

Aftertreatment Pathways to Meet China HDD Emissions Regulations

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ABSTRACT

Nowadays the Chinese legislative development and the implementation of advanced technologies to curb HDD emissions have been a subject of worldwide attention. Currently China is warping its efforts to deploy and enforce the launch of nationwide Stage IV and is also preparing for the setup and implementation of future regulation standards.

Focus discussion here is on the aftertreatment pathways to meet China current and future emissions standards, based on market uniqueness. This paper seeks to provide retrospectives of the adoption of V-SCR on China stage IV HDD vehicles, through presenting findings from two separate postmortem analyses of field returned catalyst parts and also through comparative study with local catalyst products. The paper also discusses the challenges and possible solutions meeting the WHTC requirement for Stage IV and V city vehicles. Subsequently, the authors will share perspective viewpoints on aftertreatment pathways, especially on technology recommendations, to meet Stage VI HDD emission regulations in China. Based on various aspects such as China Stage IV V-SCR usage experience and Stage VI requirement on low temperature activity, high temperature stability and system robustness, etc., it is concluded that small ring zeolite based Cu-SCR is the most suitable system solution to help meet China Stage VI regulations.

CITATION: Tang, W., Chen, B., Hallstrom, K., and Wille, A., "Aftertreatment Pathways to Meet China HDD Emissions Regulations," *SAE Int. J. Engines* 9(2):2016, doi:10.4271/2016-01-0687.

INTRODUCTION

As the economic power engine in the world, China has a severe concern over its air quality. Many believe the situation will become worse before it gets better. A substantial portion of air pollutants is contributed from the transportation sector, particularly the heavy duty diesel (HDD) engine powered vehicles.

Amid tremendous public pressure, the Chinese government is tightening the tailpipe emissions requirement. In a previous SAE article [1], Zhan et al. provided a comprehensive update on China HDD on-road diesel emission regulation as well as the development of fuel and lubricant standards. The annual SAE review papers by Tim Johnson of Corning [2-3] also provides timely and regular update of China HDD market. As an NGO, ICCT has many reports on its website about China's regulation implementation for HDDV [4-5].

Compared to legislative updates, technical papers are few and often less systematic with regards to technology routes undertaken for the China HDD market. This paper seeks to provide some retrospective and prospective viewpoints about the aftertreatment pathways to meet China current and future emissions standards.

After a brief update on China legislative development for on- and off-road HDD vehicles/machines, the paper reviews technology pathways that have been employed to meet China Stage IV and V emissions. While clearly it is a quite broad area with many topics worth to mention, the authors select in each stage one or two topics for discussion. For Stage IV, the authors describe Vanadium SCR usage experience, by presenting findings from two separate analyses of field returned catalyst parts. The common in-use failure models identified in this work should be taken into consideration when developing systems for future regulation standards. Regarding Stage V, this paper discusses the challenges and possible solutions to meet WHTC requirement for city vehicles. Finally, for Stage VI, particular attention is given to the selection of a suitable aftertreatment pathway in China, considering its technical need and market uniqueness.

The focus of this paper is to discuss technical pathways of aftertreatment systems that enable engines to meet tail pipe emissions requirements of different regulation stages in China. Needless to say that selecting, designing, and adopting an appropriate aftertreatment device alone is far towards the end. Attention must be also given on vehicle emissions reduction in real world applications and the

strategy to deal with failures to meet emissions requirement. Therefore one needs to study emission controls for non-certification cycles, *aka* RDE in use compliance. In this regard, PEMS maybe an inevitable device to use. OBD must be triggered if emissions fail to meet standard requirements. Last, but not the least, there is product consistency (conformity) of new vehicles, including monitoring and enforcement needed. Those are all important topics and each is worth a thorough discussion. However this is out of the scope of this paper.

The authors of this paper have experience in developing systems with European, US, and Chinese HDD OEMs. They intend, through this article, to provide readers some technical perspectives about the China HDD market.

LEGISLATIVE DEVELOPMENT

Figure 1 illustrates the national standards of emissions road map for China HDD and the NO_x and PM reduction requirements at different stages. HDD emission legislations progress slowly but steady. On-highway emission timeline: China MIIT announced in July 2014 to stop sales of NS III (National Stage III) vehicles effective January 2015. Beijing, Shanghai, and a couple of developed provinces are taking early adoption of Stage V. In the big picture, China is warping its efforts to deploy and enforce the launch of nation-wide Stage IV and also is preparing for Stage VI regulations for HDD vehicles.

However, the adoption is not close to smooth in many ways. For example, the nation-wide implementation of Stage IV took several rounds of postponements, and was several years behind the original intent, to reach a national-wide implementation in Jan 2015.

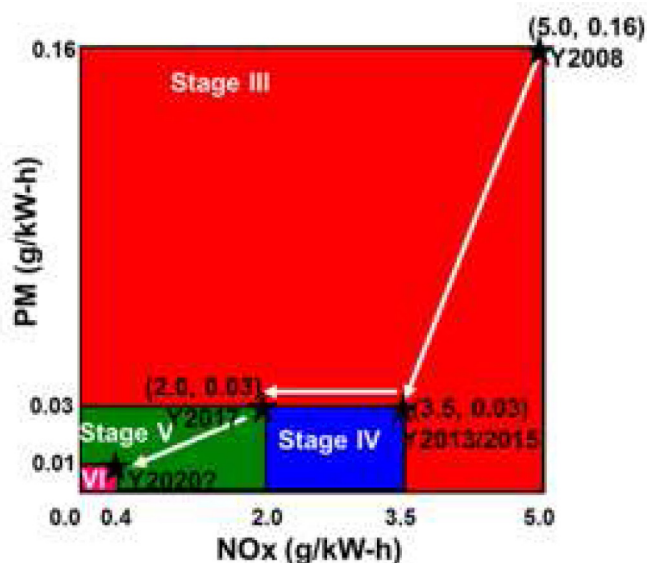


Figure 1. China national emissions standards (ETC or WHTC based certifications) for heavy duty engines used on GVW > 3500kg vehicles.

Recognizing the emission difference between real world drive condition and certification cycle (ETC), lower temperature WHTC certification is added for diesel engines on urban driving HDDVs, including city bus, garbage truck and mail delivery vans, applicable for both Stage IV and V [6]. The HJ 689-2014 was published

2014-01-16, and policy implemented was on 2015-01-01. Technical challenges and solutions to meet WHTC shall be discussed in detail later in this article.

The Chinese government also recognized the importance of vehicle emissions from the non-road segment. In 2014, a GB20891 standard was released [7]. It mandates that starting Oct 01, 2015 all new non-road diesel engines have to meet Stage III requirements (equivalent to Euro Stage III A) and Stage II off-road diesel machines are no longer allowed for sale on April 01, 2016. In terms of technical pathways, in most cases Stage III requirements can be met by base engine measures without aftertreatment. China Stage IV (equivalent to Euro Stage III B) shall require installation of catalysts in exhaust; however, as the paper is written, effective date is not publicly known.

Emissions from marine and inland river boats are also in the radar range. VECC, the research arm of China MEP, is studying contributions from this segment. According to the 2014 MoVE Conference presentation by Dr. Ding Yan of VECC [8], there is a National Action Plan of Clean Diesel Engines, now including the diesel powered river boats and domestic vessels. A legislation for those engines might be considered by the government, however, no details are known so far.

When it comes to diesel fuel quality, there has been steady process in reducing sulfur content. In major China urban areas such as Shanghai and Beijing, only ultra-low sulfur diesel is supplied in gas stations. Starting Jan 01, 2016, Stage V (10 ppm sulfur) diesel fuel for on-road diesel vehicles will be supplied to all east China regions and becomes available nation-wide on Jan 01, 2017. One caveat is that the general usage of Stage IV diesel fuel (incl. those consumed by off-road segment) will not become a nation-wide requirement until one year later, Jan 01, 2018.

EMISSIONS AFTERTREATMENT PATHWAYS

A high-level summary of technical pathways is shown in Table 1, with short comments as follows.

Table 1. General landscape of aftertreatment pathways to meet China HDD emissions standards

Regulation	Disp.	Aftertreatment Pathway
Stage IV	<5L	DOC only
	<5L	DOC+POC
Stage V	>5L	V-SCR/(+AMOX - optional)
	<5L	(DOC+)V-SCR/(+AMOX - optional)
Beijing V	>5L	DOC+CSF+Cu-SCR
	>5L	V-SCR+DOC+CSF
Stage V	all	DOC+CSF+Cu-SCR+AMOX

The V_2O_5 - W_2O_3 - TiO_2 based SCR (V-SCR) has been a proven robust catalytic solution in developed regions, namely EU IV and V regulations. In China, the use of urea SCR on HDD vehicles to reduce NO_x emission started with the 2008 Beijing Olympics when a few hundred of EU IV type engines equipped with V-SCR catalysts were put onto Beijing city buses. Even since, the V-SCR has become the predominant technology pathway for HDD vehicles to meet Stage IV and V regulations in China.

For Stage IV and Stage V aftertreatment systems, a urea solution based V-SCR solution is the dominate pathway. To illustrate this point, out of all registered Stage IV HDD engine certifications in year 2013, 84% of them are SCR. The DOC+POC pathway accounted for 13%, mostly on <5L engine platforms, as listed in [Table 1](#).

As Chinese OEMs gained more experience and become confident with SCR system, overall aftertreatment system cost and package size have been gradually shrinking. For Stage IV HDD vehicles, the SCR catalyst volume to engine displacement ratio is reduced from the typical 2.0-2.5 during early product development to the current level of 1.5-2.0 product intent.

Then there is an interesting scenario of Beijing EPB requirement of DPF for all new Stage V HDD vehicles sold in Beijing market [9], to which OEMs are working towards different system layouts. There are several important factors such as overall cost, development time, and minimal change to current Stage IV or V layout. In stage VI, it is widely anticipated the combination of both DPF and SCR in HDDVs shall become a standard and a must-have.

[Figure 2](#) shows a few critical technical drivers of the China HDD market. Fundamental driving forces for technology advancement in China are not so much different from the ones in Europe and US market. However it should be pointed out that Chinese OEMs are much more sensitive to price. Consequently, tailored technical solutions are highly sought in this emerging market. There should be an extremely delicate balance between product performance/quality and the costs associated with it. In addition, suppliers must be flexible enough to work with OEMs and meet usually quite short product development cycle.



Figure 2. Technical drivers of the China HDD market.

OEM activities are highly dependent on the maturity level of regulation standards. For Stage IV, OEMs have already accumulated considerable experience and the current activities are mostly focused on price/cost reduction, including downsizing of as-is systems or the use of alternate but less costly components. For Stage VI, most OEMs have limited knowledge at component level or systems level. A few leading Chinese OEMs with development activities in this field are focusing to identify possible solutions and work out prototype systems. In between, there are activities regarding Stage V and Beijing V systems development.

STAGE IV: VANADIUM SCR EXPERIENCE

The overall adoption of V-SCR technology has been successful. This is quite remarkable, considering in a country like China with uneven diesel fuel quality. However, as shown in the below two examples, one should keep eyes on excessive lubricant consumption in order to avoid accelerated catalyst deactivation. Also catalyst plugging was found to be a commonly seen failure model, caused by undecomposed urea solution blended with diesel particulate matter (data and reasoning shown later). This requires particular attention during system design.

Analysis of Field Returned Parts

Until the nation-wide implementation in Jan 2015, prior production of Stage IV vehicles were often at small scale, mostly applying to city buses, rather than on-highway 18-wheel haulers.

In one particular case, non-compliance of NO_x emissions was reported with a SCR equipped Stage IV Beijing city bus, powered by an 8.4L Stage IV diesel engine. The NO_x conversion efficiency measured during vehicle operation was lower than expected. After the SCR aftertreatment system was taken out and put onto a testing cell, deficiency was observed compared to a reference part.

At the time of problem identification, the engine/vehicle was logged with over 400,000 kilometers. The returned SCR vessel consisted of three bricks of SCR catalysts, 10.5"x6", 10.5"x3", and 10.5"x6" in the exhaust flow direction, respectively, for a total of 22.4 L of catalysts. A picture of the dismantled vessel is shown below in the bottom right of [Figure 3](#). Note that the third catalyst, denoted as SCR03, is a zoned brick with rear 1.5 inch being the AMOX (ammonia slip catalyst) zone with 5 g/ft³ Pt-only precious metal loading.

After decanning, parts were sent back for further analysis. An initial visual examination as well as microscope evaluation showed that the inlet face of the first brick, SCR01, appeared to be black colored and had some sediment remains, through clearly not heavily blocked. The second brick, SCR02, also had black deposits in its inlet face channels. Deposit matters were at significantly reduced level in the third brick, SCR03.

Four 1"x3" core SCR samples were drilled out of the full size parts in the direction of exhaust flow and run on a lab reactor to compare the SCR performance with fresh catalyst sample. The SCR01-F and SCR01-R were the front and the rear of the 1st brick in the flow direction, respectively; the SCR02 cores were drilled from the middle brick, and

the front 3" portion of the 3rd brick, denoted as SCR03-F - note the rear part of the SCR03 brick was not included for SCR activity testing as it was an AMOX zone.

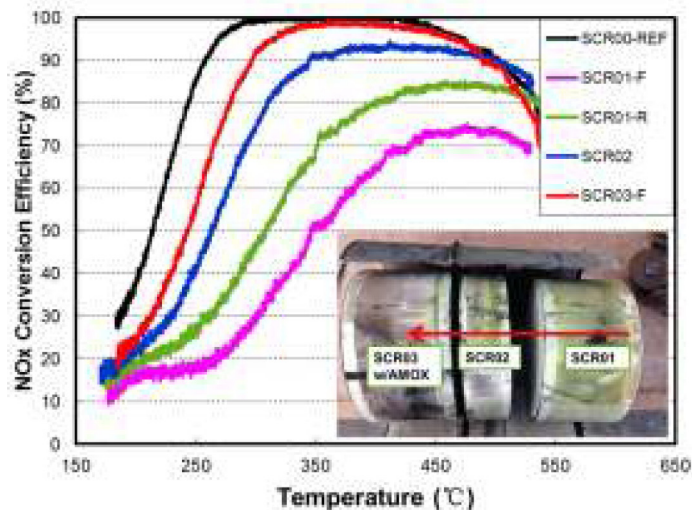


Figure 3. Comparison of NOx conversion of a 400,000 km returned SCR system with a reference sample - Sample naming in above picture: F stands for the front 3 inch and R stands for the rear 3 inch of full size samples. Test condition: 600 ppm NO, 600 ppm NH₃, 10%O₂, 5%H₂O, N₂ balance. SV=40,000 h⁻¹. Ramp rate: 10°C/min. Catalyst: 1x3 inch core.

NOx conversion efficiency comparison results are shown in Figure 3. On one side, there is considerable degradation of the catalyst performance visible. On the other side, there is a trend of degradation along the exhaust flow direction. In other words, severity of catalyst aging decreases in the flow direction, with the SCR03-F being the least impacted one where performance loss is mostly seen in the light off temperature range, below 300C. In contrast, the front section of the first brick, SCR01-F is the most impacted one. Its T50 of NOx conversion efficiency is nearly 350C, almost 180C higher than the reference parts. Even in the suitable SCR temperature range of 350-500C, the NOx conversion is merely around 70%.

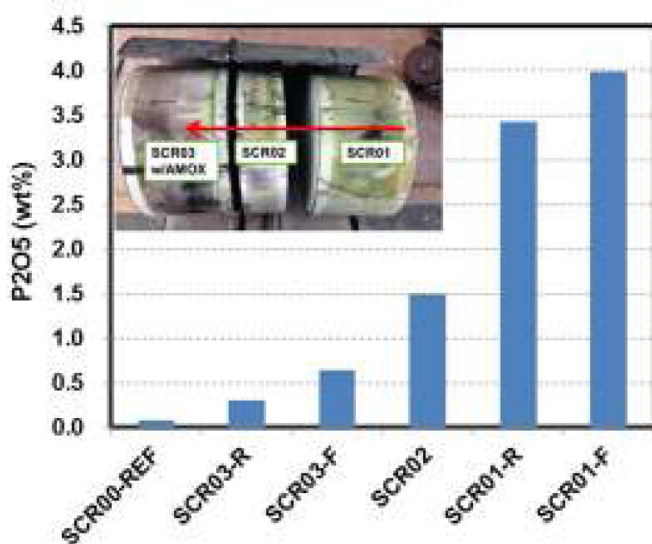


Figure 4. XRF element analysis of phosphate content in the field returned catalyst samples with 400,000 km mileage (crushed powder samples with monolith).

XRF element analysis has found significantly high amount of lube oil borne phosphate in the returned SCR samples. Results are compared with the reference in Figure 4. Corresponding to the SCR performance degradation trend, there is a lube oil ash component gradient profile in the exhaust flow direction. In other words, the profiles of performance degradation and lubricant borne ash contaminant are closely matched along the exhaust flow direction. This plausibly explains the activity loss. Therefore, the total quantity and quality of engine lubricant consumption must be given great consideration.

Analysis of Face-Plugged Catalyst

While the previous returned SCR parts perhaps can be deemed as a normal catalyst deterioration (plausibly through with excessive lube oil consumption), there are a few cases of complete failure where the engine had to be shut down and the V-SCR system had to be taken out. Coincidentally, in several such cases reported to our awareness it all started with catalyst inlet face plugging.

In such a case the engine saw excessive backpressure from the SCR system. After taken out, it was found that the SCR brick was plugged with black materials in its inlet faces, as shown in Figure 5. One could scrap off those deposits from the inlet face of the brick. There were sharp, irritating, and pungent odors emitted from those black materials.

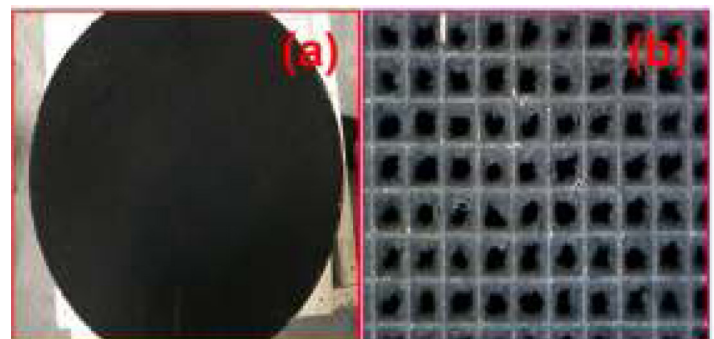


Figure 5. Inlet face image of a 60,000 km SCR part where the 7L engine has reportedly seen abnormal high backpressure from the SCR vessel. (a): as-is picture taken; (b) magnified under a microscope.

It was suspected that the plugging materials are primarily urea deposits blended with diesel particulate emitted from the engine. A laboratory reactor experiment was deliberately designed to qualitatively confirm this plausibility. One 1"x3" core drilled from the full size part was first run in oxygen free feed gas, triggering just a thermal treatment with 10C/min ramp to 500C in nitrogen carrier gas. As shown in the left part of Figure 6, (a), NO and NH₃ were measured by FTIR, a clear indication that the plugging material contains undecomposed urea and its derivatives. After this step, the core sample lost about 3% of its weight. However, the sample still appears to be black at its inlet face. The core sample was then put back onto the reactor and the same experiment was repeated, this time with 5% (vol%) oxygen in feeding gas. As a result, as shown the right part of Figure 6, (b), the FTIR detected CO and CO₂ starting at temperatures of 350C and above, products likely originating from the oxidation of soot particulates and SOF.