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VW defeat devices: A comparison of U.S. and EU required fixes

With the recent announcement in the United States of a fix for various Volkswagen Group models with 3.0L V6 diesel engines, regulators have defined required emissions-system modifications for almost all VW diesel engines in the U.S. market. That makes this a good time to step back and compare the modifications required by U.S. and EU authorities. The data continues to support earlier findings that enforcement in the United States is far more effective and stringent than in Europe.[1]

The fixes discussed in this paper specifically relate to the defeat devices that VW embedded in its software calibrations for all of its 2009–2014 diesels in Europe and 2009–2015 diesels in the U.S. A defeat device is any change that reduces the effectiveness of the emission control system under conditions which may reasonably be expected to be encountered in normal vehicle operation and use, unless the need for the AECD is justified in terms of protecting the vehicle against damage or accident. VW included software that looked for the progression of speeds used on the official emission test cycle and shut off emission controls under all other conditions. While there have been previous defeat device cases in the U.S., none involved shutting off emission controls all of the time in the real world—and no other manufacturer lied to the U.S. regulatory agencies[2] and tried to cover up their defeat device for 16 months.

1 The ICCT has published a number of papers and blogs about enforcement in the United States and Europe. See, for example, the following (with links to related content on the web page for each): Rachel Muncrief et al, "Defeat devices under the U.S. and EU passenger vehicle emissions testing regulations" (ICCT: March 22, 2016). http://www.theicct.org/publications/defeat-devices-under-us-and-eu-passenger-vehicle-emissions-testing-regulations; John German "Why are EU manufacturers claiming their defeat devices are not defeat devices?" (ICCT: February 10, 2017). http://www.theicct.org/blogs/staff/why-are-eu-automakers-claiming-defeat-devices-are-not-defeat-devices; Zifei Yang et al, "Global baseline assessment of compliance and enforcement programs for vehicle emissions and energy efficiency" (ICCT: November 14, 2017) http://www.theicct.org/publications/compliance-and-enforcement-global-baseline".

2 In the U.S., the Environmental Protection Agency (EPA) sets and enforces federal standards. The California Air Resources Board (CARB) sets and enforces standards for California. Both agencies were involved in the enforcement actions taken against VW for its defeat devices.

Prepared by John German

VW has paid a heavy price for this in the U.S., but Europe has a structural problem with enforcement and, as discussed below, the required defeat device remedies are far less effective in Europe.[3]

Table 1 summarizes the U.S. diesel fixes.[4] It includes detailed information on the repairs for most of the 2.0L and 3.0L diesels available at vwcourtsettlement.com, although there is a small number of vehicles for which modifications have not yet been defined (manual-transmission 2012–14 2.0L Passat and some 2014–16 Audi 3.0L). It has also been reported that there will not be a fix for 2009–2012 3.0L diesels and these vehicles will be scrapped.

Table 1. Announced fixes for VW Group diesel engines in the United States

				NO_x control[1]	Hardware replacement	Labor hours	Fuel economy loss	Diesel Exhaust Fluid increase
Gen 1	2009	VW Jetta, Beetle, Golf	2.0L	LNT EGR	Lean-NO_x trap Particulate filter Glow plug module	6	Up to 2 mpg[3]	N/A
Gen 1	2010–2014	Audi A3 VW Jetta, Beetle, Golf	2.0L	LNT EGR	Lean-NO_x trap	2.5 - 3	Up to 2 mpg[3]	N/A
Gen 2	2012–2014	VW Passat[2]	2.0L	SCR EGR	Software only	1	Up to 1 mpg[4]	50% - 130%
Gen 3	2015	Audi A3 VW Jetta, Beetle, Golf, Passat	2.0L	SCR EGR	SCR catalyst Particulate filter Oxidation catalyst 2nd NO_x sensor	9	None	1% - 14%
Gen 1	2009–2012	VW Touareg	3.0L	SCR EGR	No fix – vehicles will be scrapped			
Gen 2.1	2013–2014	VW Touareg Porsche Cayenne Audi Q7	3.0L	SCR EGR	SCR catalyst Cyl. pressure sensor Particulate sensor	3	Up to 1 mpg[5]	About 40%
Gen 2.1	2015	Audi Q7	3.0L	SCR EGR	SCR catalyst Particulate sensor	3	Up to 1 mpg[4]	About 40%
Gen 2.2	2015–2016	VW Touareg Porsche Cayenne	3.0L	SCR EGR	Software only	1	Up to 1 mpg[4]	About 40%
Gen 2	2014–2016	Audi A6, A7, A8, Q5	3.0L	SCR EGR	Fix not yet defined			

[1] The three main types of NO_x control are Exhaust Gas Recirculation (EGR) in the engine; Lean-NO_x Trap (LNT) aftertreatment; and Selective Catalytic Reduction (SCR) aftertreatment

[2] Automatic only – does not include manual transmission.

[3] 2 mpg (miles per gallon): A typical VW 2.0L diesel is rated at about 35 mpg, which corresponds to about 48 mpg on the test cycles, so 2 mpg is roughly equivalent to 0.3 L/100km on the European test cycle.

[4] 1 mpg: A typical VW 2.0L diesel is rated at about 35 mpg, which corresponds to about 48 mpg on the test cycles, so 1 mpg is roughly equivalent to 0.15 L/100km on the European test cycle.

[5] 1 mpg: A typical VW 3.0L diesel is rated at about 23 mpg, which corresponds to about 32 mpg on the test cycles, so 1 mpg is roughly equivalent to 0.3 L/100km on the European test cycle. (The L/100 km impact is higher than for the 2.0L as the baseline fuel consumption is much higher on the 3.0L.)

3 In Europe, emission standards are set by the Environmental Commission for all of the European Union (EU). However, certification and enforcement is done at the country level—and every country in the EU agrees to accept certification from any other country. Further, enforcement can only be done by the country in which the vehicle was certified.

4 Volkswagen/Audi 2.0L Diesel Emissions Settlement Program, Official Information Website. https://www.vwcourtsettlement.com/en/2-0-models/. Associated Press, "California and U.S. regulators approve fix for 38,000 Volkswagen diesels," October 23, 2017. http://www.latimes.com/business/la-fi-hy-volkswagen-emissions-20171023-story.html.

There is limited official Information on fixes in Europe. Table 2 summarizes what the ICCT currently knows about the VW Group diesel fixes in Europe, but this information may be incomplete.[5]

Table 2. Announced fixes for VW Group diesel engines in Europe

				NO_x control[1]	Hardware replacement	Labor hours	Fuel economy loss	Diesel Exhaust Fluid increase
Euro5	2009–2014	Audi A1, A3, A4, A5, A6, Q3, Q5, TT	1.2L	EGR	Software only[2]	0.5	None	N/A
		Seat Alhambra, Altea, Exeo, Ibiza, Leon, Toledo Skoda Fabia, Roomster, Rapid, Yeti, Octavia, Superb	1.6L		Flow transformer[3]	1.0	None	N/A
		VW Golf, Passat, Tiguan, Polo, Jetta, Scirocco, Caddy, Transporter	2.0L		Software only[2]	0.5	None	N/A
Euro5	2010–2013	Audi A7, A8 Porsche Cayenne	3.0L	EGR	Software only	0.5		N/A
Euro6	2014–2017	Porsche Cayenne	3.0L	SCR EGR	Software only	1.0		
Euro6	2014–2017	Audi A8	4.2L	SCR EGR	Software only			

[1] VW relied entirely on Exhaust Gas Recirculation (EGR) in the engine and did not use NO_x aftertreatement on its Euro5 vehicles. Lean-NO_x Trap (LNT) or Selective Catalytic Reduction (SCR) aftertreatment were used for Euro6 vehicles.

[2] The number of fuel injections and the timing of those injections were changed; an additional fuel injection phase was added; and the exhaust gas recirculation (EGR) rate was increased.

[3] A "flow transformer" was fitted directly in front of the air mass sensor to stabilize the air flow in front of the sensor and improve its accuracy.

5 1.2L, 1.6L, 2.0L sources: "Technical measures for the EA 189 diesel engines affected presented to the German Federal Motor Transport Authority," VW press release, November 25, 2015. https://www.volkswagen-media-services.com/en/detailpage/-/detail/Technical-measures-for-the-EA-189-diesel-engines-affected-presented-to-the-German-Federal-Motor-Transport-Authority/view/2925586/7a5bbec13158edd433c6630f5ac445da?p_p_auth=ftKQ9du0

"Fragen & Antworten zur Softwarethematik bei Dieselmotoren," Skoda FAQ, accessed 22 November 2017. http://www.skoda-auto.de/other1/fragen-und-antworten. Green-Motors, "VW Dieselgate: Betroffene Modelle und Online-Checks," October 15, 2015. https://www.green-motors.de/news/1510153468-volkswagen-diesel-gate-betroffene-modelle-und-online-checks. "Abgas-Manipulationssoftware steckt in vielen Modellen des Volkswagen-Konzerns: von Audi bis Seat und VW. Hier ist der aktuelle Stand," Frankfurter Allgemeine Zeitung GmbH, accessed 22 November 2017. http://www.faz.net/aktuell/wirtschaft/diesel-affaere/betroffene-autos-im-vw-abgasskandal-13821503.html

3.0L sources: "Audi - Rückruf von Fahrzeugen mit V-TDI-Motor", Österreichischer Automobil-, Motorrad- und Touring Club, accessed 22 November 2017. https://www.oeamtc.at/rueckrufaktionen/audi-rueckruf-von-fahrzeugen-mit-v-tdi-motor-19172241

"Porsche recalls around 21,500 Cayenne diesel cars," Volkswagen News, July 28, 2017. https://www.volkswagenag.com/en/news/2017/07/Software-Update.html

4.2L source: "Audi recalls approximately 5,000 A8 automobiles with V8 TDI engine in Europe," Volkswagen News, November 2, 2017. https://www.volkswagenag.com/en/news/2017/11/Audi_recalls_V8TDI.html

REQUIRED MODIFICATIONS

It is immediately apparent that U.S. regulators are requiring VW to do far more to fix their vehicles than Europe is. Except for a $10 piece of plastic on VW's 1.6L diesel,[6] all of the fixes in Europe are software-only. In the United States, only the 2012–14 Passat and the 2015–16 3.0L vehicles have a software-only fix. All others are required at least to replace the NO_x aftertreatment (LNT or SCR catalyst) and some are required to replace additional hardware components, such as the particulate trap, particulate sensor, or oxidation catalyst. To modify just 500,000 vehicles in the United States, VW repeatedly has had to set aside more money,[7] while the company has already "fixed" more than 6 million cars in Europe.

Note that VW had to replace the particulate trap on all 2009 2.0L and all 2015 2.0L diesel vehicles in the United States. This suggests that VW took advantage of tradeoffs in the engine between NO_x and particulate emissions and installed a smaller, cheaper particulate trap, knowing that in the real world the engine would be producing a lot of NO_x emissions and relatively few particulates. Fixing the NO_x emissions most likely led to more particulate emissions than the particulate trap was designed to handle over the useful life of the vehicle, requiring the particulate trap to also be replaced.

Overall, the cost of the fixes in the United States is very high. The estimated cost of installing an LNT or SCR system in new vehicles is about $500, and the cost of the particulate trap is similar.[8] The expense for retrofitting these components would be significantly higher, reflecting engineering time to redesign the systems, labor cost to install them, and administrative costs for shipping the parts to about a thousand dealers. And reports are that VW has not been able to come up with an acceptable fix at all for the 2009–12 3.0L diesels in the United States and will be forced to scrap the entire vehicle with these diesel engines.

To be fair, the 2009–14 diesels were certified to very different emission standards in the United States and Europe. The U.S. Tier 2 standards are roughly equivalent in stringency to the EU Euro 6 standards, but the diesels VW sold in Europe with the defeat devices were certified to Euro 5, not Euro 6. The NO_x standard for Euro 5 is 0.18 g/km, or 2.25 times the 0.08 g/km standard for Euro 6. Thus, while the same E189 2.0L engine was used in the United States and Europe, none of VW Euro 5 diesels needed or used the NO_x aftertreatment (LNT or SCR) that was required in the United States.

VW made an inexplicable decision in redesigning the 3- and 4-cylinder diesel engines for 2015, from the EA189 to the EA288. The EA288 engine in the United States continued to use defeat devices similar to those in the EA189 engine—but as part of the change to Euro 6 standards in Europe, the defeat devices used in the EA189 engine were removed from the EA288 engine and NO_x aftertreatment was added. Thus, the interesting result was that 2015 VW diesel engines were far cleaner in Europe than they were in the United States, despite much stronger enforcement in the United States. In

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6 The flow transformer might improve the accuracy of the air mass sensor, although only if VW used a poor design in the first place, but this only impacts the calculation of EGR rate – and even here it should have relatively small impacts on EGR function.

7 "Volkswagen Group increases provision for recall actions in North America," Volkswagen News, September 29, 2017, https://www.volkswagenag.com/en/news/2017/09/Ad_hoc_29_Sep.html

8 Francisco Sanchez et al, *Estimated cost of emission reduction technologies for light-duty vehicles* (ICCT: March 2012). http://theicct.org/sites/default/files/publications/ICCT_LDVcostsreport_2012.pdf

fact, while some VW Euro 6 diesels have been found to use different types of defeat devices and recalled to fix the inappropriate calibrations, overall VW's Euro 6 diesels are among the cleaner diesels to be found in Europe.[9] Why did VW recalibrate its 2015 European diesels to remove the EA189-type defeat devices but continue to use similar defeat devices in all of their diesels in the United States?

Further, it appears that VW may have expanded upon its defeat device strategy when it switched from the EA189 to the EA288 in the United States. The 2012–14 2.0L Passat and all of the 2015 2.0L diesels use SCR, so one would expect the fix for both would be similar. However, VW was able to obtain for a software-only fix to the 2012–14 Passat, while for the 2015 2.0L engines the automaker must replace the SCR catalyst, particulate trap, and oxidation catalyst, as well as install a second oxygen sensor. This suggests that the 2012–14 Passat had a more robust emissions control system and VW extended its defeat device strategy to install cheaper hardware on the 2015 2.0L vehicles.

AFTER-FIX NO_X EMISSIONS

There is no public data in the United States on the level of NO_X emissions after the fixes. However, it is clear that the Environmental Protection Agency and the California Air Resources Board conducted extensive testing of VW's proposed fixes to ensure that emissions remained low in the real world and to ensure durability through at least 120,000 miles.[10] There was a small allowance for the Gen 1[11] 2.0L vehicles, which were allowed to emit 0.030 g/mi HC above the full useful life FTP[12] standard of 0.160.[13] Thus, Gen 1 2.0L vehicles can emit 19% above the FTP standard, but Gen 2 and Gen 3 2.0L vehicles must meet the FTP standard over full useful life. In addition, emissions over the supplemental FTP (SFTP) test cycles[14] are allowed to increase by 77% for Gen 1, 48% for Gen 2, and 6% for Gen 3 2.0L engines, compared with the full useful life SFTP standards. Overall, the emission allowances after the fix are fairly small.

Another important point is that the U.S. agencies demanded a solution that would work throughout the remaining useful life of these vehicles, up to 120,000 miles or 193,000 km, or even 150,000 miles or 241,000 km in some cases. Ensuring that emissions remain low throughout the useful vehicle life is a fundamental principle that is lacking in the European regulations, which has contributed to the minimal fixes allowed in Europe. When the EU starts work on Euro 7, it needs to focus on lifetime emissions, greater durability, and greater allowances for deterioration.

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9 Chelsea Baldino et al., *Road Tested: Comparative overview of real-world versus type-approval NO_X and CO_2 emissions from diesel cars in Europe* (ICCT: September 2017). http://www.theicct.org/sites/default/files/publications/ICCT_RoadTested_201709.pdf

10 For example, EPA and CARB's approval letter for the 2015 Gen 3 2.0L fix states, "After thoroughly reviewing these materials, including examining and evaluating test data, software description and files, onboard diagnostic system functionality, durability demonstration results, auxiliary emission control device (AECD) descriptions, consumer disclosures, extended warranty plans, and various statements of compliance therein; and after conducting our own extensive testing of eight vehicles equipped with the Proposed Emissions Modification…" https://www.epa.gov/sites/production/files/2017-01/documents/vw-2l-gen-3-ems-modf-appvl-issued-2017-01-06-exec.pdf

11 Note that Gen 1, Gen 2, and Gen 3 vehicles were defined in Table 1.

12 FTP means Federal Test Procedure, which is the primary emission test procedure in the U.S.

13 "Volkswagen "clean diesel" marketing, sales practices, and products liability litigation," Case No: MDL No. 2672 CRB (JSC), Partial Consent Decree, Appendix B, Section 3.1.2, page 11, accessed 22 November 2017. https://www.justice.gov/opa/file/871306/download

14 The SFTP requirements are a weighted average of a high speed/acceleration rate test (28%), a test with the air conditioning on at 95°F (37%), and the FTP test (35%).

There has been limited third-party on-road testing in Europe of vehicles with the software fixes. Auto Motor Sport tested two VW Amarok vehicles before and after the fix, using a confidential real-world testing protocol developed by Emissions Analytics.[15] The magazine did not find any NO_x reductions after the fix—and the emissions before and after the fix were more than eight times the EU standard. Supporting the lack of improvement in the real world is a statement by the Italian consumer group Altroconsumo on the results of real-world testing they conducted before and after the fix on an Audi Q5 2.0L.[16] While Altroconsumo did not release the test results from its real-world testing, it stated that the on-road emissions remained the same after the fix.

Österreichischer Automobil-, Motorrad- und Touring Club (ÖAMTC), Allgemeiner Deutscher Automobilclub (ADAC), and Touring Club Switzerland (TCS) tested nine VW and Audi diesels before and after the fix. Unfortunately, while ÖAMTC asserted it tested vehicles in the real world, its published findings include only chassis dynamometer results. Table 3 summarizes the NO_x results on the BAB-130 chassis dynamometer highway cycle[17] published by ÖAMTC on its website.[18] Excluding the VW Tiguan, which more than doubled NO_x emissions after the fix, NO_x emission reductions ranged from 4% to 52%, with an average of 25%, and the after-fix emissions ranged from 2.6 to 4.1 times the standard with an average of 3.3 times the standard.

Table 3. NO_x emissions over BAB-130 chassis dynamometer highway cycle

Model	Engine	Tested by	NO_x mg/km pre-fix	NO_x mg/km after-fix	Percent change	CF* after fix
VW Golf	2.0L	ADAC	724	464	- 36%	2.6
Audi A4	2.0L	ÖAMTC	661	635	- 4%	3.5
Audi A4	2.0L	ÖAMTC	613	536	- 13%	3.0
Audi A4	2.0L	TCS	605	545	- 10%	3.0
VW Passat	2.0L	TCS	844	684	- 19%	3.8
VW Tiguan	2.0L	ÖAMTC	712	1624	+ 128%	9.0
VW Polo	1.2L	ADAC	872	655	- 25%	3.6
VW Golf	1.6L	ADAC	965	468	- 52%	2.6
VW Golf	1.6L	ÖAMTC	1018	730	- 28%	4.1
AVERAGE			**779**	**705**	**- 10%**	**3.9**
AVERAGE without VW Tiguan			**788**	**590**	**- 25%**	**3.3**

** CF: Conformity Factor, or the ratio of the tested emissions to the NEDC emission standard*

15 "VW diesel software update: VW Amarok performance equal - consumption slightly increased," Auto Motor und Sport, July 3, 2016. https://www.auto-motor-und-sport.de/news/vw-diesel-update-amarok-leistung-gleich-gut-verbrauch-leicht-erhoeht-10551733.html

16 "Dieselgate: Volkswagen keeps on cheating both consumers and authorities," Altroconsumo, July 7, 2016. https://www.altroconsumo.it/organizzazione/international/press-releases/2016/vw-dieselgate-altroconsumo-test-nox-emissions-overtake-the-limits-prescribed-by-law-after-the-recall

17 The BAB-130 is a chassis dynamometer highway cycle developed by ADAC (Allgemeiner Deutscher Automobil-Club e.V.) as part of its EcoTest car testing protocol, where BAB stands for Bundesautobahn (German for federal highway) and 130 km/h is the maximum speed.

18 "New ÖAMTC tests on VW recall: Consumption and performance still unaffected," accessed on 22 November 2017. https://www.oeamtc.at/thema/autokauf/neue-oeamtc-tests-zu-vw-rueckruf-verbrauch-und-leistung-weiterhin-unbeeinflusst-19190841

In addition to the vehicle tested by TCS on the chassis dynamometer and included in Table 3, TCS tested a single VW Passat in the real world using a portable emission measurement system (PEMS).[19] NO_x emissions decreased by only 19% after the fix and were still almost 600 mg/km, or more than three times the standard.

It is clear that the European fixes are minimal, especially compared with those required in the United States. Part of the problem is that the German government insisted that the fixes should have no effect on fuel consumption or CO_2. There are tradeoffs in all diesel engines between fuel consumption and NO_x emissions, where small reductions in fuel consumption in the engine can drastically increase engine-out NO_x. So, not only were the EU fixes software-only, but even the software changes had to be minimal to avoid affecting fuel consumption.

In summary, the fixes in the United States are far more effective than those in Europe, with the U.S. modifications controlling almost all of the excess emissions while the EU diesels are allowed to emit more than three times the standard after the fix, even on a chassis dynamometer highway test, and as much as eight times the standard in the real world.

FUEL ECONOMY

In addition to tradeoffs in the engine between engine-out NO_x and fuel consumption, LNT systems must periodically inject additional fuel to remove NO_x stored on the lean-NO_x trap and reduce the NO_x to nitrogen and oxygen. Each of these effects is generally considered to have a 2%–5% impact on fuel consumption. This is in line with the documentation for the U.S. modifications, which stated that fuel consumption may be as much as 1 mpg lower for SCR vehicles and as much as 2 mpg lower for LNT vehicles. Most of VW's 2.0L diesels have fuel economy ratings of about 33 mpg, so a 1 mpg loss is about 3% and a 2 mpg loss is about 6%. The 1 mpg loss on the 3.0L is a loss of 4%, reflecting the much lower baseline of 23 mpg.

At a recent Diesel Summit in Germany, diesel manufacturers including VW announced they can reduce NO_x emissions without fuel penalty. This is actually not possible, except perhaps for a Euro 6 vehicle equipped with an SCR system that originally deactivated urea injection. Increasing the EGR rate results in an increase in particulate matter formation and increased fuel consumption. Many engine parameters such as injection pressure, boost pressure, and injection timing can be adjusted to partly reduce the adverse effect on particulates, such as by improving the so-called EGR tolerance, but often these adjustments also have detrimental effects on fuel consumption. And, as demonstrated by the higher fuel-economy loss on VW vehicles with LNT after the fix in the United States, LNTs require additional fuel injection to work properly.

The fact that VW asserts that its fixes in Europe will not have any impact on fuel consumption leads unavoidably to the conclusion that the fixes will be quite inefficient at reducing NO_x in the real world. This is a deliberate choice by VW to prevent an increase in fuel consumption and preserve the durability of the engines. It also can only mean that an auxiliary emission defeat device strategy is still in place; it is just

19 "TCS tested VW-software updates," TCS Mobilitätsberatung, Emmen, Nov. 29, 2016. https://www.tcs.ch/mam/Digital-Media/PDF/Booklets/TCS-testet-VW-Software-Updates.pdf

triggered in a different way. VW has removed the illegal part of the code, but the company has not explained what emission calibration changes replaces it.

RECOMMENDATIONS FOR NEW EU TYPE-APPROVAL FRAMEWORK

It is clear that the required fixes for VW's diesels in Europe are relatively ineffective, especially compared with those required in the United States. This has important implications for the new type-approval framework discussion still ongoing in the EU. The third Real Driving Emissions (RDE) package introduced recently by the Environmental Commission requires manufacturers to submit an extended documentation package on auxiliary emission strategies[20] and a statement that they are not using defeat devices,[21] but these requirements are relatively minor improvements. The key is for the EU to move beyond just improving its in-use testing. It is even more important to clarify which agency has the power to conduct enforcement and to establish mandatory consequences if manufacturers fail to comply with the defeat-device requirements.

20 Auxiliary emission strategy (AES) is a European term for calibrations that change how the emission control system operates. In the United States, this is referred to as auxiliary emission control device (AECD).

21 The AES provisions are part of the amendment EC 2017/1154 to the new European Type Approval regulation (EC 2017/1151) which is in force since September 1, 2017. With this revision, these provisions are no longer linked only to RDE but also to the type approval in general, including WLTP. The extended documentation package can now be requested by the European Commission from the Type Approval Authority.