

# Urban off-cycle NOx emissions from Euro IV/V trucks and buses

Problems and solutions for Europe  
and developing countries

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## EXECUTIVE SUMMARY

This report highlights a problem currently being experienced by new Euro IV and V heavy-duty trucks and buses: Despite meeting more stringent regulatory standards for exhaust emissions during type approval, many vehicles equipped with selective catalytic reduction (SCR) systems have significantly elevated emissions of nitrogen oxides (NOx) during in-use driving, particularly when operating in urban traffic. In some cases, actual in-use urban emission levels may be as high as or higher than those from much older vehicles with engines certified to more lenient emission standards.

These high “off-cycle” NOx emissions threaten efforts to improve ambient air quality in many European cities. Of equal or greater concern is that many developing countries, including Brazil, India, and China, are implementing or are set to implement more stringent standards for new trucks and buses that are based on the European regulation. Without adjustments, the new standards in these countries are unlikely to achieve the expected air quality benefits.

The technical reason for high off-cycle NOx emissions from these vehicles is poor NOx conversion efficiency of installed SCR systems when exhaust temperature is low. The root causes, however, are deficiencies in the Euro IV/V type-approval process, which include an unrepresentative test cycle, the lack of a cold-start testing requirement, and weak in-use conformity provisions. There are numerous technical options available to improve SCR effectiveness when exhaust temperature is low—as it typically is during urban driving—but the current Euro IV/V type-approval procedures do not require manufacturers to implement them.

Beginning in the 2014 model year (MY2014), Euro VI legislation will mandate lower emissions of both NOx and PM from new heavy-duty engines sold in Europe. The Euro VI regulation will also significantly improve type-approval procedures to address the specific deficiencies of the Euro IV/V tests that have allowed high in-use NOx emissions during urban driving. The changes include the use of a new, more representative test cycle, the addition of cold-start testing, and stronger in-use conformity provisions that include an in-use testing requirement.

While Euro VI type-approved trucks and buses will likely not have the same problems with high in-use NOx emissions, there will still be as many as 5.5 million Euro IV/V vehicles on the roads of Europe for the next five to 10 years. Unfortunately, the practical options available to deal with these vehicles are few, given the cost and difficulty of wide-scale retrofit programs and the lack of authority and political will to mandate them. Nonetheless, this report recommends targeted voluntary retrofit programs for specific urban vehicle fleets in Europe, supported by a robust technology verification program for NOx retrofit technologies. It also recommends

measures to incentivize early adoption and faster fleet turnover to Euro VI-compliant vehicles.

Developing countries that follow the European road map for vehicle emission regulation—including, as mentioned, Brazil, India and China—are in the process of implementing Euro IV or V standards nationwide or in some major cities. None of these countries has yet committed to a time schedule for implementation of Euro VI standards. Without changes to Euro IV/V type-approval procedures in these countries, there is every reason to believe that the current European experience of high in-use NO<sub>x</sub> emissions during urban driving will be repeated, undercutting these countries' efforts to improve urban air quality.

This report recommends that air quality regulators in these countries implement changes to type-approval procedures for Euro IV and Euro V engines specifically to prevent high in-use NO<sub>x</sub> emissions during urban driving. Most of the recommended changes are patterned on changes implemented in Euro VI legislation. In addition to a cold-start testing requirement, they include the use of the World Harmonized Transient Cycle (WHTC) during engine type approval, as well as stronger in-use conformity provisions, such as imposition of a specific not-to-exceed limit (g/kWh) for in-use NO<sub>x</sub> emissions and mandatory in-use testing to demonstrate compliance.

Absent quick action at the national level, it may also be appropriate for provincial or city authorities, public agencies, or private companies to implement supplemental emission requirements for new vehicles. If authority exists at the local level to ensure that type-approval limits are achieved during in-use driving, these supplemental requirements could be implemented by local regulation. They could also be implemented by individual agencies or companies based on contractual requirements of new vehicle purchase contracts. Whether implemented by regulation or contract, manufacturers should be required to demonstrate compliance based on engine or vehicle testing over a test cycle representative of in-use urban driving. ICCT recommends the use of the WHTC engine cycle or the World Transient Vehicle Cycle (WTVC) for this testing. Regardless of the cycle used, it is most critical to include cold-start testing, with the “verified” emissions level being a weighted combination of cold-start and hot-start results.

## 1. INTRODUCTION AND BACKGROUND

Despite meeting more stringent regulatory standards for exhaust emissions, many new Euro IV and V heavy-duty trucks and buses equipped with selective catalytic reduction (SCR) systems have significantly elevated emissions of nitrogen oxides (NO<sub>x</sub>) during in-use driving, particularly when operating in urban conditions.<sup>1</sup> In some cases, actual in-use urban emission levels may be as high as or higher than those from much older vehicles with engines certified to more lenient emission standards. These high “off-cycle” NO<sub>x</sub> emissions threaten efforts to improve ambient air quality in many European cities. Of equal or greater concern is that many developing countries, including Brazil, India, and China, are implementing or are set to implement more stringent standards for new trucks and buses that are based on the European model. Without adjustments, the new standards in these countries are unlikely to achieve the expected air quality benefits.

This report provides background information on the reasons for the high levels of off-cycle urban emissions from current Euro IV and V vehicles, discusses technology and regulatory options to reduce NO<sub>x</sub> emissions from future vehicles, and makes specific recommendations applicable to Europe and to developing countries.

The report was developed based on a literature review of papers and reports published in the United States and Europe, and discussions with 14 individuals involved in the manufacture, testing, and regulation of heavy vehicles, including regulators, academics, consultants, and engine and aftertreatment manufacturers from the United States, Europe, Japan, and China.

### 1.1 The problem: High “off-cycle” NO<sub>x</sub> emissions in urban driving

Over the past 20 years, regulators in Europe, the United States, and Japan have implemented increasingly more stringent emission standards applicable to new heavy-duty engines used in heavy trucks and buses.<sup>2</sup> (See Figure 1.<sup>3</sup>) Prior to MY2005, European heavy-duty engines were required to meet Euro III standards. Euro IV standards applied from MY2005 to MY2007, Euro V standards apply from MY2008 to MY2013, and Euro VI standards will take effect in MY2014.

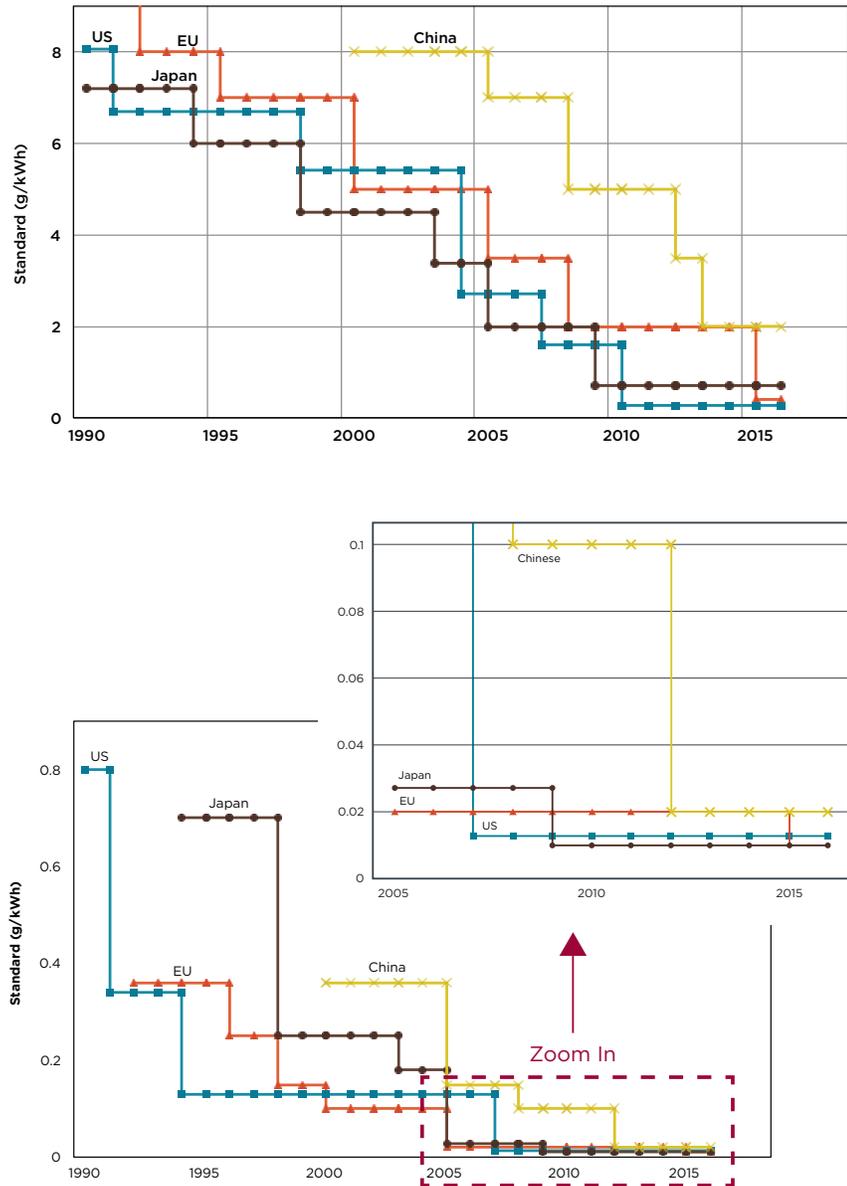
1 While certified using different procedures, the engines currently being installed in heavy-duty Japanese trucks typically use similar SCR systems as Euro IV/V type-approved engines and are type-approved using a test procedure that has allowed similarly high in-use NO<sub>x</sub> during urban driving.

2 In the United States, trucks with gross vehicle weight rating above 3,800 kilograms (8,000 pounds) are generally considered heavy-duty vehicles, and their engines are regulated as heavy-duty engines. In Europe, heavy-duty engine regulations apply to engines used in vehicles larger than 3,500 kg.

3 Note that different test cycles and test procedures are used in the United States, European Union, and Japan to certify compliance with the numerical limits shown.

As tested and certified on regulatory test cycles, Euro IV type-approved engines must have 30% lower NOx emissions and 80% lower particulate (PM) emissions than Euro III engines.

**Figure 1:** NOx and PM standards for heavy-duty engines\*



\*Source: ICCT (2011)

Euro V engines must have 60% lower NOx emissions and 80% lower PM emissions than Euro III engines.<sup>4</sup> When Euro VI comes into effect in MY2014, allowable NOx emissions will be 92% lower than Euro III limits, and allowable PM emissions will be 90% lower than Euro III limits. There is mounting conclusive evidence, however, that in-use NOx emissions (g/kWh) from Euro IV and Euro V type-approved engines are significantly higher than type-approval limits when trucks and buses are driving in urban traffic conditions. See Figures 2, 3, and 4, which plot the results of laboratory and in-use tests of European and Japanese trucks.

Figure 2 shows the results of in-use testing conducted with a portable emissions measurement system while a Euro IV and a Euro V type-approved truck were operated on German roads. In each of the charts in Figure 2, the purple line shown is the actual European Transient Cycle (ETC) test limit (g/kWh). For both trucks, NOx emissions (g/kWh) were significantly elevated during low speed urban driving compared to higher-speed driving.

Figure 3 shows results of laboratory tests of 18,000-kg delivery trucks with Euro IV type-approved engines tested over both a low-speed delivery truck cycle and a high-speed highway cycle. In these figures, the light-blue line represents the adjusted Euro IV emissions limit.<sup>5</sup> As shown, NOx emissions from all trucks were below the adjusted Euro IV limit when tested on the highway cycle, but NOx emissions from most trucks were significantly higher when tested on the delivery truck cycle.

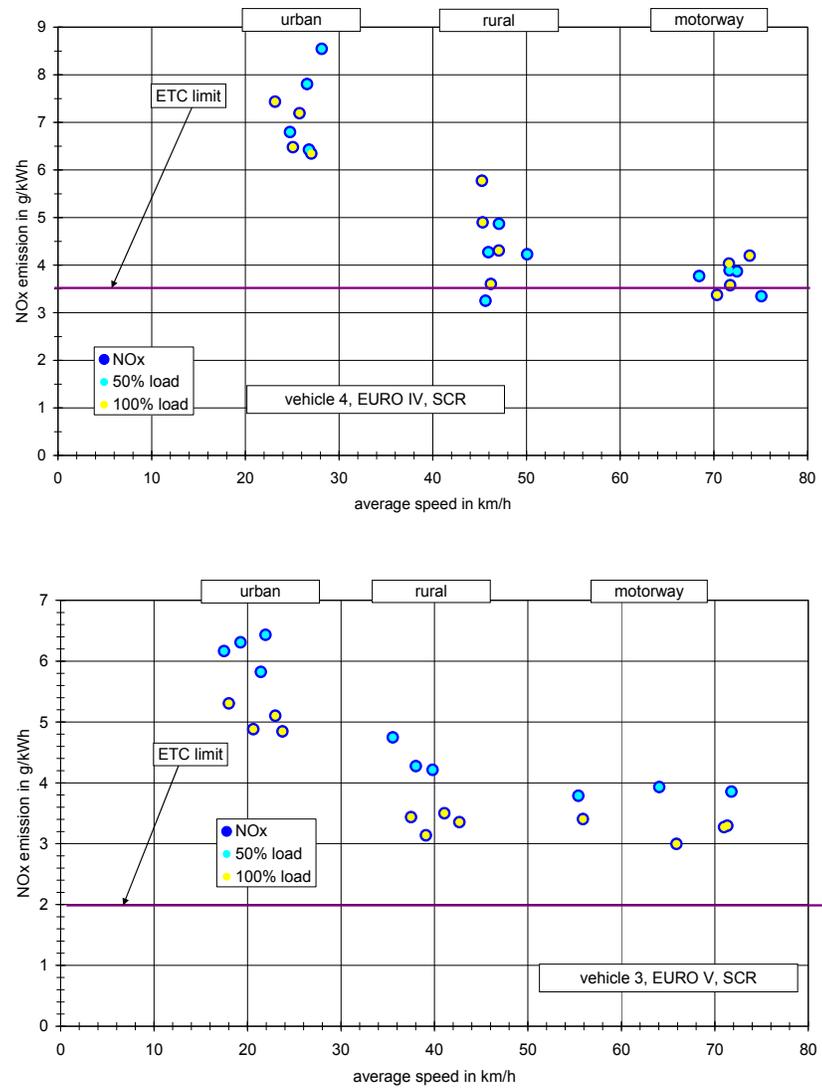
Figure 4 shows the results of laboratory tests conducted on a Japanese truck equipped with SCR. As shown, there is a clear correlation between average speed and g/km NOx emissions, with emissions during slow-speed urban driving two to four times higher than emissions measured over the JE05 certification test cycle, which is used in Japan for engine type approval.

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4 Euro IV and Euro V PM limits are the same, but Euro V NOx limits are lower than Euro IV NOx limits.

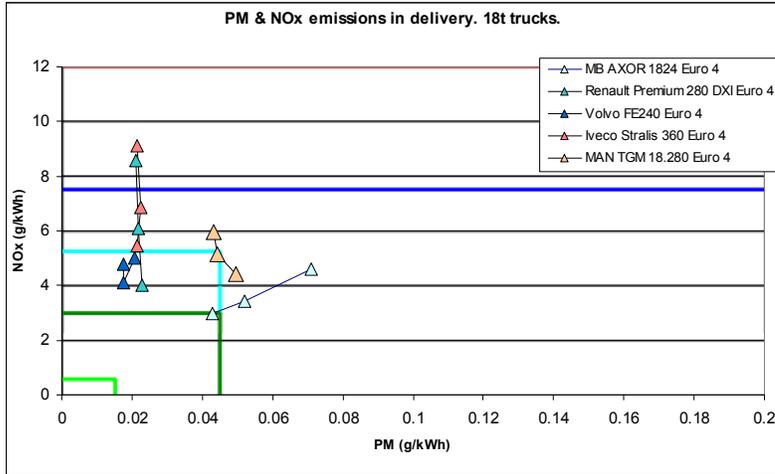
5 The limits shown are the engine limits as measured over the ETC test cycle (g/kWh) multiplied by 1.5 to account for assumed drivetrain losses between the engine and drive wheels (following the assumption of the author of the original report).

**Figure 2:** In-use NOx emissions of 18,000-kg Euro IV and Euro V tractors\*

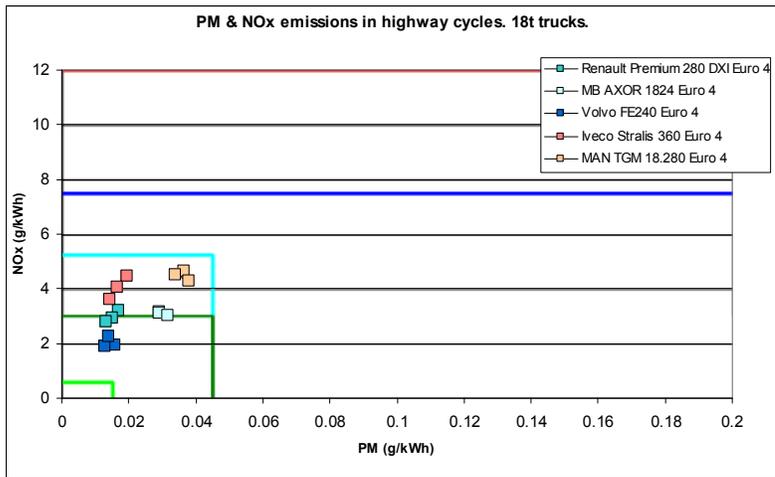


\*Source: Kleinebrahm (2008). Reproduced with permission.

**Figure 3:** NOx and PM emissions (g/kWh) of Euro IV 18,000-kg trucks in delivery and highway cycles\*



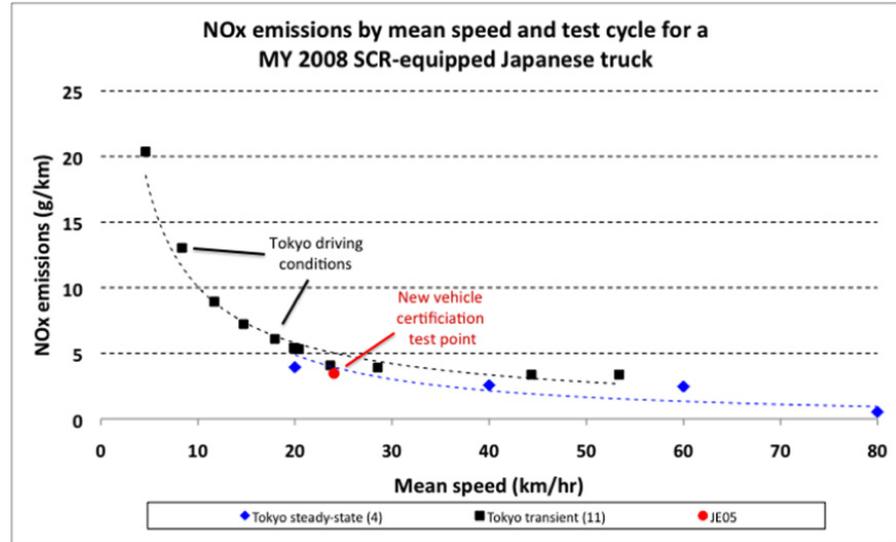
Delivery (low-speed) cycle



Highway (high-speed) cycle

\*Source: VTT (2009). Reproduced with permission.

**Figure 4:** NOx emissions (g/km) versus average speed for a Japanese SCR-equipped truck\*



\*Source: TMRI (2009). Reproduced with permission.

There are about 2.3 million Euro IV and 1.7 million Euro V heavy-duty vehicles on European roads; these vehicles currently represent approximately 18% of all heavy trucks and buses in use in the European Union.<sup>6</sup> As many as 1.5 million additional Euro V trucks and buses will be sold in Europe before Euro VI standards are implemented in model year 2014 (Kleinebrahm et al., 2008).<sup>7</sup> The higher than expected NOx emissions from heavy-duty vehicles will result in higher NO<sub>2</sub> concentrations near roadways. Although no study to date has analyzed the air quality impact throughout Europe, researchers in the Netherlands have looked at the possible consequences for attaining the NO<sub>2</sub> limit value of 40 µg/m<sup>3</sup> in their country. They found that higher NOx emissions from trucks could, by 2015, double the length of roadways along which the NO<sub>2</sub> standard could be exceeded (Velders, G.J. et al., 2011).

On a global scale, it is expected that more than 10 million medium and heavy vehicles certified to Euro IV/V standards will be put on the roads in developing countries such as Brazil, China, and India over the next five years.<sup>8</sup> The ICCT estimates that in China, about 40,000 more tons of NOx will be emitted between 2008 and 2015 as Euro IV vehicles with high

6 According to the European Environment Agency, there were 22.1 million trucks in use in the EU27 countries in 2009 (TERM 032, Size of the Vehicle Fleet, January 2011).

7 Based on sales figures for commercial trucks greater than 3,500 kg gross weight, published by the European Automobile Manufacturer's Association (ACEA); current Euro IV/V trucks on the road are total reported sales in EU27+EFTA countries from 2005-2010. Projected additional Euro V trucks based on 2010 sales of 488,706 vehicles. Of the current trucks, 41% are greater than 16,000 kg gross weight and 59% are from 3,500 kg to 16,000 kg gross weight.

8 See Table 1 in Section 1.5.3.

off-cycle emissions appear in major urban areas.<sup>9</sup> For India, estimates range from 45,000 tons to 70,000 tons between 2010 and 2015 depending on how quickly Euro IV vehicles are deployed in metropolitan centers.<sup>10</sup>

## 1.2 The reason: Poor low temperature performance of SCR systems

There are two primary ways to reduce exhaust emissions from diesel engines: 1) implement in-engine technologies to reduce engine-out emissions, and 2) implement aftertreatment technologies to clean up the exhaust after it has left the engine but before it is emitted to the atmosphere (Chatterjee et al., 2008).

When implementing in-engine technologies, there are also generally trade-offs among NO<sub>x</sub> emissions, PM emissions, and efficiency. Approaches that reduce PM emissions within the engine increase efficiency, but also tend to increase peak combustion temperature and therefore increase NO<sub>x</sub> emissions. Approaches that reduce peak combustion temperature lower NO<sub>x</sub> emissions, but tend to increase PM emissions and reduce engine efficiency.

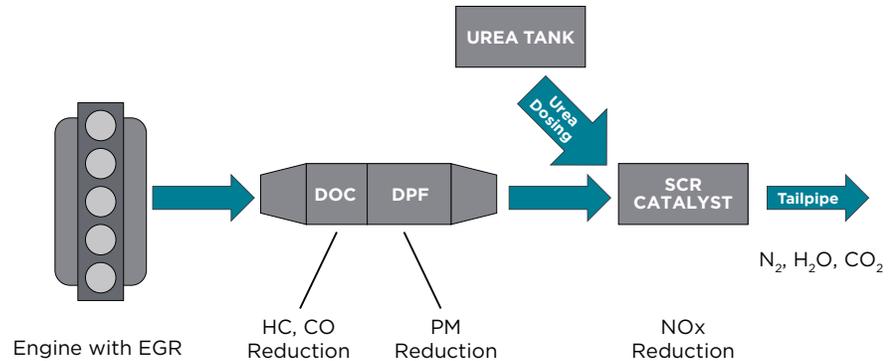
When developing engines to meet Euro IV standards, some manufacturers chose to reduce engine-out NO<sub>x</sub> emissions using exhaust gas recirculation (EGR) and to reduce PM emissions using aftertreatment by adding either a diesel oxidation catalyst (DOC) or a catalyzed partial-flow filter (PFF) on the tailpipe. Other manufacturers chose to reduce engine-out PM emissions using various in-cylinder technologies (which raise the peak combustion temperature) and to meet the NO<sub>x</sub> limits using aftertreatment—specifically SCR. When developing engines to meet the more stringent NO<sub>x</sub> limits of Euro V, almost all engine manufacturers implemented SCR for engines sold in the European market.

SCR uses a liquid reductant, in conjunction with a reduction catalyst, to reduce nitrogen oxides in diesel exhaust to elemental nitrogen. For mobile applications the reductant is usually a mixture of 32% urea (by weight) in water. The SCR reduction catalyst sits in the exhaust stream, and the urea solution is injected into the exhaust ahead of the catalyst as illustrated in Figure 5.

<sup>9</sup> Based on ICCT China Fleet Model. ICCT (2010).

<sup>10</sup> Based on ICCT India Fleet model (forthcoming)

**Figure 5:** Schematic of a SCR system with an upstream diesel oxidation catalyst (DOC) and diesel particulate filter (DPF)<sup>11</sup>



#### EGR + PFF may present other concerns

This report highlights SCR low-temperature performance issues during urban driving. Preliminary evidence indicates that Euro IV type-approved engines equipped with EGR and partial-flow filters generally have lower NO<sub>x</sub> emissions during urban driving than SCR-equipped engines (Ligterink et al., 2009), but they may have significantly higher PM emissions. A partial-flow filter (PFF) provides for physical filtration of part of the engine exhaust; carbonaceous PM particles are trapped in the filter media and destroyed via oxidation. However, these devices provide a “bypass channel” around the filter media to preclude plugging and increased engine back-pressure. During extended periods of low exhaust temperature, collected PM cannot be oxidized so the filter “fills up.” Once the filter is full, the full exhaust flow from the engine exits the device unfiltered (US EPA, 2008; Mayer, 2009).

The heat of the exhaust converts the urea to ammonia, and a chemical reduction reaction between the ammonia and nitrogen oxides takes place across the SCR catalyst. See Figure 5 for a schematic of an SCR system for mobile applications.

Urea injection must be carefully controlled to match engine operation—too little urea and tailpipe-out NO<sub>x</sub> will not be as low as desired; too much urea and tailpipe-out ammonia emissions may increase. Some systems include an ammonia slip oxidation catalyst, which oxidizes any ammonia leaving the SCR catalyst before it can enter the atmosphere.<sup>12</sup>

<sup>11</sup> This configuration is typical of engine and aftertreatment systems that meet the U.S. 2010 emission standard and is expected to be the layout for systems that meet the Euro VI standard.

<sup>12</sup> Euro IV/V type approval procedures limit ammonia emissions to no more than 25 parts per million (ppm) over the ETC test cycle. Euro VI legislation lowers allowable ammonia emissions to no more than 10 ppm.

The effectiveness of an SCR system in reducing NO<sub>x</sub> emissions (% reduction of engine-out NO<sub>x</sub>) is dependent on a host of design parameters, including catalyst material, catalyst volume, urea dosing/control strategy, and physical system layout. SCR effectiveness is also temperature-dependent: Below some threshold for exhaust temperature, the injected urea cannot be converted to ammonia. At low exhaust temperatures, catalyst activity also falls off sharply.

The exact temperature threshold at which SCR conversion effectiveness diminishes varies with system design; for most European trucks and buses equipped with SCR, catalyst activity falls off sharply below approximately 280°C, and urea cannot be injected below approximately 200°C because it will not convert to ammonia. While various aspects of system design affect these temperature thresholds, the primary driver is the use of vanadium-based catalysts in virtually all European SCR systems. While vanadium-based catalysts offer other advantages (low cost, good sulfur tolerance), they have relatively poor low-temperature performance relative to other catalyst options (see Section 2 for further discussion of these other catalyst options).

In a diesel engine, exhaust temperature generally varies with engine load. At idle exhaust, temperature could be as low as 100°C, increasing to over 500°C as load increases to near peak. Urban driving is typically characterized by low speed stop-and-go conditions, which puts relatively low average load on a vehicle's engine. Low-speed, low-load urban driving typically results in low exhaust temperatures below 300°C; in this type of driving a typical European SCR system would likely have low overall NO<sub>x</sub> conversion effectiveness due to both curtailed urea dosing and low catalyst activity.

### EEVs can have better low-temperature NOx performance

Euro V implementing legislation (2005-55-EC) includes a voluntary emission standard for an “enhanced environmentally friendly vehicle” (EEV). While the actual EEV standard requires PM but no NOx reductions compared to a Euro V type-approved vehicle, at least some manufacturers have been selling EEVs specifically designed to have both lower PM emissions and better low-temperature NOx performance in urban driving, reportedly at the request of customers (Stein, 2011).

All types of heavy vehicles are available as EEVs; for example, in 2010 in Germany, 52% of newly registered buses and coaches were EEVs, as were 32% of tractors and 19% of other trucks larger than 3,500 kg gross weight (KBA 2011). While all of these vehicles will have lower PM emissions than similar Euro V type-approved vehicles, it is not clear how many of them also exhibit lower in-use NOx during urban driving; there is evidence from in-use testing that suggests that at least some EEV buses do have lower NOx emissions during urban driving (Ligterink, 2009), but the EEV designation alone is insufficient to ensure this is the case for all EEVs.

Some transit agencies, such as Transport London, require manufacturers to demonstrate low NOx in urban driving based on testing over specific in-use urban bus test cycles (Coyle, 2010); other companies may judge in-use NOx performance based on urea use (Stein, 2011).

To achieve better low-temperature NOx performance, these vehicles use the same basic SCR hardware as Euro V vehicles, but may have a larger catalyst, different system layout, different control algorithms, and a different engine calibration. For these vehicles, lower NOx emissions during urban driving is typically achieved at the expense of a 1-2% increase in fuel use.

## 1.3 Limitations of Euro IV/V type-approval process

High in-use NOx emissions from Euro IV/V type-approved trucks and buses during urban driving are a consequence of limitations in the type-approval process. All emission certification programs require a manufacturer to demonstrate compliance with specific numerical emission limits when the engine or vehicle is tested over one or more specific test cycles (on-cycle emissions). Many programs also impose additional requirements to specifically limit in-use emissions when the engine or vehicle is operated in duty cycles different than the test cycle (in-use conformity, or off-cycle emissions). The current problems with Euro IV/V vehicles are the result of deficiencies in both the emission test procedures used for type approval and the in-use conformity requirements of the regulation.

Euro IV/V type approval is based on engine testing using the ETC and the European Steady-state Cycle (ESC). The ESC is composed of a series of steady-state engine load points (% peak engine speed and % peak engine load), while the ETC is a transient cycle in which engine speed and load are varied continually over the duration of the test. Unfortunately, neither of

these test cycles is fully representative of the range of engine conditions seen during in-use driving. Both of these cycles have relatively high average engine load over the entire test; consequently, average exhaust temperature during the test is relatively high. In addition, the test procedures allow the engine manufacturer to define pre-test engine conditioning. Virtually all manufacturers start the test with the engine fully warmed up and exhaust temperature above 300°C. Under these test conditions, an SCR-equipped engine can meet the ETC test limits of Euro IV and Euro V, even if the system has poor NOx conversion efficiency at low exhaust temperature.

These test cycle limitations are compounded by relatively weak in-use conformity provisions. Virtually the only requirements related to in-use conformity in the Euro V legislation are in Section 10 of Article 2, which states that “under all randomly selected load conditions, belonging to a definite control area and with the exception of specified engine operating conditions which are not subject to such a provision, the emissions sampled during a time duration as small as 30 seconds shall not exceed by more than 100% the limit values” as specified for testing on the ETC.

The European Commission has never fully defined the “definite control area” or “specified engine operating conditions”; neither has it defined a test program to evaluate compliance with this provision. Nonetheless, engine manufacturers typically interpret this requirement to mean that in-use emissions (for example during urban driving) can legally be twice as high as the ETC test limits—in the case of Euro IV vehicles as high as 7 g/kWh, and in the case of Euro V vehicles as high as 4 g/kWh.<sup>13</sup>

For engines equipped with SCR, it is possible to meet the legal requirements of Euro IV and Euro V type approval, even if the installed SCR system has relatively poor low-temperature NOx reduction efficiency that results in elevated NOx emissions during in-use urban driving.

The Euro IV/V implementing legislation also lacks strong enforcement mechanisms that would allow member states to force manufacturers to make changes to in-use vehicles based on high in-use emissions. Under Euro IV/V there is no requirement for manufacturers to conduct in-use testing. In addition, Euro IV and Euro V type approval for a specific engine model is effective until emission standards change—i.e., until Euro VI becomes effective in MY2014.<sup>14</sup> The absence of in-use testing, and the absence of a

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<sup>13</sup> The Euro IV/V legislation also requires that vehicles be equipped with an on-board diagnostic (OBD) system that monitors, among other parameters, actual NOx emission levels. The OBD requirements specify that measured NOx emissions higher than 5.0 g/kWh for Euro IV vehicles, or 3.5 g/kWh for Euro V vehicles, will cause a fault code to be logged and a warning light to go on, informing the driver that there is an emission control system problem. For both Euro IV and Euro V vehicles, if measured NOx emissions are greater than 7 g/kWh the engine control system is supposed to limit engine torque in a way that will clearly signal to the driver that there is an engine problem that must be fixed.

<sup>14</sup> By contrast, the U.S. EPA requires engine manufacturers to certify their engine models every model year.

requirement for a periodic renewal of type approval, provide a very limited basis for the approval authority to revoke type approval based on poor in-use performance.

## 1.4 The future in Europe: Euro VI standards coming in 2014

Compared to Euro IV/V, the Euro VI implementing legislation has changed engine type approval test procedures and in-use conformity provisions specifically to address low-load urban driving and off-cycle emissions. There is general agreement among the experts interviewed for this report that these changes will force manufacturers to improve the low-temperature performance of installed SCR systems, and that Euro VI type-approved engines will have significantly lower NO<sub>x</sub> emissions during in-use urban driving than Euro IV/V engines.<sup>15</sup>

The most important changes include the cold-start testing requirement with the engine and aftertreatment systems temperature at the beginning of the test within a specified range; the use of a different, more representative test cycle; and stronger in-use conformity requirements.

### 1.4.1 NEW TEST CYCLE: WORLD HARMONIZED TEST CYCLE

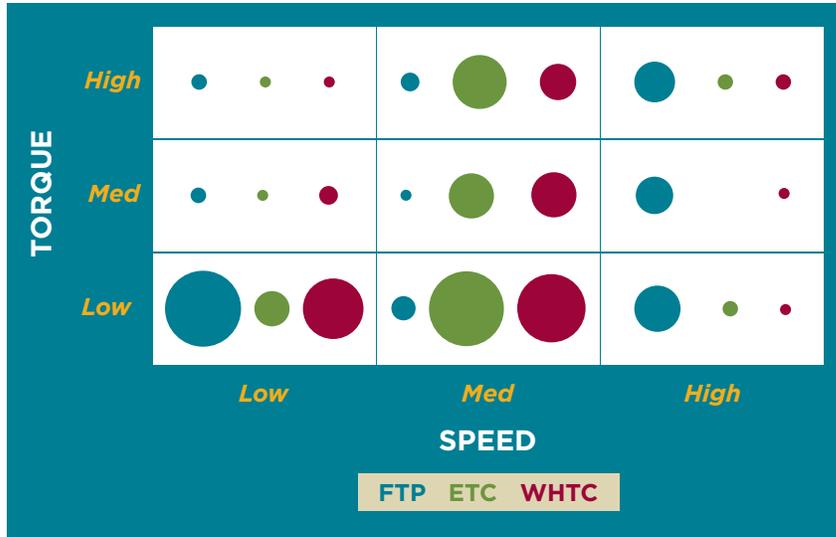
Euro VI compliance testing will be conducted using the World Harmonized Steady-state Cycle (WHSC) and the World Harmonized Transient Cycle (WHTC), which are more representative of the full range of in-use driving conditions, including urban driving, than the ESC and ETC cycles.

See Figure 6, which compares the relative percentage of time spent in different areas of the engine map on the WHTC, ETC, and U.S. Federal Test Procedure (FTP) certification test cycles. As shown, the ETC is dominated by medium speed and moderate to high engine loads, while the WHTC includes a much greater percentage of test time at low engine speed and load, which is typical of engine operation during urban driving. The time-weighted average engine speed (rpm) over the course of the WHTC is 36% of rated peak speed, while over the ETC the average is 57%. Average engine power is 17% over the WHTC, compared to 31% over the ETC. In addition, the engine is idled for 17% of the WHTC, but only 6% of the ETC. As a result, average exhaust temperature for a typical engine is likely to be lower during the WHTC than during the ETC.

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<sup>15</sup> For this project, the authors polled 14 individuals involved in the manufacture, testing, and regulation of heavy trucks, including regulators, academics, consultants, and engine and after-treatment manufacturers from the United States, Europe, Japan, and China.

**Figure 6:** Comparison of WHTC to ETC and USFTP test cycles—relative % of time in each mode



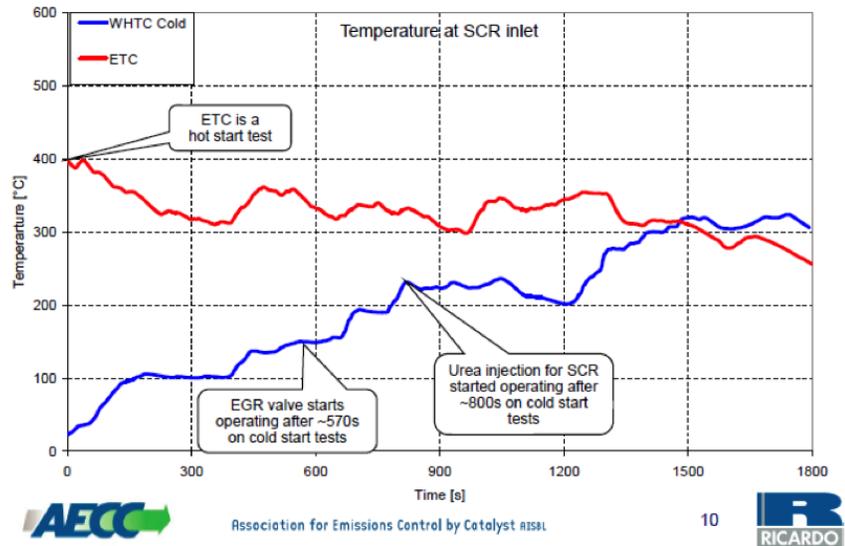
**1.4.2 COLD-START TESTING**

Another very important change is a requirement that WHTC testing start with the engine cold.<sup>16</sup> The full test protocol requires one full cold-start WHTC test, followed by a 10-minute hot-soak period (engine off and no data collected) and then one “hot-start” WHTC test. The certified emission levels for the engine will be a weighted combination of the cold-start and hot-start test results, with the cold start weighted 10% and the hot start 90%. See Figure 7, which compares exhaust temperature for a Euro IV engine, equipped with both EGR and SCR and tested on the ETC cycle used for Euro IV/V type approval, to exhaust temperature for the same engine tested over a WHTC cold-start test. As shown, while exhaust temperature was high enough for urea injection to start immediately during the ETC test, during the WHTC cold-start test urea injection could not start for approximately 800 seconds (more than 13 minutes) because the exhaust temperature was too low. During the cold-start test, even EGR could not start operating until almost nine minutes had elapsed.

The inclusion of cold-start testing for Euro VI type approval will force engine manufacturers to improve low-temperature SCR performance; if they do not, they will not be able to meet the Euro VI WHTC test limits.

<sup>16</sup> Procedures for a cold-start test are defined in UN/ECE Regulation 49, Annex 4B, Section 7.6.1-7.6.2. The regulation allows “natural or forced” engine cool-down, and the cold-start test can be started when the temperatures of the engine’s coolant, lubricant, and after-treatment systems are all between 20°C and 30°C (68-86°F). Unlike in Euro V, manufacturers are not allowed to specify their own preconditioning regimes under Euro VI.

**Figure 7:** Typical exhaust temperature, WHTC cold-start versus ETC\*



\*Source: Rickert (2007). Reproduced with permission.

### 1.4.3 OFF-CYCLE EMISSION REQUIREMENTS

The Euro VI implementing legislation also specifically requires manufacturers to take steps to limit off-cycle emissions. Emissions are required to be “effectively limited, throughout the normal life of the vehicles under normal conditions of use” including “under the range of operating conditions that may be encountered.”

To demonstrate compliance, manufacturers must undertake an in-use testing program using portable emissions measurement systems (PEMS) for each certified engine family. Testing must start no later than 18 months after type approval, and must be repeated every two years over the normal life of an engine. For all in-use testing, vehicles must operate over “typical routes” that must include urban (speeds under 50 km/h), rural (speeds of 50–75 km/h) and motorway (speeds of over 75 km/h) operation. For most vehicles, the urban portion must account for approximately 45% of the total data collected.<sup>17</sup> The minimum duration of each in-use test is based on the amount of power produced by the engine rather than time; each test must continue until the engine produces at least five times as much work as it would produce when operating over the WHTC test cycle.

The in-use test data will be analyzed using a “moving average window” method. This means that the data will not be averaged over the entire test

<sup>17</sup> For N3 vehicles (goods vehicles with gross vehicle weight greater than 12,000 kg), urban operation must be approximately 20%, rural 25% and motorway 55%.

duration, but rather over a series of subsets of the data, or “windows,” with the size of each window equivalent to the amount of work an engine does when operating on the WHTC test cycle. To be in conformity, average emissions (g/kWh) in each window must be no more than 1.5 times the WHTC test limit.

While Euro VI does not start until MY2014, it is likely that there will be very few, if any, new Euro V type approvals in the next two years, though manufacturers will continue to sell already certified Euro V and EEV engines and vehicles.

## 1.5 Developing country and emerging markets context: China, Brazil, India, and Mexico

European vehicle emission standards do not just affect Europe. The European regulatory model is followed by many developing countries around the world, though there is always a lag between when a new standard takes effect in Europe and when it takes effect in other countries.

The limitations of Euro IV/V type-approval procedures will likely lead to similar results in these countries—high NO<sub>x</sub> during urban driving. Because vehicles in these countries typically operate at lower speeds, and a greater percentage of the fleet is urban vehicles, the effects may well be magnified in countries such as Brazil, China and India, undercutting their efforts to improve urban air quality.

### 1.5.1 EMISSION STANDARDS FOLLOW EUROPEAN MODEL

See Figure 8 for the timing of changes in heavy-duty engine emission regulations for the countries with the greatest number of trucks and buses worldwide. As shown, many countries outside of Europe follow the European model for engine emission certification, including Brazil, China, India, Russia, South Korea and Thailand. Mexico has historically followed the U.S. model, but has recently changed to allow either U.S.- or European-certified engines.

As of 2012, both China and India were at the Euro III level for new heavy vehicles throughout most of the country, except in some large cities. China had intended to introduce Euro IV for new trucks and buses nationwide in 2012 but has recently decided to delay implementation until July 1, 2013; local authorities in Beijing are considering requiring new trucks and buses registered in Beijing to meet Euro V standards starting in 2012. India introduced Euro IV for new heavy vehicles in major cities in 2010.<sup>18</sup> Mexico has required the Euro IV or U.S. 2004 standards for new engines since 2008. Brazil implemented PROCONVE P7 (Euro V equivalent) in January 2012,

<sup>18</sup> Delhi, Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, Ahmedabad, Pune, Surat, Kanpur, and Agra.

leapfrogging from PROCONVE 5 (Euro III) over PROCONVE 6, which was never implemented.

None of these countries have yet adopted a timetable for introduction of Euro VI (or U.S. 2010) standards, though in mid-2011 Mexico created a regulatory working group that is looking at implementing these standards in the 2015 time frame.

With no change to current Euro IV/V certification procedures, new trucks and buses sold in these countries would be expected to exhibit similar in-use behavior as current European heavy vehicles, significantly undermining the expected benefits of the new regulations in these countries.

**Figure 8:** Heavy-duty diesel engine emission standards for major countries/regions

		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
<b>Euro pathway</b>	Europe	Euro IV			Euro V						Euro VI	
	China <sup>(1)</sup>	China II (Euro II)		China III				China IV				
	India <sup>(1)</sup>	Bharat II (Euro II)				Bharat III						
	S. Korea	Euro III			Euro V		TBD					
	Russia	Euro I	Euro II	Euro III		Euro IV			Euro V			
	Thailand	Euro III							Euro IV			
	Brazil	Euro II	PROCONVE P-5 (Euro III)						PROCONVE P-7 (Euro V)			
	Japan	New long-term standards						Post new long-term standards				
<b>Non-Euro pathway</b>	US	US 2004		US 2007			US 2010					
	Canada <sup>(2)</sup>	US 2004		US 2007			US 2010					
	Mexico <sup>(3)</sup>	US 1998 / Euro III			US 2004 / Euro IV				TBD			
		(1) Major cities have introduced accelerated adoption schedules - timelines in this table reflect nationwide adoption. (2) Canadian standards are designed to be aligned with U.S. standards. (3) Mexican standards are designed to be aligned with U.S. and Euro standards. Manufacturers may certify to either the US or Euro standard.										

### 1.5.2 FUEL SULFUR LEVELS AND EFFECT ON EMISSION CONTROL TECHNOLOGIES

The allowable level of sulfur in diesel fuel varies significantly by country. See Figure 9—as shown, most of the developed world has already imposed very low limits on allowable sulfur in diesel fuel (10–15 ppm) while countries such as Brazil, China, and India currently allow much higher fuel sulfur levels. In those same three countries, ultra-low sulfur diesel (ULSD) fuel, with less than 50 ppm sulfur, is only available in major cities. In Brazil, a limited amount of 50 ppm diesel has become available nationwide in select service stations since January 1, 2012. Availability of ULSD fuel in Mexico is limited to areas near the U.S. border and in some metro areas (specifically for bus fleets).

The level of sulfur in fuel is important, because many catalyst-based approaches to reducing both NOx and PM from diesel engines, including SCR, are sensitive to fuel-borne sulfur. As discussed in Section 2, some technical approaches to improving the low-temperature performance of Euro IV/V SCR systems, in particular the use of copper-zeolite catalysts, are

not feasible if the sulfur level of fuel is greater than 50 ppm. Other solutions are more sulfur tolerant.

Without ULSD fuel, meeting intermediate emission targets (i.e. Euro V) requires different technical solutions that are more costly and more difficult to implement—and meeting the most stringent emission targets (Euro VI) is virtually impossible.

**Figure 9:** Diesel fuel sulfur limits (ppm) for major countries/regions

		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
<b>Euro pathway</b>	Europe	50			10							
	Russia	2,000			350 <sup>(2)</sup>		50 <sup>(2)</sup>		10 <sup>(2)</sup>			
	S. Korea	100	30			15						
	Thailand	350							50			
	China <sup>(1)</sup>	2,000									350	
	India	500					350					
	Indian cities <sup>(1)</sup>	350					50					
	Brazil	2,000			1,800 / 500 <sup>(4)</sup>		1,800 / 500 / 50 <sup>(4)</sup>					
<b>Non-Euro pathway</b>	Japan	50		10								
	US	500			15							
	Canada	500			15							
	Mexico <sup>(5)</sup>	500									ULSD	

(1) Certain urban areas have had access to 50 ppm sulfur fuel since 2006 - this table reflects nationwide requirements.  
 (2) The Ministry of Energy and Industry submitted draft regulations to move to Euro 3 fuel levels by 2009, Euro 4 by 2010, & Euro 5 by 2013.  
 (3) Delhi, Mumbai, Kolkata, Chennai, Ahmedabad, Surat, Agra, Pune, Kanpur.  
 (4) Currently 1,800 ppm fuel is available in rural areas and 500 ppm fuel is available in cities. Beginning in 2012 50 ppm fuel will be available in both rural areas and cities, but the higher sulfur fuels will also be available.  
 (5) Ultra-low sulfur fuel with 15 ppm sulfur has been available in some border regions and large metro areas since 2007. A significant fuel sulfur reduction is planned for 2014, but implementing regulations not yet in place; final allowable sulfur level not yet determined.

Sources: Dieselnets (www.dieselnets.com); CAI-Asia (http://www.cleanairnet.org/caiasia/1412/articles-40711\_SulfurDiesel.pdf); Delphi (2009); UNEP Partnership for Clean Fuels and Vehicles (www.unep.org/transport/pcfsv).

### 1.5.3 VEHICLE FLEET: COMPARISON OF DEVELOPING COUNTRIES TO EUROPE

See Table 1 for a summary of average annual new truck registrations/sales between 2007 and 2010 in the United States, Europe, Brazil, China, and India.

As shown, U.S. sales of light trucks are five times higher than those in Europe or China, but many of these U.S. light trucks are not truly commercial vehicles; rather, they are used for personal transportation.<sup>19</sup> The U.S. freight-hauling sector is dominated by the largest combination trucks, while in both Europe and China a greater percentage of commercial freight hauling vehicles are medium and light trucks.

Discounting light truck sales in the United States, the Chinese truck market as a whole dwarfs truck sales in developed Western countries, with almost 2 million medium and heavy trucks and buses sold annually, compared to just over 900,000 in the United States and Europe combined.<sup>20</sup>

<sup>19</sup> The vast majority of these U.S. light trucks are pickups and sport utility vehicles. Some pickups are used commercially but most are personal vehicles. This category of vehicle also includes a small number of vans, some of which are used for passenger transport, both with and without compensation.

<sup>20</sup> Note that the data in Table 1 cover a period of recession and slow growth in the United States, and to a lesser extent in Europe. Between 2007 and 2010, average annual U.S. sales of the heaviest trucks were less than 50% of sales in 2006. Between 2007 and 2010, average European sales of the heaviest trucks were down 17% compared to sales in 2006.

The other major difference between vehicle fleets in Western countries and those in developing countries such as China and India is that a greater percentage of the vehicle fleets in the latter are dedicated “urban” vehicles, especially buses. For example, 22% of all commercial vehicles in India and 12% in China are buses, compared to less than 6% in the United States and only 3% in Europe.

Compared to U.S. and European trucks, trucks in many developing countries, including China and India, also tend to have a much lower power to weight ratio. Chinese and Indian trucks are reported to be routinely overloaded, which increases this difference. Trucks and buses in these countries also tend to operate at much lower speeds than U.S. and European vehicles, both within cities and on highways and rural roads. It is difficult to say exactly how these operating differences will affect average exhaust temperature compared to European trucks. Lower speeds would tend to reduce exhaust temperature, but lower power to weight ratios would tend to increase it.

**Table 1:** Average annual new heavy vehicle registrations for major countries/regions (2007-2010)\*

COUNTRY/ REGION	LIGHT COMMERCIAL		MEDIUM COMMERCIAL		HEAVY COMMERCIAL		TOTAL
	BUSES	OTHER	BUSES	OTHER	BUSES	OTHER	
Europe	11,000	1,791,000	38,000	341,000	24,000	243,000	2,448,000
	Up to 3,500 kg		3,500 - 16,000 kg		> 16,000 kg		
United States	NA	6,406,000 <sup>a</sup>	13,000	138,000	3,000	118,000	6,678,000
	Up to 4,500 kg		4,500 - 15,000 kg		>15,000 kg		
China	137,000	1,192,000	256,000	1,073,000	3,000	610,000	3,271,000
	Up to 3,500 kg		3,500 - 18,000 kg		> 18,000 kg		
India	NA	NA	8,200 <sup>b</sup>	73,100	57,300 <sup>c</sup>	156,400	295,000
	Up to 3,500 kg		3,500 - 12,000 kg		> 12,000 kg		
Brazil	NA	3,600	7,100	37,500	7,300	81,800	137,300
	Up to 4,500 kg		4,500 - 15,000 kg		>15,000 kg		

a Includes all light trucks <4,500 kg, many of which are used for personal transportation.

b Includes all buses <5,000 kg

c Includes all buses >5,000 kg

\*Sources: ACEA (2011)<sup>21</sup>; US Commerce (2011), Polk 2009, Polk (2010); Segment Y (2011), Polk (2011).

Developing countries’ technology paths to compliance with Euro IV and Euro V standards are expected to mirror those of Europe and Japan. For Euro IV, it is likely that some engine manufacturers will implement EGR plus DOC or PFF, while for Euro V, virtually all manufacturers will implement SCR. For example, of 553 heavy-duty engines already type-approved for sale in China at the Euro IV emissions level, 13% use EGR and 87% use SCR.<sup>22</sup> There are also an additional 72 engines that use EGR whose approval is still pending.<sup>23</sup>

21 Numbers shown are average annual registrations in EU27+EFTA3 countries for 2005–2010.

22 All of the engines that employ EGR for NOx reduction also employ catalytic aftertreatment for PM reduction. About three-quarters use a partial-flow filter plus oxidation catalyst, while one-quarter use only an oxidation catalyst, and a few use a catalyzed wall-flow filter.

23 Guan, M., VECC, personal communication, 2011.

## 2. TECHNICAL OPTIONS TO REDUCE URBAN NOX FROM SCR-EQUIPPED ENGINES

Limitations on NOx reduction efficiency of SCR systems at low exhaust temperature are based on two factors: 1) inability of urea reductant to decompose to ammonia, and 2) low SCR catalyst activity. Technical approaches to improving low-temperature urea SCR system performance therefore fall into two categories: 1) improve urea decomposition, and 2) improve low-temperature catalyst activity. The first can be accomplished using urea mixers, urea heaters, and/or urea decomposition catalysts.

See Table 2 for a summary of the different types of SCR catalysts in use. Most Euro IV/V SCR systems use vanadium catalysts, which have poor low temperature activity; the low temperature activity of vanadium catalysts can be improved by optimizing the ratio of NO to NO<sub>2</sub> in the exhaust, using an oxidation catalyst ahead of the SCR catalyst. Alternately, copper-zeolite catalysts with greater low temperature activity can be used, but these are more sensitive to fuel sulfur. Low-temperature catalyst activity can also be improved by increasing catalyst volume, regardless of catalyst material, or by optimizing ammonia storage in the catalyst via different dosing strategies. This last strategy might, however, increase tailpipe-out ammonia emissions (“ammonia slip”) in the absence of an effective ammonia slip catalyst downstream of the SCR catalyst.

**Table 2:** Characteristics of SCR catalysts\*

CHARACTERISTIC	CATALYST MATERIAL		
	VANADIUM	CU-ZEO	FE-ZEO
<b>Primary market</b>	Euro IV	United States, from 2010	Japan, from 2005
<b>Optimum operating temperature (deNOx)</b>	300° - 450°C	225° - 500°C	300° - 500° + C
<b>Cold-start performance</b>	Poor	Good	Poor
<b>Fuel sulfur tolerance</b>	2000 ppm	50 ppm	50 ppm <sup>1</sup>
<b>Cost</b>	~\$2,200 US	~\$3,200 US	~\$2,700 US
<b>Resistance to HO poisoning</b>	Higher	Lower	
<b>Thermal stability</b>	Poor <sup>2</sup>	Good	
<b>Other issues</b>	Difficult to integrate with active DPF	Low temperature performance sensitive to NO <sub>2</sub> /NOx ratio	

<sup>1</sup> Can be used with 350 ppm sulfur fuel if catalysts are periodically regenerated above 600°C  
<sup>2</sup> Decreased deNOx efficiency, V<sub>2</sub>O<sub>5</sub> emissions possible above 500°C

\*Sources: Johnson (2009); Cheng (2009); MECA (2007); Hodzen (2010).<sup>24</sup>

A related approach involves the use of a different reductant than urea, or the use of a second reductant in addition to it, which will provide greater NOx reductions when exhaust temperature is low. Potential alternative

<sup>24</sup> Hodzen, E., Cummins, personal communication, 2010.

reductants include ammonia and ammonium nitrate. Ammonia is highly toxic to humans, however, which could introduce safety issues related to distribution and on-board storage. One potential technology in the early stages of commercialization involves adsorption of the ammonia into a solid storage medium (AdAmmine™), from which it can be released on demand. Any alternative or additional reductant other than urea would require the development of a new distribution and supply infrastructure.

Another potential approach involves active exhaust thermal management—manipulating engine operating parameters to increase exhaust temperature at low engine load in order to maintain urea dosing and SCR activity even during urban driving. Exhaust temperature can be increased by retarding fuel injection timing, post-injecting fuel, and/or using an air intake and/or exhaust throttle. It is also possible to increase exhaust temperature independent of engine operation by injecting fuel directly into the exhaust (across a catalyst or in a fuel burner).

Exhaust thermal management is employed on most heavy-duty engines that meet U.S. 2010 emission standards, both to improve low temperature SCR performance and to regenerate active particulate filters. It is likely to be a significant strategy for many European manufacturers to meet Euro VI standards as well. In addition to cost and packaging issues, the most significant trade-off of this strategy is that all approaches to exhaust thermal management generally increase fuel use by 2% or more. The most sophisticated methods (in-cylinder post injection of fuel and air intake/exhaust throttling) also require high-pressure common rail fuel injection and variable geometry turbochargers, technologies not found on all Euro IV/V engines.

Finally, one could employ another method to reduce engine-out NO<sub>x</sub> at low load, so that tailpipe-out NO<sub>x</sub> emissions would still be low even with low NO<sub>x</sub> conversion efficiency from the SCR system. Approaches would include improving charge-air cooling and increasing rates of EGR. The use of higher EGR rates at low load could increase both fuel use and PM emissions.

See Table 3, which summarizes the available approaches, including their development status, constraints on their use, and the trade-offs that they involve.

When evaluating the various technical options to improve in-use performance of Euro IV/V SCR systems, one must evaluate cost and feasibility as applied to three distinct groups of vehicles:

1. MY2005–MY2012 trucks and buses already delivered and in-use in Europe and selected cities in China and India, as well as MY2012 vehicles in Brazil<sup>25</sup>

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<sup>25</sup> While Euro IV-based standards will not apply nationwide in China until 2013, they have already been implemented in select cities. Euro IV has been required in selected India cities since 2010. Euro V has been implemented in Brazil since January 2012. See Section 1.5.1 for additional details.

2. MY2013 trucks and buses not yet delivered in Europe (EU preproduction)
3. MY2013+ trucks and buses in China, India, and other developing countries (non-EU preproduction)

Changes that might be feasible and cost-effective for one group of vehicles may not be so for the others. In particular, current high fuel sulfur levels in China and India may preclude technical approaches that would be feasible in EU countries. In addition, while virtually all of the technical approaches included in Table 3 are viable for implementation on future new engines, many of them, particularly in-engine methods of exhaust thermal management, would be difficult to implement as retrofits to existing vehicles. Other methods, while technically feasible, might be cost-prohibitive, or present significant challenges with respect to vehicle integration, as retrofits on existing trucks and buses.

In addition to cost, vehicle integration is usually the most important constraint for most heavy-duty vehicle retrofit programs. Heavy-duty vehicle markets are complex and fragmented in most countries, with a great variety of vehicle types and configurations. In order to fit new or modified components into existing exhaust systems, unique designs are often required for each model/configuration of final vehicle, even if multiple configurations share the same engine and basic chassis.

NOx retrofit programs must also be supported by a robust certification/testing program for after-market retrofit devices, to ensure that retrofit implementation does not result in unintended consequences, such as increases in PM, ammonia, or N<sub>2</sub>O emissions from retrofit engines.

Costs to upgrade vehicles will depend on the specific package of technologies selected as well as whether the changes are made to original equipment or as a retrofit. Some individual technologies are fairly inexpensive. A diesel oxidation catalyst or an exhaust heater costs well under \$1,000 (ICCT, in press). Some proposed solutions are incremental changes in current systems (i.e., increasing SCR catalyst volume). It is expected that costs to upgrade vehicles to reduce urban NOx emissions will be less than the incremental cost of meeting Euro VI emission requirements; a ballpark upper bound is therefore \$5,000 per vehicle.<sup>26</sup> This is a small percentage of the total vehicle cost in the US or Europe.

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<sup>26</sup> It is expected that additional costs would be within the range of the costs of meeting Euro VI, less the costs of adding a DPF. An independent assessment of the incremental cost of meeting Euro VI from a Euro IV baseline was estimated at €4,866 (approximately \$6,200) for a 13-liter engine in 2012 (Gense et al., 2006, ICCT, in press). The ICCT estimate of costs for a DPF and the associated hardware for a 13-liter engine is approximately \$1,600 (ICCT, in press). Costs in developing countries would reflect lower labor costs.

**Table 3:** Summary of options to improve low temperature performance of SCR systems

APPROACH	TECHNOLOGY	PURPOSE	DEVELOPMENT STATUS	CONSTRAINTS	TRADE-OFFS	SOURCE
IMPROVE UREA DECOMPOSITION	Heated urea injector/reactor	Ensure urea decomposition at low exhaust temperature	In development	<ul style="list-style-type: none"> <li>Vehicle integration</li> <li>Control strategy</li> </ul>	<ul style="list-style-type: none"> <li>Added cost</li> <li>Fuel or electricity for heating</li> </ul>	Kowatari et al. 2006,
	Urea mixer	<ul style="list-style-type: none"> <li>Reduce evaporation time</li> <li>Improve reductant distribution across catalyst</li> </ul>	In development	Vehicle integration	<ul style="list-style-type: none"> <li>Added cost</li> <li>Increased back-pressure</li> </ul>	Emitec 2010
	Urea decomposition catalyst (TiO2)	Ensure urea decomposition at low exhaust temperature	In development	Vehicle integration	<ul style="list-style-type: none"> <li>Added cost</li> <li>Increased back-pressure</li> </ul>	Johnson 2011a, Zhan et al. 2010, Tenneco 2011
IMPROVE SCR CATALYST ACTIVITY	DOC ahead of SCR	<ul style="list-style-type: none"> <li>Optimize NO: NO<sub>2</sub> ratio</li> <li>Target is 50:50 for vanadium catalysts, even higher NO<sub>2</sub> for zeolite catalysts</li> </ul>	In production	Vehicle integration	<ul style="list-style-type: none"> <li>Added cost</li> <li>Increased back pressure</li> </ul>	Johnson 2011a, Kröcher et al. 2010
	Cu-zeo catalyst	<ul style="list-style-type: none"> <li>Higher NOx conversion efficiency at low exhaust temperature than vanadium catalysts</li> <li>Better thermal stability</li> </ul>	In production	<ul style="list-style-type: none"> <li>&lt;50 ppm sulfur fuel required</li> <li>Potential for HC poisoning during long-duration idle</li> </ul>	Added cost	Johnson 2011a, Walker 2010, Yang et al. 2010
	Optimize control algorithm/dosing strategy	Increase ammonia storage in catalyst during high load, which is scavenged during low load	In production	<ul style="list-style-type: none"> <li>Closed-loop control required</li> <li>Effective ammonia slip catalyst required</li> </ul>	<ul style="list-style-type: none"> <li>Potential ammonia slip</li> <li>Potential N<sub>2</sub>O production.</li> <li>Larger catalyst volume may be required</li> </ul>	Survey
IMPROVE SCR CATALYST ACTIVITY	Improved ammonia slip catalysts	<ul style="list-style-type: none"> <li>Specific selectivity to ammonia oxidation</li> <li>May allow more aggressive urea dosing strategy</li> </ul>	In development	Control strategy	<ul style="list-style-type: none"> <li>Added cost?</li> <li>Potential N<sub>2</sub>O production.</li> </ul>	Johnson 2011, Folic 2010
	Increase SCR catalyst volume	<ul style="list-style-type: none"> <li>Lower space velocity</li> <li>Potential to SCR-catalyze DPF</li> </ul>	In production	Vehicle integration	<ul style="list-style-type: none"> <li>Added cost</li> <li>Increased back pressure</li> </ul>	Johnson 2011, Walker 2010
	Improved SCR substrates	Thinner wall, higher cell density provides greater surface area	In development		Added cost?	Johnson 2011, Heibel 2010
	Low mass DPF	Speed SCR catalyst light-off during cold start compared to current DPFs	In development		<ul style="list-style-type: none"> <li>Added cost?</li> <li>DPF durability?</li> </ul>	Johnson 2011, Heibel 2010

Table 3, cont.: Summary of options to improve low temperature performance of SCR systems

APPROACH	TECHNOLOGY	PURPOSE	DEVELOPMENT STATUS	CONSTRAINTS	TRADE-OFFS	SOURCE
ALTERNATIVE or SUPPLEMENTAL REDUCTANTS	LNT+SCR	<ul style="list-style-type: none"> <li>Combine lean NOx Trap and SCR</li> <li>LNT produces ammonia during regeneration at low load</li> </ul>	In development	<ul style="list-style-type: none"> <li>Vehicle integration</li> <li>LNT regeneration control strategy</li> </ul>	<ul style="list-style-type: none"> <li>Added cost</li> <li>Fuel penalty for LNT regeneration</li> </ul>	Johnson 2011, Kodama et al. 2010, Chen et al. 2010
	Ammonia adsorption SCR (AdAmmine)	<ul style="list-style-type: none"> <li>Ammonia adsorbed into solid material in on-board "cartridge"</li> <li>Gaseous ammonia released when engine waste heat is applied</li> </ul>	Early production	<ul style="list-style-type: none"> <li>Vehicle integration</li> <li>AdAmmine on-board cartridge location/servicing</li> </ul>	AdAmmine distribution infrastructure	Johnson 2011, Johannessen 2010
	Ammonium Nitrate Injection (NH4NO3)	<ul style="list-style-type: none"> <li>Inject NH4NO3 in addition to urea</li> <li>Acts like NO2 to promote better NOx conversion across vanadium and zeolite catalysts</li> </ul>	In development	<ul style="list-style-type: none"> <li>Vehicle integration</li> <li>Control strategy</li> <li>NH4NO3 on-board storage</li> </ul>	<ul style="list-style-type: none"> <li>Second reductant required on vehicle</li> <li>NH4NO3 distribution infrastructure</li> <li>Potential corrosion/safety issues</li> </ul>	Johnson 2011, Forzatti et al. 2010.
EXHAUST THERMAL MANAGEMENT	In-cylinder post injection of fuel	<ul style="list-style-type: none"> <li>Late cycle injection of fuel (near bottom dead center)</li> <li>Unburned fuel exits cylinder in exhaust, oxidizes in tail pipe</li> <li>Increases exhaust gas temperature at SCR inlet</li> </ul>	In production (U.S. 2010)	Requires high pressure common rail fuel injection	Increased fuel use	Charlton 2010
	Air intake and/or exhaust throttle	Increase exhaust temperature at light load	In production (U.S. 2010)	Requires variable geometry turbo charger	Increased fuel use	Kodama et al. 2005, Charlton 2010
	Fuel injection into exhaust across a catalyst	<ul style="list-style-type: none"> <li>Inject fuel into exhaust in front of an oxidation catalyst</li> <li>Fuel oxidizes, raises exhaust temperature at SCR inlet</li> <li>Can use same equipment used for active DPF regeneration</li> </ul>	In production (for DPF regeneration)	<ul style="list-style-type: none"> <li>Vehicle integration</li> <li>Control strategy</li> </ul>	<ul style="list-style-type: none"> <li>Added cost</li> <li>Increased fuel use</li> </ul>	Survey
OTHER	Exhaust heater	<ul style="list-style-type: none"> <li>Add a fuel burner that exhausts into engine exhaust ahead of SCR catalyst</li> <li>Can be similar to diesel heaters used to increase/maintain engine coolant temperature</li> </ul>	In development	<ul style="list-style-type: none"> <li>Vehicle integration</li> <li>Control strategy</li> </ul>	<ul style="list-style-type: none"> <li>Added cost</li> <li>Increased fuel use</li> </ul>	Tenneco 2011
	Higher EGR rate during cold start and light load	<ul style="list-style-type: none"> <li>Higher EGR rate reduces engine-out NOx, precluding need for high NOx conversion across SCR catalyst</li> </ul>	Unknown	<ul style="list-style-type: none"> <li>Requires EGR on engine plus SCR</li> <li>Control strategy</li> </ul>	<ul style="list-style-type: none"> <li>Increased fuel use</li> <li>Potential increased PM</li> </ul>	Survey

### 3. REGULATORY OPTIONS TO IMPROVE ENGINE TYPE-APPROVAL PROCESS

The high NO<sub>x</sub> emissions during urban driving by some in-use Euro IV/V trucks and buses are the result of limitations in the type-approval process for these vehicles. This situation cannot be remedied unless the type-approval process for new engines is changed. As discussed in section 1.3, the implementation of Euro VI in model year 2014 will likely solve the problem for Europe; after 2014 all new trucks and buses sold will need to comply with the Euro VI legislation, which specifically addresses in-use urban emissions through changes to type-approval test procedures and in-use conformity requirements.

Unfortunately, none of the developing countries that follow the European model of heavy-duty engine emission certification have yet to adopt a time frame for Euro VI implementation. For the foreseeable future, new trucks and buses will continue to be sold in these countries that have the potential to emit high levels of NO<sub>x</sub> during urban driving. It is extremely unlikely that manufacturers will voluntarily improve the low-temperature performance of SCR systems on these vehicles without a government mandate, because doing so may put them at a competitive disadvantage. As discussed in Section 2, there are many technical approaches that can be used to improve SCR low-temperature performance, but virtually all of them add cost to the engine and many also result in increased fuel use relative to typical current Euro IV/V SCR systems.

When evaluating how existing type-approval procedures might be changed in developing countries to address this issue, the Euro VI legislation and current U.S. certification procedures can be used as models. To fully address the issue there are two different, but complimentary changes required to address both on-cycle and off-cycle emissions: 1) change test cycles and test procedures to better reflect low-load, low-temperature driving conditions (on-cycle), and 2) impose specific in-use conformity requirements to limit off-cycle emissions.

#### 3.1 Test cycles and procedures

The most important change to current Euro IV/V type-approval test procedures required to address low-temperature SCR performance is the addition of a cold-start test requirement. This could be done regardless of which test cycle is used (current ETC or an alternative cycle). A cold-start test must begin with the temperatures of the engine's coolant and lubricants, as well as any aftertreatment systems, within a specified range deemed to represent "typical" ambient conditions. The Euro VI type-approval test procedure specifies that the temperatures of the engine and aftertreatment must be between 20°C and 30°C at the beginning of the cold-start test.

During a cold-start test, emissions data collection begins before the engine and exhaust system have achieved steady-state operating temperature.

After completion of the cold-start test, the engine is either shut down or left running (at idle) for a short period, after which a hot-start test is run. Typically, the “certified” emissions level for the engine is a weighted combination of the average (g/kWh) measured over the cold-start test and the average measured over the hot-start test. For heavy-duty engines, the United States uses a 15%/85% cold/hot weighting, while the Euro VI standard uses a 10%/90% cold/hot weighting.

If the Euro IV/V cycle emission test limits (g/kWh) were kept constant, the requirement to demonstrate compliance with these limits based on a weighted combination of cold-start and hot-start test results would, by itself, force most engine manufacturers to improve low-temperature SCR performance in order to comply with the limits.

To provide an even stronger requirement for manufacturers to improve low-temperature SCR performance in order to gain type-approval, certification testing could be mandated over a different test cycle than the ETC. Ideally, the new test cycle would include a greater percentage of test time with the engine operating in low-load low-temperature conditions typical of urban vehicle operation than the ETC does.

Regulators could choose an existing engine test cycle or could develop a new cycle specific to the country in question. Of existing cycles, candidates for consideration could include the test cycle currently used in the United States (FTP) and the WHTC cycle, which will be used in Europe for Euro VI type-approval testing.

### 3.2 In-use conformity

In emission regulations, in-use conformity requirements are required to 1) provide the expectation that emissions will be effectively limited in the full range of in-use driving conditions, not just when in-use driving closely approximates the certification test cycle, and 2) provide a means and legal basis for the certification authority to compel a manufacturer to make changes to address excessive in-use emission levels or risk revocation of their type approval.

Ideally, in-use conformity language will 1) provide a clear statement that in-use emissions shall be limited and an inclusive set of conditions under which they shall be limited; 2) specifically prohibit so-called “defeat devices,” which change engine operating parameters or control algorithms, at the expense of increased emissions, when the engine is operated over a driving cycle different than the certification test cycle; and 3) require testing to confirm that the in-use conformity requirements are met.

Typically, in-use or off-cycle conformity is referenced to on-cycle emission test limits using a “conformity factor” or “not-to-exceed” (NTE) limit value greater than one (i.e., in-use or off-cycle emissions [g/kWh] can be greater than the average measured over the certification test cycle, but cannot be unlimited). As discussed in Section 1.3, the Euro IV/V implementing legislation has weak in-use conformity language, with an NTE value of 2.0 and poorly defined conditions under which the NTE limit applies. The Euro IV/V legislation also does not mandate any testing to demonstrate compliance with in-use limits, either at the time of type approval or after vehicles have been put into use.

Euro VI legislation has much more specific in-use conformity language, which specifies that emissions shall be effectively limited under all in-use operating conditions. Euro VI also tightens the in-use NTE limit to 1.5 times the WHTC on-cycle test limit, and specifies a program of in-use vehicle testing to demonstrate compliance.

The type-approval process used in China, India, and other countries could be significantly strengthened by adopting in-use conformity requirements similar to those in the Euro VI legislation, even while maintaining Euro IV and Euro V on-cycle emission test limits. Penalties for noncompliance are also important. The Euro-standard legislation asks member states to set penalties that are “effective, proportionate, and dissuasive” and to “take all measures necessary to ensure that they are enforced” (EC No. 595/2009). Some options that have been effective in enforcing emission standard compliance in the United States include the authority to recall and repair noncompliant vehicles and engines at the manufacturer’s expense and the ability to levy fines for the use of “defeat devices.”

## 4. RECOMMENDATIONS

The following sections provide specific recommendations for policies to address high in-use urban NOx emissions from Euro IV/V type-approved trucks. Recommendations for Europe focus on targeted retrofits and fleet turnover to address existing in-use trucks, given that implementation of Euro VI standards is imminent. Recommendations for developing countries focus on changes to type-approval procedures for new vehicles, at the national and local levels, because Euro IV/V type-approved trucks will continue to be sold in these countries for the foreseeable future.

At the end of the document, the recommended policy approaches are summarized in Tables 4 and 5.

### 4.1 Europe

In practical terms, the options available to address high in-use NOx emissions from Euro IV/V trucks and buses already on the road in Europe are limited. Changes to existing Euro V regulations will take a minimum of one year to develop and adopt, and by then Euro VI implementation will be imminent, making any changes moot. Given that Euro VI implementation is now less than two years away, it is unlikely that there will be many new engines type-approved under Euro V between now and the end of 2013 anyway.

The consensus opinion of experts interviewed for this report is that given how soon Euro VI will take effect, there is little political will to enforce mandatory retrofit requirements for existing Euro IV/V vehicles, which would be forcefully resisted by engine/vehicle manufacturers and vehicle owners.<sup>27</sup> In addition, the fact that type approval does not need to be renewed annually (as in the United States) and the weak in-use conformity requirements of the legislation effectively limit enforcement levers available to type-approval authorities.

Most of the experts interviewed expressed the opinion that any political or financial capital expended in Europe to address in-use emissions would be best spent encouraging the early adoption of Euro VI type-approved vehicles and retirement of older vehicles. Some expressed a concern that large-scale retrofit requirements broadly applied would potentially be counterproductive if applied to long-haul trucks that don't typically operate in urban areas, because most technical options to reduce NOx emissions in urban driving would result in higher fuel use (see Section 2). Others expressed concern that some retrofit options to reduce NOx emissions might increase PM, ammonia, or N<sub>2</sub>O emissions.

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<sup>27</sup> For this project, the authors polled 14 individuals involved in the manufacture, testing, and regulation of heavy trucks, including regulators, academics, consultants, and engine and after-treatment manufacturers from the United States, Europe, Japan, and China.

Despite these challenges, there are several categories of emissions control programs that regulators in Europe—especially at the local level—may consider for minimizing the air quality impact from high-emitting in-use vehicles<sup>28</sup> prior to the introduction of Euro VI in 2014. These categories are early scrappage programs, retrofit programs, and complimentary fiscal incentives for early adoption of Euro VI, as described in the following sections.

#### **4.1.1 EARLY SCRAPPAGE PROGRAMS**

The most direct method of controlling older, high-emitting vehicles is to eliminate them from the fleet altogether through mandatory or heavily subsidized voluntary scrappage. In most early scrappage programs, subsidies are only provided if the scrapped vehicle is replaced with a new (or newer used) vehicle; accordingly, the program can serve the dual goals of reducing emissions and stimulating economic growth.

Well-designed scrappage programs, such as the California Air Resources Board’s Carl Moyer Fleet Modernization program, give grants competitively, based on cost-effectiveness per weighted ton of emissions reduced (including NO<sub>x</sub>, PM, and ROG<sub>s</sub>). Each funding applicant is required to estimate in detail the expected emissions reductions resulting from each individual vehicle replaced, based on vehicle type and operation; grants are made accordingly and are subject to a maximum cost-effectiveness cap.

Scrappage programs must be carefully managed to ensure that expected emissions reductions are actually achieved. Best practices in scrappage program implementation include ensuring that replacement vehicles are similar in power and operation to the scrapped vehicle and verifying that the high-emitting vehicles are indeed scrapped (as opposed to being transferred to another country or region).

Scrappage programs will be most successful when they are complimented by additional, parallel in-use emission control programs such as retrofits and complimentary fiscal programs.

#### **4.1.2 TARGETED URBAN FLEET RETROFITS**

The targeted retrofitting of urban fleets with demonstrated high in-use NO<sub>x</sub> emissions is one strategy policymakers may consider. However, retrofitting a vehicle is a complex, engineering-intensive procedure that must be performed carefully to ensure efficacy, prevent damage to the vehicle or the retrofit equipment, and ensure durability. Internationally, most conventional pollutant retrofit experience has exclusively targeted particulate matter emissions reductions, although there is increasing precedent for retrofit

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28 This section only describes programs to reduce emissions from vehicle certified to older emission standards; it does not describe efforts to prevent “gross emitters,” defined as vehicles emitting excess pollution due to tampering or malfunction of the engine or emission control system.

systems that reduce both PM and NO<sub>x</sub> emissions together, as well as limited international experience for retrofits designed to reduce NO<sub>x</sub> emissions alone. One example is the De Lijn bus company in Belgium, which equipped 250 of its Euro III buses, about 10% of its fleet, with NO<sub>x</sub> and PM retrofits (Van Steenberghe, 2010).

A critical component of any retrofit program is robust technology verification to ensure that in-use NO<sub>x</sub> emissions are in fact reduced, without increasing emissions of other air pollutants. Many existing retrofit technology verification programs in Europe and the United States are focused on PM reduction devices (or PM + NO<sub>x</sub> together), and may not be sufficient to verify low-temperature NO<sub>x</sub> reductions.<sup>29</sup> Any government effort to encourage retrofits to reduce in-use urban NO<sub>x</sub> emissions must start with a priority effort to define an applicable verification program for retrofit devices; for example, Transport for London has developed a NO<sub>x</sub> retrofit standard based on a dedicated London bus test cycle. In general, such a verification program must use an appropriate test cycle and procedures that will adequately cover low-load, low-temperature urban operation, and must measure, at a minimum, PM and ammonia emissions as well as NO<sub>x</sub> to ensure that emissions of these pollutants don't increase due to application of the retrofit technology.

Within Europe, any mandatory or voluntary retrofit programs to address high in-use NO<sub>x</sub> emissions from Euro IV/V vehicles should target specific fleets that spend the majority of their time in urban areas, such as buses, refuse trucks, and medium-duty pickup and delivery trucks. In addition to SCR system retrofits, manufacturers should be encouraged to identify opportunities to implement more widely the low-temperature NO<sub>x</sub> reduction approaches already delivered on some EEVs—both as retrofits and on new urban vehicles delivered over the next two years.<sup>30</sup> There might also be opportunities to apply other technical approaches on a retrofit basis, such as copper-zeolite catalysts, pre-catalyst DOCs, heated urea injection, or exhaust heaters (see Section 2).

For the oldest vehicles (especially Euro II and earlier), scrappage and replacement is likely a more cost-effective strategy than retrofitting. Some in-use control programs, such as CARB's Carl Moyer Program and the U.S. EPA's National Clean Diesel Campaign, fund retrofits in addition to scrappage and replacement; this allows funding determinations to be made based on cost-effectiveness, regardless of the specific project type.

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29 To be able to verify low-temperature NO<sub>x</sub> reductions, a verification program would need to use test cycle(s) and procedures with relatively low average exhaust temperature and/or cold-start requirements. A verification program based on existing Euro V type-approval procedures would not be sufficient.

30 However, as discussed above, the EEV designation alone is not sufficient to ensure low NO<sub>x</sub> emissions in urban driving. As with retrofits, low urban NO<sub>x</sub> from these vehicles would need to be demonstrated based on a standardized "technology verification" testing program.

### 4.1.3 INCENTIVES FOR THE EARLY INTRODUCTION OF EURO VI TRUCKS/BUSES

Complimentary policies such as strong fiscal incentives or vehicle bans provide added incentives to fleet owner/operators to retrofit or otherwise upgrade their vehicles. Tax incentives may be used to encourage the early adoption of Euro VI trucks/buses. Low Emission Zones (LEZs), hundreds of which have already been implemented in Europe, ban (or levy a fee on) all vehicles not certified to a minimum emission standard. The specific requirements for entering a LEZ typically become stricter over time, promoting increasingly clean fleets in urban centers. Environmental fees, or pollution taxes, are charged to vehicles based on their certified emission standard. As discussed here, because Euro V certification alone does not guarantee low NO<sub>x</sub> emissions during urban driving, to maximize the effectiveness of LEZs they will need to have fee structures which provide significantly lower fees for Euro VI trucks and buses, and for those Euro V vehicles verified to have low urban NO<sub>x</sub>, compared to Euro V-certified vehicles without low NO<sub>x</sub> verification.

For maximum effectiveness, regulators should adopt a combination of multiple in-use control programs. For example, London's air quality improvement plan calls for the scrappage of all Euro II and earlier buses, the NO<sub>x</sub> + PM retrofitting of all Euro III buses, the introduction of a fleet of hybrid and fuel cell buses, and the implementation of a fee-based LEZ with progressively stricter limits.

## 4.2 Developing countries

In developing countries such as Brazil, China, and India, the remaining "life" of emissions regulations based on Euro IV and Euro V is much longer than it is in Europe. In these countries, new trucks and buses with engines type-approved under existing regulations will continue to be sold for the foreseeable future. As such, there is a significantly greater potential benefit from "fixing" Euro IV/V type-approval procedures in these countries than there is in Europe in addition to hastening the adoption and implementation of Euro VI.

Significant gains can be made by adopting, at a national or local level, a new test cycle and new test procedures that emphasize low-load, low-temperature engine operation, while keeping allowable cycle emission test limits (g/kWh) the same or similar as they are now. Even greater benefits can be achieved by strengthening in-use conformity requirements as well.

### 4.2.1 TEST CYCLES AND PROCEDURES

The highest priority for "fixing" current type-approval test procedures in developing countries is to add a cold-start test requirement. Cold-start test procedures, and cold/hot weighting factors, are well developed in current

U.S. heavy-duty engine regulations (40 CFR 1065) and Euro VI regulations (EU No. 582/2011); either could serve as a template for developing countries (see Section 3.1).

The second highest priority is the use of a test cycle that is more representative of in-use urban driving than the current ETC, either in lieu of the ETC or as a supplement to it. While each country could develop its own unique test cycle to represent local in-use conditions, such an effort would be time-consuming and expensive. It would also contradict the current efforts toward global harmonization of vehicle emission regulations, which recognize the global nature of the heavy-duty engine industry.

To enhance the speed of implementation, efficiency, and global consistency, it would be best to use an existing test cycle. As such, the WHTC is a logical choice. This cycle was developed by the United Nations Economic Commission for Europe as part of its overall program to create globally harmonized emission test procedures. It is based on in-use data collected from U.S., European, Japanese, and Australian trucks and therefore represents the most up-to-date data on in-use vehicle behavior; it has also been vetted by numerous experts from across the globe. This test cycle has already been adopted for type-approval testing under Euro VI regulations, and the U.S. EPA is considering its adoption for future U.S. heavy-duty engine regulations.

The WHTC could be adopted as a replacement for the ETC in current type-approval testing, or could be adopted as a second, supplementary test cycle, with engines required to meet applicable cycle limits as tested on both cycles. In the first instance, the current Euro IV/V emission test limits (g/kWh) would need to be adjusted to account for differences in cycle work and other factors between the ETC and WHTC. In the second instance, new cycle limits specifically for the WHTC would need to be established. A significant amount of work has already been done to establish correlation factors between the ETC and WHTC for Euro VI implementation. The final report to the European Commission on the subject recommended that Euro VI NO<sub>x</sub> limits originally specified on the ETC be increased by 10% for WHTC testing (Verbeek, 2008). This existing work could be used to set appropriate Euro IV/V test limits for WHTC testing.

One method of improving low-temperature NO<sub>x</sub> performance of SCR systems is to implement more aggressive urea dosing at low temperature. While this may reduce NO<sub>x</sub> emissions, it also may increase tailpipe emissions of ammonia. In Europe, Euro IV/V implementing legislation includes a limit of no more than 25 ppm ammonia emissions during type-approval testing. To protect against increased ammonia emissions when making changes to type-approval test procedures, developing countries should adopt the Euro IV/V ammonia limit if they have not already done so.

#### 4.2.2 IN-USE CONFORMITY

To ensure that the expected air quality benefits of changes in emission regulations are realized in practice, type-approval testing must be complemented by strong in-use conformity requirements applicable to the engine manufacturer. In-use conformity requirements provide the legal basis for approval authorities to hold manufacturers accountable for excess in-use emissions, and ideally also give them the tools required to identify problems early in the implementation process.

The required key components of in-use conformity include: 1) a clear prohibition against the use of defeat devices, 2) a clear statement that in-use emissions shall be effectively controlled, 3) a clear definition of the range of conditions under which in-use conditions shall be controlled, 4) a specific NTE limit (g/kWh) for in-use or off-cycle emissions, and 5) a specific in-use test program to demonstrate compliance.

As discussed in Section 3.2, the Euro VI regulations include all of these elements and provide a good model for changes to current Euro IV- and Euro V-based standards in developing countries. In particular, approval authorities in these countries should consider the adoption of an in-use NTE NO<sub>x</sub> limit equivalent to 1.5 times the ETC/WHTC NO<sub>x</sub> limit, as well as a PEMS-based in-use testing program to evaluate compliance with the NTE limits. The in-use testing program should require that in-use data be collected over typical duty cycles that include a significant amount of urban driving, and that compliance against NTE limits should be evaluated over the entire in-use data set using a “moving average window” concept.

Note that enhanced in-use conformity requirements will be most effective if paired with improvements to type-approval test procedures as discussed in section 4.2.1, because this will narrow the difference between “on-cycle” and “off-cycle” in-use emissions. It may be unrealistic, and practically and legally difficult, to hold manufacturers to a stringent in-use limit when type-approval testing is based on an unrepresentative test cycle and procedures.

**In-use conformity includes the vehicle operator**

Vehicles equipped with SCR require the use of a consumable reagent: urea. Without urea in the tank NO<sub>x</sub> emissions will be much higher than implied by the engine's type approval. To ensure that expected air quality benefits from SCR-equipped vehicles are realized in practice, there must also be an effective system in place to ensure that suppliers are selling urea of sufficient quality for use in SCR systems, and that vehicle owners are using it consistently.

This system could include such elements as:

- Vehicle spot checks at roadside and/or fuel stations
- High-level surveillance of urea sales compared to fuel sales, by city/region
- Review of fleet urea purchase records

In addition, type-approval requirements should ensure that engine and vehicle manufacturers follow best practices with respect to driver warnings and inducements related to low urea levels.

**4.2.3 LOCAL SUPPLEMENTAL EMISSION REQUIREMENTS**

Although it would be best for national authorities to implement improved type-approval procedures for all new vehicles, in some countries the time frame for changes at the national level is protracted. In these cases it may be appropriate for local or provincial authorities, public agencies, or private companies to implement their own supplemental emission requirements to ensure that any new vehicles purchased will have low NO<sub>x</sub> emissions during in-use urban driving. If the authority exists, this could be done by changes in local law; if not, it could also be implemented through contractual provisions of new vehicle purchase contracts.

Whether done by regulation or contract, manufacturers would need to demonstrate compliance with Euro IV/V type-approval emission limits as tested on some specific test cycle representative of urban conditions, and using specific test procedures. Testing could be done at the engine level using an engine dynamometer, as it is for type-approval testing, or it could be done at the vehicle level using a chassis dynamometer.

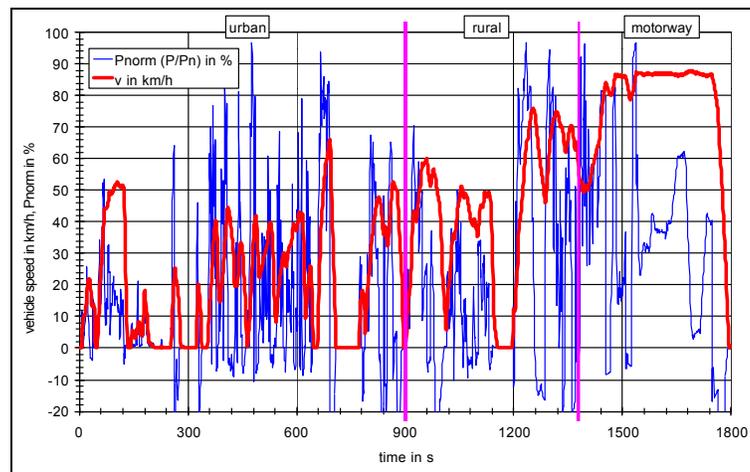
In either case, local authorities or agencies could develop their own test cycle(s) and procedures to reflect specific local conditions (see box, "Examples of local supplemental emission performance requirements"). However, this approach is potentially time-consuming and expensive, especially if these test cycles do not currently exist and the number of vehicles to be ordered is relatively small. ICCT recommends that local efforts to ensure low in-use NO<sub>x</sub> emissions from new vehicles via supplemental emission requirements use an existing, common test cycle and procedures in any local regulations or purchase contract requirements.

In the case of engine testing, ICCT recommends using the WHTC cycle, as discussed in Section 4.2.1. In the case of full-vehicle chassis testing, ICCT recommends using the WTVC. The latter is a speed versus time vehicle cycle, which was used as the basis for development of the WHTC engine cycle; the two cycles are therefore functionally equivalent. Figure 10 shows a plot of the WTVC cycle. As shown, half of the total cycle time is spent in low-speed, highly transient “urban” driving, and half is spent in higher-speed “rural” and “motorway” driving.

The use of these existing cycles for local supplemental emissions requirements, as opposed to a locally developed cycle, will provide the following benefits: 1) They can be implemented right away with no time required for data collection and cycle development; 2) their use will reduce compliance costs for manufacturers, which will reduce vehicle price; 3) other regions, agencies, or companies can benefit directly from efforts by early implementers; and 4) they will enable a quicker transition to improved national standards when the latter are adopted.

Regardless of whether compliance is demonstrated using engine testing (WHTC) or full-vehicle testing (WTVC) it is critical that the mandated test procedure require both cold-start and hot-start testing, with the “verified” emissions level calculated as a weighted average of the two tests.<sup>31</sup> See Section 3.1; as discussed there, the inclusion of a cold-start requirement during verification testing is critical to ensuring that NO<sub>x</sub> emissions will be low during actual in-use urban driving when exhaust temperature is low. The inclusion of a cold-start requirement is even more important than the specific test cycle used.

**Figure 10:** WTVC vehicle test cycle\*



\*Source: Heinz (2001). Reproduced with permission.

31 For a local supplemental limit applicable to specific vehicle type, a limit could be expressed in g/km. However in other instances, using the g/kWh limit is preferable as it allows specifying the figure as a multiple of the on-cycle limit and setting one limit for all vehicles (engines).

## Examples of local supplemental emission performance requirements

### London

Transport for London (TfL), which contracts with private operators to operate 8,500 public fixed-route buses in the city of London, England, currently tests all new bus models that they purchase to determine real-world emissions of CO<sub>2</sub>, NO<sub>x</sub>, and PM. Testing is done during the early stages of bus procurements; the primary purpose is to determine whether buses are eligible for Low Carbon Emissions Bus (LCEB) subsidies and financial incentives based on low CO<sub>2</sub> emissions. Buses are tested over the Millbrook London Transport Bus (MLTB) cycle, which is a highly transient, low-speed cycle developed based on London's Route 159.

During this testing, NO<sub>x</sub> and PM are also measured. If TfL determines that the buses are emitting higher NO<sub>x</sub> than expected based on their type-approval level, they negotiate with the bus manufacturer "voluntary" changes to the installed SCR system in order to lower emissions as tested over the MLTB cycle. Typically this involves recalibration to improve low-temperature performance. TfL has found this program to be successful, and has experienced good cooperation from bus manufacturers interested in maintaining their market share and removing incentives for more stringent mandatory emission requirements.

TfL is developing plans to retrofit up to 2,700 Euro II and Euro III type-approved buses with SCR to reduce NO<sub>x</sub> emissions by 70%. Conformity with contractually mandated reduction levels will be verified during in-use testing using PEMS (Coyle, personal communication).

### Beijing

In China, heavy-duty vehicles, especially buses, typically operate at speeds and torques even lower than US or European vehicles due to severe urban congestion problems. Not surprisingly, researchers in China have already identified cases of high excess NO<sub>x</sub> emissions from heavy-duty diesel vehicles operating outside of the certification cycle conditions. In Beijing, which has consistently been a leader in China in implementing progressive vehicle emission control measures, the Beijing Environmental Protection Bureau has sponsored several research projects to develop additional certification and in-use requirements for Euro V buses. Proposals include the addition of an NTE or moving-window emission limit requirement as well as the addition of a supplemental urban certification drive cycle (Li, 2011). To date, no concrete regulations have yet been adopted.

**Table 4:** Recommended policy options for Europe

OPTION	DESCRIPTION	IMPELENTATION ISSUES
<b>Vehicle scrappage incentives</b>	Provide monetary incentives (grants, tax incentives) to retire older vehicles and replace them with Euro VI type-approved vehicles	Must require and verify that old vehicle and engine are destroyed so they cannot be reused Must manage program to ensure that replacement vehicles do not have significant increase in size/power
<b>Fleet retrofits</b>	Retrofits to specific, urban fleets to reduce in-use NOx emissions	Target urban vehicles such as buses, refuse haulers, and pickup and delivery trucks Must develop a robust Technology Verification Program to ensure retrofit technology works Retrofit options may be cost-prohibitive for some vehicles with low residual value
<b>Low Emission Zones</b>	Within a specific geographical area (i.e. city center), levy a daily fee for vehicles which do not meet a minimum emissions level	Fee charged to Euro VI type-approved vehicles must be significantly lower than fee charged to Euro IV/V vehicles

**Table 5:** Recommended policy options for developing countries

OPTION	DESCRIPTION	ISSUES
<b>Modify type-approval process</b>	Use a different, more representative, test cycle and mandate cold-start testing for Euro IV/V engines	Recommend use of WHTC test cycle Certified emissions level a weighted average of cold and hot start results (15% cold, 85% hot) May require adjustment to Euro IV/V numerical NOx emission limits (+10% g/kWh) Should adopt a limit on ammonia emissions if not already included
<b>Stringent in-use conformity requirements</b>	Add in-use conformity to type-approval process to provide regulatory incentive for manufacturers to limit off-cycle emissions and legal basis for corrective action by approval authority	Elements include: 1) requirement to limit in-use emissions, 2) conditions under which emissions must be limited, 3) prohibition on defeat devices, and 4) specific “not-to-exceed” in-use limit Should include in-use conformity testing Most effective if combined with improved type-approval process
<b>Local supplemental emission Requirements</b>	Emission limits, more stringent than type-approval limits, implemented through local regulation or contractual requirements	Short-term solution if time frame for improvements at the national level is protracted Compliance must be verified by engine or vehicle testing Recommend WHTC (engine) cycle or WTVC (vehicle) cycle Testing must include cold start, with verified emission level a weighted combination of cold-start and hot-start results

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