Volkswagen's Defeat Device and the Probable Ramifications of Potential Fixes

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1 Introduction and Summary

This report gives a brief discussion of the characteristics and fundamental operating principles of diesel-powered vehicles with an emphasis on those aspects which are most important for understanding how Volkswagen's defeat devices could have been implemented and what the likely impacts of potential fixes of those defeat devices will be. The report focuses on the European market.

The report shows that today's vehicles are extremely complex systems with many interrelated sub-systems. The performance of these sub-systems is integrated into the complete vehicle operation via a computer system that receives signals from a multitude of sensors and, through analysis of those signals, determines the best operating conditions of the engine, aftertreatment system, and powertrain. The computer system then implements these ideal conditions by sending signals to the appropriate electromechanical actuators. The sophistication of the control system is what enabled the implementation of the defeat devices. Through the analysis of the signals it receives from the vehicle, engine, and powertrain, the control system can determine whether or not the vehicle is being subjected to an emission certification test. VW included programming in the control system so that if the system determined that the vehicle was undergoing a certification test, the engine operating conditions would be configured to limit emissions. When the control system detected that it was not undergoing testing, these operating conditions would be changed, resulting in higher emissions than would be expected based on the results of the certification test.

Based on the operating fundamentals described at the beginning of the report, the report then offers opinions as to the likely ramification of potential fixes to the defeat devices. It seems most probable that the fixes will involve changes in the engine operating conditions to reduce engine-out NOx. Examples of such changes would include changes in the fuel injection timing and rate shape, and to the rates of exhaust gas recirculation. The outcome of such changes will likely result in higher fuel consumption, lower performance, and increased particulate matter leaving the engine. Because of the likely increase in particulate emissions from the cylinder, the diesel particulate filter will fill faster and need to be regenerated more frequently. This will result in additional consumption of diesel fuel. Furthermore, the increased frequency of regenerations of the DPF will subject it to more stress, potentially decreasing its effectiveness and increasing the likelihood of durability issues.

Finally, the report discusses recent developments regarding VW's proposed fixes to the vehicles in Europe. The report observes that while VW has received initial approval for its fixes, problems with the fixes have been exposed by independent testing and implementation of the fixes has reportedly been put on hold. In the context of these independent findings, in addition to VW's prior misrepresentations and the technical concepts explained within the report, the report concludes that VW's representations about the ease, inexpensiveness, permanence, and completeness of a fix are not plausible.

2 Background on Vehicle Systems and Volkswagen's Defeat Device

The implementation of the defeat device was accomplished through manipulation of the engine and exhaust aftertreatment by the vehicle control system, the heart of which is the electronic control unit.

Meeting the regulated emission standards while maximizing fuel economy and performance requires precise control of the engine, aftertreatment system, and vehicle powertrain. Of these three sub-systems, the engine is the most adjustable, and hence plays a central role in tailoring the composition and thermodynamic state of the exhaust gas to be well matched to the aftertreatment system. In diesel engines, the engine parameters that can readily be changed during engine operation include: fuel injection characteristics, the amount of exhaust gas recirculation, the pressure and temperature of the intake gases, the exhaust gas pressure, and the pathway used to reroute the exhaust gases back to the intake side of the engine. All of these parameters will have an impact on the level of the emissions leaving the engine cylinder, which then head towards the aftertreatment system. Out of all of the possible control parameters, changes in the injection characteristics and the exhaust gas recirculation are principal.

2.1 Fuel Injection and Exhaust Gas Recirculation

The fuel injection system is responsible for introducing the fuel into the engine cylinder. The injection process can be used to control the timing of the start of combustion in the cylinder, the intensity of the mixing between the fuel and the air in the cylinder, and the duration of the combustion process. The timing of the start of combustion and the combustion duration largely determine the efficiency of the engine. For every engine operating condition, there will be an optimal time for the start of combustion and for the combustion duration. Optimal combustion gives the lowest fuel consumption and the greatest power. It also yields the highest temperatures, which is problematic for NOx emissions because NOx emissions are very sensitive to combustion temperatures. The NOx formed in the cylinder increases exponentially as the combustion temperatures increase. To minimize the

NOx formed in the cylinder, the peak temperatures need to be made as low as possible, which can be contrary to achieving maximum efficiency. An easy way to reduce the peak temperatures is to delay (retard) the start of the fuel injection. This delays the start of combustion so the peak pressure and temperature are lower. It also makes the combustion duration longer. Consequently, the NOx formed in the cylinder decreases, but so does the efficiency. As a result, the fuel consumption increases and the power decreases when the injection is retarded from the optimal timing.

In addition to NOx emissions, particulate matter is formed during the diesel combustion process. The particulate matter that leaves the cylinder is the result of the difference between two large rate processes: formation and oxidation. The formation of the particulate matter occurs during the early portion of the combustion event when the combustion processes are still largely being controlled by the fuel injection. During the early portion of the combustion event, the amount of oxygen that has been entrained into the fuel spray by the injection process is a critical factor affecting the formation of the particulate matter. The larger the amount of oxygen entrained into the spray, the smaller the particulate matter formation rate, and vice-versa. The oxidation process, which removes particulate matter, occurs more towards the end of the combustion event and is largely controlled by the intensity of the mixing of the cylinder air with the burning fuel, as well as by the temperature during the expansion stroke.[1] Particulate matter formation is minimized and its oxidation is maximized when the rate at which the fuel is injected is maximized and the temperatures in the cylinder are kept high. However, this closely coincides with the conditions for optimal combustion, which, as described above, are also conditions for maximum NOx emissions.

Since the injection system is very flexible, it is possible to use the injection system to change the combustion in an attempt to promote particulate oxidation later into the expansion stroke. One way to do this is by changing what is known as the injection rate shape. Through this process, the engine controller could retard the injection timing to make combustion start later, thus lowering the peak temperatures and reducing the NOx formation. However, the lower temperatures in the expansion stroke would result in a slower particulate matter oxidation, meaning the particulate matter emissions would increase as a result of the injection timing retard. To counter this, the fuel injection event could be changed so that it consists of multiple pulses of fuel, or multiple injections. With multiple pulses of fuel, the last portion of the injected fuel could be delayed to occur later in the expansion stroke, so that the late burning fuel keeps the temperature higher further into the expansion stroke, thus enhancing the oxidation of the particulate matter. Retarded injection with an injection rate shape change could yield lower NOx without as much of an increase in particulate matter emission. However, the efficiency of the engine would be further decreased because the delayed fuel injection from the multiple pulse injection would further elongate the combustion duration, resulting in a larger increase in fuel

[1] The expansion stroke refers to piston movement by which a cyclic motor extracts the work (power) from the force on the piston that was generated by the combustion process. This force is created by the combustion of the compressed fuel-air mixture.

consumption relative to retarding the injection timing while keeping a more conventional injection rate shape.

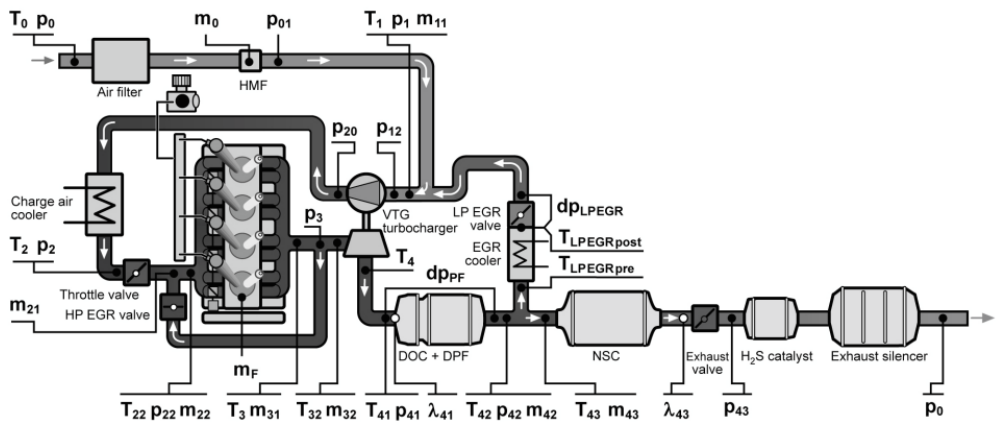
Another approach to reducing the in-cylinder NOx formation is to lower the temperature by adding exhaust gas back into the cylinder, referred to as exhaust gas recirculation (EGR). The exhaust gas acts as an inert diluent which decreases the oxygen concentration in the cylinder, thus distributing the energy released in combustion over a larger number of molecules, yielding lower temperatures in the product gases. As discussed above, lower temperatures in the product gases yield lower NOx emissions. However, the introduction of EGR increases the engines' tendency to emit particulate matter—because EGR reduces the oxygen concentration in the cylinder, the formation of the particulate matter is increased. Also, because the combustion temperatures are reduced by EGR along with the oxygen concentration, the oxidation of the particulate matter later in the expansion stroke is also reduced. For these reasons, adding EGR to the cylinder will reduce the NOx formation but increase the particulate emissions.

The discussion above gives examples of the conflicting conditions for minimizing both NOx and particulate matter emissions. Typically, actions taken to control combustion to reduce NOx cause the particulate matter to increase and vice-versa. The phenomenon is commonly referred to as the "soot-NOx trade-off" in diesel engines. Meeting the emission standards with diesel-powered vehicles requires choosing the appropriate trade-off between the NOx and particulate matter such that the emissions leaving the cylinder can be effectively dealt with by the individual components of the aftertreatment system—in this case, the NOx and diesel particulate trap sub-systems (described below in Section 1.3). Depending on the capabilities of the engine's aftertreatment system, these compromise conditions will also involve compromises in fuel economy and power.

2.2 The Vehicle Control System

The purpose of the vehicle control system is to optimally integrate the operating characteristics of the different components of the vehicle powertrain by sensing and manipulating engine operating parameters such as: intake air mass, pressure, and temperature; mass and temperature of EGR, and the path it follows before reintroduction to the engine; fuel injection pressure, injection timing, and number of injections per combustion event (rate shaping); the temperature and pressure drop across the diesel particulate filter (DPF) and its need for regeneration; and the operation of the NOx reduction system. A schematic of an engine, aftertreatment system, and many of the important operating parameters that would typically be measured is given below in Figure 1.

Figure 2.1 Example of Engine and exhaust emission management system with temperature, pressure, and operating parameter assessment points for necessary control[2]



The control system of the vehicle receives information about the engine operating condition and the status of the exhaust emission aftertreatment system from sensors like those shown schematically in Figure 1 by letters or symbols—T, p, or λ, for example—which represent sensor measurements. The control system also receives signals that indicate the demand being put on the vehicle by the operator, such as an acceleration or a demand for more auxiliary load from turning on the air conditioning. The information from the sensors is processed by a computer (or computers) within the vehicle, from which the necessary adjustments to the engine, exhaust system, and vehicle control parameters are determined in order to achieve optimal operation of the vehicle. For example, after processing the information from the sensors and the demands from the operator, the control system may determine that the injection timing should be changed, the turbocharger adjusted to increase the intake manifold pressure, or the EGR flow rate changed by adjusting the exhaust system backpressure. Additionally, the control system may determine from the sensors' data that the DPF needs to be regenerated. Appropriate signals are then sent to electromechanical actuators, which adjust the various engine, exhaust system, and vehicle operating parameters, such as injection timing, amount of EGR, adjustments to the aftertreatment system, and transmission shifts.

To determine the adjustments which should be made to the engine operating parameters, the computer system, also referred to as the electronic control unit (ECU), uses a combination of models (both analytical and empirical) and look up tables, which are determined in advance by running calibration tests in the laboratory. The advancement in computing power, sensors, and electromechanical actuators facilitates precise and seamless operation of extremely complicated, interconnected vehicle sub-systems, enabling the vehicle to meet the demands

[2] Source: Dr.Ing. J. Hadler, Dipl.-Ing. F. Rudolph, Dipl.-Ing. R. Dorenkamp, Dipl.-Ing. H. Stehr, Dr.Ing. T. Düsterdiek, Dipl.-Ing. J. Hilzendeger, Dipl.-Ing. D. Mannigel, Dr. rer. nat. S. Kranzusch, Dipl.-Ing. B. Veldten, Dr. M. Kösters, Dipl.-Ing. A. Specht, Volkswagen AG, Wolfsburg, *Volkswagen's New 2.0l TDI Engine Fulfils the Most Stringent Emission Standards*, presented at Internationales Wiener Motorensymposium 2008.

placed on it while adhering to a host of operating constraints. These operating constraints include performance metrics demanded by the operator, emission criteria required by regulatory agencies, and customer-preference features such as fuel economy. It should not be surprising that compromises need to be made while trying to achieve the acceptable performance demanded by the operator and desired features, such as achieving the best possible fuel economy while meeting required emission regulations. This defines the competitive arena for the vehicle manufacturers.

2.3 Emission Aftertreatment Systems

The aftertreatment systems in diesel engines typically consist of a diesel oxidation catalyst, a diesel particulate filter, and a NOx reduction system. However, VW did not install NOx reduction systems in their European vehicles until the introduction of the Euro 6 standards.[3]

Aftertreatment systems use sensors that are installed within the system to record data necessary to assess the status of the aftertreatment components and the operating condition of the engine. When a change in engine operation is commanded, the ECU uses the data from the sensors to determine the current state of the aftertreatment and engine systems, then uses engine maps and models to determine what the new inputs to the engine should be and sends commands to the electromechanical actuators to establish the new operating condition.

For diesel engines, both NOx and particulate matter regulations are the most challenging in terms of aftertreatment requirements. As discussed above, actions that are taken to reduce the particulate matter leaving the cylinder increase the NOx leaving the cylinder and vice versa. Consequently, modern diesel-powered cars are generally equipped with both NOx aftertreatment systems and diesel particulate filters, though VW did not use NOx aftertreatment systems in their Euro 5 vehicles.

Diesel particulate filters operate on a very simple principle. A canister with some sort of porous media filter is inserted into the exhaust stream. As the exhaust gas flows through the filter media, the particulates are trapped in the filter, in the same way that the air filter in the intake system filters dirt and debris from the air as it enters the engines. As the DPF fills with particulate matter, the flow through the filter becomes restricted and the pressure drop across the filter increases. If the pressure drop becomes too large, it impairs the engine operation by restricting the exhaust gas flow out of the engine. In the same way that the air filter must be periodically changed, the DPF needs to be periodically regenerated—that is, burned clean. There are two ways in which the DPF can undergo a regeneration, referred to as passive and active regeneration. Passive regeneration occurs when the engine controller does not specifically command a regeneration. Active

[3] See Transcript of UK Parliamentary Hearing, Jan. 25, 2016, statement of Oliver Schmidt at 19, http://data.parliament.uk/writtenevidence/committeeevidence.svc/evidencedocument/transport-committee/volkswagen-group-emissions-violations/oral/27791.pdf. This can be contrasted with the VW diesel vehicles in the United States, which used NOx storage catalysts in older vehicles and selective catalytic reduction systems in newer vehicles.

regeneration occurs when the controller initiates the regeneration via commands to the appropriate electromechanical actuator(s).

Passive regeneration can occur during normal operation of the vehicle if the exhaust gets hot enough on its own to start oxidizing the particulate matter in the DPF. This can happen if, for example, the vehicle spends a prolonged time operating at high load. Passive regeneration can also occur via NO2 serving as an oxidizer of the particulate matter in the DPF. This is accomplished with the help of the diesel oxidation catalyst. The diesel oxidation catalyst oxidizes the NO leaving the cylinder into NO2. The extra oxygen on the NO2 then becomes the oxidizer for the particulate matter in the DPF. Regeneration of the DPF via NO2 occurs at a lower temperature than regeneration using O2 as the oxidizer. However, because DPF regeneration with NO2 occurs at a lower temperature, it is slower and less complete than the higher temperature regeneration with O2 as the oxidizer.

Passive regeneration is a preferred mode of cleaning the DPF because extra diesel fuel is not needed to raise the temperature of the exhaust gases to cause regeneration.

Active regeneration occurs when the vehicle control systems actually command a regeneration event. This is accomplished by injecting some diesel fuel into the exhaust system, which then oxidizes ahead of the DPF in the diesel oxidation catalyst, thereby raising the temperature of the exhaust gas entering the DPF. The hot exhaust gas entering the DPF causes the particulate matter in the DPF to oxidize using the extra O2 in the exhaust. Typically temperatures of 500º to 600º C are required to achieve regeneration with this approach. Active regeneration is a more complete regeneration than passive regeneration using NO2, but it requires the use of diesel fuel to raise the exhaust temperature, which increases fuel consumption and the likelihood of damage to the DPF from either a runaway regeneration or from temperature gradients caused by local hot spots within the DPF during regeneration.

Additionally, when the DPF is undergoing regeneration it is common for there to be an increase in particulate emissions. As the DPF burns clean, the gases leaving the DPF can re-nucleate downstream of the DPF and cause a spike in the particulate number leaving the DPF. Then, once the DPF has burned clean and starts trapping particulate matter, particle breakthrough can occur. The particle breakthrough will occur until the DPF reaches its optimal trapping condition.

2.4 Volkswagen's Defeat Device

The sensors, ECU, and electromechanical actuators have greatly enhanced the manufacturer's ability to improve performance and vehicle desirability while still meeting emissions regulations. They have also, however, made it possible to cheat.

Because the ECU is constantly receiving a multitude of inputs detailing the operating conditions of the engine and vehicle, and because the emissions certification test cycles are a specific sequence of operation conditions, it would not be difficult to write a program which would allow the ECU to determine whether or not the vehicle was undergoing a certification test. This could be as simple as determining if all four of the vehicle's wheels were moving or not, detecting whether the steering wheel was being used, or identifying the sequence of driving conditions the vehicle was being commanded to achieve. If the ECU determined that the vehicle was not undergoing a certification test, the ECU could call on a different program that would command the engine and exhaust system to operate in modes that might be desirable to the operator or vehicle manufacturer, but that would violate the emission regulations.

It appears that when the ECUs of the VW vehicles in question sensed that they were undergoing a certification test, the engine operating conditions were adjusted to ensure that the NOx leaving the engine would meet the NOx regulation. This would have been most easily accomplished by retarding the injection timing and increasing the EGR rate. The result would be reduced NOx emissions, but at the cost of increased particulates—which would be caught in the DPF, causing it to fill faster. Furthermore, the combustion would be moved further from its optimal timing. Such conditions would not be desirable to consumers in non-test conditions, as vehicle performance would be less than desired, while fuel consumption and DPF regeneration frequency would be greater than desired. To avoid those conditions, when the vehicles were not being tested, they would be run in a way to increase performance, reduce fuel consumption, and decrease particulate production, but consequently increase NOx emissions. The net result was an increase in NOx emissions into the atmosphere.

VW accomplished two objectives by utilizing software that could identify when the vehicle was undergoing a certification test and adjust the engine operating conditions to meet the certification standard, and then adjust the engine operation to more optimal performance conditions when the vehicle was being opeated in real-world driving conditions. First, the vehicles could be "certified" by regulatory authorities. Second, the vehicle owners also received good performance and fuel economy in real-world driving conditions because of the more optimally timed fuel injection and lesser amounts of EGR. However, in real-world driving conditions, the vehicles also emitted large amounts of NOx.

Through the fuel injection timing advances and reductions in the EGR rate that would be used in the non-certification condition—that is, during real-world driving conditions—the driver would experience an increase in performance due to the more optimal combustion phasing and duration. The optimal combustion phasing and duration also allows for minimum fuel consumption. Furthermore, this condition would lead to the creation of the minimum amount of particulate emissions, meaning the DPF would not fill as fast. Less filling of the DPF means fewer regenerations are required, which means less fuel is used to keep the DPF clean, creating a secondary benefit in terms of fuel consumption.

In general, for all vehicles in which the defeat devices were active, there were large increases in the NOx emissions from the vehicle. Drivers also received benefits to fuel economy, and while precise data are not yet available, *Consumer Reports* made some measurements showing that defeat device vehicles experienced faster acceleration and lower fuel consumption.[4]

3 Challenges of Potential Fixes

3.1 What Is Currently Known about the Proposed Fixes

In Germany, VW has announced its plans to fix affected European engines.[5] The announced fixes for the vehicles with 1.2 and 2.0-liter engines is a software fix. The software changes in the ECU were not specified, but one can surmise that they will likely involve changes in injection timing, injection pressure, injection rate shapes, and EGR rates. For vehicles with 1.6 liter engines, in addition to a software fix, a flow transfer tube will be installed in front of the mass air flow sensor (MAF). It is claimed that the flow transfer tube in front of the MAF will result in more accurate measurement of the airflow into the engine, thus allowing more precise metering of the fuel for better emission control. Again, it is not clear what changes will be made to the ECU software, but they will likely involve injection timing, rate shaping, or EGR rates. Additionally, VW confirmed that the fix to the Amarok pickup truck—the only fix that has been implemented thus far—does indeed involve changes to EGR and fuel injection.[6]

3.2 Potential Problems Caused by Fixes

If VW intends to make its vehicles compliant with NOx emission standards in real-world conditions and actually be "green," "clean diesel" vehicles, then there will be no easy fixes. Changes in engine operating parameters associated with potential fixes can impact performance, fuel economy, and engine-out emissions, which in turn impacts the performance of the exhaust aftertreatment system. While the interactions are complicated, making precise predictions impossible without knowing the details of a proposed fix, it is possible to predict certain problems that will likely be caused by any fix. The absence of any NOx reduction system means that the combustion process must be altered to give engine-out NOx levels that meet the tailpipe certification. Based on the fundamentals governing engine and aftertreatment system performance, general statements can be made as to what the likely trends will be in vehicle performance, fuel consumption, and component durability after the defeat device vehicles are made emission compliant over that broad range of vehicle operating conditions.

The most likely approach to reducing the engine out NOx to the certification levels will involve EGR rate increases and fuel injection manipulation, such as injection timing retard, multiple injections, and/or injection pressure changes. The injection manipulation and increased EGR will decrease engine-out NOx, but will also

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[4] *Consumer Reports*, "How Volkswagen Diesels Perform in 'Cheat Mode'", available at https://www.youtube.com/watch?v=zUPnAA_Y3XI.
[5] *Volkswagen Group*, "Technical measures for the EA 189 diesel engines affected," available at https://www.youtube.com/watch?v=jKN8danpIfE; Jack Ewing, "Volkswagen Reveals Emissions Fix for Diesel Cars in Europe," N.Y. Times, Nov. 25, 2015.
[6] *Auto Motor und Sport*, "How is the VW Diesel Driving After the Update?," No. 5/2016.

increase particulate emissions, increase fuel consumption, and degrade engine performance.

For these reasons, attempting to fix the non-compliant vehicles with a software-only fix has the potential for large impacts on vehicle performance, both immediate and long-term. The immediate impacts would be increased fuel consumption from the different engine calibrations to reduce engine-out NOx. Along with the increased fuel consumption from retarded fuel injection timing and increased EGR rates, there will be a fuel consumption increase from more frequent DPF regeneration. Because changing the engine operating conditions to reduce engine-out NOx also increases the particulate matter leaving the engine, the DPF will need to be regenerated more frequently. Diesel fuel is used to raise the exhaust temperature to initiate DPF regeneration, meaning more fuel would be consumed by more frequent DPF regenerations.

For European vehicles, the more frequent DPF regeneration may cause the vehicle to fail the particulate number standard. During DPF regeneration, there is an accompanying increase in the number of particulates emitted. Excessive DPF regenerations could push the European vehicle out of compliance in terms of their particulate number standard.

Finally, there is concern for the durability of the DPFs of the vehicles once they are fixed. With higher particulate matter concentrations being emitted from the engine, the DPF will undergo many more active regeneration cycles during the vehicle's life. DPF durability could be a problem.

To summarize, using an understanding of the fundamental operating principles of engine/aftertreatment systems leads to a conclusion that the fixes will likely have immediate ramifications in fuel economy and vehicle performance, increased emission of the number of small particulates, and potentially long term durability issues for the aftertreatment system.

4 Recent Developments Regarding VW's Proposed Fixes

VW received initial approval for fixes to its 2.0, 1.6, and 1.2-liter vehicles in December 2015.[7] On January 27, 2016, KBA approved implementation to a small number of these vehicles, consisting of VW's Amarok pickup truck.[8] It appears that with this fix, VW is focused solely on passing the emissions tests and is not

[7] Jay Ramey, "VW's Fix Greenlit by German Authorities," Autoweek, Dec. 17, 2015, http://autoweek.com/article/vw-diesel-scandal/vws-fix-european-diesels-greenlit-german-authorities.
[8] Press Release No. 03/2016: Federal Motor Vehicle Office Grants Volkswagen the release of the technical solution for the vehicle model Amarok 2.0 Liter, Jan. 27, 2016, http://www.kba.de/DE/Presse/Pressemitteilungen/2016/Allgemein/pm03_16_vw.html.

concerned about emissions levels during real-world driving.[9] VW has acknowledged that it did not conduct real-world testing of the proposed fix.[10]

And indeed, later on-road testing has found that the fix to the Amarok does cause problems. Independent testing of the post-fix Amaroks found that the software change increased fuel consumption—in addition to not actually bringing NOx emissions into compliance with European emission standards.[11] It has been reported that as a result, approval of further implementation of the fix has been suspended by the KBA.[12] Additionally, independent research into the defeat device code found that when the vehicles operated in emissions-reducing mode for longer than VW intended, wear to the DPF increased.[13] It follows that because the fix will require vehicles to operate in a way that more effectively reduces NOx emissions, wear to the DPF will likely increase as a result.

In the context of VW's prior misrepresentations and these latest independent findings, in addition to the technical concepts explained above, VW's representations about the ease, inexpensiveness, permanence, and completeness of a fix are not plausible.

5 Conclusion

Producing diesel passenger cars that meet drivers' expectations of comfort, good performance, and low fuel consumption while also meeting strict emission regulations involves establishing a balance between maximizing engine performance and ensuring that the aftertreatment system is capable of reducing the emissions in the exhaust to levels sufficient to meet the regulations. With modern vehicles, manufacturers must control a complex system of many interacting, highly technical sub-systems. To manage the continuously varying trade-offs between optimizing engine performance, limiting fuel consumption, and meeting emissions standards, the interactions of these complex sub-systems are handled through the vehicle's control system, the heart of which is the ECU. It is possible to program the ECU to recognize when a certification test is being run and then forgo emission-compliant operation when the vehicle is not undergoing a certification test. This would allow the engine operation to be adjusted for better performance with lower fuel consumption and also conserve the fuel that would have been used in controlling the particulate emissions to keep the vehicle compliant. It would also minimize the age deterioration of the aftertreatment system.

Once the vehicles using defeat devices are fixed, one would expect that their fuel consumption will increase and their performance will decrease because of the

[9] Transcript of UK Parliamentary Hearing, Jan. 25, 2016, statement of Oliver Schmidt at 9, 30, http://data.parliament.uk/writtenevidence/committeeevidence.svc/evidencedocument/transport-committee/volkswagen-group-emissions-violations/oral/27791.pdf.
[10] Id. at 4.
[11] *Der Spiegel*, "VW-Abgasskandal: Passat-Rückruf droht Verzögerung," Feb. 19, 2016, http://www.spiegel.de/auto/aktuell/vw-abgasskandal-passat-rueckruf-droht-verzoegerung-a-1078382.html; *Auto Motor und Sport*, "How is the VW Diesel Driving After the Update?," No. 5/2016.
[12] *Der Spiegel*, "VW-Abgasskandal: Passat-Rückruf droht Verzögerung," Feb. 19, 2016, http://www.spiegel.de/auto/aktuell/vw-abgasskandal-passat-rueckruf-droht-verzoegerung-a-1078382.html.
[13] *Tagesscahu*, "Software-Update - obwohl VW gewarnt war?," Mar. 11, 2016, http://www.tagesschau.de/wirtschaft/vw-skandal-125.html.

adjustments necessary in the engine operation. There will also likely be additional increases in fuel consumption because of the more frequent DPF regenerations. Finally, concern of age deterioration of the DPFs will be of great concern, as they will experience more frequent active regenerations.