration, and driving resistances. For US conditions (Jiménez 1999) suggest a range of 3-22 kW t⁻¹, just below the maximal VSP in the US - Federal Test Procedure (FTP). The VSP in the New European Driving Cycle (NEDC) ranges up to 29 kW t⁻¹ when highway driving is included; therefore a range similar to the US is to be recommended as area of normal emission control operation. For 2002 and newer US models certified using the supplemental FTP, the upper VSP range can be higher.

test. The variability of instantaneous emissions from normally operating vehicles is reduced at such moderate engine loads (Gary A. Bishop and Stedman 2008; Rhys-Tyler and Bell 2012; R. Smit and Bluett 2011). Hence, outliers can easier be detected. On the contrary, emission rates outside the 'regulatory range' can be very high but do not necessarily indicate a malfunctioning of the vehicle (cf. Fig. 2 and comments there).

- Use cut-off levels safely above usual emission levels from normally operating vehicles. These cut-off levels can be set in relation to in-use standards, or based on prior measurements, e.g. from results of technical inspections, PEMS or modal chassis dynamometer test, or can be built up from the RS campaign itself.

For instance, for high-emitter identification in North Central Texas (McClintock 2011) cut-off levels were derived from in-use standards for the mandatory idle inspection test as well as from average inspection results over the Acceleration Simulation Mode (ASM) test. Cut-off levels are set as multiples between 1.5 and 2.5; they are differentiated by model year and thus adapted to the technical progress in emission control. Model years older than 1986 and newer than 2009 were exempt from the state's I/M program and hence not reviewed for being high-emitters. With these cut-off levels about 2-3% of the respective fleet segment in the year 2010 was identified as high-emitters.

- Require at least two records above cut-off level for any vehicle (within a certain time window) before concluding on high-emitter. Alternatively, use a High Emitter Index from past (failed) inspections (BAR 2012; Choo, Shafizadeh, and Niemeier 2007): This index ranks vehicle makes and models with respect to their past performance in emission inspection tests. Vehicle makes and models with a high percentage of failed emission tests are considered to have a high probability to become a high-emitter. Hence, one

RS measurement above cut-off level might be sufficient for vehicle identification with a high score in the High Emitter Index.

Results

We know that older vehicles have in general higher on-road emissions because their emission certification level was initially higher than for more modern vehicles (confirmed e.g. in the previous section) and simply because emission performance deteriorates with vehicle age. Consequently it has been observed that old vehicles are much more likely to exceed a fixed, vehicle-age independent emission cut-off level (cf. Fig. 6a). Importantly, (gasoline) cars and light trucks up to around 10 years of age rarely exceed the cut-off thresholds (in the US). These vehicles dominate the active fleet, and they are all equipped with on-board diagnostics (OBD-II). With age the share of vehicles with excess emissions increases: For instance, around 6% of model year 1996 cars and around 30% of model year 1986 cars were recorded above the cut-off levels used for the Southeast Michigan study. However, the older the vehicle, the lower is its share in the fleet and in usage (Fig. 6b). On average only about 2-3% of the light duty fleet is above high-emitter thresholds (McClintock 2007; McClintock 2011). These vehicles can provide a sizeable share of total emissions as the vast majority of vehicles have very low emission rates. However, given declining overall emissions, it needs to be assessed separately whether this constitutes still a problem to air quality.

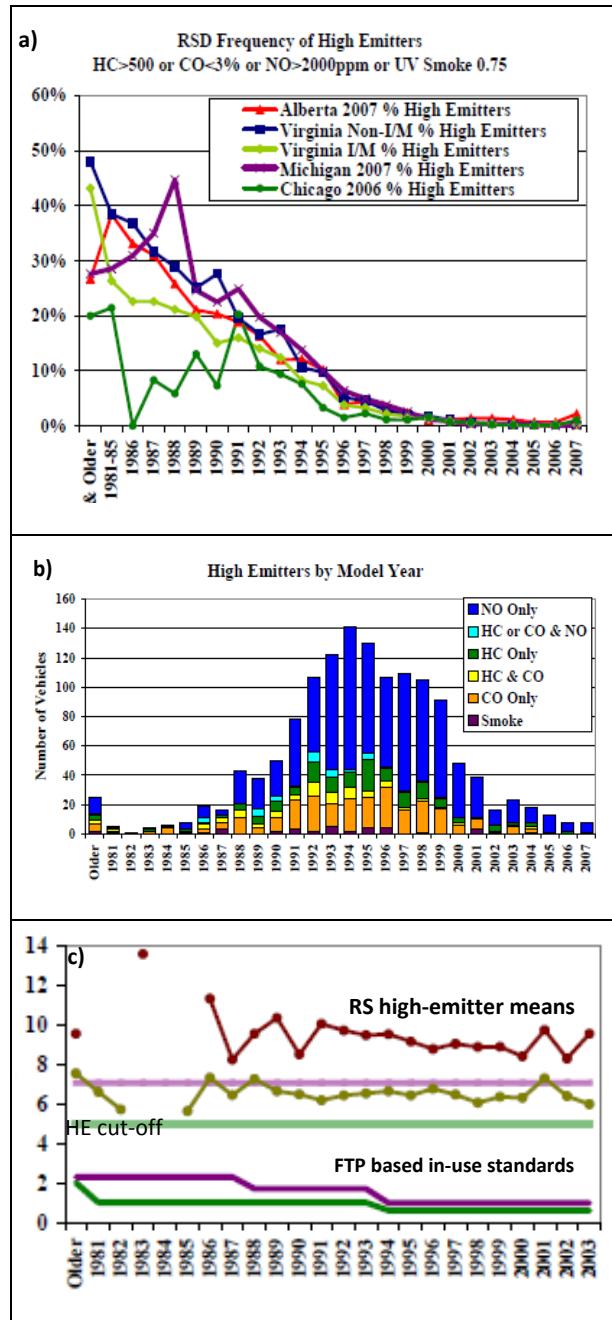


Fig. 6: (a) Share of high-emitters identified at various sites by vehicle model year. (b) Number of vehicles above high-emitter cut-off level by pollutant over model year in Southeast Michigan. Total sample: 65'500 vehicles. (c) Comparison of NO_x high-emitter cut-off points, average high-emitter RS emission in Southeast Michigan 2007, each in g NO_x per mile, and in-use standards over model year (assuming 17 and 24 mpg fuel efficiency for light trucks (purple line) and passenger cars (green line) respectively). Cut-off levels were the same for all model years and indicated in chart (a). (McClintock 2007). Copyright © 2007 Envirotest Systems. Reprinted with permission by Envirotest Systems.

Further, most vehicles exceed the cut-off threshold only for one pollutant; in the Michigan campaign vehicles mostly exceeded either the NO or the CO threshold (Fig. 6b). In general RS results do not suggest correlations between different pollutants, and hence all regulated pollutants need to be sampled (C. Mazzoleni et al. 2004).

Third, typical RS high-emitter cut-off thresholds are far higher than in-use vehicle standards. For instance, a NO_x RS threshold of 2000 ppm translates to about 5 grams NO_x per mile traveled, and is thus 5 to 8 times above the FTP based in-use standard. Lower cut-off thresholds would result in increasing false detections. The vehicles identified as high-emitters exceed this standard even more (Fig. 6c). The average emissions from gasoline high-emitters in the US can be 10 higher than fleet average for CO, NO, and smoke and up to 20 times for HC, depending on the cut-off point used (McClintock 2011).

The identified (gasoline) high emitters are estimated to contribute an extra 20% of NO and CO and up to an extra 50% of HC to the estimated hot, urban emissions of the light duty fleet (McClintock 2011).

However, detection does not mean repair. In the North Texas study, by far the majority of vehicle owners continued driving with expired or failing inspection certificate even after being notified (McClintock 2011). Therefore, *adequate enforcement is essential for effective pollution control.*

The median emission level measured by RS follows about the in-use FTP standard (McClintock 2007, for NO and HC). Therefore, there must be a significant number of vehicles above the in-use standard but below the high emitter cut-off threshold. These will hence drive undetected, and only the worst few percent are identified.

Discussion

It is quite challenging to assess an individual vehicle's emission behavior with just a few instantaneous pass-by measurements. Therefore a number of points need to be noted:

- The single measurement is shown to be accurate within the error bands stated above. However vehicle emissions are not necessarily repeatable, particularly not for high emitters (Gary A. Bishop, Stedman, and Ashbaugh 1996). Therefore it is not possible to conclude on its average emission level even though a classification as 'high' is feasible.
- Without larger numbers and thus reliable statistics it is not accurate to conclude on the exact share that high emitting vehicles contribute to total emissions. It is only clear that it must be disproportionately high.
- A better indication on the proportion might be taken from in-use tests: For instance, 6% of LDV failed the IM240 test in Colorado; their repair resulted in 8%, 23% and 24% less on-road NO_x, CO and HC emissions respectively (McClintock 2012).
- For a reliable detection of high emitters repeat measurements are recommended. This however increases the required sampling at the same sites and consequently reduces the coverage. This can be avoided if one RS record is combined e.g. with a high-emitter index.
- The more repeat measurements are required, the lower the share of vehicles above cut-off threshold (Borken-Kleefeld 2012). The use of dual high and moderately high standards can reduce the elimination of high emitters that have a second result below the high emitter standard but still well above normal.
- It is easier to capture the fleet in urban agglomerations, but efforts increase largely if vehicles in a larger area shall be captured. Therefore, RS is a very suitable tool to quickly sample a significant portion of the fleet, but increasing coverage means increasing costs over proportionally.
- There is a trade-off between an accurate identification of high-emitters and the avoidance of false detection. "On-road emissions standards [here meaning cut-off thresholds] that are too stringent could

cause vehicles that do not need repairs to be identified as high emitters. At the same time, on-road emissions standards [cut-off thresholds] that are too lenient will not identify many truly high emitting vehicles" (Dep. Env. Qual. 2007, earlier BAR 2001).

- The cut-off thresholds should depend on the model year to keep pace with the technical progress. For corrective action, in-use standards should likewise be progressively tightened.
- With decreasing unit emissions and low high-emitter shares from more modern vehicles, it remains to be seen how big their overall contribution and relevance for air quality might be in future.
- Evidence up to now suggests that excess emissions strongly increase with vehicle age notably beyond 10 years. Therefore, it might be easier and more cost-effective to target older vehicles with emission testing requirements or to extend durability requirements rather than setting-up an on-road monitoring scheme.
- The regulatory set-up is crucial for any enforcement action. Unless RS is part of the legally mandated techniques it is essentially (only) a monitoring tool, even if vehicles are detected with emissions above in-use standards. In any case, corrective action needs to be taken by additional means.
- Limit values applicable to new and in-use vehicles refer to different test cycles and are also formulated in different units. Reliable correlations between the different test protocols are needed to make results from RS directly transferable.
- Finally that some vehicles have higher emissions than other does not necessarily mean that they are malfunctioning or in breach of any emission regulation. For legal action therefore the cut-off threshold must correspond to some in-use standard.

1.4.4 Clean screening

Clean screening is a program to exempt vehicles from a mandatory inspection after being measured with very low emissions when passing RS detectors. It is intended to provide convenience to vehicle owners by exempting them from inspection while not risking vehicles with excessive emissions on the road. It has been used in several US States. In a way it is the opposite of the high-emitter screening discussed above and as such shares similar features:

- Repeat measurements are recommended – or the combination of the RS with a "low emitter index".
- The "clean pass" limits are set quite low to guarantee clean operation also under different than measured driving conditions.
- All relevant pollutants need to be measured as there are no reliable correlations among them.

Typical results:

In the following results from the latest Colorado clean screening program are discussed (McClintock 2012): During the year 2011 7.5 million unique light duty vehicles were measured, of which about 1.15 million vehicles were due for IM in the following months. About 26% of vehicles qualified for a clean screen exemption, i.e. vehicle owners did not need to go to an emission inspection³.

The clean screened vehicles had on average only half the emission level of all vehicles passing the mandatory IM240 test in that year (cf. Fig. 7). About 3% of vehicles inspected were falsely qualified as clean by RS but their emission rates were just a little higher than the average rates of the vehicles passing the IM240 test. Therefore this small rate of false detection is not important for the resulting total emissions.

³ Colorado stipulates that a maximum of 50% of the fleet can obtain a RS clean screen.

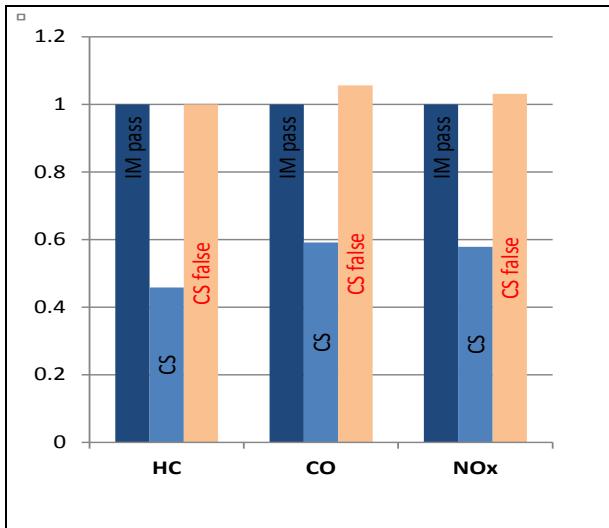


Fig. 7: Level of emissions from vehicles passing the IM240 test (set to 1), failing the test, and from vehicles qualified as clean by RS (CS). Average emission for passing vehicles on the IM240 test were 0.24, 3.23, and 0.64 g/mi for HC, CO and NOx respectively. (Data from McClintock 2012).

This shows that the clean-screen thresholds used in that study were quite stringent and absolutely sufficient to safely exempt more than one fifth of vehicles without compromising pollutant emissions. In fact, almost only vehicles younger than MY1996 received a clean-screening assessment, i.e. vehicles with advanced OBD (Fig. 9).

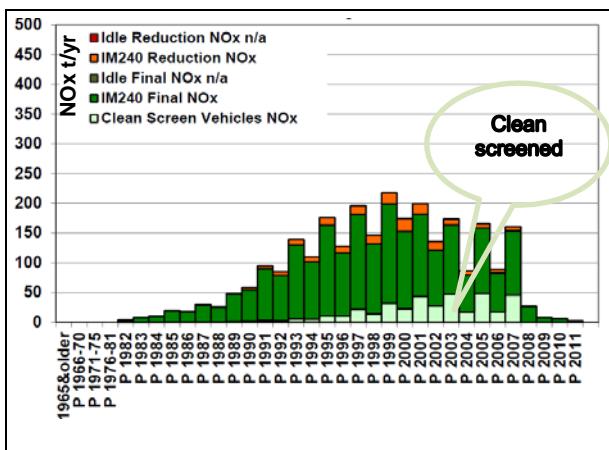


Fig. 8: Repartition of NOx emissions from passenger cars by model year that passed the IM240 test or were clean-screened in Colorado in the year 2011. In orange are emission reductions after repair, in light green the vehicles exempt because of clean screening. The latest 4 model years are exempt from IM testing, that is required biannually on Colorado. (Adapted from McClintock 2012). Copyright © 2012 Envirotest Systems. Reprinted with permission by Envirotest Systems.

The program used two approaches to qualify a vehicle as clean screened: Required were either two recent RS records each below the threshold value for all pollutants, or one RS record below threshold plus a high score in the low-emitter index ('Hybrid')⁴. Both approaches worked well but the 'Hybrid' approach had a somewhat lower rate of false detections. Hence the combination of the instantaneous on-road RS record with average test cycle results seems recommendable.

Discussion

If clean-screening is offered as legal alternative to mandatory inspection testing, a large-scale program in order to provide good coverage is required. However, in order to avoid false exemptions by RS, the low-emitter thresholds need to be quite low. Consequently, only a certain fraction of the fleet can be exempted with this approach. To increase the reliability of the remote pass-by measurements would require multiple records of the same vehicle under different driving conditions, which in turn means to increase sampling time or size. For the remainder of the fleet, to execute repairs and probably also for inter-comparison testing there will still be the need to have a garage based emission testing system running. Thus, while the clean-screening may provide convenience to vehicle owners, it effectively means setting up an extra parallel structure. Yet, by exempting clean vehicles this might safe extra garage capacities and by alerting high-emitters existing capacities might be used more effectively. In addition, one system can cross-check on the other.

The clean-screening is in a way the opposite to the high-emitter identification: While the former tends to exempt new vehicles as they have durably low emission rates, the latter tends to filter out old vehicles (plus some malfunction-

⁴ The low-emitter index is constructed from the historical pass rate in the IM240 test by make and model, for the study area. A vehicle model qualifies if the success rate has been 98% or higher over the IM240 test.

ing) because they have much higher emission rates from the start and may have deteriorated already significantly. If these findings remain true also in future, then one might consider a registration based I/M system in general exempting younger vehicles and targeting the older fleet, see also (Eisinger and Wathern 2008).

It is interesting to note that I/M failure rates and level results are not fully consistent and comparable to RS high-emitter identification rates and emission levels. That is an indication that the vehicle fleets and test conditions are not identical.

1.4.5 Cross-check on individual I/M results

RS can be used to double-check on the effectiveness of repair or I/M certificates: When high-emitters are found in RS these results might be double-checked against the latest I/M certificate. If there is a clustering of suspicious vehicles at e.g. certain I/M stations, this might be an indication for improper execution.

1.5 Costs

It is beyond the scope to make an account of the full costs and different cost components of an RS program or to compare them with alternative programs. The values cited here shall only serve as indication. In general it can be said that the RS technology is effective in identifying polluting vehicles. Whether these vehicles are then actually repaired strongly depends on the set-up and follow-up of the program.

- For high-emitter repair or removal (Keating and Taylor 1997) cite a wide range of cost-effectiveness for remote sensing and repair programs: The cost-effectiveness is highest for CO with a range of US\$ 200 to 400⁵. Cost-effectiveness for HC reductions span from US\$ 300 over 850 and 3700 to 7600. Similarly, costs for NOx reductions are quoted from US\$ 3400 over 15'000 (Berard

2009) to 33'000. Low recruitment and repair of high emitters are responsible for the highest costs: For instance the Californian "High Emitter Repair Or Scrap" Program (HEROS) identified about 15'000 potentially high-emitting vehicles by RS, but eventually only 375 light-duty vehicles were repaired or removed. Obviously, a tenfold higher participation would have strongly reduced the abatement costs. Therefore a careful and robust program design is key to its success and cost-effectiveness. This statement is however likewise true for any alternative I/M program: When it is ineffective then costs are always high.

- The purpose of a clean screening program is to verify low emissions, and not to achieve emission reductions. Hence, costs are not abatement costs, but rather costs of verification. For instance, in Colorado the fee for a clean screen exemption is US\$25, the same as for a station inspection (EnviroTest INC 2013a). With about 300'000 vehicles using the clean screen exemption in 2011, 30% of all vehicles due for inspection, the total volume for the RS program is about US\$7.5 million. Envirotest, the leading company, markets that such a scheme is self-financing (EnviroTest INC 2013b).

1.6 Conclusions

RS is an excellent tool for monitoring mean on-road fleet emissions as its large sample volume under real-driving conditions provides very accurate results. It provides an important but not complete picture of on-road emissions. However *statements on individual vehicles (e.g. high emitting or clean vehicle) are coarse and, although good for screening, do not substitute for single vehicle tests.*

RS measurements have shown that *older vehicles, and in particular vehicles without OBD*, contribute disproportionately to vehicle pollutant emissions. Therefore, *directing monitoring and maintenance of these vehicles is a key challenge for cost-effective air pollution control.*

⁵ In US\$ of 1990.

On-road screening can help to increase the effectiveness of an I/M scheme by identifying high emitters and exempting clean-vehicles from mandatory inspection. In areas with no testing infra-structure, on-road testing can be at least an initial step to help encourage maintenance and reduce high emitters.

Given the apparent better durability and thus low emission levels of modern vehicles, scheduled annual or biennial inspection of the whole fleet does not appear the best choice any longer. Further, it has been shown that off-cycle emission have higher shares. Therefore *a more comprehensive coverage of real-world driving conditions in I/M and in new vehicle certification driving cycles should be considered*. RS measurements have helped to identify how important which VSP ranges are for on-road emissions.

Results from RS emission testing could become more compelling with a clear mandatory status. So far, participation in voluntary repair or scrap programs like in California or Texas (see above) was low. While RS technology has proven its potential it strongly depends on the program set-up and implementation whether it results in pollutant reductions on the road.

1.7 Recent RS applications outside the US

The following lists a few selected sources for recent RS applications outside the US (whose sources have already been cited extensively throughout the test):

Europe

Results from RS measurement campaigns in Gothenburg/Sweden in 2001, 2002 and 2007 are described (Ekström, Sjödin, and Andreasson 2004; Sjödin and Jerksjö 2008).

Several campaigns have been conducted in the UK since 2008, with results described in (Carslaw et al. 2011; Carslaw et al. 2013; Rhys-Tyler and Bell 2012).

Long-term RS measurements have been performed at one site in Zurich/Switzerland, with latest results described in (Goetsch 2013; Borken-Kleefeld 2012).

RS campaigns were conducted in the Spanish cities of Barcelona, Granollers, Madrid, Sevilla and Valencia between 2008 and 2012 (Technet 2010; Gala 2012; Technet 2008a; Technet 2009; Technet 2008b).

Remote sensing is used in The Netherlands for improving emission factors and the traffic inventory, among others (Kraan et al. 2012).

Australia

(R. Smit and Bluett 2011) compare dynamometer test results with RS measurements for Australian light-duty vehicles.

China, Hong Kong and Taiwan

Results from RS campaigns in Hong Kong from 2001 to 2013 are reported (Chan et al. 2004; Lau, Hung, and Cheung 2012; Yam 2012).

RS campaigns have been conducted in various Chinese cities, with results reported in (Guo et al. 2007).

Results for Taiwan are presented in (Ko and Cho 2006).

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