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REVIEW OF CURRENT PRACTICES AND NEW DEVELOPMENTS IN HEAVY-DUTY VEHICLE INSPECTION AND MAINTENANCE PROGRAMS

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EXECUTIVE SUMMARY

The purpose of an inspection and maintenance (I/M) program is to identify high-emitting vehicles and mitigate their impact on air quality and climate. I/M programs require vehicle owners to subject their vehicles regularly to a certified emissions test. Vehicles that fail the test, owing either to emissions that exceed the regulatory threshold or to emissions control component malfunctions, are required to undergo repairs. High emitters are vehicles whose pollutant levels are significantly greater than expected based on the vehicle's type, certified emission standard, and age. High emitters typically make up a small percentage of a vehicle fleet but are responsible for an inordinately large amount of total emissions. Heavy-duty vehicles (HDVs) represent, on average, less than 5 percent of the global on-road vehicle population, but 40–60 percent of on-road nitrogen oxide (NO_x) and particulate matter (PM) emissions , and around 70-90 percent of black carbon emissions comes from these vehicles. Within that 40–60 percent, a disproportionate share of the NO_x and PM emissions can be attributed to a small fraction of HDVs, the high emitters.

In this paper, we review the best practices for I/M programs, evaluate existing I/M testing methods and protocols and their limitations, examine new and emerging techniques for I/M testing, evaluate a range of I/M programs across the globe, and make recommendations about how to improve I/M programs in the future.

Best practices for I/M programs have been fairly well established over the years. Five overarching best practices were identified as follows: (1) design a comprehensive institutional structure for I/M program management (2) base I/M program technical design on local impact assessment studies, subject to improvements over time (3) promote I/M program compliance and enforcement (4) obtain and manage resources (5) build up maintenance capacity in I/M programs. The bulk of this paper addresses the technical design of HDV I/M programs.

Current I/M programs for HDVs rely on two main testing methods, the free acceleration smoke (FAS) test and the lug down smoke test. The free acceleration test is the most common and least expensive method and is done by engaging the throttle in the fully open position for a few seconds. The lug-down test is a loaded test that requires placing the vehicle on a dynamometer to simulate conditions of engine load for the test. Both of these tests rely on exhaust measurements using smoke opacity meters, which will sense when tailpipe soot levels are above a certain threshold. There are many limitations of these testing techniques. First, these tests are typically only used to measure smoke, (an indicator of PM emissions), whereas other pollutants such as NO_x are not measured. Second, these tests are not suitable for newer vehicles with advanced aftertreatment systems due to the fact that the tests are not sensitive enough to detect many of the potential malfunctions of an advanced emissions control system.

There are a number of newer measurement technologies and testing methods that could be utilized to improve I/M programs. Improving the measurement of particles will likely involve a shift from conventional opacimeter to advanced technologies that can read a wider range of particle sizes and concentrations, such as laser-light-scattering photometry (LLSP). Measuring NO_x and nitrogen dioxide (NO_2) under I/M programs could be done using non-dispersive ultraviolet absorption spectroscopy (NDUV). Alternatives testing methods that can complement or replace traditional I/M methods include the use of on-board diagnostics (OBD), remote sensing, and the On-road Heavy-

duty Vehicle Emissions Monitoring System (OHMS). OBD systems , which monitor the main functionality of the engine emissions control systems, are available on newer HDVs in several countries. Adoption of OBD data for I/M programs can complement inspection measurements since OBD directly monitors the systems that affect vehicle emissions. Remote sensing, utilizing roadside emissions measurement setups to measure vehicles' emissions as they drive by, has been used for a variety of purposes, including gauging the characteristics of the fleet overall, setting in-use compliance limits, and identifying high emitters. Remote sensing can be utilized in I/M programs whereby remote sensing detects both clean and dirty vehicles and either postpones or accelerates their I/M tests accordingly. One of the most promising new methods to detect high emitters is the On-road Heavy-duty Vehicle Emissions Monitoring System. The OHMS collects HDV exhaust emissions while running the vehicle under a partially enclosed, tunnel-like structure. This system has the potential to measure particulate numbers (PN), particulate mass, and black carbon (BC) emissions, along with gaseous pollutants. The main advantage of the OHMS with respect to current FAS is that it can measure NO_x and PM for all types of vehicles, whether mechanically or electronically controlled, with or without after-treatment systems.

Some key conclusions and recommendations from this study are:

1. Only a handful of countries and sub-national governments have implemented I/M (and other) programs for controlling HDV high emitters. We recommend that all countries adopt some form of I/M program for HDVs based on their specific situation.
2. The current programs were designed based on an older fleet, and although some countries are revisiting the pass/fail criteria to take into account newer technologies (Euro III, Euro IV, EPA 2004, and their equivalents), the adoption of new measurement techniques and testing methods (such as OHMS) are needed to accommodate the cleanest fleets (Euro VI and EPA 2010) and as well as additional pollutants.
3. Refining the criteria used to assess HDV compliance with I/M testing is vital. Policy makers can investigate and discover the characteristics and distribution of noncompliant vehicles, based on local studies; pass/fail criteria should be based on those local studies and tailored by vehicle technology or certification level.
4. I/M programs ideally would be combined with complimentary measures. Measures, such as remote sensing programs, can help governments concentrate resources on monitoring and improving the vehicle types with highest noncompliance ratios and therefore increase the pass rate of I/M testing.
5. In regions where the emission standards for new HDVs require OBD systems, there is the potential for improving the I/M program for those vehicles with the system. OBD's advantage is that it will monitor and report on specific emissions control systems to be repaired, which is the main purpose of the I/M program. Also, the information gathered can be codified and utilized for a wider in-use compliance and enforcement program, checking on failure rates and potential warranties and recalls.

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1 BACKGROUND

Inspection and maintenance (I/M) programs require vehicle owners or operators to subject their vehicles to emissions inspections and to repair them in cases of failure. Inspections may be either periodic (e.g., once a year as a requirement of registration) or random (roadside pullovers). A vehicle fails the test if emissions are found to exceed limits set for that particular vehicle type. In some regions, a vehicle also fails if any component of the emissions control system is found to be malfunctioning, even if excess emissions are not demonstrated. Owners or operators of vehicles failing testing are required to take steps to repair the vehicle or face penalties. Vehicles that continue to fail inspections even after being repaired are prohibited from operating in the jurisdiction where they are registered.

The purpose of an I/M system is to identify high-emitting vehicles and mitigate their impact on air quality. High-emitting vehicles are those whose pollutant levels are significantly greater than expected based on the vehicle's technology, certified emission standard, and age. The definition of "high emitter" is not completely settled among research groups, but the most common practice is to segregate vehicles into classes defined by technology/certification standard/age and to define high-emitter cutoff points as a multiple of the respective emission standard (i.e., vehicles with emission rates X times above the corresponding certification standard are considered high emitters) or by relative position in the emission rate distribution of the fleet (i.e., vehicles with emission rates in the X^{th} percentile of the population emission distribution are considered high emitters). It should be noted that older vehicles within a fleet are not necessarily considered high emitters per se. Older vehicles can maintain emission rates close to the design emission standard through proper and regular maintenance practices. An I/M program would therefore not trigger repairs in those well-maintained older vehicles. In regions where older vehicles still constitute a large share of the fleet and are a large contributor to the local emission inventory, the most common option to reduce their emission contributions is to promote vehicle replacement programs, also known as scrappage programs.

Vehicles become high emitters for the following reasons:

1. Negligence

Improper or incorrect vehicle maintenance or operation can cause early deterioration of engine or emission control components. Examples of negligence that could lead to increased emissions are not changing the lubricating oil at regular intervals, neglecting to replace air and fuel filters, miscalibrated spark timing, unresolved fueling rate issues, and injector leaks. Refilling the tank with improper fuel can also cause higher emissions by damaging the vehicle's fuel injection systems or emission control equipment.

One special case of negligence is ignoring the malfunction indication light (MIL) that is a feature of the OBD system designed to alert the driver in case of malfunctions that can lead to increased emissions. Operating a vehicle despite MIL activation potentially leads to high emissions.

Incorrect vehicle operation can also lead to elevated emissions. Driving a vehicle that is overloaded, above its manufacturer-defined gross vehicle weight rating (GVWR), could result in excessive engine and transmission demands, with potential damage to engine components and after-treatment systems, thereby causing high emissions.

2. Tampering

Tampering refers to the deliberate modification of a vehicle, engine, or emission control device that leads to emissions increases. Such tampering is typically the result of the owner's or operator's attempts to boost vehicle performance, save costs, or improve vehicle fuel economy. For example, the reprogramming of the vehicle's electronic control unit (sometimes called reflashing) or removal of a vehicle's catalytic converter or exhaust gas recirculation (EGR) system to raise performance can increase emissions and may be considered illegal tampering. I/M programs generally aim to identify vehicles whose excess emissions are caused by owner/operator negligence or tampering.

3. Manufacturer defects

Vehicles may also become high emitters because of design or manufacture defects. For example, a defective component, inadequate quality control on the production line, or poor durability of components could all cause a vehicle's emissions to exceed limit values.

Other types of defects that result in high in-use emissions stem from a disconnect between the design conditions used for developing the emission control systems (i.e., laboratory engine testing) and the conditions that the vehicles experience during daily use. As an example, high in-use NO_x emission during city operation have been reported from HDVs fitted with selective catalytic reduction (SCR) systems, owing to the lower exhaust temperatures experienced under low-speed urban driving conditions (Lowell and Kamakaté, 2012).

Inspection and maintenance programs are different from in-use compliance and enforcement programs, which are primarily aimed at early detection of excess emissions caused by manufacturer defects.[1] A large database of I/M test results may be useful to compliance regulators as a way of identifying issues if a particular vehicle model consistently fails across multiple inspections. In specific cases I/M programs have been able to detect manufacturer defects before in-use compliance programs flag the models in question. In Europe, high in-use NO_x emissions from diesel vehicles have been identified with remote sensing programs (Chen and Borken-Kleefeld, 2014), and that information resulted in proposed changes to the European type-approval regulatory process for passenger cars, namely, the prospective adoption of Real Driving Emissions testing.

HIGH EMITTERS AND AIR QUALITY

Diesel engines are widely used around the world in commercial and heavy-duty applications owing to their higher efficiency, superior torque at low engine speeds, reliability, and durability. However, untreated diesel exhaust, which is made up of numerous gaseous and solid chemical compounds, is widely recognized to be a public health hazard and damaging to the climate. Specific emissions of concern include ozone precursors, such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs); particulate matter (PM) and PM precursors (e.g., NO_x and sulfur oxides—SOx); and toxic and carcinogenic compounds such as formaldehyde. In addition, black carbon (BC), the light-absorbing carbonaceous fraction of PM, absorbs solar radiation and re-emits it as heat, making this short lived climate pollutant (SLCP) the second-largest contributor of energy to the climate system after carbon dioxide.

1 Some examples of in-use compliance programs are: in-use conformity, conformity of production testing, selective enforcement audits, and in-use verification programs and surveillance testing.

Known health effects of diesel exhaust include cancer (especially lung cancer), heart disease and stroke, asthma, bronchitis, and other respiratory infections and diseases, as well as acute effects such as irritation, lung function changes, headaches, nausea, and fatigue (e.g., see Kagawa, 2002; Sydbom et al., 2001; ARB, 1998). Many of the health effects caused by diesel exhaust are linked to particle size and composition, including the presence of toxic compounds. Diesel emission particles can penetrate into the deepest portion of the lungs because of their small size (less than 100 nanometers, or 0.1 micrometers, in aerodynamic diameter), where they can pass through cell walls and be transported via the bloodstream to other organs of the body (Gehr, 2010; Prasad and Bella, 2010). Smaller particles also offer more surface area overall for adsorbing toxic organic compounds. These health impacts of diesel exhaust result in significant societal losses in the form of premature deaths, forgone productivity, missing work days, increased medical spending for hospital admissions and emergency room visits, restricted activities, and more.

HDVs, both new and in use, are attractive targets for policymakers hoping to reduce PM, BC, and NO_x emissions and improve local air quality. Owing to a combination of higher rates of operation (i.e., distance traveled each year) and elevated emission rates (grams of pollutant per distance traveled), diesel HDVs are responsible for a high share of PM, BC, and NO_x emissions from motor vehicles in both developed and developing countries. In addition, in many nations around the world, HDV emission control programs have lagged behind programs for passenger vehicles. Table 1-1 summarizes the relative contribution of HDVs to highway emission inventories for selected countries and regions around the world, not including high emitters. Heavy-duty vehicles represent, on average, less than 5 percent of the global on-road vehicle population, but 40–60 percent of on-road nitrogen oxide and particulate matter emissions, and around 70-90 percent of black carbon emissions come from these vehicles. On a national and regional level, these values can vary dramatically, as illustrated in Table 1-1.

Table 1-1. Examples of HDV shares of total highway vehicle emissions around the world

Region	Year	HDV percentage of vehicle fleet	HDV percentage of vehicle NO_x emissions	HDV percentage of vehicle PM emissions	HDV percentage of vehicle BC emissions	Reference
Australia	2010	19%	67%	59%	81%	ICCT Roadmap
Brazil	2009	3%	46%	45%	—	Ministry of the Environment (Brazil), 2011
Canada	2010	15%	74%	52%	92%	ICCT Roadmap
California	2008	1%	48%	44%	—	ARB, 2009
China	2009	4%	40%	57%	—	MEP, 2010
Europe	2010	11%	68%	47%	68%	ICCT Roadmap
Hong Kong (Special Administrative Region of China)	2011	19%	70%	91%	—	HKEPD, 2013
U.S.	2010	5%	58%	36%	85%	ICCT Roadmap

High-emitting heavy-duty vehicles account for an even smaller percentage of the overall vehicle fleet but are responsible for an inordinately large share of total emissions. According to measurements of BC emissions performed by George Ban-Weiss and colleagues (2009) on 251 trucks in California, 45 percent of BC emissions come from 13 percent of high-emitter trucks. A 2013 study by the Texas A&M Transportation Institute (TTI) in collaboration with the University of Denver (DU) found that higher-emitting vehicles contribute a large percentage of emissions: 6.8 percent of vehicles tested were responsible for 19.2 percent of total NO_x emissions measured (TTI/DU, 2013). A study conducted in Canada shows that the impact of high emitters on total PM and NO_x emissions is more pronounced for a cleaner fleet: in the case of vehicles without after-treatment (pre-2008), the 25 percent of them considered high emitters were responsible for 40 percent of total PM and 35 percent of total NO_x emitted by this group; in the case of vehicles with after-treatment systems (DPF and selective catalytic reduction, or SCR), the 20 percent of them considered high emitters were responsible for 56 percent of total PM and 52 percent of total NO_x (Envirotest Canada, 2013). Measurements carried out by Xing Wang and others (2011) in Beijing demonstrate that around 50 percent of PM and BC emissions come from high-emitting vehicles.

Modeling estimates for high-emitter contributions relative to total on-road fleet emissions estimate that these vehicles are projected to be responsible for more than 50 percent of PM and BC emissions by 2020. Global modeling of PM emissions by vehicle model and technology performed by Fang Yan and colleagues (2011) estimates that high-emitting vehicles will become the largest contributors of PM emissions by 2020, especially those from Asia, Africa, and Latin America. The 2011 UNEP Integrated Assessment of Black Carbon and Tropospheric Ozone identified elimination of high-emitting on-road and off-road engines as one of two key measures for mitigation of international emissions of black carbon in the transport sector (Shindell et al., 2011). These findings suggest that detection of high emitters contributes to air quality and is even more effective when implemented in cleaner fleets.

Although there is a general consensus on the magnitude of HDV high-emitters' contribution to local and international emission inventories, the benefit flowing from I/M programs is rarely explored in the literature, and the data vary greatly as a function of local fleet characteristics, testing procedures, and pass/fail criteria. For HDVs, most of the data on high-emitter contributions come from a handful of study cases focused on the I/M effect on pre- and post-inspection emissions. Robert L. McCormick and associates (2003) studied the effect of I/M repairs on 26 vehicles reporting visible smoke emissions, 14 of them pre-1991 models, and reported that after the repair the average smoke opacity of those vehicles had declined to between 26 and 30 percent and PM declined by around 40 percent, while NO_x emissions actually increased by 15–30 percent. TTI and DU estimated (they did not measure directly) that the benefit of repairing the group of high-emitting vehicles identified during the study was amounted to around 8 percent in NO_x reductions (TTI/DU, 2013).

Countries and regions looking into adopting new I/M programs or improving current ones could ideally carefully evaluate the potential benefits based on locally run testing campaigns and complementary data from remote sensing programs. This would permit the tailoring of pass/fail criteria and test procedures to the local fleet composition and the relative contribution of various pollutants.

BEST PRACTICES FOR INSPECTION AND MAINTENANCE PROGRAMS

Inspection and maintenance (I/M) programs are in place in many countries, especially for light-duty vehicles, and have been operating for several decades, resulting in a wealth of experience from which the best practices presented here have been sifted (USAID, 2004; Wagner and Rutherford, 2013; Fung and Suen, 2013). Best practices can be organized around four common topics: institutional design, technical design (impact assessments, test procedures, standards, vehicles), public awareness, and resource management.

1. Design a comprehensive institutional structure for I/M program management

National policymakers should develop the general policy framework, while local ones should adapt and strengthen the program to meet area-specific air quality challenges. I/M program implementation and especially individual project grant determinations ideally should be handled by municipal policymakers, who have a detailed understanding of local needs and conditions, including fleet composition and fuel use. Local policymakers will be better suited to making estimates of the expected emissions reduction (useful for maximizing cost-effectiveness) as well as to ensuring that older vehicles are retired properly. National policymakers and enforcement officials, through the quality assurance system, can play a role in local I/M programs.

There is broad consensus among I/M program reviews in the literature that the inspection function ought to be conducted in a specialized facility (USAID, 2004; Fung and Suen, 2013). There are two institutional design options: a small number of centralized testing hubs or a larger number of more dispersed testing facilities. In the case of the more comprehensive facilities in a few locations, the high volume of inspections makes it easier to spread the costs over a greater number of clients, while allowing for easier oversight of the testing facilities and protocols. A larger number of more limited facilities can make access easier for drivers, but oversight becomes burdensome, and investments in advanced equipment as well as proper calibration and repair of testing equipment can pose a challenge.

Another difficult question of institutional design is whether vehicle inspections should be performed by government agencies or private outfits. There are pros and cons for each option. A report from USAID (2004) favors private firms over government agencies, the reason being that a capital-starved public operation could be constrained in trying to provide the range of services offered by a well-funded private inspection company. The issues of subpar quality standards and equipment and technical competence can be addressed by making sure that funds raised by the I/M testing fees are dedicated to personnel training and to proper maintenance and upgrading of the testing equipment and facilities. The bottom line is that, independent of public or private operation, adequate testing equipment and staff training, with close oversight, is required.

A third option with respect to I/M program design, which has been tried out in the United States, is self-testing. The self-certification program allows proprietors of vehicle fleets to perform tests in their own maintenance facilities, as long as the testing and repairs are certified to the standards of the state in which the facility is based and results are reported to the state (ARB, 2014). Self-certification is advantageous for vehicle fleet operators that have their own facilities and certified technicians and inspectors but also requires a robust oversight program.

Independent of the program design and phase-in options, the I/M program needs strict oversight and quality assurance in order to achieve the expected environmental benefits. Oversight, which national officials can conduct, preferably with some input from third-party experts, aims to make sure that no vehicles that should fail inspection are somehow getting a pass. Quality assurance seeks to guarantee that the testing equipment, protocols, and technical staff are up to the job within certain specified criteria.

Program phase-in is another important element to consider. I/M programs should be designed with some degree of flexibility around their implementation dates. In some cases the phase-in corresponds to the type of vehicles subject to the rules (e.g., according to HDV OBD fleet penetration), and in other cases the phase-in covers the emission limit itself (the threshold for passing the I/M test becomes stricter over time). This phase-in flexibility is important to allow for public awareness and for the development of the program managers' technical capacity.

Although not part of the I/M program, complementary policies that cover vehicles lacking emission control systems, such as vehicle replacement, retrofitting, or repowering programs, can be developed in parallel to remove from circulation the worst emitters, thus helping to reach the envisioned levels of emission reductions. More information on complementary policies can be found in the ICCT reports by Posada et al. (2015) and Wagner and Rutherford (2013).

2. Base I/M program technical design on local impact assessment studies, subject to improvements over time

Even though test procedures and emission thresholds are commonly chosen by the national government for deployment in the vast majority of circumstances, I/M programs should ideally be adapted to fit local needs, redesigned around a data-driven local impact assessment study. The study should determine the types of vehicles in circulation and vehicle use profiles, which pollutants are being monitored, I/M emission test pass/fail levels, and costs and benefits. Vehicle type specifications and vehicle use profiles identify those that contribute the most to local/regional air quality. The species of pollutants being controlled by the I/M program depends upon testing capabilities and equipment and their relative importance in local air quality inventories. Countries and regions that have fuels with a high concentration of ethanol in gasoline should pay special attention to formaldehyde emissions; high volumes of natural gas–powered vehicles require special attention to methane (a greenhouse gas) emissions and leakage. I/M programs must design the emission test pass/fail level taking under consideration the age distribution of the fleet, the emission control technologies in use, and the level of air quality improvement that can be feasibly achieved through vehicle maintenance at a reasonable cost.

As new vehicle emission standards become more stringent over time, the I/M program standards should evolve to take into account the penetration rates of new technologies and cleaner vehicles among the fleet. The evolution of OBD systems and sensors should also figure into updates on the regulation.

A cost and benefit or cost-effectiveness analysis would be required to determine at what cost a range of benefits in terms of air quality and health improvements can be secured. The cost analysis should cover capital and operating costs of the inspection process. The benefit analysis should forecast metric tons of pollutants reduced on an annual or phase-in-length basis and evaluate the impact in terms of public health; in the case of cost-effectiveness analysis, the final cost per ton of pollutant removed can be compared against international or regional benchmark values or complementary programs (retrofitting, repowering, or replacement) and used as input for program design.

I/M testing protocols are intended to reach a balance between accuracy, testing time, and costs. The best testing protocols are expected to be reasonably cost-efficient and accurate enough to indicate whether vehicles perform within compliance limits. The goal is not to verify that the vehicle meets the emission standard, but to check whether it exceeds a certain threshold.

The periodicity of inspection is commonly between six months and two years (USAID, 2004). The longer time period between tests is suitable for newer vehicles, based on statistical data and analysis of emission contributions. Older vehicles or high-mileage-use vehicles should be tested more frequently. The periodicity should also take into account the availability of testing centers, the size of the fleet, and the composition of the fleet in terms of older and newer vehicles and other vehicle characteristics.

3. Promote I/M program compliance and enforcement

I/M programs should be obligatory and be made part of the periodic vehicle registration system. According to the USAID report (2004), vehicle registration, with annual or biannual updates, is essential to construct a database that can help with program design and can target those vehicles and their operators not in compliance. A certificate attesting that the vehicle has passed inspection and is roadworthy should be incorporated into the vehicle annual registration process. As part of its compliance and enforcement efforts, the I/M program should make use of visible vehicle labels or stickers so that authorities can monitor whether a vehicle has been tested and has passed recently.

4. Obtain and manage resources

One of the most important aspects of I/M program design is determining the proper price for the inspection service. The value should be estimated in accordance with expected vehicle volumes and should cover the capital and operating costs of the testing stations. One way to reduce the capital costs, as suggested in the USAID report, would be to obtain local government subsidies for land or facilities; reduction or waivers of import taxes on testing equipment also would be helpful. In case inspection is performed by private organizations, the contract ought to anticipate that fee revenues must be directed toward proper maintenance, calibration, and renewal of testing equipment, as well as covering the training of technical staff.

One additional concern of resource management that the I/M program should account for is the training of personnel involved in maintenance, separately from those that conduct inspections. This can be done practically by incorporating the topic into technical colleges, with the participation of original equipment manufacturers and vehicle makers.

A percentage of the program’s fee-generated resources can be directed toward funding its own oversight, as well as spreading word about the benefits of the program among the community. This helps build confidence and enhances participation in the program.

5. Build up maintenance capacity in I/M programs.
Regulators need to focus as well on the ‘M’ in I/M and improve the capacity of the service sector to provide adequate maintenance and repairs for vehicles that fail I/M tests. In developing countries, the vehicle service enterprises that would most likely attend to the older, more problematic vehicles are usually small or family-owned repair shops. These small shops may lack the requisite training for diagnosis and repair of specific emission control technologies. Thus, I/M programs should encompass measures that offer assistance to the service sector for the proper electronic and mechanical evaluation of vehicles, including access to training, tools, and repair manuals.

SCOPE

This report focuses on I/M testing for heavy-duty vehicles, including both trucks and buses. I/M programs targeting light-duty vehicles (e.g., passenger cars) have a long history and ample international precedent; for this reason a brief survey of I/M programs for LDVs will be given. Although heavy-duty vehicles can be a larger source of air pollution in urban areas, especially in developing countries, I/M programs for HDVs have not been widely implemented and in most cases require upgraded testing protocols.

The report presents a review of current I/M testing protocols, including a brief description of typical LDV I/M protocols and more specifics for HDV I/M testing. Next, the authors explain why current I/M testing is not adequate for newer diesel vehicles and give an overview of new developments in I/M testing programs, notably, the use of OBD, remote sensing, and the On-Road Heavy-duty Vehicle Emissions Monitoring System (OHMS). The last section of the report summarizes HDV I/M programs around the globe.

2 REVIEW OF CURRENT I/M TESTING PROTOCOLS

Inspection and maintenance testing protocols are intended to reach a balance between precise and extensive compliance and type-approval test procedures, which are costly to conduct, and test procedures that are quick, inexpensive, yet accurate enough to define a pass/fail limit. This section provides a brief overview of I/M testing protocols for light-duty vehicles and examines those for heavy-duty vehicles in greater detail.

I/M tests are often grouped in the literature into "loaded" or "unloaded" categories (Faiz, Weaver, and Walsh, 1996; Erlansson and Walsh, 2003). In unloaded tests, the engine idles at either high or low speeds, with the clutch disengaging the engine and transmission, which implies that these tests can be carried out on the street. They are often short and simple but do not yield consistent results. Unloaded testing is fast and cheap yet is ineffective at identifying newer-model high emitters (vehicles with diesel particulate filters or advanced after-treatment systems). Common unloaded tests include idling and two-speed idling. Loaded tests use more complex equipment, including a chassis dynamometer. In this case, "load" is placed on the engine by restricting the movement of the wheels or by means of placing the wheels onto rollers. Loaded tests can be subdivided into steady-state and transient tests. In a steady-state loaded test, the vehicle's wheels are rotated at a constant speed. In a transient loaded test, the vehicle's wheels are accelerated and decelerated following a vehicle speed trace to mimic more closely real-world driving.

In terms of accuracy, loaded tests are superior to unloaded tests and require more skill to operate thanks to the sophistication of the equipment used. Loaded tests are also more time-consuming, often requiring upward of a twenty-minute waiting time for the driver (not including travel time to and from the testing site).

The pollutants monitored are typically carbon monoxide (CO), nitrogen oxides (NO_X), and hydrocarbons (HC). Particulate matter (PM) has been historically more difficult to gauge with inexpensive, portable equipment, which meant resorting to checking smoke exhaust as a proxy measurement. Cleaner diesel vehicles equipped with particulate filters cannot be tested using smoke detectors since the emission concentrations are too low for proper detection.

LDV I/M TESTING

Unloaded tests—idle tests and two-speed tests

Most LDVs in countries with I/M programs target gasoline vehicles, employing tests under unloaded conditions with the engine idling. This type of simple idle testing has been used to measure HC and CO concentrations in older Tier 0 (in the United States) and pre–Euro 1 (in the European Union) gasoline-powered vehicles fitted with carburetors (Kolke, 2005). Germany, Finland, Sweden, and the United States[2] improved the idle test by adding tests at higher engine speeds, typically 2,500 revolutions per minute (rpm). According to Faiz, et al. (1996), the two-speed idle test was developed for carbureted engines, as this air-fuel management technology presents similar air-fuel ratios at idle and under load. Thus, the measurement of CO and HC under idle and at 2,500 rpm provided a reasonable overview of emissions across the range of operations. Vehicles with electronic controls for the air-fuel ratio controls usually engage in different air-fuel ratios at idle and high load conditions, depending on coolant temperature and other engine condition inputs. For

2 In the United States, each state has an obligation to comply with the Clean Air Act requirements, adopting local measures developed under its own State Implementation Plan. I/M programs are one of the tools that state regulators can use to comply with federal air quality standards.

these advanced systems, the idle/2,500 rpm test was inadequate, leading to the adoption of a warming period (three minutes) before testing. This reduced the impact of the engine warm-up temperature on the two-speed testing results, yet there was only a tenuous correlation with the U.S. Environmental Protection Agency (EPA) Federal Test Procedure (FTP) emission test results, leading to the development and adoption of loaded tests for I/M programs (Faiz, Weaver, and Walsh, 1996).

Loaded tests—Acceleration Simulation Mode (ASM) test and IM240

According to Faiz et al.(1996), the need for better capabilities to identify high NO_x emission malfunctions and the evolution of air-fuel control and emission after-treatment systems resulted in the development of the Acceleration Simulation Mode (ASM) test. The ASM test is a loaded test carried out in a dynamometer. The test applies to gasoline-fueled vehicles only and is used in vehicles with catalytic converters and oxygen sensors that do not have on-board diagnostics (OBD) systems. HC, CO, and NO_x emissions can be monitored during this test. There are three types of ASM tests, the 50/15, 25/25, and 40/50 modes:

- The ASM 50/15 tests the vehicle at a high load and at low speed. In the 50/15 mode, the vehicle is tested on the dynamometer simulating the use of 50 percent of the vehicle's available horsepower to accelerate at a rate of 3.3 miles per hour per second (mph/s) to a constant speed of 15 mph
- The ASM 25/25 tests the vehicle at a moderate load and moderate speed. The vehicle is tested on the dynamometer simulating the use of 25 percent of the vehicle's available horsepower to accelerate at a rate of 3.3 mph/s to a constant speed of 25 mph.
- The ASM 40/50 test is the European adaptation of the ASM test. It involves a vehicle speed of 50 km/h (31 mph) and 40 percent of the New European Driving Cycle (NEDC)'s maximum acceleration rates.

In some programs the ASM50/15 and the ASM 25/25 are combined into a single test, the ASM2. The ASM2 has been adopted in Georgia, Texas, and Virginia in the United States and British Columbia in Canada for older, non-OBD gasoline vehicles. The state of Connecticut uses the ASM25/25, while New Jersey uses the 50/15.

The IM240 is an improvement over the ASM. The IM240 is the recommended test in the United States for I/M programs and requires vehicle testing on a chassis dynamometer, following the speed trace of the first 240 seconds of the FTP. This type of I/M test requires more complex dynamometers with flywheels to simulate vehicle inertia and faster gas analyzers. Faiz, Weaver, and Walsh (1996) cite a body of literature supporting the strong correlation between IM240 test results and chassis testing under the FTP. Tests carried out in California show that the IM240 correlates better with the FTP than does the ASM; Faiz, Weaver, and Walsh (1996) concluded that the IM240 is three times more accurate than the idle test for detecting high emissions. It should be noted that these test results describe the behavior of air-fuel management and catalytic converter technologies of the early 1990s, which included electronic fuel injection and first-generation three-way catalysts. The benefits of the IM240 procedure are better accuracy, allowing for lower pass/fail threshold levels and thus reducing the risk of failing a vehicle that is in good condition, and efficiency—the testing saves time on visual inspections of engine and after-treatment components.

The laboratory-grade equipment called for by the IM240 is expensive and is therefore only cost-effective in centralized I/M programs (i.e., programs with a small number of inspection facilities). The EPA, though, allows states to establish decentralized programs and to use different equipment and tests, as long as they can reliably identify most of the high-polluting vehicles. In the early 1990s, Massachusetts decided to implement a decentralized I/M program with a simpler test and less expensive equipment, suitable for small-scale facilities, called MA31.[3] The MA31 drive trace is the same as the BAR31 drive trace that was developed by California's Bureau of Automotive Repair (BAR) and is currently used in the Oregon and Rhode Island I/M programs. Extensive testing was carried out to correlate IM240 testing with MA31, while making sure that the MA31 is capable of detecting high emitters.

HDV DIESEL I/M TESTING

I/M test procedures for diesel engines have historically focused on particulate matter emissions. Because PM emissions require complex and costly equipment to conduct readings, the common practice is to measure smoke (soot), one of the main components by weight of diesel PM. Smoke emissions can be measured using the Bosch and Hartridge method or the opacimeter method.

In the Bosch/Hartridge method, a sample of smoke is passed through a filter paper, from which the particles are measured. The filter is read by a photoelectric device, which indicates the degree of blackness by a numeric scale. The method is limited when it comes to detecting particles that are not very dark and thus correlates poorly with PM measurements overall, but it correlates better for soot (black carbon) (McCormick et al., 2003).

The opacimeter method, on the other hand, measures the attenuation of a beam of light passing through a plume of exhaust gases. The reading is presented in terms of opacity percentage and includes the effects of both light absorption by soot particles and light scattering by oil and fuel aerosols, providing a better indication of the whole PM spectrum. Based on the density of smoke emitted, opacity readings from 0 percent (no smoke) to 100 percent (smoke blocks light entirely) are recorded (Giechaskiel et al., 2013). For I/M testing, the opacity readings are compared with pre-established criteria values for determining whether a vehicle passes or fails. Most countries have historically used this opacimeter method for diesel inspection in I/M programs.

The most commonly used opacity tests for I/M programs are the free acceleration smoke test and the lug-down test.

Free acceleration or snap-idle smoke test

The free acceleration smoke (FAS), also known as the SAE J1667 test, measures smoke emissions from diesel vehicles. Diesel particulate matter registers as very low under idling conditions, which means that proper measurement requires testing the engine under load. The FAS test is also known as the "snap acceleration" or the "free acceleration" test. Peak opacity is measured after engaging the throttle in the fully open position for a few seconds. The load is provided by the engine's own inertia. The Society of Automotive Engineers (SAE) developed the test protocol J1667 in order to improve the method's accuracy. In the SAE J1667 method, the average of the maximums recorded in three snap-idle tests is used to determine passing or failing (SAE, 1996). The

3 Commonwealth of Massachusetts, Executive Office of Environmental Affairs, July 21, 2003. MA31 Conversion Factor Analysis and Interim Test Effectiveness Evaluation: Massachusetts Enhanced Emissions and Safety Test. Retrieved from http://www.vehicletest.state.ma.us/program-reports/itechrpt.pdf

FAS test is convenient because of its simple setup requirements. It can be done at the roadside, or in a truck depot or repair facility, and can be used for self-certification. Most of the nine U.S. states with their own HDV I/M programs use FAS tests with multiple pass/fail limits, depending on vehicle model year.

The smoke test shows high test-to-test variability. In one study that analyzed six short I/M tests against the Australian Composite Urban Emissions Drive Cycle (CUEDC) for diesel vehicles, the FAS test resulted in the least dependable indicators of fine and ultrafine particle levels (Anyon et al., 2000). Similarly, Robert L. McCormick and his coauthors (2003) found that, for vehicles without after-treatment systems (pre–EPA 1998 standards), use of proxy data, either CO or CO plus HC, from an FAS test was a significantly better predictor for detecting high PM emitters than smoke opacity measurements. According to Faiz, Weaver, and Walsh (1996), the FAS test serves as a rough indicator of serious emissions malfunctions, much like the idle tests for gasoline vehicles. Tests in European diesel passenger cars show that FAS does not correlate well with any driving cycle and that this is particularly true in the case of the NEDC, where no correlation at all was found (Samaras et al., 2005). In addition, Zissis Samaras and colleagues concluded that the preconditioning of the vehicle (e.g., engine warming) has a strong influence on FAS test results, making the test "even less reliable."

Loaded tests—lug-down smoke test

The lug-down test is a loaded test ("lug down" means to slow the engine by raising its load) and requires placing the vehicle on a dynamometer to simulate conditions of engine load for the test (St. Denis and Lindner, 2005). The International Organization for Standardization specifies a test method (ISO 7644) for measuring opacity using a dynamometer-based lug-down test. The accelerator is depressed to wide-open throttle (WOT) without load until the engine reaches the maximum speed, or "governor" speed. Load is then applied to the dynamometer until the engine speed decreases to 90 percent and then 80 percent of the top speed at WOT. Smoke measurements are taken at all three speed/load conditions. In some areas, such as Colorado in the United States, the engine speed is decreased to 70 percent as well (CDPHE, 2015). The criteria for passing require that all the readings fall below certain threshold emissions. The lug-down test, as a basic loaded test, has been used in various jurisdictions for HDVs, including Colorado, Hong Kong, Singapore, and Beijing (Fung and Suen, 2013).

The literature suggests that the lug-down test is effective at detecting high emitters, but its testing protocol presents some challenges. According to Energy and Environmental Analysis (2000), measured HC and NO_x emissions for 1998 and earlier model year vehicles under lug-down testing show reasonable correlation with emissions in the more representative drive cycles carried out during chassis testing. However, many studies have shown that the correlation between exhaust smoke opacity and PM/NO_x emissions from diesel vehicles is weak, even when measured under a controlled load on a dynamometer (Erlansson and Walsh, 2003; McCormick et al., 2003; Norris, 2005). Therefore, even if the lug-down test can lead to repairs that limit smoke, particle or NO_x emissions are not necessarily reduced as a consequence. It was also found that diesel engines that are adjusted to reduce visible smoke may in fact have increased NO_x emissions (Fung and Suen, 2013).

Australia's diesel test—DT80

The DT80 is a loaded inspection emission test for HDVs in Australia. It is designed to track both PM and NO_x emissions. The DT80 is an aggressive, mixed-mode test with idling periods, three stages of WOT acceleration, ultimately to 80 kilometers per hour (50 mph), followed by a steady-state 80 km/h cruise. The total duration of the DT80 is 250 seconds. This test requires the use of a chassis dynamometer.

The National Transport Commission in Australia studied the adoption of the DT80 for its HDV I/M program in 2001 as a potential replacement for the FAS for I/M testing (Campbell, 2006; NHVR, 2015). Experiments carried out in Australia found that emissions measured under the DT80 have a high correlation with expected on-road emissions performance (Anyon et al., 2000).

Given that the DT80 requires an inertia-simulating chassis dynamometer, it is conducted as a centralized program, operated by private contractors. The DT80 may be used for further testing of specific vehicles with high emissions after these have been screened through remote sensing techniques . In Australia currently, there are only three laboratories equipped to provide DT80 testing (NHVR, 2015). Nonetheless, the DT80 is being used in some areas as a requisite to qualify for a fuel tax credit.[4]

SUMMARY OF CURRENT INSPECTION AND MAINTENANCE TESTING PROTOCOLS FOR LDVS AND HDVS

Table 3-1 presents a summary of the testing protocols for LDVs and HDVs presented in this section. The summary covers the test requirements (roadside servicing or chassis dynamometer), pollutants tested, and comments on the pros and cons of each protocol.

Table 2-1. Summary of testing protocols for I/M programs

Test Name	Loaded or Unloaded	HDV or LDV	Test requirements	Pollutant measured	Comments
Idle test and two-speed test	Unloaded	LDV	Roadside	CO and/or HC	Poor correlation with chassis test emission results.
Acceleration Simulation Mode (ASM)	Loaded	LDV	LDV chassis testing	HC, CO, and potentially NO_x	Improvement over unloaded test; strong correlation with certification testing results. Applies to vehicles with three-way catalytic converters but not OBD.
IM240	Loaded	LDV	LDV chassis	HC, CO, and NO_x	NO_x, CO, and HC emissions results correlate better with certification chassis testing than with the ASM. Requires a centralized program to amortize the costs.
MA31/BAR31	Loaded	LDV	LDV chassis	HC, CO, and NO_x	Shorter chassis-based test but has been deemed just as capable of high-emitter identification.
FAS or SAE J1667	Unloaded	HDV	Roadside	Smoke opacity	Designed for mechanically operated diesel vehicles. It is inadequate for PM screening or for measuring NO_x.
Lug-down	Loaded	LDDV and HDV	Chassis test	Smoke opacity	Targets older, smoky vehicles. Not designed for measuring PM or NO_x.
DT80	Loaded	HDV	Chassis test	PM, NO_x	The most comprehensive protocol among all HDV loaded I/M testing.

Note: LDDV: Light-duty diesel vehicles.

4 Australian Government, Department of Transport and Regional Services. Fuel Tax Credits for Heavy Diesel Vehicles: Guidelines for Satisfying Environmental Criteria. Retrieved from http://www.infrastructure.gov.au/roads/environment/fuel_tax_credit/pdf/Fuel_Tax_Credit-Environmental_Guidelines.pdf

LIMITATIONS OF CURRENT I/M TESTING FOR LEGACY AND CLEAN DIESEL VEHICLES

Global emission standards for HDVs have evolved over time, inducing the adoption of advanced technologies in new vehicles and, in consequence, greatly reducing the exhaust concentrations of particulate matter (PM) and nitrogen oxides (NO_x) emitted. Figure 1 shows the progression of emission control technologies for HDVs and provides a sense of the emission limits for NO_x and PM under the European and the U.S. Environmental Protection Agency (EPA) regimes, respectively. The adoption of selective catalytic reduction (SCR) systems for NO_x control, starting with the Euro IV standards and EPA 2010 standards, and the introduction of diesel particulate filters (DPFs) with the Euro VI and EPA 2007 standards are milestones that present the biggest challenges for effective I/M programs as they strive to keep up with evolving technologies.

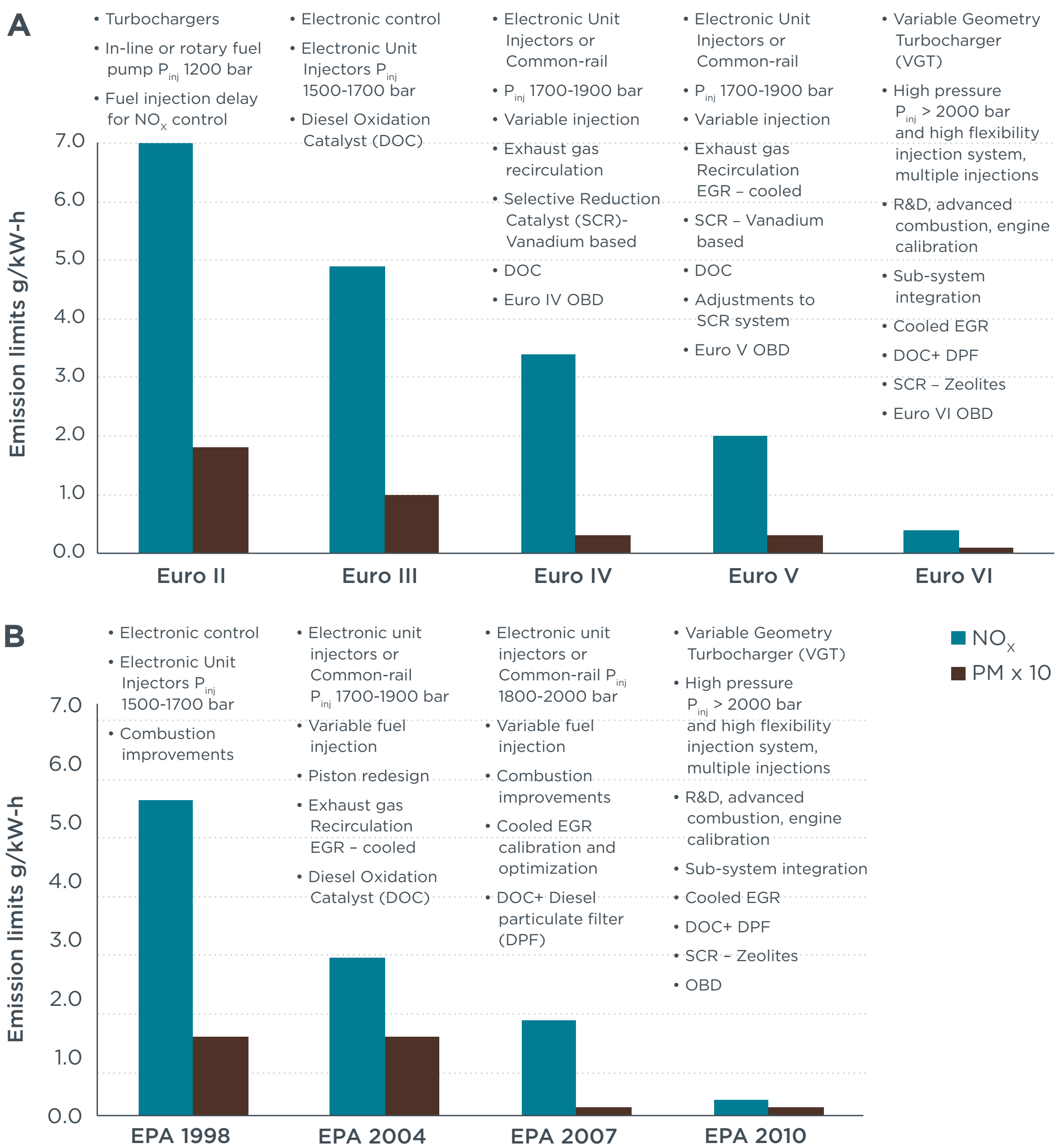

Figure 1. Progression of emission standard levels and adoption of new technologies for heavy-duty vehicles: a) European program; b) U.S. EPA program

PM emissions levels and composition are different for vehicles with and without PM filters. The effect of diesel oxidation catalysts (DOCs) and particle filters on the amount and composition of particulate matter in exhaust is dramatic when contrasted with engines lacking after-treatment systems (Khalek et al., 2011; Herner et al., 2011). Ruehl et al. (2014) recently reported on PM composition and particle size distribution changes between a 1998 vehicle and a 2010 vehicle; the 1998 vehicle has no after-treatment and a mechanically operated fuel injection system (representative of most "legacy" heavy-duty diesel vehicles across the world), while the 2010 vehicle is equipped with electronically operated common rail fuel injection systems and both DPF and SCR systems. The researchers found that, independent of the testing cycle used, the PM emitted from the 1998 engine consists almost exclusively of organic carbon (that is, carbon bound to other elements in compounds) and elemental carbon (OC and EC). These two chemical components constitute the majority of diesel PM from trucks without after-treatment, with the proportion of each dependent on the specific engine technology and engine operation. The cleaner 2010 engine produces about fifty times less PM by mass. However, the PM from the 2010 engine is composed not only of EC and OC but of a large fraction of sulfates and, to a lesser extent, nitrates (with the relative proportions dependent upon the duty cycle, or the speed and load conditions under which an engine operates, as can be seen in Figure 2). The sulfates and nitrates are produced by chemical reactions that occur in the exhaust catalyst.[5]

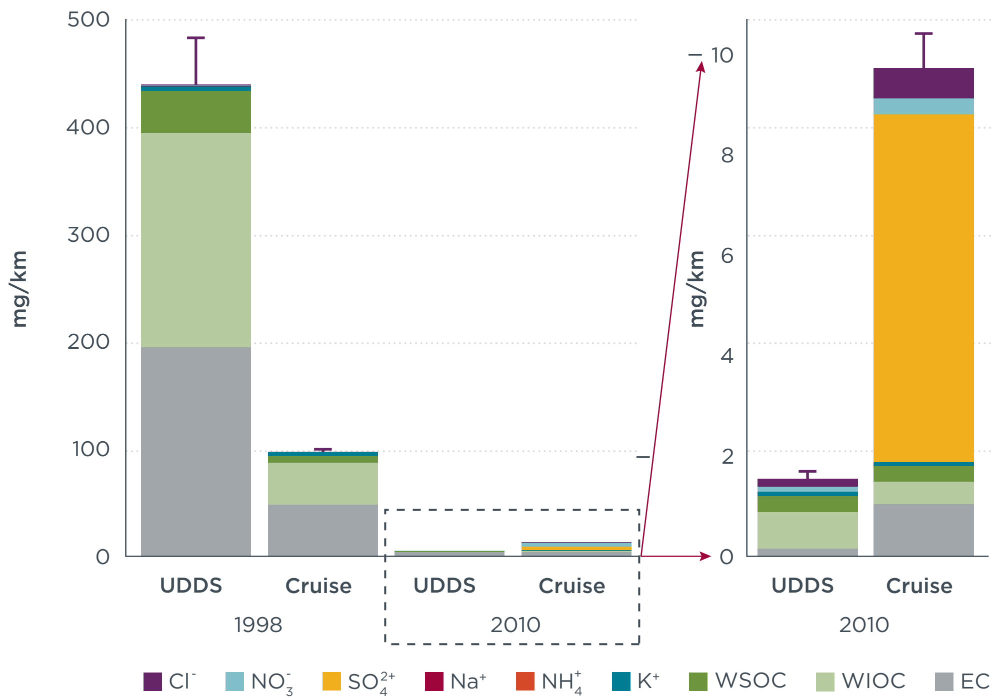

Figure 2. PM composition from a 1998 (uncontrolled, no after-treatment) and a 2010 heavy-duty truck. Note that the scale in the right panel (2010) has been magnified from the central panel to show the 2010 PM composition better. WSOC means water-soluble OC and WIOC means water-insoluble OC. UDDS stands for urban dynamometer driving schedule. ***Source***: Ruehl et al., 2014.

5 Sulfates come from oxidation of sulfur compounds found in diesel fuel, while nitrates are the product of NO_x reduction reactions.

Regarding size distribution, Ruehl and coauthors report that the 1998 engine emissions display a unimodal distribution with a peak at 100 nanometers (nm), while the 2010 engine emissions show a bimodal distribution, with a principal peak identical to that of 1998 but at a much lower concentration and a second peak around the 20 nm mark. Interestingly, particles clustering around the second peak (~20 nm) are composed mostly of sulfates.

This change in PM levels and composition is problematic with respect to the soot-based PM measurement used in conventional I/M programs. Currently, these programs for HDVs focus on soot readings using the free acceleration smoke (FAS) test or lug-down test, but these tests have difficulty correlating PM emissions from smoke measurements. These tests and the corresponding smoke opacity measurement technique were developed to detect high emitters that have mechanically controlled engines and no after-treatment system. As discussed in the previous section, the relationship between smoke and PM emissions under these testing conditions is unclear.

The problem of low correlation between smoke measurement and PM emissions makes the smoke detection method an unreliable option for discovering high emitters of PM. Brodrick, et al. (2000) point out that a malfunctioning puff limiter (a device to curtail excess smoke) results in a thick, black puff of smoke when the vehicle accelerates, but that does not affect emissions under any other operating condition. The defect would produce very high readings on the smoke opacity meter under an FAS test but little impact under a lug-down test. Conversely, a dirty air filter or worn-out fuel injector could have a large impact on PM emissions but only a small effect on smoke opacity measurements during acceleration. Thus, smoke opacity meters may be able to detect high smoke emissions under some testing conditions, and caused by certain malfunctions, but they are poor indicators of high PM emissions in other circumstances or in the case of different kinds of malfunctions.

Moreover, a review of literature on soot measurement techniques by Giechaskiel et al. (2013) found that opacity measurements are not suitable for post-1998-model engines because the emissions are far below the detection limit. These engines, even without DPF, show average opacity values around 3 percent or less, which is close to the opacity detection limit. Moreover, tests carried out with cracked DPFs showed that the opacity meters were not capable of identifying those with damaged filters.

NO_x emissions, on the other hand, have been historically excluded from I/M programs because of the higher testing costs entailed, as these can only be measured through lug-down tests, with more sophisticated measurement equipment. One of the reasons NO_x cannot be tested with reasonable reproducibility using methods that do not incorporate loading is that engine-out NO_x is fairly proportional to engine load (Faiz, Weaver, and Walsh, 1996). During FAS testing the loading demands are minimal, resulting in meaningless NO_x readings. Thus, loaded testing on a dynamometer, or any other means to simulate load on the engine, is required to use NO_x measurements as indication of engine and emission system condition.

In the early 2000s, California carried out a pilot program to study an I/M testing reform for heavy-duty vehicles (ARB, 2003). The concept was focused on reducing excess NO_x emissions. During this program, 67 HDVs were tested on a repair-grade chassis dynamometer. Most vehicles were in the 1990–2001 certification groups, with NO_x limits between 4.0 and 6.0 grams per brake horsepower–hour. Results showed that 15 percent of the vehicles tested may have exhibited excess NO_x, with the highest emitter group demonstrating NO_x emissions greater than 12 g/bhp-hr. Vehicles with NO_x emission rates above 10.0 g/hp-hr (about 1.6–2.4 times their certification standard) were considered to be failing the I/M test and were required to undergo repairs. During the pilot, 21 vehicles were sent for fixes. Testing of repaired vehicles subsequently revealed very small NO_x improvements of around 2.1 percent. Overall, the pilot results indicated high costs for repairs and only minor emissions benefits. The conclusion of the pilot program was that the proposed I/M design was not practical for identification of high NO_x emitters. California's Air Resources Board decided that alternative testing concepts would be needed to move forward with a NO_x screening program for heavy-duty vehicles. (Lyons, 2015; St. Denis and Lindner, 2005).

3 PROPOSED METHODS AND NEW DEVELOPMENTS

Most current inspection and maintenance (I/M) programs for heavy-duty vehicles were created to target high emissions of particulate matter (PM) for vehicles with little or no PM emission control technology. Those vehicles, mostly pre–Euro II standard (in the European Union) or EPA 1998 or earlier (in the United States), emit PM with a composition that makes soot sensing the right technology for detecting malfunctions. Newer vehicles with advanced PM and nitrogen oxides (NO_x) emission control technologies, such as common rail fuel injection systems, diesel particulate filters (DPFs), and selective catalytic reduction (SCR) systems, emit pollutants at levels that are more difficult to evaluate with the emission measurement techniques of legacy I/M programs.

This section introduces new methods for identifying high emitters via traditional I/M programs and also through complementary programs. Traditional I/M programs can benefit from new developments with regard to particulate matter and gaseous emission measurement systems. Improved testing protocols and on-board diagnostics (OBD) systems are tools that can be incorporated within the framework of existing heavy-duty vehicle (HDV) I/M programs. Remote sensing and the On-road Heavy-duty Vehicle Emissions Monitoring System (OHMS) are other technical options to extend the tests conducted under HDV I/M programs into the realm of real-world driving conditions.

NEW DEVELOPMENTS INVOLVING PM AND NO_x MEASUREMENT EQUIPMENT FOR I/M TESTING

It was previously noted in this report that opacity readings do not correlate well with particulate matter measurements and that NO_x measurements are not covered by the large majority of I/M programs. A review of recent pilot projects and studies into better instruments for particle measurements under very low emission concentrations (typical of DPF-equipped vehicles) and for inspection-grade NO_x measurement reveal that there are a handful of measurement devices that can be deployed in HDV I/M programs that offer a reasonable trade-off between accuracy and cost.

The conclusions from the Test Diesel (TEDDIE) project, a joint effort by the European Commission and the International Motor Vehicle Inspection Committee (CITA) to improve diesel vehicle emissions measurement, including I/M testing, suggest that there are commercially available instruments for I/M testing with the right technical characteristics to measure PM at lower levels than can be measured with current opacimeters. Under this project, laser light scattering photometry (LLSP) instruments and a diffusion-charging real-time particle counter were evaluated (Text Box 1).

The three LLSP instruments tested present good accuracy at very low and very high PM emission concentrations. Moreover, excessive PM emissions can be clearly identified with LLSP instruments, and their correlation with type-approval emission testing is much stronger than what current opacimeters offer. The costs of LLSP are similar to those of opacimeters. The LLSP devices are also easy to handle and require about the same amount of training as do opacimeters. It should be noted that a change in the type of instrument used would require a corresponding shift in emission limits values and units, from smoke density (m^{-1}) to milligrams per cubic meter (mg/m^3).

The results from TEDDIE on LLSP coincide with an investigation carried out by Parsons in 2000, on behalf of the National Environment Protection Council of Australia, aimed at improving their I/M testing protocols for diesel vehicles (Parsons, 2001). The authors concluded that smoke opacity did not correlate well with PM measurement under local chassis testing cycles. In contrast, they deemed that LLSP, in conjunction with effective vehicle preconditioning techniques, can be an accurate, robust, and reliable method of measuring particulate mass and has potential as an effective, low-cost I/M tool.

NO_x measurement instruments for I/M programs are not as developed as PM/soot sensors. Given that there is no significant market for them at the moment, it is not a surprise that literature on this topic is scarce. The TEDDIE project evaluated some of the most promising sensors, and its conclusions and recommendations are summarized here. According to the observations, non-dispersive ultraviolet absorption spectroscopy (NDUV) is the most suitable technology for nitric oxide (NO) and nitrogen dioxide (NO_2)—the two components of NO_x—measurement during I/M testing. Electrochemical cells, similar to those used by NO_x sensors in advanced vehicle aftertreatment systems, were also evaluated but were found to be inferior to NDUV's performance because of wide-range calibration issues and instability of measurements. The authors of the TEDDIE report concluded that the NDUV instrument performed well during type-approval testing and that it was technically suitable for I/M testing, although cost was perceived as an obstacle to broad adoption (CITA, 2011).

SENSORS FOR PM AND NO_x MEASUREMENT

There are a number of instruments in different stages of development for measuring PM, black carbon (BC), and NO_x. A brief overview of the instruments most likely to be applied in advanced inspection and maintenance programs (since research groups have found them to be simple, portable, and capable of raw exhaust gas measurements) is presented in the following paragraphs. Further literature on this area can be found at Gautam et al. (2000), CITA (2011), Giechaskiel et al. (2013), and Giechaskiel, Riccobono, and Bonnel (2014).

Particulate matter and black carbon measurement
One of the most common direct reading instruments is the *optical sensor* (Giechaskiel et al., 2013). These instruments read the interactions between particles and a light source. Opacimeters currently used by I/M programs measure the amount of light that is blocked by soot particles (mostly BC). Some candidate optical-sensor-type instruments for I/M testing measure light scattering, while others use a completely different technique that involves particle sizing and distribution.

CONTINUED

Laser light scattering photometry (LLSP)

Scattering is the deflection of light in various directions by irregularities in an aerosol sample. Either halogen light or a laser light source is used to illuminate the sample gas. A mirror set at a 90-degree angle to the light source captures the scattered light through a sensor. The scattered light received by the sensor is dependent on the wavelength of the light source and the particle size. LLSP is suitable for very low particle concentrations, with measurement ranges of 0.1–200 mg/m^3, well below the opacimeter range. (CITA, 2011). An evaluation of this type of instruments for I/M purposes is available at Durbin T. (2010)

Diffusion charge sensors (DCS)

Diffusion charge sensors are designed to measure particle size distribution by charging, classifying, and counting the particles. The sample drawn from the exhaust pipe moves through a confined space where particles are electrostatically charged. The particles enter the measurement chamber, which consists of a high-voltage positively charged electrode surrounded by electrometers. The particles change their trajectory as a result of repulsion forces and end up on the electrometers at different locations depending of size. This design allows for continuous measurement of particle size and number, and the accuracy depends on the quantity of electrometers in the chamber. DCS is the most likely instrument to be deployed for PN measurements as part of the Real Driving Emissions regulation in Europe. A detailed discussion on DCS and PN measurement can be found at Giechaskiel et al. (2014).

NO and NO_2 measurement

Several technologies are currently used for NO_X measurement in different applications. Only nondispersive ultraviolet absorption spectroscopy (NDUV) and electrochemical cells have been considered previously for I/M programs (Gautam et al., 2000; CITA, 2010). These two and two other methods, chemiluminescence and nondispersive infrared absorption spectroscopy (NDIR), are presented here for the sake of completeness.

Nondispersive ultraviolet absorption spectroscopy (NDUV)

NDUVs operate under the principle that a gas absorbs a particular band of wavelength in the ultraviolet spectrum, while it will transmit all other wavelengths (Gautam et al., 2000). Special detectors capture the amount of absorption of light energy, and, from that, concentration is inferred. NDUV sensors are used in portable emission measurement systems (PEMS) for on-road measurements, showing good correlation with laboratory-grade instruments (CITA, 2011). The advantage of NDUV readings is that they do not show cross-sensitivity with water vapor and carbon dioxide.

CONTINUED

Electrochemical cells
These sensors were developed as a result of fuel cell technology and are commonly used to detect oxygen concentration. In these instruments, the oxidation of NO generates a small electrical current, proportional the amount of NO present (Gautam et al., 2000). The technology was used to develop smart NO_x sensors in the 1990s by NGK/VDO (a Japanese electronics manufacturer in combination with a German equipment supplier). Widely available now, NOx sensors with this technology are currently used in all Euro VI and EPA 2010 heavy-duty vehicles for on-board diagnostics (OBD) functions.

Nondispersive infrared absorption spectroscopy (NDIR)
NDIR instruments operate under the same principle as NDUV (Gautam et al., 2000). Unfortunately, NDIR and Fourier transform infrared spectroscopy show cross-sensitivity to water vapor, which prevents them for being applied in typical I/M testing environments (removing the cross-sensitivity implies additional system complexities, which, although technically feasible, increase costs) (CITA, 2011). NDIR analyzers are currently used to measure carbon monoxide, carbon dioxide, sulfur dioxide, and some hydrocarbons (Gautam et al., 2000).

Chemiluminescence detector (CLD)
The chemiluminescence detector is the standard instrument for measuring NO and NO_2 during type-approval tests (CITA, 2011). CLD measures the light emitted when NO reacts with ozone (O_3). During the reaction, about 10 percent of the NO that is converted to NO_2 emits photons, which the CLD instrument picks up as a proxy for NO concentration in the sample gas. For NO_2 measurement, the NO_2 in the sample is dissociated from NO and then added up to the original NO (Gautam et al., 2000).

ALTERNATIVES FOR IMPROVING I/M TESTING FOR HDVS

Besides enhancements to current I/M testing, which requires better and more representative yet short drive cycles, as well as more accurate and inexpensive gas and particle analyzers, there are alternatives that can complement or potentially replace traditional I/M methods. These encompass OBD, remote sensing, and the OHMS.

Changes to I/M protocols

A review of the literature shows that changes to the protocols are closely related to the new technologies that are emerging for PM measurement and others directly incorporated into vehicles (i.e., use of SCR and DPF).

The TEDDIE report, which as of the writing of this paper was the best source on new developments in the field, suggests that detecting high emissions of PM from older and newer vehicles can still be accomplished through FAS testing, by adopting better instruments (e.g., LLSP) and by changing the pass/fail criteria. The adoption of LLSP would require additional studies for establishing appropriate vehicle-specific emission limits (by age or technology group) as well as instrument calibration and certification procedures for the use of LLSP within HDV I/M programs (CITA, 2011).

The TEDDIE report concluded that the biggest challenge for current FAS testing with respect to NO_x emissions is that SCR systems are not warm enough during the test, resulting in inconclusive readings. That is, the SCR system can be operational, yet the low exhaust temperature range does not allow it to function as intended.

This implies that today's FAS testing would not be suitable for NO_x testing in regions following the European standards (e.g., India and China). The alternatives for overcoming this problem are either to modify the current vehicle pre-conditioning protocol for FAS, to switch to loaded chassis testing (lug-down or Australia's DT-80), or to adopt OBD as part of the inspection.

On-board diagnostics

OBD systems monitor the performance of engine and after-treatment components, including those responsible for controlling emissions.[6] The OBD system is designed to help ensure proper operation of the emission control equipment, alerting the driver in case of malfunctions, so as to keep vehicular emissions within certain limits during daily use. OBD systems are a valuable tool for vehicle owners and technicians since they provide important feedback about maintenance needs and potentially urgent repairs. OBD assists in the service and repair of vehicles by providing a simple, quick, and cost-effective way to identify problems by retrieving vital automotive diagnostics data.

OBD was first introduced to heavy-duty vehicles (HDVs) in 2005 in Europe for its Euro IV standard. The phase-in schedule of CARB/EPA OBD requirements started with HDVs with a gross vehicle weight rating (GVWR) below 14,000 lbs between 2005 and 2008 in the United States, as a continuation of technologies developed for LDVs. OBD requirements were extended to the heavier categories starting in 2010.

Other countries have adopted HDV OBD requirements following the European program model. India instituted OBD rules for its Bharat IV emission standards starting in 2013; Brazil has adopted OBD regulations similar to Euro IV/V since 2012 for its PROCONVE P-7 HD standards; China requires OBD as part of the China IV HDV standard (equivalent to Euro IV) since July 2013. A summary global overview of OBD systems for HDVs can be found in Posada and Bandivadekar (2015).

Adoption of OBD data for I/M programs can complement inspection measurements since OBD directly monitors the systems that affect vehicle emissions. OBD systems monitoring covers two main categories: threshold monitoring and nonthreshold monitoring. Threshold monitoring requirements apply to critical emission control systems. The malfunction indicator light (MIL) turns on when sensors detect signals likely to lead to emission levels above a specified threshold value, known as OBD threshold limits (OTL).[7] Each emission threshold limit value is related to the vehicle emission standard, as a multiplier or as an added value in the case of NO_x. It should be noted that European OBD regulations set thresholds only for PM and NO_x, while the U.S. OBD requires in addition nonmethane hydrocarbons (NMHC) and carbon monoxide (CO). Nonthreshold monitoring involves functional, and electrical monitoring

6 Definition according to the U.S. Environmental Protection Agency.

7 Some OBD sensors perform direct measurements (e.g., oxygen concentrations), but most rely on lookup tables or virtual sensing techniques, which are mathematical model predictions of the target parameter based on available inputs (e.g., model-driven "NO_x sensors" predict engine-out NO_x concentrations based on engine parameters).

of 75–100 signals per engine. This includes tracking of engine and certain after-treatment components for total failure, ability to reach a particular target, response rate to reach the predetermined target, circuit continuity, voltage, current, and many more characteristics of each separate system involved in reducing emissions.

A list of heavy-duty vehicle systems monitored by vehicles compliant with Euro IV, V, and VI standards and EPA 2010 are presented in Table 4-1. This systems monitored cover after-treatment systems (DPF, SCR), engine systems (e.g., fuel injectors and turbochargers), and other relevant systems (electrical systems and sensors). Some of the systems are monitored against OTLs, while others are monitored only for functionality issues. Thanks to the wide coverage of all the systems involved in vehicle emission control, OBD can serve as a tool for observing the mechanical and maintenance status of in-use vehicles.

OBD testing is incorporated into I/M programs during vehicle annual inspections. During an OBD test, the mechanic taps into the OBD port on the vehicle and retrieves any diagnostic trouble code (DTC) saved by the system to determine the type and status of the fault. (In the event of an emission-related component fault, following a systematic trouble code evaluation, a DTC is stored in the memory of the control module responsible for that component, and the malfunction indicator light on the dashboard will illuminate to alert the driver of the malfunction.) The DTC can be retrieved using a diagnostics logger or OBD DTC reader (or scanning tool). Currently, use of OBD as part of I/M programs for HDVs is limited to Ontario in Canada and Oregon in the United States.

Table 3-1. Summary of global HDV OBD monitoring requirements. Source: Posada and Bandivadekar, 2015

OBD Requirement	Euro IV/V Stage 1 and 2	Euro VI	US EPA 2010
Implementation years	2005 and 2008[1]	2013–16[1]	2010–16
Diesel threshold monitoring and OTL ratios[2]	NO_x and PM	NO_x (3.2_x–2.6_x) and PM (2.5_x)	NO_x (3.0_x–2.5_x), PM (5.0_x), NMHC (2.0_x), CO(2.0_x)
Catalyst—DOC	Removal and major failure	Conversion efficiency for hydrocarbons	NMHC catalyst conversion; DPF heating
Lean NO_x trap (LNT) or NO_x absorber		Conversion efficiency; reductant delivery if used	Conversion efficiency—NO_x OBD threshold limits (OTL) monitoring; reductant delivery if used; feedback control
SCR system	Conversion efficiency; OTL for NO_x; major failure (removal, electrical failure of sensors and actuators)	Conversion efficiency—OTL for NO_x; reductant delivery (quantity, quality, consumption rate)	Conversion efficiency—OTL for NO_x monitoring; reductant delivery (quantity, quality, consumption rate); feedback control
SCR urea system	Monitoring of urea quantity, quality, and consumption	Monitoring of urea quantity, quality, and consumption	Monitoring of urea quantity, quality, and consumption
DPF system	Conversion efficiency; OBD threshold limits (OTL) for PM; major failure (removal, electrical failure of sensors, clogged filter)	Conversion efficiency—OTL for PM; major failure (removal, electrical failure of sensors, clogged filter); regeneration	Filtering performance—PM and NMHC OTL monitoring; pressure differential; regeneration (frequency, completion); missing substrate; active regeneration (fuel delivery); feedback control
Combined $deNO_x$+DPF	Conversion efficiency and thresholds for NO_x and PM; major failure		
Fuel systems	Monitoring quantity, timing, and circuit integrity	Pressure; quantity; timing; control	OTL monitoring; pressure; quantity; timing; control
Air boost systems	Mass air flow; boost pressure and inlet manifold pressure	OTL monitoring; flow rate; response; cooler operation; control; VGT-commanded geometry	OTL monitoring; flow rate; response; cooler operation; feedback control; VGT-commanded geometry
EGR systems	Monitor for failure conducive to exceeding thresholds; no explicit mention of EGR cooling systems	OTL for NO_x; flow rate; response; EGR cooler performance	OTL monitoring; flow rate; response; cooler operation; feedback control
Variable Valve Timing Systems — VVT	Not explicit	VVT target and response	PM, NMHC, and CO OTL monitoring; VVT target and response
Engine cooling systems	Not explicit	Thermostat and total failure	Thermostat; engine coolant temperature; circuit malfunction
Sensors and actuators	Monitor for electrical disconnection — circuit integrity	Proper operation; voltage; circuit integrity; monitoring capacity	OTL monitoring for exhaust gas sensors; performance (voltage, current); circuit continuity; feedback control; monitoring capacity

[1] For Europe, type approval dates; first registration dates start one year later.
[2] OBD monitors for malfunctions that lead to emissions above OBD thresholds for NO_x, PM, hydrocarbons, and CO. The ratios are presented as multiple of the corresponding standard (e.g., NO_x 2.0_x means 2.0 times the NO_x standard).

Remote sensing devices

Another way to identify high-emitting vehicles is through remote sensing devices (RSD) technology. Remote sensing consists of a light beam directed through the exhaust plume of vehicles passing by. The increment in pollutant concentrations relative to the background air is measured and expressed as an instantaneous emission factor in the unit grams of pollutant per kilogram of carbon dioxide (CO_2) or fuel. Speed and acceleration are measured as well, thus connecting the emission factor to the driving situation or engine load. A camera captures a picture of the license plate to allow linking of the emissions data to vehicle registration information, notably, to engine family and model year or emission certification. Once the vehicle and the owner are identified, if repeated readings exceed high-emitter thresholds, the owner is notified for I/M testing. Remote sensing devices are common tools to screen LDVs, as the technique does not interrupt the flow of vehicular traffic.

Remote sensing has been used for a variety of purposes, including gauging the characteristics of the fleet overall, setting compliance limits, and identifying high emitters. Because of its potential for quick mass sampling it can be an efficient method for high-emitter identification. The use of remote sensing in detecting high emitters is known as "dirty screening." "Clean screening" can also be employed, whereby remote sensing detects clean vehicles and either waives their I/M tests or postpones them for an interval. Remote sensing has been used for research purposes since this type of emission measurement method can gather large amounts of data over years of program application (Borken-Kleefeld, 2013). Remote sensing is best used in conjunction with roadside inspection practices (USAID, 2004).

Remote sensing technology is not appropriate as a substitute for an I/M program on its own, but the techniques described here can complement and improve the efficiency of a well-rounded I/M program. Remote sensing has the capacity to measure most gaseous pollutants and smoke opacity. RSD has been typically deployed to measure CO_2, carbon monoxide (CO), hydrocarbons (HC) as propane equivalents, NO, and opacity as a proxy for PM. The latest remote sensing devices also measure NO_2, ammonia (NH_3), and sulfur dioxide (SO_2) (Borken-Kleefeld, 2013). In particular the simultaneous measurement of NO and NO_2 is highly desirable for an accurate determination of total NO_x emissions from diesel vehicles with modern after-treatment devices.

An exercise exemplifying the potential of remote sensing was carried out on heavy-duty vehicles in Canada by Envirotest. Researchers tested 6,000 heavy-duty vehicles over a period of 55 days. The measurements were taken at highway weigh stations. PM was measured with ultraviolet (UV) opacity instruments calibrated to ultrafine particle measurements.[8] Regarding fleet characterization, the measurements allowed researchers to identify three different sets of vehicle emission groups:

- The 2007 and older HDVs, with PM and NO_x emissions respectively ten and six times higher than newer models, on a grams per kilogram of fuel basis;
- The 2008–2010 HDV group, with markedly lower PM emissions, thanks to DPF use, and NO_x emissions similar to the 2007-and-older group. It should be noted that the

8 RSD uses UV light (~230 nanometers) to measure opacity because of its far greater sensitivity to fine particle matter than the traditional green light (550nm) used in commercial-grade opacimeters. At that wavelength the channel is more sensitive to the particles composing most of the particulate mass emitted by today's diesel vehicles.

NO_x control phase-in started in 2007–2009 with 50 percent of sales and reached 100 percent in model-year 2010;

» The 2011 and newer models, with very low PM and NO_x emissions.

Results of the remote sensing measurement campaign are presented in Figure 3 for PM and NO_x, respectively. According to the report, 76 percent of heavy-duty vehicles observed were 2007 or older models, and these were responsible for 90 percent of NO_x and 98 percent of PM measured emissions. It is important to note how the actual emission trends, especially for PM, roughly parallel the line indicating the progression of emission standards equivalents, reflecting the steady penetration of emission control technology.

Figure 3. HDV PM and NO_x emissions measurements with remote sensing devices (purple and blue markers). ***Source***: Envirotest Canada, 2013

One of the most significant applications for remote sensing programs is the ability to identify high emitters and to develop emission cutoff points tailored to local fleet characteristics. Researchers from Envirotest and the University of Denver developed two different sets of cutoff points for identifying an HDV as a high emitter. The first set was for the worst performers overall, and the second was directly linked to vehicle emission standards plus allowances accounting for test variability. According to the researchers, the first method identified 8 percent of tested HDVs as high emitters, responsible for around 17 percent of total NO_x and PM from the tested fleet. The second method, linked to emission standards, identified 26 percent of HDVs as high emitters, responsible for 42 percent of the PM and 38 percent of the NO_x emitted by the tested fleet. Repairs to the flagged HDVs under the first method would result in around a 9 percent reduction in NO_x emission rates, while repairs to vehicles flagged as high emitters under the second method would result in significantly greater emission rate cuts, by 23 percent for PM and 16 percent for NO_x. The researchers recommended adding an odometer reading to gain an idea of the collective distance traveled annually and in this way to assess the total tons of pollutants eliminated (Envirotest Canada, 2013).

On-road Heavy-duty Vehicle Emissions Monitoring System (OHMS)

The On-road Heavy-duty Vehicle Emissions Monitoring System was developed as an outgrowth of remote sensing techniques (Stedman, 2013). The OHMS collects HDV exhaust emissions over about an eight-second acceleration cycle, including gear changes, while running the vehicle under a partially enclosed structure. The system measures particulate number, mass, and black carbon emissions, along with gaseous pollutants. This is achieved by setting up a shed or tent structure, mostly without side walls, over the roadway, where the acceleration occurs. In the roof of this structure is placed longitudinally a perforated sampling tube that collects exhaust gases and air and drives them into the exhaust measuring system. Total vehicle testing time takes about 4–5 minutes, including instructing the driver on how to proceed through the tent. Figure 4 shows a photograph of the system in use.

Figure 4. OHMS setting. The sampling pipe is located in the left corner of the tent; gas analyzers and other monitoring equipment are located in the mobile unit to the right. ***Courtesy: F. Posada***

Testing conducted by the OHMS development team shows that the OHMS method can detect emissions of PM for both older and newer DPF-fitted HDVs. Figure 5 shows OHMS particulate matter results from several thousand diesel HDVs measured at a weigh station in Vancouver (Envirotest Canada, 2013). Also shown are the vehicle emission standards converted into units of grams per kg of fuel and measurement taken with conventional RSD. Observe that the OHMS results follow the pattern of the emission standards, particularly for the DPF-equipped fleets having almost undetectable on-road particulate emissions. The newest vehicle's PM emissions are extremely low, registering as below the emission standards. The measurement differences between OHMS and RSD were attributed to differences in vehicle operating mode during testing, i.e., higher PM emissions under engine idle conditions (RSD testing) and lower PM emissions under loaded conditions (OHMS/Tunnel).

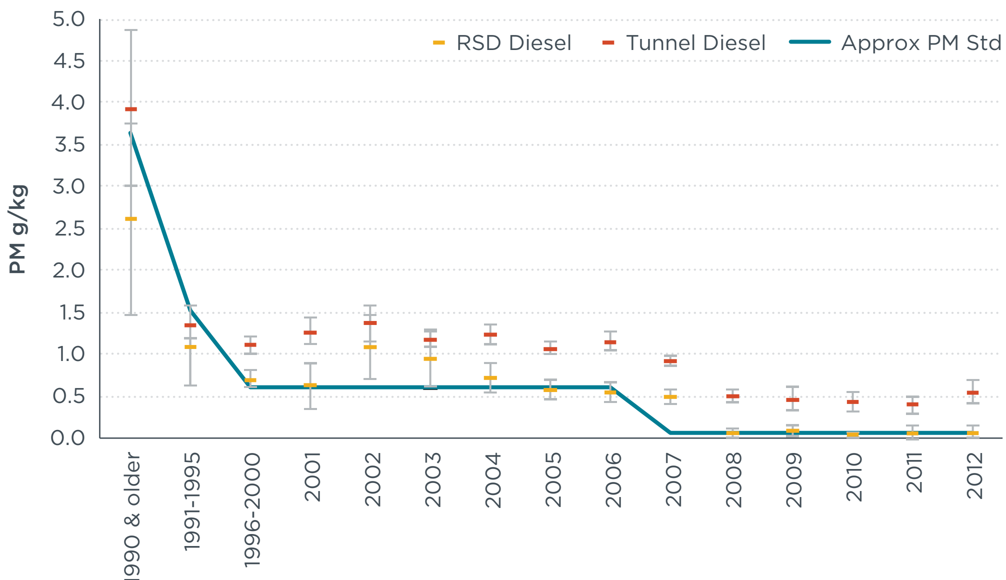

Figure 5. OHMS testing results for PM measurements of HDVs. OHMS (Tunnel) and RSD.
Source: Envirotest Canada, 2013

OHMS can be tailored to measure not just PM but also GHG species such as BC. The OHMS was recently deployed to take measurements at a location within the Port of Los Angeles and at a truck weigh station in northern California (Bishop et al., 2015). More than 3,000 tests were carried out during the test campaign. The port site heavy-duty fleet has been entirely equipped with diesel particulate filters since 2010. The research team concluded that both PM and BC increase with vehicle age. Average PM and BC emissions were higher for the weigh station fleet, which is composed of older vehicles. HDVs fitted with DPFs reported PM emissions a factor of 30 lower than the mean for vehicles without DPFs. Total PM and BC measurements show that only 3 percent of the vehicles measured at the port exceed expected emission limits (Bishop et al., 2015).

Figure 6 shows the results of OHMS testing for NO_X, comparing with the classic remote sensing device setup for different model year HDV measurements. The tests were carried out in British Columbia. The NO_X data using the OHMS are labeled as "tunnel" data. The remote sensing equipment measures only nitric oxide (NO), one of the two components of nitrogen oxides, while the OHMS measures both NO and nitrogen dioxide (NO_2). Both sets of equipment show similar trends on a grams per kilogram of fuel basis and follow the pattern of the NO_x EPA emission standards (converted to g/kg). It should be noted that although engine-out NO_x is mostly NO, the after-treatment systems on newer vehicles have technologies that significantly affect the NO/NO_x ratio. Diesel oxidation catalysts (DOCs) and diesel particulate filters are capable of oxidizing the NO into NO_2, and this is used for DPF regeneration and for proper SCR operation. NO_x emissions were the lowest for the 2011 and 2012 models, increased with age for the 2010 to 2008 models, and were highest for 2007 and older models.

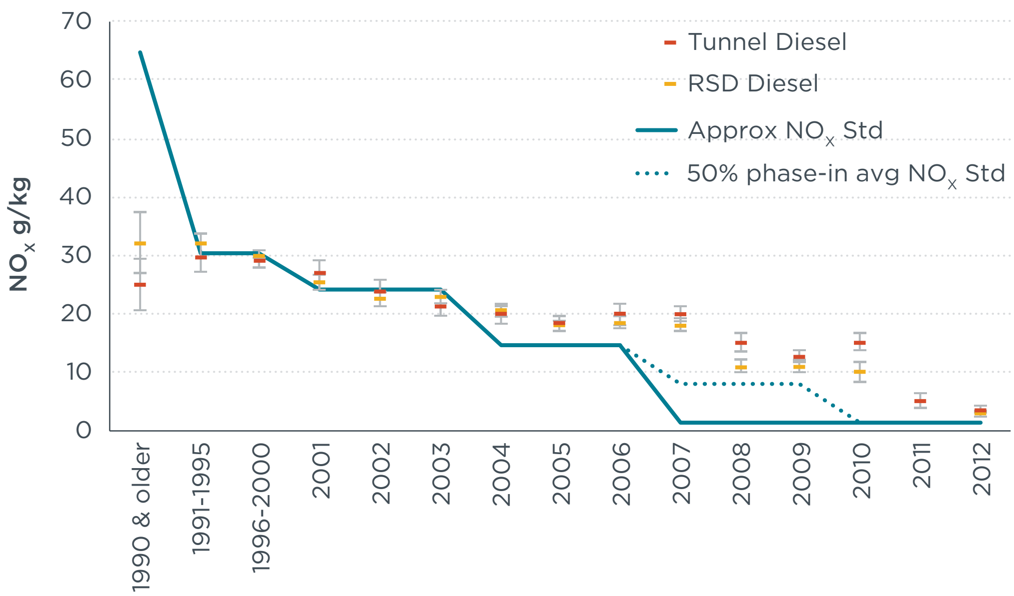

Figure 6. OHMS (Tunnel) and remote sensing device (RSD) NO_x measurement for HDVs.
Source: Envirotest Canada, 2013

The emissions measurements obtained with the OHMS have been compared against portable emission measurement systems (PEMS) testing while the vehicle passed through the tunnel (TTI/DU, 2013). PEMS systems are self-powered testing devices that measure raw emissions rates of vehicle pollutants, including NO_x, CO, HC, and particulate matter. PEMS testing is part of the certification process for HDVs under the EPA program and are also part of the HDV in-use conformity testing program of the European Commission. Measurements of NO_x with the OHMS and PEMS were performed on a sample of 10 heavy-duty vehicles. Although OHMS data overestimated NO_x emissions, OHMS data are well correlated with PEMS data. The research team at TTI concluded that the OHMS methodology was therefore a feasible technology for I/M programs or screening programs. The overestimation of NO_x readings suggests that further calibrations are required before deploying the system under an official I/M program (TTI/DU, 2013).

INTEGRATING OBD, REMOTE SENSING, AND OHMS INTO I/M PROGRAMS

In regions where the emission standards require OBD adoption for HDVs, I/M programs can be improved through the process of incorporating OBD. As OBD is introduced into the new vehicle fleet, it will take a number of years of vehicle turnover before the majority of on-road HDVs are equipped with OBD systems. OBD is beneficial in that it will report on specific emissions control systems to be repaired, which is the main purpose of the I/M program. Also, the information gathered can be codified and deployed for in-use monitoring, checking on failure rates and potential warranties and recalls. This makes OBD a valuable component of not only I/M but a much wider vehicle compliance and enforcement program.

However, there are obstacles to integrating OBD into I/M systems on a global scale. This is in part because of a lack of standardized protocols for communication among HDV OBD systems for Euro IV and similar (China IV, Bharat IV) standards. The other issue is the vulnerability to OBD tampering of Euro IV and Euro V systems, as well as their global counterparts. Chinese environmental officials have mentioned that the OBD systems of China IV HDVs (patterned after the Euro IV OBD requirement) allow for parts of the emission control system (notably, the DPF) to be removed without this being detected as a malfunction (Posada and Bandivadekar, 2015). The Euro VI standard has corrected this design flaw and has established strict rules for the detection of malfunctions and the storage of malfunction codes in the OBD control unit.[9] Still, the capacity of Euro VI OBD systems to detect tampering, store data, and avoid code clearing must be thoroughly tested before OBD can be fully integrated into I/M programs.

Recent tests in Europe demonstrate the Euro V OBD system's ability to detect failures of NO_x after-treatment systems (CITA, 2011). As part of a research program to improve I/M testing in Europe, a single Euro V engine equipped with OBD was subjected to system malfunctions, while its emissions were measured on chassis testing, and the responses of OBD codes were observed. The malfunctions induced in the after-treatment system (SCR) were disconnection of the urea doser, emptying of urea, and mixing of urea with water. The OBD system was capable of detecting all of the malfunctions and stored a code for each one. Significantly, the induced malfunctions were not detected by emission testing procedures, which included FAS and loaded, steady-state tests. The conclusion of the study's authors was to incorporate OBD with strong threshold limits within the I/M program (CITA, 2011).

The use of remote sensing devices and OHMS can be the backbone of programs for clean screening, high-emitter identification, and on-road fleet monitoring. The cleanest vehicles, or those having emissions well below the standards, would be exempt from further testing for a certain period. High emitters could be directed to further testing, including OBD checks (if available), or chassis dynamometer loaded tests.

9 Maciej Szymanski, Policy Officer at the Directorate-General for Enterprise and Industry, European Commission, personal communications, December 2014.

SUMMARY OF ADVANCED I/M TESTING METHODS

Table 4-2 presents a summary of new developments and potential testing protocols for HDV I/M programs presented in this section. The summary covers the test requirements (roadside or chassis dynamometer), the role of each within the I/M program, the pollutants tested, and comments on the pros and cons of each protocol.

Table 3-2 Summary of potential protocols for I/M programs

Test Name	Test requirements	Role	Pollutants measured	Pros	Cons
RSD	Roadside testing	Identify potential high emitters for further I/M testing	All criteria pollutants Opacity is measured as proxy for PM	• High rate of vehicle testing • Can be run inside cities • This method can be used for random inspections • Well-known technology and has been deployed in many cities • Potential for monitoring criteria pollutants and all others as needed • Testing capacity of about 200 tests per day.	• Emission measurements occur in a fraction of a second; single data point of vehicle operation
OBD	No hardware requirements, except for OBD scan tools	Stand-alone or as complementary I/M testing	Measures or estimates emission of CO, HC, NO_x, and PM; note that the European OBD only monitors for NO_x and PM emissions	• Can be part of both random and annual HDV inspections • Inexpensive and fast, as reading the OBD takes just a few minutes • Monitors/estimates the most health-relevant pollutants: NO_x and PM	• Euro IV and V HDV OBD might allow for undetected tampering of emission controls systems; verification program should be run before adopting OBD as part of IM for Euro IV and V HDV vehicles • CO and HC not covered under the European HDV OBD system
OHMS	Requires special testing equipment, but deployment is highly adaptive (roadside tests, weigh stations, or parking lots)	Stand-alone or as complementary I/M testing	All criteria pollutants are measured	• Emission tests have shown good correlation with remote sensing and PEMS emission testing • Ensures that the engine is tested under a wide range of operational points, which is an advantage over remote sensing • Duration of the test is very short, about 20 seconds per vehicle, but, realistically, perhaps four minutes total per vehicle in an I/M application.	• Still at the research level, but there is wide interest among stakeholders in making it an official test protocol, which implies further standardization

4 INTERNATIONAL EXPERIENCE

This section covers the handful of nations, regions, or local jurisdictions worldwide that have implemented inspection and maintenance (I/M) programs targeting heavy-duty vehicles. It will look at Australia, Canada, China, Guangdong province (China), the Hong Kong special administrative region of China, Europe, and selected U.S. states (California and Colorado). For each case, current practices will be examined as well as what steps, if any, are being planned to improve the programs. Information on the benefits accruing from these programs, in terms of the percentage or total tons of emission reductions, was only available for one of the programs studied, according to the available literature.

AUSTRALIA

Heavy-duty vehicles in Australia are subject to the Heavy Vehicle (Vehicle Standards) National Regulation, as part of the Heavy Vehicle National Law, which was implemented in February 2014 across all states and territories (NHVR, 2015). The I/M program is included in Part 8 (control of emissions). It presents the DT80 HDV test procedure (detailed in section 3) and pass/fail criteria, and it specifies measurement conditions, including nitrogen oxides (NO_X) and particulate matter (PM) diluted (as opposed to raw) measurements and smoke raw measurements. These regulatory conditions imply that measurement requires a dilution tunnel or partial dilution equipment, each of which is more expensive than raw measurement equipment.

It should be noted that the DT80 is a voluntary testing program. The incentive for vehicle owners to participate comes from fuel tax reductions associated with undergoing and passing the DT80 test. This is a diesel rebate under the Federal Fuel Tax Credits Program (NEPC, 2011)

In areas where the DT80 is available, such as the state of New South Wales, the adoption of this test has allowed the local traffic authority to take emission testing to fleet depots and conduct tests quickly. The state's Roads and Maritime Services agency is currently building a database to assist with the analysis of DT80 data collected from all states and territories. This HDV diesel testing infrastructure allows Roads and Maritime Services to conduct vehicle emissions audits for the Clean Fleet program, investigate new emissions management technologies, and promote the use of cleaner vehicles and technologies (NEPC, 2011). Moreover, the Clean Fleet program is one of the tools to incentivize proper maintenance of HDVs in Australia. Clean Fleet participants are eligible to seek the diesel fuel rebate mentioned above.

In the state of Western Australia, the DT80 and remote sensing methods have been employed for not for enforcement but for evaluating in-use vehicle emissions performance. The DT80 has been used for research purposes, while remote sensing is being used for community education projects aimed at having local vehicle owners test their vehicles (NEPC, 2011).

Australia has implemented a sound HDV I/M program, defined by national regulations and implemented independently by local authorities. Local implementation of HDV I/M testing is based on centralized facilities with specialized measuring equipment, complying with best practices for institutional design.

No information was available regarding whether Australia's HDV I/M program is data driven and based on specific air quality targets. However, the program has evolved over time, and significant technical design improvements have been added to the regulations, such as the development of the DT80. Moreover, Australia has undertaken preparations for an in-service emissions study focusing on diesel vehicles and a review of the in-service DT80 emissions test procedures (NHVR, 2015). Unfortunately, the Australian program falls short in one critical respect because it lacks mandatory I/M inspections, instead relying on the incentives provided by fuel tax benefits awarded for passing the inspections test.

CANADA

In Canada, monitoring and controlling in-use emissions from HDVs are within the jurisdiction of the individual provinces and territories. HDV emission I/M programs are currently operating in British Columbia and Ontario. The I/M program of British Columbia started in 1999 and is built around a roadside smoke test. This means that only visibly smoky vehicles are required to undergo free acceleration smoke (FAS) testing. If the vehicle fails the smoke test, then repair is required; neglecting to do so results in registration denial. The I/M program in Ontario, which also started in 1999, has two components, a roadside smoke test and an annual test. The random smoke test is similar to that carried out in British Columbia, targeting smoky vehicles. Contractors at decentralized facilities carry out the annual test. In Ontario, failing the roadside smoke test results in a fine, while failing the annual smoke test results in registration denial.

Canada's HDV I/M programs are based on a decentralized model that carries out periodic and roadside testing, which is in accordance with best practices for institutional design and compliance/enforcement. Although the technical design of the I/M programs is outdated, officials at the provincial level are engaged in incorporating remote sensing devices and On-road Heavy-duty Vehicle Emissions Monitoring System (OHMS) technology into their I/M programs.

CHINA

I/M regulation in China is covered under the Air Pollution Prevention and Control Law, and the programs are managed by provincial- and municipal-level Environmental Protection Bureaus (EPBs). In 2005, the central government's Ministry of Environmental Protection (MEP) released a *Notice on In-use Emissions Inspection Station Technical Manual* (Yang, Qiu, & Muncrief, 2015), standardizing the management and monitoring of in-use vehicle emission inspection stations, including procedures for loaded and unloaded I/M tests and specifying emission limits. All I/M inspection stations are "test-only" facilities that are not allowed to conduct any vehicle adjustments or repairs.

Local governments are required to adopt the MEP I/M test procedures and limits. Regions suffering from severe air pollution are advised to use the loaded test for I/M testing. Currently 345 local EPBs have established I/M programs, 50 of them conducting loaded tests—Acceleration Simulation Mode (ASM) or IM240 for light-duty vehicles. For HDVs, at a national level the required test is the FAS. Some provinces or cities with severe pollution problems, such as Beijing and Guangdong province, require the more intensive lug-down test and have also adopted remote sensing screening. According to the MEP's annual report, 14 out of 23 provinces have adopted the lug-down test as part of their local I/M HDV programs (MEP, 2015). Only smoke opacity is measured under both testing protocols. China has launched studies to look into the feasibility of using loaded tailpipe tests to measure NO_X, nitrogen dioxide, and PM emissions from heavy-duty diesel vehicles (Fung and Suen, 2013).

GUANGDONG, CHINA

Guangdong started to authorize inspection stations to conduct vehicle emission tests in addition to safety tests for I/M in 2006 (Yang, Qiu, & Muncrief, 2015). From May 7, 2013, the province decentralized the authorization of inspection stations to local environmental protection bureaus. Municipal EPBs are now responsible for both the assessment and approval of new inspection stations, as well as management of existing ones. The Guangdong EPB requires that all light- and heavy-duty diesel vehicles in the Pearl River delta region be subject to the lug-down test during annual inspections, while diesel vehicles in other regions in Guangdong must pass the FAS (Guangdong Government, 2008). Currently, all four principal cities in Guangdong province (Guangzhou, Shenzhen, Dongguan, Foshan) have issued regulations with detailed implementation measures for I/M inspection stations to carry out their work, including lug-down testing, filing data reports, and fixing penalties for violations. Commercial trucks 10 years old or newer must be tested every year, while older vehicles and school buses of any age have to be tested two times per year.

Guangdong has been complementing the I/M program with smoke detection remote sensing since 2009. Additionally, it has encouraged local EPBs to carry out on-road vehicle spot checks. By 2010 there were about 14 remote sensing mobile units and 52 remote sensing locations (Yang, 2015). The basic practice features roadside spot checks that focus on high-emitting and visibly smoky vehicles and parking lot spot checks targeting companies with more than 10 vehicles in operation. The owners of vehicles deemed out of compliance must fix them by a given deadline and pay a fine for the violation.

Vehicle emission I/M management in China was structured in such a way that policy outlines were drawn up at the national level, with localities having some freedom to go further and to manage their own facilities, which is in agreement with best practices for institutional design. Regarding enforcement and compliance, the national program has a combination of obligatory periodic testing and random testing. On an urban level there are additional enforcement provisions, such as grounding vehicles that fail I/M testing until they are able to meet the standards. The program design allows for sufficient fees to be charged to keep the stations running, although data on their expansion or budgeting for the future is unavailable.

EUROPE

I/M testing programs were first introduced in some member states of the European Union in the early 1980s, and these have since been merged into an EU directive with some amendments. In 1996, the first consolidated roadworthiness directive (96/96/EC) included basic requirements for I/M programs. The current legislation is contained in the directives 2009/40/EC and 2010/48/EC. In addition, Directive 2000/30/EC addresses emission measurement during roadside roadworthiness tests. It should be noted that each member state has an emission testing program that takes the EU legislation as the minimum requirement but with modifications to suit local conditions. For example, for passenger cars, Sweden adds a hydrocarbon (HC) standard to the minimum carbon monoxide (CO) standard, and Germany includes on-board diagnostics (OBD) and chassis testing.

The European program mandates FAS tests for diesel HDVs and sets pass/fail limits according to vehicle age. Prior to the tests, a vehicle undergoes a visual inspection, making sure that the engine is warm and in satisfactory mechanical condition. The primary criterion for passing a test is that the opacity must not exceed the level recorded on the manufacturer's plate on the vehicle. In the exceptional cases where this information is not available or where the member state decides not to use it, the opacity must not exceed the level cited by the manufacturer or the limit values defined by the European Commission or the state (see Table 5-1).

European stakeholders have recognized that the current I/M roadworthiness directive and those implemented by member states are outdated and risk technical obsolescence and loss of public credibility (CITA, 2011). For example, the German project Emission 2010 for diesel vehicles has investigated new test equipment for opacity measurement, adjustments to the thresholds for I/M testing, and the response of OBD to fault simulation. In light of this, the European Commission Directorate-General for Mobility and Transport and members of the International Motor Vehicle Inspection Committee (CITA) launched a pilot study to investigate possible measures for improving the I/M program (CITA, 2011).

The technical part of the program focused on cost-effective equipment and procedures for measuring emissions of nitric oxide (NO), nitrogen dioxide (NO_2), and particulate matter (PM). Instruments that are suitable for measuring NO and NO_2 during short I/M emission tests are typically based on electrochemical cells or nondispersive ultraviolet (NDUV) spectroscopy. The NDUV instrument tested performed well (CITA, 2011). In the PM measurement arena, the program tests involved three different instruments using the laser light scattering principle (LLSP). Results of induced malfunctions showed that the PM instruments were sufficiently accurate and stable and had the necessary dynamic response characteristics and resolution for testing modern clean-diesel vehicles. Excessive PM emissions could clearly be identified, and the correlation with results from type-approval tests was significantly better than that for the opacimeter in current use. The cost of the LLSP instruments was similar to the cost of commercial opacimeters (CITA, 2011). It should be noted that, as of the writing of this report, the recommendations of the CITA study had not been implemented.

Europe's HDV I/M program was established on an EU-wide basis, with each state applying the program or expanding it as needed. The program is in harmony with best practices for institutional design, with vehicles tested in centralized, comprehensive facilities. With respect to best practices for technical design, the program is outdated, but policymaker awareness of this fact and of the importance of I/M programs for air quality has spurred the development of pilot programs and research for adopting OBD and other complementary measures for the large share of clean-diesel HDVs in the European fleet. Inspections are periodic, thus complying with best practices in this area.

HONG KONG, SPECIAL ADMINISTRATIVE REGION OF CHINA

Vehicle emission inspection is one part of the annual safety and roadworthiness testing required for annual registration. The Hong Kong government's Transport Department (TD) administers the program, and the Environmental Protection Department (EPD) provides support by establishing the test procedure and standards (Fung and Suen, 2013). Inspection is carried out by a mix of government-owned and privately operated testing facilities. Three facilities for HDV testing are operated by TD and one by private contractors. Buses are tested at their depots by TD personnel.

The tests are typically unloaded tests, and only smoke opacity is measured. An interesting feature of the Hong Kong I/M program is that 10 percent of HDVs are selected to undergo lug-down tests in a chassis dynamometer–equipped facility. Buses are excluded from the random lug-down testing. According to data provided by TD, more than 100,000 HDVs were tested in 2011 in Hong Kong (Fung and Suen, 2013).

According to Fung and Suen (2014) the EPD has recently implemented improvements in I/M testing for the liquefied petroleum gas fleet and have launched aggressive vehicle replacement programs for pre–Euro IV vehicles. This calls special attention to the prospect that Euro IV and newer HDVs that are going to dominate the fleet in the coming years. According to the researchers, the early retirement incentive program for pre–Euro IV diesel commercial vehicles and the mandatory 15-year limit on vehicle service life promulgated on February 1, 2014, together will mean that by 2020 all diesel commercial vehicles in operation will be Euro IV–compliant or newer. This suggests that better I/M testing methods need to be implemented for these types of clean-diesel vehicles equipped with SCR and for future ones with DPF systems.

There is a strong regulatory and administrative system for HDV I/M programs in Hong Kong, and the program is of mixed public-private operation, which complies with best practices in institutional design. The program is based on annual testing, and random lug-down tests are applied; in addition, regulators are striving to update the testing procedures and incorporate OBD, remote sensing, or OHMS testing, which would make the Hong Kong program compatible with best practices for technical design and compliance/enforcement.

CALIFORNIA, US

The I/M program in California is the responsibility of the state's Air Resources Board (ARB). ARB tests heavy-duty trucks and buses (gross vehicle weight rating greater than 6,000 pounds) for excessive smoke or tampering. Any heavy-duty vehicle operating in California, including vehicles registered in other states and foreign countries, may be tested. For HDVs, ARB performs testing at roadside, weigh stations, fleet facilities, or border crossings with Mexico. Inspection is carried out using the FAS test plus a visual scrutiny for signs of tampering and for the purpose of recording the Emission Control Label (ECL). The ECL shows the inspector that the vehicle operating in California, independent of place of registration (Mexico, Canada, or any other U.S. state), has an engine that meets emissions standards at least as stringent as U.S. federal standards for the model year in which the engine was manufactured.

California has one of the most comprehensive programs in the United States, and it has several options for I/M testing, including specialized facilities, roadside inspections, and self-testing programs, which accords with best practices for institutional design. Regarding best practices for technical design, ARB, like most agencies of its kind, is relying on increasingly obsolescent smoke measurements but is already working on improving PM detection and adding NO_x testing. California's I/M program has both annual inspections and roadside tests, in keeping with best practices for compliance and enforcement. ARB is carrying out actions toward strengthening the current I/M program and issued a request for proposals for a prototype HDV I/M study to be carried out in 2016.

COLORADO, US

In Colorado the I/M program is divided by fleet size. The Colorado Department of Public Health and the Environment (CDPHE) curtails diesel exhaust smoke by means of two diesel inspection and maintenance programs, one for fleets of nine or more heavy-duty vehicles and another for smaller fleets and privately owned vehicles. Fleets of nine or more vehicles participate in a Diesel Fleet Self-Certification Program, which demands that fleet owners and operators self-inspect and certify their vehicles annually to maintain compliance with state smoke opacity standards. Smaller fleet operators and private diesel HDVs participate in the Diesel Opacity Inspection Program. This program requires eligible vehicles (10 model years old or newer) to be inspected every two years. Vehicles that are 11 model years old or older must be inspected annually. The program uses a loaded, dynamometer-based test.

Like California, Colorado complies with best practices in institutional design, given its dual-mandate HDV I/M program, with flexibility according to fleet size. Technical design standards are on a level with California's although there is no documented source of significant changes in Colorado's I/M program that aim to adapt the program to newer, cleaner-diesel vehicle fleets. The tests are carried out on an annual basis, which agrees with best practices for compliance/enforcement.

SUMMARY OF REGIONAL I/M TESTING PROGRAMS FOR HDVS

The main elements of the I/M programs discussed in this section are presented in Table 5-1.

Table 4-1. Summary of I/M testing programs for HDVs

Region	Vehicles	Testing and Pollutants	Pass/Fail Criteria	Considering Updates?	Source
Australia	Diesel HDVs; voluntary	DT80 NO_x, PM, and smoke	**For post-1995**: NO_x: 1.2–2.0 g/km/ton **PM**: 0.03–0.15 g/km/ton **Smoke opacity** < 0.25	Yes	NEPC, 2011; NHVR, 2015
Canada, Ontario	Diesel HDVs; GVWR> 8,500 lbs	Roadside FSA—smoke opacity	**1990 and older**: 55% **1991 and Newer**: 40% If below 20 percent, vehicle is allowed to skip next year's annual inspection	OBD has been added to the I/M testing procedures as an advisory tool only, having no impact on pass/fail decision	St. Denis and Lindner, 2005; Ministry of the Environment and Climate Change, Ontario, 2015
Canada, British Columbia	Diesel HDVs; GVWR> 11,000 lbs	Roadside FSA—smoke opacity	**1990 and older**: 55 percent% **1991 and Newer**: 40percent%	N/A	St. Denis and Lindner, 2005
China, National	Diesel HDVs	National: FAS—smoke opacity Beijing, Guangdong: lug-down tests—smoke opacity	**All HDV Diesel**: Opacity limits: 1.065 inverse meters (m^{-1}) to 2.26m^{-1}, depending on engine size and maximum rotational engine speed. **Turbo** adds 0.5 m^{-1} to the base limit.	Considering updating the lug-down tests with NO_x measurements in addition to smoke tests	Fung and Suen, 2013, and Standard GB3847-2205
China, Guangdong	Diesel HDVs	Lug-down tests—smoke opacity	**Limits by first registration date:** • Before Sep. 2001: Smoke density (K) = 1.86 m^{-1} and Hartridge smoke units (HSU) = 55% • Between Sep. 2001 and Sep. 2004: K=1.61 m^{-1} and HSU= 50% • Sep. 2004 and newer K=1.39 m^{-1} and HSU= 45%	—	Standard DB 44/593-2009
China, Beijing	Diesel HDVs	Lug-down tests—smoke opacity	**Limits by first registration date:** • Before 2003: K =1.61 m^{-1} and HSU = 50% • Between 2003 and 2005: K = 1.19 m^{-1} and HSU = 40% • 2006 and newer K=0.80 m^{-1} and HSU= 29%	—	Standard DB 11/121-2006
Europe	Diesel HDVs	FAS—smoke opacity	* **Pre Euro IV**: 2.5 m^{-1} for naturally aspirated diesel engines and 3.0 m^{-1} for turbocharged diesel engines * **Euro IV, V, and electric vehicles**: 1.5 m^{-1} applies to GVWR > 5.5 tons	Expands from Smoke to PM testing and includes NO and NO2 measurements. Recommends inclusion of OBD.	CITA, 2011
Hong Kong, Special Administrative Region of China	Diesel HDVs and additional testing for smoky vehicles	All vehicles: FAS—smoke opacity Smoky vehicles: lug-down tests—smoke opacity	Smoke ≤ 60 HSU, or light absorption ≤ 2.13 m^{-1} **All other**: Smoke ≤ 50 HSU or light absorption ≤ 1.61 m^{-1}	The move to I/M testing procedures that can cover Euro IV and later vehicles being discussed	Fung and Suen, 2013; Fung and Suen 2014
US, California	HDVs; GVWR <=14,000 lbs HDVs; GVWR > 14,000 lbs	Roadside FSA—smoke opacity and OBD if installed	**1990 and older**: 55percent **1991 and newer**: 40percent	ARB currently looking into testing methods to adopt NO_x testing as part of I/M	ARB 2015
US, Colorado	HDVs; GVWR >8,500 lbs	Large fleets: FAS Small fleets: lug-down	Turbocharged: 20 percent Naturally aspirated: 35 percent	N/A	CDPHE, 2015

5 SUMMARY AND RECOMMENDATIONS:

SUMMARY OF CURRENT I/M PROGRAM STATUS

The purpose of an I/M program is to identify and mitigate emissions from high-emitting vehicles. High emitters typically make up a small percentage of a vehicle fleet, but emit a disproportionately large amount of total emissions. HDVs represent, on average, less than 5 percent of the global on-road vehicle population, but 40–60 percent of the on-road NO_x and PM emissions comes from these vehicles. Within that 40-60 percent a disproportionate share of the NO_x and PM emissions may come from a small fraction of HDVs, the high emitters.

Current I/M testing methods for HDVs, rely on a handful of I/M testing methods, and the most common one, the FAS test, is capable of detecting just a small fraction of malfunctions for limited types of diesel vehicles, and only for smoke. NO_x emissions are not included as part of I/M programs because of their higher testing costs since they can only be measured using lug-down tests, with more sophisticated measurement equipment. During FAS testing, the loading requirements are minimal, making this an unsuitable method for NO_x inspection tests.

Newer vehicles with advanced PM and NO_x emission control technologies, such as common rail fuel injection systems, diesel particulate filters (DPF), and SCR systems, emit pollutants at levels that are more difficult to evaluate with the emission measurement techniques of legacy I/M programs. The effect of diesel oxidation catalysts (DOC) and particle filters changes the final PM emissions level and composition dramatically compared with engines without after-treatment.

NEW DEVELOPMENTS REGARDING I/M TESTING METHODS

There are a number of newer measurement technologies and testing methods that could be utilized to improve I/M programs. Improving the measurement of particles will likely involve a shift from conventional opacimeter to advanced technologies that can read a wider range of particle sizes and concentrations, such as laser-light-scattering photometry (LLSP). Measuring NO_x and nitrogen dioxide (NO_2) under I/M programs could be done using non-dispersive ultraviolet absorption spectroscopy (NDUV). Alternatives that can complement or replace the traditional I/M methods include use of on-board diagnostics (OBD), remote sensing, and the On-road Heavy-duty Vehicle Emissions Monitoring System (OHMS).

Adoption of OBD for I/M programs can complement inspection measurements as the OBD system directly monitors the systems that affect vehicle emissions. OBD is already available for HDVs in several countries, and some regions have incorporated it as part of their I/M programs, following the path set by passenger car I/M programs. OBD for HDVs is already available for new vehicles in the United States, Europe, China, India and Brazil. The challenge to OBD incorporation is a lack of standardized OBD communication for Euro V and earlier standards and pre–EPA 2013 HDV models, as well as the slow turnover of the HDV fleet. Despite these obstacles, OBD usage is still expected to increase globally, and harmonization is in effect for Euro VI (and equivalent) and post–EPA 2013.

Another way to identify high-emitting vehicles is through remote sensing device (RSD) technology. Remote sensing has been used with a variety of purposes, including characterizing the fleet, setting compliance limits, and identifying high emitters. It is an effective tool for enforcement.

One of the most promising new methodologies to detect high emitters is the On-road Heavy-duty Vehicle Emissions Monitoring System developed by the University of Denver. The OHMS collects the HDV exhaust emissions over about an eight-second acceleration cycle, including gear changes, while running the vehicle under a partially enclosed structure. This system measures particulate number, mass, and black carbon emissions, along with gaseous pollutants. The main advantage of the OHMS with respect to the current FAS is that it can measure NO_x and PM for all types of vehicles, mechanically or electronically controlled, with or without aftertreatment systems. The studies on OHMS concluded that the methodology correlates well with portable emissions measurement system (PEMS) testing, and it was found to be a feasible technology for I/M programs.

Looking at remote sensing devices and OHMS integration, EnviroTest Canada (2013) concluded that both methods are effective at detecting high and low emitters. The same trends in vehicle emissions were evident under both methods for the HDVs tested for PM and NO_x. The use of remote sensing and OHMS can serve as the backbone of programs for clean screening, high-emitter identification, and on-road fleet monitoring.

RECOMMENDATIONS

The review of current I/M testing methods for HDVs show that even though these vehicles are a large contributor to local pollution inventories only a handful of countries have implemented programs for controlling high emitters. The current programs were designed based on an older fleet and although some countries are revisiting the pass/fail criteria taking into account newer technologies (Euro II, IV, EPA 2004 and equivalents), the biggest challenge yet is how to accommodate the cleanest fleets (Euro VI and EPA 2010) and how to incorporate NO_x testing, and even better, NO_2, into the I/M program.

Most current programs rely on FAS testing, which is not ideal for all technologies and cannot be effectively used for NO_x measurements, especially for vehicles with SCR systems that require high exhaust temperatures for the SCR system to operate properly. Only Beijing in China has adopted lug-down tests at a wide scale, which is a step above FAS testing, and can be improved with better PM testing equipment and adding NO_x measurements.

Improve the compliance test and pass criteria of HDV I/M testing based on data driven studies. Tests should be adapted to respond to the HDV fleet share increase of newer HDV technologies, such as electronically controlled engines, SCR systems and the use of DPFs. Cities can investigate and estimate the characteristics and distribution of non-compliant fleets, based on local studies and characterization of the fleet; pass/fail criteria should be based on those local studies, and tailored by vehicle technology or certification level.

Combined with other measures, such as remote sensing programs, cities can concentrate resources to monitor and improve the vehicle fleet with highest noncompliance ratios and therefore increase the compliance and pass rate of I/M testing. RSD can be used to identify high emitters in advance of their stipulated inspection time, avoiding emissions that would otherwise occur without this safeguard.

Locating RSD stations across multiple locations inside cities can help identify serious offenders in multiple locations and accelerate the notification process to the driver.

In regions where the emission standards require OBD adoption for new HDVs, the integration of OBD into the I/M program has the potential for improving the I/M program for the share of the HD fleet that is equipped with OBD systems. The use of OBD has the advantage that it will monitor and report on specific emissions control systems to be repaired, which is the main purpose of the I/M program. Also, the information gathered can be codified and used for a wider in-use monitoring program, checking on failure rates and potential warranties and recalls. This makes OBD an indispensable component of the I/M program and of a much wider vehicle in-use compliance and enforcement program.

However, the issue is vulnerability to OBD tampering of Euro IV and Euro V systems, as well as other similar global systems remains to be verified. The Euro VI standard has improved this aspect of the OBD design and has established strict rules for the detection of malfunction and the storage of malfunction codes in the OBD control unit. The ICCT recommends testing the capacity of Euro IV, V and VI, and their international equivalent, OBD systems to detect tampering and to avoid code clearing before OBD can be fully integrated into HDV I/M programs.

The use of RSD and OHMS can be the backbone of programs for clean screening, high emitter identification and on-road fleet monitoring. The cleanest vehicles or having emissions well below the standards would be exempt of further testing or could gain one more extra period before annual Inspection is due. High emitters could be directed to further testing, including OBD checks (if available in the vehicle), or chassis dynamometer loaded tests. Local studies have to be carried out to investigate the benefits of combined measures and to estimate their costs.

BIBLIOGRAPHY

Air Resources Board (ARB), California (1998). *Findings of the scientific panel on the report on diesel exhaust.* Retrieved from http://www.arb.ca.gov/toxics/dieseltac/de-fnds.htm

Air Resources Board (ARB), California (2003). Public meeting to update the Board on the status of efforts to reduce in-use NO_x emissions from on-road heavy-duty diesel vehicles (Element M17 of the California SIP); Board item 03-1005. Retrieved from www.arb.ca.gov/msprog/m17/m17.htm

Air Resources Board (ARB), California (2009). *Emission inventory data.* Retrieved from http://www.arb.ca.gov/ei/emissiondata.htm

Air Resources Board (ARB), California (2014). Enforcement of California's Periodic Smoke Inspection Program (PSIP). Advisory no. 351. Revised, April. Retrieved from http://www.arb.ca.gov/enf/advs/advs351.pdf

Air Resources Board (ARB), California (2015). Meetings of the Research Screening Committee. Cal/EPA Headquarters Building. July 8th.

Anyon, P., Brown, S., Pattison, D., Beville-Anderson, J., Walls, G., and Mowle, M. (2000). *Proposed Diesel Vehicle Emissions National Environment Protection Measure—Project 2, Phase 2: Emissions performance testing of 80 in-service diesel vehicles, evaluation and correlation of short test protocols.* Report prepared by Parsons Australia Pty Ltd, Ninderry, Australia.

Ban-Weiss, G. A., Lunden, M. M., Kirchstetter, T.W., and Harley, R.A. (2009). Measurement of black carbon and particle number emission factors from individual heavy-duty trucks. *Environmental Science and Technology, 43*(5), 1419–1424.

Bansal, G., and Bandivadekar, A. (2013). *Overview of India's vehicle emission control program: Past successes and future prospects.* International Council on Clean Transportation.

Bishop, G. A., Hottor-Raguindin, R., Stedman, D. H., McClintock, P., Theobald, E., Johnson, J. D., Lee, D.-W., Zietsman, J., and Misra, C. (2015). On-road Heavy-duty Vehicle Emissions Monitoring System. *Environmental Science and Technology 49*(3), 1639–1645.

Borken-Kleefeld, J. (2013). *Guidance note about on-road vehicle emissions remote sensing.* Report prepared for the International Council on Clean Transportation. July. Retrieved from http://www.theicct.org/sites/default/files/publications/RSD_Guidance_BorKlee.pdf

Brodrick, C.-J., Sperling, D., and Weaver, C. S. (2000). Multiple smoke opacity measurements as indicators of particulate emissions for heavy-duty diesel vehicle inspection and maintenance programs. University of California Transportation Center, September 1.

Campbell, A., (2006) *Vehicle Emissions Pilot Project—Diesel Vehicles*. Prepared for the New Zealand Ministry of Transport by Fuel Technology Ltd, Wellington, New Zealand.

Chen, Y., and Borken-Kleefeld, J. (2014). Real-driving emissions from cars and light commercial vehicles—Results from 13 years remote sensing at Zurich/CH. *Atmospheric Environment*, *88*, 157–164.

CITA—International Motor Vehicle Inspection Committee (2011). *TEDDIE: A new roadworthiness emission test for diesel vehicles involving NO, NO2 and PM measurements*. Report prepared for the European Commission, Directorate-General for Mobility and Transport. December 7.

Colorado Department of Public Health and Environment (CDPHE), Air Quality Control Commission (2015). Regulation No. 12: Reduction of Diesel Vehicle Emissions, 5 CCR 1001-15. Retrieved from https://www.colorado.gov/pacific/sites/default/files/5-CCR-1001-15.pdf

EnviroTest Canada (2013). *Greater Vancouver Regional District Remote Sensing Device Trial For Monitoring Heavy-Duty Vehicle Emissions.* Available at: http://www.metrovancouver.org/about/publications/Publications/2013_RSD_HDV_Study.pdf

Energy and Environmental Analysis (2000). *Documentation and analysis of heavy-duty diesel vehicle emission test data.* Prepared for the New York Department of Environmental Conservation. Arlington, Va. December. Retrieved from http://www.dec.ny.gov/docs/air_pdf/CMAQ.pdf

EnviroTest Canada (2013). *Greater Vancouver Regional District Remote Sensing Device Trial for Monitoring Heavy-Duty Vehicle Emissions.* Retrieved from http://www.metrovancouver.org/about/publications/Publications/2013_RSD_HDV_Study.pdf

Erlansson, L., and Walsh, M. P. (2003). Motor vehicle inspection in the National Capital Region (NCR) of India: Recommendations for short-, medium- and long terms—"A plan for progess." March 7. Retrieved from http://www.walshcarlines.com/pdf/delhi_im_report.pdf

Faiz, A., Weaver, C. S., and Walsh, M. P. (1996). *Air pollution from motor vehicles: Standards and technologies for controlling emissions.* Washington, DC: World Bank.

Fung, F., and B. Suen (2013). *A Review of the Hong Kong Inspection and Maintenance Programme for On-road Vehicles*. Civic Exchange (Hong Kong). August 1. Available at: http://www.civic-exchange.org/en/publications/164986987.

Fung, F., and B. Suen (2014). *Improving Hong Kong's Emission Inspection Programme for On-road Diesel Commercial Vehicles*. Civic Exchange (Hong Kong). September 29. Available at: http://www.civic-exchange.org/en/publications/4816935.

Gautam, M., Clark, N. N., Thompson, G. J., Carder, D. K., and Lyons, D. W. (2000). Evaluation of mobile monitoring technologies for heavy-duty diesel-powered vehicle emissions. Department of Mechanical and Aerospace Engineering, West Virginia University.

Gehr, P. (2010). *Health effects due to inhaled engine emitted solid nanoparticles.* Paper presented at the Technical Workshop on DPF Retrofits, Beijing, October 27. Retrieved from http://www.vecc-mep.org.cn/news/news_detail.jsp?newsid=40627

Giechaskiel, B., Schiefer, E., Schindler, W., Axmann, H., and Dardiotis, C. (2013). Overview of soot emission measurements instrumentation: From smoke and filter mass to particle number. *SAE International Journal of Engines, 6*(1), 10–22.

Giechaskiel, B., Riccobono, F., Bonnel, P. (2014). *Feasibility study on the extension of the Real Driving Emissions (RDE) procedure to particle number (PN): Experimental evaluation of portable emission measurement systems (PEMS) with diffusion chargers (DCs) to measure particle number (PN) concentration.* JRC Science and Policy Reports. Joint Research Centre, European Commission. Brussels: Publications Office of the European Union. Retrieved from http://publications.jrc.ec.europa.eu/repository/handle/JRC93743

Guangdong Government. (2008). Guangdong Automotive Emission Prevention and Control Implementation Plan. Retrieved from http://www.gd.gov.cn/govpub/zfwj/zfxxgk/gfxwj/yfb/200809/t20080910_63841.htm (Chinese)

Herner, J. D., Hu, S., Robertson, W. H., Huai, T., Oliver Chang, M.-C., Rieger, P., and Ayala, A. (2011). Effect of advanced aftertreatment for PM and NO_X reduction on heavy-duty diesel engine ultrafine particle emissions. *Environmental Science and Technology, 45*(6), 2413–2419.

Hong Kong Environmental Protection Department (HKEPD) (2013), *Hong Kong Air Pollutant Emission Inventory* (in English). Retrieved from http://www.epd.gov.hk/epd/english/environmentinhk/air/data/emission_inve.html.

Kagawa, J. (2002). Health effects of diesel exhaust emissions—A mixture of air pollutants of worldwide concern. *Toxicology, 181–182,* 349–353.

Khalek, I. A., Bougher, T. L., Merritt, P. M., and Zielinska, B. (2011). Regulated and unregulated emissions from highway heavy-duty diesel engines complying with U.S. Environmental Protection Agency 2007 emissions standards. *Journal of the Air and Waste Management Association, 61*(4), 427–442.

Kolke, R. (2005). Inspection & maintenance and roadworthiness. Module 4b in *Sustainable transport: A sourcebook for policy-makers in developing cities.*— Eschborn, Germany: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ).

Lyons, Allen (2015) Personal Communications. Subject: “RE: I/M Programs for HDVs”. Air Resources Board. Staff Air Pollution Specialist ECARS Division. February 10.

Lowell, D., and Kamakaté, F. (2012). *Urban off-cycle NO_X emissions from Euro IV/V trucks and buses: Problems and solutions for Europe and developing countries.* White paper no. 18. International Council on Clean Transportation. March. Retrieved from http://www.theicct.org/urban-cycle-nox-emissions-euro-ivv-trucks-and-buses

McCormick, R. L., Graboski, M. S., Alleman, T. L., Alvarez, J. R., and Duleep, K. G. (2003). Quantifying the emission benefits of opacity testing and repair of heavy-duty diesel vehicles. *Environmental Science and Technology, 37*(3), 630–637.

Ministry of Environmental Protection (MEP) (China) (2008). Equipment Specifications and Quality Control Requirements for In-Use Vehicles Equipped with Compression Ignition Engine in Free Accelerating Smoke Test. Report no. HJ/T 395—2007 (in Chinese). Retrieved from http://www.sepa.gov.cn/info/gw/gg/200712/W020071221474838874261.pdf

Ministry of Environmental Protection (MEP) (China) (2010). *China vehicle emission control annual report: 2010* (in English). Retrieved from http://www.vecc-mep.org.cn/news/e_home_gg/2010engreport.pdf

Ministry of Environmental Protection (MEP) (China) (2015). *China vehicle emission control annual report: 2015.*

Ministry of the Environment (Brazil) (2011). *Primeiro inventário nacional de emissões atmosféricas por veículos automotores rodoviários.*. Executive summary (in Portuguese). Retrieved from http://www.mma.gov.br/estruturas/163/_arquivos/inventario_veicular2010_163.pdf

Ministry of the Environment and Climate Change, Ontario (Canada) (2015). Drive Clean. Retrieved from http://www.ontario.ca/environment-and-energy/drive-clean-ontario

Miller, J., and Façanha C., (2014). The State Of Clean Transport Policy: A 2014 Synthesis Of Vehicle And Fuel Policy Developments. International Council on Clean Transportation. Retrieved from http://www.theicct.org/state-of-clean-transport-policy-2014

National Environmental Protection Council (NEPC) (Australia) (2011). NEPC report on the implementation of the Air Toxics NEPM, 2009–2010. Retrieved from http://www.parliament.nsw.gov.au/prod/la/latabdoc.nsf/0/b8d26f2d7211b909ca25788c0023ad1a/$FILE/AR_Jur_All_NEPMs_09-10.pdf

National Heavy Vehicle Regulator (NHVR) (Australia) (2015). *Heavy Vehicle (Vehicle Standards) National Regulation*. Retrieved from https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/H/HeavyVehVSNR.pdf

Norris J. O. W. (2005). Low Emission Diesel Research—CP17/18/770: Phase 3—Report to Vehicle and Operator Services Agency (VOSA). Report AEAT/ENV/R/1873/Issue 1. AEA Technology—Environment, Didcot, U.K. February. Retrieved from http://www.transportoffice.gov.uk/crt/repository/Low%20Emission%20Diesel%20Research.pdf

Parsons (2001) In-Service Emission Testing – Pilot Study, Fault Identification and Effect of Maintenance. Prepared for the National Environment Protection Council of Australia (NEPC) by Peter Anyon, Stephen Brown and associates.

Posada, F., and Bandivadekar A. (2015). Global overview of on-board diagnostic (OBD) systems for heavy-duty vehicles. White paper. International Council on Clean Transportation. January. Retrieved from http://www.theicct.org/global-overview-board-diagnostic-obd-systems-heavy-duty-vehicles

Posada, F., Wagner, D. V., Bansal, G., and Fernandez, R. (2015). *Survey of best practices in reducing emissions through vehicle replacement programs*. White paper. International Council on Clean Transportation. March. Retrieved from http://www.theicct.org/vehicle-replacement-program-best-practices-mar2015

Prasad, R., and Bella, V. R. (2010). A review on diesel soot emission, its effect and control. *Bulletin of Chemical Reaction Engineering and Catalysis, 5*(2), 69–86.

Ruehl, C., Herner, J. D., Yoon, S., Collins, J. F., Misra, C., Na, K., Robertson, W. H., Biswas, S., Oliver Chang, M.-C., and Ayala, A., (2014). Similarities and differences between "traditional" and "clean" diesel PM. *Emission Control Science and Technology, 1*(1), 17–23.

St. Denis, M., and Lindner, J. (2005). Review of light-duty diesel and heavy-duty diesel gasoline inspection programs. *Journal of the Air and Waste Management Association, 55*(12), 1876–1884.

Samaras, Z., Ntziachristos, L., Thompson, N., Hall, D., Westerholm, R., and Boulter, P. (2005). *Characterization of exhaust particulate emissions from road vehicles.* Directorate-General for Transport and Energy, European Commission. April. Retrieved from http://lat.eng.auth.gr/particulates/deliverables/Particulates_D16.pdf

Society of Automotive Engineers (SAE). *Snap-Acceleration Smoke Test Procedure for Heavy-Duty Diesel Powered Vehicles*. February 1996.

South Australia (Government) (undated). *Road Traffic (Vehicle Standards) Variation Rules*. Retrieved from http://www.legislation.sa.gov.au/LZ/V/R/2010/ROAD%20TRAFFIC%20%28VEHICLE%20STANDARDS%29%20VARIATION%20RULES%202010_244/2010.244.UN.RTF

Stedman, D. H. (2013). *System and method for quantifying the presence of components in the exhaust of commercial and/or heavy-duty vehicles.* US 8429957 B2. Retrieved from: http://www.google.com/patents/US8429957

Stedman, D. H., Bishop, G., and Misra, C. (2014). "A heavy-duty emissions detection system to remotely integrate HDDV pollutants." Paper presented at the Air and Waste Management Association (AWMA) annual conference, Long Beach, Calif., June 24–27. Retrieved from http://www.researchgate.net/profile/Donald_Stedman/publication/233533410_Comparison_of_the_MOVES2010a_MOBILE6.2_and_EMFAC2007_mobile_source_emission_models_with_on-road_traffic_tunnel_and_remote_sensing_measurements/links/5436e33d0cf2bf1f1f2d42b9

Sydbom, A., Blomberg, A., Parnia, S., Stenfors, N., Sandström, T., and Dahlén, S.-E. (2001). Health effects of diesel exhaust emissions. *European Respiratory Journal, 17*(4), 733–746.

Texas A&M Transportation Institute and Denver University (TTI/DU) (2013). *Heavy-Duty Diesel Inspection and Maintenance Pilot Program.* Report prepared for the North Central Texas Council of Governments and the Texas Department of Transportation. May (revised, October). Retrieved from http://www.nctcog.org/trans/air/hevp/documents/NCTCOG_DieselIM_Final_Report_UpdatedOctober2013.pdf

United Nations Environment Programme and World Meteorological Organization (2011). Integrated assessment of black carbon and tropospheric ozone. Nairobi. Retrieved from http://www.unep.org/dewa/Assessments/Ecosystems/ClimateChange/tabid/7002/Default.aspx

U.S. Agency for International Development USAID (2004). Vehicle inspection and maintenance programs: International experience and best practices—A report for the Office of Energy and Information Technology, prepared by PA Government Services. Washington DC: PA Government Services. October.

Wagner D. V., and Rutherford D. (2013). *Survey of best practices in emission control of in-use heavy-duty diesel vehicles*. International Council on Clean Transportation. August. Retrieved from http://www.theicct.org/best-practices-emission-control-in-use-hdvs

Wang, X., Westerdahl, D., Wu, Y., Pan, X., and Zhang, K. M. (2011). On-road emission factor distributions of individual diesel vehicles in and around Beijing, China. *Atmospheric Environment 45*(2), 503–513.

Yan, F., Winijkul, E., Jung, S., Bond, T. C., and Streets, D. G. (2011). Global emission projections of particulate matter (PM): I. Exhaust emissions from on-road vehicles. *Atmospheric Environment, 45*(28), 4830–4844.

Yang, Z., Qiu, Y., & Muncrief, R. (2015). Review and comparative analysis of in-use vehicle emission control programs in Guangdong Province. International Council on Clean Transportation (ICCT). Washington DC