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Developing a World Class Technology Pathways Program in China

INTERNATIONAL PRACTICES FOR VEHICLE EMISSION STANDARDS

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EXECUTIVE SUMMARY

In many countries around the world, increasing wealth and economic activity have lead to an increased reliance on motorized transport for passenger and goods movement. Although there are many benefits to this rapid motorization, some of the significant negative externalities include increased air pollution, greenhouse gas emissions, congestion, and noise. Focusing on air pollution, emissions from mobile sources are a large contributor to environmental degradation and adverse health effects. The two dominant prime movers in on-road transportation—gasoline and diesel engines—emit carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), and many other toxic substances. Regulatory efforts to control these emissions date back to the late 1960s and early 1970s in the mature vehicle emission control programs of the United States, Japan, and the European Union. Since the late 1990s, China has ratcheted down the emission limits for its major vehicle categories, following the "Euro" path. Major cities and regions, such as Beijing, Shanghai, and Guangdong, have led the way with accelerated adoption of standards. In the face of massive growth in vehicle stock and activity, China's vehicle emission control program has been effective in curbing conventional pollutant emissions. However, despite the emission reductions and concomitant health benefits achieved by the current program, continued improvements and more stringent policy measures are required to mitigate the negative health and climate effects of the significant projected growth trends in the vehicle market. China's 12th Five-Year Plan, approved and released in March 2011, assigns high priority to environmental protection, energy efficiency improvement, and clean energy development. As supporting plans are finalized to meet key targets under the plan—especially the 10% total NOx emission reduction goal—it is clear that strong policies for both new and in-use vehicles will be required in key regions and nationwide over the next 5 years.

The implementation of China IV standards nationwide, which will phase in between 2011 and 2013, will result in emission reduction benefits. However, further action is required so that emission trajectories do not mirror the booming growth patterns in vehicle activity. In terms of future standards, China V (assuming that the Euro 5/V limit values are adopted)[1] will result in NOx reductions and very modest PM reductions. The China VI (again, assuming Euro 6/VI limits are adopted) standard is expected to force the best available control technologies for both light- and heavy-duty vehicles, resulting in substantial NOx and PM reductions. The benefits of swift China VI adoption and a strong overall vehicle emission control program include the following:

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[1] The European Union has Arabic numberals for light-duty and Roman numerals for heavy-duty vehicles; the China levels for both light-duty and heavy-duty sectors are characterized with Roman numerals.

- Protecting public health and the climate by avoiding significant NOx and PM emissions and establishing the base technology for fuel efficiency improvement
- Becoming a world leader in the production of vehicles with state-of-the-art emission control technology by fostering the ability to export vehicles to any country/region in the world

A thorough discussion of the engine and emission control technologies that have diffused into the light- and heavy-duty markets in Europe over the past decade gives the context of the tasks ahead for Chinese industry and government in implementing future regulations. In China, the pathways for light-duty conventional gasoline vehicles toward more stringent standards are fairly straightforward and include improvements in combustion and three-way catalyst configuration. Gasoline direction injection (GDI) is a technology that has gained market share in the passenger vehicle space in recent years because of its superior fuel efficiency performance. As emission standards are tightened, PM control strategies for GDI vehicles may even include particulate filters, because particle emissions from GDI vehicles are much higher than their conventional counterparts are. Light-duty diesels will require advancements in exhaust gas recirculation as well as the increased presence of NOx and PM aftertreatment devices as emissions standards are tightened.

Continued progress in the heavy-duty sector will be complex and require large-scale transition from mechanically to electronically controlled engines and the development of a nationwide urea infrastructure to support vehicles using selective catalytic reduction (SCR) for NOx control. Although SCR introduction presents this and other new challenges for environmental regulators, policymakers in China can learn from the experiences of Beijing and Shanghai as well as countries/regions such as the European Union, United States, and Japan that already have SCR-equipped vehicles on the road.

In addition to NOx control, reducing PM emissions is of paramount importance, especially given the rapid growth in freight movement, which is dominated by heavy-duty diesel vehicles that are responsible for most PM emissions from the on-road transport sector. For both light- and heavy-duty diesel vehicles, low-sulfur (<50 parts per million or ppm) fuel enables the use of diesel particulate filters, which typically eliminate >90% of particulate emissions that pose a significant threat not only to human health but to the climate as well. Cities and regions such as Beijing, Shanghai, and Guangdong have taken advantage of their early access to low-sulfur fuels by adopting standards ahead of schedule that will force the use of diesel particulate filters.

Another significant issue is that although there is a strong base of Chinese manufacturers who are already producing China IV–compliant engines and vehicles and who are well positioned to adapt these platforms to meet future standards, many domestic manufacturers have been slower to modernize their products. This situation has been identified as one of the barriers to the on-schedule implementation of China IV.

Over the past 10 years, China has begun the process of building a world-class vehicle emission control program that can match its position as a leading world vehicle market. Continuing that development will require building on the foundation established by the current program and incorporating lessons learned from mature programs in the European Union, United States, and Japan. It will also require cultivating creative and innovative policy ideas to adapt these best practices from around the world to the Chinese context. Looking into the future, the advancement of China's vehicle emission control program is critical for safeguarding climate and air quality and fostering technology developments to enable China to be positioned as the true world leader in automobile manufacturing around the world.

OBJECTIVES AND OUTLINE

The purpose of this paper is twofold: (1) to describe international practices for vehicle emission standards and (2) to discuss China's various pathways for developing a world-class program that reflects the best of these practices. A comprehensive discussion of emission control strategies will provide a context for the opportunities and challenges facing China. The paper is organized into the following five sections and includes three appendixes for additional technical detail:

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[2] Many on- and off-road vehicles/equipment (e.g., motorcycles, rural vehicles, construction equipment) are an important part of China's mobile source emission control program, but a discussion of these vehicles and their emission control technologies is beyond the scope of this paper.

LIST OF FIGURES

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ABBREVIATIONS

A/F	air - fuel
CC	closed-coupled
CH_4	methane
CI	compression ignition
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CRT	continuous regenerating trap
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EGR	exhaust gas recirculation
g	gram
GDI	gasoline direction injection
GPF	gasoline particulate filter
GVW	gross vehicle weight
HC	hydrocarbon
HCHO	formaldehyde
IDI	indirect injection
KM	kilometer
KW	kilowatt
KWh	kilowatt - hour
LNT	lean NOx trap
LPG	liquefied petroleum gas
LTC	low temperature combustion
M1	Vehicles designed and constructed for the carriage of passengers and consisting of no more than eight seats in addition to the driver's seat
M2	Vehicles designed and constructed for the carriage of passengers, consisting of more than eight seats in addition to the driver's seat, and having a maximum mass ("technically permissible maximum laden mass") not exceeding 5 tonnes
M3	Vehicles designed and constructed for the carriage of passengers, consisting of more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes

MEP	Ministry of Environmental Protection
MPFI	multipoint fuel injection
NO_2	nitrogen dioxide
N1	Vehicles designed and constructed for the carriage of goods and with a maximum mass not exceeding 3.5 tonnes
N2	Vehicles designed and constructed for the carriage of goods and with a maximum mass exceeding 3.5 tons [AQ: Tonnes meant?] but not exceeding 12 tonnes
N3	Vehicles designed and constructed for the carriage of goods and with a maximum mass exceeding 12 tonnes
NH_3	ammonia
NOx	nitrogen oxides
Nm	newton meter
NMHC	non-methane hydrocarbon
NTE	not-to-exceed
OBD	on-board diagnostics
OC	oxidation catalyst
OSC	oxygen storage component
PCCI	premixed charge compression ignition
PFF	partial flow filter
PFT	partial flow technology
PGM	platinum group metal
PM	particulate matter
ppm	parts per million
SCR	selective catalytic reduction
SI	spark ignition
SOF	soluble organic fraction
SOx	sulfur oxides
TWC	three-way catalyst
Vd	displacement volume
VGT	variable geometry turbocharger
VVT	variable valve timing

1 INTERNATIONAL VEHICLE EMISSION STANDARD PRACTICES

Emission standards, limits on the amount of pollutant released by or evaporated from new vehicles and engines over a predefined test cycle, are a crucial element of all vehicle emission control programs. Vehicle standards go hand in hand with fuel quality requirements—specifically, sulfur limits—that enable advanced emission control technologies to be used and optimized. Compliance and enforcement measures are crucial elements of a successful emission control program, because they ensure standards are met over the vehicles' useful lives. Although fuel standards and compliance and enforcement are inexorably linked to the success of the vehicle emission control program, a full discussion of these measures will not be covered in this paper. The following sections describe the six elements that are ideally included in vehicle emission standards and how best practices in these areas can be incorporated in China's existing program.

1.2 Exhaust Emissions Standards

Significant developments in engine technology and aftertreatment devices have allowed for a steady tightening of emissions standards over time, as shown in Figures 1 and 2, which illustrate nitrogen oxides (NOx) and particulate matter (PM) limits for heavy-duty vehicles. The upcoming Euro VI (heavy-duty) limits for both NOx and PM are 95% more stringent than those of Euro I. Appendix A contains tables detailing the exhaust emissions limits and other requirements of standards in the United States, European Union, China, and Japan. Similar trends and advancements are evident for light-duty vehicles as well.

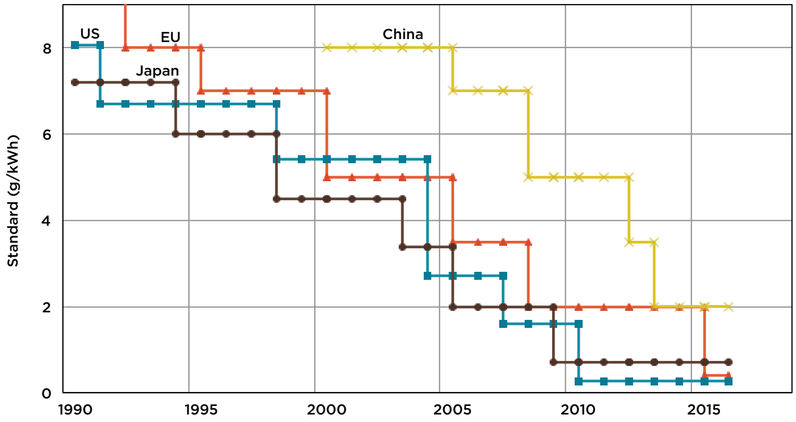

Figure 1. NOx standards for heavy-duty vehicles in the United States, European Union, Japan, and China

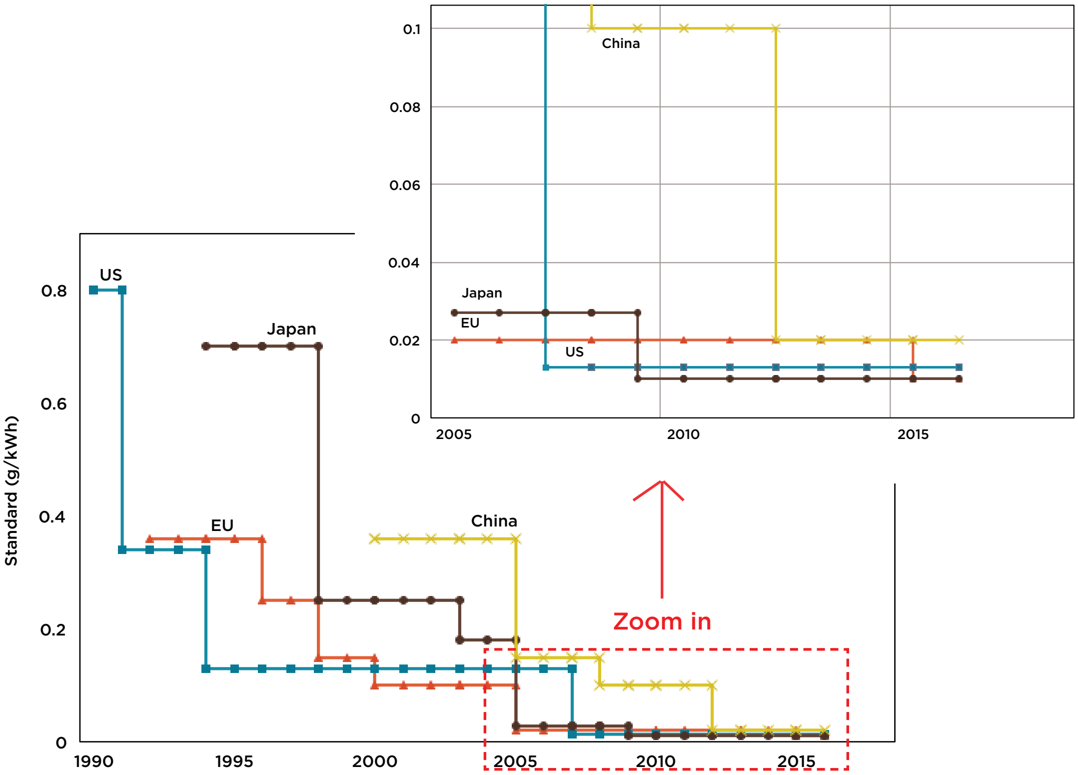

Figure 2. PM standards for heavy-duty vehicles in the United States, European Union, Japan, and China[3,4]

Ideally, as emission control equipment steadily evolves and improves, standards should continually force the use of commercially available engine and aftertreatment technologies with the best performance. In addition, as the understanding of the health impacts of vehicular emissions improves, standards will be revised and technologies will be further developed to combat harmful pollutants. As China prepares to adopt China (Euro[5]) IV standards, major cities and regions, including Beijing, Shanghai and Guangdong that already or will soon have a supply of 50 parts per million (ppm) sulfur fuels, could require China IV enhanced with a diesel

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[3] The stringency of an emission standard is influenced by the applicable type approval test cycle. Because different test cycles are used in the United States, Europe, and Japan, there are limits to the accuracy of a simple comparison of numerical emission values.

[4] These figures have the approximate date of nationwide implementation. In China, major cities and regions, such as Beijing, Shanghai, and Guangdong, have introduced emission standards ahead of the rest of the nation (see Figures 3 and 4).

[5] Like many countries around the world, China has chosen to mirror its vehicle and fuels programs after those set forth by the European Commission. In the Euro program, the Arabic numerals and Roman numerals denote standards for light- and heavy-duty vehicles respectively; however, in China, there is no official distinction, and Roman numerals are used to represent both light- and heavy-duty standards. As with the Euro program, increasing number values imply greater stringency of the standard.

particulate filter (DPF) to capture the maximum health benefits from PM reduction enabled by lower sulfur fuels. DPFs, which are the best available control technology for PM, require diesel fuel with sulfur levels <50 ppm. The pathways section that follows and Appendix A have a full discussion of DPFs and the suite of control technologies for both light- and heavy-duty vehicles. Low and near-zero (10-ppm) sulfur fuels also open the door to early adoption of China VI standards.

1.3 Off-Cycle Emissions

Emissions that occur under conditions not well represented by the laboratory-based test cycles are called off-cycle emissions. The growing sophistication of engine technology and advanced electronic control systems has greatly increased the potential that emission control systems will be modified under conditions not included or underrepresented on the laboratory test procedures, resulting in substantially higher emission levels under actual driving conditions. For this reason, not-to-exceed (NTE) protocols are an important measure in helping to ensure that heavy-duty engines will operate at or below the lawful emission limits on the road by requiring that emission control technologies are effective under all normal operating conditions. NTE limits have been in effect in the United States since 1998, and the European Union will soon adopt the World Harmonized Not-To-Exceed (WNTE) regulation in conjunction with the Euro VI standard.

1.4 Evaporative Emissions Standards

Evaporative emissions are the result of HC vapors escaping from the vehicle's fuel system. Because of the lower volatility of diesel fuel, evaporative emissions are not a concern from diesel-fueled vehicles. However, they are an issue for gasoline-fueled vehicles. The on-board evaporative emission control system universally adopted to meet the emission limits uses an adsorption canister filled with charcoal, which is connected to both the fuel tank and the engine intake manifold.[6] The fuel vapors adhere to the charcoal, until the engine is started, and engine vacuum can be used to draw the vapors into the engine, so that they can be burned along with the fuel/air mixture. The evaporative emission control system also requires the use of a sealed gas tank filler cap.

Although there has been an increasing environmental concern with evaporative emissions, much more attention is typically paid to exhaust emissions. This has especially been the case in the European Union, where, contrary to the United States, Japan, and Australia, no evaporative emission limits were applied until 1993. In China, limits on evaporative

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[6] An additional step in controlling evaporative emissions is by installing a vapor recovery system at gasoline-dispensing facilities. Such systems have been widely adopted at refilling stations in Beijing and are being gradually deployed in the Guangdong province.

emissions have been in place since the adoption of the China I standards. China can strengthen its program by tightening the evaporative limit, which has not been changed since China I.

1.5 Onboard Diagnostics and Fail-Safe Mechanisms

Modern vehicles with on-board computers can monitor a vehicle's emission control system and report potential malfunctions. Systems that monitor emission control systems as a means of determining if there are potential emissions exceedences are called on-board diagnostics (OBD). Advanced OBD[7] has been required for all vehicles in the United States since 1996 and in the European Union and Japan since 2001. In China, OBD requirements for light-duty vehicles were introduced in July 2008 when all vehicle model types were subject to the China III standard.[8] Heavy-duty diesel vehicles certified as China IV vehicles were subject to the OBD requirement beginning in 2010.[9] The OBD requirements in China are the same as those specified by the European Union.

1.6 Manufacturer Responsibility and Durability Requirements

Successful in-use emissions performance of the pollution control system could be jeopardized if the manufacturer were to design systems that required more extensive or more frequent maintenance than the operator could reasonably be expected to perform. Therefore, standards generally require that manufacturers warrant to the initial purchaser and each subsequent purchaser that the vehicle and engine are designed, built, and equipped to conform at the time of sale with all applicable regulations and that the vehicle or engine is free from defects in materials and workmanship that would cause the vehicle or engine to fail to conform with regulations at any time throughout its full useful life. As shown in Table 1, China's durability requirements are generally comparable to the European Union in terms of period of years of coverage; however, aside from the durability requirements for vehicle certification, China does not mandate automakers to provide warranty for protecting consumers from paying the costs of repairs for emission-related failures resulting from defects in design, materials, or workmanship that cause the vehicle or engine to exceed the emission standards. Vehicle warranties are now offered on a voluntary basis. The year of coverage is generally shorter than the durability requirements, the typical period is 60,000 km (2 to 3 years), and the scope of coverage varies

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[7] Commonly referred to as OBD-II, EOBD (European OBD), or JOBD (Japanese OBD).

[8] Heavy-duty gasoline vehicles were required to have OBD starting in July of 2009. Vehicles with more than six seats and a gross vehicle weight rating >2.5 tonnes were subject to the OBD regulation starting in July 2010.

[9] All new diesel engine models certified as China IV engines were subject to the OBD regulation as of January 1 2010; the OBD requirement for diesel engines that have been previously certified is planned to go into effect on January 1, 2012, but the actual implementation date has not yet been announced.

by manufacturer. China can strengthen its program by requiring a specific number of years or kilometers in the warranty and mandating that failures of key emissions-related components (like the three-way catalytic converters) not caused by misuse or improper maintenance be covered under warranty.

Table 1. Durability Requirements for Heavy-Duty Vehicles in the European Union and China

VEHICLE CATEGORY*	PERIOD (whichever event occurs first)		
	EURO IV, V	EURO VI	CHINA II/III/IV
Passenger vehicles (M1)	100,000 km/5 years	100,000 km/5 years	80,000 km/5 years
N1 and M2	100,000 km/5 years	160,000 km/5 years	80,000 km/5 years
N2	200,000 km/6 years	300,000 km/6 years	100,000 km/5 years
N3 ≤ 16 tonnes			
M3 Class I, II, Class A, and Class B <7.5 tonnes			
N3 > 16 tonnes	500,000 km/7 years	700,000 km/7 years	250,000 km/6 years
M3 Class III, and Class B >7.5 tonnes			

*Note. See Appendix C for a description of the different vehicle categories

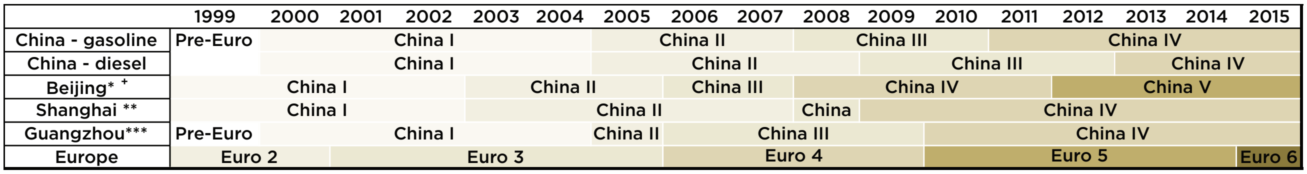
1.7 Crankcase Emission Control

Crankcase emissions, also referred to as blowby gases, are the gases vented from the engine's crankcase to prevent high pressures from building up. Historically, many countries have prohibited crankcase emissions from all highway engines, with the exception of turbocharged, heavy-duty diesel engines. The most common way to eliminate crankcase emissions has been to vent the blowby gases into the engine air intake system so that the gases can be recombusted. For turbocharged heavy-duty diesel engines, however, this policy has raised concerns about fouling that could occur by routing the diesel particulates (including engine oil) into the turbocharger and aftercooler. These concerns are now alleviated by newly developed closed crankcase filtration systems, specifically designed for turbocharged heavy-duty diesel engines.

2 PATHWAYS TO CHINA VI AND BENEFITS OF SWIFT ADOPTION

In the late 1990s, China began setting limits for its major vehicle categories following the Euro pathway, with major cities such as Beijing and Shanghai leading the way with accelerated adoption of standards. The European Union introduced Euro 1/I in 1992. Figures 3 and 4 show that over the past 10 years, the adoption time lag between China (not including major cities) and the European Union has decreased from 8 years to just more than 5 and 4 years for light-duty and heavy-duty vehicles, respectively.

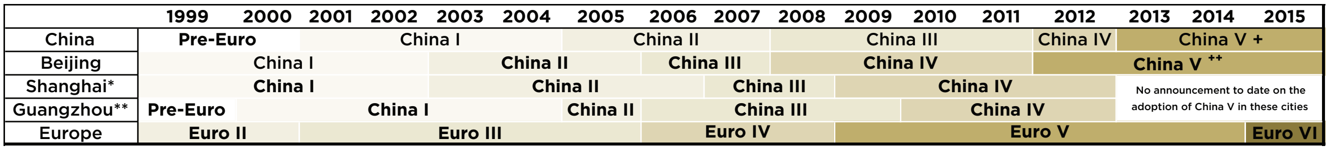
Figure 3. Light-duty vehicle standard adoption timeline in China and European Union.



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
China - gasoline	Pre-Euro	China I					China II			China III			China IV				
China - diesel		China I					China II				China III				China IV		
Beijing* +	China I				China II			China III		China IV				China V			
Shanghai **	China I				China II					China	China IV						
Guangzhou***	Pre-Euro	China I					China II	China III				China IV					
Europe	Euro 2		Euro 3					Euro 4				Euro 5					Euro 6

*China III was adopted in Beijing on December 30, 2005, but without on-board diagnostic (OBD) requirements. OBD were required starting on December 1, 2006.
**China IV standards were implemented in Shanghai in November 2009.
***China IV standards took effect in Pearl River Delta starting on June 1, 2010.
+Beijing has announced plans for advanced implementation of China V vehicle standards in 2012, but standards have not yet been released.

Figure 4. Heavy-duty vehicle standard adoption timeline in China and European Union.



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
China	Pre-Euro		China I			China II				China III				China IV	China V +		
Beijing	China I				China II			China III		China IV				China V ++			
Shanghai*	China I				China II				China III		China IV				No announcement to date on the adoption of China V in these cities		
Guangzhou**	Pre-Euro	China I				China II		China III				China IV					
Europe	Euro II		Euro III					Euro IV			Euro V						Euro VI

*Shanghai required all city buses, sanitation trucks, and construction trucks to meet China IV standards starting November 2010.
**China IV standards took effect in Pearl River Delta on June 1, 2010.
+Proposed implementation date when the standard was announced in 2005; feasibility to be reviewed by Ministry of Environmental Protection.
++Beijing has announced plans for advanced implementation of China V vehicle standards in 2012, but standards have not yet been released.

To enable dramatically lower emissions, regulations requiring nationwide use of lower sulfur fuels are critical for the protection of public health, especially as vehicle numbers continue to quickly rise. In the meantime, some progress in adopting health-protective emission standards can be made by maintaining the schedule for China IV standards, which can still provide some benefits with current fuels.

To model the impacts of regulatory progress, the ICCT team developed the China Fleet Model, which is a China-specific simulation tool that can estimate past, present, and future vehicle emissions and fuel use on the basis of key policy timelines. One such policy lever in the China Fleet Model is the timing of implementing China V, VI, and beyond.[10] The benefits of swift China VI adoption are illustrated in Figures 5 and 6, which show four distinct pathways for implementation, whose timelines are summarized in Table 2. The two 2020 scenarios represent much less aggressive adoption timelines in which China VI is not implemented until 2020. These two scenarios are meant to illustrate the considerable emissions penalty associated with delayed action. Introducing China VI by 2015 is an ambitious goal, but, as shown by the PM and NOx trends in Figures 5 and 6, the emission reduction benefits are quite substantial compared with the scenarios in which China VI is not adopted until 2020. Indeed, the trend for PM emissions—which are associated with the most serious health impacts—is nearly identical between the 2020 Leapfrog (China IV to VI in 2020) and 2020 Step-by-Step (China IV to V to VI by 2020) scenarios because heavy-duty vehicles are the main (>50%) contributor to PM emissions. For heavy-duty vehicles, there is no PM benefit in terms of standard stringency in moving from China IV to V.

Table 2. Pathways to China VI Standards

SCENARIO	CHINA IV	CHINA V	CHINA VI
China IV to VI in 2015	2011	—	2015
China IV to V to VI by 2015	2011	2012	2015
China IV to VI in 2020	2011	—	2020
China IV to V to VI by 2020	2011	2015	2020

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[10] The China Fleet Model produces estimates out to 2030, and, as such, the project team determined it would be reasonable to assume that a China VII regulation would be adopted in that timeframe.

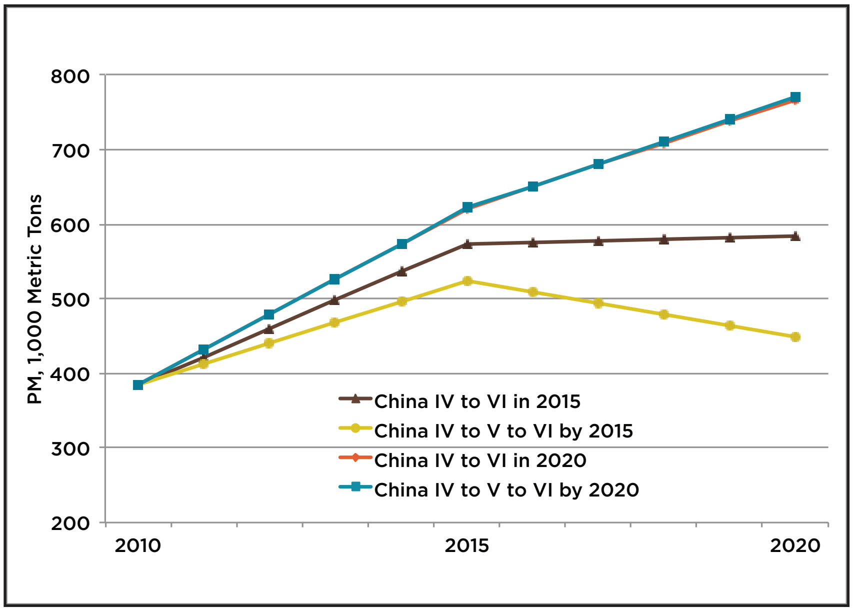

Figure 5. Particulate matter (PM) trends for different China VI adoption pathways.

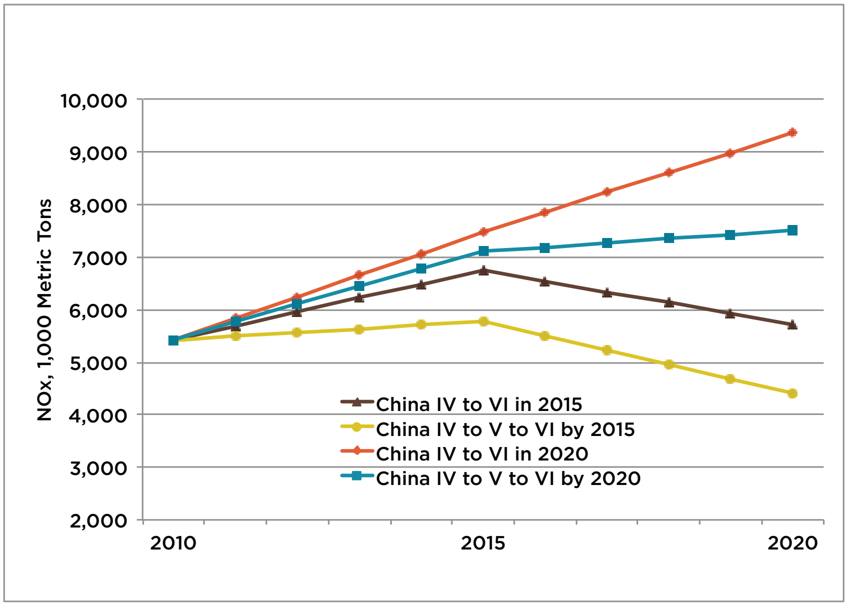

Figure 6. Nitrogen oxides (NOx) trends for different China VI adoption pathways.

3 TECHNOLOGY PATHWAYS IN THE EURO SYSTEM

This section describes the evolution of technologies that have been or soon will be required for Euro pathway light- and heavy-duty vehicles. The discussion of technologies that have been prevalent in the European market is highly relevant to the Chinese context, because China has modeled its vehicle emission and fuel standards after the example set forth by the European Union.

The information presented in this section was gathered from government agencies, technical journals, industrial associations, and commercial literature. A report from the Association for Emissions Control by Catalyst (Favre et al., 2011) that summarized the various technologies used for mobile course emissions control in Europe offered a useful survey that framed much of the technical discussion in this section and Appendix A. The European regulatory information agency gathers all the relevant documents associated with each specific regulation, including impact assessments and responses from various stakeholders that evaluate the technical feasibility of proposed emission limits. The set of technologies initially defined on those impact assessments and response documents were used to define a first draft of technologies included in each of the Euro levels. Journal articles and available literature from industrial and technical associations was later used to refine the set of technologies for each Euro level and fuel type. The set of technologies required for light-duty and heavy-duty vehicles is presented by compliance level (Euro 3/III to 6/VI), with Euro 3/III defined as the baseline. This information is summarized in Tables 3a, 3b, and 4 at the end of this section. In addition, all of the emission control technologies for both light-duty and heavy-duty vehicles are described in greater detail in Appendix A.

3.1 Light-Duty Technologies

The light-duty vehicle category consists of passenger vehicles and light commercial vehicles (categories M1 and N1, respectively). M1 passenger vehicles have a gross vehicle mass (GVM) <3,500 kg and carry fewer than nine people.[11] N1 vehicles are commercial vehicles (goods transport) with a GVM up to 3,500 kg. The following tables summarize the technologies used to move from Euro 3 to 6 limits.

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[11] In China, there is no weight limit for M1 class passenger vehicles.

Table 3a. Light-Duty Diesel Vehicle Emission Control Technology Developments

DIESEL	**M1 LIGHT-DUTY VEHICLES (1.2 <VD< 2.0 L) LIGHT-DUTY TRUCKS (GROSS VEHICLE WEIGHT <3.5 TONS)**								
	EURO 3 TO EURO 4			**EURO 4 TO EURO 5**			**EURO 5 TO EURO 6**		
Regulated pollutants	NOx	PM	CO	NOx	PM	CO	NOx	PM	CO
Emissions target (g/km)	0.25	0.025	0.5	0.18	0.005[a]	0.5	0.08	0.005[a]	0.5
Emissions reduction (%)	50%	50%	23%	28%	80%	0%	56%	0%	0%
Base technology	• Electric fuel timing and metering • EGR, with cooling system • Direct injection combustion and high-pressure fuel injection • Diesel oxidation catalyst			Euro 4 equipment plus–			Euro 5 equipment plus–		
Engine-out emissions and A/F control	• PM reduction through fuel injection pressure and nozzle redesign. NOx control through engine tuning (EGR and injection timing/metering). • Turbocharging with intercooling			Combustion improvements			• PCCI[c], LTC[b] • VGT		
Aftertreatment System[d]	—			DOC + DPF or DPF only			DOC + DPF + LNT or DPF + LNT		

[a] 0.0045 g/km using the PMP measurement procedure.
[b] Air–fuel management improvements aim to avoid high temperatures that led to NOx formation.
[c] Includes multiple fuel timing and metering, allowing for a multimodal combustion engine.
[d] In some heavier light-duty vehicles, SCR is used for NOx control.

Note. A/F = air–fuel; CO = carbon monoxide; DOC = diesel oxidation catalysts; DPF = diesel particulate filter; EGR = electric exhaust gas recirculation; LNT = lean NOx trap; LTC = low temperature combustion; NOx = nitrogen oxide; nitrogen oxides; PCCI = premixed charge compression ignition; PM = particulate matter; PMP = Particle Measurement Programme; SCR = selective catalytic reduction; Vd = displacement volume; VGT = variable geometry turbocharger.

Table 3b. Light-Duty Gasoline Vehicle Emission Control Technology Developments

GASOLINE	M1 LDVS. (1.2 <VD< 2.0 L) LDTS GVW <3.5 TONS										
	EURO 3 TO EURO 4			EURO 4 TO EURO 5				EURO 5 TO EURO 6			
Regulated pollutants	CO	NOx	HC	CO	NOx	HC	PM[a]	CO	NOx	HC	PM[a]
Emissions target (g/km)	1.0	0.08	0.1	1.0	0.06	0.1[b]	0.005	1.0	0.06	0.1[b]	0.005
Emissions reduction (%)	57%	47%	50%	0%	25%	0%	N/A	0%	0%	0%	0%
Base technology	• Stoichiometric combustion • Electronic injection • Electronic ignition • MPI • Second O_2 sensor required for OBD • Improved controller and hardware • Three way catalyst (underbody)			Note: increased use of GDI–lean combustion- forces regulations to include PM emissions levels for GDI vehicles				Note: With Euro 6, there may be a need for GPFs, depending on the particle number limit that is set			

Engine-out emissions and A/F control	Euro 3 plus–
	• Improved fueling strategy to keep CC catalyst at right temperature range for cold start emissions control
	• Increased use of EGR for NOx control during low load operation
				Euro 4 plus–
				• Combustion improvements
				• VVT
				• GDIs require:
				  • Improved injectors
				  • Higher pressure injection
				  • Linear range O_2 sensor for A/F control
								Euro 5 plus–
								• Improvements focused on fuel economy-CO_2 emission reduction
								• Combustion system improvements
								• Turbos and engine downsizing
								• GDIs require: Linear range O2 sensors for A/F control, usually two under closed loop control			

After-treatment system	The elimination of warm up period during the test cycle and increased restriction on HC and CO emissions required the addition of a CC cold start catalyst			• TWC: Increased OSC capacity allows for PGM reduction. Improved coating techniques (double-layer TWC) • CC catalyst requires increase of OSCs loading • GDIs require LNTs				Same as Euro 5 vehicles			

[a] For GDI vehicles only
[b] NMHC limit = 0.068 g/km

Note. A/F = air–fuel; CC = closed-coupled; CO = carbon monoxide; GDI = gas direct injection; GPF = gasoline particulate filters; GVW = gross vehicle weight; HC = hydrocarbon; LNT = lean NOx trap; MPI = multipoint injection; NMHC = nonmethane hydrocarbon; NOx = nitrogen oxide; O2 = oxygen; OBD = on-board diagnostics; OSC = oxygen storage component; PGM = platinum group metal; PM = particulate matter; TWC = three-way catalyst; VVT = variable valve timing.

3.11 EURO 3 AND OLDER

Technologies required for compliance with Euro 1 emission levels marked the introduction of three-way catalyst (TWC) for gasoline vehicles. The TWC requires the use of oxygen sensors for keeping the average concentration of oxygen in the exhaust atmosphere around stoichiometric conditions. In these Euro 1 systems, electronic ignition takes the place of electromechanical distributors.

For gasoline light-duty vehicles with larger engines (engine displacement >1.6 L), Euro 2 marked the shift to multipoint fuel injection (MPFI). Exhaust gas recirculation (EGR) is used for NOx control in some of the larger vehicles and light-duty trucks. Compared with pre-Euro and Euro 1 systems, oxygen sensor technology evolved into more responsive heated oxygen sensors.

With Euro 3, emissions control systems for light-duty vehicles evolved significantly from Euro 2 systems because of the elimination of the warm-up period (40s) during tests on the New European Driving Cycle (implemented starting in 2000). At the time, limiting cold start emissions was a significant focus for Euro 3 compliant vehicles.

In Euro 3 vehicles, air–fuel control systems for gasoline engines became more advanced, with electronic systems for controlling the injection of fuel and ignition (spark timing), especially during cold start operation. MPFI technology is the prevailing strategy for fuel delivery on gasoline vehicles. OBD systems required in Euro 3 vehicles forced vehicle manufacturers to install secondary heated oxygen sensors after the catalyst to monitor its performance. Tighter controls on NOx forced the use of EGR valves for most of the medium- and large-sized gasoline light-duty vehicles. Aftertreatment systems for Euro 3 vehicles use TWCs in an underbody configuration in small- and medium-sized vehicles and a combination of closed-coupled (CC) and underbody in large light-duty vehicles.

Euro 3 diesel vehicles are fitted with fuel injectors capable of electronic fuel metering and timing, a significant improvement over cam-controlled injectors. The first generation of common rail fuel injection system started gaining market share in larger vehicles. The main characteristic of Euro 3 fuel injection systems, whether using common rail or unit-pump injection, is the high fuel pressure delivered by the injector that is intended for better air–fuel mixing and lower PM emissions. However, despite the low in-cylinder production of PM caused by high-pressure fuel injection, diesel oxidation catalysts (DOCs) are required for compliance with Euro 3 levels. NOx emissions are controlled with electronically controlled cooled EGR.

3.12 EURO 3 TO 4

Emission limits requiring 50% reduction in NOx and PM for diesel vehicles and 50% in NOx and HC for gasoline vehicles forced new technological developments for Euro 4 compliant vehicles.

Gasoline vehicle manufacturers met the Euro 4 limits with improvements in fueling strategy, EGR, and changes in the configuration of the TWC. Limiting cold start emissions is a critical issue for Euro 4 certification because of the reduction in emissions limits and the lack of a warming period during the test cycle. Cold start emissions are controlled with an integrated approach, combining the use of flexible fuel MPFI systems with a CC catalyst. The fueling strategy is adjusted to keep the CC catalyst at the right temperature range for cold start emissions control. NOx control is also partially controlled during combustion with EGR during low load operation.

Compliance for diesel vehicles is achieved with engine tuning using fuel timing and metering strategies along with cooled EGR. Euro 4 vehicles are fitted mainly with common rail fuel injection systems with injection pressures around 1,600 bar. The soluble organic fraction of the PM is controlled with improved DOC technology.

3.13 EURO 4 TO 5

Transitioning from Euro 4 to 5, the modest reduction in the NOx limits for gasoline light-duty vehicles is met with combustion improvements through engine calibration. Variable valve timing technologies that began appearing in luxury vehicles during the Euro 4 period diffused into the mainstream market, providing better performance and fuel economy.

Diesel vehicles comply with an 80% reduction in PM emission levels by using catalyzed DPFs or the combination of a DOC and a DPF in almost all of the passenger vehicles size classes. The NOx emission limit is 28% lower and is achieved with combustion improvements and cooled EGR. Large Euro V diesel light-duty vehicles sometimes require NOx aftertreatment devices, such as a lean NOx trap (LNT).

Increasing concerns about climate change, fuel price escalation, and energy security have provided a fertile ground for the introduction of high efficiency GDI vehicles in Europe and around the world. Emission limits on PM from GDI vehicles were explicitly included in the Euro 5 regulation and matched the PM limits for diesel vehicles. In-cylinder emissions control from GDI vehicles required improvements in fuel injectors and air–fuel management. Air–fuel management for GDI involved the implementation of linear range oxygen sensors, also known as universal exhaust oxygen sensors, which are required for measuring the air–fuel ratio in lean exhaust environments. In-cylinder NOx control is achieved through relatively high EGR rates (around 30%). HC and CO are low in lean gasoline combustion, however NOx and PM have become a problem. Standard TWC systems cannot achieve Euro 5 NOx limits and, thus, the use of LNTs is required.

3.14 EURO 5 TO 6

When they are phased in at the beginning of 2014, Euro 6 emission limits for gasoline vehicles will be identical to those of Euro 5. As a result, the technologies for emission control will most likely remain the same as for Euro 5 vehicles. However, evolutionary improvements in fuel economy through engine downsizing, turbocharging, and hybridization can be expected in the coming years.

In the transition to Euro 6, diesel vehicles will require continued research and development in combustion improvements. This includes multimode fuel injection strategies and variable geometry turbocharging, which delivers tailored amounts of fuel and air at specific operational conditions. As in Euro 5 vehicles, the use of DPFs is mandatory for PM control. The NOx limit reduction of 66% from Euro 5 levels will force the use of NOx aftertreatment devices in addition to in-cylinder measures such as cooled EGR. LNTs have shown NOx reduction performance and durability that is on par with SCR systems. LNTs may be more economical for engines with displacements <2.0 L (Kubsh, 2007) compared with SCR technologies.

3.2 Heavy-Duty Technologies

The heavy-duty vehicle category consists of large passenger and commercial vehicles with a GVM >3,500 kg (categories M2, M3, N2, and N3). Table 4 summarizes the technologies that have been used to achieve Euro III to VI limits. Note that engines—not entire vehicles—are subject to testing, and the limits are given in grams of pollutant per work output of the engine (g/kWh). Although these limits apply to both compression ignition (diesel) and spark ignition (gasoline, natural gas, or liquefied petroleum gas) engines, this table covers only diesel vehicle technologies, because the diesel is the dominant power plant in the heavy-duty sector. For discussion of emission control technologies for compressed natural gas (CNG) and liquefied petroleum gas (LPG) vehicles, please see the sections on emission control for gasoline, CNG, and LPG vehicles and heavy-duty CNG technologies in Appendix A.

Table 4. Heavy-Duty Diesel Vehicle Emission Control Technology Developments

	REGULATION											
	EURO III TO EURO IV				**EURO IV TO EURO V**				**EURO V TO EURO VI**			
Reg. pollutants	NOx	PM	HC	CO	NOx	PM	HC	CO	NOx	PM	HC	CO
Emissions target (g/kWh[a])	3.5	0.02	0.46	1.5	2.0	0.02	0.46	1.5	0.4	0.01	0.13	1.5
Emission reduction[a] (%)	30%	80%	30%	29%	43%	0%	0%	0%	80%	50%	72%	0%
Base technology	• High-pressure fuel injection • Electric fuel timing and metering, including timing retard for low NOx • Electric EGR, with cooling system				—				—			
Engine-out emissions and A/F controls	• Improvements in engine combustion and calibration for PM control • Turbocharging with intercooling • NOx control[b]: EGR cooled				• Improvements in engine combustion and calibration • Multiple injection fuel system (pilot-main-post) • VGT • NOx controlb: EGR cooled				• VGT • Combustion research • PCCI[c], LTC[d]			
After-treatment system[e]	• NOx controlb: SCR systems (open loop) • PM control: DOC + PFF				• NOx controlb: SCR systems (closed loop) • PM control: DOC + PFF				• NOx control: SCR systems (closed loop) • PM control: DOC + DPFs			

[a] Emissions measured over the ESC engine dynamometer test cycles.
[b] NOx control through EGR or SCR is manufacturer's choice.
[c] Premixed Charge Compression Ignition (PCCI) includes multiple fuel timing and metering, allowing for a multimodal combustion engine.
[d] LTC are A/F management improvements aim to avoid high temperatures that led to NOx formation.
[e] In general, for Euro IV and V, manufacturers typically follow one of two emission control pathways: (a) engine tuning for low PM and high NOx + SCR for NOx control or (b) engine tuning for low NOx and high PM (as well as EGR for additional NOx control) and a DOC, PFF, DPF for PM control. For Euro VI, systems will require aftertreatment for both NOx (SCR) and PM (DPFs).

Note. A/F = air/fuel; CO = carbon monoxide; DOC = diesel oxidation catalyst; DPF = diesel particulate filter; EGR = exhaust gas recirculation; ESC = European Stationary Cycle; HC = hydrocarbon; LTC = low temperature combustion; NOx = nitrogen oxides; PCCI = premixed charge compression ignition; PFF = partial flow filter; PFF = partial flow filter; PM = particulate matter; SCR = selective catalytic reduction; VGT = variable geometry turbocharger.

3.21 EURO III AND OLDER

Euro II trucks in the lower range of engine displacement are fitted with direct injection technologies and turbochargers with aftercooling. In-cylinder development for NOx-PM tradeoff control includes an increase in valve number (3–4 per cylinder), fuel injection technologies with higher pressures and metering control (common rail and electronic unitary injectors), and nozzle redesign aimed at improving the fuel spray pattern for better mixing with air and to reduce fuel dribbling at the end of the injection. Further NOx reduction is achieved by using fuel injection timing retardation during some engine conditions (because of lower peak combustion temperatures). EGR is not required for most heavy-duty engines.

3.22 EURO III TO IV

The Euro IV standard required 80% reduction in PM and 30% reduction in NOx, HC, and CO. There were two technical approaches to achieve these levels: (a) engine-based PM control and NOx controlled with aftertreatment devices, or (b) NOx control through EGR and PM control by an aftertreatment device—typically, a DOC or partial flow filter (PFF).

The first strategy, which has been most commonly used in Europe, combines engine calibration for low PM emissions and does not use EGR. Low PM engine calibration requires adequate fuel atomization, through high-pressure fuel injection, and early fuel injection during the compression stroke. The fuel injection advancement results in higher combustion temperatures leading to high NOx levels that need to be addressed with aftertreatment. SCR systems using urea as a reductant with 50% to 60% NOx reduction capability are required to meet the targets (Johnson, 2002). The injection advancements and combustion optimization increase the engine's fuel efficiency. An additional benefit of this approach is that the fuel penalty associated with EGR (4%–7%) is avoided and can offset the costs associated with having to supply the vehicle with urea. Hallstron and Schiavon (2007) indicated that the approach based on SCR and engine tuning for low PM opens the possibility of reaching Euro IV levels in countries where ultra low sulfur fuel may be not available.[12]

For environmental regulators, SCR poses new challenges that may not be immediately apparent. Because SCR consumes urea, mobile source SCR systems require the development of an extensive urea delivery infrastructure for geographically disperse mobile sources and the incorporation of robust on-board fail-safes to ensure that drivers properly fill onboard urea tanks. Furthermore, in-use SCR-equipped vehicles may have significant

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[12] In addition to oxidizing species such as HC and CO, DOCs can oxidize the sulfur into sulfate compounds. The lack of a DOC in a vehicle that uses engine tuning for low PM emissions and SCR for NOx control eliminates this issue.

off-cycle and unregulated emissions because of the temperature dependence of catalytic activity, improper urea dosing, catalyst poisoning, and the formation of catalytic byproducts.

The second approach is tuning the air–fuel management system to produce engine-out PM with a highly soluble organic fraction (SOF), which may be controlled with DOCs or PFFs, and using cooled EGR for in-cylinder NOx reduction. The use of PFFs requires higher EGR use and lower engine-out NOx levels. Because partial flow filters are a relatively new technology, there are still concerns about the long-term durability of these systems and their ability to consistently control PM under varying operating conditions (Majewski, 2008; Mayer et al., 2009). This option is most useful for urban low-load heavy-duty vehicles. The technical reason for selecting EGR + DOC or EGR + PFF over SCR is that SCR systems using vanadium catalysts can have limited efficiency in low-exhaust temperature ranges typical of urban driving. The performance of SCR systems is highly dependent on exhaust temperature, the choice of catalyst, urea dosing method, and other factors. However, real-world evidence from researchers in Europe (Ligterink et al., 2009; Rexeis, 2009) suggests that some of the heavy-duty vehicles using EGR may be underperforming in stop-and-go driving conditions as well. In these cases, the EGR system has been designed by the manufacturer to turn off at very low exhaust temperatures to avoid the potential formation of sulfuric acid, which can rapidly destroy the EGR cooler and then progressively damage the entire engine. For both EGR and SCR systems to meet NOx performance expectations across the spectrum of exhaust temperatures, these systems must be designed and tested using test cycles that better encompass the full range of driving conditions—especially low engine loads. Euro VI testing on the World Harmonized Transient Cycle, which includes a cold-start portion, is expected to largely resolve the issue of underperformance at low speeds that are typical of urban driving.

3.23 EURO IV TO V

Moving from Euro IV to V, only NOx is subject to a more stringent limit, which is 43% lower. The options to reach this emission target are based on improvements over Euro IV technologies. The fundamental way to keep all regulated pollutants under Euro V limits is intensive air–fuel management control involving fuel injection timing, fuel injection pressure, and MPFI strategies coupled with variable geometry turbochargers. The SCR systems have higher urea injection rates. Improved SCR reduction can be achieved if a DOC is used upstream of the SCR to provide extra NO2 for NOx reduction. NOx control based on EGR may require the use of cooled EGR coupled with advanced air–fuel management systems. However, the higher use of EGR that Euro V requires may lead to an undesirable increases in PM emissions under specific speed–load conditions. Under this strategy—and depending heavily on the specific air–fuel management strategy—PM control may be achieved with the combination of a DOC and PFF or may require the use of DPFs. The use of a DPF may be required in larger engines or when the air–fuel management system is unable to maintain low PM with high EGR use during the test cycles. Sulfur levels are a key constraint on catalyzed DPFs or uncatalyzed DPFs that are used with an upstream DOC. For these systems, diesel sulfur levels must be <50 ppm; for optimal performance and durability, 10-ppm fuel is preferred. A more detailed discussion of the sulfur effects on aftertreatment technologies is included in the section on sulfur impacts on emission control technologies.

3.24 EURO V TO VI

Heavy-duty diesel engines will require significant reductions in NOx, PM, and HC emissions (80%, 50%, and 72% on the World Harmonized Stationary Cycle, which will replace the European Stationary Cycle with the introduction of Euro VI). The low PM mass value of 0.01 g/kWh and newly instituted particle number limit[13] is expected to force the use of DPFs. At such low levels, mass measurement becomes more and more challenging. It is envisioned that the inclusion of particle number testing in the standard will be the main driver to force the most efficient filtration devices. As mentioned earlier, low sulfur (<50 ppm) diesel is required for use with catalyzed DPFs or DOC + DPF devices. HC and CO control can be achieved with an oxidation catalyst (OC) or using DPFs with catalyzed surface membranes. DOCs formulated for Euro VI applications will be designed for improved oxidation capabilities at low temperatures. The heat generated during HC and CO oxidation can be combined with another heat source and used for active DPF regeneration. The oxidation also affects NO, which is oxidized into NO2 and then used for passive DPF regeneration because NO2 greatly reduces the temperature at which the trapped soot will combust. Increasing NO2 generation in the DOC is an option for facilitating passive soot oxidation but requires integrated NOx control downstream of the DPF (Andersen, 2008). A system diagram of this emission control configuration is shown in Figure 7. It is expected that most manufacturers will use a combination of EGR and SCR to reach the Euro VI NOx limit of 0.4 g/kWh. NOx aftertreatment control may require improved closed loop SCR systems, with sensors to keep regulated ammonia levels under control (Murata et al., 2008).

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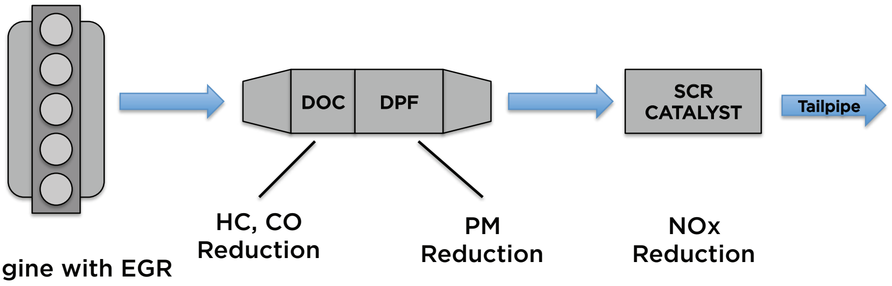
[13] In a draft proposal, the particle number limits have been set at 8.0 × 1011 for the World Harmonized Stationary Cycle and 6.0 × 1011 for the World Harmonized Transient Cycle.



Note. CO = carbon monoxide; DOC = diesel oxidation catalyst; DPF = diesel particulate filter; EGR = exhaust gas recirculation; HC = hydrocarbon; NOx = nitrogen oxides; PM = particulate matter; SCR = selective catalytic reduction.

Figure 7. Emission control diagram for a U.S. 2010[14] compliant heavy-duty engine.

The significant challenge of Euro VI and the current emissions standards in the United States and Japan have prompted intensive research in multi-modal combustion engines and sophisticated in-cylinder control strategies. Multimodal engines are engines capable of keeping electronic control over many variables to achieve in-cylinder reduction in both NOx and PM emissions. Fuel injection is controlled for timing and quantity, including multiple injections in a single cycle (pilot, main, and post injections). The flexibility of fuel injection is also accompanied with variable geometry turbochargers able to match the response of electronic fuel injection controls with the proper amount of air for improved combustion. Johnson (2009) summarized the literature published on expected Euro VI in-cylinder emission control technologies for engines with minimum rated power of 300 kW (402 hp): two-stage turbocharging, 25% EGR at full load, 220 bar peak in-cylinder pressure (during combustion), and common rail fuel injection pressure at 2,200 bar.

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[14] Euro VI heavy-duty engines are expected to be roughly identical to U.S. 2010 engines in terms of control technologies and configuration.

Table 5. Summary of Emission Control Technologies for Light- and Heavy-Duty Diesel Vehicles

TECHNOLOGY	CONTROL EFFICIENCY, % REDUCTION				FUEL SULFUR (PPM) REQUIREMENT (PPM)	COMMENTS
	PM	NO_x	HC	CO		
A/F management (CI engines only)	—	—	—	—	—	• Fuel injection system: electronic fuel timing and metering, including single or multiple injections • High-pressure injection (1,600–2,200 bar) with redesigned nozzle and piston bowl. • Air handling system: turbocharging with aftercooling; variable geometry turbo for better speed-load response • Improvements in design for intake manifold, valves, nozzle, piston crowns (bowls), and cylinder heads • Approximately 90% reduction in PM and 70% in NOx was achieved between Euro I and III.
EGR (w/ cooling)	(a)	20–80	(a)	—	<350	• NOx reduction depends on load conditions: higher loads lead to higher reductions. • PM and HC can be controlled with electronic fuel timing and metering and VGT • U.S. 2010 engines and Euro V engines with proper A/F management systems may be able to achieve in-cylinder reduction of both NOx and PM. • EGR is used at mid loads in both gasoline and NG engines
DOC	20–25 (a) up to 50 (b)	—	> 80	> 80	<350 viable <50 preferred	• (a) High load tests • (b) Low load tests • DOC reduces only SOF out of the total PM (no fine particles • Formaldehyde and acetaldehyde can be reduced by 50%–90%, which is especially helpful in CNG vehicles. • DOC durability is well proven.
PFF	30-60	—	> 80	> 80	<350	• Also known as PFT, this catalyzed filter is a flow-through device. It is composed of a DOC upstream that provides NO2 for soot oxidation downstream in catalytic coated metallic or fiber mesh. • PFFs generate lower exhaust backpressure and no maintenance is required. • Long-term durability has yet to be proven. The various performance challenges with these systems are described in Appendix A.

Table 5. Summary of Emission Control Technologies for Light- and Heavy-Duty Diesel Vehicles (Cont.)

TECHNOLOGY	CONTROL EFFICIENCY, % REDUCTION				FUEL SULFUR (PPM) REQUIREMENT (PPM)	COMMENTS
	PM	NO_x	HC	CO		
DPF	>70–99 (a) 50–90 (b)	—	>80	>80	<50 required for catalyzed DPF <10 preferred	• Passive systems are referred to as catalyzed particulate filters or the combination DOC + uncatalyzed wall-flow filter (commercially known as CRT). • Only technology that significantly reduces ultra-fine particles; low sulfur fuels improve DPF performance • (a) Elemental carbon filtration (soot) • (b) SOF; conversion by catalytic oxidation
Lean NOx catalyst	—	5–15 (a) 50–60 (b)	—	—	<50 required	• Technology in development • (a) Passive regeneration is catalyst based. • (b) Active regeneration requires late fuel injection or upstream fuel addition.
Lean NOx traps (NOx adsorbers)	—	70–90	—	—	<50 required <10 preferred	• Fuel economy penalty associated with regeneration periods • Commercialized in GDI engines • Commercial applications in Dodge Ram and Mercedes-Benz E320 • Heavy-duty application still in development
SCR	(a)	50–95	—	—	<2,000 (b) <50 (c)	• Performance depends on control system configuration. • Allows improved engine efficiency (fuel economy) • Requires urea supply infrastructure and special failsafe provision • (a) PM emissions may be affected by fuel sulfur level • (b) Sulfur tolerance for vanadium catalysts; 350-ppm is recommended • (c) Sulfur tolerance for zeolite catalysts
Three Way Catalyst (SI engines only)	—	>90	>90	>90	<500	• Applies to stoichiometric gasoline and NG engines • Well-established technology

Note. A/F = air/fuel; CI = compression ignition; CNG = compressed natural gas; CO = carbon monoxide; CRT = continuously regenerating trap; DOC = diesel oxidation catalyst; DPF = diesel particulate filter; EGR = exhaust gas recirculation; GDI = gasoline direction injection; HC = hydrocarbon; NG = natural gas; NOx = nitrogen oxides; PFF = partial flow filter; PFT = partial flow technologies; PM = particulate matter; SCR = selective catalytic reduction; SI = spark ignition; SOF = solid organic fraction; VGT = variable geometry turbochargers

4 SULFUR IMPACTS ON EMISSION CONTROL TECHNOLOGIES

As is indicated in Table 5, sulfur levels in fuels are often the primary limiting factor for emission control technologies—particularly catalytic aftertreatment devices. In general, the lower the sulfur levels are, the wider the range of available control technologies will be and the higher the reduction potential for NOx, PM, and other emitted species will be. The sections that follow describe sulfur's adverse effects on the various in-cylinder and aftertreatment systems used for light-duty and heavy-duty vehicles. For more information about these technologies, see Appendix A.

4.1 NOx Control Technologies

4.11 EXHAUST GAS RECIRCULATION

The presence of sulfur does not directly affect EGR systems in diesel engines, but the increased presence of sulfuric acid from SO_2 oxidation can diminish overall engine durability and reliability. Lower exhaust gas temperature, which is one of the results of using EGR, can lead to condensation of sulfuric acid in the recirculation system. Higher sulfuric acid levels result in the need for premium components and increase maintenance costs (Walsh, 2004).

4.12 LEAN NOx TRAPS

LNT—also known as NOx storage catalysts or NOx adsorbers—are designed for effective NOx reduction in an oxygen-rich environment. In these systems, NO is catalytically oxidized to NO_2 and stored on an adjacent chemical trapping site as solid nitrate. The stored NOx is released by creating a fuel-rich atmosphere with injection of a small amount of diesel fuel. The released NOx is quickly reduced to N_2 by reaction with CO (a by-product of the fuel-rich combustion) on a precious metal catalyst site [Manufacturers of Emission Controls Association (MECA), 2000]. NOx reductions in excess of 90% can be achieved using LNTs, but their efficacy is highly dependent on levels of sulfur in the fuel [European Automobile Manufacturers Association (ACEA), 2000; MECA, 2000; Walsh, 2004]. Given the similarities in the chemical properties of gaseous sulfur oxides (SOx) and NOx, LNTs are also very effective at storing SO_2. Unfortunately, SO_2 storage is the preferred mechanism, so SOx are stored on the trap as solid sulfates and require much higher temperatures for removal than the nitrates. Thus, they tend to stay in place during the normal regeneration process and quickly lock up the storage sites. This high temperature requirement is particularly troublesome in the case of diesel engines, which have lower exhaust temperatures than do gasoline engines. Over a period of time, the sulfates occupy most of the space on the trap, and NOx storage declines significantly. As fuel sulfur levels increase, deterioration of

NOx storage capacity over time accelerates substantially. For that reason, there is consensus that LNTs should be used only with fuels having a sulfur content of <15 ppm (ACEA, 2000; Hallstrom & Schiavon, 2007).

4.2 Selective Catalytic Reduction

SCR systems are less sensitive to fuel sulfur levels than other diesel aftertreatment strategies, notably LNTs and catalyzed particulate filters, although that sensitivity varies by catalyst. For lasting performance of an SCR system, a maximum sulfur content of 350 ppm is recommended for vanadium catalysts (Chatterjee et al., 2008), although copper–zeolite catalysts are inappropriate for use with fuel sulfur levels >50 ppm because of their vulnerability to poisoning by SO_2 and SO_3 (Johnson, 2009). If an upstream DOC is used in tandem with SCR, fuel sulfur will limit the efficacy of the DOC, resulting in an increase in PM emissions. Also, sulfur reactions in urea-based SCR systems can form ammonium bisulfate, a severe respiratory irritant (Mautz et al., 2001).

4.3 PM Control Technologies

4.31 DIESEL OXIDATION CATALYSTS

Sulfur in diesel fuel adversely affects DOC functionality in the following ways. First, as sulfur levels rise, sulfur occupies more space on the catalyst, thus rendering the DOC less effective in oxidizing HC, CO, and the PM SOF. The high temperatures required to remove sulfur from the catalyst contribute to thermal aging of the catalyst [ACEA, 2000; Diesel Emission Control Sulfur Effects (DECSE), 2001]. Second, increased presence of unwanted SO_2 on the catalyst surface raises the temperature at which the maximum conversion efficiency (or “light-off” temperature) is reached. As light-off temperatures increase, fewer HC, CO, and PM SOF are oxidized under normal operating conditions (ACEA, 2000). Last, at high-torque (high exhaust temperature) conditions, there is a significant increase in secondary PM when using high sulfur fuel because of the accelerated conversion of SO_2 to SO_3, which thereby increases the SO_4 fraction of the PM (ACEA, 2000; DECSE, 2001). Although DOCs may be designed to withstand high sulfur concentrations, the use of lower sulfur fuels (<50 ppm) improves particulate reduction efficiency (DECSE, 2001; Walker, 2004; Chatterjee et al., 2008).

4.32 PARTIAL FLOW TECHNOLOGY

Because the partial flow technology (PFT) system combines a DOC and a open-flow filter device, susceptibility to sulfur levels is controlled by the DOC, which is the more sensitive of the two. As mentioned earlier, to avoid large increases in SO_2 oxidation and secondary PM formation, the maximum sulfur level recommended is 350 ppm, and sulfur levels <50 ppm will improve efficiency.

4.33 DIESEL PARTICULATE FILTERS

Unlike the DOC and the PFT systems, the PM removal efficiency of two kinds of passively regenerated DPFs (continuously regenerating DPF and catalyzed DPF) is highly dependent on sulfur levels for several reasons. The effects of sulfur on DPFs are summarized as follows:

- SOx compete for storage space on the catalyst and thus decrease the conversion of NO to NO_2. Therefore, high sulfur levels raise the regeneration temperature required for continuous PM combustion and decrease the efficiency of the DPF (ACEA, 2000).
- Operation with higher sulfur fuels can cause the filter to be overloaded with soot, and uncontrolled soot burning can occur, which can damage the filter (ACEA, 2000).
- As mentioned earlier in the DOC section, increased sulfur levels result in higher SO_2 oxidation and sulfate species formation, which leads to an increase in PM emissions.
- In active regeneration, increased back pressure caused by higher sulfate levels can lead to the more frequent need for regeneration and the concomitant penalties of higher fuel consumption and shorter maintenance intervals (ACEA, 2000).
- Diesel particulate filter systems typically incorporate periodic desulfation events (i.e., sustained high temperature soot combustion) to regenerate the filter and slow down the sulfur degradation rate.

5 CHALLENGES AND OPPORTUNITIES OF TECHNOLOGY PATHWAYS IN CHINA

To enable dramatically lower PM emissions from both light-duty and heavy-duty vehicles, regulations requiring nationwide use of lower sulfur fuels (≤50 ppm) and DPFs are critical. These regulations will protect public health, especially as vehicle numbers continue to rise quickly. The sulfur content in current fuel is one of the greatest barriers to further progress on emission standards, especially for diesel vehicles. The best available emission control technologies, including TWCs, DPFs, and zeolite SCR catalysts are sensitive to sulfur. In the meantime, some progress in adopting health-protective emission standards can be made by maintaining the schedule for China IV vehicle standards, which can still provide some benefits with current fuels.

Another barrier to advancing emission standards in China is the significant differences in the level of technical expertise and access to advanced technologies between domestic and foreign manufacturers. These differences result in a much slower modernization of manufacturing processes and products, especially in the light-duty truck, heavy-duty, and nonroad sectors. For example, the lack of domestic manufacturers of electronically controlled fuel injection systems in diesel engines has been identified as a barrier to the on-schedule implementation of China IV. The shift to electronically controlled engines would not only enable meeting more stringent emissions standards but also result in a significant gain in fuel efficiency. For consumers, the lifetime fuel savings could partially offset the higher costs of the electronically controlled systems. The current technology gap also significantly limits the export potential of Chinese engines and trucks to markets with tight regulations. However, this is not to say that all domestic manufacturers have been slow to modernize. As is discussed in more detail in Appendix B, certain domestic heavy-duty engine manufacturers as well as foreign–domestic joint ventures are well positioned to achieve China V and VI levels with little change in architecture because they are already producing China III and IV engines that are electronically controlled and use SCR for NOx control. For these manufacturers, reaching China V and VI NOx limits will require only modest combustion improvements and changes in the urea-dosing amounts and controls.

In terms of NOx control, pathways to China IV, V, and VI are relatively straightforward for the light-duty segment and include improvements in combustion, EGR, and TWC configuration. However, NOx control technology for heavy-duty vehicles—in particular, SCR—poses more pressing challenges for both industry and government. Because SCR consumes urea, mobile source SCR systems require the development of an extensive urea delivery infrastructure for geographically disperse mobile sources and the incorporation of robust, on-board fail-safes to ensure that drivers properly fill onboard urea tanks. Furthermore, in-use SCR-equipped vehicles may have significant off-cycle and unregulated emissions because of the temperature dependence of catalytic activity, improper urea dosing, catalyst poisoning, and the formation of catalytic byproducts. Recent evidence from Europe suggests that heavy-duty vehicles equipped with SCR and meeting Euro V standards may be underperforming in urban, stop-and-go (i.e., low exhaust temperature) applications. The principal reason for underperformance is the mismatch between the test procedure cycle to which the system is optimized and the in-use duty cycle. With China VI, if China adopts the Euro VI testing requirement of the World Harmonized Transient Cycle, which includes more rigorous testing at low temperatures, heavy-duty vehicles are expected to have much better NOx performance in real-world urban driving. Testing is currently under way at the Beijing Institute of Technology for the Ministry of Environmental Protection to determine the NOx emissions characteristics of SCR-equipped heavy-duty vehicles operating in Beijing. Rather than waiting for the introduction of China VI to combat urban in-use emissions, some local officials and research organizations are considering developing a supplemental test procedure that better captures highly transient, low-exhaust temperature conditions or adding an additional in-use testing requirements (like the NTE approach adopted by the United States) to the China V standards.

In assessing the transition to more stringent standards, the Ministry of Environmental Protection should continue to consider several options. One option, as mentioned previously, includes modifying the test procedures to include the improvements planned for Euro VI expected to address the current test cycle issues. Another option is skipping China V and leapfrogging to China VI as soon as possible. Given the significant growth in the vehicle fleet, substantial emission reduction benefits would be associated with the transition to China VI standards. The sooner these are adopted, the faster these climate and health benefits will accrue. Regions such as Beijing, Shanghai, and some parts of Guangdong that already have access to ≤50 ppm sulfur fuel have the opportunity to adopt standards that require the use of best available control technologies. In doing so, these important cities can continue to be places that nurture the development of new technologies and knowledge transfer to industry, government, and end-users in the rest of the country.

Despite the many challenges that lie ahead, China has already taken the critical first steps in the development of a world-class vehicle emission control program that can match its position as a leading world vehicle market. Continuing that development will require building on the foundation established by the current program and incorporating lessons learned from mature programs in the European Union, United States, and Japan. It will also require unleashing creative and innovative policy thinking to adapt best practices to the Chinese context.

APPENDIX A: EMISSION CONTROL TECHNOLOGY OVERVIEW

Diesel combustion technology is defined as compression ignition, a situation in which air is compressed and its temperature raised creating suitable conditions for autoignition of fuel once injected into the cylinder without a spark. The diesel combustion process is considered lean because the air-to-fuel ratio is higher than the stoichiometric[15] ratio for diesel fuel. CNG and LPG engine technology are similar to gasoline engines, in which combustion of the air–fuel mixture is triggered by spark ignition. Spark ignition combustion can be achieved in both lean and stoichiometric conditions. Lean spark ignition combustion implies direct or indirect in-cylinder fuel injection, and stoichiometric spark ignition combustion requires premixed air and fuel. Each type of fuel and combustion technology undergoes a characteristic combustion process, producing a characteristic spectrum of pollutants which control requires specific in-cylinder and aftertreatment technologies.

PM emissions are not significant in stoichiometric spark ignition engines (gasoline, natural gas, and LPG) because of homogenous mixing of air and fuel before combustion starts, but they are an issue in both compression ignition diesel engines and lean spark ignition engines where the fuel is nonhomogeneously distributed before ignition. Engine-out NOx emissions are higher in stoichiometric engines than they are in lean engines (diesel and gasoline), but the high engine-out NOx levels of stoichiometric engines are relatively easy to control with aftertreatment devices compared with the low engine-out NOx levels of lean engines, as will be explained later. Unburned HCs and CO are also higher in stoichiometric engines because there is less availability of oxygen (O_2) to complete the HC oxidation. In addition to these four pollutants, natural gas–powered engines (lean and stoichiometric) are regulated on methane (CH_4) emissions according to European standards.

The set of technologies required for control of regulated pollutants is presented in the following sections for each engine type, compression ignition and spark ignition. A brief description—including operating principles, emission reduction capabilities, and the impacts of fuel sulfur—is provided for each technology.

A1 NOx Control for Diesel Vehicles

NOx is created as a by-product of combustion. Air contains primarily nitrogen (N_2) and oxygen (O_2). The heat generated during combustion

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[15] Stoichiometric combustion is defined as the theoretical or ideal combustion process in which fuel and oxygen are completely consumed, with no unburned fuel or oxygen in the exhaust. Lean burn combustion, by contrast, is accomplished with excess air in the combustion chamber. The resulting exhaust contains significant amounts of oxygen.

causes these elements to merge to form NOx. Its formation is directly proportional to peak combustion temperature and pressure. It can be mitigated with engine controls that decrease combustion temperature or aftertreatment. Typical aftertreatment technologies for NOx control are EGR, LNT, and SCR.

A1.1 IN-CYLINDER NOx CONTROL

Improvements in engine combustion to reduce NOx emissions have occurred in both compression ignition and spark ignition engines. For compression ignition direct injection engines, improvements in engine combustion involve the use of high-pressure injection with redesigned nozzles and piston bowls. The fuel injection timing and the rate of fuel injection have been used to control both NOx and PM. Air intake and turbocharger tuning have been used to control the combustion process (Johnson, 2000). Intake air tuning includes special design of swirl and tumble in the combustion chamber; turbocharger tuning is focused on the use of variable geometry turbochargers to provide the right amount of air under specific engine operational conditions.

EGR is the most effective technology for in-cylinder NOx reduction in diesel-powered engines and has been used in gasoline and natural gas engines. EGR's ability to reduce NOx is based on its dilution effect, which works in two ways: by reducing the peak temperatures during combustion, thus avoiding the high temperatures where NOx is formed, and by reducing the concentration of O_2 available for NOx formation. In diesel engines, the EGR fraction is tailored during engine calibration at specific engine operational conditions and may vary from 0% up to 40%. At higher load demands, the NOx reduction can reach up to 80%. Most heavy-duty diesel engine manufacturers in the United States used EGR as the technology for NOx control to meet U.S. 2004 and U.S. 2007 levels. In Europe, EGR was chosen by some engine manufacturers to meet Euro IV and V levels.

A1.2 NOx AFTERTREATMENT DEVICES

For some engines and vehicles, tighter emission levels for NOx are difficult to meet with EGR and in-cylinder NOx reduction strategies and require aftertreatment for NOx control. The most common options for aftertreatment NOx control are LNTs and SCR.

A1.21 LEAN NOx TRAPS

LNTs—also known as NOx storage catalysts or NOx adsorbers—are designed for effective NOx reduction in an oxygen-rich environment. In these systems, NO is catalytically oxidized to NO_2 and stored on an adjacent chemical trapping site as solid nitrate. The stored NOx is released by creating a fuel-rich atmosphere with injection of a small amount of diesel fuel. The released NOx is quickly reduced to N2 by reaction with CO (a by-product of the fuel-rich combustion) on a precious metal catalyst site (MECA, 2000). NOx reductions >90% can be achieved using LNTs, but their efficacy is highly dependent on levels of sulfur in the fuel (ACEA, 2000; MECA, 2000; Walsh, 2004). Given the similarities in the chemical properties of gaseous SOx and NOx, LNTs are also very effective at storing SO_2. Unfortunately, SO_2 storage is the preferred mechanism, so SOx are stored on the trap as solid sulfates and require much higher temperatures for removal than the nitrates. Thus, they tend to stay in place during the normal regeneration process and quickly lock up the storage sites. This high temperature requirement is particularly troublesome in the case of diesel engines, which have lower exhaust temperatures than do gasoline engines. Over a period of time, the sulfates occupy most of the space on the trap, and NOx storage declines significantly. As fuel sulfur levels increase, deterioration of NOx storage capacity over time accelerates substantially. For that reason, there is consensus that LNTs should be used only with fuels having a sulfur content of <15 ppm (ACEA, 2000; Hallstrom & Schiavon, 2007).

A1.22 SELECTIVE CATALYTIC REDUCTION

In SCR, ammonia (NH_3) is injected into the exhaust stream, and the hydrogen from the ammonia reduces NO and NO_2 to N_2 and water (H_2O). Ammonia is carried onboard the vehicle in the form of a nonhazardous urea solution. Various different SCR catalysts may be used, depending on the vehicle application—they are either vanadium-based or zeolite-based catalysts mounted on a ceramic monolith. SCR systems can achieve NOx reduction efficiencies on the order of 70% to 90%. However, as discussed earlier, performance of SCR systems is highly dependent on exhaust temperatures and many other factors, and care must be taken in engineering and regulatory design to ensure that systems are achieving the expected NOx reductions over the entire range of operating conditions.

Although SCR systems have the distinct advantage of allowing engines to be tuned for high-NOx and high efficiency, they present two key challenges. First, given the variable power requirements of vehicle systems, it can be difficult to achieve precise dosing of urea. Consequently, either very precise urea measuring systems with a downstream sensor and a feedback loop must be used, or an ammonia slip oxidation catalyst must be placed downstream of the SCR device to prevent the unreacted urea from being emitted as ammonia, which is a toxic pollutant with severe human health impacts.[16] SCR systems can vary in many design parameters, including urea

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[16] Although ammonia has severe impacts at high concentrations, the levels that are likely to be emitted—even without an ammonia slip catalyst—are much lower than the levels that would cause these serious health reactions.

mixers, injection strategy, and choice of catalyst. Because of the variability of different types of SCR and the inherent complexity of these systems, there is a wide range of quality and NOx reduction efficiencies in the SCR market. Second, SCR requires the use of urea as a reagent to ensure NOx emissions are reduced. Development of an adequate urea infrastructure is a critical step for enabling SCR technology so that urea is widely available to truck operators. Another key consideration is that SCR systems need to be coupled with failsafe measures to make sure urea is used and the tank is replenished. Options for driver inducements range from warning lights for tank levels, urea quality sensors to make sure tank is filled with urea and not other substances, and limits to the performance of the vehicle if the vehicle is operated when the tank is empty (e.g., drastically reduced speeds or inability to start the engine).

A2 PM Control for Diesel Vehicles

PM is composed of elemental carbon particles that agglomerate and adsorb other species, such as nitrates, sulfates, metals, and condensed HCs, creating a complex substance of diverse physical and chemical properties. Typically, PM exhaust from diesel engines distributes in bimodal fashion into so-called nuclei mode particles or accumulated mode particles. The nuclei mode contains the smallest particles—also know as nanoparticles—that have diameters varying from 0.005 to 0.05 um and are formed from volatile precursors during the exhaust gases cooling process. The accumulation mode particles are composed mainly of carbonaceous agglomerates formed directly by combustion and range from 0.1 to 0.3 … um. Accumulation mode particles represent most of the PM mass in diesel exhaust, whereas most of the particulate number is found within the of nuclei mode (Kittelson, 1998). However, the relative percentage of particulate numbers between the two modes are very dependent on fuel sulfur levels. PM is generally divided into three groups based on chemical and physical properties: the solid fraction composed of elemental carbon and ash; the SOF, which is made up of organic material derived from engine lubricating oil and fuel; and the sulfate particulates (SO_4) that originate from the sulfur present in the fuel and lube oil. The relative proportions of each group depend on the specific engine technology, aftertreatment system, and operating conditions.

As with NOx, the strategies used to control PM can be classified as in cylinder or as aftertreatment. In addition, reducing fuel and engine lubricant sulfur levels lowers PM sulfate emissions.

A2.1 IN-CYLINDER PM CONTROL

The air management system involves proper selection of turbocharger, including variable geometry and dual-stage turbos for tighter emission levels and improved design of intake ports, valve geometry, and piston bowls for improved air–fuel mixing. The fuel injection system design should be carefully matched to the air management system. Improvements in fuel injection involve modifying injection pressure, timing and duration, and nozzle geometry and opening pressure. The main goal is to carefully control the local concentration of fuel and air inside the combustion chamber and to avoid the conditions that lead to PM formation. Advanced engine calibration techniques and the implementation of electronic controls have improved the air–fuel mixtures and produced significant in-cylinder emission reductions in both PM and NOx.

A2.2 PM AFTERTREATMENT DEVICES

A2.21 DIESEL OXIDATION CATALYSTS

A DOC is a flow-through catalytic converter composed of a monolith honeycomb substrate (high contact surface area) coated with platinum group metal catalyst. These devices oxidize pollutants such as CO, HC, and the SOF of PM to carbon dioxide (CO_2) and water in the oxygen-rich diesel exhaust stream. A DOC is very effective at oxidizing the SOF and gaseous HC but does not reduce the number of exhaust soot particles. The SOF portion of PM can vary from 10% to 90%, depending on the engine and operating conditions, but values are typically on the order of 20% to 40% (Chatterjee et al., 2008; Kittelson, Arnold, & Watts, 1998). As a result, reductions in overall PM emissions (mass basis) from DOCs are typically cited at 20% to 50% [Chatterjee et al., 2008; DECSE, 2001; Northeast States for Coordinate Air Use Management (NESCAUM), 1999; Walker, 2004]. Although DOCs are effective at reducing the total PM mass, because they do not collect or burn the soot portion of the exhaust, they do not significantly reduce the particle number (Chatterjee et al., 2008).

A2.22 PARTIAL FLOW TECHNOLOGY

A PFT system or PFF is a PM reduction device consisting of a DOC and a flow-through filter element. The SOF portion of the exhaust is oxidized in the DOC as described in the previous section, and then some portion of the remaining soot is captured and combusted in the filter element.

In a PFT, the filter element can be made up of a variety of materials and configurations such as sintered metal, metal mesh or wire, or a ceramic foam structure. Whatever the material and design combination may be, the exhaust gases and PM follow a circuitous path through a relatively open network. The partial filtration occurs as particles collide with the rough surface of the mesh or wire network of the filter. Partial filters can be catalyzed or uncatalyzed and are less sensitive to sulfur than wall flow filters. If temperatures are sufficiently high, the soot trapped in the filter is continuously combusted by the NO_2 generated by the upstream DOC; thus, the filter is regenerated, allowing for additional soot collection.

However, if temperatures are too low to sustain regeneration, the filtration efficiency will continue to decrease, and the media will become loaded with soot up to its full capacity. In a soot-saturated condition, the filtration efficiency will eventually either drop to zero or oscillate between positive and negative values caused by particle accumulation and blow-off (uncontrolled release of soot) cycles.

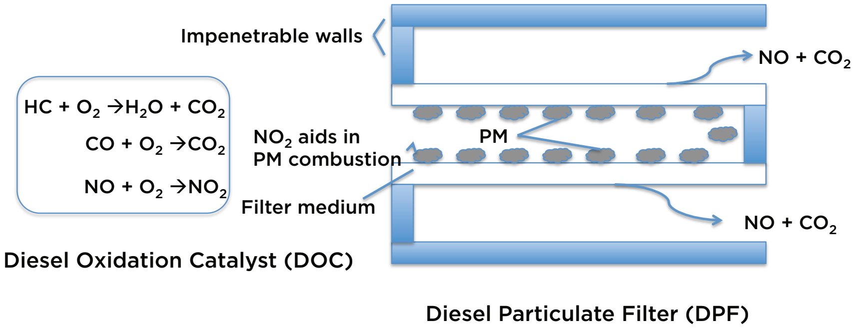
Although PFT systems are generally more effective than the DOC in lowering PM mass—reductions are typically cited as being >50% (Chatterjee et al., 2008; Jacobs et al., 2007)—the technology is relative new, and its performance and durability have yet to be fully characterized in published literature. Some concerns about PFT systems can be summarized as follows:

- Extended periods of idling or low temperature operation may cause a soot overload. A larger body of research is needed to better understand the conditions and durations necessary for a soot-laden PFT system to fully regenerate.
- Particle number reduction capability also needs to be better characterized. Manufacturers of the PM-Metalit (Emitec, Lohmar, Germany) product have reported particulate number reductions of 80% to 95% (Maus and Brück, 2007), which represents a reduction of approximately an order of magnitude.
- PFT systems may be prone to blowing off accumulated soot, especially in transient operations (Majewski, 2008; Mayer et al., 2009).
- Long-term durability of various types of PFT systems has yet to be demonstrated (Mayer et al., 2009).

A2.23 DIESEL PARTICULATE FILTERS

A DPF is a wall-flow PM control device. These filters usually consist of either cordierite (a clay-derived material) or sintered silicon carbide. Figure 1 illustrates how exhaust gases are redirected by impenetrable barriers and channeled through the porous walls as they escape to the filter exit. After the PM is trapped in the filter, the next stage is to combust these carbonaceous particles, because the filter would otherwise quickly become blocked. There are two basic methods for combusting the captured PM: passive and active regeneration.

In passive regeneration, trapped PM is combusted during the normal operation of the vehicle—neither the vehicle operator nor the engine management system needs to induce the regeneration process. To facilitate combustion under normal operating temperatures (200–400ºC for most heavy-duty vehicles), nitrogen dioxide (NO_2) can be introduced. Most NOx emissions from diesel vehicles are in the form of NO, so an oxidation catalyst is used to convert NO to NO_2. This oxidation can be done upstream of the filter in a DOC or a catalyst can be coated onto the DPF itself. The former DPF technology is called a continuously regenerating DPF, and the latter is called a catalyzed DPF.



Note. PM = particulate matter; CO = carbon monoxide; HC = hydrocarbon; SO2 = sulfur dioxide; NO = nitrogen oxide; CO2 = carbon dioxide; H2O = water.

Figure A1. Diesel particulate filter operating principle

Some vehicles that have urban, low-speed driving profiles do not have exhaust temperatures high enough for passive regeneration, and active regeneration is required. In active regeneration, sophisticated engine controls measure backpressure in the filter (which increases as PM levels increase). When pressure reaches a certain level, fuel injection is modified to increase the temperature of the exhaust gas. The added injection of fuel ensures sufficiently high temperatures in the DOC to combust the HC and CO. The resultant heat causes the DPF temperatures to rise, leading to a rapid combustion of PM.

Of the three particulate control technologies, the DPF is the most efficient, with mass basis PM reductions typically cited between 85% and 95% (DECSE, 2001; Kleeman et al., 2000; Walker, 2004). Moreover, in addition to effectively filtering and combusting PM mass, number reductions can be on the order of 99.5% or more compared with engine-out emissions (Maus & Brück, 2007; Vaaraslahti et al., 2006). The durability and long-term performance of DPF systems is well established for a wide variety of heavy-duty applications, including buses, municipal vehicles, long haulers, and construction equipment. Hundreds of thousands of DPFs have been installed on new vehicles as well as in retrofits.

In any DPF using a catalyst (either upstream in the form of a DOC or a DPF that has catalyzed filter media), sulfur—in its competition for space on the catalyst surface—has similar negative effects as those discussed with regard to DOCs. Particular to DPF functionality, operation with higher-sulfur fuels can cause the filter to be overloaded with soot, and uncontrolled soot burning can occur, which can damage the filter. In addition, in active regeneration, increased backpressure caused by higher sulfate levels can lead to the more frequent need for regeneration and the concomitant penalties of higher fuel consumption and shorter maintenance intervals (Chatterjee et al., 2008).

A3 Emission Control for Gasoline, Compressed Natural Gas, and Liquefied Petroleum Gas Vehicles

Spark ignition engines may be designed as either stoichiometric or lean burn, but the configuration of lean combustion engines is more complex in terms of air–fuel handling. The stoichiometric spark ignition engine requires a homogenous air–fuel mixture, which is achieved in the intake manifold by throttle-body injection or MPFI. Lean-burn engines usually require a stratified mixture, which is achieved through in-cylinder indirect fuel injection or direct injection of fuel. Indirect and direct fuel injection require special design of the cylinder heads and valves. Each lean-burn system requires specific air–fuel mixture control strategies to keep the mixture at the right values for proper spark ignition and emission control.

Stoichiometric engines generate higher engine-out emissions levels than lean–burn engines do but are better suited for further reductions in NOx emissions with aftertreatment devices. Aftertreatment for stoichiometric engines is based on the TWC. In a spark ignition engine, the air–fuel ratio fluctuates constantly between rich and lean conditions. During the lean periods, the TWC catalyst is able to oxidize HC and CO with the temporary excess O_2. During the rich periods, the TWC reduces the NOx with temporarily available HC. A TWC is capable of conversion efficiencies >95%, provided that the control system keeps the engine under stoichiometric conditions.

For a lean–burn engine, the high concentration of O_2 in the exhaust stream does not allow for NOx reduction using the TWC. However, this is not an issue for CNG vehicles because the engine-out NOx levels are typically below regulated levels. CO and HC can be oxidized using an oxidation catalyst, similar in principle to those used for diesel vehicles. Oxidation catalysts are also required to oxidize CH_4. Methane has been explicitly controlled in Europe since the Euro III regulations (2000). Euro IV regulations require approximately 60% CH_4 conversion in aftertreatment devices, which calls for the use of specially formulated oxidation catalyst (Hu & Williams, 2007).

A4 Heavy-Duty Compressed Natural Gas Technologies

A CNG engine can be designed as either a stoichiometric or a lean-burn engine. The first generation of heavy-duty CNG engines was lean burn, with higher fuel efficiency and lower heat rejection compared with stoichiometric engines. CNG engines provide power and torque comparable to diesel engines. The engine-out PM emission levels from a lean-burn CNG engine without any aftertreatment system is much lower than a conventional diesel engine without aftertreatment (Hesterberg et al., 2008).

A4.1 EURO III AND IV

A lean-burn CNG engine with a proper injection system and a universal exhaust gas oxygen sensor can achieve Euro III compliance. If the emission target requires further reduction in CO, HC, and PM levels, the addition of an oxidation catalyst can provide the coverage required to achieve Euro IV levels. Euro IV levels of compliance can be achieved only if proper fuel injection system, closed loop control, and overall engine tuning are included in the CNG engine development process, as well as an appropriate oxidation catalyst. Regarding nonregulated species, the addition of an oxidation catalyst also reduces approximately 90% of the formaldehyde (HCHO) produced by the CNG lean-burn engine.

A4.2 EURO V AND VI

CNG heavy-duty engine manufacturers are combining stoichiometric combustion with a TWC to meet Euro V and VI/U.S. 2010 emission levels. The primary challenge with stoichiometric combustion for heavy-duty applications is the high in-cylinder mixture temperatures during combustion, which leads to high production of NOx, and the excessive amount of heat that must be removed. In addition to higher thermal stress, lower brake efficiency is expected because of the low compression ratio required for suitable stoichiometric combustion. EGR, a technology borrowed from diesel engine emission control technologies, was used to curb the excessive high temperature and heat production in the stoichiometric CNG engine. The EGR in the stoichiometric engine dilutes the concentration of fuel in the cylinder, which reduces the rate of the combustion reaction and lowers its temperature while keeping the air-fuel ratio at the stoichiometric value. Because part of the cylinder volume is occupied by inert recirculated gas, there is a reduction in volumetric efficiency that can be corrected by adding a turbocharger. The turbocharger recovers the loss of power that results from dilution with EGR. In most cases, the EGR requires an intercooling circuit. Because the exhaust gases from the stoichiometric engine contain negligible oxygen, a TWC can be applied as aftertreatment, which allows for NOx reduction during rich periods of operation. The set of technologies required for compliance with each of the European emission standards is presented in Table A1.

Looking at the nondiesel market, most CNG engine manufacturers for heavy-duty applications are offering their engines certified at Euro III levels. The CNG or CNG/LPG engines operate in lean-burn combustion mode with electronically controlled air–fuel ratio. Turbocharging with intercooling is offered in all engines, and there is no mention of aftertreatment. Although all manufacturers offer the engines with multipoint electronic control, one manufacturer (FAW) offers Euro III certified engines with throttle body injection and Euro IV levels with MPFI. More details for each manufacturer can be found in Table A2.

Table A1. Summary of CNG Technologies Required for Euro Level Emissions Targets

EMISSION LEVEL NOx/PM (G/KWH)	CNG COMBUSTION	AIR/FUEL SYSTEM	AFTER-TREATMENT
Euro III 5.0/0.016	Lean burn	• Throttle body, but multipoint injection is preferred • Open loop/ lambda1 sensor	—
Euro IV 3.5/0.030	Lean burn	Closed loop/ universal oxygen sensor (wide range oxygen sensor)	Oxidation catalyst
Euro V 2.0/0.030	Mixed (lean burn and stoichiometric) or stoichiometric + EGR and turbocharging	Closed loop/ universal oxygen sensor (wide range oxygen sensor) + secondary lambda sensor for OBD requirements	TWC for CNG (includes some capability for CH4 oxidation)
Euro VI 0.4/0.010	Stoichiometric + cooled EGR and turbocharging. Improved design of combustion chamber and overall system (engine + TWC) tuning.	Closed loop/ universal oxygen sensor (wide range oxygen sensor) + secondary lambda sensor for OBD requirements	TWC for CNG (includes some capability for CH4 oxidation at temperatures below 350°C)

Note. CH4 = methane; CNG = compressed natural gas; EGR = exhaust gas recirculation; OBD = on-board diagnostics; TWC = three-way catalyst configuration.

Table A2. Technology Survey of Chinese Heavy-Duty CNG and LPG Engine Manufacturers

MANUFACTURER	EMISSION LEVELS	ENGINE CATEGORY	TECHNOLOGIES
Yuchai (2010)	Euro III	4-cylinder, 5.25 L, 132 kW, 650 Nm 6-cylinder, 6.4 L, 140–155 kW, 650–710 Nm 6 cylinder, 9.8 L, 214–250 kW, 1220-1350 Nm	• CNG/LPG (lean combustion) • Electronic air–fuel control (closed loop) • UEGO
Weichai (n.d.)	Euro III	6-cylinder, 6.2 L, 155 kW, 680 Nm 6-cylinder, 9.7 L, 206 kW, 1060 Nm	• CNG/LPG bus engine (lean combustion) • Electronic high-energy ignition, multipoint electronic air-fuel control • Turbocharger with intercooling
FAW (n.d.)	Euro III and Euro IV	6-cylinder, 7.7 L, 188–203 kW, 890–990 Nm	• CNG truck and bus engine (lean combustion) • Electronic air–fuel control with UEGO sensor (closed loop operation) • Turbocharger with intercooling • Throttle body fuel injection (Euro III) and multipoint fuel injection (Euro IV)
Dongfeng-Cummins (2011a)	Euro III, EPA U.S. 2004	6-cylinder, 112–172 kW, 508-678 Nm	• Natural gas • Advanced lean burn combustion closed loop electronic control

Note. CNG = compressed natural gas; FAW = Changchun FAW SiHuan Engine Manufacturer Co.; LPG = liquefied petroleum gas; UEGO = universal range oxygen sensor.

APPENDIX B: HEAVY-DUTY VEHICLE MARKET SURVEY

Six Chinese heavy-duty engine manufacturers were surveyed for information on current engines and those that will comply with upcoming regulations (China IV, V). This list by no means includes every company producing heavy-duty engines in China. Many regional engine and vehicle manufacturers throughout China most likely have not yet incorporated modern features such as electronic engine controls that will be necessary for compliance with China IV levels. At the time of this writing, detailed information about the Chinese heavy-duty engine/vehicle market was not available for the authors to assess the market share of individual manufacturers and the technology options currently being offered.

As summarized in Table B1, China III compliant engines produced by three manufacturers (HAEP, Saic-IvecoHongyan, and Dongfeng-Cummins) offer four valves per cylinder, electronically controlled common rail fuel injection, and turbochargers with intercooling. These kind of advanced technologies are being used in engines with displacement volume <9.7 L.

Some manufacturers (SIH, FAW-WUXI Diesel Engine Works) are offering China IV engines based on advanced China III engine technologies designed to upgrade to China IV and V levels without modifying engine hardware. It is clear that manufacturers using electronically controlled high-pressure injectors—whether it is a unit injector or common rail—can take advantage of this fundamental in-cylinder emission control technology and add EGR systems or aftertreatment system for compliance with future regulations. As an example, one Chinese engine manufacturer is already offering aftertreatment systems for China IV engines. The 8.4-L diesel engine produced by Yuchai has a SCR system in addition to advanced electronically controlled high-pressure fuel injection used in its China III models.

For manufacturers who are already using electronic fuel injection system to meet the China III standard, the cost for upgrading to meet China IV is mainly the cost of the SCR system. The cost of a SCR system used to be approximately 20,000 to 30,000 yuan (U.S. $2,800 to U.S. $4,300), but now some systems are offered at <10,000 yuan (U.S. $1,400) per set as some domestic manufacturers are now entering into the market. This cost of 10,000 yuan represents roughly a 10% to 25% increase over a baseline electronically controlled China III engine, which range from 40,000 yuan (U.S. $5,600) for a 150-kW engine to 70,000 to 80,000 yuan (U.S. $9,800 to U.S. $11,200) for a 250-kW engine.

For manufacturers who have been using mechanically controlled fuel injection, the costs to go from China III to China IV is the sum of the SCR system and the electronic fuel injection system. A common rail fuel injection system costs from 10,000 to 15,000 yuan (U.S. $1,400 to U.S. $2,100), and a set of electronic unit pumps costs approximately 12,000 yuan (U.S. $1,700). Therefore, for these manufacturers, if the cost of an SCR system is approximately 10,000 yuan, the total per engine cost for developing a China IV compliant engine ranges from approximately 30,000 to 40,000 yuan (U.S. $2,800). This represents a substantial cost increase over a mechanically controlled China III engine, which costs between 5,000 and 10,000 yuan.

Table B1. Technology Survey of Chinese Heavy-Duty Diesel Engine Manufacturers

MANUFACTURER	EMISSION LEVELS	ENGINE SPECIFICATIONS	TECHNOLOGIES
Hangzhou Engine Co., Ltd, China National Heavy-Duty Truck Group. (n.d.)	Euro III	6 cylinder, 9.7 L, 198 kW (270 hp), 1150 Nm peak torque	• Four valves per cylinder • Electronically controlled common rail fuel injection 1,600 bar • Multiple fuel injection: pilot, post and late injection • Turbocharger with intercooling • Euro IV achievable with aftertreatment (not specified)
Yuchai Machinery Co., Ltd. (2010)	Euro IV	6 cylinder, 8.4 L, 177–243 kW, 950–1280 Nm peak torque	• Four valves per cylinder • EUP or common rail • SCR
		6 cylinder, 6.5 L, –132–180 kW, 650–890 Nm peak torque	• Four valves per cylinder • Electrically controlled common rail fuel injection • SCR
FAW (n.d.)	Euro IV (potentially)	6-cylinder, 7.7 L, 235 kW, 1300 Nm	• Four valves per cylinder • Electronically controlled common rail fuel injection-1,600 bar • Multiple fuel injection • NOx control not specified
Hino Motors, Ltd. (2011)	Euro IV	6-cylinder, 7.6 L, 173–192 kW, 706–746 Nm peak torque	• Electronic common rail fuel injection • Turbocharging and intercooling • Variable nozzle turbocharger and cooled EGR • DOC
IVECO (2010)	Euro III	6-cylinder, 8.7 L, 270–400 hp, 1300-1600 Nm.	• Four valves per cylinder • Common rail fuel injection system • Variable geometry turbocharger • Designed to be upgraded to Euro IV–V with no engine modifications
Dongfeng-Cummins (2011b)	Euro III	6-cylinder, 8.9 L, 213–275 hp, 1050-1550 Nm 6-cylinder, 5.9 L, 110–162 kW, 550-820 Nm	• Four valves per cylinder • Electronically controlled high-pressure common rail fuel injection • Turbocharging and intercooling • Wastegate for low speed operation • No aftertreatment required
		6-cylinder, 103-210 kW, 450-970 Nm	• Electronically controlled high-pressure common rail fuel injection

Note. EGR = exhaust gas recirculation; EUP = unit pump systems; FAW = Changchun FAW SiHuan Engine Manufacturer Co.; NOx = nitrogen oxides; SCR = selective catalytic reduction.

APPENDIX C: EMISSION STANDARDS IN THE UNITED STATES, EUROPEAN UNION, CHINA, AND JAPAN

Table C1. United States: Light-Duty Vehicle Emission Standards (FTP-75 chassis dynamometer test*)

STANDARD	MODEL YEAR	VEHICLES	EMISSION LIMITS AT FULL USEFUL LIFE (100–120,000MI) MAXIMUM ALLOWED GRAMS PER MILE (G/MI)				
			NOx	NMOG	CO	PM	HCHO
TIER 2 PROGRAM							
Bin 1	2004+	LDV, LLDT, HLDT, MDPV	0.00	0.00	0.0	0.00	0.000
Bin 2	2004+	LDV, LLDT, HLDT, MDPV	0.02	0.01	2.1	0.01	0.004
Bin 3	2004+	LDV, LLDT, HLDT, MDPV	0.03	0.055	2.1	0.01	0.011
Bin 4	2004+	LDV, LLDT, HLDT, MDPV	0.04	0.070	2.1	0.01	0.011
Bin 5	2004+	LDV, LLDT, HLDT, MDPV	0.07	0.090	4.2	0.01	0.018
Bin 6	2004+	LDV, LLDT, HLDT, MDPV	0.10	0.090	4.2	0.01	0.018
Bin 7	2004+	LDV, LLDT, HLDT, MDPV	0.15	0.090	4.2	0.02	0.018
Bin 8a	2004+	LDV, LLDT, HLDT, MDPV	0.20	0.125	4.2	0.02	0.018
Bin 8b	2004–2008	HLDT, MDPV	0.20	0.156	4.2	0.02	0.018
Bin 9a	2004–2006	LDV, LLDT	0.30	0.090	4.2	0.06	0.018
Bin 9b	2004–2006	LDT2	0.30	0.130	4.2	0.06	0.018
Bin 9c	2004–2008	HLDT, MDPV	0.30	0.180	4.2	0.06	0.018
Bin 10a	2004–2006	LDV, LLDT	0.60	0.156	4.2	0.08	0.018
Bin 10b	2004–2008	HLDT, MDPV	0.60	0.230	6.4	0.08	0.027
Bin 10c	2004–2008	LDT4, MDPV	0.60	0.280	6.4	0.08	0.027
Bin 11	2004–2008	MDPV	0.90	0.280	7.3	0.12	0.032

Table C1. United States: Light-Duty Vehicle Emission Standards (Cont.)

STANDARD	MODEL YEAR	VEHICLES	EMISSION LIMITS AT FULL USEFUL LIFE (100-120,000MI) MAXIMUM ALLOWED GRAMS PER MILE (G/MI)				
			NOx	NMOG	CO	PM	HCHO
TIER 1 PROGRAM							
LDV	1994–2003	LDV	0.60	0.31	4.2	0.10	—
LDT1	1994–2003	LDT1	0.60	0.31	4.2	0.10	0.800
LDV diesel	1994–2003	LDV diesel	1.25	0.31	4.2	0.10	—
LDT1 diesel	1994–2003	LDT1 diesel	1.25	0.31	4.2	0.10	0.800
LDT2	1994–2003	LDT2	0.97	0.40	5.5	0.10	0.800
LDT3	1994–2003	LDT3	0.98	0.46	6.4	0.10	0.800
LDT4	1994–2003	LDT4	1.53	0.56	7.3	0.12	0.800

*Effective for Model Year 2000, vehicles had to be additionally tested on the U.S.06 cycle (aggressive, high speed driving) and the SC03 cycle (use of air conditioning).

Note. CO = carbon monoxide; HCHO = formaldehyde; HLDT = heavy light-duty truck, between 6,001 and 8,500 lbs gross vehicle weight rating (includes LDT3 and LDT4); LDV = light-duty vehicle; LLDT = light light-duty truck, up to 6,000 lbs GVWR (includes LDT1 and LDT2); MDPV = medium-duty passenger vehicle, truck between 8,500 and 10,000 lbs gross vehicle weight rating; NMOG = nonmethane organic gas; NOx = nitrogen oxides; PM = particulate matter.

Table C2. United States: Heavy-Duty Diesel Truck Engine Emission Standards (FTP Transient and SET test cycles)

	GRAMS PER BRAKE HORSEPOWER-HOUR (G/BHP-H)			
	HC	CO	NOx	PM
1988	1.3	15.5	10.7	0.60
1990	1.3	15.5	6.0	0.60
1991	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.10
1998	1.3	15.5	4.0	0.10
2004	0.5	—	2.0	0.10
2010	0.14	—	0.2	0.01

Useful Life Requirements
Light heavy-duty diesel engines (8,500–19,500 lb GVWR): 8 years/110,000 mi (whichever occurs first)
Medium heavy-duty diesel engines (19,500–33,000 lb GVWR): 8 years/185,000 mi
Heavy heavy-duty diesel engines (> 33,000 lb GVWR): 8 years/290,000 mi

Note. CO = carbon monoxide; GVWR = gross vehicle weight rating; HC = hydrocarbon; NOx = nitrogen oxides; PM = particulate matter.

Table C3. European Union: Emission Standards for Passenger Cars*
(ECE15 + E.U.DC chassis dynamometer test)

GRAMS PER KILOMETER (G/KM)						
DIESELS	**DATE**	**CO**	**HC**	**HC+NOX**	**NOX**	**PM**
Euro 1[f]	July 1992	2.72 (3.16)	—	0.97 (1.13)	—	0.140 (0.180)
Euro 2, IDI	January 1996	1.00	—	0.70	—	0.080
Euro 2, DI	January 1996a	1.00	—	0.90	—	0.100
Euro 3	January 2000	0.64	—	0.56	0.50	0.050
Euro 4	January 2005	0.50	—	0.30	0.25	0.025
Euro 5	September 2009[b]	0.50	—	0.23	0.18	0.005[e]
Euro 6	September 2014	0.50	—	0.17	0.08	0.005[e]
GASOLINE						
Euro 1[f]	July 1992	2.72 (3.16)	—	0.97 (1.13)	—	—
Euro 2	January 1996	2.20	—	0.50	—	—
Euro 3	January 2000	2.30	0.2	—	0.15	—
Euro 4	January 2005	1.00	0.1	—	0.08	—
Euro 5	September 2009[b]	1.00	0.1[c]	—	0.06	0.005[d,e]
Euro 6	September 2014	1.00	0.1[c]	—	0.06	0.005[d,e]

*Category M1 vehicles. For Euro 1 through 4, vehicles greater than 2,500 kg were type approved as Category N1 vehicles
[a] After September 30, 1999, vehicles with direct injection engines had to meet the indirect injection limits
[b] January 2011 for all models
[c] Nonmethane hydrocarbon limit = 0.068 g/km
[d] Applicable only to vehicles with direct injection engines
[e] 0.0045 g/km using the Particle Measurement Programme measurement procedure
[f] Euro 1 values in brackets are conformity of production limits

Useful Life Requirements

- Euro 3: 80,000 km or 5 years (whichever occurs first); in lieu of an actual deterioration run, manufacturers may use the following deterioration factors:
    - Spark ignition (gasoline): 1.2 for CO, HC, and NOx
    - Compression ignition (diesel): 1.1 for CO, NOx, HC+NOx, and 1.2 for PM
- Euro 4: 100,000 km or 5 years (whichever occurs first)
- Euro 5/6: in-service conformity of 100,000 km or 5 years; durability testing of pollution control devices for type approval is 160,000 km or 5 years (whichever occurs first); in lieu of a durability test, manufacturers may use the following deterioration factors (Euro 6 deterioration factors to be determined):
    - Spark ignition: 1.5 for CO, 1.3 for HC, 1.6 for NOx, and 1.0 for PM
    - Compression ignition: 1.5 for CO, 1.1 for NOx and HC+NOx, and 1.0 for PM

Note. CO = carbon monoxide; HC = hydrocarbon; NOx = nitrogen oxides; PM = particulate matter.

Table C4a. European Union: Emission Standards for Heavy-duty Diesel Engines

	DATE	TEST CYCLE	GRAMS PER KILOWATT-HOUR (G/KWH)			
			CO	HC	NOx	PM
Euro I	1992, < 85 kW	ECE R-49	4.5	1.1	8.0	0.612
	1992, > 85 kW		4.5	1.1	8.0	0.36
Euro II	October 1996		4.0	1.1	7.0	0.25
	October 1998		4.0	1.1	7.0	0.15
Euro III	October 1999, EEVs* only	ESC & ELR	1.5	0.25	2.0	0.02
	October 2000		2.1	0.66	5.0	0.10 0.13[a]
Euro IV	October 2005		1.5	0.46	3.5	0.02
Euro V	October 2008		1.5	0.46	2.0	0.02
Euro VI	January 2013		1.5	0.13	0.4	0.01

[a] For engines with swept volume per cylinder <0.75 dm3 and rated power speed greater than 3,000 min-1

Note. CO = carbon monoxide; ECE = urban driving cycle; EEV = enhanced environmentally friendly vehicle; ELR = engine test for smoke opacity measurement exhaust gas recirculation; ESC = European Stationary Cycle; HC = hydrocarbon; NOx = nitrogen oxides; PM = particulate matter.

Table C4b. European Union: Emission Standards for Heavy-duty Diesel Engines

	DATE	TEST CYCLE	GRAMS PER KILOWATT-HOUR (G/KWH)				
			CO	NMHC	CH_4[a]	NOx	PM[b]
Euro III	October 1999, EEVs only	ETC	3.0	0.40	0.65	2.0	0.02
	October 2000		5.45	0.78	1.6	5.0	0.16, 0.21[c]
Euro IV	October 2005		4.0	0.55	1.1	3.5	0.03
Euro V	October 2008		4.0	0.55	1.1	2.0	0.03
Euro VI	January 2013		4.0	0.16[d]	0.5	0.4	0.01

[a] For spark ignition engines only; Euro III through V: natural gas only; Euro VI: natural gas and liquid petroleum gas
[b] Not applicable for Euro III and IV gasoline engines
[c] For engines with swept volume per cylinder <0.75 dm3 and rated power speed >3,000 min-1
[d] Total hydrocarbon for diesel engines

Note. CH4 = methane; CO = carbon monoxide; EEVs = enhanced environmentally friendly vehicles; ETC = European Transient Cycle; HC = hydrocarbon; NMHC = nonmethane hydrocarbons; NOx = nitrogen oxides; PM = particulate matter.

Table C4c. Useful Life Requirements

Effective October 2005 for new type approvals and October 2006 for all type approvals, manufacturers must adhere to emission limits over the following useful life periods:

VEHICLE CATEGORY	PERIOD (WHICHEVER EVENT OCCURS FIRST)	
	EURO IV, V	EURO VI
N1 and M2	100,000 km/5 years	160,000 km/5 years
N2	200,000 km/6 years	300,000 km/6 years
N3 < 16 tonnes		
M3 Class I, Class A, and Class B < 7.5 tonnes		
N3 > 16 tonnes	500,000 km/7 years	700,000 km/7 years
M3 Class III, and Class B > 7.5 tonnes		

Table C5. China: Emission Standards for New[†] Light-duty Vehicle Type Approval (ECE_{15} + E.U.DC chassis dynamometer test[*])

DIESELS	CHINA	BEIJING	SHANGHAI	GUANGZHOU	PRODUCTION CONFORMITY	IN-USE SURVEILLANCE	DURABILITY	ON-BOARD DIAGNOSTICS REQUIREMENT
China I	January 2000 (T1) January 2001 (T2)[a]	1999			Sample of one	No	80,000 km	No
China II	July 2004 (T1) July 2005 (T2)	2002	March 2003	July 2005	Sample of one	No	80,000 km	No
China III[b]	July 2007	January 2007	December 31, 2007	September 2006	Sample of three	Yes	5 years or 80,000 km	July 2008 (<6 seats, GVWR <2.5 tonnes); July 2010 for other vehicles
China IV	July 2010				Sample of three	Yes	5 years or 80,000 km	July 2010
GASOLINE								
China I	January 2000 (T1) January 2001 (T2)[a]	1999			Sample of one	No	80,000 km	No
China II	July 2004 (T1) July 2005 (T2)	2002			Sample of one	No	80,000 km	No
China III[b]	July 2007	December 31, 2005			Sample of three	Yes	5 years or 80,000 km	July 2008 (<6 seats, GVWR <2.5 tonnes [AQ: Acceptable as edited?]); July 2010 for other vehicles
China IV	July 2010	March 2008	November 2009		Sample of three	Yes	5 years or 80,000 km	July 2010

[†] Standards for existing models typically implemented one year later than standards for new models

[*] Speed points are mostly the same as in ECE15 and extra urban driving cycles, except for some transient speed points

[a] Type 1 M1 light-duty vehicles carry no more than 6 seats and weigh no more than 25 tonnes; T2-other non-type 1 light-duty vehicles

[b] The China 3/III standard was supposed to be effective in 2007 for all new vehicle type approval, but a transition period of one year was allowed, so all approved vehicles could still be sold until 2008 (January for heavy-duty vehicles and July for light-duty vehicles)

Table C6. China: Emission Standards for New[†] Heavy-duty Vehicle Type Approval*

DIESELS	CHINA	BEIJING	SHANGHAI	GUANGZHOU	PRODUCTION CONFORMITY	IN-USE SURVEILLANCE	DURABILITY	ON-BOARD DIAGNOSTICS REQUIREMENT
China I	September 2000	1999	1999		Sample of one	No	—	No
China II	September 2003	2002	March 2003	July 2005	Sample of one	No	5 years or 80,000 kme; 5 years or 100,000 kmf; 6 years or 250,000 kmg	No
China III[b]	January 2007	December 31, 2005	December 31, 2007	September 2006	Sample of three	No	Same as Euro II	No
China IV	January 2010	July 2008[a,c]	November 2009[c]		Sample of three	Yes	Same as Euro II	Yes
GASOLINE								
China I	July 2002	1999			Sample of one	No	5 years or 80,000 km	No
China II	September 2003				Sample of one	No	5 years or 80,000 kmd	No
China III[b]	July 2009	December 31, 2005			Sample of three	No	5 years or 80,000 kmd	July 2009
China IV	July 2012	July 2008[a]			Sample of three	Yes	5 years or 80,000 km	July 2012

[†] Standards for existing models typically implemented one year later than standards for new models.

[*] China follows the same test cycle schedule as the European Union but uses the Japan05 test for durability in Euro III and later models.

[a] Requires on-board diagnostics for NOx

[b] The China 3/III standard was supposed to be effective in 2007 for all new vehicle type approval, but a transition period of one year was allowed, so all approved vehicles could still be sold until 2008 (January for heavy-duty vehicles and July for light-duty vehicles)

[c] In Beijing, China IV covers diesel public buses and diesel trucks used for postal and public sanitary (garbage collection) services; in Shanghai, it covers those categories regulated under China IV in Beijing plus construction trucks

[d] Took effect on October 1, 2007

[e] Durability requirement for M1 vehicles with gross vehicle weight greater than 3.5 tons and M2 vehicles

[f] Durability requirement for M3 vehicles less than 7.5 tons; N2 and N3 vehicles less than 16 tons

[g] Durability requirement for M3 vehicles over 7.5 tons and N3 vehicles over 16 tons

Table C 7. Japan: Emission Standards for Gasoline and LPG fuelled Vehicles

	NEW MODEL	ALL MODELS/ IMPORTS	TEST CYCLE	UNIT	CO	HC[a]	NOx	PM
PC	October 2000	September 2002	10–15 mode	g/km	0.67/1.27	0.08/0.17	0.08/0.17	—
			11 mode	g/test	19.0/31.1	2.20/4.42	1.40/2.50	—
Mini CV	October 2002	September 2003	10–15 mode	g/km	3.30/5.11	0.13/0.25	0.13/0.25	—
			11 mode	g/test	38.0/58.9	3.50/6.40	2.20/3.63	—
Light CV	October 2000	September 2002	10–15 mode	g/km	0.67/1.27	0.08/0.17	0.08/0.17	—
			11 mode	g/test	19.0/31.1	2.20/4.42	1.40/2.50	—
Medium CV	October 2001	September 2003	10–15 mode	g/km	2.10/3.36	0.08/0.17	0.13/0.25	—
			11 mode	g/test	24.0/38.5	2.20/4.42	1.60/2.78	—
NEW LONG TERM (MEAN/MAX)								
PC	October 2005	September 2007	10–15 mode + 11 mode	g/km	1.15/1.92	0.05/0.08	0.05/0.08	—
Mini CV	October 2007	September 2008/ September 2007			4.02/6.67	0.05/0.08	0.05/0.08	—
Light CV	October 2005	September 2007			1.15/1.92	0.05/0.08	0.05/0.08	—
Medium LCV					2.55/4.08	0.05/0.08	0.07/0.10	-

Table C7. Japan: Emission Standards for Gasoline and LPG fuelled Vehicles (Cont.)

	NEW MODEL	ALL MODELS/ IMPORTS	TEST CYCLE	UNIT	CO	HC[a]	NOx	PM
POST NEW LONG TERM[c]								
PC	October 2009	October 2009/ September 2010	JC08H + JC08C	g/km	1.15/1.92	0.05/0.08	0.05/0.08	0.005/0.007
Light LCV					1.15/1.92	0.05/0.08	0.05/0.08	0.005/0.007
Medium LCV					2.55/4.08	0.05/0.08	0.07/0.10	0.007/0.009

[a] From 2005, HC is measured as NMHC
[b] Mean = to be met as a type approval limit and as a production average; max = to be met as type approval limit if sales are less than 2,000 per vehicle model per year and generally as an individual limit in series production
[c] New PM measurement method; technically modified methods for CO and other gases

Useful Life Requirements
- PC, trucks, and buses with GVWR less than 3.5 tonnes: 80,000 km
- PC, trucks, and buses with GVWR greater than 3.5 tonnes: 250,000 km

OBD – Diesel, Gasoline, and LPG
- J-OBDII: enhanced on-board diagnostics requirement for passenger cars and commercial vehicles with GVWR less than 3.5 tonnes from October 2008
- E.U./U.S. on-board diagnostics standards accepted as equivalent

Note. CO = carbon monoxide; CV = commercial vehicle; GVWR = gross vehicle weight rating; HC = hydrocarbon; NMHC = nonmethane hydrocarbon; NOx = nitrogen oxides; PC = passenger car; PM = particulate matter.

Table C8. Japan Emission Standards for Diesel Vehicles

	NEW MODEL	ALL MODELS/ IMPORTS	TEST CYCLE	UNIT	CO	HC[a]	NOx	PM
NEW SHORT TERM (MEAN/MAX[b])								
PC < 1,265 kg	October 2002	September 2004	10–15 mode	g/km	0.63/0.98	0.12/0.24	0.28/0.43	0.052/0.11
PC > 1,265 kg					0.63/0.98	0.12/0.24	0.30/0.45	0.056/0.11
Light CV					0.63/0.98	0.12/0.24	0.28/0.43	0.052/0.11
Medium CV	October 2003				0.63/0.98	0.12/0.24	0.49/0.68	0.06/0.12
NEW LONG TERM (MEAN/MAX)								
PC < 1,265 kg	October 2005	September 2007	10–15 mode + 11 mode	g/km	0.63/0.84	0.024/0.032	0.14/0.19	0.013/0.017
PC > 1,265 kg					0.63/0.84	0.024/0.032	0.15/0.20	0.014/0.019
LCV					0.63/0.84	0.024/0.032	0.14/0.19	0.013/0.017
Medium CV					0.63/0.84	0.024/0.032	0.25/0.33	0.015/0.020
POST NEW LONG TERM[c]								
PC	October 2009	October 2009/ September 2010	JC08H + JC08C	g/km	0.63/0.84	0.024/0.032	0.08/0.11[e]	0.005/0.007
Light LCV					0.63/0.84	0.024/0.032	0.08/0.11	0.005/0.007
Medium LCV	October 2010[d]				0.63/0.84	0.024/0.032	0.15/0.20	0.007/0.009

[a] From 2005, HC is measured as NMHC

[b] Mean: to be met as a type approval limit and as a production average; max: to be met as type approval limit if sales are less than 2,000 per vehicle model per year and generally as an individual limit in series production

[c] New PM measurement method; technically modified methods for CO and other gases

[d] October 2010 for Medium CV with 1,700 kg < GVWR < 3,500 kg; October 2009 for medium commercial vehicles with 2,500 kg < GVWR < 3,500 kg

[e] For vehicles not exceeding 1,265 kg; for vehicles greater than 1,265 kg, the values are 0.15/0.20

Note. CO = carbon monoxide; GVWR = gross vehicle weight rating; HC = hydrocarbon; LCV = light commercial vehicle; GVWR less than 3,500 kg (2,500 kg before 2005); NMHC = nonmethane hydrocarbon; NOx = nitrogen oxides; PM = particulate matter.

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