Improving Hong Kong’s Emission Inspection Programme for On-road Diesel Commercial Vehicles

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About Civic Exchange

Civic Exchange is a Hong Kong-based non-profit public policy think tank that was established in September 2000. It is an independent organisation that has access to policy makers, officials, businesses, media and NGOs reaching across sectors and borders. Civic Exchange has solid research experience in areas such as air quality, energy, urban planning, climate change, conservation, water, governance, political development, equal opportunities, poverty and gender. For more information about Civic Exchange, visit http://www.civic-exchange.org.

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In August 2013, Civic Exchange published a report reviewing the inspection and maintenance programme for on-road vehicles in Hong Kong. It was our first attempt to help policy makers and the public better understand the importance of including a well-designed inspection and maintenance programme in Hong Kong’s comprehensive vehicular pollution control strategy in order to realise the city’s emission reduction targets.

This second report is a follow-up study. Civic Exchange has realised, through the first research, that one of the major defects of the current inspection and maintenance programme is the failure in effectively measuring emissions (particularly NO$_x$ and PM) coming out from diesel commercial vehicles. According to the latest official data, there were over 41,000 heavy goods vehicles in Hong Kong in 2011 and they were the biggest emitters of PM$_{2.5}$ and NO$_x$ among different types of goods vehicles. A better inspection and maintenance programme for diesel commercial vehicles is needed to ensure their emissions are kept low and therefore reduce the risks posed to public health. This report looks at the latest developments in emission inspection programmes for commercial diesel vehicles, in other parts of the world and identifies the lessons Hong Kong can learn.

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Executive summary

Deteriorating roadside air quality and rising public concerns over the health impacts of air pollution have prompted the HKSAR Government to undertake a series of measures for combating vehicular emissions. Three programmes costing a total of HK$11.5 billion have been launched this year to pay for replacing catalytic converters and sensors on liquefied petroleum gas (LPG) taxis and minibuses, enforcing a rigorous emission inspection regime for petrol and LPG vehicles in operation, and replacing all pre-Euro IV diesel commercial vehicles, which account for two-thirds of the fleet, with low-emitting ones in the coming few years.

As a result of these programmes, the entire vehicle fleet is expected to become much cleaner in a few years, since almost all diesel vehicles will meet Euro IV or more stringent emission standards by 2020 (except for franchise buses, which are subject to different retirement requirements). Also, petrol and LPG vehicles will be more diligently maintained and stayed clean, thanks to the stricter emission monitoring and inspection programme. There is, however, an important missing piece – an effective emission inspection programme for on-road diesel vehicles.

The existing annual and roadside emission tests for diesel vehicles only monitor smoke emissions. They were developed for mechanical diesel vehicles and are not effective in measuring emissions from advanced diesel vehicles as emissions from these vehicles, which consist of fine particulate (PM$_{2.5}$), and nitrogen oxides (NO$_x$), are predominately invisible and smoke emission level is very low. Also, the free acceleration smoke (FAS) test used for inspecting most of the diesel vehicles does not measure NO$_x$, which is an important diesel pollutant and a precursor of ozone and PM$_{2.5}$. FAS test is not only open to fraud and allows vehicles passing the test with temporary fixes, its test cycle also cannot simulate on-road driving conditions. The existing tests for diesel vehicles, therefore, are not able to force repair of gross emitters among advanced diesel vehicles. As the share of advanced diesel vehicles will steadily increase in the coming few years, there is an urgent need to develop a new set of diesel emission tests that will identify on-road diesel vehicles with excess emissions.

Advanced diesel vehicles are characterised by their much lower level of emissions, and the use of advanced emission control devices for the best emission control performance. The malfunction of any advanced emission control devices, whether it is a sensor, a catalyst, a valve, or a fuel injector, can cause high emissions. For vehicles equipped with selective catalytic reduction (SCR) devices for NO$_x$ control, emission control performance would be seriously compromised if the drivers do not regularly replenish urea, which is a reductant used for cleaning up NO$_x$ emissions. An effective test for advanced diesel vehicles, therefore, must be performed under load in order to monitor NO$_x$ emissions, conducted using more sensitive analysers in order to track fine PM and
NO\textsubscript{X} emissions, and must include roadside screening to offer year-round surveillance. The latter will induce drivers to diligently refill urea, deter tampering of emissions control equipment and promote more diligent repairs.

A number of advanced emission methods have been piloted in the United States (US) and Canada for inspecting and identifying advanced diesel vehicles with excessive emissions. Three of these methods, which appear to be promising options for use in the inspection and maintenance (I/M) programme in Hong Kong, are introduced in this report: remote sensing devices (RSD), on-road heavy-duty measurement System (OHMS), and simplified chassis dynamometer test.

These methods are all conducted under load and performed using advanced emission analysers, hence they are able to evaluate NO\textsubscript{X}, PM\textsubscript{2.5}, and other pollutants of concern. The tests with OHMS or RSD can be applied to roadside screening, and therefore can be used to deter tampering with emission control devices, and encourage timely refilling of urea. The chassis dynamometer test and the test with OHMS can be considered for use at scheduled periodic tests. With respect to adopting these tests in Hong Kong, RSD appears to be best suited for roadside monitoring. While the simplified chassis dynamometer test appears to be a more accurate test for use in the I/M setting as it is conducted in a more controlled setting, the costs for having all diesel vehicles undergoing this test periodically may be prohibitively high. The OHMS, which has only recently been piloted in the US and Canada, could be a promising alternative. However, validation of the OHMS results against findings from other proven methods, like the portable emissions measurement system (PEMS) or chassis dynamometer test, are needed to demonstrate accuracy and repeatability of the OHMS. Also, reconfiguration of the set-up to better suit Hong Kong’s fleet is a necessary step for adapting these tests.

It should be noted that these methods are still evolving, and Hong Kong can take advantage of the newly developed technologies. For instance, new emission analysers have been developed that may considerably improve sensitivity of RSD. One example is a laser-based remote sensing equipment called emissions detection and reporting (EDAR), which may allow for remote sensing measurement in multi-lane locations. More tests will be needed to demonstrate its benefits over other widely used measurement devices.

By adopting a combination of these three methods, the HKSAR Government can significantly improve the effectiveness of annual emission tests for diesel vehicles, and ensure that pollution control equipment of diesel vehicles will operate properly year-round through undertaking roadside screening.
To implement a more rigorous inspection programme in Hong Kong, a greater number of well-trained vehicle mechanics will be required to carry out proper repairs. The emission control system that is now commonly used in new diesel vehicles is complex, and will demand a sufficient pool of capable mechanics for diagnosing and repairing emission-related faults. The share of advanced diesel vehicles in the fleet will continue to increase, since only Euro V and newer diesel vehicles can be registered in Hong Kong. The HKSAR Government should therefore make sure that the training programmes designed for mechanics will be more focused on the diagnosis and repair of advanced emission control systems, and that these courses are offered at a reasonable cost. Establishing a mandatory certification scheme for mechanics is highly recommended as a way to ensure the capability of the newly certified mechanics, and to guarantee the quality of continuous training for all mechanics. The HKSAR Government may also consider following the European Union (EU) and the US regulations by requiring vehicle manufacturers to give the repair industry free access to repair-related information and tools. This move will ensure that adequate tools and equipment become available and are used properly by mechanics during repairs of advanced vehicles. On-board diagnostic (OBD) system, which is installed in Euro IV or newer heavy-duty diesel vehicles, has proven to be an effective diagnostic tool for repairing light duty vehicles. Even though Hong Kong imports vehicles from countries that are using different OBD systems, the HKSAR Government should consider better leveraging this tool for vehicle diagnosis in the future, as the share of OBD-equipped diesel trucks continue to rise. In the longer term, the HKSAR Government could consider using OBD as an emission inspection tool.

Going forward, the HKSAR Government should tighten the emission standards for heavy-duty diesel vehicles to be on par with Euro VI and the US 2010 standards. These two standards have brought forth the best commercially available emission control technologies to the EU and the US markets. Also, these standards require pollution control equipment to last longer than those on Euro V vehicles, which in turn may lessen the repair burden on vehicle operators and drivers. With generous government subsidy on offer in Hong Kong, money should be used to replace old polluting diesel commercial vehicles with the lowest emission vehicles that are currently available, so as to get the greatest emission reduction and public health benefits.
In *A Clean Air Plan for Hong Kong*, the Government committed to substantially improve air quality and set the goal of meeting Hong Kong’s new Air Quality Objectives by 2020. A targeted effort aimed at improving roadside air quality, in particular on cleaning up in-use vehicles, was launched to reduce public health risks from air pollution.¹

Two important and far-reaching initiatives have been rolled out by the Environmental Protection Department (EPD) since the announcement of the clean air plan. The first is a government-funded programme for replacing catalytic converters and sensors on liquefied petroleum gas (LPG) taxis and light buses, coupled with the implementation of a much strict emission monitoring and inspection programme for LPG and petrol vehicles on the road. The second initiative is subsidising the retirement of pre-Euro IV diesel commercial vehicles (including goods vehicles, non-franchised buses, and light buses), and mandating these vehicles that registered on or after 1 February 2014 to retire after 15 years of service.²

These two initiatives are expected to substantially reduce vehicle pollution as they target the three vehicle categories that account for the largest share of road vehicle pollution, namely diesel commercial vehicles, LPG taxis and light buses. Based on 2011 data, the diesel fleet (goods vehicles, franchised and non-franchised buses, but not diesel light buses)³ only accounted for 20 per cent of the city’s vehicle population and 37 per cent of total mileage, but it was responsible for 91 per cent of particulate matter (PM₁₀) and 70 per cent of oxides of nitrogen (NOₓ, a precursor of ozone and secondary fine particulate) from the road sector. LPG taxis were the third largest source of vehicular NOₓ emissions in 2011, after goods vehicles and franchised buses.⁴

However, past experience shows that vehicular emission control is far from straightforward. For example, LPG vehicles (including taxis and light buses), which were considered a clean alternative to diesel vehicles when introduced in Hong Kong in 2000, became gross emitters mainly because many of them had malfunctioning emission control systems⁵ and the emission inspection regime for LPG then vehicles was unable to identify a vehicle with high emissions in order to enforce timely replacements or repairs.⁶

The experience with LPG vehicles highlights why an effective vehicle inspection programme is vital for making sure emissions from vehicles on the road are kept low. No matter how clean a new vehicle is when it leaves the showroom, without proper maintenance to keep its emission control system in effective condition, emissions will worsen as vehicle components age and deteriorate. An effective emission...
An improved inspection programme for diesel vehicles is urgently needed

The vastly improved emission monitoring and inspection programme for LPG and petrol vehicles, that came into effect on 1 September 2014, is designed precisely to address this problem, but it only applies to LPG and petrol vehicles. Our last report *A Review of the Hong Kong Inspection and Maintenance Programme for On-road Vehicles*, released in August 2013, highlighted that emission inspection for diesel commercial vehicles, which checks only for smoke instead of NO\textsubscript{X}, is inadequate for identifying advanced diesel vehicles with excessively high NO\textsubscript{X} or PM emissions. An improved inspection programme for diesel commercial vehicles, that is as vigorous as the programme for LPG and petrol vehicles, is urgently needed.

Latest overseas emission inspection programmes will be reviewed in this report to determine applicability to Hong Kong

With all the above in mind, the purpose of this report is to review the latest overseas development of emission inspection programmes for commercial diesel vehicles, with the goal of informing the design of an enhanced programme for Hong Kong. The review provided in this report specifically focuses on tests that suit Euro IV or more advanced vehicles for two reasons: first, as a result of the early retirement incentive scheme for pre-Euro IV diesel commercial vehicles and the mandatory 15-year limit on vehicle service life promulgated on 1 February 2014, all diesel commercial vehicles in operation by 2020 will be Euro IV-compliant or newer vehicles. An emission monitoring and inspection programme would deliver the biggest long-term benefits if it could identify problems with the emission control systems of these advanced vehicles in need of repair; second, between now and 2020, the pollution contribution of pre-Euro IV vehicles will diminish as the population of these vehicles dwindles away due to attrition and/or early retirement incentives. Essentially, the early retirement incentive programme quickens the process of eliminating old, polluting vehicles, whether or not they are well maintained.

This report also looks into other policy measures that support better vehicle maintenance. In the next five years, over 80,000 diesel goods vehicles will be retired and replaced with new ones using advanced emission control systems. The availability of well-trained service technicians and the freedom of access to vehicle service data are critical in enhancing the standard of vehicle maintenance.
Currently inspection and maintenance programme for diesel commercial vehicles in Hong Kong

2.1 Diesel commercial vehicles in Hong Kong

The category of diesel commercial vehicles (DCVs) includes diesel goods vehicles, franchised and non-franchised buses, and diesel light buses. As shown in Figure 1, goods vehicles contribute the largest share of PM\textsubscript{10} and NO\textsubscript{X} from vehicles, while buses have a disproportionally high share of NO\textsubscript{X} and PM emissions. This is especially true for franchised buses, which represent only 1 per cent of the fleet but contribute one-fifth of NO\textsubscript{X} and 6 per cent of PM\textsubscript{10} emissions. Among different types of goods vehicles, vehicles in the heaviest vehicle category (those with gross vehicle weight ratings over 15 tonnes) produce the largest amount of PM\textsubscript{10} and NO\textsubscript{X} emissions (see Figure 1) both in absolute amount (total from this category) or relative quantity (emissions per vehicle). This suggests that heavy goods vehicles and franchised buses should be the focus of the in-use diesel vehicle emissions control programme.
Figure 1: Breakdown of total vehicle population and pollution by vehicle type; and breakdown of goods vehicle population and pollution by weight category

Note: LGV stands for light goods vehicles and HGV stands for heavy goods vehicles. The vehicle categories presented in this figure are based on the categories used for developing the emission inventory, therefore they are not consistent with the vehicle categories defined by the Hong Kong Transport Department for vehicle registration and licensing.
2.2 Tightening vehicle emission standards and new emission control pathways

Since 1995, Hong Kong has incrementally tightened emission standards for new diesel commercial vehicles. Currently, new diesel commercial vehicles sold in Hong Kong include Euro V vehicles as well as heavy-duty diesel vehicles that meet the United States (US) 2010 and Japan’s Post-New Long-term Standards. Diesel vehicles sold in Hong Kong predominantly comply with Euro V and the Japanese standards, but the split of vehicles meeting European Union (EU) versus Japanese standards is not available. Figure 2 shows the trend of tightening the NO\textsubscript{X} and PM standards for diesel commercial vehicles (with weight > 3.5 tons) in the EU, the US and Japan, and the implementation timeline of various standards in Hong Kong in the past two decades.

The Euro IV standard implemented in Hong Kong since 2006 requires an 80 per cent reduction in PM, and 30 per cent reduction in NO\textsubscript{X}, HC and CO emissions from the Euro III standard. For meeting the significantly stricter standard, in-cylinder emission control alone (such as fuel injection with high pressure and metering control, fuel injection retardation, fuel nozzle redesign) was not sufficient. Euro IV and cleaner vehicles require the use of both engine improvement and advanced emission control systems. As shown in Figure 3, the point labelled “starting point” represents the PM and NO\textsubscript{X} emissions coming out from a HDV engine (engine-out emissions) after the engine design is optimised. This point falls outside the Euro IV emission limits of 3.5g NO\textsubscript{X}/kWh and 0.02g PM/kWh, hence additional emission control technologies have to be used to bring emissions down to the Euro IV limits.
Figure 2. NO\textsubscript{X} and PM emission standards for heavy-duty diesel engines in EU, the US and Japan and implementation timeline of the Hong Kong standards\textsuperscript{13}
Two main technology control pathways have emerged for meeting Euro IV and V standards:

- **SCR pathway**: engine-based PM control (fuel injection pressure, timing and metering combined with turbocharging), and aftertreatment devices for NO\textsubscript{X} control – typically using a selective catalytic reduction (SCR) devise

- **EGR + PM aftertreatment pathway**: NO\textsubscript{X} control through exhaust gas recirculation (EGR), and PM control by an aftertreatment device – typically using a diesel oxidation catalyst (DOC) or a partial flow filter (PFF).

The Euro VI standard, the most stringent standard currently enforced in Europe, requires the use of SCR and EGR together with a diesel particulate filter (DPF) to meet the strictest emission limits on NO\textsubscript{X} and PM. These new engine developments highlight that Euro IV and newer vehicles will increasingly rely on aftertreatment emission controls.
2.3 Implications for the design of the inspection and maintenance programme

The complex advanced emission control systems on Euro IV and newer diesel vehicles pose a number of challenges to vehicle maintenance and emission inspection.

2.3.1 Limitations of traditional emission tests for diesel vehicles

The current emission tests for diesel commercial vehicles are fast acceleration smoke test and lug-down smoke test. Both tests were initially adopted based on the premise that excessive visible smoke is a sign of poor combustion resulting from malfunction, maladjustment or misfueling. These are typically causes of excessive emissions from mechanically controlled engines (Euro II or older vehicles plus some Euro III models). However, vehicles with electronic controlled engines and fuel systems (Euro IV or newer vehicles) usually release very low levels of smoke which are below the detection limit of opacity meters used in these tests.\(^\text{15}\) Numerous research have also shown that visible smoke has poor correlation with PM emissions from diesel vehicles. Traditional emission tests for diesel vehicles only monitor visible smoke, and therefore are not suitable for Euro IV and newer vehicles.

2.3.2 Reliance on vehicle operators to refill urea supply regularly

While there are two technology pathways for meeting Euro IV and V standards, SCR is the technology of choice for most heavy-duty diesel vehicles (HDVs). By using SCR, engines can be tuned to run at higher NO\(_X\) emissions levels and lower PM (and hence low fuel consumption which is an appealing point for vehicle buyers), with excess NO\(_X\) being cleaned up by using the SCR device. SCR is also used on all Euro VI compliant heavy-duty diesel engine models introduced in the market to date. However, the proper functioning of the SCR device requires the vehicle operators to diligently replenish the vehicle’s supply of urea (commercially called Adblue in Europe or Diesel Exhaust Fluid, or DEF, in the US), which is a reductant that converts NO\(_X\) to nitrogen and water with the use of a catalyst. Since engines are tuned to have high NO\(_X\) emissions (typically several times the amount of NO\(_X\) emissions from Euro III-compliant engines),\(^\text{16}\) if vehicle operators do not refill the urea supply in a timely manner, or refill with low quality urea, the NO\(_X\) control performance of Euro IV, V and more advanced vehicles will be seriously compromised. All Euro IV and newer vehicles are required to have an on-board “failsafe” device which includes a driver warning system to notify drivers in case of insufficient urea volume, quality and dosing, as well as a vehicle performance degradation system that compels drivers to refill or fix malfunctioned urea systems by limiting performance of the vehicle to an unacceptable level. However, news reports in Mainland China showed there are companies offering courses for mechanics on how to disable the SCR failsafe systems.\(^\text{17}\) Year-round surveillance, as opposed to annual tests, would therefore be needed to deter SCR tampering and induce operators to diligently refill urea.
2.3.3 Dependence on the functioning of all components of the emission control system

Emission performance of Euro IV and newer diesel vehicles depends on the precise control and correct functioning of the emission control system (including the engine and fuel system, the turbocharge system and catalysts in the aftertreatment devices, as well as a set of sensors that monitors operation of these emission control components). Failure of any one or more of these components could result in higher emissions. Ideally, performance of these components needs to be monitored not only during the annual inspection but continuously, so it could deter tampering, as well as promote proper maintenance and timely replacement of faulty components.

Both the SCR and DPF aftertreatment devices require high exhaust temperatures to maintain a good emission control performance, so emission control of vehicles equipped with SCR or DPF could be weakened in urban traffic.\(^{18}\)

2.4 Limitations of the existing emission tests for diesel commercial vehicles

Emissions from diesel commercial vehicles are inspected using the free acceleration smoke (FAS) test and the lug-down smoke test. Box 1 summarises how these two tests are used in Hong Kong. More details of the existing diesel commercial vehicle emission control programme can be found in our earlier report, *A Review of the Hong Kong Inspection and Maintenance Programme for On-road Vehicles*.\(^{19}\)

2.4.1 Free acceleration smoke test

During the FAS test, a vehicle is held stationary with the brake on, and the throttle pedal is pressed quickly to its full throttle position, while the engine is accelerated to its maximum governed engine speed with the transmission in neutral. The amount of smoke emitted is measured using an opacity meter to determine if the smoke emissions exceed the standard.\(^{20}\)

While this test is quick, cheap and easy to conduct, it has a number of key limitations rendering it as an ineffective method to identify highly polluting diesel vehicles.

**Limitations related to the test procedure:**

- **Poor repeatability and open to fraud**: smoke readings from the FAS test can be affected by many factors, including the rate at which the accelerator pedal is pressed, the extent to which the pedal is pressed, vehicle preconditioning and the engine temperature. Furthermore, dilution of the exhaust stream can result in lower smoke readings. Therefore, vehicles with excessive smoke could still pass the FAS test if the exhaust is incidentally or intentionally diluted or the engine is accelerated gently.\(^{21}\)
• **Inability to force permanent repairs:** The FAS test only checks smoke level, but not engine power. It is well known that temporary repairs, such as adjusting the fuel injection pump to reduce fuel delivery or resetting the engine’s speed governor to a lower resolution, can reduce smoke and ensure that vehicles with excessive smoke can pass the FAS test. Since these fixes lower engine power, they are reversed once the vehicles passed the FAS test. Therefore, FAS test is ineffective in forcing permanent repairs that reduce smoke emissions from in-use diesel commercial vehicles;\(^{22}\)

• **Test cycle not representing real-world driving conditions:** The FAS test is conducted under one speed and without any load on the engine, but real-world vehicles almost always operate under load and at varying speeds. Tests have shown poor correlation between the PM reading from the FAS test and real-world emissions;\(^{23}\) and

• **No measurement of NO\(_X\):** NO\(_X\) is a major pollutant from diesel vehicles. Its concentration has been rising in the past five to six years,\(^{24}\) and it has significant environmental and health impacts because it is a precursor of ozone pollution and forms secondary PM\(_{2.5}\) pollution. Implementing the FAS test alone, therefore, would leave NO\(_X\) emissions from diesel vehicles unchecked. For vehicles with SCR devices, this limitation of the FAS test is particularly problematic because a vehicle equipped with a SCR system is tuned to operate with high engine-out NO\(_X\). If the SCR is defective, or not operating due to a lack of urea or other defects of the SCR system, FAS test would be unable to identify the problems.

**Limitations related to the test instrument:**

Traditional opacity meters are being used in the FAS test and the lug-down smoke test in Hong Kong. By using green light (with wavelength at \(~550\text{nm}\)) or deep red light (wavelength at \(~680\text{nm}\));\(^{25}\) these traditional opacity meters are suitable for measuring smoke levels of mechanically controlled vehicles (Euro II or older), but they cannot reliably measure smoke levels of advanced diesel vehicles for the following reasons:

• **Insufficient resolution:** As the emission standard ratchets down to Euro IV and stricter standards, the smoke levels of the advanced diesel engines are close to the detection limits of traditional smoke meters, rendering smoke meters unsuitable devices for measuring smoke levels of Euro IV and newer diesel vehicles;\(^{26}\)

• **Insensitivity to small particulates:** A large portion of diesel engine particulates have diameters below 200nm, yet traditional opacity meters use visible light (with wave length of \(~550\text{nm}\)) or deep red light (wavelength of \(~680\text{nm}\)) which have much poorer sensitivity to smaller particulates and would underestimate small particles as a result;\(^{27}\) and
• **Cross sensitivity with nitrogen dioxide (NO\textsubscript{2}):** NO\textsubscript{2} absorbs green light that is typically used in opacity meters, and that could affect the effectiveness of conventional smoke meters. Oxidation catalysts in modern diesel engines could increase the share of NO\textsubscript{2} in the total NO\textsubscript{x}, so the interference effect on opacity meter readings will be higher for Euro IV and more advanced vehicles.\textsuperscript{28}

### 2.2.4 Lug-down smoke test

The lug-down smoke test is performed with the test vehicle placed on a dynamometer in order to simulate a loaded condition similar to a vehicle ascending a slope. The tester depresses the accelerator pedal until it reaches the maximum fuel delivery position, and holds it until the engine reaches maximum speed and the smoke level is measured. The dynamometer load is then gradually increased to slow down the engine speed to reach 90 per cent and 80 per cent of the maximum engine speed, at which two more smoke readings are measured. A vehicle would fail the test if any one of the three smoke readings exceeds the regulatory smoke limits (see Box 1). Maximum engine power is checked during the test,\textsuperscript{29} and if the maximum engine power is found to be lower than 50 per cent of the designed maximum engine power specified by the vehicle manufacturer – an indication that the engine power has been adjusted to pass the test – the test is also considered failed.

Compared to the FAS test, the lug-down test better represents real-world conditions as the test vehicle is loaded. By following a series of computer-guided steps, the lug-down test typically produces more consistent results.\textsuperscript{30} The requirement of checking maximum engine power could also deter engine tampering, even though 50 per cent of the manufacturer’s maximum power is considered grossly too low.\textsuperscript{31} As a result, lug-down test could more likely force permanent repairs on smoky vehicles by addressing the test-procedure-related limitations of FAS test discussed above.\textsuperscript{32}

While it is an improvement over the FAS test, the lug-down smoke test in Hong Kong has a number of limitations:

- The lug-down test in Hong Kong uses traditional opacity meters, so the same limitations related to opacity meters mentioned above also apply to lug-down smoke test: insufficient resolution, insensitivity to small particulates, and cross sensitivity with NO\textsubscript{2}. More sensitive smoke measurement devices, therefore, should be adopted to improve the effectiveness of the lug-down test for testing vehicles with advanced emissions controls;

- The lug-down test in Hong Kong does not check NO\textsubscript{x} emissions; and

- The lug-down test, by emphasising maximum power, may cause physical damage to the drivetrain, particularly on older/high-mileage vehicles.\textsuperscript{33}
Box 1. Existing emission tests for diesel commercial vehicles in Hong Kong

All diesel commercial vehicles are currently required to undergo emission testing during the annual roadworthiness inspection for licence renewal. The annual roadworthiness test is managed by the Transport Department (TD). The Environmental Protection Department (EPD) proposes the type of emission tests performed as part of the roadworthiness tests, and recommends the pass or fail criteria. Of all the diesel commercial vehicles presented for annual roadworthiness testing, 90 per cent of the vehicles undergo a free acceleration smoke test, and 10 per cent are selected to undergo a lug-down dynamometer test.

In parallel with the annual emission test, EPD operates a smoky vehicle control programme, under which volunteer spotters are trained to identify smoky in-use vehicles. Owners of vehicles reported by spotters as suspected smoky vehicles are requested to bring their vehicles to one of the designated vehicle testing centres for a lug-down test. EPD also works with the Police Department to regularly set up roadside smoky vehicle inspection stations. A diesel vehicle pulled over by the police is required to undergo a FAS test at the spot. If the vehicle is determined to be non-compliant, the vehicle owner would be fined HK$1,000 and the vehicle is required to be repaired and retested at one of the designated vehicle test centres using a lug-down test within 12 days.\textsuperscript{14}

2.5 Key attributes of an enhanced I/M programme for diesel commercial vehicles in Hong Kong

In light of the limitations of the existing emission inspection tests for diesel commercial vehicles and the fact that diesel vehicles are a major source of PM and NO\textsubscript{x} pollution in Hong Kong, new emission inspection and maintenance programmes that can identify excessive emissions from advanced diesel commercial vehicles are critically important for ensuring the vehicle fleet is properly maintained and complies with the emission standards.

Considering the characteristics of Euro IV and more advanced vehicles discussed earlier, an enhanced emissions control programme for diesel commercial vehicles should possess the following attributes:

- Include roadside screening and annual emissions inspection: Roadside screening is needed to ensure that emissions control systems are working properly on a daily basis, instead of only during inspection. This is particularly important as SCR becomes a commonly adopted technology on diesel vehicles starting from Euro IV, and roadside screening could effectively deter vehicle operators from refilling with poor quality urea or not replenishing the urea. However, roadside screening alone is unlikely to replace...
mandatory annual inspections because there are constraints on where roadside screening can be set up (more discussions on this point in Section 3.2.3), and increased coverage would mean more sets of equipment being introduced in parallel, and hence an increase in costs. Besides, drivers may change routes after they know the locations of the roadside screening tests. Roadside screening therefore is unlikely to inspect all diesel commercial vehicles in operation, so annual inspection is still needed;

- **Vehicles must be loaded when being tested:** Testing a vehicle under load is the only way to check NO\textsubscript{X} emissions. It also measures PM emissions under conditions that better mimic real-world condition;

- **Not prone to fraud:** A test that is susceptible to cheating is ineffectual in getting real emissions reductions, and will also erode public support of the overall emission control programme. Unfortunately, unscrupulous individuals seem to have found ways to cheat on all scheduled tests. In some cases, bribing the inspector would cost less than repairing the vehicle. A well-organised test should therefore be centralised and fully automated to make it difficult for anyone to alter the test results; and

- **Tests should be able to achieve good accuracy at a reasonable cost:** When a commercial vehicle is taken out of service, the vehicle operator and owner suffer a loss of income as the period of repair prolongs. As shown in Figures 1 and 2, large cargo trucks are the biggest pollution sources among all diesel commercial vehicles. Drivers of these trucks that mainly provide long-haul freight transport are particularly sensitive to downtime. Time needed to undergo annual inspection tests or roadside screening should be taken into account while achieving sufficient accuracy.
3.1 Advanced emission tests being developed or tested in major automobile centres

Since measuring smoke opacity during free acceleration or idle is easy, less time consuming, and does not require highly skilled inspectors, many countries adopt it for monitoring in-use diesel vehicle emissions.\(^{36}\) While the limitations of smoke tests have been widely documented,\(^{37}\) more effective inspection methods for in-use vehicles have not yet been adopted in major automobile markets, like the US, the EU and Japan. The US, which has the world’s most comprehensive regulatory and enforcement programmes for certification of new vehicle models, believes that imposing increasingly stricter new vehicle standards (including longer durability and in-use emission testing requirements) is more cost-effective for controlling real-world vehicle emissions than upgrading the inspection programme of vehicles in operation. This partly explains why more attention has been given to improving new vehicle certification programmes in these major automobile markets.

Even so, many tests and methods have been developed to measure emissions from HDVs in real world conditions. Some of the tests were developed for establishing emission factors of various types of vehicles, in order to make emissions inventories. These tests include the plume chasing approach\(^{38}\) and exhaust sampling using a mobile lab.\(^{39}\) Other tests were developed for regulatory enforcement, in which most notably, the portable emission measurement system (PEMS) test that was developed for demonstrating compliance with the in-use testing requirement of the US and the EU standards (see Box 2).\(^{40}\) However, a number of tests have been developed specifically for identifying grossly emitting vehicles, including remote sensing, On-road Heavy-duty Measurement System (OHMS) test, and simplified chassis dynamometer test.\(^{41}\)

The review below focuses mainly on remote sensing, OHMS test and simplified chassis dynamometer test. Remote sensing and OHMS test can measure emissions for a large sample of vehicles in a short period of time, so it is well suited for roadside screening of HDVs. Besides, these tests, which are all conducted with the vehicles under load, can address the limitations of the FAS test, which are the unloaded test condition, absence of NO\(_x\) measurements, and smoke measurement being a poor surrogate of PM detection. This section provides a short description of these tests, and discusses how they may be applied in Hong Kong.
Box 2: Portable Emissions Measurement Systems (PEMS)

The PEMS test was developed for demonstrating compliance with the in-use emission testing standards (called Not-to-Exceed standard, or NTE). The in-use emission testing standards was introduced by the US Environmental Protection Agency (EPA) as part of the new engine certification requirements in a 1998 Consent Decree with heavy-duty engine manufacturers. As part of the US new engine/vehicle certification requirements, the NTE standard was introduced to ensure emissions from HDVs are controlled over the full range of speed and load combination commonly experienced in use. The PEMS test was developed for enforcing this standard as it measures vehicle emissions while the vehicles operate on the road. Beginning with Euro VI, the EU also requires all new heavy-duty diesel engines to be certified to comply with a similar in-use emission testing requirement, which is called the in-use conformity testing requirement.

Besides being used for certifying compliance with the NTE and in-use conformity testing requirements, the PEMS test has also been used in many regions (including Hong Kong) for developing emission factors in order to establish more accurate emissions inventories in real-world conditions.

However, preparing a vehicle for the PEMS test and removing the PEMS after the test take a long time (typically one to two days in total), hence the test is unsuitable for monitoring emissions of a large vehicle sample.

3.2 Remote sensing test

Remote sensing devices (RSD) are an increasingly popular tool for monitoring on-road vehicle emissions because they do not disrupt traffics and can generate a large sample of emission readings under real-world conditions. RSD has been used for years in the US, Hong Kong, Mainland China, Taiwan, South Korea and other countries for monitoring on-road vehicle emissions, but most of these programmes target light-duty vehicles only.

As of today, remote sensing programmes have been mainly used for:

- Identifying low-emission vehicles that can be excluded from periodic emission inspections (clean screening);
- Identifying high-emission vehicles, or gross emitters (dirty screening) for follow-up actions;
- Developing an emission profile of a given vehicle fleet; and
- Cross-checking on I/M performance.

Studies looking into using RSD for measuring emissions from HDVs began in the mid-1990s. While the RSD technologies are still emerging, a few studies conducted in the past few years have shown that RSD is viable for measuring HDV emissions. The latest commercial RSD devices are capable of measuring a wide range of pollutants, such as carbon monoxide (CO), HC, NO, NO\textsubscript{x}, carbon dioxide (CO\textsubscript{2}, as a proxy for fuel use), and opacity (as a proxy for PM).
The RSD unit directs beams of infrared (IR) and ultraviolet (UV) light across the road, where a receiver measures the absorption of IR and UV by the plume of passing vehicles. The absorption rate is positively correlated to the concentration of a specific absorbent (pollutant). The difference in concentration relative to the background determines the pollutants emitted from the vehicles that pass through the test site. An automatic licence plate recognition system can be set up to capture the vehicle licence number for obtaining more vehicle details if desired. Measurement of speed and acceleration is obtained upstream of the emissions measurement to estimate the engine load leading to the emissions. Figure 4 shows a schematic of the dual RSD system set up designed by the EPD for measuring petrol and LPG light-duty vehicles in Hong Kong.

**Figure 4. Schematic diagram of the dual remote sensing system’s set-up in Hong Kong**

**3.2.2 RSD for testing diesel commercial vehicles in Hong Kong**

**Location of vehicle exhaust pipe outlets:**

While RSD testing for light-duty vehicles has been researched extensively in Hong Kong since the early 1990s, it has not been applied to heavy-duty vehicles (HDVs) partly due to the varying location of vehicle exhaust pipe outlets.

To address concerns about the different orientations of exhaust pipes and the different sizes of HDVs, one of the remote sensing equipment providers, ESP, has prepared a detailed guidance document offering suggestions for RSD deployment configurations to suit different vehicle sizes and various exhaust pipe orientations and configurations. Communications with the EPD suggested that...
its research on RSD has already successfully resolved problems with measuring emissions from HDVs with different exhaust pipe positions.\(^5^3\)

**Setting enforcement cut-points:**

Another factor that could make it difficult to use RSD for screening high-emission HDVs is the unstandardised definition of trucks as gross polluters. One way to define a dirty truck is to relate the on-road emissions measured by RSD with the respective new vehicle certification standards. As an example, the RSD programme just launched by the EPD for petrol and LPG vehicles defines a grossly polluting vehicle as vehicles with emissions exceeding two times its design emission standard when the given vehicle was certified.\(^5^4\)

The cut-points set for enforcement are more easily defensible, as they are directly related to the new vehicle standards and appear to be less arbitrary. However, it is difficult to define cut-points from RSD readings of diesel vehicles. An RSD device measures ratios of pollutants to CO\(_2\) emissions (i.e. PM/CO\(_2\), NO/CO\(_2\), etc.) of the dilute exhaust plume or ratios of pollutants to fuel use, and conversion from grams of pollutant per gram of CO\(_2\) to grams of pollutant per unit of horsepower (the metric of HDV design emission standards) requires the knowledge of the brake specific fuel consumption (litre of fuel/kWh) of each of the vehicles being inspected. Unlike petrol or LPG vehicles which typically run at a stoichiometric burn ratio and have a constant brake specific fuel consumption, the air fuel ratio of diesel engines and their brake specific fuel consumption vary depending on the load and engine efficiency.\(^5^5\) As a result, it is nearly impossible to precisely define cut-points for different vintages of vehicles that correlate closely with their respective vehicle design emission standards.\(^5^6\)

There is another way to set the cut-points that the Government could consider. The cut-points could be set by evaluating the emission profile of the fleet and targeting the dirtiest fraction of the fleet. According to the plume chasing testing of 242 vehicles conducted by the City University of Hong Kong, nearly half of the on-road NO\(_X\) and black carbon (a subset of PM) emissions are believed to come from 5 per cent of the highest emitting vehicles.\(^5^7\) Since RSD can measure emissions from a large number of vehicles in a short time, the RSD readings could be used to establish an on-road emissions distribution of most of the diesel vehicles, based on which the cut-points are set at a level that ensures the highest emitting vehicles are forced to repair, while most of the vehicles would not fail. Advanced diesel vehicles with broken aftertreatment devices or with tampered devices typically have emissions several times higher than emissions from correctly functioning diesel vehicles, so the cut-points should be able to catch those vehicles with faulty or tampered emission control systems.\(^5^8\)
PM measurement using RSD:

To measure particulates, conventional RSD for heavy-duty vehicles uses an ultraviolet beam to check opacity. While it is not a direct measurement of particulates, an ultraviolet beam with a shorter wavelength (230nm) has been shown to provide a higher sensitivity to small particles emitted from modern diesel engines, compared to the visible light (with wavelength of 550 – 680nm) used in traditional opacity meters. A study conducted in Japan has shown reasonably good correlation (R square equals 0.68) between PM measurement from a PEMS test and RSD opacity readings using 230nm ultraviolet light. Therefore, RSD smoke readings should be a good proxy for PM measurements.

3.2.3 Road and weather conditions

To obtain RSD measurements that represent real-world conditions for driving, the following road and weather conditions are preferred:

- Single lane traffic, so that emissions can be easily attributed to individual vehicles;
- A location with a small incline to ensure that the engine is under load;
- Free flowing traffic with constant acceleration would be the best. For instance, a site where vehicles accelerate from a stop sign or traffic light is not desirable;
- RSD should not be placed where vehicles are likely operating at cold-start conditions (e.g. right after long idling) to exclude falsely high emitters;
- A dry, non-dusty road is preferred since road dust reduces the signal’s hit rate, hence affects accuracy; and
- Good, dry weather enables the test to obtain high validity results. While inclement weather conditions, like rain or fog, do not affect the accuracy of the test, they lower the number of valid results being captured.

The above conditions for obtaining the best RSD results could constrain the locations at which RSD testing could be deployed. This, in turn, would make it more costly to deploy sufficient RSD units to cover all diesel commercial vehicles.

Other than location constraints, RSD is not designed to provide a complete picture of emissions from the vehicle fleet. For instance, RSD typically excludes emissions during idling or under deceleration as they are too low to measure. Cold start emissions are also intentionally excluded to avoid false reporting of gross emitters, even though emissions during cold start for modern vehicles could be a significant share of the vehicle’s total emissions.
For these reasons, remote sensing measurement should be considered a coarse reading of the emission level of an individual vehicle, and RSD-based testing should not replace periodic emission tests that cover the entire vehicle fleet.

3.2.4 Remote sensing using advanced emission measurement devices

New measurement devices have been developed for remote sensing applications to improve the accuracy of the tests by addressing the limitations of traditional RSD tests discussed above. For instance, the Hong Kong EPD is exploring the application of ultra-sensitive infrared camera during remote sensing to quantify exhaust emissions from diesel vehicles.61

Another example of advanced measurement devices is the Emissions Detection And Reporting (EDAR) system, which is a laser-based technology that remotely measures infrared absorption of gaseous pollutants coming out of a moving vehicle, including petrol and diesel vehicles in their normal operating environment. This technology uses a laser to scan the entire exhaust plume and simultaneously measure the absolute amount and relative concentration of CO₂, CO, NO, NOₓ, HC, as well as opacity (as a proxy for PM).62 The EDAR device scans the traffic from above, allowing the unit to take measurements on multilane roadways (see Figure 5). This approach seems to get around many of the siting problems typically associated with RSD (for example, having to limit siting to single lane roads to avoid mixing plumes), and potentially the exhaust pipe location issue discussed above.

Other advantages of EDAR over traditional RSD equipment, as suggested by the manufacturer, include a higher sensitivity to changes in gaseous pollution concentration within an exhaust plume, a higher sampling rate, a minimised interference from adjacent vehicle exhaust plumes, no interference from ambient temperature fluctuations, no calibration (traditional RSD equipment needs to be regularly calibrated every few hours) and no onsite staff required.63

The device is now offered as a commercial product, and is being used in the States of Tennessee and Connecticut for monitoring light-duty vehicle emissions.64 Efforts have been made to measure the correlation between test results using EDAR and PEMS. Recent studies, which were shared with the authors and not yet published, show the ratio of emissions to CO₂ measured with EDAR matched well with results from PEMS.65
3.3 On-road heavy-duty measurement system test

The On-road Heavy-duty Measurement System (OHMS)\textsuperscript{57} test was invented by researchers at the University of Denver to provide a “less intrusive and better test” (than the FAS test) for measuring emissions from heavy-duty vehicles.\textsuperscript{58} The OHMS test was tested in two pilot projects in North America – in the Dallas-Fort Worth area of Texas and Vancouver in British Columbia – to evaluate its applicability for measuring in-use HDV emissions.\textsuperscript{59} Another pilot project is currently being undertaken in California, but the project’s findings have not been published. The OHMS test has the potential to measure a wide range of pollutants, including particulate mass, particulate number, black carbon, NO\textsubscript{X} (NO and NO\textsubscript{2}), HC and CO.

3.3.1 Operating principles and test set-up

Measurements of pollutants are made by accelerating a diesel vehicle from a stop through an exhaust-sampling tent. Exhaust accumulates under the roof and is sucked into a set of longitudinally perforated tubes that are connected to emission analysers. An inline fan draws air mixed with vehicle exhaust to the end of the pipe, with an integral exhaust sample of 6 to 8 seconds taken each time a truck passes through the tent. The samples are then measured by a set of analysers for different concentrations of various pollutants. Figure 7 shows the set-up of an OHMS test sampling tent. Figure 7 is a schematic diagram of the OHMS test and the emissions measurement devices used in the pilot tests.
The dimensions of the sampling tents built for the Vancouver and Texas pilots are 50 feet (L) x 12 feet (W) x 15 feet (H), and 50 feet (L) x 15 feet (W) x 18 feet (H), respectively. The vehicle driver stops at the OHMS test tent entrance and then drives through the tent in an acceleration mode. The length of the tent allows exhaust from an accelerating vehicle to be collected through the perforated tubes on one side or both sides of the tent. The analysers used are the same as those typically used for light-duty vehicle transient tests like the IM240 test (as listed in Figure 7). Specifically, particulate mass, particulate number and black carbon were monitored by direct particle mass measurement and separate black carbon measurements, so the measurements are more unequivocal than PM measurements derived from optical opacity in the RSD test. Besides, compared to the instantaneous measurement for RSD, the measurement time is longer for the OHMS test as emissions are accumulated before being analysed, so the OHMS test could potentially provide more reliable results than RSD.71

The OHMS test can use the same analysers in chassis dynamometer tests and potentially provide more reliable results than RSD

Figure 6. Set up of an OHMS test exhaust-sampling tent

Exhaust sample blower
Perforated exhaust sampling tube
Analytical instruments
3.3.2 Verification of OHMS test results

In this newly developed emission test, the Vancouver and Texas pilot studies examined how the OHMS test results matched with those measured using conventional methods, like the PEMS or RSD.

In the Vancouver pilot test, readings from the OHMS test were compared with remote sensing results obtained from over 900 diesel vehicles (see Figure 8, results obtained from the OHMS test and the RSD test are labelled as “Tunnel Diesel” and “RSD Diesel” respectively). The measurements were closely aligned in trends and levels, except for the PM results from RSD indicating a higher level of PM emissions. The Vancouver study team suggested that the higher PM readings from the RSD test were probably resulted from the trucks operating at a lower average power than that of the OHMS test.73
In the pilot test conducted in Texas, a sample of trucks underwent the OHMS test and also had their emissions checked by the PEMS to verify the accuracy of the OHMS test. The NO\textsubscript{X} measurements from the OHMS tests were found correlating fairly well with the PEMS NO\textsubscript{X} results, with an $R^2$ value of 0.8 (see Figure 9).\textsuperscript{75}
3.3.3 Adopting the OHMS test in Hong Kong

The two pilot OHMS tests conducted to date have shown that the OHMS test could be a viable test for measuring emissions of on-road diesel commercial vehicles. The OHMS test can be deployed as a screening tool, or provided with sufficient verification in an I/M setting as a replacement for the loaded dynamometer test.

Using OHMS test for roadside screening:

Regarding roadside screening, one of the advantages of the OHMS test over RSD is that the OHMS test is less sensitive to weather conditions, hence it can be performed during foggy or rainy days. However, finding a suitable site for setting up the OHMS test along corridors with heavy-duty diesel commercial vehicle traffic in Hong Kong can be challenging. The tent structure can be easily seen from afar, and hence drivers may be alerted and would inform their peers to avoid passing through the testing locations. In the Vancouver study, a much lower traffic count than expected was observed at the OHMS testing site, suggesting that drivers intentionally avoided passing the testing site where the drivers might need to undergo the test. The truck drivers in Hong Kong are likely to behave in the same way as those in the Vancouver study. Therefore, adopting the OHMS test as a
mandatory test at a centralised I/M location may be a more effective use of the OHMS application in Hong Kong.

**Using OHMS for periodic inspection:**

As the OHMS test procedure is simple, it has been shown that emissions can be monitored with a vehicle spacing as little as 20 seconds. It takes about 20 minutes for the lug-down test to be completed. It means that the OHMS test can measure emissions of a much larger number of vehicles in a day than another periodic testing option – the chassis dynamometer test (see discussion in the next section). Since the OHMS test essentially uses the ground as the dynamometer, it can test vehicles of different weight, regardless of the number of axles. Thus, offering a more flexible (and cheaper) way to simulate real-world driving than using a chassis dynamometer.

Compared to dynamometer tests, the OHMS test takes much less time to conduct as it does not require tying the vehicle up on the chassis dynamometer. In terms of the test operator training, OHMS test requires essentially the same training as a dynamometer test because several monitoring instruments are identical.

**Improved control on test variability and repeatability:**

One potential weakness of OHMS is that its test cycle is not standardised as that used in a dynamometer test. Therefore, a driver’s behaviour can have significant influence on the test results. In contrast, a dynamometer test with a predefined drive trace and a set of test conditions, like vehicle load, allows for standardisation of the test procedure with repeatable results.

If the OHMS test is to be used in a permanent I/M setting, more attention should be paid to control the driving mode and the vehicle load, in order to eliminate the possibility of cheating and ensure consistent testing results. This could be done by specifying the time it takes for the drivers to drive through the tent, and mandating the vehicle to be weighed before undergoing the test. If a truck takes longer to reach the end of the tent, the driver can be instructed to go around again. Another way to enhance the control of driving mode would be to use a slightly longer runway after the sampling tent, for instance 100m with the driver instructed that s/he must arrive at the end of the 100m pathway and stop after a certain time, for instance less than 20 seconds. This forces the drivers to accelerate through the sampling tent and checks if the drivers have exerted enough power to pull the load of vehicles and applied enough brakes to stop. If the drivers are too slow, they will be sent around again. As long as the driving mode is well controlled, like the two test procedures stated above, previous tests have shown highly consistent results for all types of vehicles.
The OHMS sampling tents built for the pilot projects in Texas and Vancouver were only for demonstrations and were designed for diesel vehicles with vertical exhaust pipes. If the OHMS test is used in periodic emission tests in Hong Kong, where almost all trucks have exhaust pipes close to the ground, a permanent shed should be built, and reconfiguration of the tent and pipes are needed. The University of Denver research team in fact has designed an improved configuration that enables monitoring of low and high exhaust (see US patent 8429957). In this design, an additional set of perforated tubes is positioned on or close to the roadway. Air flow calculations showed that it is easier to get an adequate sample for vehicles with exhaust pipes close to the ground, than for vehicles with vertical tailpipes. It is because exhaust is confined under the body of the vehicle. However, this improved configuration has not been tested in the US because almost all trucks in the US have vertical exhaust pipes.

Defining cut-points:

As with the RSD, the OHMS test measures the ratios of pollutants to $\text{CO}_2$ emissions. Therefore, the same challenge remains with setting a set of reasonable and defensible cut-points for the OHMS reading. It is because the OHMS readings cannot be directly correlated to the vehicle design emission standards.

### 3.3.4 Cost of conducting the OHMS test

When estimating the costs of the OHMS test, three elements need to be considered: costs of building the sampling tent, measurement equipment, and patent payment.

According to Professor Donald Stedman, one of the inventors of the OHMS test, the construction cost of the sampling tent, perforated pipes and fans should not cost much. The measurement equipment for $\text{CO}_2$, CO, HC, NO, NO$_x$, particulate mass and number of black carbon cost about US$350,000 (or HK$2.7 million). There is an additional cost for the patent, but it is not known yet as the OHMS test has not been sold commercially.

### 3.4 Chassis dynamometer test

A traditional way to carry out a loaded emission test is to operate a vehicle on a chassis dynamometer. A chassis dynamometer is a treadmill-like device which simulates on-road driving conditions for measuring exhaust emissions under controlled and repeatable circumstances. Therefore, dynamometers have been used for certifying light-duty vehicles, i.e. demonstrating new vehicle models meet the design emission standards, before they can be produced and sold.
For monitoring on-road vehicle emissions, light-duty vehicle dynamometer tests using a simplified test cycle have been conducted in many states in the US (for vehicles without on-board diagnostics, or OBD) for some time, and have been increasingly adopted in major cities in Mainland China. The recently adopted chassis dynamometer test for petrol and LPG vehicles in Hong Kong is an example of a chassis dynamometer test running on a short test cycle.

For HDVs, a number of places, such as Hong Kong, Singapore, Beijing and South Korea, have implemented lug-down smoke tests which use garage grade (lower cost) dynamometers to measure smoke opacity. Australia is probably the only country that has introduced a dynamometer test for measuring on-road HDV NO\textsubscript{X} and PM emissions, but the test is implemented only on a voluntary basis.

### 3.4.1 Operational principles and test set-up

During a chassis dynamometer test, a vehicle is mounted on a dynamometer and connected to emission measurement devices. The vehicle is driven by a precise “route” (test cycle) designed to simulate real-world driving conditions. As the test is conducted in a standardised and controlled manner, following a pre-defined drive trace and under a given loading condition, the measurements should be more stable and repeatable.

A simpler and relatively less costly dynamometer can mimic driving at constant load (a steady state test) while more expensive dynamometers can simulate acceleration, deceleration and idling (a transient cycle). A lug-down test can be considered a steady state test at three loading conditions: 100 per cent, 90 per cent and 80 per cent maximum engine power.

Figure 10 shows a heavy-duty tractor secured on a Hong Kong government owned inspection grade HDV chassis dynamometer, with wheels placed on rollers, ready to undergo a transient emission test. The dynamometer is procured by the EPD for carrying out transient cycle testing versus steady state testing.
3.4.2 Issues need to be considered in adopting dynamometer emission tests

**Costs:**

Very few places have opted for heavy-duty vehicle chassis dynamometer tests as a periodic emission test partly because the test equipment is expensive. For instance, one inspection grade steady-state HDV dynamometer which can simulate driving at constant load costs at least HK$600,000, excluding the cost of emission measurement devices. In Hong Kong, there are more than 125,000 diesel commercial vehicles and buses. If each vehicle needs to undergo a dynamometer test once a year, at least 12 dynamometer testing units would be required, providing that the test centres are...
open for 10 hours every day and each test takes 20 minutes. It is suggested that purchasing chassis dynamometers cost HK$7.2 million. If a longer test cycle is used, more dynamometers will be needed.

In addition, each dynamometer needs to be connected to a set of emission measurement devices. Assuming that the same estimates provided by Professor Donald Stedman could also be applied to the dynamometer test, 12 sets of measurement devices will cost an additional HK$33 million to the total capital cost.

**Test cycle:**

If a government decides to adopt a dynamometer test, one option is to modify the lug-down test to include NO$_x$ and PM measurements. One advantage of the lug-down test is that the test procedure is relatively simple, and many stakeholders (vehicle owners, mechanics and emission test inspectors) are familiar with the procedure. Besides, the HKSAR Government can utilise the dynamometers already installed at the designated test centres. However, more dynamometers will need to be installed if the lug-down test becomes mandatory for all diesel vehicles.

Officials in Mainland China are in the process of updating the annual emission test for HDVs, and considering upgrading the lug-down smoke test by including a NO$_x$ emission measurement.

For Hong Kong, the Government can develop a short test cycle that reflects Hong Kong’s specific driving conditions. The EPD of Hong Kong has just procured an inspection grade transient dynamometer (as shown in Figure 10), together with PEMS testing equipment at the Jockey Club Heavy Vehicle Emissions Testing and Research Centre. It can be used to identify a short test cycle for Hong Kong, or evaluate if short test cycles developed in other countries, such as the power-curve test cycle developed in California, are suitable for use in Hong Kong.

### 3.5 Summary of characteristics of the three in-use emissions tests

Table 1 presents the key characteristics of the three in-use emission tests discussed above. All three tests can measure NO$_x$ and PM emissions under load, and analyse exhaust emissions using advanced emission analysers. These tests should be effective for identifying high emission HDVs with advanced emissions control. Remote sensing and the OHMS test can both be used for roadside screening, and the OHMS and chassis dynamometer tests can be considered for use at periodic inspection. Also, if these tests are designed well and are automated to a maximum extent, the likelihood of cheating can be minimised.
## Table 1. Characteristics of remote sensing test, the OHMS test and chassis dynamometer test

<table>
<thead>
<tr>
<th>Test</th>
<th>Loaded test?</th>
<th>Measure PM and NOx?</th>
<th>Periodic test vs. roadside screening</th>
<th>Prone to fraud?</th>
<th>Accuracy / repeatability</th>
<th>Sensitive to weather?</th>
<th>Testing capacity (no. of HDVs tested per day)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote sensing test</td>
<td>Yes</td>
<td>Yes, indirect measurement of PM &amp; NOx in exhaust plume Measure opacity as proxy of PM</td>
<td>Roadside</td>
<td>No</td>
<td>Coarse reading for spotting high emitters Best if deployed under certain road and weather conditions</td>
<td>Yes for traditional ultra violet and infrared system</td>
<td>~ 200</td>
</tr>
<tr>
<td>OHMS test</td>
<td>Yes</td>
<td>Yes, indirect measurement of PM &amp; NOx in exhaust plume</td>
<td>Both roadside and periodic</td>
<td>No, if driving mode can be well controlled</td>
<td>Pilot tests showed good agreement with remote sensing and PEMS results Driving mode needs to be well controlled Configuration to be optimised to suit Hong Kong conditions</td>
<td>No</td>
<td>~150</td>
</tr>
<tr>
<td>Chassis dynamometer test</td>
<td>Yes</td>
<td>Yes, direct measurement</td>
<td>Periodic</td>
<td>No, if test is fully automated</td>
<td>Repeatable and accurate results</td>
<td>No</td>
<td>~30</td>
</tr>
</tbody>
</table>

Notes
* Testing capacity of remote sensing depends on traffic volume, assume a valid reading is taken every 2.5 minutes; assume each dynamometer test takes 20 minutes, and each OHMS test takes 4 minutes.
An effective emission inspection programme for diesel commercial vehicles should include annual inspection and roadside screening, as noted in Section 2. Based on the three tests discussed in the last section, there are at least three possible combinations of tests, as shown in Table 2, that will upgrade Hong Kong’s emission inspection programme for diesel commercial vehicles:

**Table 2. Possible combination of test options in Hong Kong**

<table>
<thead>
<tr>
<th>Option</th>
<th>Annual inspection</th>
<th>Roadside screening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Primary screening</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Verification</td>
</tr>
<tr>
<td>1</td>
<td>Dynamometer test</td>
<td>Remote sensing test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dynamometer test</td>
</tr>
<tr>
<td>2</td>
<td>Dynamometer test</td>
<td>OHMS test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dynamometer test</td>
</tr>
<tr>
<td>3</td>
<td>OHMS test</td>
<td>Remote sensing test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OHMS test</td>
</tr>
</tbody>
</table>

**Option 1:** Remote sensing test is deployed to screen gross emitters, followed by a dynamometer test to verify compliance, similar to what has been launched for petrol and LPG light-duty vehicles. In parallel, a dynamometer test is introduced to replace the FAS test and the lug-down test as part of the annual roadworthiness inspection at centralised facilities.

**Option 2:** OHMS test is used to screen out high emitters, followed by a dynamometer test to verify compliance, while using a dynamometer test for annual inspection at centralised facilities.

**Option 3:** Remote sensing test is used to screen out high emitters, followed by an OHMS test to verify compliance, while using an OHMS test for annual inspection at centralised facilities.

**Roadside screening:**

Both the RSD test and OHMS tests are designed for roadside screening and are able to measure emissions of a large number of vehicles in a short time period. Since these two tests obtain indirect measurement of the exhaust plum, as opposed to directly measure exhaust emissions at the tailpipe, it is desirable to retest vehicles which are identified as gross emitters during roadside screening in a more controlled environment. As shown in the last column of Table 2, the verification test is suggested to be the same as the test adopted for annual inspection for simplicity of the programme.

**The RSD test is best suited for roadside screening in Hong Kong**

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Option 4: Possibility of combination of these options along with a compact inspection programme for diesel commercial vehicles.
As noted above, the effectiveness of the OHMS test may be affected by the fact that the sampling tent is easy to be seen from afar, and drivers may change their route to avoid screening. Finding a number of suitable sites for setting up the OHMS test may also be more challenging than for RSD test since the sampling tent takes larger space than the the RSD equipment. Furthermore, concerns have been raised that the OHMS test may cause too much disruption to the normal operations of cargo trucks, as vehicles need to be diverted to undergo the test. RSD, therefore, appears to be a better choice for roadside screening in Hong Kong. However, the question discussed in Section 3.2.2 regarding the setting of cut-points for enforcement remains an issue to be resolved.

Annual inspection:

In terms of accuracy and test repeatability, the chassis dynamometer test is preferred to the OHMS test. It is because it allows direct emissions measurement and standardisation of test procedures. However, the costs of requiring all vehicles to take a dynamometer test could be prohibitively expensive.

To provide an idea of the relative costs for adopting the chassis dynamometer test and the OHMS test, Table 3 below compares the costs and the testing capacity of the chassis dynamometer test and the OHMS test, based on some preliminary data on equipment costs. It should be noted that these costs are indicative only and more research should be conducted to determine the actual costs of adopting these tests in Hong Kong.

Table 3. Comparison of the costs and testing capacity of the chassis dynamometer test and the OHMS test

<table>
<thead>
<tr>
<th>Test</th>
<th>Testing capacity* [No. of tests conducted in a 10-hour day]</th>
<th>Cost</th>
<th>Operating cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis dynamometer test</td>
<td>~ 30</td>
<td>HK$0.6 million*</td>
<td>HK$ 2.7 million</td>
</tr>
<tr>
<td>OHMS test</td>
<td>~ 150</td>
<td>Costs for constructing the shed (should be less than the cost of a dynamometer)</td>
<td>Patent payment (unknown)</td>
</tr>
</tbody>
</table>

Notes:

+ Assume each dynamometer test takes 20 minutes, and each OHMS test takes 4 minutes.
* Based on information provided by Prof. Ge Yunshan of the Beijing Institute of Technology.
** Based on cost data provided by Prof. Donald Stedman of the University of Denver; assume the same emissions measurement devices are used for both tests.
Since the OHMS test is designed to use similar emission measurement devices as those used in the dynamometer test, the capital cost, maintenance and repair cost for the emission measurement devices should be comparable for both tests. It is also assumed that the training cost of the test operators for both tests is similar, as the emission measurement devices are the same even though the test procedures are different. The number of inspectors responsible for conducting the test is believed to be similar assuming that the vehicle owners will be operating their own vehicles during both tests.

Because of the lower throughput of the dynamometer test, one set of OHMS test equipment can at least inspect five times as many vehicles as the dynamometer test per day. So a fair cost comparison would be to multiply the costs of the dynamometer test by five. The OHMS test appears to be a cheaper test option. However, it should be noted that the patent payment cost is unknown, which may turn out to be a large commitment. Due to the limited scope of this study, a detailed cost analysis of the two test options is not conducted. However, it is recommended that the EPD should investigate with caution these cost items while deciding which test to be used.

The OHMS test appears to be a promising test option. It could be a cost-effective means to test a large number of HDVs in an I/M setting. If the patent payment is not prohibitively expensive, it is recommended that the government should launch a full trial to examine the feasibility and applicability of OHMS test to the Hong Kong vehicular fleet. During the trial, findings from the OHMS test should be compared with other proven methods, such as PEMS or dynamometer test. In addition, the drive mode and configuration of the OHMS test should be examined and optimised to minimise test variations.

For evaluating the feasibility and applicability of the OHMS test in Hong Kong, a full trial is recommended.
Upgraded emission tests can identify vehicles with excessive emissions during annual inspections. It is also important to capture in-use vehicles with malfunctioning components between two annual emission tests through roadside screening. Even with an effective annual inspection test and roadside screening, vehicle operators should closely monitor the proper functioning of emission-related components of their vehicles and fix any problem swiftly, in order to keep the emissions at a low level. In light of this, the following sections briefly discuss other supporting policies that will help promote timely and proper vehicle maintenance.

5.1 Strengthening mechanics training and mandating the registration scheme

5.1.1 Importance of competent vehicle repair mechanics

Retiring old vehicles will deliver substantial immediate emission reductions. However, to maintain the emission control performance of the replacement vehicles over their useful life, proper maintenance and repairs are required. This is particularly true in Hong Kong, as two-thirds of the diesel commercial fleets in Hong Kong will be retired by 2020 and a large share of them will be replaced with vehicles using advanced, electronically controlled emission control systems. There is an urgent need to enhance the capability of the repair industry, so that the mechanics can properly repair the advanced vehicles.

5.1.2 Strengthening the current training programmes for mechanics

In Hong Kong, in collaboration with the Vocational Training Council (VTC) and the Hong Kong Productivity Council (HKPC), the EPD has been offering training sessions and seminars on vehicle maintenance to reduce smoke emission from diesel vehicles since 1999. As the share of advanced vehicles increases, there is an urgent need to improve the capability of the mechanics.

As the share of advanced vehicles increases, there is an urgent need to improve the capability of the mechanics.

The Vocational Training Council (VTC) training sessions are not mandatory nor specific enough for the mechanics.

The Pro-Act Centre of the VTC provides practical training courses to the automobile industry, such as LPG vehicle servicing, automobile testing and measuring equipment, vehicle electrical systems, diesel engine repair and maintenance, as well as courses on OBD. Among the 19 courses offered, only two are about diesel vehicles, and the courses appear to only cover the basics of electronically controlled systems and common rail fuel injection systems, as well as the repairing of these systems. Apparently, there is a need for more in-depth training specifically in diagnosing and repairing defects of these technologies.
in response to the increasing number of vehicles equipped with advanced emission control technologies, like SCR, EGR, and DOC. In addition, mechanics need to pay for the courses from their own pockets and attend the courses during their spare time. Right now, there is no mandatory certification scheme for mechanics, and the voluntary certification scheme has no requirements on training (more discussion in the next section), which explain why the mechanics do not have any motivation to attend the training courses.\(^{32}\)

Besides the VTC courses, the EPD offered a series of free seminars and training workshops for mechanics and the public in mid-2014, introducing the new remote sensing and chassis dynamometer test programmes for LPG and petrol vehicles. EPD also commissioned the VTC to offer free in-depth mechanic training workshops for proper diagnosing and repairing of LPG and petrol vehicles which fail the more rigorous emission tests. These seminars and training workshops are designed to enhance the capability of mechanics in repairing emission control systems when the stricter standards for LPG and petrol vehicles are imposed.\(^{33}\)

Some large garages (usually affiliated to authorised dealers) also provide internal training to prepare mechanics for the new vehicle models. This kind of training introduces advanced emission technologies used in new LDV and HDV models together with the maintenance procedures, and is typically offered about six months before the launching of new models in Hong Kong.

To improve the situation, there is a need to upgrade the existing mechanic training to ensure that all mechanics, whether they are working for small- or large-scale garages, are well-trained and equipped with the right tools for diagnosis and repair of today’s and future vehicles with advanced emission control devices. To achieve this, the HKSAR Government should ensure that training will focus on diagnosing and repairing faulty advanced emission control systems and be offered at reasonable costs to all mechanics.

5.1.3 Mandating the registration scheme for vehicle repair mechanics

With the aim of enhancing the standard of the local vehicle maintenance trade, the HKSAR Government launched a voluntary registration scheme for vehicle repair mechanics in 2007.\(^{34}\) Repair mechanics are qualified by the scheme as registered mechanics provided that they have enough experience, attended a certain number of hours of related courses or passed certain tests. The registration needs to be renewed every three years, with the requirement that they have been employed as mechanics for 1.5 years inside the three years prior to taking the test, and have taken 20 hours of continuous professional training. According to discussions with mechanics, employers usually encourage mechanics to become registered, even though mechanics do not typically get subsidies or time off for attending continuous training.\(^{35}\) In some large-scale garages, most of the mechanics are registered.
The definition of continuous training for the mechanics is very broad, which includes training courses offered by the Pro-Act Center to enhance language and customer service skills. Apparently, the existing registration renewal requirements are difficult to impose a minimum quality assurance on the continuous professional training received by the mechanics.

The HKSAR Government should consider making the registration scheme mandatory, and require the training that are recognized for obtaining and renewing the mechanic registration to be provided by certified schools or training institutes. As an example, the Bureau of Automotive Repair (BAR) of the State of California administers a repair technician licensing scheme which lays out clear requirements, including passing an examination on vehicle repair and diagnosis, for a mechanic to obtain a repair technician licence. Renewal of the licence requires completing a certain level of training in a BAR-certified school. California’s repair technician licensing scheme therefore can ensure all certified mechanics achieve a given level of performance standards.

5.2 Promoting free access to vehicle repair information

Distributors (or dealers) of vehicles and associated large-scale garages have to pay the overseas manufacturers for repair manual of different vehicle models sold in Hong Kong, both old and new ones. In order to sustain their business by retaining the advantage in repair capability over smaller garages, these large-scale garages are not willing to share their assets with their competitors. Manufacturers may charge small scale garages a high price for repair information since they are not either dealerships or business partners. If small garages cannot afford such costs, they can only repair vehicles relying on their experience and skills, leading to higher chance of ineffective repairs.

Therefore, the government should consider requiring manufacturers to share repair-related information among the repair industry. In Europe, beginning with Euro V standards for light-duty vehicles and Euro VI for HDVs, manufacturers are required to make available easy, restriction-free and standardised access to vehicle repair and maintenance information. Similar provisions can be found in the US regulations. The provision of such information would significantly lower the cost that small-scale garages need to bear for improving their capability to repair new vehicle models, and as a result create a more competitive and fair market. The AE DataBase Centre of VTC, which was set-up in around 2001 to provide repairers (members) with vehicle data and related training and support, is a platform for sharing the latest vehicle repair and maintenance information made available by manufacturers under the Euro VI requirement.
5.3 Promoting the use of on-board diagnostics

5.3.1 Principle and applications of OBD

An OBD system monitors engine and aftertreatment systems (including emission-related components) of a vehicle through the use of on-board computers and sensors. It is capable of detecting malfunctions of the monitored emission systems, lighting up a malfunction indicator light (MIL) to alert the vehicle operator about potential malfunctions that may affect emission control performance, and storing fault codes which identify the detected faults. Mechanics and enforcement officials can access fault codes stored in the OBD system using an OBD scanner. With this information, mechanics should be able to quickly identify malfunctions and repair the vehicle more effectively.

The OBD system also serves as a cross-checking tool for regulators and emission inspectors to determine whether a vehicle is properly repaired and maintained. Therefore, the vehicle’s OBD system has two roles, both as a diagnostic tool to facilitate maintenance and repair, and as an inspection tool to check if emission-related components are operating properly.

Given the robust nature of today’s emission control components, an individual component can become defective without causing an immediate increase in tailpipe emissions. In such circumstances, other components, such as the catalyst and reagents, can temporarily compensate for the defective part. However those other components can become defective eventually if the malfunctioning part(s) is/are not fixed in a timely manner. An OBD system is designed to enable the mechanics to identify the defective components of these modern vehicles more precisely, sometimes even before the malfunctioning components causing an increase in emissions.

OBD systems were introduced into LDVs in the US in the early 1990s and in Europe about 10 years later. Beginning with the Euro IV standard, HDVs are required to be equipped with OBDs. The first OBD system was very basic. Additional requirements were introduced subsequently with Euro V. Euro VI regulations introduced a number of additional “performance monitoring” requirements that are gradually phasing in from 2013 to 2017. By 2017, all new HDVs sold in Europe are subject to the most rigorous OBD requirements. More details about the OBD requirements can be found in the appendix.

5.3.2 OBD monitoring on emission control devices

Figure 11 below summarises the major emission control devices and components monitored by an OBD system. An OBD performs a self-diagnostic function through the use of sensors (such as pressure sensor, oxygen sensor and temperature sensor) connected to the emission control system, and directly monitors the functionality of important emission control components. For some of the key emission control components, faults are detected by checking if predetermined emission thresholds are exceeded.
As discussed in Section 5.3.1, malfunctioning of the emission control components of an OBD-equipped vehicle will be recorded and stored as fault codes. During an emission inspection, an inspector can plug in an analyser designed for the OBD system (the OBD scanner) and read the stored information regarding the malfunctioned emission-related components.

An OBD test provides more accurate information that leads to effective repairs. The inspection time is short and can be conducted at an affordable cost to the vehicle owner. OBD also enables early detection of potential emission exceedance and timely maintenance.\(^\text{107}\) It is with these benefits that the US Clean Air Act requires all mandatory I/M programmes to include OBD checks for all 2006 or newer LDV models. Europe has also included an emission-related OBD test as one of the requirements of vehicle inspection. For example, in the Netherlands, an annual emission measurement with OBD scanning tools is required since April 2012 for vehicles built in and after 2006 as part of the periodic technical inspection.\(^\text{108}\)

However, it is not yet the right moment to introduce the OBD test as part of the annual inspection for HDVs in Hong Kong. It is because the share of OBD-equipped HDVs is still low, and the comprehensive OBD requirements will only be fully phased in in the EU by 2017.\(^\text{109}\)
Figure 11: Typical emission control components monitored by a heavy-duty OBD system

5.3.4 Promoting the use of OBD as a diagnostic tool in Hong Kong

While it remains at least a few years before OBD can be considered for annual inspection, OBD has already been used by mechanics for repairing vehicles at large-scale repair garages in Hong Kong. According to the discussion with the industry, mechanics from large garages (which are usually affiliated to vehicle dealers) have begun using proprietary diagnostic scanners to check and repair Euro IV and Euro V (and some Euro III) HDVs. However, the diagnostic scanners which the mechanics are using are manufacturer- and even model-specific.

All the elements for the OBD check-up package, including the scanner, computer software, and repair manuals of individual models, have to be purchased from the manufacturers at a high cost (tens of thousands of Hong Kong dollars per package, plus service charges). That cost could be prohibitively expensive for small-scale repair garages, and some of these small-scale garages may choose to use universal scanners that may not be as accurate and up-to-date as scanners provided by the manufacturers. To create a more competitive and fair market, and to ensure that the vehicle
operators have access to good and reasonably priced repair service, the government may consider offering training to all mechanics and requiring manufacturers to offer free access to repair-related information, as suggested in Section 5.2.

5.3.5 Points to consider for adopting OBD testing in I/M and annual tests

Even though it will be at least several years before OBD becomes the standard for HDVs, given the benefits of using OBD tests in an I/M programme, the government should be encouraged to keep this option open. Based on the US experiences with the OBD tests for LDVs, the following factors on when and how to implement an OBD-based I/M programme should be considered:

- Are there enough OBD-equipped vehicles in the fleet aged enough to support a testing network that is sized so that the test providers/operators can make a healthy profit while customers are subjected to reasonable waiting time, travel distances, and test fees?

- What is the degree of standardisation within the OBD-equipped portion of the fleet? OBD is still an evolving technology. Different designs or versions of OBD are spread across different age groups of vehicles, and the basic ones introduced with Euro IV vehicles, for instance, tend to be more proprietary as there is no requirement yet for standardisation. As a result, it may not be practical to attempt to design an OBD-based I/M programme around these older, non-standard OBD systems. Rather, it would be more cost-effective to require using OBD tests for monitoring emissions of vehicles with more standardised OBD systems;

- Another important factor to consider when implementing an I/M programme, which is not unique to OBD, is the provision of sufficient programme oversight to deter testing fraud, repair fraud, and various forms of programme avoidance, such as registration fraud, if the programme is enforced through registration revocation or denial; and

- Are both the testing community and vehicle repair community adequately trained so that the tests are performed correctly, and repair technicians are capable of diagnosing and repairing failed vehicles?

The US experiences have shown that OBD tests are fast, effective and cheap to operate. However, since regulations on OBD systems are different for various vehicle markets, the design of OBD systems such as computer programmes, plugs and sockets, amongst manufacturers are also different.

In Hong Kong, vehicles meeting a fairly wide range of international certification standards are in use in the local vehicle fleet, including...
vehicles with either no OBD system or OBD systems certified to different OBD standards (from the US, the EU or even Japan). This diversity of OBD systems could make implementing an OBD-based I/M programme cumbersome, depending on whether all the OBD systems in Hong Kong have enforcement system ready (such as in the US) and possibility to direct vehicles compliant with a specific OBD standard to designated testing locations specifically equipped for testing those vehicles. This would require substantial integrations of different OBD systems in a test centre and a worldwide vehicle registration database to identify which OBD standard for a given vehicle meets and determine whether there are sufficient numbers of each type of certification to justify dedicated stations. 114
Conclusion

It is encouraging to see the Government’s efforts in the past two years in targeting various local pollution sources. The success in rolling out two major initiatives to enforce stricter in-use emission requirements for petrol and LPG vehicles and to encourage early retirement of diesel commercial vehicles shows the government’s commitment to reducing vehicular pollution.

As a result of the early retirement subsidy programme for diesel commercial vehicles, we are expecting advanced emission control technology to become the norm rather than the exception. Operation of these advanced vehicles is controlled electronically, exhaust emissions are very low, and such emissions are predominantly invisible (fine PM and NO\textsubscript{x}). The existing I/M programme for diesel commercial vehicles, which only monitors visual smoke, will no longer effectively identify advanced vehicles with malfunctioning emission control systems.

It is therefore critically important for the government to upgrade the existing I/M programme for diesel commercial vehicles by introducing roadside screening and adopting an effective emission test for PM and NO\textsubscript{x}, as part of the vehicle annual roadworthiness inspection.

Remote sensing test, the OHMS test and chassis dynamometer test are three viable options for inspecting vehicles with advanced pollution control equipment. Operation of these advanced vehicles is controlled electronically, exhaust emissions are very low, and such emissions are predominantly invisible (fine PM and NO\textsubscript{x}). The existing I/M programme for diesel commercial vehicles, which only monitors visual smoke, will no longer effectively identify advanced vehicles with malfunctioning emission control systems.

Remote sensing test, the OHMS test and chassis dynamometer test are three viable options for inspecting vehicles with advanced pollution control equipment. This paper discusses how these tests have been used in other countries and issues to consider when the tests are adopted in Hong Kong. Using dynamometer tests for periodic inspection combined with remote sensing for roadside screening appears to be the best means for identifying diesel commercial vehicles with excessive emissions. However, the capital costs for mandating dynamometer tests be undertaken by all diesel vehicles may be too high.

A full trial is recommended for checking the validity and feasibility of the OHMS test. The OHMS test is possibly a lower cost, simpler, and more accurate option for periodic emissions tests. However, since the OHMS is only recently developed, the feasibility and validity of adopting the OHMS test as the periodic emission test should be carefully evaluated. It includes checking the cost of patent and launching a trial in Hong Kong to validate this approach against other well-established methods like PEMS and dynamometer tests. The trial could also look into ways for optimising the shed configuration to best suit the vehicle fleet in Hong Kong. The newly established inspection grade heavy-duty vehicle transient dynamometer of the EPD greatly enhances the agency’s capability in evaluating and validating each of these testing options and developing details of the test programme, such as the test cycle and in-use emission limits (the cut-points).
Vehicle maintenance is critically important, but often an overlooked element of a vehicle emission control programme. As the share of HDVs with advanced engines and pollution control equipment increases, mechanics need to be better trained so that they can properly diagnose and repair failed emission control components on these advanced vehicles. Assuming a more effective emission test captures greater numbers of polluting vehicles, more well-trained mechanics will be likely needed to carry out the related repairs. One improvement that should be considered is to make sure that mechanics training focuses on diagnosis and repair of advanced emission control systems are made available at reasonable cost to all vehicle mechanics. Establishing a mandatory mechanic certification scheme is also recommended to make sure that all mechanics will reach a certain level of capability.

OBD offers an important tool for diagnosing and identifying defective parts related to emission control on advanced diesel vehicles. However, the complexity of the system presents challenges for the vehicle repair industry to make good use of this tool. Nevertheless, from conversations with mechanics, it seems that large garages are already using proprietary diagnostic systems to repair Euro IV and newer vehicles. The biggest obstacle for spreading the use of this tool appears to be the high cost of the diagnostic scanner and repair information, especially for small garages. Since the EU and the US governments have imposed requirements on manufacturers to provide the repair industry with restriction-free access to repair and maintenance information and tools, the HKSAR Government should explore ways to set similar requirements. In the future, as OBD systems become more standardised on diesel commercial vehicles, the government could explore the adoption of the OBD test in the I/M programme.

**Going forward:**

The Euro VI standard that are fully implemented in the EU countries in 2014 have seen substantial improvements in the test cycle, tightened emission standards and extended durability requirements to ensure that vehicles are built with more robust and durable emission control systems. The Euro VI and the US 2010 standards are similar in stringency and compliance requirements, and both will bring forth similar set of best available control technologies. The long durability requirements in the Euro VI and the US 2010 standards, in particular, may also lessen the repair burden on vehicle owners as the emission control components are made to last longer. Currently, Hong Kong still allows sales of vehicles meeting Euro V and the Japan’s Post New Long Term standards, which lack of rigorous testing requirements to ensure emissions are well controlled over the full range of driving conditions commonly experienced in-use. As two-thirds of Hong Kong’s diesel commercial fleet is going to be replaced in the next five years, the government should, as early as possible, tighten the emission standards to a level similar to that of Euro VI and US 2010 standards. This would ensure new vehicles sold in Hong Kong will all be equipped with the latest and most effective emission control technologies.
Appendix: On-board diagnostics requirement for heavy-duty vehicles

The US OBD Requirement:

In 2009, the US EPA published regulations requiring OBD systems in 2010 and later heavy-duty engines to be used in vehicles weighing over 14,000 lbs as well as revisions to OBD requirements for diesel highway HDVs under 14,000 lbs. The requirements contain three main categories: threshold monitoring, non-threshold monitoring and OBD testing and validation.

Threshold monitoring is used at the main emission control system with a combustion engine so as to monitor whether the emission level of a particular gas indicator, or a technical parameter of some major components of the emission control system, exceeds thresholds set by the requirement. Emission control systems that are monitored include NO\textsubscript{X} aftertreatment system,

Table A1: The US OBD thresholds for diesel-fuelled / compression-ignition engines meant for placement in applications greater than 14,000 lbs GVWR (g/BHP-hr).

<table>
<thead>
<tr>
<th>Component</th>
<th>Monitoring System</th>
<th>NMHC</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Years 2010-2012</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO\textsubscript{X} aftertreatment system</td>
<td>SCR and Lean NO\textsubscript{X} Catalyst, NO\textsubscript{X} Absorber / Lean NO\textsubscript{X} Trap (LNT) System</td>
<td>-</td>
<td>-</td>
<td>+0.6</td>
<td>-</td>
</tr>
<tr>
<td>DPF System</td>
<td>DPF System Monitoring</td>
<td>2.5x</td>
<td>-</td>
<td>-</td>
<td>0.05/+0.04</td>
</tr>
<tr>
<td>Air-fuel ratio sensors of aftertreatment devices (upstream)</td>
<td>Exhaust Gas Sensor</td>
<td>2.5x</td>
<td>2.5x</td>
<td>+0.3</td>
<td>0.03/+0.02</td>
</tr>
<tr>
<td>Air-fuel ratio sensors of aftertreatment devices (downstream)</td>
<td>Exhaust Gas Sensor</td>
<td>2.5x</td>
<td>-</td>
<td>+0.3</td>
<td>0.05/+0.04</td>
</tr>
<tr>
<td>NO\textsubscript{X} Sensors</td>
<td>Exhaust Gas Sensor</td>
<td>-</td>
<td>-</td>
<td>+0.6</td>
<td>0.05/+0.04</td>
</tr>
<tr>
<td>&quot;Other monitors” with emissions thresholds</td>
<td>Fuel System, EGR System, Turbo Boost Control System, Variable Timing (VVT) System</td>
<td>2.5x</td>
<td>2.5x</td>
<td>+0.3</td>
<td>0.03/+0.02</td>
</tr>
<tr>
<td><strong>Model Years 2013 and Later</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO\textsubscript{X} aftertreatment system</td>
<td>SCR and Lean NO\textsubscript{X} Catalyst, NO\textsubscript{X} Absorber / Lean NO\textsubscript{X} Trap (LNT) System</td>
<td>-</td>
<td>-</td>
<td>+0.3</td>
<td>-</td>
</tr>
<tr>
<td>DPF System</td>
<td>DPF System Monitoring</td>
<td>2.0x</td>
<td>-</td>
<td>-</td>
<td>0.05/+0.04</td>
</tr>
<tr>
<td>Air-fuel ratio sensors of aftertreatment devices (upstream)</td>
<td>Exhaust Gas Sensor</td>
<td>2.0x</td>
<td>2.0x</td>
<td>+0.3</td>
<td>0.03/+0.02</td>
</tr>
<tr>
<td>Air-fuel ratio sensors of aftertreatment devices (downstream)</td>
<td>Exhaust Gas Sensor</td>
<td>2.0x</td>
<td>-</td>
<td>+0.3</td>
<td>0.05/+0.04</td>
</tr>
<tr>
<td>NO\textsubscript{X} Sensors</td>
<td>Exhaust Gas Sensor</td>
<td>-</td>
<td>-</td>
<td>+0.3</td>
<td>0.05/+0.04</td>
</tr>
<tr>
<td>&quot;Other monitors” with emissions thresholds</td>
<td>Fuel System, Engine Misfire, EGR System, Turbo Boost Control System, Variable Timing (VVT) System</td>
<td>2.0x</td>
<td>2.0x</td>
<td>+0.3</td>
<td>0.03/+0.02</td>
</tr>
</tbody>
</table>

Notes:
2.5x means a multiple of 2.5 times the applicable emissions standard or family emissions limit (FEL);
+0.3 means the standard of FEL plus 0.3;
0.5/+0.04 means an absolute level of 0.05 or an additive level of the standard of FEL plus 0.04, whichever level is higher.
Not all monitors have emission thresholds and some rely on functionality and rationality checks.
diesel particulate filter (DPF) system and air-fuel ratio sensors. The thresholds are usually expressed in multiples (2 to 2.5 times in general) of or deviations from absolute values of applicable emission standards. Table A1 shows the OBD emission thresholds for diesel heavy-duty engines used in 2010 model year vehicles and later with gross vehicle weight rating (GVWR) greater than 14,000 lbs, required by the US EPA.\textsuperscript{118}

For other parts of the vehicles without any corresponding threshold requirement, non-threshold monitoring is used to detect any malfunction under normal driving conditions, and avoid false passes and false malfunction indications through functional, ratio and electrical monitoring of nearly a hundred signals per engine. These signals are not standardised and could even differ between models produced by the same manufacturer.\textsuperscript{119}

The requirement for OBD testing and validation ensures the OBD system functions correctly under the established threshold value. Manufacturers are required to correlate component and system performance with exhaust emissions to determine if deterioration will cause emissions to exceed a certain threshold.\textsuperscript{120}

**European OBD requirement:**

Requirements of European On-Board Diagnostics (EOBD) follow the development of emission standards in Europe and were introduced in 2005 for Euro IV vehicles. In 2008 they were modified for Euro V vehicles with a standardised OBD system across manufacturers and also access to repair information. The latest Euro VI OBD requirement will be phased in between 2013 and 2016. All new vehicle types (i.e. vehicle models that are type-approved) in the EU will have to be equipped with OBD beginning 2016, and all models that have been type-approved will have to comply with the OBD regulation beginning in 2017.\textsuperscript{121}

Similar to the OBD in the US, current EOBD also monitors various components of engines including those controlling emissions. However, threshold limits are only applied to emissions of pollutants but not to particular monitoring components. The threshold limits for NO\textsubscript{X} and PM are tightening from January 2013 to January 2016 and these limits apply to new vehicle types, while type-approved vehicles have one more year to comply. In addition, the EOBD threshold limits are only applicable to engines fitted to passenger vehicles with maximum mass exceeding 5 tonnes, goods vehicles with maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes and goods vehicles with maximum mass exceeding 12 tonnes (equivalent to vehicle classes M3, N2 and N3 respectively).\textsuperscript{122} Table A2 and Table A3 show OBD monitoring details and threshold values respectively.
Table A2: Systems or components required to be monitored by the EOBD system on diesel Vehicles

<table>
<thead>
<tr>
<th>Components</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric / electronic Components</td>
<td>The functionality of components of the emission control system should be monitored, including pressure sensors, temperature sensors, exhaust gas sensors, oxygen sensors, etc. Wherever a feedback control loop exists, the EOBD should able to monitor the system’s ability to maintain feedback control as designed.</td>
</tr>
<tr>
<td>DPF System</td>
<td>The EOBD should able to monitor the presence of the DPF substrate, any clogging of the DPF, filtering as well as the regeneration process.</td>
</tr>
<tr>
<td>SCR</td>
<td>Active/instructive reagent and its injection system should be monitored for the performance of the emission control device. SCR catalyst conversion efficiency should also be monitored for the catalyst’s SCR ability.</td>
</tr>
<tr>
<td>Oxidation catalysts (including Diesel Oxidation Catalyst – DOC)</td>
<td>HC conversion efficiency should be monitored for the oxidation catalyst’s ability to convert HC upstream / downstream of other aftertreatment devices.</td>
</tr>
<tr>
<td>EGR</td>
<td>The flow rate and cooling performance should be monitored to ensure adequate performance.</td>
</tr>
<tr>
<td>Fuel System</td>
<td>Fuel system pressure and injection timing should be monitored.</td>
</tr>
<tr>
<td>Air handling and turbo charger / Boost pressure control system</td>
<td>Boost pressure and charge air-cooling process should be monitored.</td>
</tr>
<tr>
<td>VVT System</td>
<td>The performance of the VVT system should be monitored to achieve the required valve timing within the manufacturer’s specified time interval.</td>
</tr>
<tr>
<td>Misfire</td>
<td>No prescription</td>
</tr>
<tr>
<td>Crankcase Ventilation System</td>
<td>No prescription</td>
</tr>
<tr>
<td>Engine Cooling System</td>
<td>Engine coolant temperature should be monitored to ensure the engine is working at an adequate temperature</td>
</tr>
<tr>
<td>Exhaust Gas and Oxygen Sensors</td>
<td>The EOBD should monitor the electrical elements of the exhaust gas sensor on the engine for proper operation.</td>
</tr>
<tr>
<td>Idle Speed Control System</td>
<td>The EOBD should monitor the electrical elements of the idle speed control system on the engine for proper operation.</td>
</tr>
</tbody>
</table>

Table A3: EOBD threshold limits (mg/kWh)

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Period</th>
<th>NOx (1.12 g/BHP-hr)</th>
<th>PM (0.02 g/BHP-hr)</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression Ignition</td>
<td>Phase-in</td>
<td>1,500</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>General requirements</td>
<td>1,200</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Spark Ignition</td>
<td>Phase-in</td>
<td>1,500</td>
<td>-</td>
<td>To be confirmed</td>
</tr>
<tr>
<td></td>
<td>General requirements</td>
<td>1,200</td>
<td>-</td>
<td>To be confirmed</td>
</tr>
</tbody>
</table>

Note: 1 kWh = 1.341 BHP-hr
**HDV OBD Phase-in Schedule:**

OBD systems have been used on LDVs in the US and the EU for several years even though their implementation time-lines are slightly different. In order to extend the coverage of OBD systems to different types of vehicles, including HDVs, for better control of emissions as shown in Table A4, both regions are now extending their OBD programme to cover all HDVs. OBD is expected to be applied to all HDVs in the US in 2016 and a year later to those in the EU. The schedule of implementation tends to converge after 2017 and all vehicles are expected to be equipped with OBD system after that.

**Table A4: HDV OBD Schedule of Deployment in the US and the EU**

<table>
<thead>
<tr>
<th>Year</th>
<th>EU</th>
<th>US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 2013</td>
<td>• Euro V OBD &amp; NO(_x) control monitoring NO(_x)</td>
<td>• US2010</td>
</tr>
<tr>
<td>2013</td>
<td>• Euro VI Phase-in (1 January 2013, for new vehicle types)</td>
<td>• OBD Phase-in for Diesel HDV (HDDV, GVWR&gt;14,000 lbs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Full OBD for 1 to 3 engine families per year, extrapolated OBD for the rest</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• OBD is standardised across manufacturers</td>
</tr>
<tr>
<td>2014</td>
<td>• Euro VI Phase-in: (1 January 2014, for all vehicle types)</td>
<td>• Full OBD for 1 to 3 engine families per year, extrapolated OBD for the rest</td>
</tr>
<tr>
<td></td>
<td>• OBD PM sensors evaluated in September 2014</td>
<td>• GHG/FE Phase-in</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td>• Full OBD for 1 to 3 engine families per year, extrapolated OBD for the rest</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• PM sensor phase-in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Urea quality sensor</td>
</tr>
<tr>
<td>2016</td>
<td>• Euro VI Final OBD: (1 January 2016, for new vehicle types)</td>
<td>• Full OBD for HDVs, all engines, all vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Full PM sensor</td>
</tr>
<tr>
<td>2017</td>
<td>• Euro VI Final OBD: (1 January 2017, for all vehicle types)</td>
<td>• GHG/FE Full Stringency</td>
</tr>
</tbody>
</table>
Endnotes


3. In Hong Kong, light buses are powered by LPG, diesel or petrol. The emissions data obtained from EPD only provides a breakdown of emissions by vehicle type, so the total emissions of light buses are available, but not the share of emissions from diesel light buses.

4. Detailed discussions about the problems with the then annual emission test for LPG vehicles and why the tests were not capable of forcing proper maintenance can be found in: Fung, F. and Suen, B. (2013), A Review of the Hong Kong Inspection and Maintenance Programme for On-road Vehicles, August 2013, Hong Kong: Civic Exchange, http://www.civic-exchange.org/en/publications/164986987 (accessed 31 July 2014). The emissions data presented in the report are based on data from 2011, provided by the HKSAR Environmental Protection Department on 20 May 2013. An up-to-date vehicle emissions inventory will be released in late 2014.

5. See note 1.


7. Throughout this report, “diesel commercial vehicles” refers to diesel vehicles with a permissible maximum laden mass of over 3,500 kg. While about 1 per cent of commercial vehicles over 3,500kg in weight are powered by petrol; the focus of this report is on diesel commercial vehicles.

8. Data provided by Dr. Carol Wong of HKSAR Environmental Protection Department, 23 July 2014.


10. Communications with Dr. S.T. Mak of the HKSAR Environmental Protection Department on 8 September 2014.

11. Hong Kong began accepting models certified with the Japanese standards in 2006.


28. Ibid.


32. See note 30.


35. Communications with Prof. Donald Stedman of the University of Denver on 29 August 2014.


40. Portable Emission Measurement System (PEMS), the plume chasing approach and mobile lab test are not discussed in details in this report as they are not considered suitable for use in identifying high emission vehicles in Hong Kong. While PEMS test can obtain fairly accurate measurement of emissions of the test vehicles, the long time for setting up and taking off the PEMS equipment renders it not suitable for use as periodic emission test. The plume chasing technique and the mobile lab test for screening high emission vehicles are not considered the most suitable method for screening high-emission vehicles as the number of tests that can be conducted are much less than those captured by remote sensing. Also, the mobile lab setting in the US study is only suitable for checking emissions coming out from vertical exhaust pipes, so cannot be directly applicable to the HDV fleet of Hong Kong.


42. The United States Environmental Protection Agency (USEPA) has found that since the early 1990s, heavy-duty engine manufacturers used computer programmes to cause the engine switch to low fuel consumption (but high NOX) driving mode during highway cruising. As a result, heavy-duty engines that were certified to comply with the NOX emissions standard could actually emit much higher NOX when in operation. In 1998, a court settlement was reached between the USEPA, the Department of Justice, the California Air Resources Board and heavy-duty engine manufacturers over this issue, and one of the provisions in the Consent Decree is the introduction of the NTE standard to ensure that all HDVs have effective control of emissions under all driving conditions that could reasonably be expected to be seen in normal vehicle operation and use. More information can be found in: Environmental Protection Agency, Control of Emissions of Air Pollution from 2004 and Later Model Year Heavy-Duty Highway Engines and Vehicles; Revision of Light-Duty On-Board Diagnostics Requirements – Final Rule, 6 October 2000, in Federal Register 61:195, p.59896, http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=2000_register&docid=00-20144-filed.pdf (accessed 10 September 2014).

44. Borken-Kleefeld, J., Guidance note about on-road vehicle emissions remote sensing, October 2013, The International Council on Clean Transportation, http://www.theicct.org/road-vehicle-emissions-remote-sensing, (accessed 3 March 2014); Borken-Kleefeld noted that RSD can also be used for cross-checking performance of onboard diagnostic system (OBD), but this may not be entirely correct since OBD monitors systems that RSD cannot, like evaporative emissions, and also, OBD can identify faults before tailpipe emissions increase and can be detected by tailpipe testing like RSD.


47. Bishop, G.A. et al. (2012), “Multispecies remote sensing measurements of vehicle emissions on Sherman Way in Van Nuys, California”, Journal of the Air & Waste Management Association, 62:10, pp.1127–33, http://www.tandfonline.com/doi/abs/10.1080/10962247.2012.699015#.U.6pkNK1bYg (accessed 28 August 2014). Note that this RSD study also measure ammonia (NH₃), sulphur dioxide (SO₂) and nitrogen dioxide (NO₂), but the NH₃, SO₂ and NO₂ capabilities are not yet commercially available in RSD.


51. In the context of Hong Kong, heavy-duty vehicles (HDVs) have a slightly different meaning. Diesel commercial vehicles (DCVs) in Hong Kong refer to all diesel vehicles that are not private cars, so they include diesel light-duty vehicles like delivery vans. In the US, HDVs are vehicles with gross vehicle weight over 14,000 lbs (equivalent to 6.4 tonnes). In the report, however, we will use these two terms interchangeably since two categories of vehicles have a lot of overlap.

52. See note 25.

53. Communications with Mr. Casey Lee of the HKSAR Environmental Protection Department on 11 September 2014.


55. See Appendix A of Envirotast Canada (2013) in note 46.

56. Communications with Mr. Casey Lee of the HKSAR Environmental Protection Department on 11 September 2014.
57. See note 38.

58. Communications with Prof. Donald Stedman of the University of Denver on 6 September 2014.


61. Communications with Mr. Casey Lee of the HKSAR Environmental Protection Department on 11 September 2014.

62. Communications with Ms. Yolla Hager of Hager Environmental and Atmospheric Technologies on 3 September 2014.


64. Communications with Ms. Yolla Hager of Hager Environmental and Atmospheric Technologies on 11 August 2014. The survey for Tennessee was performed with the cooperation of Tennessee Department of Environment and Conservation and Tennessee Department of Revenue, and the survey for Connecticut was conducted together with the Connecticut Department of Motor Vehicles.


66. Pictures provided by Yolla Hager of Hager Environmental and Atmospheric Technologies on 3 September 2014.

67. Ibid.

68. The OHMS test was previously known as the Streamlined Heavy-Duty Emissions Determination (SHED) System test, or Heavy Duty Emission Tunnel (HDET) test.


70. Pictures provided by Prof. Donald Stedman of the University of Denver on 29 August 2014.


72. Schematic and photos provided by Prof. Donald Stedman of the University of Denver on 29 August 2014.

73. See Envirotest Canada (2013) in notes 46.


75. Texas A&M Transportation Institute (2013) in note 41; Due to malfunctioning of the PEMS device for PM, no valid PM emissions data were collected, therefore comparison of PM readings from the OHMS test and PEMS test could not be performed.


77. Communications with Prof. Donald Stedman of the University of Denver on 15 May 2014.

78. Ibid.


80. Communications with Prof. Donald Stedman of the University of Denver on 6 September 2014.

81. Heavy-duty vehicles are certified by running the emissions tests on the engines, not on the whole vehicle, since a lab grade heavy-duty chassis dynamometer is extremely expensive. Furthermore, performing a whole-vehicle test for the large number and many types of models, from bucket trucks, fire trucks to short haul trucks, long haul trucks, and dump trucks, would also be very expensive and time consuming.

82. In the US, the Clean Air Act requires that serious ozone nonattainment areas reduce
NO\textsubscript{X} emissions (one of the ozone precursors). Some form of loaded test is required to be adopted in these non-attainment areas for light-duty vehicles not equipped with on-board diagnostic (OBD) systems, in order to identify vehicles that are in need of NO\textsubscript{X}-related repairs. Vehicles that are equipped with OBD should undergo OBD test in the non-attainment areas. See US Clean Air Act, Section 182 (c)(3) – Enhanced Vehicle Inspection and Maintenance Program. In Mainland China, large cities are required to use loaded tests for periodic emissions inspections for petrol vehicles (steady state test cycle). See Ministry of Environmental Protection, “Notice on the Evaluation and Monitoring of Total Pollutants Control in the 12\textsuperscript{th} Five-Year Plan”, 24 January 2013, People’s Republic of China: Central People’s Government, http://www.gov.cn/gongbao/content/2013/content_2396625.htm (accessed on 26 August 2014). (Chinese only)


84. Photos provided by Mr. Bryan Suen of Civic Exchange on 27 June 2014.

85. Communications with Prof. Ge Yunshan of the Beijing Institute of Technology on 10 August 2014.

86. Communications with Dr. Hu Jingnan of the Chinese Research Academy of Environmental Sciences on 15 May 2014.


90. Communication with Mr. Yuen Wai-ming of the Pro-Act by Vocational Training Council on 8 April 2014.

91. Ibid.

92. Communication with an anonymous mechanic on 31 July 2014.


95. Communication with an anonymous mechanic on 31 July 2014.


105. Ibid.


111. Communication with Mr. Dave Sosnowski of the United States Environmental Protection Agency on 11 June 2014.


114. Communication with Mr. Dave Sosnowski of the United States Environmental Protection Agency on 11 June 2014.


116. The problems with the excess in-use NOx emissions of the Euro V standard and the Japan standards are well documented in Lowell, D. and Kamakate, F., *Urban off-cycle NOx emissions from Euro IV/V trucks and buses*, 10 April 2012, the International Council on Clean Transportation, http://www.theicct.org/urban-cycle-nox-emissions-euro-ivv-trucks-and-buses; See also note 16.


120. Ibid.

121. Ibid.

122. See note 103, p.4.


125. See note 103, p.4.